Proceedings for the 23rd Annual Conference of the Society for Astronomical Sciences (Formerly the IAPPP-Western Wing)

Symposium on Telescope Science

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Preface

The title says this is the 23rd annual proceedings, but in another sense they are the 1st under the auspices of the Society for Astronomical Sciences. The Society for Astronomical Sciences can trace its roots to the International Amateur-Professional Photoelectric Photometry (IAPPP), which was formed in June, 1980. The role of the IAPPP was to facilitate collaborative astronomical research between amateur, student, and professional astronomers, by providing a medium for the exchange of practical information not normally discussed at symposia or published in other journals.

The Western IAPPP Symposium, was held annually in the Southern California area starting in 1982. The symposium is held in Big Bear, California in the days before the RTMC Astronomy Expo. In 1998, the Western Wing of the IAPPP was formed. In 2002, the Western Wing incorporated and in 2003 renamed itself the Society for Astronomical Sciences (SAS). The Society for Astronomical Sciences is a non-profit corporation exempt under I.R.S. Code Section 501(c)(3).

So, while under a new name and with some new directions, one thing that has not changed is the annual meeting, now called the Symposium on Telescope Science. Through this two-day event, the Society hopes to foster new friendships and new collaborations among amateur and professional astronomers with the goals being the personal scientific advancement of Society members, the development of the amateur-professional community, and promoting research that increases our understanding of the Universe.

It takes many people to have a successful conference, starting with the Conference Committee. This year the committee members are:

- Lee Snyder
- Robert Stephens
- Robert Gill
- Dave Kenyon
- Dale Mais
- Brian D. Warner

There are many others involved in a successful conference. The editors take time to note the many volunteers who put in considerable time and resources. We also thank the staff and management of the Northwoods Resort in Big Bear Lake, CA, for their efforts at accommodating the Society and our activities.

Membership dues alone do not cover the costs of the Society and annual conference. We owe a great debt of gratitude to our corporate sponsors: Sky and Telescope, Software Bisque, Santa Barbara Instruments Group, and Apogee Instruments, Inc.

Finally, there would be no conference without our speakers and poster presenters. We thank them for making the time to prepare and present the results of their research.

- Dale Mais
- Dave Kenyon
- Brian D. Warner
Conference Sponsors

The conference organizers thank the following companies for their significant contributions and financial support. Without them, this conference would not be possible.

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SAS Partners

This is the first year of the Partners Program where businesses that sell to the astronomical community have joined with the Society for Astronomical Sciences to help promote research by amateurs around the world.

The following companies have joined the inaugural effort by agreeing to include a flyer promoting the Society and its activities with some or all of their products. Through this effort, we hope to encourage those who might not otherwise be inclined to take part in research after the purchase of their camera, telescope mount, or software to contact the Society and learn more about what they can contribute and how to go about it.

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If you are vendor that caters to the potential astronomical researcher and would like to take part in the Partners program, please contact one of the committee members at the conference or send an email to info@socastrosci.org
The A.L.P.O. Near Earth Object Photometry and Shape Modeling Program

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http://www.bitnik.com/mp/alpo/

Abstract: I will introduce and outline the new Near Earth Object Photometry and Shape Modeling Program of the Association of Lunar and Planetary Observers.
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References
2. For the purposes of this program, a close approach is considered to be within 0.1 AU of Earth or an object whose brightness allows for sufficient signal to noise ratios utilizing a typical amateur sized telescope.
4. “Asteroid Models from Disk-integrated Data” Mikko Kaasalainen, Stefano Mottola, Marcello Fulchignoni, _ Asteroids III_ University of Arizona Press, 2003
5. Personal Correspondence, Lance Benner, March, 2003

1. Introduction

During the 19th century, amateur astronomers conducted a large percentage of asteroid studies. Indeed, amateurs pioneered several fields of asteroidal study, including discovery of these objects utilizing photography, as well as attempts at rotational period determination and spectroscopic analysis. [1] As the 20th century dawned, amateur contributions to astrometric and physical observations declined due to the necessary increase of telescope apertures required by observers to remain active in the field. Only a very few amateurs continued to make asteroid observations for the next 80 years.

In the last decade, amateur discovery and observations of asteroids saw a dramatic rise in amateur interest, due to the availability of inexpensive computers and CCDs. At that time even relatively small backyard telescope could discover and track literally hundreds of new objects. In the closing years of the 1990’s, professional NEO surveys, such as Spacewatch, LINEAR, and LONEOS came online. As a result of the torrent of discoveries and ancillary astrometry, amateurs are now finding that they are again being squeezed out of the field due to their limited telescope apertures, just as their brethren had been a century earlier. The most recent “Golden Age” of amateur asteroid discovery and astrometry is rapidly coming to an end.
2. The A.L.P.O. NEO Program

While nearly a century had elapsed from one amateur “Golden Age” to the next, in these modern times, amateurs don’t have to wait decades to become useful again. Indeed the newest Golden Age is already rapidly dawning! Professional astronomers are aware of the value and powerful potential held by the backyard observer. The A.L.P.O. NEO Photometry and Shape Modeling Program is being developed to allow amateurs with commonly available telescopes and CCD cameras to continue to provide valuable observations of asteroids, and specifically, Near Earth Objects, for the foreseeable future. Amateur observers are the only group with the opportunity to accomplish the goals of this program. Their sheer numbers as well as their ability to observe with virtually unlimited telescope time and to immediately respond to Targets of Opportunity, make the amateur observer a vital component in our understanding of these fascinating objects.

The professional surveys are tasked to provide an inventory of 90% of all NEOs which are 1 km in diameter and larger. While discovering and following these objects to determine if they are on a trajectory that could impact the Earth is their primary concern, this knowledge adds little to our overall understanding of their physical makeup. Obviously the best method to understand the actual shape and makeup of these objects is to visit them with robotic probes. While there have been several successful missions which visited a few of these objects, with several more ready to fly or in the planning or construction phase, we have no ability to react quickly to explore the vast majority of NEOs in situ.

Following my discussion you will hear how teams of professional astronomers utilize the radio telescopes at Arecibo and Goldstone to make radar observations of NEOs. These astronomers can determine the size, shape, rotational period and pole position of these objects as well as potentially imaging surface features, such as craters. While many of these observations are planned well in advance, [3] newly discovered objects present targets of opportunity for these teams. Amazingly, amateur astronomers utilizing their backyard telescopes can also gather much of this information as well!

The A.L.P.O. NEO Photometry and Shape Modeling Program has been developed to form a core of photometric observers for the purposes of rotational period, pole determination and shape modeling.

The program is broad ranging enough to provide relatively new photometrists a large number of interesting targets of study and we offer the experienced photometrist that will stretch the capabilities of his telescope and challenge his photographic skills.

3. Observational Requirements and Procedures:

The A.L.P.O. NEO Photometry and Shape Modeling Program’s primary collaborator will be a team lead by Mikko Kaasalainen normally of the University of Helsinki, but now on leave at the University of Oulu in Sodankyla, Finland.

Mikko and his team are currently studying inverse problems in the fields of solar system studies, exoplanetary systems research, and dynamical galactic modeling. [3] Using this advanced method, the team can take photometric lightcurves of an asteroid, made over several apparitions to derive the object’s shape, its rotational state, pole position and the scattering properties of its surface. This method has been tested rigorously and resulting models have been confirmed via several spacecraft fly-bys. It has been determined that the resolving capacity of lightcurve inversion lies between the space telescope and radar observations. [4]
Now I will not be discussing the science and mathematics behind the actual shape modeling, as I am not qualified to do so. What I am here to discuss is what it will take for an observer to contribute vital data for this effort.

The participating observer may use any telescope at his or her disposal and it has been found that typical amateur sized telescopes of approximately 20 cm aperture can make useful and valuable contributions to this effort! The primary objective for this program is for the observers to obtain precise photometry (on the order of 1%-2%) with several tens of data points per rotation of the object.

The use of a V filter for these observations is preferred. The observer may substitute an R filter instead. This will allow for the observations of multiple observers to be combined more easily. However, unfiltered observations are also permissible to allow for the highest signal to noise ratios possible with smaller telescopes. The primary use of the data does not require rigidly standardized magnitudes, but instead utilizes the variation in intensity of the light measured over several apparitions.

For objects with previously obtained lightcurves, a shape model may become possible with the addition of only a modest amount of new observations. The preferred method would be to observe the object well before opposition, during opposition and again well after opposition. The rather minimal requirements of aperture and filters, and the possibility to run unattended in a robotic mode, this program ideally suited to a large number of amateur astronomers around the world.

Kassalainen’s team currently has an “Alert List” of both Near Earth Objects and Main Belt Objects. Many of these objects require only a few additional rotations worth of data to confirm their shape models. Indeed a larger number of these objects are relatively bright and can be observed with the typical amateur telescopes available today. We are encouraging ongoing observations of these objects to provide useful data for this most basic effort as well as preparing our observer core to be ready for when things get very interesting.

The interesting part occurs several times per year when newly discovered NEOs make close approaches to the Earth. We are attracting a skilled and active core of observers who will be able to respond quickly to these Targets of Opportunity and obtain photometric data during these very short events. Indeed it is understood that these objects are often near their peak brightness when they are initially discovered and only the amateur community can respond rapidly enough to obtain the required data.

With sufficient coverage over a large change in lighting and viewing (phase) geometry, a shape model for these objects can be determined.

The second group of professional collaborators with the A.L.P.O. NEO team are the professional teams who make radar observations of known and newly discovered NEOs. Early photometric determination of rotational periods made by amateurs will allow the radar teams to perform several vital functions, including the planning of their own observations as well as greatly enhancing their ability to reconstruct three dimensional shapes using radar data. Additionally, there are a number of NEOs that have been observed with radar, but for various reasons, no shape model could be determined. Additional photometric observations of these objects to determine a rotational period could provide sufficient constraints to significantly increase the value of radar data that has already been collected. [5]

Finally, by obtaining photometric observations of an object over its entire apparition, the shape models determined by the Helsinki team and the radar teams will provide vital confirmations for each modeling method.
Participating observers would be notified of program targets both via direct email and via the Helsinki Standard Asteroid Photometric Catalogue (SAPC) website (under construction). The resulting reduced observations will be uploaded directly to the SAPC website to be combined with the data from other observers. Participants will also be notified of newly discovered Targets of Opportunity via direct email notification. Publication of the resulting shape models will be in batches of 10 to 20 objects, submitted to journals such as Icarus and Astronomy and Astrophysics. [6] Observers submitting data will be named as coauthors in any paper that utilizes their data. Brian Warner’s Collaborative Asteroid Lightcurve Link [7] website will also provide details and mirror some of the functions of the SAPC site. Additional information about this program will be published in the Minor Planet Bulletin and the JALPO. The data would remain the property of the observers and they will be free to submit it for publication as they see fit.

I do want to be clear on this point. Basic unfiltered relative photometry is acceptable and we encourage new photometrists to join us and obtain data for the program. We also have a need for advanced and expert photometrists. There is plenty of work for all of us!

4. Conclusion

In the last decade, due to advancements in computer and detector technologies, amateurs have regained their rightful place in the field of minor planet research. While there is less opportunity for observers with limited instrumentation to enjoy the “glamour” and excitement of being able to discover new asteroids, there is still much useful science that can be obtained by tapping into the resources of virtually unlimited telescope time and an available, skilled and motivated group of observers. The dawn of the third “Golden Age” of amateur asteroid studies is upon us. The A.L.P.O. NEO Photometry and Shape Modeling Program will be able to provide an important, direct link between the amateur observer and the professional scientist in building our knowledge of these fascinating and important objects in the years to come.

For current program details and campaigns, please visit the program web pages at: http://www.bitnik.com/mp/alpo

Acknowledgements

I would like to thank Alan W. Harris, Lance A. M. Benner, and Mikko Kaasalainen for their assistance in the development of this paper. I am also indebted to Steven Larson and Frederick Pilcher for their input, support and patience while I have been working on the early stages of this program and this introductory paper.
Abstract. Over the past decade, several all-sky photometric surveys have taken place or are underway. The typical amateur astronomer might think that these surveys have found everything there is to discover in the sky in the magnitude ranges of their telescopes, and that there is no reason to consider a photometric program. Similar surveys have been performed for asteroids, for example, and it is very hard for an amateur to now discover new, bright asteroids. In fact, the optical photometric surveys have quite the opposite effect for variability studies. While the surveys have been very proficient at finding variable objects, they are not well suited for detailed studies of the objects they find. This talk will highlight the most current surveys and what kind of objects and limitations are present in each.

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References


1. Introduction

Creating surveys is a direct follow-on to the research of many astronomers: studying a specific class of objects. What better way to study that class than to find all of its possible members? Surveys have been performed in various passbands, covering the entire sky only once or a small portion of the sky multiple times, and with different instrumentation from direct imaging to spectroscopy. Many of these surveys have little interest for the typical variable-star observer, but many of the recent ones have direct relevance. What will be covered in this paper will be some of the photometric surveys that can be useful to the observer. This paper covers much of the material presented in Henden (2003), but from a different perspective.

One of the main concerns from both amateurs and professionals alike is whether existing surveys are general enough that they encroach on the possible observational research projects that can be done by individuals. This has happened in the asteroid community, for example. About a decade ago, it was easy for small telescope users to find new asteroids, spend a few nights obtaining astrometry and becoming the discoverer of those asteroids. The incentive for many amateurs is that the discoverer of an asteroid has the privilege of naming that asteroid. However, several professional sites obtained funding to implement asteroid searches, primarily to locate near-earth objects that had the potential to impact the earth and cause significant damage. These sites, such as LINEAR, NEAT, Spacewatch and LONEOS, soon developed instrumentation and software sufficiently complex to pretty much discover any asteroid brighter than about 20th magnitude. Since this is the limiting magnitude for many small telescopes, the number of individual discoveries has dropped dramatically. There are certainly other asteroid-related...
projects that small telescopes can do effectively, but discovering new asteroids is not one of them anymore.

Will the same thing happen for variable-star enthusiasts? This depends on the details of the current ongoing and future surveys. In most cases, the surveys help rather than hinder, and this paper is designed to show how one can use the surveys to further their own variable-star and other photometric research.

2. Astrometric Surveys

There have been astrometric surveys for centuries. The recent ones have built upon the massive photographic surveys carried out by the meter-class Schmidt telescopes during the last half of the twentieth century. These large photographic plates were digitized by groups at the Space Telescope Science Institute (STScI), CalTech, U.S. Naval Observatory (USNO), Royal Greenwich Observatory, and others. The most frequently used products from these digitization efforts is the USNO-A2.0 and USNO-B1.0 catalogs. These provide all-sky coverage, astrometric accuracy in the 0.25arcsec range, and with a limiting magnitude of around 21st. Their main deficiency is the inability to deblend the crowded Milky Way fields. However, for most variable-star and asteroid work, the USNO-B catalog provides a reference frame for determining the object positions, and by going to the pixel servers such as

http://www.nofs.navy.mil/data/FchPix/

You can download small extractions of the digitized plates that cover specific areas.

We have used these extractions when determining which of a close pair of stars was variable (since there are often 5 or more plates that cover a specific region, and those plates were taken many decades apart), the progenitor of novae, approximate colors of objects, etc.

Some variability studies have been performed using the Sky Survey plates. Drissen et al. (1994) used the SRC-J plate overlap regions (one square degree corners of each plate) to look for variable objects. Since the plate corners have the most photometric problems, only high amplitude variability can be studied in this manner. However, the digitized plate material has not been datamined beyond Drissen’s study.

There are other astrometric surveys, of course. The Hipparcos satellite carried an experiment called Tycho that surveyed all stars brighter than about 11th magnitude, determining quality photometry in two colors as well as astrometric positions that have typically a few tens of milliarcsec accuracy. An ongoing astrometric survey is UCAC, involving CCD imaging of the entire sky down to 16th magnitude and with similar accuracy as Tycho. There are a couple of other smaller astrometric surveys, such as the CAMC, that have good accuracy but do not cover the entire sky.

The main use of the astrometric surveys/catalogs is for astrometry. They rarely have good photometry since their primary goal is the positions of objects.

3. Photometric Surveys

There have been many photometric surveys in various passbands. These surveys try to cover the entire sky to some limiting magnitude, typically only acquiring one observation per object. The primary use of these surveys (as far as the variable star enthusiast is concerned) is for providing a photometric reference frame for observations.
Tycho2 is the catalog produced by the Tycho team for the Hipparcos satellite. This instrument surveyed the entire sky with a photoelectric photometer in two passbands that are very similar to Johnson B and V. The limiting magnitude is about 11, with photometric errors increasing dramatically beyond about 10\textsuperscript{th} magnitude. You can download the entire 2-million star catalog from

http://www.astro.ku.dk/~erik/Tycho-2

(and a CD is available), but most users just access the catalog from the VizieR site:

http://vizier.cfa.harvard.edu/viz-bin/VizieR

(plus several mirror sites around the world). In fact, many of the catalogs mentioned in this paper can be searched from VizieR, and it should be the first place anyone looks. VizieR, for example, provides columns of converted Bt/Vt magnitudes into Johnson B/V magnitudes. We will discuss Tycho2 in more detail in the next section.

The Carlsberg Meridian Telescope (CAMC) is a converted transit telescope that uses a CCD to map the southern sky, primarily for precise astrometry. However, they do use the SDSS r’ filter, similar to Cousins R, and provide magnitude information in their catalog. You can access the catalog from

http://www.ast.cam.ac.uk/~dwe/SRF/camc.html

The USNO CCD Astrometric Catalog (UCAC) is again primarily an astrometric catalog. They used a 20cm telescope with CCD and a non-standard filter that is halfway between Johnson V and Cousins R. The photometry is relatively good, and is quite good differentially (stars within the same small field). You can access the catalog at

http://ad.usno.navy.mil/ucac/

The Two-Micron All Sky Survey (2MASS) was an all-sky survey in the JHK passbands. The photometry is good, and can often be used in conjunction with a single optical passband (such as V) to provide color information necessary for selecting comparison stars in a field or doing transformations. The main site is

http://www.ipac.caltech.edu/2mass/

but again you can access it through VizieR.

The Deep Near-Infrared Survey (DENIS) was a competitor to 2MASS, covering only the southern sky in SDSS I’ and near-IR JK passbands. This single-epoch catalog has reasonable quality photometry, gives an optical passband, and can be used in conjunction with 2MASS to look for variability. You can access the catalog at

http://www.denis.iap.fr/denis.html

The Roentgen Satellite (ROSAT) point source catalog contains some 95K sources over about 15percent of the entire sky, covering from about 0.1 to 2.0 kev energies. You can access the catalog through VizieR, or go to the home page

http://wave.xray.mpe.mpg.de/rosat/rra/

The Faint Images of the Radio Sky at Twenty Centimeters (FIRST) survey began in 1993 using the VLA at a frequency of 1.5GHz. It is slated to cover 10K square degrees of the North and South Galactic Caps and is essentially complete. You can access the catalog through VizieR or at the FIRST home page

http://sundog.stsci.edu/
The Midcourse Space Experiment (MSX) used a 35cm space telescope to survey the entire sky in 6 bands from 4.3 to 21 microns. The catalog contains 529724 point sources and is more complete and with higher spatial resolution than IRAS, but without the long wavelength bands. The MSX mission is described on its project page

http://www.ipac.caltech.edu/ipac/msx/msx.html

The InfraRed Astronomical Satellite (IRAS) was a mission that covered the entire sky in the 12, 25, 60 and 100 micron regions. The point source catalog, containing some 250K sources, can be obtained through VizieR.

The Sloan Digital Sky Survey (SDSS) is an ambitious ground-based project that is covering about 10K square degrees of the sky in 5 wavelengths (ugriz) down to 22nd magnitude. About a million objects will also have spectra; most of these are galaxies, but a fair number are stars. You can access the current data release at

http://www.sdss.org

The photometry is very good, saturating at about 14th magnitude. Conversions from the SDSS ugriz system into the Johnson-Cousins system are available.

Note that very few of these all-sky catalogs cover the visual wavelengths, and those that do typically have non-standard filters. Their primary use is in determining colors of objects in your fields, for finding objects with peculiar colors, and studying objects at wide wavelengths.

4. Variability Surveys

There have been a few surveys designed either specifically for finding variable objects, or with survey attributes that permit variability searches.

The Robotic Transient Search Experiment (ROTSE) operated a very wide-field unfiltered camera system in New Mexico for many years. One year’s worth of data was processed and searched for variable objects. That database can be interrogated at

http://skydot.lanl.gov

Called the Northern Sky Variability Study, it contains information on millions of stars down to about 14th magnitude.

The All-Sky Automated Survey (ASAS) is an ongoing survey using small automated telescopes at Las Campanas Observatory. It provides V-band photometry over the entire southern sky. The web page

http://www.astrouw.edu/pl/~gp/asas/asas.html

has a user interface to obtain both photometric and time series information for any star or region of the southern sky. A northern hemisphere version of this survey (HAT) is underway at KPNO.

The Amateur Sky Survey (TASS) uses pairs of 10cm telescopes to image 4x4 square degrees in the sky simultaneously at V and Ic. They have covered the entire northern sky at least once, and intend to revisit all fields as often as possible for several more years. They have a photometric catalog available at

http://www.tass-survey.org

The catalog is relatively complete from about 7th to about 13th magnitudes, with crowding problems in the Milky Way.

The Lowell Near-Earth Object Survey (LONEOS) uses a 0.5m Schmidt telescope plus CCD array to image large regions of the sky every night. Their photometric data has been archived
and is being searched for variable objects. You may be able to access specific objects by checking with the LONEOS team

http://asteroid.lowell.edu/asteroid/loneos/loneos.html

Note, however, that LONEOS observes unfiltered. Similar datasets are potentially available from NEAT, LINEAR, SPACEWATCH and other NEO surveys.

The Quasar Equatorial Survey Team (QUEST) used the CIDA Schmidt telescope in Venezuela to survey the equatorial zone between -6 and 6 degrees declination in BVR, along with obtaining objective prism spectra of many of the objects. A complete catalog has not been posted on-line, but you might try the web site

http://www.astro.yale.edu/bailyn/quest.html

to get more information.

SDSS. As mentioned above, SDSS provides 5-filter photometry of a large region of the northern sky. It also covers a southern strip multiple times to search for variable objects, and intends to expand its program to perform more galactic structure projects in the near future. In addition, there are overlap regions on most of the scans that can provide variability information, albeit with only a few visits. The variability information is not yet available, but you can check at the web site for updates.

The Massive Compact Halo Object (MACHO) experiment used the Mt. Stromlo 50-inch telescope and a twin-beam CCD camera to obtain simultaneous V and R photometry for many millions of objects in the Galactic Bulge, LMC and SMC. The data is on-line at

http://www.macho.anu.edu/au/Data/MachoData.html

While the spatial coverage is not large, this database is great if your stars happen to fall within one of their fields.

The Optical Gravitational Lensing Experiment (OGLE) uses a 1.3m telescope with V and I filters at Las Campanas to image dense star regions such as the Galactic Bulge, SMC and LMC to look for MACHO events. Their data is also useful to look for any kind of variability. You can find results at


However, their full catalog is not available on-line. Note that there are many other surveys for MACHO-like events, again covering only small regions of the sky.

There are several ongoing experiments to look for planetary transits (such as STARE) that cover small regions of sky, much like the MACHO experiments. If your objects happen to fall in those regions, then considerable photometry will be available.

5. Future Surveys

The Galaxy Explorer (GALEX) will survey the entire sky in two UV wavelength bands. It has started to release data. See the web page

http://www.srl.caltech.edu/galex/

for more details.

The Panoramic Survey Telescope and Rapid Response System (PanSTARRS) is an innovative design for wide-field imaging. Using 4 2-meter telescopes, each with a 3 degree field of view, it is planned to cover the entire sky several times each month. The first telescope is planned to be on-line in 2006. What filters (if any) that will be used is still to be decided; how-
ever, since it is funded by the federal government, all data will be publicly accessible. See the web page

http://pan-starrs.ifa.hawaii.edu/public/index.html

for more details.

The Global Astrometric Interferometer for Astrophysics (GAIA) spacecraft is expected to obtain precise positions (and parallaxes) for all objects brighter than 18\textsuperscript{th} magnitude. It will also obtain photometry in several passbands and spectra of most objects brighter than about 15\textsuperscript{th} magnitude. The launch date is still uncertain, but probably not before 2012. The web page is

http://astro.esa.int/gaia

QUEST2, like its predecessor QUEST, was conceived as a quasar survey experiment. The camera is already in use at the Palomar 1.2m Schmidt telescope. This experiment is now envisioned as a stellar survey as well, with multiple visits per field to obtain variability information. See the web site

http://hepwww.physics.yale.edu/quest/palomar.html

for more information. The camera is being shared with the NEAT team.

The Large-aperture Synoptic Survey Telescope (LSST) is a proposed 8-meter telescope with a very large field of view. It is designed to do repeated observations of about 20K square degrees of sky very rapidly, perhaps every few days depending on the final science goals. This telescope is unlikely to go on-line until 2010-2020 timeframe. See the main web page at

http://www.dmtelescope.org

SWIFT (no acronym) is a multi-wavelength space mission designed to study gamma-ray bursts in detail. At the same time, it will be performing a sensitive survey of the sky in a hard x-ray band. Launch is expected in the Fall of 2004. See its web page

http://swift.gsfc.nasa.gov/

for more detail.
6. Using the Surveys

Even the existing variability surveys do not usurp the role of the small telescope. There is just too much sky to cover, especially when multiple wavelength coverage or high time resolution are needed. What most of the variability surveys provide is knowledge as to whether a star is variable or not. The constant stars are then usable as comparison stars for performing differential photometry in a field. The variable stars may have crude light curves from the surveys that can be improved by detailed observing of each object. For example, eclipsing binaries can use time-series data in multiple passbands to provide input for analytical models of the systems. Long period variables like Miras and RV Tauri variables may have good light curves in the variability surveys, but usually only in one wavelength band and often only for a few years. The long-term light curves such as provided by the AAVSO may contain far more useful scientific information on long period variables than any short-term survey. So the main role of the variability surveys is to provide a long list of targets for which detailed studies are desired.

Summary

This paper has primarily given a long list of existing and future survey projects. Web links for most of these surveys are provided. While links have a habit of disappearing in short timescales, most of these projects have been adequately funded to provide a home for their databases for many years to come. Archival sites like VizieR and the upcoming Virtual Observatory program will be another means of keeping these datasets on-line. When you are studying variable objects, investigate some of these datasets and see if additional photometric information might be available. Sometimes it can help you decide whether an object is worth further study, or to choose a set of objects that are convenient to study with the equipment in hand. There are thousands of variable objects in need of photometry, so enjoy the process!
Uncool Science: Photometry and Astrometry
with Modified Web Cameras and Uncooled Imagers

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Abstract: This paper discusses techniques that allow useful scientific observations to be performed with digital still cameras, modified webcams and low cost uncooled astronomical imagers. The paper emphasizes technique changes relative to the use of traditional cooled CCD sensors that are required to get good results. Areas discussed include dark subtraction, statistical considerations in automatic image stacking, QE, sampling theory of color and interlined sensors. © 2004 Society For Astronomical Sciences, Inc.

References:

1. Introduction

In the last few years, development of a robust consumer market for solid state imaging has led to the creation of several new products that can now be used for scientific imaging. These devices are now produced in sufficient quantity that they are priced within the means of most interested amateurs. Normal prices of consumer grade imagers are about $1/10^{th}$ the price of similar format cooled scientific imagers. Examples of such new uncooled imagers include
Using an uncooled consumer imager for astronomical imaging is very similar to using a scientific camera in many ways, but uncooled imagers have some characteristics that require different techniques to reach their full potential. This paper seeks to explain how to use these uncooled imagers to their best effect and to recognize and characterize their fundamental limitations.

2. Contrasting The Technologies

Consumer grade imagers actually offer some advantages relative to cooled scientific imagers. Foremost among these is price. An uncooled VGA format imager can be purchased for around $100 USD, while the least expensive cooled CCD of similar dimension costs about $1500. Similarly, large format digital still cameras in the 4 mega-pixel range cost about $1000 USD, while cooled CCD cameras in the same format run upwards of $10,000 USD.

Like cooled CCD’s, consumer grade imagers offer the advantages of direct digital readout and linear response to light over their useful dynamic range. Thus, both are arguably superior to film in this respect. Consumer grade imagers however, tend to have fewer bits per pixel than scientific imagers. Typical uncooled sensors have 8 to 10 bits of resolution, while cooled CCD’s tend to have 12 to 16 bits per pixel.

Due to the efforts of several dedicated amateurs and some professionals, there is a wide variety of software that is either bundled with the cameras, or inexpensively available off the Internet for science data acquisition with these cameras. Once image acquisition is complete, the same image reduction and processing packages that are commonly used with cooled cameras can be used. Some such common packages include IRAF, CCD-OPS, Maxim DL, Autostar IP, and Astromet.

Although a few uncooled imagers are available with monochromatic sensors, most common models are “one shot” color imagers. In this respect they differ from cooled scientific cameras. This is both a benefit and detriment. One does obtain a perfectly registered and color balanced image in a given exposure, but in doing so, one sacrifices spatial resolution. The figure below is illustrative of the problem:
The imager is overlayed with a set of filters deposited directly on the surface of the imager. Typically, these filters are in the form of a Bayer Pattern where a 2x2 submatrix of the pixels has the form:

```
G R
B G
```

This pattern has two undesirable effects, first it means that you need to over sample by a factor of 2X relative to a monochromatic sensor to assure the same astrometric accuracy. Secondly, by doubling your sample rate, you get on ¼ the light falling on a given pixel, requiring longer exposure of your image to achieve comparable signal to noise ratios. Finally, the filter material deposited on these chips is not as transmissive as the interference filters used with cooled scientific imagers. Epitaxially deposited filters are typically only half as transmissive as interference filters.

The defining difference in consumer cameras is the lack of active cooling of the imagers. The lack of active cooling means that the thermal noise in these imagers is higher. While thermal noise can be effectively reduced by dark subtraction techniques, it is the buildup of thermally generated electrons in these sensors that ultimately limits the duration of the exposures that can be obtained. When the accumulation of thermally generated electrons added to the imaged photo-electrons exceeds the linear operating range of the sensor, you have reached the maximum exposures. The good news is that fabrication processes and packaging have improved to the point where some of these sensors can be run up to a minute before this practical limit is reached. In practice, exposure times of 10 to 20 seconds are more typical.

One of the positive impacts of the relatively short exposure time, is that for most applications, no telescope guiding is required. Most good, properly aligned mounts track well enough open loop to allow 20 second exposures with out objectionable trailing. Since images will be built up by combining multiple exposures, guiding can be eliminated in favor of shifting and aligning the individual images prior to combining them. Another benefit of this combination of many frames is that variation in the seeing and tracking, tend naturally cause the images to be dithered enough to compensate for the bayer pattern filters. In other words, you do not suffer the loss in astrometric accuracy if a statistically large number images are combined.
3. The Mathematics of Stacking

To compensate for the limited exposure time of an uncooled imager, you must, instead of taking a single long exposure, take a series of shorter exposures and add, average or otherwise combine them together to build up a good image. This stacking of many, many images is the key to getting good results with uncooled cameras.

In order to understand how good an image we can get relative to a comparable cooled imager, we need to talk about image quality in terms of signal to noise ratio, or S/N. This is an unbiased quantitative measure of image quality. It is the ratio of signal information, to random contamination in an image. Perceptually, images with poor signal to noise ratios appear “grainy”.

For the sake of this discussion, let us assume that we have two imagers. One is cooled and one is not. Further, assume that the sole source of noise in our images is read noise, and both cameras’ read circuits perform equivalently. Read noise results from random effects while digitizing the pixels and reading them out of the camera. While this is not strictly the case in the real world, it is the most significant component of noise after we have performed our dark subtraction. Suppose that for a cooled camera we have the following system read noise

\[ S = N(\text{exposure}(T)) = X \]

Increasing the exposure time by a factor of \( m \) therefore improves the signal to noise ratio to:

\[ S = N(\text{exposure}(mT)) = mX \]

Simply because we have gather \( m \) times as much signal and still have only one read’s worth of noise in the image. For our uncooled imager, if our maximum exposure time is \( T \), then we must take \( m \) exposures and add them together. Doing so, does not achieve the same signal to noise ratio. Due to the net effects of averaging noise, our signal to noise ratio is:

\[ S = N(m \times \text{exposure}(T))^\frac{1}{2} \approx \frac{1}{m}X \]

This demonstrates the fundamental limitation of image stacking. For equal total exposure times, uncooled imagers signal to noise ratio under performs a single long exposure by the one over the square root of the exposure count.

To understand what this means in practical terms let us work through an example. Assume:

1. Our uncooled imager can take exposures up to 10 seconds before running out of dynamic range.
2. It has filters \( \frac{1}{2} \) as transmissive as the interference filters on the monochromatic cooled camera.
3. The read noise performance of the cameras is similar.
4. The cooled camera will needs to take 3 exposures, R, G and B filtered.

The question we need to answer is: “How many exposures and how much time will it take to make a color image with our uncooled camera as good as one made from 3 one minute filtered imagers with the cooled camera?” For the cooled camera we get the signal to noise from the functions above:
\[ S = N_{\text{cooled}}(\text{exposure}(60)) \times X \]

With our uncooled camera our S/N in a single images is as:

\[ S = N_{\text{uncooled}}(\text{exposure}(10)) \times \frac{X}{12} \]

Since we need 12 squared images to get to the same signal to noise ratio, we get the following total times:

\[
\begin{align*}
\text{Time}_{\text{cooled}} &= 3 \times 60 = 180 \text{sec} = 3 \text{min} \\
\text{Time}_{\text{uncooled}} &= 12^2 \times 10 = 1440 \text{sec} = 24 \text{min}
\end{align*}
\]

This example clearly demonstrates both the benefits and limitations of using uncooled imagers. Firstly, the analysis ignores the difficulties and time involved with framing and focusing the target. Assuming your are a skilled technician, this effort can still take a couple of minutes. Even so, it is pretty clear that the user of a cooled camera is going to be more productive than you are. The consolation is you spent a whole lot less money, and as an amateur, you are supposed to be enjoying the time you spend doing this, so you get more fun per image!?

4. Tips and Tactics

There are several other key elements that go into making successful images with uncooled imagers. Firstly, select the best imager possible. There are two technologies prevalent in the market, CMOS and CCD. CMOS imagers are cheaper since both the imager and readout electronics can be placed on a single chip. CMOS’s drawback is that it has significantly lower QE than CCD chips. If possible select a camera with a CCD image sensor.

Regardless of what sensor you have, you must be able to Turn Off All Compression. Image compression for all of these consumer grade imagers is lossy. That means information is lost during the compression process. Data compression will make it impossible to dark subtract, calibrate and benefit in any predictable way from stacking. Be sure the camera you select allows you to save images without compression.

Similarly, the camera must allow you to override any automatic gain, and black or white level settings. At a minimum, you must be able to disable AGC. If the gain changes from image to image, you cannot sensibly combine or calibrate them. Some cameras automatically set the black level. This can make it difficult to perform dark subtraction. There are some software packages with routines that attempt a dynamic, least noise offsetting of dark frames for cameras that cannot disable automatic black level controls, but it is much easier if this problem can be avoided.

Assuming you have black offset control set the background level so that no pixel in your dark frames has a zero values. This guarantees you will be able to calibrate all your images effectively. The histogram in Figure 6 demonstrates how a properly configure image capture software should appear.
Further on the subject of dark frames, though the camera may not be cooled, that does not mean that it runs at a constant temperature. The electronics in the camera generate heat. This generated heat needs to be dissipated to the outside environment. Only when the camera sheds heat at the same rate that it generated it does it reach thermal equilibrium with its environment. Only then will its temperature stabilize. You should therefore, start your camera running at the frame rate and exposure time you will be using and give it some time to reach equilibrium, then take your sequence of dark frames. As with everything we do with uncooled imagers, you should take many (50+) dark images and average them together to form your master dark image. Additionally, you need to take new darks anytime the point of thermal equilibrium changes. That can mean an increase in the breeze that changes convective cooling, or a drop in the ambient temperature as the night deepens. Additionally, you will need to take new darks whenever you change the camera duty cycle, exposure time or inter frame delay.

If possible, you should get an imager that has square pixels. Imagers without square pixels are going make astrometry and photometry more difficult. You will have to resample your images. In doing so, you will need to use a routine that is flux conserving. This means that the scaling routine must accurately preserve the total ADU counts in your images even after scaling. There are not many Windows based image processing programs that satisfy this requirement.

Always expose at the highest ISO or gain setting available with your camera. Most uncooled imagers have limited number of bits per pixel, that means that they are coarsely dividing the signal you are receiving. Since our exposure are necessarily short anyway, better to turn up the gain and spread these over as large a range as possible.

Use floating point pixels when combining your images. Related to the previous comment, you are attempting to make up in quantity, what our imager lacks in quality. It is important the software you use to combine images keeps the fractions of pixels around. One way to appreciate this is to suppose you add 8000 eight bit images together. If your program cannot represent numbers larger than 65536 (16 bits) you will end up with numerically saturated images since the largest value you might reasonably obtain is 2,040,000. Furthermore, you probably do not want to add your images, but rather average them. This will allow you to reasonable compare runs from different nights made up of different integration periods. Under these conditions, floating point numbers are a requirement.
Another implication of the tactic of stacking overwhelmingly large number of images is that you either need software that can do this on the fly, or you are going to need lots and lots of memory. Particularly if you are a digital still camera user, bring lots of chips, or a pair of them and a computer so that you can read one into the computer while you fill the other.

5. The Video Fallacy

The notion that you will ever be able to achieve satisfactory results with web cameras or video cameras that have maximum exposure times of a fraction of second is fallacious. You are going to have to get a digital still camera, modify a web camera for long exposures, or purchase one of the new uncooled astro imagers that allows longer exposures. To illustrate this point let us revisit the stacking example above, except assume you have a video camera that can only expose \(\frac{1}{60}\)th of a second images. Again assume you have the same read noise as the cooled imager and filters with 50 percent the transmissivity. Again we have the S/N for the cooled camera:

\[
S = N_{\text{cooled}}(\text{exposure}(60))@X
\]

For our video web camera we have:

\[
S = N_{\text{uncooled}}(\text{exposure}(\frac{1}{60}))@\frac{X}{7200}
\]

Now look at the time comparison:

\[
\text{Time}_{\text{cooled}} = 3 \times 60 = 180\text{sec}
\]

\[
\text{Time}_{\text{uncooled}} = 7200^2 \times \frac{1}{60} = 2884000\text{sec} = 240\text{hrs}!
\]

The conclusion is obvious. Save video for targets that are very bright such as planets and the Moon. For planetary images, the short exposure time which hinders your efforts at deep sky photography actually benefit you by allowing you to employ selective image reconstruction. An uncooled imager can even outperform cooled imagers in this regime. The method takes many images and selects only those imagers that freeze instants of perfect seeing and combines and aligns only those images. In order to make very short exposures, most uncooled imagers are electronically shuttered, so they transmit no mechanical vibration to the telescope as shutters open and close. Additionally, the support streaming output formats that are better suited to storing and processing collections of upwards of 50,000 images.

6. Image Acquisition Software

The key to using an uncooled camera is to gather many images under controlled circumstances and combine them. Doing such a thing manually is beyond tedious. With uncooled imagers you are not talking about tens of imagers, you are talking about hundreds, thousands and tens of thousands of images. Processing such collections by hand, or using point and click image processing is unthinkable. To solve this problem several good software packages are available. Though they differ slightly in philosophy and emphasis, they all do a reasonably good job of
automating this process. While I am sure I am omitting some worthy entries, here is a partial list of what is available and some key elements of the package.

**Astro-Snap**
http://www.astrosnap.com/index_uk.html
Complete acquisition system for modified web cams, scope control, camera assisted alignment, and limited off line processing.

**AstroVideo**
http://www.ip.pt/coaa/astrovideo.htm
Complete acquisition system for video or modified web cams, scope control, alignment, selection, autoguiding, ftp support.

**Autostar Suite**
http://www.meade.com
Bundled with Meade LPI. Automated, on the fly dark calibration, alignment and stacking. Automatic image selection. Autoguiding. Full featured offline image processing.

**AviEdit**
http://www.am-soft.ru
Avi stream capture, assembly, disassembly and editing. Useful for converting AVI streams to collections of BMP images for offline processing.

**K3 CCDTools**
http://www.pk3.org/Astro
AVI stream capture, assembly, disassembly, good time lapse support, FITs output, Alignment, and Image selection.

**K3 Nikon**
http://www.pk3.org/Astro
Palmtop control of the Nikon Cool pix cameras. Programmable cable release.

7. Suitable and Unsuitable Projects

Now that I have gone over the mechanics of acquiring and operating an uncooled imager, I want to consider what are reasonable and unreasonable uses for such devices.

7a. Pretty Pictures

Clearly, the first thing you want to do is take some pretty picture. Firstly, it develops your skill and technique with the new system. It also helps you justify the time and expense to your significant other. In this category, the latest generation of digital still cameras are looking more and more likely to start pushing emulsion based imaging into smaller and smaller niches.

The image in Figure 7 was produced using a Cannon EOS 10D camera. It was made through an astrophysics refractor combining images totaling about 100 minutes exposure time.
7b. Occultation:
Beyond pretty pictures, video and webcams are well suited to occultation timing. The better capture programs offer programmable frame rates and exposure times. Images are time stamped by the processor. Provided the computer’s clock is synchronized with a GPS, internet time server or other accurate standard, the digital nature of the an imager data stream makes handling and processing occultation data much easier. Calibrating video tapes will become a thing of the past. Additionally, electronically shuttered cameras can look deeper than video. Integrating for a second per image allows you to look up to 4.5 magnitudes deeper than video. This alone should increase the number of potentially observable events tremendously. I expect webcams will dominate occultation timing in the near future. Figure 8 shows two frames from a sequence taken of Callisto being partially eclipsed by Ganymede.

7c. Planetary Studies
Without question, webcams and selective image reconstruction techniques have changed the way we observe planets. Reviewing the world wide web and popular literature over the past year, I routinely see planetary images that a few years ago I would have concluded came from spacecraft or our most accomplished imagers. The ease of imaging the planets with uncooled imagers provides amateurs with opportunities push the frontiers of planetary observing. Among potential long term projects are monitoring the Moon for transient lunar phenomena, weather studies of Mars, cloud and vortices tracking on Jupiter and Saturn.

Fig. 7: Andromeda Galaxy ©2003 Steve Cannistra
7d. Multiple Star Astrometry
Although modern surveys vacuum the skies for transients, spectra, and asteroids, a relatively few observers are deeply involved in positional astronomy, once a mainstay of the science. Uncooled imagers offer amateurs a unique opportunity to study bright close binary star systems astrometrically. Multiple star systems in the brightness range, magnitude 1 to 6 are too bright for most large professional telescopes. Although Hipparcos and Tycho measured these objects, the relatively short duration of that mission does not allow the catalog to absolutely separate high proper motion stars from longer period multiple systems. Using selective image reconstruction techniques, combined with data mining of Tycho/Hipparcos data and available plate libraries such as DSS, there are opportunities for amateurs to help refine orbital elements of multiple star system astrometrically.

7e. Long Period Variable Star Photometry
Long period variable star studies have long been one of the mainstays of amateur astronomical science. The inexpensive availability of uncooled imagers should hasten the end to visual magnitude estimation. With moderate care, differential photometric observations accurate to +/- 0.05 magnitudes are within the reach of almost any observer.

8. Unsuitable Activities
Due to the longer integration times required by uncooled imagers, some project should be skipped. Long integration times make short period eclipsing star systems, cataclysmic variable, asteroid detection and asteroid rotation curves a poor choices for uncooled imager projects. Similarly, extra solar planet transit searches that require superior signal to noise ratios in the data are not best pursued with uncooled imagers.
9. Summary

The development of inexpensive uncooled imagers that can be adapted to the service of astronomy has created an opportunity to bring quantitative observation within the means of many more amateur astronomers. Amateurs who have long histories in digital imaging are the ones who have the experience and knowledge to foster development of this emergent technique. While it may be a retrograde step in their observing, they can make a contribution by promoting and assisting amateurs who elect to use this means to venturing into quantitative observation for the first time.

I expect that imager development will follow a price/performance trend similar to Moore’s law for semiconductors. If I am correct, the future will see uncooled imaging move progressively into areas formally occupied solely by custom cooled scientific cameras.
Dispatch Scheduling of Automated Telescopes

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Abstract: Automated telescope scheduling systems have traditionally focused on optimizing the use of the observatory, minimizing overhead and maximizing shutter-open time. However, educational and amateur observatories do not enjoy consistently good skies. Conditions can change significantly during an observing session, leading to schedule breakage. This gives rise to the need for a scheduling system that is capable of recovering from periods of bad skies, wind, etc. without operator intervention. The concept of dispatch scheduling, where the scheduler makes a "best" choice for the next observation, will be discussed. The choice of next target must consider constraints such as minimum altitude or maximum air mass, moon illumination, and sky condition, as well as timing constraints that may arise from linked observations and/or target phasing requirements. It also must be as fair and efficient as practical. A dispatch scheduler (ACPS) was constructed and used to perform a number of simulations with both isolated and multiple/linked observations, and noisy timing. By varying "best next target" choice algorithm, these simulations provided insight into the behavior of a dispatch scheduler. This talk will describe the scheduler and present the results of these preliminary simulations, some conclusions that arose from them, and outline areas for further research.

References:

1. Introduction

The process of acquiring data for astronomical science involves planning, scheduling, and observing. These three phases of data acquisition may be viewed as what, when, and how, respectively. When designing tools for data acquisition, it is important to keep these three activities clearly separated.

- **Planning** establishes what data is needed for the science mission, and may place constraints on the data in order to assure that it meets the minimum quality needed to support the science mission. Typically, this is done by the investigator.

- **Scheduling** makes the decision as to when requested data can and should be acquired, in order to meet the constraints. This is the role of a scheduler.

- **Observing** involves the manipulation of the observatory instruments and software to capture a unit of data (which may be multiple images at multiple wavelengths, for example). The use of a scheduler implies that a sequencer is used to automate the data acquisition process when directed by the scheduler.
This paper, and the engineering work it describes, focuses only on scheduling. The implications of this may not be immediately obvious. Suppose a request is submitted for an observation with coordinates and/or constraints that make it impossible to observe at any time during the year regardless of weather. It is not the scheduler’s job to alert the user that he has entered an impossible request. It simply will never schedule the impossible request. It is the planning tool’s job to assist the investigator in setting up an observing plan that is practical as well as supportive of the science mission. One can envision multiple specialized planning tools that feed their requests into the scheduler through a common protocol. Finally, the actual observation is handled by a separate module, the Sequencer (and of course the observatory instruments under its control).

2. Background

During the initial phase of this project, it was found that virtually all of the research on scheduling of resources has optimal resource utilization as the goal. This typically involves a time-consuming process that produces a static schedule for an entire night’s observing. The success of such an optimized schedule depends on (a) error-free execution of each observation, (b) perfect knowledge of the time duration needed for each observation, and (c) perfect fore-knowledge of the weather throughout the night. Once an observation fails, any linked observations also must fail, leaving holes in the schedule. If the telescope needs an un-forecast refocusing, the schedule is broken, requiring observations (and possibly linked observations) to be skipped. If the sky conditions or weather changes, it can eliminate an entire class of observations from consideration due to their constraints being violated. For example, a thin cirrus layer could preclude all-sky photometry, but there could be other as-yet unscheduled observations that could be made without deleterious effect.

These considerations led to the desire to make the scheduler dynamic in some way, able to adapt to changing conditions and acquisition errors while still maintaining reasonable efficiency. Further research in this direction produced the Steele and Carter paper (ref. 1). The concepts discussed in their paper provided the basis for the design of the scheduler. Very little detail is contained in Steele and Carter, and the difficult problem of handling linked observations is not treated at all. The basic concepts presented in their paper will be briefly described in the following sections. No claim of originality is made for these concepts.

3. Scheduler Design

Steele and Carter[1] identify the following three criteria for a “good schedule”: fairness, efficiency, and sensibility. A fair schedule balances time allocations between users such that they all share good and bad observing times equitably. An efficient schedule is one that maximizes instrument utilization and strives to match observations with required conditions. A sensible schedule is one that attempts only those observations that are possible under the current observing conditions.

The ACP Scheduler (ACPS) is a practical adaptation of Steele and Carter’s concepts combined with the specific implementation needed to turn their basic ideas into a practical scheduling engine. It is designed to handle observation requests from multiple users. Requests are kept in a permanent store; requests can be entered months ahead of the time at which constraints will first be met. Throughout this paper, many of the fine-grain details and features of ACPS are
omitted for clarity, as they don’t affect the basic conceptual knowledge gained from the simulations.

In order to understand the descriptions of scheduler behavior in later sections, it is necessary to define some terminology. The ACPS request database is hierarchical and consists of the following node types:

<table>
<thead>
<tr>
<th>User</th>
<th>Top-level node. Represents a user or using organization, not necessarily an observer or investigator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project</td>
<td>Child of User. Represents a scientific project that may require multiple sets of data</td>
</tr>
<tr>
<td>Plan</td>
<td>Child of Project. This is the basic schedulable unit. It represents one or more observations that must be performed as a group and within a single night.</td>
</tr>
<tr>
<td>Observation</td>
<td>Child of Plan. Represents a single target at a single time. Constraints are applied to Observations. Linked observations are entered as separate Observations with the same parent Plan.</td>
</tr>
<tr>
<td>ImageSet</td>
<td>Child of Observation. Represents one or more images to be acquired back-to-back and at a single wavelength.</td>
</tr>
</tbody>
</table>

Table 1. ACPS Data Hierarchy

The simplest Plan is one with a single Observation and a single ImageSet that specifies a single image. Plans with more than one Observation form linked observations with a specified time interval between them.

Each Observation carries with it a set of constraints that limit the times at which the observation can be taken. Example constraints include air mass, seeing, moon elongation, and limiting magnitude. ACPS supports an open-ended set of constraints through a plug-in facility. For this paper, only a basic “above the horizon” constraint was used in simulations. A more complex set of constraints would serve only to make it more difficult to interpret results.

Priorities are supported, and are applied to Plans. Rather than impose a fixed priority range on everyone, each User is allowed to assign any priority values to their Plans. During the scheduling cycle, (see below) priorities are normalized in a way that maximizes fairness between Users.

4. Scheduler Operation - Overview

Fundamentally, ACPS is a dispatch scheduler. At each scheduling cycle, it decides which of the eligible Plans to start next. Once started, a Plan must run to completion or fail completely. If a Plan fails, it is re-queued and will be attempted again later. No special considerations are given to re-queued Plans with respect to those that have never been started, though this may be easily changed.

When an Observation is completed, the scheduler will look to see if a new Plan can be started before an already-running Plan’s next linked observation comes up for acquisition. If the candidate Plan has linked observations, all of them are checked against all of the linked observations in already running plans. If there are any clashes, the candidate Plan will not be started. There is no requirement that linked observations be spaced at regular intervals.
5. Scheduling Cycle

ACPS runs a continuous loop consisting of the following steps:

1. Normalize priorities
2. Apply constraints to Plans
3. Select an Observation from an already running Plan or start a new Plan and select its first Observation
4. Send selected Observation to sequencer
5. Wait for data from Sequencer
6. Loop back to 1

Priority normalization is done by converting each User’s Plan priorities into a new value such that the mean priority of all of that User’s Plans is 0.5. This scheme came from Steele and Carter\(^1\). It is the fairest of all of the priority schemes studied. It is done at every pass through the scheduling loop to allow for addition of “live” requests during the night.

Application of constraints and selecting the “best” next Observation are the core of the scheduling system, and are discussed in detail below. Once the next Observation has been chosen, it is given to the Sequencer to execute. As you may recall, an Observation applies to a single target, and consists of one or more ImageSets, each of which is one or more images at a single wavelength. The Sequencer performs the slew to the target, perhaps checks the pointing with a short validation and adjustment exposure, performs an Autofocus if requested or indicated, and activates the auto-guider if applicable. It then commands the imager to acquire images per the ImageSets, switching filters and refocusing as needed.

6. Scheduling Rules

Early simulations led to a couple of basic rules that guided the design of ACPS. Recall that the Plan is the basic schedulable unit, and may consist of multiple linked Observations (targets) with specified time intervals between them. These rules are:

- ✓ Once a Plan has been started, it must either run to completion (in one night) or fail completely.
- ✓ Time separation of linked observations must include a non-zero time tolerance.
- ✓ If a Plan has been started, its linked Observations must be considered inviolable.

For the simple case, a Plan that has a single Observation, the above are intuitively obvious. However, for a Plan that has multiple linked Observations, it means that a Plan cannot be started unless the following conditions are met:

- ✓ All of its linked Observations’ constraints can be met if it is started now.
- ✓ None of its linked Observations will clash with those of Plans that have already been started, regardless of their priority.
These rules lead to the following corollaries:

a) Constraints must be applied to all Observations of a candidate Plan before starting it. The proposed Plan start time, the estimated times needed to execute each of its Observations, and the specified time interval between its Observations, all must be used to project forward each Observation in time, and compute its constraint for that time.

b) A higher priority unstarted Plan can never force the failure of a lower priority running Plan, it can only prevent a lower priority Plan from getting started.

c) The projected times for starting each of the candidate Plan’s Observations must be checked that they do not overlap/clash with the nominal time spans of the remaining linked Observations of Plans that have already been started.

d) Once constraints and timing-clash checks have been applied to an entire Plan, it can be started with a high degree of confidence that it will complete successfully. There is, however, a non-zero chance that it will fail because a constraint is not met at the actual time of observation. This condition can arise as a result of imperfect estimates of times needed for other Observations.

It should be clear that constraints are first applied to all Observations of each unstarted Plan, with forward time projection. If any constraints are not met, the Observation and its parent Plan are “vetoed” and eliminated from consideration during this scheduling pass. The Plan will be re-queued and reconsidered in subsequent scheduling passes, as the constraints could be met at this later time. Thus, the veto processes eliminates Plans that cannot be started at the current time.

7. Application of Constraints

ACPS has a standard set of constraints (see Table 2) that may be applied. If no constraints are applied, observations will be eligible based solely on astronomical night (Sun below –18 degrees) and instrument limitations retrieved from the Sequencer. In addition, custom constraints can be added via a plug-in API. Thus, applications with unusual requirements can be supported without changes to the main ACPS engine.

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizon</td>
<td>Observation must be made above the given elevation (with respect to the local mathematical horizon)</td>
</tr>
<tr>
<td>Air Mass</td>
<td>Observation must be made at or below the given air mass.</td>
</tr>
<tr>
<td>Sky Quality</td>
<td>Observation must be made at given (or better) sky quality. Four sky qualities are defined: excellent, good, fair, and poor.</td>
</tr>
<tr>
<td>Dark Time</td>
<td>Observation must be made with Moon “down”, namely 15 degrees below the mathematical horizon</td>
</tr>
<tr>
<td>Moon Distance</td>
<td>Observation must be made when the target and the Moon are separated by at least the given angular distance</td>
</tr>
<tr>
<td>Moon Avoidance</td>
<td>Observation must be made at or below the given moonlight level. This is expressed in terms of a Lorentzian weighting that is a combination of angular distance from the Moon and the illumination at its current phase.</td>
</tr>
</tbody>
</table>

Table 2. ACPS Standard Constraints
8. Selection of Next Observation

Once the unstarted Plans have been winnowed down to those that could be started now, the scheduler must decide what to do next, specifically, which Observation to send to the Sequencer at this time. The possibilities include (a) one of the remaining linked Observations that belong to plans that have already been started, or (b) a first-Observation of one of the currently eligible Plans that have not yet been started. Remember, if a Plan is eligible to be started at this point, the scheduler has already done its best to assure that all of its Observations’ constraints can be met and that none of its Observations will clash with those of already running Plans.

It is known to a high degree of confidence that any eligible Observation whose estimated start time is in the future cannot be overlapped by any of the other eligible Observations. Thus, any Observation whose estimated start time is in the future is skipped for this scheduling cycle. The other thing that is known is that any Observation that is eligible for running now will not overlap a scheduled linked Observation. Thus, any Observation whose estimated start time is not in the future can safely be started now. Finally, the adopted scheduling rules require that Observations that belong to running Plans always have preference over those belonging to unstarted Plans. Thus, if there are any Observations belonging to running Plans that can be started now, one of them must be chosen; a new Plan must not be started in this schedule cycle.

9. Efficiency Function

At this point, each of the eligible Observations is tested by computing the efficiency index. The Observation with the highest efficiency index is the one chosen to do now. The purpose of the efficiency index calculation is to decide which Observation to execute considering both the scientific priority and the best use of the current observing conditions. This is done using an Efficiency function of the form:

\[ e(n) = \beta_1 E_1(n) + \beta_2 E_2(n) + \cdots + \beta_k E_k(n) \]

This generic form is taken from Steele and Carter. However, the specific terms of this function, both the choice of the individual efficiency terms \( E_i(n) \), as well as their coefficient values \( \beta_i \), were studied via extensive simulations. The knowledge gained via these simulations provided insight into the behavior of a dispatch scheduler.

By varying the \( \beta_i \) coefficients, the behavior of the scheduler can be adjusted to meet the needs of the observatory users as a group. After significant research, the details of which are beyond the scope of this paper, the following efficiency functions were chosen for ACPS.

Scientific Priority

ACPS allows each User to assign their own scientific priorities to their Plans rather than forcing everyone onto a single priority system. In order to assure that allocation of the observatory is fair, each User’s priorities are transformed into a normalized system where the mean value of their priorities is 0.5:

\[ \frac{\sum_{i=1}^{N} P_i}{N} = 0.5 \]
where N is the total number of Plans in the system for that User. At the time of writing of this paper, it was planned to study whether the priority of a Plan should be scaled according to its number of linked Observations. This would assign a weight proportional to the resources that the Plan uses. A further refinement might be to weight according to the observatory time needed for the Plan.

In any case, the Plan’s normalized priority is applied to all of its Observations when they are considered in the Efficiency function, thus

\[ E_i(n) = p(n) \]

**Nearness to Transit Altitude**

It is intuitively obvious that it is advantageous to observe objects at as low an airmass as possible. The simple interpretation of this would imply an \( E \) function of the form

\[ E_2(n) = \frac{A_C(n)}{90^\circ} \]

where \( A_C(n) \) is the current altitude of Observation \( n \). However, this would unfairly favor objects whose declination is near the latitude of the observatory (as observed by Steele and Carter\(^1\)). A better criterion is the distance of the object from its transit altitude. This implies an \( E \) function of the form

\[ E_2(n) = \frac{A_C(n)}{A_T(n)} \]

where \( A_C(n) \) and \( A_T(n) \) are the current and transit altitudes of Observation \( n \).

But there is an additional consideration that is non-intuitive but became obvious after early simulations: If the candidate Observation would be the first of an unstarted Plan that contains multiple linked Observations of *different* targets, it would be incorrect to use the current altitude of the first (or any other) of the Plan’s Observations in the above test. Instead, it was decided to test the use of the *centroid* (in local horizontal coordinates) of all of the Observations of the Plan. Thus,

\[ E_2(n) = \frac{A_C(P)}{A_T(P)} \]

where \( A_C(P) \) and \( A_T(P) \) are the current and transit altitudes of the centroid of the Observations of Plan \( n \).

Simulations revealed that this is an excellent way to treat a Plan with multiple linked observations at possibly different coordinates. It turns out that the Plan is most often started at the most efficient time, and the individual Observations are done as closely as practical to their transit altitude, on average. It is planned to evaluate adding a cosine of declination term to this number. Intuitively this makes sense, as a target at the pole can be acquired without regard to its right ascension.

**Slewing Overhead**

It is more efficient to observe nearby targets when possible, so a slewing overhead term is included in the Efficiency function. Simulations and logic have shown that considering only the time needed to slew to the target unfairly penalizes Observations that take a compara-
tively long time to complete. For example, if a candidate Observation is expected to take an hour to complete, a thirty-second slew is not significant. If the Observation consists of a single ten-second exposure, the thirty-second slew has a significant impact on efficiency. Thus, slewing overhead is represented by an $E$ function of the form

$$E_s(n) = \frac{t_O}{t_S + t_O}$$

where $t_O$ is the estimated time needed to complete the Observation, and $t_S$ is the estimated slewing time needed to get to the target coordinates of the Observation.

**Retry Count**

The ACPS scheduling rules state that a Plan must either complete successfully within a night, or fail completely. In cases where a Plan fails due to changes in sky condition, weather shutdowns, or (rare) scheduling errors that cause an Observation’s specified time window to be missed, ACPS re-queues the Plan, making it eligible to be started again. This could be in the same night (if constraints can still be met) or it may cause it to be delayed until a succeeding night.

In order to provide some level of preference to failed and re-queued plans, ACPS keeps a count of the number of times a Plan has been re-queued due to failure. This retry counter is used to provide a boost in preference in the Efficiency function. This term is represented simply as

$$E_4(n) = R$$

where $R$ is the retry count ($= 0$ if the plan is being started for the first time). The intention is to have the $\beta_4$-weighting coefficient set to a low value, providing only a mild boost in priority for re-tried Plans. Setting this to a high value could cause a failed plan to become stuck in a failure loop. Further study is planned to look for instabilities that might be caused by this term in the Efficiency function.

**Meridian Crossing**

When the telescope is on a German equatorial mount, a cost is associated with every crossing of the celestial meridian. The mount must “flip”, which can take considerable time. Besides the actual flip time, additional time may be needed to assure precise pointing to the sky. Thus, meridian crossings have a significant impact on efficiency. ACPS includes a meridian crossing “penalty” term in the Efficiency function, as

$$E_5(n) = 1 \ M$$

where $M$ is 1 if a meridian crossing is required to reach the Observation’s target coordinates, and 0 if no meridian crossing is required. For non-German mounts, the $\beta_5$-weighting coefficient is set to 0, effectively eliminating this term from the Efficiency function.

**Observing Conditions**

One of ACPS’ standard constraints is sky condition. Application of constraints prevents a Plan from getting started if sky conditions are poorer than required. However, if sky conditions are better than required, efficiency dictates that the better conditions should not be wasted. If there is a lower priority observation that requires the better conditions, it should
perhaps be run in preference. The simplest scheme would be to require that observations be made only at their required conditions. This is not efficient, though, as it would prevent usage in better conditions than needed even when there is nothing else to do. Instead, we use a term suggested by Steele and Carter.

In ACPS, sky condition can be one of four values, excellent, good, fair and poor. We assign numeric values of 4, 3, 2, and 1 to these conditions, respectively. Then we calculate the $E$ term as

$$E_6(n) = \frac{1}{|C_R - C_A| + 1}$$

where $C_R$ is the required condition number and $C_A$ is the actual condition number.

### 10. Simulation Design Issues

The development of ACPS used simulations throughout. In the early design phase, narrow-focus simulations were used to evaluate various candidate terms in the Efficiency function. These simulations are beyond the scope of this paper. They served primarily to assist in the selection of the final set of terms in the Efficiency function.

Once the framework of ACPS was integrated into a working scheduler, a second phase of simulations was undertaken to confirm its expected behavior, look for anomalies, and get some feel for its performance under various conditions. In particular, the effects on behavior due to variations in the $\beta_i$ weighting coefficients were studied. These simulations will be described along with a few illustrative results.

### 11. Input to Simulations

In order to provide real-world conditions for simulations, a facility was added to ACPS for generating a Project consisting of multiple Plans of various kinds. The generator is capable of creating Plans that are representative of the astronomy missions shown in Table 3. When generating a test workload, it is possible to selectively include or exclude each of these mission types.

The fraction of the total workload represented by each mission type is variable. In Table 3, the “fraction of total load” values given are those that result if all of the mission types are selected. If one or more mission types are disabled, the relative mix changes based on the relative frequency of the remaining mission types.

For the simulations described below, the variable star and precision photometry plan types were not used (hence they are grayed-out in Table 3). Some simulations used a sub-set of the remaining plan types, and this will be clearly indicated in the description of the simulation.
<table>
<thead>
<tr>
<th>Mission Type</th>
<th>Fraction of Total Load*</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random single image</td>
<td>0.4</td>
<td>Single exposure, random interval 240 sec mean, 60 sec. std. dev. Random priority mean of 5, std. dev. of 2.</td>
</tr>
<tr>
<td>LRGB Astro-photography</td>
<td>0.2</td>
<td>4 exposures, base (L) exposure of 300 sec. Scientific priority of 3.</td>
</tr>
<tr>
<td>Asteroid/Comet search and follow-up</td>
<td>0.2</td>
<td>4 observations, each image 180 sec. integration, spaced 45 min apart with a +/- 10 min tolerance. Scientific priority of 5.</td>
</tr>
<tr>
<td>Variable star photometry</td>
<td>0.1</td>
<td>30 observations, each image 30 sec. integration, spaced 10 min apart with a +/- 1 min tolerance. Scientific priority of 10.</td>
</tr>
<tr>
<td>Precision/All-Sky photometry</td>
<td>0.1</td>
<td>4 observations, each image 10 sec. integration, spaced 5 minutes apart with a +/- 1 min tolerance. Scientific priority of 8.</td>
</tr>
</tbody>
</table>

* with all workload types turned on.

Table 3. Load Generator Mission Types

Target/Observation locations are generated randomly above 35 degrees elevation over the “dark sky” for the entire night on the date and geodetic location set in the scheduler. For Plans with linked observations of different targets, it is possible for targets to be unreachable due to the timing. This is a real world.

Finally, the workload for the night can be set to one of the following levels:

- Lightly booked (20% of the night)
- Fully booked (70% of the night)
- Over-booked (150% of the night)

The percentages refer to the amount of time that all of the scheduled Observations are estimated to require, not just to shutter-open time.

12. Simulated Sequencer

In order to create as realistic an environment as possible, a simulated sequencer was built and attached ACPS’ sequencer interface. The simulated sequencer looks at the dispatched Observation and its ImageSets, and simply creates a time delay equal to that which a real observatory would require to complete the observation. The following common process items are given separate time estimates:

- Slewing time (based on rates and settling time, runs start with telescope at parked position 0 HA, 0 Dec)
- Guider startup time (for “long” images only)
- Filter switching time (assumes focus offsets supported)
- Imager download time (varies by binning)
- Post processing time (plate solving, calibration, stacking)

The actual values of the timing parameters are shown in Table 4 below.
Table 4. Sequencer Simulator Timings

<table>
<thead>
<tr>
<th>Slew Rate</th>
<th>3.5 degrees/second</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slew Settling</td>
<td>15 seconds</td>
</tr>
<tr>
<td>Guider Startup</td>
<td>30 seconds</td>
</tr>
<tr>
<td>Minimum Unguided Exposure Interval</td>
<td>120 seconds</td>
</tr>
<tr>
<td>Imager download</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Filter Switching</td>
<td>45 seconds</td>
</tr>
<tr>
<td>German Flip</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Auto-Focus Time</td>
<td>60 seconds</td>
</tr>
<tr>
<td>Image Post-Processing</td>
<td>15 seconds</td>
</tr>
<tr>
<td>Timing Noise (uniform distribution)</td>
<td>5% of interval*</td>
</tr>
<tr>
<td>Image Failure Probability</td>
<td>0.05*</td>
</tr>
</tbody>
</table>

* Disabled for some simulations.

The sequencer simulator can be configured to add a random variation to the timing values. In addition, the sequencer simulator can be configured to fail observations randomly. Failure of any of the images in an Observation will cause the Observation (and the Plan) to fail, so the more images are in a Plan, the more likely it is to fail, all else being equal. The reason for including random failures was to test the effectiveness of the re-queuing Observations after failure.

13. Time Simulation

It is clearly required that time be accelerated for scheduler simulations. Since scheduling itself is a CPU and disk/database bound activity, it is not clear how to treat scheduling time as part of the overall observatory efficiency. The solution is to accelerate the clock only during the time the sequencer simulates acquiring the data for the dispatched Observation and ImageSets and when the scheduler is sleeping (no work to do). The clock runs at real time during the scheduling phase. This most accurately reflects the effect of scheduling time on overall efficiency. All sources of time, including time stamps in the log file, come from the 2-mode clock.

14. Simulations and Results

This section presents the results of some of the simulations, showing the effects of varying the $\beta_i$ -weighting coefficients on timing and hour angle at acquisition. Two data sets were generated: one consisting of random targets of one exposure each, with random exposure intervals and random priorities, and the other consisting of a mixture of the random targets and sets of random targets of four time-spaced linked observations of each with fixed exposure intervals and priorities. See Table 3 for specifics.

The number of targets was chosen so that a few would not be acquired due to time constraints (slightly overbooked situation). The test loads were generated by using the timing information in Table 4 and generating random targets, computing the total time needed to acquire each image of that target, and adding that to a running total. Since slewing time is not known (it is order-dependent) a guess of 45 degrees is used. When the running total reached 70% of the total night-time from astronomical twilight to astronomical twilight, generation was stopped. For example, since the random targets also had randomly varying exposure intervals, sometimes the guider would be needed (incurring additional guider startup time).

Each of these target sets were simulated over a night three times, with each of three of the terms in the Efficiency equation set for $\beta_1 = 1.0$ and the rest set to 0.0 (disabling them). The three
terms studied were Priority, Transit Altitude, and Slew Time. Finally, a fourth run was made with three the $Ei(n)$ turned on via having their $\beta_i$ set to non-zero values.

15. Random Single Images

The first set of simulations uses a Project consisting of 66 Plans, 1 Observation and 1 ImageSet in each. Figure 1 shows the distribution of targets in equatorial coordinates.

![Figure 1. Coordinates of Random Image Simulation](image)

Priorities are random with Normal distribution, mean of 5.0, standard deviation of 2.0. Exposure intervals are random with Normal distribution, 240 second mean, standard deviation of 60 seconds.

The first simulation with the random-images data set was run with only the Priority term in the Efficiency equation. This caused the dispatcher to always pick the eligible Plan that has the highest scientific priority. Figure 2 below shows the resulting distribution of acquisition locations relative to the meridian.

For this test, 60 of the 66 total available Plans (images in this case) were completed. Reviewing the log file of the run confirmed that the Plans that were not run were those with the lowest scientific priority. Because, in this scenario, the targets were picked totally without regard to slewing time, the excessive slewing time (clearly visible in Figure 2) adversely affected the efficiency of the dispatcher.
Next, the same random-images data set was re-run, this time with only the Transit-Altitude term in the Efficiency equation. This caused the dispatcher to always pick the eligible target that is closest to its transit altitude. The results of this test are shown in Figure 3 below. Predictably, the deviation from the meridian was far less. As the scheduler ran out of Plans to choose from, it started picking the remaining targets which were all to the east of the meridian, so the trend is to the east (positive hour angle).

In this case, 61 of the 66 Plans (images) were completed. Analysis of the log file revealed that those that were missed were early evening targets (lowest right ascension) whose meridian passage had already occurred. At the beginning of the night, there are plenty of targets approaching their meridian passage, and these are of course given preference in this scenario (transit-altitude-only). By the time the dispatcher got low on eligible targets, those early targets had dropped below the 35-degree altitude limit in the west. The large deviation towards the end occurred when the dispatcher ran out of targets near the meridian and picked up one of the missed early targets that were setting in the west.

The random-images data set was run again with only the Slew-Overhead term in the Efficiency function. This caused the dispatcher to always pick the Plan whose target is closest to the previous one. The results of this test are shown in Figure 4 below. Minimizing slew time allowed
the complete set of 66 Plans to complete, however the dispatching behavior was somewhat surprising, at least for this one run. It is planned to study the minimum-slew behavior with more simulations.

Finally, the random-images data set was run with the Priority, Transit Altitude, and Slewing Distance terms in the Efficiency function, with the $\beta_i$ set to 1.0, 0.8, and 0.7 respectively. This caused the dispatcher to pay the most attention to scientific priority, followed by nearness to the meridian and slewing overhead, in that order. The results of this test are shown in Figure 5 below. The $\beta_i$ coefficients resulted in quite reasonable behavior and efficiency (61 of the 66 Plans were completed).

16. Combined Single and Quadruplets

The second simulation consisted of 36 Plans consisting of 22 single images similar to the ones in the previous section (but at different randomly chosen target coordinates) and 14 Plans consisting of four linked Observations (one 180-second image of each) of the same target (a simulated asteroid follow up) for 78 images total. The purpose of this simulation is to study the behavior of
the dispatcher with linked observations and to validate the clash-detection logic that precedes the dispatch decision. The linked observations were spaced 45 min apart with a 10 min tolerance and a fixed scientific priority of five. Figure 6 shows the distribution of targets in equatorial coordinates.

![Figure 6. Coordinates of Combined Targets Simulation](image)

This data set was simulated using the Priority, Transit Altitude, and Slewing Distance terms in the Efficiency function, with the $\beta_1$ set to 1.0, 0.8, and 0.7 respectively. This caused the dispatcher to pay the most attention to scientific priority, followed by nearness to the meridian and slewing overhead, in that order. The results of the simulation are shown in Figure 7 below.

![Figure 7. HA Cos(Dec) for Combined Targets Simulation](image)

The overall behavior of the scheduler under this difficult scenario was quite good. It was able to acquire all of the single-image Plans, and all but one of the 4-image linked Plans, for 74 out of
78 images total. The 4-image Plans were all at a fixed scientific priority of 5 (the mean priority of the single image Plans), resulting in the dispatcher starting them sooner on average. Within the first part of the night, there were 4 simultaneously running 4-image Plans, and this stayed within the range of 3 to 5 for virtually the entire evening.

One interesting feature shown in Figure 7 is the acquisition of single-image targets well east of the meridian during the first half of the night. This illustrates the dispatcher’s ability to fill the gaps between the linked observations with something, keeping overall efficiency up. The remaining easterly targets (not marked in Figure 7) are all members of 4-image Plans. By the end of the evening, the dispatcher was running out of things to do, so it started the remaining Plans when it could, resulting in their starting out east of the meridian. In addition, toward the end of the night, some single-image targets appeared on the eligible list, and by then the dispatcher had very little to do, so they were run to the east also. This is desirable, as by this time sunrise is not far off.

17. Conclusions and Follow-Up

The simulations results show that a dispatch scheduler is a practical alternative to queue-based optimizing schedulers. It has the advantages of (a) being able to accept changes and additions to observing requests during the evening, and (b) being able to re-try failed observations automatically. It has the disadvantage of being less efficient in telescope use when compared to a queue-based optimizing scheduler.

The behavior of the dispatcher under the test conditions exceeded expectations. More tests are needed, however, to validate “edge conditions” and to check for stability problems when recycling Plans that have failed.

In addition, more tests are needed to determine where efficiency could be improved. For example, some of the targets that were missed were the westernmost ones. They set below the western horizon before being dispatched. It may be necessary to include another term in the Efficiency function that counteracts this behavior, but it could also counteract the meridian distance term. Perhaps some sort of composite term is needed. Another example is the use of the centroid of a multi-observation Plan for the transit altitude \( E_i \) term. Is this really the best way to handle them?

This paper was submitted for review and publication to the Society for Astronomical Sciences on March 30, 2004. It represents the development status of ACPS at that time. A revised version of the paper will be available at the time of the Symposium on Telescope Science 2004, at which the author will present the paper.

Acknowledgements:

My heartfelt thanks go to Dr. Frederick Hessman of the University of Göttingen, Germany. Once he understood that I was looking at dispatch scheduling, he pointed me to the Steele and Carter paper [1]. In addition, he suggested the open-ended constraint design, including the idea of plug-in modules for constraints. This turned out to be an excellent suggestion.
The Stratospheric Observatory for Infrared Astronomy (SOFIA)

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Abstract: The Stratospheric Observatory for Infrared Astronomy, SOFIA, will carry a 3-meter-class telescope onboard a Boeing 747SP aircraft to altitudes of 41,000 to 45,000 ft, above most of the atmosphere’s IR-absorbing water vapor.

The telescope was developed and built in Germany and has been delivered to the U.S. in September 2002. The integration into the B747SP has been completed and functional tests are under way in Waco, Texas. In early 2005 flight-testing of the observatory will initially be dedicated to the re-certification of the modified aircraft, then performance tests of the telescope and the electronics and data systems will commence. Later in 2005 after transferring to its home base, NASA’s Ames Research Center in Moffett Field, California, SOFIA will start astrophysical observations. A suite of specialized infrared cameras and spectrometers covering wavelengths between 1 and 600 \mu m is being developed by U.S. and German science institutions. In addition to the infrared instruments, a high-speed visible range CCD camera will use the airborne observatory to chase the shadows of celestial bodies during occultations.

Once SOFIA will be in routine operations with a planned observing schedule of up to 960 hours at altitude per year, it might also be available as a platform to serendipitous observations not using the main telescope, such as recordings of meteor streams or the search for extra-solar planets transiting their central stars. These are areas of research in which amateur astronomers with relatively small telescopes and state-of-the-art imaging equipment can contribute.

References:
1. Introduction

Ground based observatories attempting to observe astrophysical phenomena in the infrared spectral region use large telescopes, presently with up to 10 meters diameter, offering superb light gathering power and spatial resolution. On the ground, telescopes and their often delicate high-tech infrared receivers are also readily accessible to astronomers and technical support personnel. Unfortunately, measurements are limited to narrow atmospheric ‘windows’ in the 1 to 5 µm range, and around 10, 20 and 30 µm. The problem is atmospheric water vapor absorbing the IR-radiation. Therefore, the most favorable places for IR observations are high and dry, with the least possible amount of water vapor above the telescope. The best sites on earth, like Mauna Kea, Hawaii or the high altitude deserts in Chile, offer column densities of a millimeter of precipitable water during their driest seasons. Still the observations remain restricted, as even under the most favorable conditions water vapor keeps the atmosphere completely opaque between 30 and 300 µm.

But many interesting spectral lines lie at these obscured wavelengths, e.g. the OI line at 63 µm, the NII line at 205 µm and the CII line at 158 µm, which play a vital role in understanding the chemistry and physics of the interstellar medium. The wavelength restriction on the ground also limits observations and temperature estimates of objects with temperatures of 15K to 100K, while much of the energy in the universe is emitted by objects in this temperature range.

Ideally, the atmospheric absorptions are overcome by putting infrared telescopes in space. Not only are the atmosphere’s absorption and thermal emission eliminated, the vacuum of space also allows to cool the complete telescope to temperatures below the threshold of thermal emission in the wavelengths ranges desired for observation. In 1983 the Infrared Astronomical Satellite, IRAS started such endeavors with great success, producing an all sky survey in four wavelength bands centered at 12, 25, 60 and 100 µm. The point source catalogue derived from that survey contains about 250,000 sources. In 1995 the Infrared Space Observatory (ISO) was launched and followed up on many of these sources with longer integration times, larger detector arrays and higher resolution spectrometers. The detectors of ISO pushed the long wavelength coverage out to about 220 µm, enabling for example the detection of dust at a temperature of only 15 K in the Andromeda galaxy M31\(^1\). In August 2003 the Spitzer Space Telescope (formerly Space Infrared Telescope Facility, SIRTF) was launched and is operating very successfully. The next steps in space based IR exploration will be taken by the HERSCHEL Space Observatory (HSO) to be launched later this decade, and the James Webb Space Telescope (JWST). The limitations of space based infrared telescopes are their relatively small size of less that 1 meter diameter so far, due to limited launch capacities, and their limited lifetime. As soon as their reservoir of cryogenic coolant, e.g. liquid helium runs out, their optics and infrared detectors warm up and become useless. The long development times of space missions, typically a decade or longer, prevent that the newest and most sensitive detector technology is flown onboard of satellites. Once they are launched, there is no access for service or maintenance, as all attempts to design such service or cryogen-refill-missions for infrared satellites had to be given up for cost reasons.
2. Airborne IR-Observations

Long before space based IR observations could be thought of or realized, astronomers have overcome the atmospheric restrictions by putting telescopes on aircraft. Depending on the geographic latitude and the seasons, the troposphere that contains almost all of the atmosphere’s water vapor ends at altitudes between 12 and 15 km (39,000 to 49,000 ft) and merges into the very dry stratosphere. Precipitable water content at such altitudes is typically 10 µm or less, so the entire IR range becomes observable, except for very strong water vapor absorptions in some narrow spectral bands. So far the most successful project of airborne astronomy has been the Kuiper Airborne Observatory, KAO. Stationed at NASA’s Ames Research Center in Moffett Field, California it operated between 1974 and 1996 carrying a 91cm telescope onboard a C141 aircraft.

Based on the successful observations with the KAO, U.S. and German astronomers developed a desire for a larger, more powerful airborne telescope. The first ideas on how to realize this date back to 1986. Over the years, technology studies were conducted in the U.S. and in Germany to find the best and most cost effective overall concept and solutions to specific subsystem problems, such as light weight telescope technology and precise telescope stabilization on an aircraft flying in turbulence. Finally, in 1996 a Memorandum of Understanding was signed by NASA and the then German Aerospace Agency DARA (now German Aerospace Center, DLR) to jointly develop and operate the Stratospheric Observatory for Infrared Astronomy, SOFIA. For its development NASA provided funding for the purchase of a Boeing 747SP aircraft, its modification to accommodate the telescope system, the development of several U.S. built scientific instruments as receivers, and to prepare the necessary ground support facilities for the observatory’s operations. In Germany, DARA/DLR provided funding to build the 2.5m-diameter IR telescope. Several German science institutes share the development of two additional science instruments. The U.S. and Germany contribute 80% and 20%, respectively, to the development costs of SOFIA. The same split will apply to the operational costs of the observatory and the sharing of its observing time during the planned 20 years of lifetime.

In addition to its IR capabilities, the airborne SOFIA telescope will offer the advantage of accessibility to observers and instrument builders, and its mobility around the globe. Observing flights will typically last for about 8 hours, then the aircraft will return to its home base. Astronomers will fly with the telescope and its science instrument to judge the data quality online. Therefore, they will be able to optimize their data taking strategy and - to some extend within the limitations of flight planning - their observing plan to react on changing atmospheric conditions and instrumental effects or on surprises the infrared sky might provide. Trained instrument operators and instrument scientists will also accompany the flights to optimize the performance and efficiency of the receivers. Astronomy students will be able to gain hands-on experience with airborne observations and instruments. Finally, the education and public outreach program of the SOFIA will provide flight opportunities for teachers and science journalists.

The accessibility of SOFIA will also enable instrument builders to upgrade existing instruments or to develop new ones using the latest technologies and bring them onboard in a timely manner. SOFIA can therefore apply new technologies, e.g. new IR detectors or optics rather fast. Gaining practical experience with ‘cutting-edge’ technology will not only benefit SOFIA’s science, but will also prepare them for use in future space missions such as the planned Single Aperture Far-Infrared Telescope, SAFIR or space infrared interferometers.
Once operational, SOFIA will offer higher spatial resolution at far-infrared wavelengths than has any other telescope before. Its telescope with a 2.5 meter effective aperture will have a resolution $\theta / D = 8.25$ arcsec at 100 $\mu$m, outperforming IRAS and ISO by a factor of 4.2, SIRTF by a factor of 3, and its airborne predecessor KAO by a factor of 2.8. At more than 70% of the spatial resolution of the 3.5 meter HERSCHEL telescope, SOFIA will also be a valuable tool to prepare for and follow up on HSO observations, currently planned to start in 2007.

With its large aperture telescope, the almost unrestricted infrared wavelength coverage, and its continued accessibility for maintenance and improvements, SOFIA combines the advantages of ground and space based infrared telescopes.

In addition, the mobility of the aircraft will enable observations of localized targets of opportunity such as comets or supernovae. A special area of science is related to occultations. When the moon, planets or asteroids move in front of other objects, namely stars, they cast their shadows on earth which are typically a few 10 to 100 km wide and visible only in very localized regions. The observation of these events can reveal the composition or changes in planetary atmospheres, the size and shape of the occulting objects and lead to improved orbital data for asteroids. Most notable was the KAO’s detection of Uranus’ rings during an occultation of the star SAO 158687 by the planet in 1977. SOFIA will pursue this kind of observations with two specialized science instruments, one working in two visible wavelength bands and one in the near-infrared. In the future, mid- and far-infrared observations of occultations might open new possibilities.

3. The Airborne Observatory

Figure 1 shows a cutaway drawing and an in-flight rendition of the Boeing 747SP SOFIA aircraft. This aircraft model was chosen for its wide to install the telescope, and for its flight performance, allowing for observations from altitudes up to 13.7km (45,000ft). The major modifications of the aircraft required in order to transform it into an astronomical observatory were the creation of a telescope cavity, the cutting of the fuselage opening for the telescope to look out, the fuselage modification for structural integrity, stability and control of the airflow, and the conversion of the passenger cabin into a control room.

A pressure bulkhead was built into the fuselage section aft of the wings, to separate the cabin which offers an ambient work environment for astronomers and technical personnel from the open port telescope cavity at stratospheric pressure and temperatures. This bulkhead supports the telescope assembly’s main bearing, which is a 1.2 meters diameter hydrostatic spherical bearing. The telescope with the primary, secondary and a tertiary folding mirror is attached to the aft side of the bearing. On the forward or cabin side of the bearing there is a balancing system to counterbalance the weight of the telescope and an attachment structure onto which various scientific instruments can be mounted. Details of the telescope system are shown in figure 2.

The fuselage aft of the telescope compartment contains a cooling system that pre-cools the telescope before take-off to the expected operating temperature at altitude around -45C, and a desiccant system, to provide dry air for re-pressurizing the telescope compartment during descent before landing. The fuselage aft of the main bulkhead remains unpressurized during flight. For take-off and landing the telescope compartment will be closed with a roll-away door. The fuselage around the telescope compartment has been reinforced so it can carry the weight of the telescope (about 10 metric tons). The exterior of that section has been shaped based on extensive wind tunnel tests, to facilitate the controlled detachment of the laminar airflow from the fuselage.
and its re-attachment aft of the telescope port. This so-called shear layer control is essential for maintaining decent flight properties of the aircraft and to minimize the seeing effects of a turbulent air layer in front of the telescope.

The telescope is separated mechanically from the aircraft by a system of vibration isolators located between the bulkhead and the bearing. These isolators passively protect the telescope from aircraft vibrations by dampening. Within this isolated reference frame, the telescope is actively pointed and stabilized by a ‘coarse drive system’ (which allows telescope movement in elevation between 15° and 70°) and a ‘fine drive torque motor’ arranged in segments around the spherical bearing (for telescope elevation motion within ± 3°). The fine drive system can move the telescope in cross-elevation and the line-of-sight axis by ± 3°. Telescope pointing outside this range is done by choice of the flight trajectory, e.g. flying West for objects in the South, or flying East for objects in the North. Target acquisition and tracking uses three laser gyros for reference and three cameras, i.e. a wide field, a fine field and a focal plane imager with a 6°, 70 arcmin and 8 arcmin field-of-view, respectively. A detailed description of the SOFIA telescope and its subsystems can be found in *Airborne Telescope Systems II* (2002)².

Achieving highly precise pointing stability of the telescope onboard the aircraft is indeed one of the major challenges of the project. Residual vibrations from the aircraft and wind loads on the telescope in the open port compartment need to be compensated. In addition, these two external disturbances will introduce bending of the telescope structure that needs to be corrected as well. The system is so complex, that a special ‘modal survey test’ will be conducted after the telescope and its support structures are finally assembled in their flight configuration. The results of this test will be used to ‘train’ the pointing control system on how to react to the different disturbances the telescope might experience in flight. Finally, the actuated secondary mirror might be used for the finest level of image stabilization, to reach the specified value of 0.2 arcsec (RMS). But use of the secondary mirror for image stabilization must be kept to a minimum (< 1 arcsec corrections) because of the unwanted infrared background variations introduced by such a method.
Figure 1  The Stratospheric Observatory for Infrared Astronomy, SOFIA

Figure 2  Structure of the SOFIA Telescope
The central support of the SOFIA telescope is a hydrostatic 1.2 meters diameter spherical bearing mounted to the new pressure bulkhead of the aircraft. Aft of the bearing is the open trusswork ‘tube’ of the telescope which is made out of carbon fiber material. On the bottom of this structure is the primary mirror cell containing the light-weighted Zerodur mirror of 2.7 meters physical diameter. On the top end of the structure is the three-armed spider carrying the chopping secondary mirror. The secondary defines the entrance aperture of the telescope and uses 2.5 meters of the primary’s diameter (effective optical aperture of the telescope). A tertiary mirror is mounted into the central hole of the primary at 45° to send the beam coming down from the secondary at a 90°-angle through the Nasmyth tube into the cabin of the aircraft. At the end of the Nasmyth tube is a mounting flange for scientific instruments. The vertical plate at this flange carries weights to counter-balance the telescope and a mounting rack for instrument electronics. The ?-shaped structure is a so-called cable drape alleviator, which runs electrical and cables and supply lines from the aircraft cabin to the moving telescope without introducing torques to the coarse drive of the telescope.

4. Telescope Integration

The complete telescope system has been developed by a consortium in Germany and was delivered to Waco, Texas in September 2002 for integration into the aircraft (figure 3). In the first step of the integration the telescope’s central support structure including the big hydrostatic spherical bearing was installed into the new aircraft bulkhead in January 2003 (figure 4). Subsequently, the metering structure of the telescope and its secondary mirror were installed (figure 5). Finally in July 2003, as the last critical heavy lift, the primary mirror was lifted into the aircraft and mounted to the metering structure (figure 6).

The installation of telescope components and their first functional tests, e.g. the secondary mirror system, target acquisition and guiding cameras, the integration with the computers of the Mission Control System, and the completion of the telescope cavity door system will continue until late 2004. In parallel, the modification of the aircraft, e.g. installation of avionic equipment, mission control systems, and the engines, need to be completed before test flights for the flight-certification of the integrated observatory will start in early 2005. Once officially flight-certified, SOFIA will be transferred from Texas to its future home base at NASA’s Ames Research Center in Moffett Field, California.

After that transfer, scientists and engineers of the SOFIA development team will test the observatory. Extensive preparations are already under way to write test plans and procedures for the various components, such as the telescope optics and its imaging quality, the functionality and accuracy of the pointing and tracking system and the auxiliary imaging cameras, the chopping secondary mirror, for the checkout of the Mission Control System, and to make sure that the telescope’s environment (temperatures, background radiation etc.) will be as specified for high sensitivity infrared observations. These tests will characterize the observatory and optimize its operational parameters in preparation of the scientific use of SOFIA by the international astronomical community.

A general description of SOFIA and updates on the project can be found at http://sofia.arc.nasa.gov.
In September 2002 the SOFIA telescope was airlifted from Germany to Texas. In the left picture, the framework of the metering structure is unloaded. On the right, the primary mirror cell is lifted from an Airbus Industries Beluga cargo aircraft.

The main support structure of the telescope (suspension assembly) including the large spherical bearing at a total weight of 8,990kg/19,800 lbs was installed in January 2003. A special lifting tool (6400kg/14,000lbs) had been constructed to securely lift it into the telescope compartment of the aircraft. The lift proceeded over a two day period. The entire 34,000 lbs load cleared the main sill beam of the aircraft, was lowered into the telescope compartment, moved forward and attached to the forward bulkhead. Clearances of this load at entry into the aircraft were at several points less than 4 inches. Over two hours, loads were then transferred alternately in 200 to 500 lbs increments to the second crane, insuring a gradual transfer of the weight to the aircraft.
bulkhead. Additionally, this weight transfer process insured that the lifting device could securely be lifted back out of the telescope compartment.

The metering structure of the SOFIA telescope is an open structure made of carbon fiber material. In the left picture it is lifted into the aircraft and attached to the main telescope bearing. On the right, the three armed spider with the chopping secondary mechanism in its center has been installed. All parts are still wrapped in plastic foil to protect the Ball IR Black paint that has been applied to reduce stray light.

The 2.7 meter primary mirror was installed in July 2003. The mirror of 820kg/1800lbs is supported in a 1820kg/4000lbs carbon fiber mirror cell. At left, the complete assembly is lifted into the telescope cavity of the aircraft. The middle picture shows the primary mirror cell attached to the telescope structure. This installation completed the telescope except for the secondary mirror which still needs to mounted to its support structure and actuating mechanism. The right hand picture shows a close-up of the light-weighted honey-comb structure of the Zerodur primary mirror and details of its support structure.
5. Science Instruments

For the reception and analysis of the light collected by the SOFIA telescope, nine scientific instruments are currently under development, seven by astronomical institutions in the U.S. and two by institutes in Germany. Table 1 shows the type of the instruments and where they are being built. There are three categories or instrument types, defining basically their modes of operation:

**Facility Science Instruments**

Facility science instruments are developed by institutes supported by grants from the SOFIA prime contractor Universities of Space Research Association, USRA. After their completion they will be delivered to the observatory, including appropriate documentation, and their operation and maintenance will be taken over by observatory personnel. Facility instruments are designed to be versatile using established technology for broad community use. General observers will work with the observatory’s science staff to prepare their proposals, plan and conduct their observations, and to reduce their data. The SOFIA facility instrument program is assisted by the development of a data cycle system, including pipeline processing and archiving of data.

**Principal Investigator Science Instruments**

Principal investigator (PI) instruments are developed very similarly to the facility instruments but are not formally delivered to the observatory. Instead, the PI-team remains in charge of operating and maintaining their instrument and will visit the observatory with a group of personnel needed to conduct observing flights. The teams are flexible to update their instruments to the most recent and best technologies, e.g. the most sensitive detectors, within the regulations of flight certification (see below). PI instruments are available to general observers by collaborating with the PI-team for planning and proposing their observations, obtaining the data and reducing them. This instrument program works very similarly to science programs on the Kuiper Airborne Observatory.

**Specialty Science Instruments**

Specialty science instruments are developed and operated like PI-instruments but are focused on a specific scientific topic. Currently there is one specialty instrument being developed, HIPO - a fast 0.35 - 1.1 \( \mu \)m CCD system for occultation observations. Two instruments, HIPO and FLITECAM have been designated as test instruments. They will be used by the SOFIA development team to test the telescope and the integrated observatory before it will be made available to the astronomical community.

A substantial part of the instrument development efforts is the flight certification process. The design of all critical parts, i.e. structural components, cryogen containers and electrical/electronic components needs to be approved by Federal Aviation Association (FAA) officials. Materials and manufacturing processes need to be certified, documented and are monitored.

Except for the test instruments HIPO and FLITECAM which will be needed as early as summer 2004, all development teams are working towards completion of their instruments by late 2005 when SOFIA will commence observing flights.

Further information on the first generation of SOFIA instruments can be found at [http://sofia.arc.nasa.gov/Science/instruments/sci_instruments.html](http://sofia.arc.nasa.gov/Science/instruments/sci_instruments.html) and in Krabbe et al. (2002)³.
Table 1  First generation SOFIA science instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Principal Investigator</th>
<th>Institute</th>
<th>Type of instrument</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASIMIR</td>
<td>J. Zmuidzinas</td>
<td>Caltech</td>
<td>Heterodyne Spectrometer 250 - 600 ( \mu \text{m} ) ( \Rightarrow 10^3 \ldots &gt; 10^7 )</td>
<td>PI instrument</td>
</tr>
<tr>
<td>EXES</td>
<td>J. Lacy</td>
<td>University of Texas</td>
<td>Echelon Spectrometer 5 - 28 ( \mu \text{m} ) ( \Rightarrow 3000 - 10^5 )</td>
<td>PI instrument</td>
</tr>
<tr>
<td>FIFI-LS</td>
<td>A. Poglitsch</td>
<td>MPE Garching</td>
<td>Imaging grating spectrometer 42 - 210 ( \mu \text{m} ) ( \Rightarrow 1400 - 6500 )</td>
<td>PI instrument</td>
</tr>
<tr>
<td>FLITECAM</td>
<td>I. McLean</td>
<td>UCLA</td>
<td>Near-infrared camera 1 - 5.5 ( \mu \text{m} ) ( \Rightarrow 5 - 8 ) (filters), 1000 - 2000 (grisms) occultation mode</td>
<td>Facility &amp; Test instrument</td>
</tr>
<tr>
<td>FORCAST</td>
<td>T. Herter</td>
<td>Cornell Univ.</td>
<td>Mid-infrared camera 5 - 40 ( \mu \text{m} ) ( \Rightarrow 7 - 20 ) (filters)</td>
<td>Facility instrument</td>
</tr>
<tr>
<td>GREAT</td>
<td>R. Güsten</td>
<td>MPIfR Bonn</td>
<td>Heterodyne Spectrometer 63 - 188 ( \mu \text{m} ) ( \Rightarrow 10^4 \ldots &gt; 10^7 )</td>
<td>PI instrument</td>
</tr>
<tr>
<td>HAWC</td>
<td>D.A. Harper</td>
<td>University of Chicago</td>
<td>Far-infrared bolometer camera 40 - 300 ( \mu \text{m} ) ( \Rightarrow 10 - 20 )</td>
<td>Facility instrument</td>
</tr>
<tr>
<td>HIPO</td>
<td>T. Dunham</td>
<td>Lowell Observatory</td>
<td>High speed imaging photometer 0.3 - 0.6 ( \mu \text{m} ), 0.4 -1.1 ( \mu \text{m} ), ( \Rightarrow 100 )</td>
<td>Specialty &amp; Test instrument</td>
</tr>
<tr>
<td>SAFIRE</td>
<td>H. Moseley</td>
<td>NASA-GSFC</td>
<td>Imaging Fabry-Perot spectrometer 100 - 655 ( \mu \text{m} ) ( \Rightarrow 2000 - 10^4 )</td>
<td>PI instrument</td>
</tr>
</tbody>
</table>

6. Ground Support Facility

SOFIA will be stationed at NASA’s Ames Research Center in Moffett Field, California. To ensure that the observatory’s objective of conducting at least 960 successful science flight hours per year will be met, a ground support facility called SOFIA Science and Missions Operation Center (SSMOC) is being developed. This new science institute will be located in the aircraft hangar housing the Boeing 747SP. The SSMOC will include laboratories supporting the aircraft and its scientific payload; office space for 80 scientists, engineers, technical support personnel and flight crews; a mirror coating facility; a pre-flight integration facility for the pre-alignment of science instruments; a system integration laboratory supporting the observatory’s software, communications and data acquisition systems; computer, library and data archive facilities for observing preparation, data reduction and data archiving; and facilities for SOFIA’s education and public outreach program. SOFIA and the SSMOC will be jointly operated by the U. S. and German project partners. Details can be found in Wolf (2002).

7. Summary

The SOFIA development aims at operating the biggest astronomical airborne telescope ever at very high precision. Its development included a number of technology challenges, most notably the light-weighting of its primary mirror and the achievement of the 0.2 arcsec pointing stability. The modification of the aircraft to safely accommodate the telescope and other observatory components has been an avionic challenge that is still ongoing until flight certification will be granted, presumably in mid 2005. The instrument development teams are also in the process of breaking new grounds. The detector arrays of FIFI-LS with 16x25 pixels at 100 and 200 \( \mu \text{m} \),
and the HAWC 16x32 bolometer array will be the largest far-infrared detectors ever built. Although the heterodyne instruments that are currently under development will initially use single channel receivers, preparations for receiver arrays have already been started.

The project is in its final development phase. Joint teams of the German and U.S. SOFIA consortia are working through the remainder of 2004 in Waco, Texas to integrate, align and test the observatory. After the FAA certification process will be completed, SOFIA will be transferred to California for the final checkout before its scientific mission begins, most likely in late 2005.

8. Outlook - Serendipitous Science

Once SOFIA will operate routinely, the aircraft may become available as a platform for serendipitous observations during flights. First ideas call for using the upper deck of the B747 (see figure 1). If aircraft windows of the upper deck can be replaced with optical quality glass windows, small telescopes or cameras could be positioned to observe through them. Examples for such research are the monitoring of meteor showers possibly including spectroscopy of meteor trails, and the high-precision photometric monitoring of stars, to search for small (~1% or less) dips in their light flux due to the transit of an orbiting planet. The detection of “star occultations” by an orbiting planet with a small telescope has been proven on the ground (HD209458) already by professional and amateur astronomers. At flight altitude these observations would benefit from the absence of atmospheric scintillation. However, the image movement onboard the aircraft would have to be compensated by an articulated mirror system, or accounted for by a suitable sampling scheme. All telescope equipment will need to be certified for flying on SOFIA.

Acknowledgement

The development of the SOFIA telescope is sponsored and managed by Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Bonn-Oberkassel. The support of the DLR Institut für Weltraumsensorik und Planetenerkundung in Berlin and of the DLR SOFIA Project in Bonn-Oberkassel, as well as of Hans-Peter Röser and Thomas Wegmann of Universität Stuttgart for my assignment to the SOFIA-USRA science team is greatly appreciated.
www.transitsearch.org: A Status Report

Tim Castellano
NASA Ames Research Center

Abstract: Extrasolar giant planets that “transit” their host stars are rare and valuable. Recent observations of the atmosphere of the best studied transiting extrasolar planet HD 209458-b demonstrates that detailed study of the physical nature of these planets is possible. The objective of the ongoing transitsearch collaboration is to discover and study additional transiting hot Jupiters with the help of amateur astronomers and students using small telescopes and charge coupled device (CCD) imagers. A status report is presented. The reward for contributing quality data could be a flight on NASA’s SOFIA 747 aircraft in 2005 and beyond.

References:
3. www.transitsearch.org
4. www.skywokker.com/transitsearchobservingprocedures.htm
5. www.sofia.arc.nasa.gov/Edu/edu.html
6. www.galaxycrystal.com

1. Status

Transitsearch has been steadily growing since it was first described to this audience two years ago. Notable events include:

- A workshop was held for professional and amateur astronomers on September 1, 2003 along with the AAS DPS Meeting in Monterey California. Participants requested more “photometry how to” and as a result RTMC and Stellafane hands on workshops are scheduled for this summer.

Press coverage has helped get the word out:
- “Laser Focus World” Magazine, editorial, May 2003
- Christian Science Monitor, October 24, 2002
- NASA press release, October 3, 2002
- New Scientist, September 28, 2002
- Space.com, September 25, 2002
- Reuters News Service, September, 2002
- www.transitsearch.org has received over 200,000 hits
- Over 80 participants in 12 states and at least 11 countries.
2. **Rewards for participants**

If you need a little more incentive to search for transiting exoplanets, a recent partnership agreement between Transitsearch.org and NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) Education and Public Outreach program will allow Transitsearch volunteer observers to fly (all expenses paid) as outreach partners on SOFIA modified Boeing 747 jet in 2005 and beyond. Participants will also be eligible to receive a special edition laser etched crystal of the three dimensional locations of the nearby stars orbited by planets.

3. **Summary**

Transitsearch is alive and well and still needs qualified observers!
Radial Velocity Detection of Extrasolar Planets

Thomas G. Kaye
Spectrashift.com

Abstract: Spectroscopy has long been an ignored corner of amateur astronomy and is generally regarded as difficult if not impossible with small telescopes. With the advent of robotic scopes and high efficiency CCD’s, this aspect of astronomy is now open for exploration. The Spectrashift.com project is a team of amateurs that have constructed and implemented a spectrograph and telescope system capable of measuring radial velocities down to approximately 100 meters per second. This level of precision can detect extrasolar planets known as “hot Jupiters”. The system’s performance has been demonstrated on the star Tau Boötis.

References:

1. Introduction

Historically, spectroscopy was rarely attempted at the amateur level. The inherent nature of the process spreads the light from a single star over a much greater area on the detecting medium, putting small amateur telescopes at a severe disadvantage. The mid 1990s consensus was that high resolution amateur spectroscopy was only practical for solar studies [1]. The advent of CCD’s has changed all this and in many cases, created order of magnitude efficiency gains in small telescopes.

Astronomical spectroscopy generally falls into two areas, elemental studies and radial velocity measurements. Maurice Gavin [2] pioneered the use of rainbow gratings and successfully measured the first galactic redshifts on quasars in the late 1990s. Amateur stellar redshift measurements were still unknown at that time. The Spectrashift Project was conceived in 1998 with the goal of pursuing precision radial velocities.

The Spectrashift team consists of amateur astronomers with individual professional capabilities in optics, mechanics, software and physics. The effort to date has resulted in the construction of a fiber fed, granite based, thermally stabilized spectrograph capable of velocity measurements to approximately one hundred meters per second. The spectrograph is coupled to a 16 inch Meade LX200 with light gathering ability to fifth magnitude stars. As proof of concept, the system has detected the extrasolar planet around Tau Boötis by measuring the wobble of the parent star.
2. Methods

Radial velocity measurements are conceptually simple in that all one has to do is measure the spectral shift. The complexity arises when the goal is to try and measure accurately a shift of only one millionth of an inch on the detector. A spectrograph of sufficient resolution is required but higher resolution also means less efficiency in collecting and measuring the spectrum.

Professional planet hunters typically use spectrograph resolutions in the range of 60,000 to 80,000 [3] to achieve velocities better than fifty meters per second. Our system resolution is 15,000 for the best balance between efficiency and precision. In order to monitor instrumental drifts arising from thermal and mechanical effects, a thorium-argon lamp is used to feed two additional input fibers for a non-moving reference spectrum. The star is centered and precisely tracked on one of seven fibers coming from the cassegrain focus of the telescope. Integration times are typically on the order of ten to forty minutes to achieve one hundred to one signal-to-noise ratios.

The final image consists of three horizontal spectrum “stripes” approximately four pixels tall, two from the reference source and one from the star of interest (Fig. 1). Sequences of images ranging over a given time from days to weeks are recorded as a data set. The first image is used as a baseline to measure the rate of change in subsequent images. In this way only the change in velocity is detected, not the absolute velocity. All the images in the data set have the individual spectra extracted and compared to the first image. The shift in the stationary reference spectra are first subtracted from the stellar fiber. Changes due to the Earth’s rotation and orbit are calculated and subtracted for a final result. To detect an extrasolar planet, the residual velocity variations are plotted with respect to time looking for periodic, sinusoidal-like variations in the orbit.

![Fig. 1. Raw spectrum “stripes”. Top and bottom spectra are from the reference lamp, the middle spectrum is the stellar fiber from the telescope.](image)

3. Equipment

The spectrograph is a granite bench mount with fiber optic feed as shown in Fig. 2. It is enclosed in a wooden and foam enclosure that is cooled and temperature controlled to 60F. An optical layout is shown in Fig. 3. A 150mm diameter mirror is used to collimate the fiber outputs to a 100 x 127mm, 1800 line/mm grating blazed at 500 nanometers. The camera mirror then focuses the collimated beam from the grating, through a flat secondary mirror, into the detector. This is a typical Czerny Turner design that allows changing the mirrors to achieve different resolutions. The camera is an Apogee AP7 thinned and back illuminated, which is water cooled to 50 degrees F below ambient. The dispersion is approximately 0.1 angstrom per pixel. A photomultiplier tube is fed from a small pick off mirror to monitor photon counts and assist with centering the star on the fiber. The optical fibers are run one hundred and fifty feet through an armored cable from the telescope to the spectrograph which is located in a temperature controlled basement.
The telescope is a Meade LX200 with modifications to hold proper focus. It is run robotically with the assistance of video cameras mounted on the finder scope and on a flip mirror looking at cassegrain focus. Since any guiding errors will show up as spurious shifts in the data, an AO7 tip/tilt system is coupled to the guide chip on an ST7 and is used to actively track and hold the star on the fiber. The flip mirror, video camera, AO7 and ST7 are all situated on a custom machined instrument mount as shown in Fig. 4.
A large selection of software is used to drive the telescope, spectrograph, monitor the variables and accomplish the data reduction. In all, six different computers are used throughout the system. The telescope is pointed with Starry Night Pro and Astronomers Control Panel. MaximDL who customized the software for our needs, drives tracking for the AO7. The spectrograph’s AP7 is again controlled by MaximDL which is also used for dark subtraction and flat fielding. A custom Labview program continuously records the spectrograph temperatures and photomultiplier tube counts. The weather is monitored and recorded through the WS2000 system from Rainwise to check for large changes in barometric pressure that can affect the readings. A Linux system runs IRAF for the actual spectrum extraction and cross correlation of the shifts, with Excel finishing up the data presentation. A detailed description of the spectrograph construction and data pipeline can be found in the book Practical Amateur Spectroscopy [3].

4. Results

The star Tau Boötes was chosen as the specific target because it was one of the brightest at magnitude 4.5 and it had a high amplitude short duration “hot Jupiter” in orbit around it. The velocity swing over several days is more than eight hundred meters per second, which was within the range of this system’s capability. The telescope and spectrograph were transported to the Winer Observatory in Sonoita Arizona in February of 2000 to take advantage of the clear skies and elevation. The observing run was hampered by bad weather and a defective grating which had to be half blocked off at the start of the run. Over the next three weeks one hundred forty usable exposures were collected.

Figure 5 shows the data points in a phased orbit. After final reduction, this data showed an orbital period of 3.15 days and amplitude of 368 ms. This closely matched Marcy and Butlers parameters of 3.312 days and 469 ms [4].
Fig. 5. Phased data points plotted as squares on top of solid line representing the published orbit.

5. Discussion

While the results were very good for a first attempt on an extrasolar planet, they do not meet the professional criteria for a three sigma detection. Experience gained from the first run dictates that a longer period of observations should be used in order to more precisely calculate the orbit. The single three week run at this level of precision would not cover enough orbits to average out the error. In addition, to get more precise amplitude measurements, the run has to cover a number of days when the orbit is passing through the velocity extremes. With Tau Boo’s short three day orbit, many peaks can occur during the day and be missed completely in a short duration run. At the time of this writing, a second and third observing run is scheduled for 2004 to complete the detection.

6. Summary

The Spectrashift Team’s goal is to discover a new extrasolar planet. Construction is underway on a 1.1 meter telescope and high resolution Echelle spectrograph in order to be competitive with professional searches. The obstacles are more to do with time and money than scientific capability, and this fact is sure to reflect in future collaborations between professionals and amateurs. In conclusion, this project demonstrates that capability at the amateur level has increased dramatically with the advent of robotic telescopes coupled to high performance CCD’s and real science is within the reach of anyone dedicated to achieving it.

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Mira Variable Stars:  
Spectroscopic and Photometric Monitoring of this broad class of Long Term Variable and Highly Evolved Stars-II

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Abstract: We have been monitoring Mira variable stars, which encompass spectroscopic classes of type M, S and C during the past year and a half. These stars are closely related in terms of their long term variability, position on the Hertzsprung-Russell diagram their intermediate mass (from ~0.8 to ~8 solar mass) and the fact that class M evolves into the S and C type stars. These stars are very interesting from the stand point that they can produce heavy elements beyond iron and also carbon which can appear at the surface of these stars during periods in their evolution. In addition, it is suspected that these type stars, in particular, the M type Mira’s can flare up over periods of hours to days by several tenths of a magnitude or more. The spectroscopic changes, which occur during these flare episodes, ultimately driven by core burning evolution, remain relatively unexplored. This project was initiated in order to monitor a group of program stars of these classes in the V and R photometric bands in the hopes of “catching” some of these stars during one of these flare ups and thus to be able to conduct spectral analysis of the flare-ups in real time and compare these spectra to the non-flare spectra. This paper will give an update of the project and describe the strategies being employed to monitor these stars.  
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1. Introduction

Among all the stars of the heavens, there exists a small sub-group, which has served as a key to our understanding of stellar evolution through spectroscopic examination. These stars are broadly called Mira variables and include the oxygen stars (M types), carbon stars (C type) and the S stars. They represent stars of the initial mass range from ~0.8 solar mass to ~8 solar masses
which have evolved off the main sequence. These stars are peculiar in a variety of respects be-
cause of their high ratio of carbon to oxygen and the often-high abundance of heavy elements
they contain, which are synthesized by the slow neutron capture process. They are also long pe-
riod variable stars, of the Mira class and the sequence from M to S to C types represent an evo-
lutionary pathway during certain core burning events in their post-main sequence lives.

Over the past several years, evidence has accumulated to suggest that Mira variables may go
through flare up stages which result in brightening on the order of several tenths of a magnitude
and can last hours to days in length (Schaefer, B., 1991, Maffei, P., and Tosti, G., 1995 and de
Laverny, P., et. al., 1998). Very little is known about these events, especially spectroscopic
changes that may occur during these events. This project was initiated with the view of monitor-
ing a set of program stars in the V and R photometric bands and establishing baseline spectro-
scopic observations of moderate resolution in the red and near infra-red. In this manner, potential
flare up episodes can be studied in this spectroscopic region.

2. Background, Results and Discussions

My primary instrument for spectroscopy is a Celestron 14 with a Paramount ME system. The
Santa Barbara Instrument Group (SBIG) Self Guiding Spectrometer (SGS) is linked to the tele-
scope with a focal reducer giving a final f6 ratio. The CCD camera attached to the spectrometer
is the SBIG ST-8E with 9-? m pixel size. In this paper only results obtained using the 18-? m slit
will be presented. The grating of 1200 or 1800 lines were utilized which represent a resolution of
~0.5 and 0.3 Angstroms per pixel, respectively. Wavelength calibration was carried out using the
emission lines from a thorium-argon gas discharge tubes using the software package Vspec. Ab-
sorption and emission line identifications were also carried out using Vspec.

Photometry was conducted with an Astrophysics 5.1-inch f6 refractor using an ST-10XME
camera and 2x2 binned pixels and the Johnson V and R filters. Images were obtained in dupli-
cate for each band and two reference stars used per variable star for analysis. Image reduction
was carried out with CCDSOFT image reduction groups and specially written scripts for magni-
tude determinations, which allowed for rapid, nearly real time magnitudes to be found.

The spectra of these stars are closely related, in part because their temperatures are nearly the
same. Differences arise because of changes in their outer atmosphere chemistries and can be seen
in figure 1. The prominent TiO molecular bands so prominent in M types gradually give way as
one proceeds to S types and essentially disappear in C types. H? lines can be in emission for any
of these types and is often variable with the phase of the variability. Also, one often observes an
enhancement of s-elements (heavy elements) in their atmospheres. These are elements synthe-
sized by the slow neutron capture method in shell regions around the core of these stars. Car-
bon/oxygen ratio increases in these stars from a typical value of 0.4 up to values often greater
than 1. Finally, the molecular bands of titanium oxide (TiO) observed in the spectra of cooler M
type stars often disappears and are replaced by zirconium oxide (ZrO) bands and vanadium oxide
(VO). (Zirconium is a slow neutron capture element).
Figure 1. As stars of ~0.8 to 8 solar masses evolve away from the main sequence, they expand and cool and move into the red giant M type stars (A). From here they enter into Mira type long period variability and gradually evolve into S (B) and ultimately C type (C). In the thermally pulsing phase many of heavy elements synthesized deep down are brought to the surface including carbon and zirconium. As a result, there is a gradual increase in the C/O ratio. The newly made zirconium has a higher affinity to react with free oxygen than titanium, resulting in the disappearance of TiO bands and the appearance of ZrO bands in their place. Either of these molecular species can be observed only in cooler stars such as M, S or C types. H? emission may appear in any of these types and is often variable.

The lower temperatures of these stars give rise to many metal lines in the spectra and typical spectra of these stars is shown in Figure 2. This shows a high resolution spectrum of Mira, (omicron Ceti) in the blue region of the spectrum with some of the many lines identified. Note the prominent molecular TiO band around 4590 Angstroms. These type molecular bands (due to TiO) are the first to go as stars evolve into S type (to be replaced by ZrO or ZrS bands). As the evolution proceeds into the C type Mira’s, it is not uncommon to see essentially complete disappearance of the blue region of the spectrum due to the very heavy absorption of diatomic carbon (C2). The ZrO bands remain but can be seen only more toward the red region of the spectrum (Figure 1).
Figure 2. Spectrum of Omicron Ceti (M type Mira) obtained near maximum light in the blue region of the spectrum using a moderate resolution grating (1200 line, ~0.5 Å/pixel). The large number of lines, many blended, is typical of these type cooler stars as is the molecular TiO bands (one such seen at ~4590 Å). These bands give way to ZrO bands in S stars and finally molecular C\textsubscript{2} bands in the C types as the evolution of these long period variables proceed.

There have been recent studies that suggest that these stars, especially the M type Mira’s undergo flare up episodes with a brightening of several tenths to over 1 magnitude, lasting from hours to days. Schaefer (1991) reviewed what was known about these events from the literature and while suggestive, the evidence is not compelling; Maffei and Tosti (2000) performed a similar analysis. The strongest evidence came from a study of results obtained with Hipparcos observations by deLaverny et. al. (1998). Their analysis of thousands of individual observations on 251 Mira’s over a 37 month period indicated what appeared to be 51 flare up events in 39 M type Mira’s. No similar type flare-ups were observed with S and C type stars but the sample size was small for these type stars, which easily could account for the lack of observed events. De Laverny notes that these events occur in the later M type stars rather than earlier types and suggested that these events could be related to opacity changes that occur with the molecular bands of TiO and/or possibly VO.

Despite the challenges of verifying the existence and frequency of the "microflares" among selected Mira variable stars, it remains possible to speculate on causes. At least three scenarios present themselves: (1) shock induced; (2) magnetically induced, and (3) planet induced events.

1. Many Mira variables exhibit radio maser emission arising from excited molecules of SiO in the outer atmosphere of such stars. The patchy nature of the bright SiO maser spots seen in VLBI maps varies in response to the Mira optical variation. If a consistent phase for microflares can be established, they could be related to shock propagation and interaction altitude.
2. The same type of maser observations can be used to deduce magnetic field strengths via Zeeman line splitting. The analogy with solar magnetic phenomena [spots, flares, eruptive prominences, coronal holes and mass ejections] is compelling. However, in analogy to the R CrB phenomenon, brightness variation could also be a consequence of dust formation (fading) and dissipation (brightening) in front of a star’s visible hemisphere. Additional observations will be required to discriminate which is occurring. True flare stars include Sun-like red dwarf stars with half the surface temperature and a fraction of the solar mass. These appear to have sizeable starspots and intermittent flaring behavior. In those cases, extensive spots and concentrated fields give rise to high energy output in UV and X-rays. The latter emissions are not seen in the case of Mira variables, suggesting a strong limit to the size and strength of spots. A more “dilute” and large-scale eruptive prominence analogy might suggest measurable changes in mass loss diagnostics, such as the cores of H-alpha or Ca II K, if these could be extensively monitored for microflares (Stencel, R., and Ionson, J., 1979, Stencel, R., 2000).

3. An interesting speculation involves extending the discovery of extra-solar planets to their role around evolved stars like Mira variables. As the Mira red giant expands and engulfs its Jupiters, several kinds of accretion “fireworks” might accompany digestion (Struck et al., 2002). However, the duration and frequency would be limited to either orbital periods or one-time events. Existing maser maps would appear to rule out large scale planetary wakes around some Mira variables, but additional observations are always merited.

The approach we took toward this project a year and a half ago was to select a group of program stars. Of the 39 M type Mira’s described in the deLaverny paper, 20 of them are relatively bright and visible from the northern hemisphere. These along with a variety of brighter S and C type stars were also chosen. The Hipparcos data did not rule out a sample size effect of the S and C types as to why none were observed in these stars. Therefore it was felt to be prudent to include a good size group. The brighter stars were chosen since they represented stars with magnitudes, especially in the H? region (6562 Å) and higher, bright enough such that moderate resolution spectroscopy could be performed as part of the monitoring process. The final breakdown in program stars include 25 M-type, 16-S type and 57 C-type Mira’s.

To accomplish this in a semi-automated manner, the telescope, camera and filter wheel are controlled by a single computer with Orchestrate. Once the images are reduced, a script written by one of the authors (David Richards) runs through the images performing an image link with TheSky. The images obtained in this manner are stamped both with the name of the variable star since this was how Orchestrate was instructed to find the object, and the position of the image in the sky. This allows TheSky to quickly perform the linkage with its database. Figure 3 shows the flow scheme for data acquisition. Once the astrometric solution is accomplished, the program reads through a reference file with the pertinent data such as reference star name and magnitudes along with variable star of interest. The results file is readily imported to excel where the various stars and their magnitudes can be plotted, almost in real time. This is an important aspect of this project, the ability to see changes (flare-ups) quickly and as a result respond to these changes with spectroscopic observations. Figure 4 shows the script page that carries out these reductions.
Figure 3. The flow of data acquisition and reduction for variable star monitoring. The imaging camera and filter wheel are controlled by CCDSOFT while the Paramount ME is controlled by TheSky. All of this is under the umbrella of Orchestrate which allows for non-intervention in acquiring images of varying length with different filters, dark subtraction and saving of images. The images are then reduced using CCDSOFT reduction groups routines and finally the use of a visual basic script written by one of the authors completes the data reduction with the magnitudes reported in an Excel format.

The project has been underway now for only about 1.5 years and involves a total of 98 stars. While there are certainly many more of these type stars, only those that had a significant part of their light curve under magnitude 8 were considered. This was because of magnitude limitations in the spectroscopy part of the project. Fortunately, these stars are much brighter in the R and I bands, often by 2-4 magnitudes when compared to their V magnitudes and many of the interesting molecular features are found in this region of the spectrum. Many of the stars have now completed a complete cycle of variation and some interesting features can be discerned in their light curves as will be discussed below. The photometric analysis involves using 2 different reference stars. Their constant nature is readily discerned over the time period by the horizontal slope of their light curves, both in the V and R bands. After considerable effort, magnitudes are now determined at the sub 0.01 magnitude level. Thus any flare-ups in the range of 0.1 and above should be readily discerned.

The light curves of Mira’s have been classified into different types, mainly based on their shapes, not their lengths. The top of figure 5 shows 2 different periods of M type Mira’s. In addition, this figure shows 2 different types of curves based on the curve shape. In most cases for these stars the curve shapes are smooth and sinusoidal in shape while for a sub-type of Mira’s, they possess a “Cepheid bump like” phenomenon as indicated by the arrows. These have been described before (Melikian, 1999). We see these bumps on about 20% of the light curves for the
program stars, irrespective as to the type of Mira. These bump Mira’s are of longer period and higher luminosities but beyond that not much is known as to the physics producing these phenomenon.

A typical light curve of S Cam, an S type Mira, is shown in the bottom part of figure 5 in both the V and R bands. Again, note the bump on the ascending part of the light curve as indicated by the arrow. The analysis of the light curve is shown in figure 6. The best fit of the growing light curve is determined and with this best fit equation, residuals between calculated and observed magnitudes can be found. A plot of these residuals for the V band is shown along with residuals for one of the standard stars. Clearly, there is more scatter in the variable residuals than for the standard. Perhaps what is being observed here are micro-flares in the variable or even the presence of large star spots on the surface of the variable resulting in greater scatter. To date however there has been no compelling evidence for flare-ups for any of the stars observed at the 0.15 magnitude level or more. Observations will continue to complete at least several complete light curves.
Figure 5. Typical light curves obtained for the first several months of the project. Shown above are 2 typical M type Mira, displaying 2 different types of curves both in period and in shape. Note the “Cepheid bump like” phenomenon near maximum light, seen for many of these variables at phase 0.6-0.8 (arrow). Below is shown the curves of R Cam, an S-type star in both V and R bands along with a polynomial best fit to the data.
Early on it was felt that semi-automating the process was the only way to go. The use of a mount such as the Paramount along with the Suite of software by Software Bisque got the project 80% of the way there. It turns out the real consumer of time in these efforts was the magnitude determinations. This took far longer than the actual acquiring and processing of the images. Fortunately, TheSky in conjunction with CCDSOFT lends itself to scripting and a script was put together that automated the magnitude determinations. It is now not even necessary to view any of the images. To give an example of how this has streamlined the effort, on a typical night using Orchestrate to control the telescope, camera and filter wheel, 40 stars, visible at the time, are imaged in duplicate in each of the V and R bands. This takes about 1 hour. Reduction of the images using image reduction groups in CCDSOFT takes another 5 minutes. The script that determines the magnitudes takes about 10 minutes to churn its way through all the images. Within another 20 minutes, the data, via Excel, has been added to each variable stars growing light curve. Thus in less than 2 hours all of the program stars have been observed and their results tallied. Until more of your program stars rotate into view, one is free to pursue spectroscopic examination of the program stars, establishing baseline observations.

3. Summary

We have described the initiation of a program to follow Mira type long period variables to attempt confirmation of flare-up episodes. If flare-ups are observed, to follow up with spectroscopic observations of moderate resolution. A group of 98 stars are part of the program and photometric observations are being conducted, currently, in the V and R bands. The photometric observations and data reduction have been automated to a large extent using software aimed at control of telescope-camera-filter wheel for image acquisition and image reduction. To date there have been no observed flare up episodes among these stars at the 0.15 magnitude or greater level. A script is described which proceeds to carry out the magnitude calculations. Hands-on analysis...
is kept to a minimum. This script could find wider use among those in the amateur community interested in variable star work as it removes the most time consuming part of the analysis.
NASA’s High Energy Vision:
Chandra and the X-Ray Universe

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Abstract: The Chandra X-Ray Observatory is the most sophisticated X-ray observatory launched by NASA. Chandra is designed to observe X-rays from high-energy regions of the universe, such as the remnants of supernovae explosions, colliding galaxies, black holes, pulsars, neutron stars, quasars, and X-ray binary stars. The spectacular results from the first five years of Chandra observations are changing and redefining theories with each observation. Every exciting new image shows glimpses of such exotic phenomena as super-massive black holes, surprising black hole activity in old galaxies, rivers of gravity that define the cosmic landscape, unexpected x-ray activity in proto-stars and failed stars, puzzling distributions of elements in supernovae remnants, the sound waves from a super-massive black hole, and the even the tantalizing possibility of an entirely new form of matter - the strange quark star. On September 14, 2000, triggered by alerts from amateur astronomers worldwide, Chandra observed the outburst of the brightest northern dwarf nova SS Cygni. The cooperation of hundreds of amateur variable star astronomers and the Chandra X-Ray scientists and spacecraft specialists provided proof that the collaboration of amateur and professional astronomers is a powerful tool to study cosmic phenomena.

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1. Introduction

On September 14, 2000, triggered by alerts from amateur astronomers worldwide, NASA's Chandra X-Ray Observatory observed the outburst of the brightest northern dwarf nova SS Cygni. The amateur astronomers provided Chandra scientists with a crucial early warning of this outburst by reporting their visual observations of SS Cygni as soon as they saw the star begin to brighten.

The data the amateur astronomers provided about the star’s optical brightening, about the combined with the X-ray spectra gathered by the Chandra satellite, helped reveal the nature of the flow of gas from the small red companion star into an accretion disk and onto the surface of the white dwarf in SS Cygni.

Dr. Janet A. Mattei, Director of the American Association of Variable Star Observers (AAVSO) - a non-profit organization made up of mostly amateur astronomers - and her technical staff coordinated the collection of optical observations of SS Cygni and communicated them to
Dr. Christopher Mauche at Lawrence Livermore National Observatory, CA who is the Principal Investigator for all Chandra observations [1].

The dwarf nova, SS Cygni, is a type of star known as a cataclysmic variable. SS Cygni is a close binary star system in the constellation of Cygnus that contains a red dwarf star and a white dwarf. A red dwarf is a star a little cooler and smaller than the Sun. The white dwarf was once as large as the Sun but subsequently ran out of hydrogen in its core underwent a core collapse, blew its outer atmospheric layers into space, and collapsed to form a white-hot ember, the size of Earth. The dense white dwarf, with its strong gravitational potential, pulls a steady stream of gas off of its companion star. This transferred gas collects in a disk, called an accretion disk, around the white dwarf.

The dramatic brightening by many orders of magnitude in this system is the result of an instability in the disk, which forces the disk material to drain down onto the surface of the white dwarf. This causes a titanic energy release equivalent to that of billions of atomic bombs exploding every second. Such stellar explosions, which often occur without warning and rarely last more than one or two weeks, serve as floodlights that brighten a dim star system for scientists to study.

The start of the SS Cygni outburst was discovered in its very early stage by tens of amateur astronomers who have been keeping a vigil to catch the outburst. It was then confirmed by other amateurs, many of whom are members of the AAVSO. They e-mailed or phoned-in their observations to the AAVSO. Dr. Mattei communicated this information to Dr. Mauche and advised him to submit the request to start the X-ray observations. Within hours of Dr. Mauche's request on a Sunday, he was speaking with Dr. Fred Seward and Dr. Pat Slane of the Chandra team on the specifics of the requested observations. Thanks to their and other Chandra team’s efforts, Chandra observations began in an amazingly short time - on Sept. 12.7 UT - and continued until Sept. 14.5 (Sept 12.7 UT is Sept 12, 16:48 UT or Sept. 12, 12:48 EDT or in Julian Date - 2451800.2) [1].

Dr. Mauche also spoke with Marty Eckert, the Extreme Ultraviolet Explorer (EUVE) Science Planner, to arrange for simultaneous observations of SS Cygni with NASA’s EUVE satellite. EUVE measures the brightness and spectra in the extreme ultraviolet, providing unique information about the very short (10 sec) quasi-period oscillations that appear only during outburst in SS Cygni. The Extreme Ultraviolet Explorer, the Chandra X-Ray Observatory, and the amateur astronomers all observed SS Cygni at the same time [1].

Once again, on January 16 and 17 of 2001, thanks to alerts from amateur astronomers in thirteen countries, NASA’s Chandra X-Ray Observatory and the Rossi X-Ray Timing Explorer (RXTE) made unique coordinated observations of the bright northern dwarf nova SS Cygni. Together, the data from the satellites and the backyard observers revealed even more information about the flow of gas to the white dwarf SS Cygni from its companion star. After dozens of amateur astronomers had kept an intense and dedicated vigil for 72 days – which was 22 days longer than had been anticipated - SS Cygni finally started to brighten on January 12. The volunteer amateur observers immediately sent detailed reports to the Headquarters of the
American Association of Variable Star Observers (AAVSO), as had been requested by Director Dr. Janet A. Mattei. In less than 24 hours, by January 13, the outburst of SS Cygni was confirmed - SS Cygni was definitely on the rise. Late on January 13 SS Cygni surged to near maximum optical brightness, then finally reached maximum.

As the data came in from the observers by email, fax, and phone, Dr. Mattei communicated with collaborators Dr. Christopher Mauche at Lawrence Livermore National Observatory, CA, Principal Investigator (PI) for the Chandra observations, and Dr. Peter Wheatley at the University of Leicester, England, PI for the RXTE observations, both of whom had been waiting anxiously for weeks for word from the AAVSO’s observers. Once the outburst was clearly established, Dr. Mattei triggered the Chandra Target-of-Opportunity observations (TOO) via a webform, on a Sunday morning, Jan. 14, at the request of Dr. Mauche, who was skiing in Utah and had no access to a computer.

Catching the outburst of SS Cygni at peak optical brightness was crucial. The previous Extreme Ultraviolet Explorer (EUVE) satellite observations the year before had demonstrated that in SS Cygni there is a delay of 1.5 days between the rise of the optical and extreme ultraviolet/soft X-ray flux. Soft X-ray emission peaks and then stays bright for about 4 days, then declines, first slowly and then sharply. In order to acquire optimum data, it was essential to observe SS Cygni at optical and soft X-ray peak, that is, within 4 days of the SS Cygni binary system erupting and reaching its optical maximum. The graph on the right is a light curve (graph of light variation) showing the behavior of SS Cyg from January 2000 to date. Each dot represents one optical observation.

Recognizing the urgency of this time limit, Chandra Director Dr. Harvey Tananbaum, who was informed of the TOO request triggering within half an hour, advised the Chandra planners and schedulers to see if observations of SS Cygni could be scheduled within three days. The Chandra planners and schedulers made a Herculean effort, and Chandra observations were scheduled for January 16, 4:30 PM EST to Jan 17, 5:40 AM EST.

In the meantime, Dr. Wheatley, having been alerted by Dr. Mattei, sent a request, on Sunday, Jan. 14, to the RXTE satellite planners and schedulers for hard X-ray observations to be made simultaneously with those of Chandra. Although optimally 72 hours are needed to schedule RXTE, the team made a tremendous effort and was able to schedule RXTE to start observing SS Cygni just a few hours after Chandra started.

Previous coordinated observations had utilized Chandra’s high-energy transmission grating spectrometer (HETGS) to study the spectrum of the hard X-rays emitted by the tenuous upper “atmosphere” of the boundary layer between the accretion disk and the surface of the white dwarf. During the current observations, Chandra's low-energy transmission grating spectrometer (LETGS) was used to study the spectrum and temporal characteristics of the dominant light curve.
spectral component of the inner accretion disk and boundary layer, a "big blue bump" in SS Cygni's spectrum which peaks at extreme ultraviolet/soft X-ray energies. The new measurements filled in the missing piece of the puzzle of the X-ray spectrum of SS Cygni in outburst, and will be used to study the physics, physical development, and characteristics of the boundary layer. This information is crucial not only for understanding SS Cygni itself, but also active galactic nuclei, which also show a similar "big blue bump" in their emission spectra [2].

2. Summary

Chandra and RXTE proved to be a powerful combination, with Chandra pinning down the boundary layer spectrum in great detail and RXTE simultaneously probing its most rapid variability. The EUVE in combination with Chandra gave added detail to the spectral analysis at the lower end of the X-ray range. These projects were a wonderful collaboration of professional and amateur astronomers and NASA's Chandra, EUVE, and RXTE Directors and Operations Teams to observe the brightest dwarf nova SS Cygni simultaneously with two NASA satellites. For years, amateur astronomers have informed professionals of novae, supernovae and other cataclysmic events. The cooperation between an organized group of dedicated amateur astronomers, and the professional astronomers who need these observations, is now quite finely tuned. When scientists are in need of ground-based observations to follow simultaneous satellite observations, they know that this worldwide network of amateurs can be depended upon for fast, efficient, and reliable results.

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Modern Asteroid Occultation Observing Methods

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Abstract: This presentation reviews current working methods for asteroid occultations developed by the International Occultation Timing Association (IOTA). Reduction of multiple tracks or “chords” observed during stellar occultations provides valuable measures of the relative sizes and shapes of asteroids. Traditionally, predictions for asteroid occultations were prepared by regional IOTA computers, distributed annually in “hard copy” format to IOTA subscribers and in publications such as Sky & Telescope magazine and the annual RASC Observers Handbook. IOTA – like many other organizations – is now using worldwide internet services and e-mail to distribute frequently-updated predictions based upon the latest astrometry. The IOTA web pages provide an easily accessible, centralized source of information on lunar and solar system occultation events. IOTA’s web pages feature a variety of articles on current activities, plans for observing campaigns and expeditions, and “how to do it” information on the latest technology and techniques. The latest updated predictions for asteroid events are made available as they are produced, providing more accurate observing tracks and efficient coordination of observers. The IOTA e-mail list provides a dynamic forum for the exchange of technical information and communication of observing plans in a timely manner. Individuals may now generate customized occultation predictions using the WinOccult software package. The author presents some examples of recent occultation events, showing the benefits of coordinated observations. Also described are some of the latest innovations, featuring low-cost video camera equipment, devices for time insertion based on Global Positioning Satellite (GPS) technology, and a new approach using unattended secondary field station equipment to multiply the number of tracks observed. © 2004 Society for Astronomical Sciences, Inc.

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1. Introduction

IOTA – the International Occultation Timing Association – exists to foster observations of occultation phenomena and collaboration by amateurs and professionals worldwide [1]. The organization has about 250 subscribing members (2003). IOTA was incorporated as a non-profit corporation in the United States ca. 1975, and has IRS Federal tax-exempt status, meaning that volunteers supporting IOTA’s activities may submit expenses for tax deductions.

1.1. IOTA As A “Virtual” Organization

With the increased interest and activity on the Internet, IOTA is now operating mostly as a “virtual” organization. In the past, IOTA observers relied upon annual mailings of printouts of event and track predictions, prepared by regional “computors” using mainframe software. A PC version of the “WinOccult” prediction software is now available for downloading by subscribers from the IOTA web pages [2]. Predicted events and frequent, timely updates (based on current astrometry) are now posted on the web pages, which greatly facilitates planning of regional observing “expeditions”. Subscribers will receive printed copies of the Occultation Newsletter (ON) and annual mailings of occultation predictions on floppy disk (printouts are also available on request). Frequently Asked Questions (FAQs) and explanatory information is available on the web pages [1]. Lively, current discussions are carried on in the IOTAoccultations e-group [3]. There is also a separate European organization [4].
2. Why Observe Asteroid Occultations?

Direct methods of determining the shapes of small solar system bodies such as asteroids typically involve very expensive operations such as imaging spacecraft, radar observations employing very large radio telescopes, or interferometry. All of these methods typically involve Government support and funding. When a solar system body such as an asteroid passes in front of a star, the asteroid literally “casts a moving shadow” onto the surface of the Earth. Figure 2 illustrates schematically the geometry of the situation for a target star and an asteroid.
An observer who is in the right place, at the right time, may observe a “chord” of some duration (seconds to tens of seconds) which literally maps the shape of the occulting body. (See Figure 3.) By combining a number of these “chords” from observers in different locations, an accurate profile of the occulting body may be determined. In addition, asteroid satellites may be detected. Observing occultations allows meaningful participation and collaboration by amateurs, with only small investment.

Some of the drawbacks and limitations of this approach include:
- Uncertainty in positional data for the asteroid and the target star leads to uncertainty in the predicted event track
- Few observers are available to produce multiple chords
- Portable equipment is needed
- Travel and setup time and expense is involved
- Geographic and weather factors sometimes limit the observations.
3. Some Asteroid Occultation Results

Some typical examples of successful asteroid occultation results are shown in Figures 4 through 6. Other examples are discussed by Dr. David Dunham [6] and Richard Nugent [7].

\textbf{(2) Pallas 1983} Figure 4 (courtesy of Paul Maley, Houston, TX) illustrates the results from 130 observers for the 1983 occultation of the star 1 Vulpecula by the large asteroid (2) Pallas. In the diagram, pairs of dots are plotted that represent the disappearance and reappearance as seen from each observing site. Dots shown as 1D and 1R indicate the disappearance and reappearance timed by the most northerly station, while 130D and 130R are those by the most southerly ground observer. The distance between the dots is the time duration (not indicated) during which the star had disappeared. The essentially round profile of the 300 km diameter asteroid is clearly shown. The cutoff at the bottom of the diagram was due to clouds in southern Texas.

![Figure 4. Plot of Results from 1983 Occultation of 1 Vulpecula by (2) Pallas. Diagram Courtesy Paul Maley.](image)

The Pallas expedition was one of the most successful asteroid occultation events ever documented. According to Maley, volunteer observations were attempted by 262 amateur astronomers in Texas and Oklahoma, 82 amateurs in Arizona and New Mexico, 18 in Louisiana and Mississippi, 28 in California, 80 in Florida, and 24 in other locations, also including some professional astronomers. Successful observations included 68 chords from Texas, 40 from Florida, 6 in Arizona, 4 in Baja California, 3 in Louisiana, and 1 in Mexico proper.

The Pallas profile coverage was so extensive that Bill Darnell in Houston, at the very tip of the asteroid, observed a “flicker” just as the star began a 1.0 second fade to invisibility. Observers north of Darnell saw no occultation. Normally, only a few observers are even in position to actually observe a given asteroid occultation, because the path of the occultation is confined to a small geographic region (relative to the shadow width, which represents the diameter of the asteroid) and the accuracy of the predicted path can be unreliable. The reason that this particular event was so widely observed was due to the bright 4.7 magnitude star involved and also the large size of Pallas, the second largest minor planet in the solar system. This enabled the track prediction to be developed months ahead of time with a reasonable amount of reliability. There were 130 timings of the occultation; but “miss” observations are also of value. Up until that time
the previous best-observed asteroid occultation event had collected 20 timings. Until 2002, no other asteroid occultation had even come close to this level of grand success. See the account in *Astronomy* magazine.\(^8\)

(Quoting from Maley), “Before 1977, only 7 asteroid occultations had ever been observed! Between 1977 and the Pallas event, observations increased six-fold. When the analysis of the Pallas occultation was finished, 90 percent of the useable data was contributed by amateurs. Professional data alone found a value of 522 km for the asteroid’s diameter, while 516 km was the result from just the amateur data. This shows that off-the-shelf telescopes and tape recorders combined with verbal timings resulted in just a 1 percent difference in the overall result.” Maley assembled the first compendium of a history of asteroid occultations, published in 1982, which logged 29 events.\(^9\) The first asteroid occultation was seen optically in Sweden in 1958, while the first photoelectric observation was made three years later. An updated list of all known observed events has been compiled by Dr. David Dunham, including references to publications of the observations.\(^10\)

**Diotima** Figure 4 shows a sky-plane plot of observations of an occultation by (423) Diotima on March 15, 2001. An oval has been fitted to represent the profile indicated by the timings from a dozen observers.

![Figure 4](image)

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**Metis** Figure 5 is a sky-plane plot of observations of an occultation by (9) Metis on September 7, 2001.\(^11\) The model ellipse matching the observations shows an elongated profile for the asteroid. Several observations plotted (marked “R” for “Remote”) were made by Dr. David
Dunham, using additional video station setups that operated unattended! This arrangement has the potential to multiple the results possible from each observer.

Figure 6. Sky-Plane Plot of September 7, 2001 Occultation by (9) Metis. Chords Marked “R” were Obtained Using Unattended (Remote) Video Equipment. (Illustration from Sky & Telescope, March 2002.) (Courtesy David Dunham and Sky Publishing.)

4. Occultation Predictions and Planning

Frequent updates of asteroid occultation event predictions and tracks are now made available on IOTA-sponsored web pages, maintained by Steve Preston.(12) For Eastern U.S. observers, and coordination of important North American events, Dr. David Dunham maintains a frequently updated web page.(13) IOTA paid subscribers receive an annual “North American Supplement” detailing all predicted solar system occultation events for the upcoming year, based on calculations by Edward Goffin. Goffin’s predictions for 2004 and 2005 are now available on the internet.(14),(15) Similar resources are available for observers in foreign countries on various web pages, from the IOTA European Section (IOTA-ES) and other organizations.

Figures 7 and 8 show a sample upcoming asteroid event track map and prediction sheet for North America. A description of the information contained in the prediction summaries and track maps is outside the scope of this presentation, but there is ample explanatory material available on the above-referenced web pages.

A PC version of the “WinOccult” occultation prediction software is available for downloading by subscribers from the IOTA web pages.(2) The GUIDE software by Project Pluto also produces useful track maps. (See suppliers list in Section 7.) Use of the latest Hipparcos/Tycho star catalog positions results in improved accuracy for the predicted event tracks. Last-minute updates and potential track shifts are supported by astrometry from professional sources, and relayed to interested observers through the IOTA web resources.(1),(3)
**Figure 7. Sample Predicted Asteroid Occultation Track Map from IOTA Web Pages**

*491 Carina occults TYC 0403-01460-1 on 2004 Jul 06 at 11h 26m to 11h 42m UT*

**Star (2000):**
- $m_v = 9.3$
- $m_p = 10.2$
- $\alpha = 13^h 42^m 25.450^s$
- $\delta = 2^h 44^m 57.00^s$
- Max Duration = 7.6 secs
- Mag Drop = 4.1

**Sun:**
- Dist = 153 deg

**Moon:**
- Dist = 50 deg

**Asteroid:**
- Mag = 14.0
- $\text{Dia} = 39^\text{km}$, $0.056^\circ$
- $\text{Parallax} = 3.703^\text{"}$
- Hourly $\text{SMA} = -1.735^\text{"}$

Uncertainty:
- Major = 0.015", Minor = 0.021", PA = 89°
- $\Delta \text{Sec} = -8.01''$
Figure 8. Sample Asteroid Occultation Prediction Sheet from Annual IOTA “North American Supplement” – (491) Carina Event, July 6, 2004.
(Prediction by Edward Goffin).
5. Observing Setups and Equipment

The remainder of this presentation focuses on “how to do it” and some descriptions of modern occultation observing methods and data collection techniques.

5.1 Typical Observing Setups

Some typical examples of observing setups are shown in Figures 9 through 14 (photos provided by Dr. David Dunham). The minimum recommended equipment list for a visual observer (Figure 9) consists of a medium-sized telescope (5 to 8 inches aperture or larger, preferably with clock drive, equipped for portable operation), a short wave (SW) receiver for WWV time signals, and an audio tape recorder and microphone. Figures 9 through 14 show several different portable setups. Many IOTA observers are now using the newer, inexpensive security type TV cameras, which can detect stars down to 10th magnitude (or fainter) and a VCR or camcorder to record the time signals and the video. Two recommended cameras that are successfully being used are the SuperCircuits models PC-23C and PC-164C. Detailed suggestions and information about video equipment and setups is given on the IOTA web pages. (See hardware suppliers list in Section 7.)

![Figure 9. Portable Equipment Setup for Visual Observations by Dr. David Dunham.]

![Figure 10. Three Setups by Dr. David Dunham for Video Observations.]
Figure 10. Dunham Station "A" – C-5 Telescope and PC-23C Video Camera with f: 6.3 Focal Reducer. Note Built-In Microphone on Camera and Combo Monitor and Video Recorder. All Equipment Operated from 12 VDC Battery.

Figure 11. Dunham Station "B" – Digital Camcorder For Bright Star Events (Lunar and Asteroid Occultations) and Possible Unattended Operation.

Figure 12. Dunham Station "C" – C-8 Telescope and Watec 902H Video Camera with Meade f:3.3 Focal Reducer. Camcorder Used to Record External Video from Camera.
Figure 13. Dunham Portable Setup No. 2 Using Telephoto Lens and Camcorder to Record External Video.

Figure 14. Richard Nugent’s Portable Setup Using 4-Inch Meade 2045 SCT with PC-164C Camera, Showing SW Radio and Camcorder. (Note Videotaped Solar Eclipse Image on Monitor.)
5.2 Video Cameras and Tape Recording of Occultations

The advantages of using a video camera and videotape recording of occultation events are several fold:

- The video camera “never blinks”
- Video camera, recorder, and telescope may be set up to observe in unattended operation
- Recorded observations can be conveniently reviewed and shared with others for instruction and analysis
- Time accuracy is typically plus or minus 1 video frame, or 1/30th second.

The observation data consists of three types of records:

1. Observer’s precise position (from USGS 7.5 minute topographic map, or GPS readout)
2. Event time (and epoch)
3. Event(s) and duration(s).

The time duration of the event(s) is the main item of interest. (This is covered more thoroughly in the next section.) When several “chords” by observers at different locations are combined, an accurate profile of the asteroid can be assembled.\(^{(5),(6),(7)}\) As noted in Figure 6, a new technique being pioneered by Dr. David Dunham includes observations made with an unattended video setup (Figures 11 and 13) at a second (“remote”) location, effectively doubling the output of an individual observer. (Details are given on Dunham's web pages.)

6. Timing Data and Equipment

As mentioned above, the traditional modern method of recording occultations consists of recording the observer’s verbal comments together with audio signals of the NIST short-wave (SW) time broadcasts. In North America, time signals are broadcast from stations WWV (Fort Collins, CO) or WWVH (Hawaii) on various radio frequencies. There are similar time signal broadcasts in Europe and foreign countries.

6.1 GPS Timing Systems

With the advent of the Global Positioning Satellite (GPS) system, technically savvy IOTA observers are turning towards the use of GPS time signals, typically superimposing digital data onto videotape recordings. Several designs for video time insertion “gadget boxes” have recently been developed and discussed on the IOTAoccultation e-group.\(^{(3)}\) There are also several commercial suppliers of such devices, so the interested observer has some “make-or-buy” decisions possible, depending upon his/her own technical abilities. There are some remaining technical issues with the use of the GPS time inserter designs, including suitability and limitations of selected GPS hardware, and issues of cost. Generally, reception of GPS signals is better than the traditional Short Wave (SW) time broadcasts (stations WWV and WWVH), which are subject to fading and electromagnetic interference. Some representative hardware/software suppliers are listed in Section 7.

A typical setup of GPS time inserter and video camera equipment by IOTA Secretary Arthur Lucas is shown in Figure 15. A block diagram of the circuit is shown in Figure 16, and a typical video screen display of GPS data is shown in Figure 17. This setup uses the STVAstro GPS time inserter box by BlackBox Video in the UK, with an OEM-type Garmin Model 16 or Model 35.
GPS engine, which outputs a 1 pulse per second signal required for the timing data. (See hardware suppliers list in Section 7.) One limitation of some GPS equipment is that many of the handheld GPS units do NOT output the required 1-pps signal used for timing.

Figure 15. Portable Video Setup by Arthur Lucas with GPS-Driven STVAstro Video Time Inserter. (Note Battery-Operated Combo Monitor and Video Recorder.)

Figure 16. Block Diagram Schematic of Video Recording Setup by Art Lucas with GPS-Driven STVAstro Video Time Inserter.
7. Sources of Hardware/Software

Some source information for hardware and software suppliers mentioned in the presentation is given below. (No commercial endorsement is implied.)

- **WinOccult** prediction software – subscribers may download from the IOTA web pages:  
  http://www.lunar-occultations.com/iota/iotandx.htm
- Project Pluto – GUIDE software (Bill Gray):  http://www.projectpluto.com/
- SuperCircuits Model PC-23C and PC-164C low light video cameras:  
  http://www.supercircuits.com
- Adirondack Video Astronomy (Cameras, adapters, flip mirrors, filters, etc.):  
  http://www.astrovid.com/
- Scopetronix (camera adapters, accessories, etc.):  http://www.scopetronix.com/
- STVAstro Video Time Inserter – BlackBox Video UK (Simon Blake):  
  sales@blackboxcamera.com Web page:  
  http://www.blackboxcamera.com/Stv5730a/astro.htm
- Horita time insertion equipment:  http://www.horita.com
- Garmin model 16 or model 35 GPS engines:  http://www.gpscity.com
- KIWI GPS to PC Time Interface/Software (Geoff Hitchcox):  

8. Conclusion and Summary

Occultation observations yield direct measures of asteroid profile shapes and sizes. Observations of stellar occultations by solar system objects can be routinely accomplished by amateurs, yielding valuable scientific results with minimum investment. IOTA observers are taking full advantage of modern internet resources and improved event and track predictions. New, inexpensive low-light sensitive video cameras and GPS equipment are revolutionizing asteroid occultation observing methods.
Acknowledgements

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Asteroidal Occultation Results

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Abstract. Over 520 occultations of stars by asteroids have been observed since the first one reported in 1958. Most of these have been seen or recorded by just one observer, but more than 100 of them have been observed from three or more separated stations, allowing a determination of the size and shape of the asteroid’s outline. This success is the result of a robust collaboration between professional and amateur astronomers.

References:
7. D. Dunham. A list of all observed events known to the author, including references to publications of the observations, when available, is at http://iota.jhuapl.edu/mpocc1.txt while results of many of the better-observed events since 2002 is at http://iota.jhuapl.edu/astob119.htm.

1. Introduction

The first observation of an occultation of a star by an asteroid was made in 1958, a visual observation in Sweden involving (3) Juno, while the third didn’t occur until 1975, when the first multiple observations of an occultation, of ? Geminorum by (433) Eros, were made [1]. With concerted astrometric efforts, there were several successes during the next two decades, but there were failures, too. A good background of this new field of observations, and results obtained through 1988 March, are given in articles in the first two Asteroids books [2,3].
2. Recent Results

Successful predictions and observations of these events have increased markedly during the last seven years with the availability of the HIPPARCOS [4] and related high-accuracy star catalogs, especially Tycho-2 [5] and the ongoing US Naval Observatory CCD Astrometric Catalog (UCAC). Asteroid ephemerides have been effectively updated using UCAC and Tycho-2-based astrometry, especially at USNO – Flagstaff and Table Mtn. Obs., to generate good occultation path predictions usually a few weeks in advance. This astrometry together with the spreading Internet has resulted in a major expansion in both interest in, and observations of, asteroidal occultations. Over 530 asteroidal occultations have now been observed, with 113 recorded in 2003 alone. Ellipse parameters have been determined for the asteroidal outlines for dozens of these events. Some of the better ones determined since the list given previously [6] will be shown at the meeting and are mostly available on my Web site [7].

![Fig. 1. Occultation of SAO 121499 by (41) Daphne, 1999 July 2.](image1)

![Fig. 2. Occultation of SAO 118158 by (308) Polyxo, 2000 January 10](image2)

Outlines determined from two occultations are shown in Fig. 1 and 2. North is up and east is to the left, being the view from the Earth. For Fig. 1, the ellipse shown has the following parame-
ters: 2a, 215.8±3.0 km; 2b, 166.6±2.4 km; PA, 61.6±3.0°; Xo, -20.2±2.0 km; and Yo, -102.5±1.4 km. The observers, from upper right to lower left, are I. & L. Blommers, Leiden, NL; J. Arlot, Meudon, FR; P. Vingerhoets, Morsel, BE; T. Alderweireldt, Hove, BE; R. Bouma, Groningen, NL; P. Dupouy, Dax, FR; J. Lecacheux, Licq-Atherey, FR; O. Canales, Pinsoro, ES; and J. Winkel, Zeddam, NL. Vingerhoets, Bouma, and Lecacheux timed the reappearance, but not the disappearance due to clouds. Durda and Stern’s timings were made from a video camera in a small jet [8].

In another instrumental first, D. Dunham used an unattended stationary 50mm telephoto lens, image-intensified videocamera, and camcorder to record the occultation of the 6.1-mag. close double star HIP 30570 by (9) Metis on 2001 Sep. 7, while he also recorded the occultation with a 13-cm telescope at another location 37 km (road distance) away in California.

Besides the elliptical outlines, there have been some unusual observations. In January 1991, an occultation by (216) Kleopatra, the largest M-class asteroid, was timed from nine stations across North America. This asteroid has a large-amplitude light curve, and it was known that the 1991 event would occur near the maximum of the light curve, with the asteroid broadside. The unusual cigar-shape, almost four times as long as it was wide, was published a year later [9]. Partly as a result, when the Arecibo radio telescope was recently upgraded, Kleopatra was one of the first main-belt asteroids to be imaged by the refurbished instrument. The strange dog-bone shape of the asteroid resulting from the Arecibo observations is now well-known [10]. The observations probe the space around asteroids, allowing detection of satellites. Asteroidal satellites were claimed from some occultations many years before Galileo discovered Dactyl.


Asteroidal occultations provide good opportunities for collaboration between amateur and professional astronomers. These include observing and timing the occultations, making astrometric observations to update asteroidal occultation paths, making photometric observations to supplement asteroidal occultation observations, and using occultation results to select targets for other observations, such as with large aperture adaptive optics and radar. With the proliferation of CCD and inexpensive but sensitive video recording devices, amateurs can now accurately time many of these events. Please visit http://www.lunar-occultations.com/iota/asteroids/astrndx.htm or contact the lead author to become involved. More observers distributed across the paths give better determinations of asteroid shapes.

Acknowledgements

We thank the hundreds of observers worldwide who provided the observations. Before 2002, the following high school mentor students helped the lead author analyse many of the occultations using stellar data from HIPPARCOS and related catalogs: Doug Faust, Danny Pan, Peter Lindahl, Christina Dwyer, and Sruti Sathyanadham. The Johns Hopkins University’s Applied Physics Laboratory coordinated the mentor program that benefited this work so well. Part of the work was supported by a NASA grant for occultation star catalogue improvement using HIPPARCOS data.
Abstract: It is well known that amateur observers are full of ability and enthusiasm. Their sheer numbers are an important solution to problems such as weather and longitudinal gaps in coverage of the sky. However, they are also sophisticated professionals with experience and expertise in many high technology areas. They are just as willing to use their computer as their telescope to help professional astronomers. We present some ideas about how to leverage this untapped resource along with some examples and best practices.
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1. Introduction

It is important to begin this discussion by redefining a popular term. What we currently refer to as an "amateur community" is actually made up of amateurs, students, retired professionals and those who hold astronomy degrees but chose to pursue careers in another field. In addition, the pure "amateurs" are amateurs in astronomy only. Most have successful careers in their own right and many have rare and valuable skills in other areas of technology. As a result, as a whole I will refer to the group as the "non-professional community" as the term amateur does not do their skills justice.

2. The Situation

Since the first eyeball looked up at the night sky, non-professionals have dominated astronomy. Astronomy is unique in that the entire world has access to the same laboratory - the night sky. (It is a shame that that time may be coming to an end due to light pollution.) In recent history (beginning perhaps with the church and court appointed astronomers) society has been fortunate enough to fund a few lucky individuals to devote their careers to studying the sky beyond Earth. The numbers of these "professionals" ebbs and flows based on politics, economics and technological advances. Right now, thanks largely to the space age, professional astronomers abound. However, this will change in the future.

Public sector spending on astronomy as a percentage of the overall budget will likely decline in the long run. In addition, new observatories and technologies are becoming very expensive. This is having the effect of halting construction of and closing down small and medium sized observatories as universities and foundations pool their money into a few behemoth projects. Astronomy is gaining access to new technology to open up new frontiers, but it is losing a workforce.

The new technology is tremendously productive and creating large amounts of data. Modern astronomical databases are becoming so large that key breakthroughs lie undiscovered. Who
better to mine this data than nonprofessionals who have been identified with an affinity for and expertise in databases and computer science?

The level of technology is exploding among consumers. Consumer grade detectors now rival professional detectors in their sensitivity. Private individuals are building meter class observatories in their backyards. And the Internet has brought about a revolution in computer science that allows almost anyone with access to a computer to participate in scientific research and software development. The first two examples are well known and have been covered in the press quite adequately. However, the last example remains a largely untapped resource.

3. Blurring the Line

Non-professional astronomers have been doing their own data analysis for years. Any CCD observer knows they have to spend as much time reducing their data as observing. Once armed with the final data, their natural curiosity drove them to learn how to pull information from it. Whether it is Fourier analysis looking for periodicity, astrometry looking for minor planets or creating free software for the astronomy community as a whole they were all doing some form of basic analysis. Many have taken this a step further and been published. Some worked with a professional to get in a professional journal and some worked alone and submitted to one of the few refereed journals that accepts non-professional papers. These are the trailblazers.

4. A Call to Keyboards!

For every trailblazer there are a large number of people ready to follow in their footsteps. Now is the time for the professional community to tap this resource and help solve their manpower shortage. A program that is setup to coordinate qualified non-professionals to work with professional projects would be a huge success. The American Astronomical Society’s (AAS) Working Group on Pro-Am Collaboration (WG-PAC) is working on creating a list of amateurs and their skills which professionals can turn to for help.

This is a good start. However, to be fully effective a program needs centralized coordination and training. Non-professionals have ability, but they still need to be trained on the levels of precision needed in professional investigations. Also, managing non-professional volunteers can be very time consuming so it requires an organization with time and patience (the latter can come from finding a resource that is truly enthusiastic about working with non-professionals).

The SETI@Home project was the first serious attempt to make use of this resource. Its success illustrates the potential available to the astronomical community. However, SETI@Home was a passive project that required very little on behalf of the participant. There is much more that the community can do when properly organized for real hands-on work. For example, imagine the building of a computer science team. This team could consist of a few programmers, a quality control professional and a technical writer. They could work together to develop software a professional needs to do their work. Another example is a data mining team. A team of non-professionals could be given large stacks of data (ex: MACHO data) and told to sift through the data looking for specific information. A final example involves education and public outreach. Imagine a team that consists of a journalist, public relations professional, and an illustrator. Any professional who is about to announce a major discovery could call upon this team. They could draft press releases, get them into the right hands and even illustrate it. This would give powerful E/PO capabilities to even the smallest of astronomical organizations.
The plan becomes very powerful when the teams work together. For example, the computer science team could be asked to write a program that the data mining team will use to look for micro lensing effects in a large photometric database. The data mining team turns their results over to a professional, who culls through it more carefully and pulls out the real results from the false positives. He/She rights a paper and the E/PO team puts out a press release upon publication.

There are many keys to success. First, the non-professionals have to be identified based on their skill set and reliability. Second, teams must be put together and trained on the scientific merits and requirements of the project. Third, the professional needs to clearly define the needs of the project and be available to answer questions from the coordinator. Finally, the team needs full acknowledgment of their contribution such as with co-authorship on any published papers.

There is also an important outreach aspect of this that should not be overlooked. Each of these non-professionals is a member of communities distributed all over the world. What better ambassador for science than an enthusiastic volunteer who is actually participating and being part of science in action? They can be organized to give talks to local clubs, museums and talk to local newspapers about their work. The AAVSO has done this with our International High Energy Network, which has given over 157 talks, papers and presentations in over 6 countries.

5. AAVSO Examples

The AAVSO has developed this methodology for work on two key projects. First, we have a team of members who are making new variable star charts and revising old ones. This team consists of observers who sky-check the fields, data miners who cull through the various photometric databases looking for good comparison stars, a programmer who works on a database we use to keep track of all the work and a team leader who coordinates it all. Some of these volunteers do not own telescopes; they just like to participate in the team! And our comparison sequence experts are so good at knowing the strengths and weaknesses of the photometric databases that sometimes they get asked questions by professionals. We have a similar team working to document every comparison star on every AAVSO chart. It is a project that is creating a giant photometric database of over 50,000 stars and will be extremely valuable to the professional community. The project is made exclusively up of non-professionals who work almost every night on it. The teams do not work alone. Each team has a professional liaison who keeps an eye on activities and throws out some advice every now and then.

The AAVSO is about to take this project to the next level. All 11 million+ observations in the AAVSO International Database is being validated and will be online for download by the end of 2004. In order to make sure all the data is used we will be training our members on data analysis and mining techniques and giving them stars to investigate. We received a grant from the AAS to write three Windows-based programs (along with ports that will run on Linux and OS X) which will do basic time series examination including Fourier and wavelet analysis.
6. Summary

Non-professional astronomers are key to the future success of astronomy. They can help mitigate the effects of budget consolidation and increased demands on existing manpower. The key is to effectively organize and train them to leverage their professional skills and apply them to astronomy. Astronomy will get an enthusiastic work force of highly skilled labor and the public will get a grassroots network of science enthusiasts. It is a win-win scenario for both.

Acknowledgements

This paper is dedicated to Dr. Janet Mattei, who did as much as anyone in history to turn pro-am collaboration into a scientifically valid and accepted relationship.
Pro-Am Collaborations:
The Global (néé GLAST) Telescope Network

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Abstract: The NASA/EPO Group at Sonoma State University is creating the Global Telescope Network, a series of small, generally amateur-run telescopes to support the science and education goals of several NASA orbiting observatories. The ground-based telescopes will observe the same targets as the orbiting observatories, providing a multi-year baseline of behavior patterns. The other major goal of this project is to provide an educational opportunity for high school and college students to use real astronomical data. This professional-amateur collaboration will help astronomers understand the nature of the physics powering a variety of astronomical objects.

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1. Introduction

Space is the place, but there’s no place like home

NASA currently employs a fleet of orbiting observatories which target a wide variety of astronomical objects over nearly the entire electromagnetic spectrum. Many of these observatories detect high-energy photons; i.e. gamma and X-rays, from exotic sources such as supernovae, pulsars, black holes, and active galaxies. The Earth’s atmosphere absorbs essentially all high-energy photons, making space-based telescopes a necessity.

However, ground-based observations are critical in observing these objects as well. Many of the targets can suddenly flare, increasing their energy across the electromagnetic spectrum. Since the small number of high-energy orbiting observatories cannot possibly observe every target, these flares can get missed. However, there are far more small telescopes on the ground than orbiting observatories, which means they can observe more objects more often. Ground-based telescopes are far more likely to catch a flare, and can alert an orbiting observatory that something interesting is going on.

Most of these objects also exhibit long-term changes in brightness. This can monitored currently only through ground-based telescopes, again due to the large number of potential observers. Likewise, very short-term changes (“microvariability”) can be observed via ground-based telescopes over longer time baselines than can orbiting observatories. Furthermore, the physics behind these changes in brightness can be better understood in terms of multi-wavelength observations, meaning that simultaneous observations of targets by ground-based and orbital tele-
scopes (perhaps using a “campaign” of observations focusing on a particular object) can yield critical insight on the engines powering these objects.

A global network of ground-based telescopes can therefore greatly enhance the science of high-energy astronomy. A large number of these targets are easily within the grasp of small (25+ cm) telescopes equipped with CCDs, which naturally means amateur astronomers can participate in such a network.

Birth of a notion

The idea for this network originated with the Gamma-ray Large Area Space Telescope (GLAST) mission. GLAST, due for launch in 2007, will detect gamma rays from active galaxies (including quasars and blazers) and a large variety of other high-energy objects. GLAST has a dedicated and extensive Education and Public Outreach (E/PO) effort lead by the NASA E/PO Group at Sonoma State University (SSU; http://epo.sonoma.edu). The idea of a telescope network was born there. Originally called the “GLAST Telescope Network”, it was envisioned to observe active galaxies that were also GLAST targets.

However, other space missions quickly joined in. The Swift gamma-ray burst satellite will also observe high-energy targets when it is launched in late 2004. The XMM-Newton has been observing X-rays from astronomical sources since 1999. Both these missions (which have E/PO efforts, not coincidentally, lead by SSU) threw their hats in with the GLAST Telescope Network. By this time, the abbreviation “GTN” was being used extensively by the project, so it was decided that changing the name to the “Global Telescope Network” (GTN) would minimize the pain of transition.

Because of the addition of other space-based observatories, the goals for the GTN have broadened. Instead of just active galaxies, the GTN will also observe gamma-ray bursts (GRBs), polars (magnetic white dwarfs which can flare dramatically in X-rays and visible light), and other types of targets as deemed necessary.

Also, because the project is lead by an E/PO group, education will have a major role. The educational goal of the GTN is to get the images and data into the hands of students across the country and the world. The students can use the data to learn how real astronomical images are processed and analyzed. This not only teaches them the math and science behind astronomical imaging, but it also gives them a sense of ownership over the data. This in turn can inspire them to become active in astronomy, as an amateur or to pursue it as a career.

To meet the scientific and educational goals, images taken from various observatories will be stored in an online archive at SSU. Participants in the GTN (observers and educators) will have accounts with the archive, and will be able to access the data.

2. Participation by Amateurs

This sounds great! How do I participate?

Amateurs can participate in the GTN in two ways: directly by joining the GTN, or indirectly through the American Association of Variable Star Observers (AAVSO).

If you want to join the GTN, you have to meet a set of requirements, which includes access to a telescope and a CCD system, and a willingness to contribute observations to the archive (see section 3, “The GTN Archive”). Joining the GTN means that there is a commitment to observing
at least a minimum amount, but benefits include working with professional astronomers and other GTN participants, receiving announcements sent out by the GTN team about upcoming opportunities and targets of interest, receiving GTN updates, accessing tutorials on observing and robotic telescopes, and of course getting the warm fuzzy feeling of knowing you are helping in cutting-edge science (and the astronomy education of students).

If you aren’t up for such a commitment, then that’s okay too. The GTN has partnered with the AAVSO, which has added GTN objects to their target lists, and has created finder charts for the objects as well. The GTN complements the already-existing AAVSO High Energy Network (http://www.aavso.org/observing/programs/hen/). You can observe GTN targets and submit your observations through the AAVSO, and you don’t even have to be a member of the AAVSO to do so.

Current participants include the Sonoma State University Observatory (equipped with a 14” Celestron, an Apogee AP47 CCD, and a Paramount robotic mount; located in Sonoma County, California), and Elk Creek Observatory (equipped with a 16” Meade LX200 and ST10 MXE CCD; located in Holton, Kansas). Many other observatories have expressed interest in participating as well.

*I’ll do it! So what do I do?*

The actual observing part of the GTN falls under many categories. In all cases, observations using one or more standard BVRI filters are preferred, and should be processed using standard CCD techniques which include dark/bias subtraction and flat fielding. Unfiltered high time resolution sequences to access microvariability of active galaxies and to search for GRB afterglows can also be useful. Some (but not all) of the observation categories are as follows:

a) **Active Galaxy Surveillance**

The observer will monitor several active galaxies from the GTN observing list at least once a night whenever possible. The galaxies and sequence stars should have SNR>100 and result in photometry good to about 1%. The minimum commitment is observations in the V and I bands of two GTN active galaxies once a month.

b) **High Time-Resolution Datasets**

The observer will monitor an active galaxy or polar from the GTN observing list for microvariability. They will track on the target field and take images as rapidly as possible for several hours at a time. The targets and sequence stars should have SNR>100. The minimum commitment is to obtain a high time resolution data set for a GTN target at least once a year.

c) **Gamma-Ray Burst Tracking**

The observer will attempt to record a GRB or its afterglow when bursts are reported by the GRB Coordinates Network or the AAVSO Gamma Ray Burst Network. They will obtain observations of the reported fields that go as faint as possible. The more rapid the response capabilities, the more likely it will be that some aspect of a GRB can be recorded; the bursts themselves typically last only a few seconds (possibly minutes?). The afterglows may be detectable for hours or days. It is estimated that bursts may happen once a day, and may be observable from a particular location on the earth once or twice a week. The minimum commitment is to attempt to record a burst or afterglow at least once
a year. If a burst or afterglow is detected, continue taking data as long as possible. It should be noted that afterglows have already been observed by amateurs, and one was seen by an amateur before the professionals!

How do I find out more?

All this information, and much more, is available on the GTN website at http://gtn.sonoma.edu.

3. The GTN Data Archive
The GTN will establish and maintain an online archive of all data obtained by all participants. It is expected that participants will submit data to the archive. These data will normally be CCD images obtained by the GTN telescopes. The archive will be searchable, and data may be retrieved by GTN participants.

The data contained within the archive should be considered to be “owned” by the individual or group which submits the data to the archive. Owners of the data are free to publish or to use their data in any way. While access to the data archive is unrestricted to any GTN participants (including educational venues), users of the data in the archive should consult with the owner of the data before using the data in a publication or to seek funding. It is expected that the owners of data to be used in a publication will be asked to become collaborators for any publication. Collaborators will normally become co-authors. Researchers which use data from the archive should acknowledge the archive as the source of the data.

4. Summary

The Global Telescope Network is a growing collaboration of small, mostly amateur-run telescopes which will augment observations made by orbiting observatories. The multi-wavelength coverage of these objects can reveal the underlying mechanisms producing their variability, and the archived data will be used by students to learn about astronomy. The GTN encourages amateurs, or anyone with the proper facilities and commitment, to join the network.

More information is available at the GTN website: http://gtn.sonoma.edu
Data Acquisition and Reduction Methods for Slitless Spectroscopy

John E. Hoot
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Abstract: This paper is a tutorial on simple methods for getting spectroscopic information from amateur instruments using spectroscopic gratings. The paper demonstrates a couple of methods for inexpensively upgrading a telescope into a spectrograph, explains methods for using the instrument effectively and presents techniques for data reduction using off the shelf software such as, Excel, AutostarIP or Maxim DL.

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References

1. Introduction

A slitless spectrograph is simply any of the traditional spectrograph designs where the slit is omitted. The omission of the slit means that all of the objects within the field of view, or proximate to it, project their spectra onto the image plane of the instrument. For point source targets, such as stars, the spectra produced is equivalent to having a slit size equal to the apparent seeing disk size at the image plane. Such instruments are attractive for a number of reasons.

1) Without a slit, precise centering and guiding are not required to get good spectra of the target.
2) Such instruments can be realized very easily and inexpensively.

The most cost-effective realizations of slitless spectrographs use objective prisms or object Gratings as shown in Figure 1, or use non-object gratings as shown in Figure 2. In each of these designs, a dispersing element is inserted into the optical path. At their simplest, such gratings can be plastic films printed or replicated at very low cost. A more sophisticated implementation is the Littrow design shown in Figure 3. It offers the advantages of higher dispersions and flatter fields over the simpler alternatives.
Fig. 1. Objective Prism or Grating Design

Regardless of the design chosen, the result is an image composed that the 0’th order images flanked on either side by the first order spectra. For very bright objects 2nd and 3rd orders may also be visible, but the energy falls off very rapidly at higher orders. Figure 4 shows a typical image from a slitless spectrograph.
Fig 4. Slitless Spectra of SAO 11291 (A3)

Such images differ from the traditional images produced by long slit spectroscopy. Images requires a little data processing to turn the them from the figure above into the example in Figure 5 below, which is a slice of the image data from the bright star in Figure 4 presented in traditional long slit format.

Fig. 5: Stretched Spectra

The disadvantages of slitless spectrographs are:
1. Their use is usually limited to point sources. Extended asymmetric sources mix different wavelengths greatly reducing the resolution or confusing the spectra.
2. For the simplest implementations, resolution is limited by several factors. The seeing disk of the instrument determines the effective slit size. Narrow dispersion angles are required to keep the object and its spectra within the aperture of the instrument or detector.
3. Because of the clutter of background objects, care must be taken when composing an observation to eliminate as many background objects from the spectra as possible. Additional observations from different angles may be required to eliminate background clutter.
4. Because of the cluttered field, the data reduction task often involves more processing to get good data from imagery.
5. Because there is no slit to anchor the spatial reference frame, it is not possible to directly introduce calibration source into the instrument. Often calibration needs to be derived from indirect methods, or standards fitting.

2. Fundamentals of Operation

For objective prism or grating instruments, the principles of operations are summarized by Figure 6 below. Prior to entering the instrument, the light passes through the grating of prism. The resulting diffraction causes the light to bend as a function of its wavelength.
In the case of light on axis, where the prism blaze is small or the grating coarse, the diffraction simplifies as shown below:

\[ m\lambda = d(\sin(\alpha) + \sin(\beta)) \]

**Fig. 6 Objective Prism Light Path**

For this simple case, to the first order, the dispersion is proportional to the wavelength. Although the mathematical argument is slightly different, inserting the dispersing element in the optical path just ahead of the focal plane of the instrument produces a very similar result. The most significant difference in that implementation is that you will not be able to have both the 0'th order image and the 1st order spectra simultaneously in focus with a non-objective transmission spectrograph.

### 3. Basic Observation Method

Making data observations with a slitless spectrograph are performed similarly to standard imaging with a couple of additions. What you normally wish to do is to orient your dispersing element so that it is perpendicular to the declination lines in your instrument. This orientation means that any PEC or tracking errors will thicken the spectra, but not blur the wavelength information. Furthermore, you should place your target near one of the edges of the frame in the direction of the dispersion. This placement will put one of the first order dispersions out of the field of view, and the other across the center of the frame.

When making the exposure, do not worry about over exposing the 0th order image, but be certain that over the entire length of the spectra, none of the image is saturated or outside of the dynamic range of your detector. As with any imaging session, signal to noise can be improved by taking multiple exposures to be combined during the data reduction phase.

Finally, as with any scientific observation, include all pertinent information in the image header including target, special instrumentation concerns, air mass, orientation etc.
4. Basic Data Reduction

The first steps in data reduction for slitless spectrograph images are exactly the same as with any other type of astronomical image data. Assuming a CCD camera is used as the detector, you must dark subtract and flat field your images. Finally, if multiple exposures were taken, align and combine the images using one or more of the background stars to align the images. Once these basic steps are complete you will need to extract the spectra from the image.

As with many scientific data reduction processes, there are several ways to accomplish the extraction of the spectra. The method presented here is chosen for its directness and its ability to be performed with PC Windows based software, not necessarily because it is the “best” method of extraction in terms of getting the most information from the image.

That said, the steps recommend to simply extract the spectra are as follows. Rotate the image so that the spectra is horizontal. Once that step is completed, if the 0’th order object is not on the left of the image, mirror flip the image on the horizontal axis or rotate the image 180° to put the target on the left. The result should appear similar to Figure 5 below.

![Image of data extraction from rotated image]

Using the highlighting or line profiling tool in your image processing program, draw a box around the dispersed spectra. Once this is done, most image processing programs offer the ability to profile and extract the data from the image. In Figure 6, you can see that the example offers several different profile extraction methods. Select a column summation or average and write the results to a tab delimited text file. This numeric data is the raw spectra information that will be subsequently processed.
In actual practice, it may be beneficial to include not only the dispersed spectra, but also the 0’th order object in your profile selection box. It leads to larger text files, but can provide some help in wavelength calibration later.

For Windows users, I recommend that the balance of work with your spectra be done in a spreadsheet. The examples in this paper will employ Microsoft’s Excel, but if your computer does not include a copy of this program, a free alternative, Open Office, can be downloaded from http://www.openoffice.org.

The first thing that needs to happen is to import your text data into a spreadsheet. This is accomplished by opening your extracted text in a spreadsheet program. During this phase you may be prompted to describe your data format. Depending on the image processing program you used to extract the data, you will need to either select column ranges, or delimiters that separate your columns.

Once you have successfully imported your observation into a spreadsheet. You should be looking at a screen very similar the Figure 8. The first column of your spreadsheet will contain a pixel location, and the second column will contain the sum or average of the columns at that pixel of your observation.
To make a rough wavelength calibration of your data, use your image processing program to locate the centroid of the star’s 0’th order image. In Figure 8 above, this position is X pixel 219. Assuming you know the dispersion factor of your instrument, you can create a spreadsheet column that displays the approximate wavelength by taking the pixel value, subtracting the position of the center of the 0’th order image and scaling that by your dispersion factor. In Figure 8 above we have previously determined that the dispersion factor \((k)\) for this system is 1.565 pixel/nm. You will end up with an Excel formula similar to:

\[
\text{=(cell - center\_x)/dispersion}
\]

copied into a column parallel to your Raw pixel column.

Next we need to get rid of the sky background. There are a couple of different ways to accomplish this feat. If you used “pixel average” in your profile extraction, you can take the direct approach of going back to your image processing program and using the “image statistics” tool to measure the mean sky background in an empty region near where the spectra is on the image. The spreadsheet based method is to take the minimum value along the spectra flux. This should occur in the wavelength range of 100 to 300 nm where radiation cannot penetrate the atmosphere, therefore, the counts there are sky background. You can use some fancier math such as median over the range, 180-220 nm, but the results should be similar.

Unlike slit spectra, where you must concern yourself with the removal of telluric lines, those lines caused by elements in our atmosphere, slitless spectrographs spread the telluric flux uniformly across the image and subtracting the sky background, essentially eliminates this issue.

So you now need to create a column for the sky subtracted, normalized, instrumental flux. It will use a formula of the form:

\[
\text{=(cell-minval)/maxval*1000}
\]
where \textit{minval} is a single cell containing the sky background number, and \textit{maxval} is a single cell containing the largest instrumental flux value in your spectra. Application of the formula is shown in Figure 9 below.

The final step in basic image reduction is producing a spectral graph. It is the spreadsheet’s powerful graphing capabilities that motivates us to use this tool for analysis, and its ability to handle large arrays of numbers arising from our observations. To create a basic graph, select the two adjacent columns that contain the \textit{wavelength} and \textit{normalized flux}. Then use your spreadsheet to generate a “XY” plot with connecting lines between observation and no data point. The Excel settings for this choice are shown in Figure 10.
The generated graph can be tailored by overriding the default range, title, and background settings to produce a graph similar to the example in figure 11.

![Graph of normalized flux vs. wavelength](image)

**Fig. 11. Sample XY Scatter Plot of Stellar Spectra Showing Interactive Cursors**

One of the other advantages of spreadsheets is shown in Figure 11. Moving the cursor over a portion of the graph opens a pop up window with the numeric data under the cursor. In this example we are checking to be sure one of the Hydrogen emission lines is registered correctly.

5. Advanced Observation Techniques

One of the challenges of good spectroscopy is finding the best focus. Focus is especially difficult in the case of a non-objective spectrograph. In this design, a dispersing element is placed in the optical path just ahead of the imager. This type of spectrograph is the absolutely easiest to make. By inserting a $1.00 holographic plastic grating into a filter wheel location, you get an instant spectrograph. Figure 12 shows a quick test setup made by super gluing a grating to a 2” draw tube adapter used for imaging with a CCD Camera.
The penalty for this simplicity is shown by Figure 13 below. In the non-objective implementation, the light rays are slightly convergent at the point where they pass through the grating. Additionally, a larger dispersion angle is required to cover the same field of view when contrasted to an objective prism or grating which works at the instrument’s total focal length.

As Figure 13 shows, different wavelengths come to focus at different depths. None of these focal points correspond to the point where the 0’th order image comes to focus. No matter what
your focal length, focus is going to be a compromise. I recommend you select either the middle of the spectra, or a wavelength range of interest and peak the focus at that location and settle for degraded focus as you move off of that point.

Two practical methods of measuring focus are to either peak the flux in the area of interest or use a one dimensional FWHM measure to achieve optimal focus. Most CCD acquisition programs will perform the peak reporting function without problems. For FWHM however, you are going to need to create and evaluate line profiles of transverse cuts of the spectra between focus adjustments to judge when the narrowest FWHM is obtained.

Another method that can help you quickly evaluate your data while observing is what I call the quick look trick. It is show schematically in Figure 14 below. This method takes a raw image, not dark subtracted, calibrated, or rotated. Simply crop two equal sized sub images. The first is a box containing the spectra, the second, an empty area somewhere else in the image. Subtract the empty image from the spectra and then extract the average pixel values. Now view the profile. Since both sub-images contained sky and dark in many columns, you will get a pretty good estimator of both from the empty sky flux and dark noise. Subtracting this from your target spectra comes pretty close a fully calibrated result, but fast, so you can see if you are on the right track.

![Fig 14. Quick Look Extraction](image)

### 6. Advanced Image Processing Methods

One of the challenges of slitless spectroscopy is removing background object and spectra from contaminating your data. Here are a couple of tricks that can be used to reduce this problem. The images in Figure 15 show two original images that were taken with the 0’th order on the left and right respectively. Once these images are rotated square, all possible mirror symmetric images that have the 0’th order on the left are generated. All of these images can then be combined selecting either the minimum value, median value, or sigma clipped average. The resulting “clean” image is shown in Figure 16.
Fig. 15: Flip Flop Combination. The top two frames show original images, one with the 0'th order on the left and the other with the 0'th order on the right. These are all then rotated square and all four mirror symmetries are generated that have the 0'th order on the left.

Fig. 16. Image Cleaned by Flip Flop Folding.

7. Advanced Wavelength Calibration

The best way to calibrate the dispersion of your slitless spectrograph is using a standard calibration star. Stars of MK class A1 are known for having the most prominent Balmer Hydrogen absorption lines. Select a bright early class A star that has low radial velocity and image it with your system. Reduce the data as you normally would. Stop as soon as you have imported the spectra into the spreadsheet and generate an XY scatter plot of pixels verses instrumental flux. You should have a graph similar to the one shown below:
Use the interactive cursor to locate a pair of prominent Balmer lines from the table in figure 18.

<table>
<thead>
<tr>
<th>Line</th>
<th>n</th>
<th>Observed by Balmer (angstroms)</th>
<th>Calculated by Balmer (angstroms)</th>
<th>Observed by W. E. Curtis (1914) (angstroms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα</td>
<td>3</td>
<td>6562.10</td>
<td>6562.08</td>
<td>6562.79</td>
</tr>
<tr>
<td>Hδ</td>
<td>4</td>
<td>4860.70</td>
<td>4860.50</td>
<td>4861.33</td>
</tr>
<tr>
<td>Hγ</td>
<td>5</td>
<td>4340.10</td>
<td>4340.10</td>
<td>4340.47</td>
</tr>
<tr>
<td>Hβ</td>
<td>6</td>
<td>4101.30</td>
<td>4101.20</td>
<td>4101.74</td>
</tr>
</tbody>
</table>

Fig. 18. Balmer Lines of Hydrogen

Note both the pixel positions. Now apply simple algebra to solve for a linear fit that converts from pixels to wavelength. In the example above:

\[
\delta(\text{pixel}) = \text{pixel} = k + \text{of f set}
\]

\[
\frac{\text{pixels}}{0} = \frac{701 \text{ Å} 628}{486.08 \text{nm ÷ 434.01nm}} = \frac{73}{52.07} = 1.402
\]

\[
\frac{701}{1.402} + \text{of f set} = 486.08
\]

\[
\frac{701}{1.402} \times 486.08 = \text{of f set} = 13.92
\]

Once you have solved for the dispersion factor of your instrument, all you need to do is find the offset for a given spectra to recalibrate new observations. In reality, your spectra is not actually linearly dispersed. You can address this issue by fitting higher order polynomial solutions to your data. If this is your intent, the best approach is to use multiple observations and the least squares method to fit your parameters. Remember the scalar offsets can be solved last. It is best to use only the pixel indices relative to your shortest wavelength, this will preclude scalar
offsets contaminating your results. The calibrated result from this example plots as shown in Figure 19.

Fig. 19. Wavelength Calibrated Example.

8. Estimating System R Value

Spectrograph resolution is estimated in terms of $R$ value. This is the ratio of the observed wavelength to the smallest resolvable feature size. To estimate the $R$ of your system, select one of your well exposed spectra and take a vertical line profile of the spectra using your image processing program as shown in Figure 20. It is important to take a vertical cross section, not a diagonal one here. Taking a diagonal cross section will lead to incorrect estimations due to aliasing. If your spectra is considerably misaligned you may scale the FWHM later using the cosine of the rotation angle, but this effect is usually minimal.

Fig. 20. Spectra Cross Section Profile Extraction
Extract the line profile data and plot the pixel verses flux values using your spreadsheet. The results from Figure 20 are shown in Figure 21. Using graphical or analytical methods, estimate the FWHM of your spectra. This value accurately captures the combined effects of apparent stellar disk disk size, non-convergent light, dispersion and distortion. You can think of your spectra as being a perfect point spectra convolved with the rotation of this cross section. Essentially, your system will not accurately measure any feature smaller than this aperture.

![Fig. 21. FWHM Profile](image)

In this example we have a FWHM of approximately 4 pixels. We then need to multiply this by our dispersion factor to convert from pixels to \( \text{nm} \) and then calculate our \( R \) value.

\[
R \approx \frac{\delta \lambda k}{\text{FWHM}} = \frac{600 \text{nm} \times 1.402}{4} = 210
\]

For this example we estimate the \( R \) value as 210, modest by professional standards.

### 9. Extinction

Extinction is the change in spectral response that occurs when an object is measured through different air masses. Atmospheric absorption and scattering of light is a wavelength dependent phenomenon. Removing the effects of extinction is the next step in improving the accuracy of your data. To apply extinction correction to your data you will need to construct a model of atmospheric energy transmission as a function of both wavelength and air mass. Once you have this model, you can then apply it to your observational data to remove the extinction effect. Rather than trying to develop a closed form model, an easier method is to create an empirical model. To create a model, observe the same source at several different air masses on a night with photometric conditions. Reduce and plot the results of each observation. The result will appear similar to the plot in Figure 22 below:
From these observations, you can use numerical methods to generate a table that plots the $K$ term in the equation below as a function of wavelength. Substituting values for $K$ back into this equation will allow you to remove extinction effects from your data.

$$F_{\lambda O} = F_{\lambda}K_{\lambda}^{X}$$

Figure 23 shows several fits of extinction the data in the example above. In this case, I would trust most the 50 point moving average fit shown in orange. It is best between 350nm and 750nm. Outside of that range, the signal to noise ratio of the data is so poor it renders values suspect. The plot does show the expected result that extinction is nearly linear and increases as the wavelengths becomes shorter. At longer wavelengths, beyond 700nm, water vapor in the atmosphere dust causes discontinuities in the extinction curves and extinction again begins to increase.

One other point to note is that spectra are expressed in flux units, i.e. energy per unit area per unit time. This is different from photometric results that are expressed a Magnitudes, a log scale unit. Therefore the expression of extinction ratios has an exponential term rather than the multiplicative term familiar to photometrists.
10. Absolute Calibration

Absolute calibration of spectra is beyond the scope of this tutorial. But briefly, there are two techniques that can be employed. The first uses black body radiation models of hot MK class O stars to calibrate your instrument. The other method uses other observers’ measurements of standard stars. You make observations of the same sources, resample the standard data down to your $R$ value and then fit the data to your observations and compute the observed ratio to the standard. Like absolute photometry, absolute spectroscopy is the most demanding form of observation requiring impeccable technique, and excellent observing conditions.

11. Advanced Sharpening

If you are primarily interested in spectral absorption and transmission features, you can use sharpening techniques to accentuate these features. In the image itself you can use simple convolution kernel sharpening filters, unsharp masking techniques and finally maximum entropy deconvolution (MED). Of these techniques, MED requires a point spread function to operate effectively. The psf to use in this application is the FWHM derived from the spectra, rotated and fitted to a gaussian surface of rotation. Once processed, you can extract the “enhanced” spectra and process it as normal with your spreadsheet.

MED is a dangerous road. It generates an image it deems most likely to have produced the image your actual exposed, given its assumptions about your system noise and psf. While MED can help you locate suspected features, get other unprocessed supporting evidence before asserting anything.

Finally, you can also write one-dimensional Unsharp and convolution filters and apply them directly in the spreadsheet.
12. Summary

The simplicity of fabrication of slitless spectrographs for any amateur, possessed of a CCD camera, puts the instrument within reach of many amateur astronomers. I hope this tutorial will encourage more to take the plunge into spectroscopy.
Lessons from Bohemia

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Abstract: This paper presents a “true life adventure” into asteroid photometry methods, which hopefully will be encouraging and useful to other amateur astronomers who are doing asteroid photometry. The key themes are: (a) a densely-sampled light curve, and fine sampling of the Fourier analysis errors, are very valuable in establishing the asteroid’s rotation period; (b) the reliability of the “Hardie method” of determining atmospheric extinction is improved by taking account of the colors of standard stars; and (c) determination of asteroid absolute magnitude and “slope parameter” requires special efforts to achieve photometric accuracy of .03 magnitude or better.

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References:

1. Introduction

Several of last year’s IAPPP speakers pointed us to projects that take advantage of the key advantage that amateur astronomers have over professionals: our access to telescope time is limited only by our interest and our endurance. Long runs of densely-packed data points can bring out features in a light curve that may be skipped over by the necessarily sparser data sets that typically come from professional studies. The speakers also emphasized the skills that amateur astronomers must strive for in order to do reliable science:
- know your instrument and the details of what it can (and cannot) do;
- review the professional literature on the topic you’re interested in;
- learn from other’s experiences;
- meticulously check both your methods and your results; and
- collaborate with other amateurs and with professional astronomers.

After a couple of years experience in gathering unfiltered asteroid light curves, I used a study of 371 Bohemia for my self-education on techniques for multi-color (BVR) photometry of asteroids. I set out to determine the asteroid’s rotation period, color index, absolute magnitude and slope parameter, and to search for possible color variations as it rotated. The project provided a “hands-on” lesson in the value of doing all the things that last year’s speakers recommended.

2. Light curve period determination

Previous professional studies apparently had trouble with this object. Two studies done during the 1993 apparition reported rotational periods of 3.8 hours and 12.48 hours, respectively. In retrospect, both of these studies probably suffered from insufficient data. Riccioli’s [1] data is shown in Figure 1. Note that it is a very sparse data set, and that only one maximum was observed, so that they had to use quite a bit of inference to conclude that the rotational period is 12.48 hours.

![Figure 1: Riccioli’s sparse data set indicated P= 12.48 hours](image-url)
Figure 2 shows Mohamed’s [2] data. The derived rotation period of 3.792 hrs relies almost totally on the data from a single night (10/20/93), and in retrospect, the fit between the four nights isn’t very good.

Meanwhile, the Geneva Observatory web site [3] had reported preliminary observations from 2001-2 which appeared to match an 8.7 hour period. Clearly, these disparate results couldn’t all be correct!

I gathered V-band data on three nights, which seemed to yield a good-quality light curve and a good estimate of the asteroid’s rotation period. This subset of data is shown in Figure 3, wrapped with an apparently well-defined rotation period of 4.37 hours – tolerably close to Mohamed’s estimate, and a vaguely similar shape.
Fig 3. A tolerable fit when wrapped at P= 4.37 hours?

However, note that this solution depends on treating the “little hump” near phase = 0.4 as the secondary maximum.

Since I needed additional data for other parts of this project, I updated the light curve estimate after night 4 was complete. Yikes! The apparent rotation period had slowed to P= 8.76 hours, as shown in Figure 4. This result seemed to be a good match to the report from Behrends [3] (whose provisional estimate was P= 8.77 hours). The “little hump” (now appearing at phase = 0.6) is revealed to be a manifestation of the asteroid’s shape, not one of the major maxima. That “little hump” is evidence that this object isn’t a “tumbling football” (i.e. it isn’t a triaxial ellipsoid: maybe there is some sort of a ridge or canyon that distorts the light curve).
Then, three weeks later, I gathered another night’s worth of V-band data, and discovered that it didn’t fit in with the 8.76 hour period at all – but that it did give a good fit using $P=10.76$ hours, as shown in Figure 5.
Finally, I was circling in on the correct rotation period. Adding in night #6 confirmed the asteroid’s rotation rate at $P = 10.737$ hrs, as shown in Figure 6.

The complex shape of the light curve may explain how the other studies were misled by their sparse data sets and/or short intervals of observation.

This is a real lesson in the importance of re-evaluating asteroids with previously-reported light curves. It also shows the great value of the amateur’s freedom to make profligate use of telescope time. Full coverage and dense data clarified an otherwise ambiguous light curve.

Dr. Behrends at Geneva Observatory was gracious in responding to my request (on the CALL website) for additional data. Ultimately he and I shared our data (including his 2001 and 2003 runs), and in response to my result his team gathered additional runs in 2004. This collaboration turned out to be wonderful. His data reduction validated my period estimate (his result, using all of our data, is $P = 0.447463 \pm 0.000007$ day = 10.739 hours). Better, he is hopeful that the wealth of data and a now-certain light curve can be used to determine other parameters of the asteroid (such as whether its rotation is prograde or retrograde).
This project also showed me the value of a topic that Warner [4] discusses, and uses in the Canopus software: complete evaluation of the Fourier analysis error over the range of candidate periods. The Fourier analysis routine in Canopus tries a sequence of candidate periods, wraps the data at each candidate period, and calculates the resulting error. The period with the smallest error is usually the best fit. Since this method samples a series of candidate periods, the candidates need to be closely spaced in order to avoid the risk of “jumping over” the truly best fit (e.g. the best fit might fall between two candidates). Warner advises using an interval between candidate periods of no more than

\[ d = 0.1 \frac{P^2}{T} \]

where \( P \) is the assumed period, and \( T \) is the total time over which observations are made (i.e. the time from the first observation to the last). In the case shown in Figure 6, \( T \) is nearly 30 days, so

\[ d \approx 0.1 \cdot \frac{11^2}{24 \cdot 30} \approx 0.017 \text{ hours}. \]

Yes, I really did run Canopus through the whole range from \( P = 2 \) hours to \( P = 15 \) hours, checking every .01 hour interval (i.e. \( P = 2.00 \) hrs, \( P = 2.01 \) hrs, etc.) to be sure that I wasn’t jumping over a potentially good period estimate!
3. Extinction coefficients

The first step in reducing instrumental magnitudes to standard magnitudes is determination of the atmospheric extinction. Hardie’s [5, 6] method is quite efficient in terms of telescope time: you take images of a Landolt standard field near the zenith, another near the horizon, and from that information you can calculate the extinction coefficient. Most writers advise that the standard stars used in the two fields should have similar color indices, but this advice is not quantified – e.g. how similar is “similar-enough”? My attempts to use this method prompted a re-examination of the relevant equations in Hardie’s original papers. I evaluated the effects of star-color mismatch, and found a simple method of improving the confidence in Hardie-derived extinction coefficients. This revised Hardie method has been incorporated into the latest version of Brian Warner’s PhotoRed program.

3.1 Color index effects in the Hardie method of determining extinction: The “Hardie method” of determining extinction is convenient because by imaging two standard fields, you can determine the extinction values and “zero points” for the night. This information (plus the color index transforms for your system) enables you to reduce your instrumental magnitudes to standard, exo-atmospheric magnitudes.

The concept is simplicity itself. Find a field with Landolt standard stars that is near the zenith, and make images in each filter that you’ll be using during the night. Call this “field 1” (or, the “zenith field”). Find another Landolt field that is near the horizon, at about 30 to 40 degrees elevation angle, and make images of it. Call this “field 2” (the “horizon field”). Pick a standard star from field 1, whose standard magnitude is \( V_1 \), and whose instrumental magnitude is \( n_1 \); and pick a standard star from field 2 whose standard magnitude is \( V_2 \) and whose instrumental magnitude is \( n_2 \).

The fundamental equation for observed magnitude in the presence of atmospheric extinction (neglecting second-order extinction) is

\[
V_{0,1} = n_1 - k' \cdot X_1
\]

(with a similar equation for \( V_{0,2} \)). Using the definition of the nightly zero point,

\[
V_1 = V_{0,1} + ZP
\]

it isn’t hard to derive the “Hardie equation”, which is most often written [4]:

\[
\frac{(V_1 - V_2) - (n_1 - n_2)}{(X_2 - X_1)} = k' \cdot \frac{V_1 - V_2}{X_2 - X_1} \quad \text{Eq. (1)}
\]

In this equation, I’m using the standard nomenclature:

- \( V_i \) is the standard, exo-atmospheric magnitude of the \( i^{th} \) star
- \( n_i \) is the measured instrumental magnitude of the \( i^{th} \) star
- \( X_i \) is the air mass for the measurement of the \( i^{th} \) star
- \( ZP \) is the “zero point” that relates camera ADUs to magnitudes
- \( k' \) is the extinction coefficient (in magnitudes per air mass)
I’ve implicitly assumed that we’re working v-band, but the same form of equations will be used for all other bands as well.

In order to take advantage of the fact that there will be several standard stars in each field of view, it is common practice to form “Hardie pairs”, matching each star in field 1 with several stars in field 2, using Equation (1) to calculate an estimated extinction coefficient for each pair, and then averaging all of the individual extinction estimates to get a best estimate of the actual extinction value, \( k_v' \).

It is not unusual to see quite a bit of scatter in the \( k_v' \) values calculated by individual Hardie-pairs. Figure 7 shows a typical result:

![Fig 7. Typical example of “scatter” in calculated \( k_v' \) from many Hardie pairs formed by stars in field 1 (zenith field) and field 2 (horizon field). The best estimate is \( k_v' = \text{average} \langle k_v' \rangle \).](image)

I was taken aback by the wide scatter in the individual estimates of extinction when using this method – s.d. = 40% in this example. We should be able to do better than that! Figure 8 shows the spreadsheet analysis that led to Figure 7.
Each cell in the outlined box is the extinction value derived from a single pair of stars. If I average all of the individual values in the box, I get \( k'_V = 0.219 \) (a plausible value for my observatory, which is at nearly sea level), with std dev = 0.09. But look closely at the individual values – one pair of stars gives a calculated extinction coefficient of \( k'_V = 0.07 \), while another pair of stars gives \( k'_V = 0.40 \). In other cases, I’ve found situations where some pairs of stars will give a calculated extinction that is negative – a physical impossibility! The color index data for the standard stars explains what’s going on. The most out-of-the-norm extinction values occur when the two standard stars have wildly different color indices. For example, Field 1 star 5 is pretty red, with B-V = 1.418, and when it’s paired with the much bluer Field 2 star 1 whose B-V = - .004, the calculated extinction coefficient is only 0.06 – hard to believe from my location.

The conventional wisdom is that when using the Hardie method, you should create “Hardie pairs” of stars that are approximately the same color. Henden and Kaitchuck [7] recommend picking only spectral type A0 stars, to ensure against color mismatch effects. The example in Figures 7 and 8 illustrates what can happen if you don’t closely match star’s colors. Alas, the conventional wisdom also says that you should use quite a few pairs (in order to get the benefit of averaging). But it’s not likely that you can do both at the same time. And besides, how close do two stars have to be, to have “about the same color”?

In Hardie’s original papers (for example reference [5]), he implicitly assumed that the standard stars had been calibrated for the instrument’s spectral band. My system isn’t too far from the standard system, but it isn’t perfect. Let’s go back to the Hardie equation, and modify it to recognize that instrumental magnitudes must be transformed into standard bands:

\[
V_1 = n_{0,1} + T_v (B_1 - R_1) + ZP
\]

where \( T_v \) is the (possibly not-yet-known) transform that will turn instrumental magnitude into standard V-band magnitude.

If I measure star 1 at air mass \( X_1 \), and star 2 at air mass \( X_2 \), then the difference will be:

\[
(V_1 - V_2) = (n_1 - n_2) + T_v [(B_1 - R_1) - (V_2 - R_2)] - k'_v (X_1 - X_2)
\]

and the Hardie equation becomes:

\[
\frac{(V_1 - V_2) - (n_1 - n_2) - T_v [(B_1 - R_1) - (B_2 - R_2)]}{(X_2 - X_1)} = k'_v
\]

Equation (3) shows what’s going on. If the two stars are exactly the same color, then the term \( T_v [(B_1 - R_1) - (B_2 - R_2)] \) will drop out, because the term in square braces equals zero. Equation (3) then reduces to the “conventional” Hardie equation. But if the two stars aren’t the same color, this color-mismatch term can have a noticeable effect.

This equation also suggests plotting the calculated extinction versus the B-R “color mismatch” of the two stars, as shown in Figure 9:
calculated extinction coefficients
vs degree of color-index mismatch between Hardie pairs

Fig 9. Calculated extinction vs. color mismatch (B-R)

(The circles are the v-band data from the spreadsheet shown in Figure 8. The squares are
data from the same night in the b-band, and the triangles are from r-band data.) Note that the
data fall along straight lines, as expected from Equation (3). The y-intercept of the best-fit line
represents the extinction that would have been calculated if I had two stars with no color mis-
mismatch.

In the case of the v-band data, the y-intercept is $k'_v = 0.2328$, which is very close to the value
calculated by averaging without regard to color mismatch. In this example, there are about as
many mismatched pairs in one direction as in the other, so the average worked out OK. But
there are cases where you have mostly-blusih stars in one field, and mostly-reddish stars in the
other, and hence the “average” extinction coefficient will be noticeably different than the “zero
local mismatch” value.

By plotting $k'_{v,i}$ versus (B-R), and using the y-intercept to define $k'_v$, there is no need to ad-
dress the question “how close in color is close-enough”.

In this analysis, I used B-R as the “color mismatch parameter” instead of B-V or V-R be-
cause it seemed to capture the full range of variation better. There’s no deep science in this
choice – it just seemed to work best with my instrument and my data. The key is to take account
of color-mismatch effects when using the Hardie method.

Signal-to-Noise requirement for Hardie-Method extinction: There is another piece of advice re-
garding Hardie-method extinction that bears some quantification: “be sure that you have a suffi-
cient signal-to-noise ratio” (SNR) in the standard star images that you use. How much is suffi-
cient? This question came up when I tried to determine B-band extinction coefficients using star
images with SNR~ 20:1, and simply could not get consistent results. (This is a particular prob-
lem for CCD imagers using B-band, where the sensitivity of the CCD falls off pretty severely,
comared to V- or R-band). The ultimate solution was, of course, longer exposure times and
higher signal-to-noise ratio, but it was useful to discover how SNR affects the extinction calculation.

There are two ways to understand the effect of SNR on the accuracy of k' determination: the first is heuristic, the second is a more rigorous statistical analysis.

**Heuristic approach:** Using the Hardie method is roughly equivalent to trying to detect the change in a star’s brightness as it moves from air mass $X_1$ to air mass $X_2$. We can use some “typical” numbers and “rules of thumb” to get an idea of how accurate that measurement must be.

For my location, typical R-band extinction is about $k'_r = .15$; for the V-band a typical value is $k'_v = .25$.

The Landolt standard stars are on the celestial equator. For my latitude (33º N), the celestial equator never rises higher than 57 degrees elevation, so the smallest possible air mass for the “zenith field” is $X_1 = \sec(57º) = 1.19$. Realistically, $X_1 \sim 1.25$ is what I usually achieve. The “horizon field” should be at the greatest possible air mass, but not greater than $X_2 = 2.0$ (elevation angle = 30 degrees), because at lower elevation angles effects such as differential refraction become serious. As a practical matter, I’ve found that elevation angles of ~ 35 to 40 degrees are typical for my “horizon fields”, because it doesn’t usually work out that I’m ready at the same time that the standard field is optimally placed; and star-rise waits for no man. Hence, $X_2 = \sec(35º \text{ to } 40º) \sim 1.55$ to 1.74. Figure 10 illustrates the situation.

![Air mass vs Zenith angle](image)

**Fig 10. Air mass vs. Zenith angle, and typical situation for Hardie-method extinctions**

Thus, we’re trying to measure the change in a star’s apparent brightness that is caused by moving from $X_1 \sim 1.25$ to $X_2 \sim 1.65$, i.e. $X \sim 0.4$ air mass. Using the “typical” $k'_v = .25$, that amounts to a brightness change of $m = 0.4 \times k'_v = 0.1$ magnitude.
A well-respected rule of thumb in metrology is that your measuring error should be about 10 times smaller than the effect you’re attempting to measure. In this example, the measurement accuracy should be about 0.01 magnitudes. The standard deviation of stellar photometric measurement – the accuracy – is usually taken to be $m = 1/SNR$, where SNR is the signal-to-noise ratio of the stellar image.

Combining all of this implies that reliable Hardie-method determination of atmospheric extinction requires a signal-to-noise ratio of SNR $\geq 100$.

The exact numbers aren’t central to this discussion. The key points in this line of reasoning are that it’s very important to get SNR $\geq 100$ or higher, and equally important to get that “horizon field” as close to 30 degrees elevation as possible, to maximize the air-mass difference $|X_2 - X_1|$.

3.2.2 Statistical Analysis: A more rigorous statistical analysis of the Hardie equation (assuming one star in each field), which I won’t reproduce here, yields the standard deviation of $k'$:

$$k = \frac{[(1/SNR_1)^2 + (1/SNR_2)^2]^{1/2}}{|X_2 - X_1|}$$

Eq. (4)

where SNR$_1$ and SNR$_2$ are the signal-to-noise ratios of star #1 and star #2 respectively. If the stars are of equal SNR, and we expand the analysis to use $n$ stars in field 1 and $m$ stars in field 2, then the benefit of averaging the results from the $n \cdot m$ unique “Hardie pairs” yields a calculated extinction coefficient with an accuracy of:

$$k = \frac{2^{1/2}}{SNR} \frac{|X_2 - X_1|}{|X_2 - X_1| [n \cdot m]^{1/2}}$$

Eq. (5)

Re-arranging this equation, the required signal-to-noise ratio to achieve a desired accuracy ($k_{\text{des}}$) is:

$$\text{SNR}_{\text{reqd}} = \frac{2^{1/2}}{k_{\text{des}}} \frac{|X_2 - X_1| [n \cdot m]^{1/2}}{|X_2 - X_1| [n \cdot m]^{1/2}}$$

Eq. (6)

As a practical example, suppose that we want to estimate the extinction to an accuracy of about 5%, i.e. to about $k_{\text{des}} = .01$ mag/air mass; and that there are 3 standard stars in each field ($n = m = 3$). With $|X_2 - X_1| = 0.4$ the required signal-to-noise ratio is

$$\text{SNR}_{\text{reqd}} = 118$$
Equation (6) can be used to estimate the required SNR for other cases. It quantifies the general rules: get high signal-to-noise ratio, get as large an air-mass difference as practical, and use as many standard stars in each field as are available.

4. Absolute Magnitude

I have seen plots of asteroid brightness vs. phase angle in some professional studies. It would be neat to document the opposition-effect of my chosen target: the rapid brightness increase as the asteroid approaches phase angle $=0$ (fully illuminated, analogous to a “full moon”). Beyond the inherent “neatness” of witnessing it, the shape of the asteroid’s brightness-versus-phase curve turns out to have several important uses. First, the brightness at zero phase angle defines the absolute magnitude, $H$. Second, within some broad limits, the shape of the curve (the so-called “slope parameter”, $G$) sets constraints on the albedo; and if you know the albedo and the absolute magnitude, you can determine the physical size of the asteroid (its projected area). Third, the slope parameter also offers some clues about the surface texture of the asteroid [8].

The relevant equations are found in reference [9]. First, all of the brightness measurements are transformed to standard V-magnitude. Then, the V-magnitudes are converted to “reduced” magnitudes, by:

$$V_R = V - 5 \cdot \log(r \cdot d)$$

where

- $V$ = the measured V-magnitude
- $d$ = the distance of the asteroid from the Sun (in AU)
- $r$ = the distance of the asteroid from the Earth (in AU)

This takes out the effect of the constantly changing distance from the Sun and Earth, so that the only remaining reasons for brightness change are the rotational light curve, and the changing phase angle.

The asteroid’s “absolute magnitude” is defined as the brightness that the asteroid would have when fully illuminated (phase angle $=0$), at a distance of 1 AU from the Sun, and observed at 1 AU from the Earth. The “absolute magnitude” can be found by plotting $V_R$ vs. $a$, and extrapolating the curve to $a = 0$. The curve has a specific shape, defined by the “slope parameter” $G$, and phase functions $F_1$ and $F_2$, which are described in reference [9].

I calculated the “reduced magnitude” and determined the Sun and Earth distances to the asteroid for each good observing run. Since the asteroid’s brightness is changing as it rotates, I also used the light curve to compensate for the rotational phase at the time of the observation.

4.1 Results: My results are shown in Figure 11. They show the expected trend, but aren’t sufficient to distinguish between two previously-reported $G$, $H$ values (references [10] and [11]).
My data suffer from two weaknesses. First, the accuracy required for G, H determination is .03 magnitude or so. The need for this level of accuracy can be seen by plotting the predicted V<sub>R</sub> for various values of G and H, as in Figure 12. The curves are only a few tenths of a magnitude apart in most places.

Second, I wasn’t able to observe the asteroid at its minimum phase angle of a= 1.4 degree (it was raining that week). Observations at both large and very small phase angle are needed to reliably determine G. That requires some advanced planning. In order to get large-phase-angle data, you have to observe the asteroid long before it reaches opposition (or long after it passes opposition). For most asteroids, the maximum observable phase angle occurs when the asteroid is in quadrature, i.e. when it rises at about local midnight. Since it will take a couple of hours to rise to >30º altitude, that means getting your initial observations in the wee hours of the morning! For the 2003/4 apparition of Bohemia, the maximum achievable phase angle was 20 degrees, in late October 2003. As it worked out, my first good measurement wasn’t made until late December 2003, at a = 12 degrees.

This is a project worth doing. Most of us have heard Brian Warner’s lesson that there are thousands of asteroids in need of accurate lightcurves. That is even more true for slope parameter. Scan down the ASTORB or similar database, and you’ll find that the majority of asteroids are listed as G=0.15. Most of those aren’t well-measured values; G=0.15 is the “default” value that is assumed when there’s insufficient data available.
Fig 12: Photometry must be very accurate to distinguish between different G, H values

Accuracy requirements for G, H Determination: Realizing that future projects to determine H and G are going to require greater emphasis on accuracy and repeatability of V magnitudes, I got to thinking about all of the factors that can confound this goal. One rainy night, I re-read the “propagation of errors” section in Henden and Kaitchuck (7) and dredged up some of the statistics that I learned in college. For those who have blissfully forgotten that class, here’s the summary version.

The determination of V-magnitude is a function of many different parameters:

\[ V = f(a, b, c \ldots n) \]

The general statistical theorem is that the variance of V is

\[ \sigma_V^2 = \sigma_a^2 \left( \frac{\partial f}{\partial a} \right)^2 + \sigma_b^2 \left( \frac{\partial f}{\partial b} \right)^2 + \ldots + \sigma_n^2 \left( \frac{\partial f}{\partial n} \right)^2 \]

where \( \sigma_a^2 \) is the variance of parameter a, etc. The form of the function f is found as follows: The exo-atmospheric instrumental magnitudes are:

\[ v_0 = v - k'_V X \quad \quad r_0 = r - k'_r X \]

We determine the transforms and zero-points by measurement of standard stars, and then calculate the color index
\[(V-R) = T_{VR}(v_0-r_0) + Z_{VR}\]

and the standard V-magnitude

\[V = v_o + T_{V,VR}(V-R) + Z_V\]

Substituting all of this into a single equation gives:

\[V = v - k'_v X + T_{V,VR} T_{VR} (v-r) + T_{V,VR} T_{VR} (k'_r - k'_v)X + T_{V,VR} Z_{VR} + Z_V\]

Of all the factors going into V, only the air mass (X) can be considered as a reliably known value. The other factors are random variables affected by a variety of noise and other random errors.

The result of taking the partial derivatives, and evaluating the probable standard deviations of the various parameters, is summarized in Figure 13:

| Parameter      | Partial Derivative             | Typ value \[| V/ x |\] | Standard Deviation         |
|----------------|--------------------------------|-----------------|---------------------------|
| instr mag      | \(V/ v = 1 + T_{V,VR} T_{VR}\) | 1.05            | \(v = 1/\text{SNR} + \sigma\) |
|                | \(V/ r = - T_{V,VR} T_{VR}\)  | .05             | \(r = 1/\text{SNR} + \sigma\) |
| extinction     | \(V/ k'_v = -(1+T_{V,VR} T_{VR})X\) | 1.3             | \(k'_v = 2^{3/2} \sqrt{\text{nm}}^{1/2}\) |
|                | \(V/ k'_r = T_{V,VR} T_{VR} X\) | .07             | \(k'_r = 2^{3/2} \sqrt{\text{nm}}^{1/2}\) |
| zero point     | \(V/ Z_{VR} = T_{V,VR}\)      | .05             | \(Z_{VR} = \sqrt{(n)^{1/2}}\) |
|                | \(V/ Z_V = 1\)                | 1               | \(Z_V = \sqrt{(n)^{1/2}}\) |
| transforms     | \(V/ T_{V,VR} = T_{VR} (v-r) + T_{VR} (k'_r - k'_v)X + Z_{VR}\) | 1.2             | \(T_{V,VR} = \text{see below}\) |
|                | \(V/ T_{VR} = T_{VR} (v-r) + T_{VR} (k'_r - k'_v)X\) | .06             | \(T_{VR} = \text{see below}\) |

Fig 13: Partial Derivatives and typical values for photometric accuracy

The partials show that the most important parameters are v-instrumental magnitude, v-extinction, v-zero point, and V-transform. These are the measurements that deserve the most attention, toward increasing their accuracy and reducing their variance. The partials associated with r-band instrumental magnitude, r-band extinction and (V-R) transform are negligible – they don’t have much effect on the absolute accuracy.

The equations for Standard Deviation quantify the usual advice about how to improve the accuracy, e.g. get high SNR, and use multiple stars to determine extinction coefficients.

As noted above, determining H and G requires photometric accuracy of \(\sqrt{\text{V}} \approx 0.03\) or better. My limited experience in this area is that when you’re striving for accuracy of a few hundredths of a magnitude, everything about your instrument, imaging, and data reduction is a potentially significant factor! This raised several questions about the repeatability of my instrumentation (e.g. are flat-fields repeatable after motion of the filter wheel? Do transform coefficients change from night to night?).
Scintillation-type errors: The photometric accuracy of instrumental magnitude is often stated as
\( v = 1/\text{SNR} \). This equation assumes that photon-counting statistics are the only error source,
which isn’t quite true. There is such a thing as atmospheric scintillation (probably not a factor
for typical imaging conditions) and at least three other effects that can cause a scintillation-like
noise: imperfect flat-fielding, imperfect tracking or guiding, and imperfect measuring-aperture
placement. This “scintillation-like” noise is labeled \( s \) on the table above. I’ve made some
measurements indicating that “scintillation-like” noise in my set-up can get as large as \( s \sim .02 \)
magnitude.

Where is this fluctuation coming from? My best guess is that it’s driven by a slight non-
repeatability of the position of the filter wheel as I cycle it from \( v \) to \( b \) and \( r \), and then back to \( v \).
My system has the inevitable dust-donuts, and (since I use an F/6.3 focal reducer) some vignet-
ting. A typical flat-frame shows overall shading of about 7% peak-to-peak (due to vignetting),
and the deepest dust donut has a depth of about 3%. These can be effectively compensated by
normal flat-fielding methods (I use a light box, that I’ve tested against twilight-flats). However,
if the filter wheel doesn’t register to \textit{exactly} the same position each time it is rotated, then the
vignetting will be slightly different, and this difference will cause slight variations in the instru-
mental magnitude even after flat-fielding (since the filter position – and hence the vignetting – in
the flat-field won’t be \textit{exactly} the same as the conditions during imaging).

I tested this theory by making a series of \( v \)-band flats, then \( r \)-band, then \( b \)-band, then \( v \)-band
again. Call the first set of \( v \)-band flats “\( V \)-flat-1” and the final set “\( V \)-flat-2”. There were a
dozen images in the “\( V \)-flat-1” series. Taking the first 6 of these, median-combining, and then
using them to “flat field” the second 6, gave a nearly-perfectly-uniform frame, as desired. Then,
I took the median-combined “\( V \)-flat-1” series and used it to flat-field the “\( V \)-flat-2” series. The
result was not-quite-perfect: there were subtle remnants of vignetting and hints of portions of the
dust donuts. The resulting overall non-uniformity was about 2% (peak-to-peak) in this test.
Since this correlates pretty well with the “scintillation-type” noise I’ve seen in some standard-
star runs, I’ve assumed \( s = .02 \) in the error analysis for my absolute magnitude results. The ex-
act value isn’t as important as the recognition that it exists. If it’s critical to achieve 0.01 mag-
nitude or better accuracy, then the filter wheel should be left untouched during the imaging ses-
sion and flat-field exposures. For situations where the filter wheel must be moved during a
night’s session (e.g. monitoring for color changes as the asteroid rotates or binary star revolves),
then the practical accuracy is going to be \( \sim .02 - .03 \) magnitude, regardless of how high the sig-
nal-to-noise ratio is.

4.2.2 Transform and Zero Point accuracy: I guess unless you own a spectrophotometer, you’ll
never know exactly what the transforms of your system are. The best I could do was measure
them frequently, and pay attention to the repeatability of the measurements. I measured the
transform \( T_{V,VR} \) on five separate occasions during the study of Bohemia, and the results were
quite consistent, with a standard deviation of \( T_{V,VR} = .02 \), which (using Figure 13) contributes
about .02 magnitude standard deviation to the absolute magnitudes.

5. Conclusion

The advice given by several speakers at last year’s IAPPP conference was well founded. The
availability of nearly unlimited telescope time permits the amateur astronomer to conduct proj-
ects that would be difficult for a professional to justify, and today’s high-quality and modestly-
priced imaging equipment puts interesting projects within the reach of dedicated amateurs. However, in order to achieve the accuracy required, and be able to have confidence in your results, the amateur must spend a fair amount of time getting a quantitative understanding of the capabilities of his/her equipment. I hope that my experiences described here will encourage some other beginners, and be useful examples of the sorts of things to watch out for. There are a lot of asteroids and variable stars out there that need our attention!
Statistical Properties of a Two-Stage Procedure for Creating Sky Flats

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Abstract: Accurate flat fielding is an essential factor in image calibration and good photometry, yet no single method for creating flat fields is both practical and effective in all cases. At Winer Observatory, robotic telescope operation and the research program of Near Earth Object follow-up astrometry favor the use of sky flats formed from the many images that are acquired during a night. This paper reviews the statistical properties of the median-combine process used to create sky flats and discusses a computationally efficient procedure for two-stage combining of many images to form sky flats with relatively high signal-to-noise ratio (SNR). This procedure is in use at Winer for the flat field calibration of unfiltered images taken for NEO follow-up astrometry.

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References:
1. See URL http://www.winer.org for additional information
2. URL http://www.minorplanetobserver.com/astlc/PhotometryGuide.htm

1. Introduction

Good flat fielding is important to the science programs, both ongoing and planned, at the Winer Observatory. The Observatory was incorporated in 1983 in Maryland under Internal Revenue Service rules for non-profit public charity organizations performing scientific research, and its research program initially focused on lunar and minor planet occultations. The Observatory moved to Arizona in 1990 and, with completion of the Sonoita Field Station in October 1997, now provides facilities and services under dark southeastern Arizona skies for robotic telescopes operated primarily by universities for faculty and graduate student research and undergraduate instruction [1].
A collaboration involving the authors is establishing a new research program (not yet fully operational as of this writing) directed toward astrometric follow-up of Near Earth Objects (NEOs) listed on the Minor Planet Center’s (MPCs) Near Earth Object Confirmation Page. Once adequate experience is gained with NEO follow-up, we intend to expand into other research areas. Topics of mutual interest include differential photometry for minor planet rotational studies, eclipsing binary star lightcurves, and exoplanet searches using photometric techniques.

Our NEO astrometry program has available to it two telescopes (see Table 1). The Rincon telescope is a 0.5-m f/9 corrected Newtonian on a robotic German equatorial mount using a commercial CCD camera with a thinned, backside illuminated detector. The Winer telescope is a 0.5-m f/8 Ritchey-Chretien on a robotic altitude-azimuth mount, designed and built at the University of Iowa and acquired from them in 2003 after installation of a new Iowa telescope. The Winer telescope also features a commercial CCD camera with a thinned, backside illuminated detector.

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Image calibration is covered extensively in the literature, from which merely three references are the Collaborative Asteroid Lightcurve Link (CALL) photometry tutorial [2], Berry [3] and Massey [4]. Newberry [5] has shown that a flat field must have a substantially higher signal-to-noise ratio (SNR) than any pixel of interest if the image calibration is to avoid degrading the SNR of the data. Thus, to obtain 1% photometry the flat field must have a precision\(^1\) in the range of 0.25% to 0.5%. Obtaining accurate flat fields of high precision is notoriously difficult. Doing so requires illuminating the telescope pupil with a source of illumination that varies spatially (over the detector) by less than the desired precision of the result and that has a spectral distribution appropriate to the intended targets.

At Winer, broadband photometry will be done initially only to obtain NEO magnitude estimates for submittal with astrometric positions to the MPC. NEO photometry of this type is often done in unfiltered “white” light and with only approximate calibration to a broadband color magnitude (often of uneven quality itself) found in astrometric catalogs. The MPC’s stated goal

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\(^1\) The term precision is used in the sense of the repeatability of a measurement. A precision stated as a percentage (e.g., 1%) is equivalent to a signal-to-noise ratio equal to the reciprocal (e.g., 100).
is to obtain photometry at the 5% level [6], but the quality of the available observations is often less. Such a tolerance is considerably less demanding than that of stellar photometry, where 2%, 1%, or even greater precision is often needed. For example, the CALL Web site states a minimum requirement of SNR ~ 50 (2% precision) and a preference for SNR ~ 100 (1% precision) in the differential photometry used for determining rotational periods. The goal at this stage in our research program is to work toward the capability of performing 1% photometry, for which flat fields of 0.25% to 0.50% precision will be required.

Many methods are used to create high SNR flat fields, although no single method appears to be both practical and effective in all circumstances. Dome flats are a common solution to the flat field illumination problem at professional observatories. Great efforts are made to achieve uniform field illumination, using special screen materials or paints, and special lamps are selected to provide the correct spectral distribution. In return, flat fields of very high SNR can be obtained in a few images. Light boxes are a conceptually similar, but less sophisticated, solution to the flat field problem at amateur facilities. Twilight flats may also be used, as are sky flats in some research programs, and there are methods for combining dome flats with twilight or sky flats to improve the uniformity of field illumination. Massey (op cit) discusses a range of alternatives for obtaining satisfactory flat fields at the community-use telescopes at Kitt Peak National Observatory.

At Winer Observatory, we are experimenting with sky flats created from the science images taken in our NEO astrometry program. Sky flats are nothing more than composites of many images that are formed using a median-combine process to reject pixels that are illuminated by bright objects (e.g., stars and galaxies) in the individual images. Sky flats are similar in principle to dome and twilight flats – i.e., illuminate each pixel with the same light intensity, in this case generated by the sky background, and record the response of the telescope and detector system. The assumption made is that, over the field of view, the sky background does not vary by more than the precision we seek. Unlike twilight and dome flats, however, the pixel counts from the sky background are small, and their Poisson variation relatively high, so the SNR of the sky background in a single image is too low to be of use as a flat field. To ensure that we achieve a sufficient SNR at every pixel, without contamination from stars, several to many individual images are combined to form the sky flat.

Sky flats have several advantages from our current perspective, in that they avoid the need for dome flat equipment and can be created in a data processing pipeline using the science images taken robotically during a night. Another advantage is that their color automatically matches the characteristics of the night sky, giving us the best color match for images taken to detect faint objects against the sky background. Twilight flats are basically sky flats taken at twilight with much higher illumination levels, but the twilight sky has a different color than the night sky.

We acknowledge that sky flats may be less suitable for color filter photometry. The spectrum of the night sky is not continuous, but is characterized by naturally occurring emission lines and by urban light pollution in both narrow (low pressure sodium vapor lighting) and broad (high pressure lighting) spectral bands. Thus, the night sky may not provide spectrally flat illumination across the filter passbands of interest, and the resulting sky flats may be a poor match to the colors of astronomical targets or of comparison and check stars. The problem of non-uniform spectral distribution should be of less concern the narrower the filter passband of interest.

An obvious disadvantage of sky flats is that the SNR of the sky background in a single image will be low. Thus, many images must be combined to boost the SNR to a precision of 0.5% or
better. This problem will be exacerbated by the reduction in photon counts when observing through broadband filters, but the reduction can be offset by increasing the number of images used in the creation of the flats. The study summarized in this paper was conducted to understand the statistical properties of sky flats and to develop practical computational techniques for creating sky flats from large numbers of images.

2. Basic Properties of Sky Flats

Sky flats are conventionally created using the median operator to combine N astronomical images in a single step. Each pixel value in the output image is defined as the median value of the N individual values taken on by that pixel in the input images. Before the combine, the input images are first normalized to the same brightness level to account for variations in the brightness of the sky background across the fields. Under suitable conditions, the resulting output image will record the response of telescope and detector to uniform illumination by the sky background.

Any of several procedures can be used for the normalization before images are combined, including equalizing the average pixel value across the image (or within the central portion of the image) or equalizing the median or modal (most frequent) pixel value. Because pixels illuminated by sources other than the sky are to be rejected by the median operator, a normalization method (such as median or modal) that equalizes the sky background brightness is to be preferred over methods based on average values that are affected by the pixel counts of astronomical objects.

The basic properties of sky flats are easily understood. As a simplification, let us consider that images are composed of two types of pixels – sky pixels, which are illuminated by sky background, and non-sky pixels, which are illuminated by astronomical objects or cosmic rays. Sky and non-sky pixels are distinguished by the fact that non-sky count levels typically far exceed sky count levels. A particular output pixel in the composite image will be assigned a sky value by the median-combine process whenever a majority of the input images have a sky value in that position. It will be assigned a non-sky value whenever a majority of the input images has a non-sky value in that position.

As an example, if there are 21 images to be combined, the output pixel will take on a sky value if that position is a sky pixel in 11 of the input images (or more). If there are 22 images, then the output pixel will take on a sky value if it is a sky pixel in 12 images or more (because the median of an even number of values is defined as the average of the two central values – the 11th and 12th in this case). On the other hand, chip defects such as hot or dead pixels will flow through to the output image, because such pixels will be consistently high or low in the input images, and appropriately characterize the (non-linear) detector response at those positions.

Rejection of Non-Sky Pixels. An important property and desired of the median-combine process is that, under suitable circumstances, it will reject astronomical objects and cosmic ray hits with high statistical confidence and yield a composite image composed of the system response to a spatially uniform sky background. The requisite circumstances are that:

1. The images are sufficiently displaced from each other spatially that the values taken on at a particular pixel position are uncorrelated across the input images.
2. A minority of the values at each pixel position are non-sky pixels.
3. The gradient in the brightness of the sky background across each image must be less than
the precision desired in the final result. (Differences among images in the average sky
background level can be removed by the pre-normalization.)

The first requirement (spatial displacement) can be satisfied when the image set consists of
star fields imaged after independent pointings, even when the fields are of the same target, be-
cause random pointing errors of ~1 arc minute or larger in amateur equipment will be sufficient
to break pixel-scale correlations. The technique is much less likely to reliably reject non-sky
pixels when the images are composed of extended objects or contain bright objects consistently
positioned near the centers. Nor will the technique reject non-sky pixels when the image set
follows the same field throughout the night without repointing.

The second requirement (a minority of non-sky pixels) must be met at every pixel position if
the output image is to be completely free of contamination from non-sky pixels. Although it is
minimally sufficient that a pixel position take on a bare minority of non-sky values in the image
set, the rejection process has much greater power when the non-sky pixels comprise a small mi-
nority in each image.

The third requirement (small brightness gradient) will be easier to meet in images that have
small fields of view, are not taken near bright objects, and are positioned away from sources of
light pollution on the horizon. When this requirement is violated, the sky flat will suffer from
systematic errors caused by the gradient in field illumination. It may be possible to correct for
this problem, but it would be necessary to deconvolve the gradient in sky illumination in the im-
ages from the potential gradient in pixel response across the chip. We have not, as yet, found a
treatment of this issue in the literature, and we plan to reassess this issue empirically after a suit-
able dataset of sky flat frames has been obtained.

The basic statistical properties of sky flats are not difficult to assess quantitatively as an ap-
plication of the binomial theorem, under the simplifying assumption that images are composed of
sky and non-sky pixels that occur with equal probability at each pixel position. For a single out-
put pixel, the probability \( \text{prob}_{NS} \) that a non-sky pixel survives to the output image is given as
follows. Let \( p \) be the fraction of non-sky pixels in an image and \( 1-p \) the fraction of sky pixels; let
\( N \) be the number of images combined, where \( N = 2n + 1 \); and let \( m \) be the number of sky values
that may occur. Then:

\[
\text{prob}_{NS} = \sum_{m=1}^{n} C_{N,m} (1-p)^m p^{N-m}
\]

where \( C_{N,m} \) is the combinatorial operator giving the number of ways that \( N \) things can be
chosen \( m \) at a time. The terms in the summation give the probability of encountering \( m \) sky pix-
els and \( N-m \) non-sky pixels at a given pixel location. The summation runs from \( m=1 \) through
\( m=n \) because these are the cases in which the sky pixels are a minority of the values present in
the input images and the median operator selects a non-sky value for the output.

The statistical reliability of the process can be measured by the probability \( \text{prob}_{NS} \) that the
median-combine fails to reject non-sky values at a given pixel. If there are \( k \) pixels in an image,
then \( k * \text{prob}_{NS} \) is the expected number of non-sky pixels present in the output image. This value
can be thought of as a contamination rate and used as an overall measure of the reliability of the
process.

Figure 1 shows that the expected number of non-sky pixels surviving the median combine
operation is highly sensitive to \( p \), the fraction of non-sky pixels in an image. The values given
are for a 1k x 1k CCD image, but may be scaled to other image formats in proportion to the total number of pixels. When 11 images are combined, approximately 100,000 pixels in the output image will be non-sky pixels if \( p \) is as large as 0.30. For 11 images, the number of non-sky pixels falls to 10,000 when \( p \) equals 0.20, and to 300 (< 0.05%) when \( p \) equals 0.10. The contamination rates fall very quickly as the number of images increases. As long as \( p < 0.50 \), the number of non-sky pixels in the output can theoretically be driven to low values by combining a sufficient number of images. However, the median-combine process is most effective and reliable when \( p \) is small.

![Figure 1. Statistical Reliability for Rejecting Non-Sky Pixels (1k x 1k image)](image)

The fraction of non-sky pixels in an image will vary with a number of factors including the astronomical target (star field, cluster, extended object, etc.), galactic latitude, image scale, seeing conditions, and depth of exposure. While we cannot provide general guidelines on the values of \( p \) that will be encountered in astronomical imaging, based on our experience to date we believe that \( p \) values in the range 0.10 to 0.15 are typical of the non-cluster star fields imaged in the course of NEO studies, using our equipment and exposure times of 60 to 120 seconds. Even if \( p \) is as large as 0.20 in some cases, we are easily able to acquire many more than the 60 images in a night that are needed to reduce the contamination rate below 1 pixel per frame. Therefore, we should be able to acquire sufficient images to form sky flats composed only of sky pixels.

**Variance Reduction.** A second important property of the median-combine process is its ability to attenuate the variance that is present in the input values. As a result, the output image has reduced variance and higher SNR than was present in the sky backgrounds of the input images. Variance reduction occurs because the median operator is an estimator for the central tendency of the data, much like the mean value operator. If \( \sigma^2 \) is the variance of the input values, then the variance of the median is given asymptotically by [7]:
\[ s^2_{\text{median}} = \left( \frac{1}{2} \right)^2 / N \]  

(2)

Compare this to the familiar result for the mean value operator:

\[ s^2_{\text{mean}} = \frac{s^2}{N} \]  

(3)

As a result, the standard deviation of a median value will be about 25 percent higher than the standard deviation of an average value computed from the same data. Equation (2) is valid asymptotically; there is no precise point at which the asymptote is approached, but a sample of 30 or more is often considered to be sufficient.

Combining more images will reduce the standard deviation of the result in proportion to \( 1/\sqrt{N} \) and increase the SNR in proportion to \( \sqrt{N} \). To demonstrate this, we conducted a Monte Carlo simulation in which pixel values were chosen randomly from a Poisson distribution to fill a pixel sample of size \( N \). The mean and median values were computed for each sample and the results stored. The process was then repeated 3000 times so that the standard deviation of the median and mean values could be accurately determined for the sample size. Sample sizes from \( N=5 \) to \( N=300 \) were investigated. The SNR is estimated for each sample size as the ratio of the mean (or median) pixel count divided by the standard deviation of the count across the repeated samples. Only the Poisson variation in the sky background was considered, and noise sources related to read noise and dark current in CCD images were excluded.

Figure 2 presents the results of the Monte Carlo simulation, showing the increase in SNR as a function of the number of images combined and the method of image combination. The vertical axis measures the SNR relative to that for a single image. For example, the lower line in the figure shows an increase in SNR of approximately 13 for \( N=300 \) images. Therefore, if the sky background in one image has an SNR of 10, the sky background of a median-combined sky flat formed from \( N=300 \) images would be approximately 130. The upper line shows the result if images were combined using the mean value operator (averaging). The mean value operator is more efficient at variance reduction, but it would not reject non-sky pixels\(^2\). For samples of \( N=30 \) images or more, the variance of the median-combined image is 25 percent greater than would result from averaging, in accordance with Eqs. (2) and (3). This gap can be thought of as the price one pays to reject non-sky pixels.

The sky background in unfiltered images taken from our location can have a SNR \( \sim 50 \). Therefore, we can create sky flats with SNR \( \sim 200 \) (0.5% precision) by combining 25 images, and flats with SNR \( \sim 400 \) (0.25% precision) by combining 100 images. When imaging through broadband filters (or with smaller apertures), the SNR in single images will be much less, and we must be prepared to combine larger image sets to achieve comparable results. These results suggest to us that we should be able to achieve satisfactory SNRs in sky flats for both current and future programs. However, such flats will still fall short of the very high SNRs that can be achieved with dome or twilight flats (not withstanding issues regarding uniform illumination and color match).

\(^2\) There are iterative techniques (often called “sigma clipping”) in which outliers (both high and low) are rejected based on their distance from the mean value until all remaining values are statistically consistent. Such techniques would allow image combination and rejection of non-sky pixels using an averaging process. We do not consider these techniques here.
**Computational Complexity.** Tests conducted during the development of a data processing pipeline for our research program showed that combining more than about 100 images was a computational bottleneck. When the number of images being combined exceeds a threshold that is specific to the configuration of each computer system, slow virtual memory (disk) is used in place of fast physical RAM. Beyond that threshold, the time required to complete the median combine operation escalates rapidly as increasing use is made of virtual memory.

![Image Combination SNR Graph](image)

*Figure 2. Increase in SNR Through Image Combination (relative to a single image)*

The data in Table 2 suggest that the threshold for our computer system (1.2 GHz processor, 512 MB RAM) is approximately 70 images. The processing time per image is essentially constant through at least 70 images, but the processing time and disk access activity escalate rapidly as substantially more images are processed. These values are specific to our processing computer, and each computer will have its own curve with a threshold that depends primarily on the ratio of available RAM to image size.

3. **Properties of a Two-Stage Process**

While sky flats can give acceptable SNRs when formed from many images, a single-stage median-combine process may be impractical. This discovery led to development of a two-stage process for performing the median combine that is more computationally efficient. In the first stage, one combines images in n sets of smaller size, with the set size chosen to be large enough to reject non-sky pixels with high probability, but small enough to avoid use of virtual memory. If non-sky pixels are reliably rejected in the first-stage, then the n first-stage images may be combined in a second-stage by averaging (or summation), without loss of precision in the final result compared to a one-stage combine. If non-sky pixels are not rejected with sufficient reliability in the first stage, the n first-stage images can be combined again using the median operator, although with additional loss of precision as shown by simulation later in this section.
Table 2. Dependence of Processing Time on Number of Images Combined

<table>
<thead>
<tr>
<th>Number of Images</th>
<th>Total Processing Time</th>
<th>Processing Time per Image (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1 min 30 secs</td>
<td>0.05</td>
</tr>
<tr>
<td>70</td>
<td>3 min 15 secs</td>
<td>0.05</td>
</tr>
<tr>
<td>100</td>
<td>8 min 4 secs</td>
<td>0.08</td>
</tr>
<tr>
<td>150</td>
<td>22 min 45 secs</td>
<td>0.15</td>
</tr>
<tr>
<td>300</td>
<td>1 hr 57 mins</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Based on characteristics of our images and the capability of our processing computer, we elected to combine images in batches not smaller than 35 and not larger than 70. Figure 3 shows how this so-called “35-70 Rule” divides the total number of images into an increasing number of groups of size always greater than 35. When the probability of non-sky pixels does not exceed $p = 0.15$, median combining a group of 35 images produces a frame that, on average, will contain 0.5 pixel contaminated with a non-sky value (for a 1k x 1k chip). We found this result to be acceptable as a worst-case condition, and we expect a better outcome (lower probability of contamination) in most circumstances. When $p = 0.10$, only 1 frame in 1000 resulting from the median-combine of 35 images will be contaminated with a non-sky pixel, and in most cases, more than 35 images will be combined in each group.

The $n$ frames produced in the first stage are combined in a second stage to produce a final sky flat. Under conditions typical of our asteroid images, first stage frames produced using the 35-70 Rule can be combined by averaging while running only a small risk that the final sky flat is contaminated with non-sky pixels. If the second stage averages $n=5$ frames, each of which has a 1-in-1000 chance of 1 contaminated pixel, then the final sky flat will, on average, have a 1-in-200 chance of 1 contaminated pixel. Under worst-case conditions ($p=0.15$ and 35 images), the final sky flat would, on average, have $5 \times 0.5 = 2.5$ contaminated pixels out of ~ 1 million pixels in the image. We judged these outcomes to be acceptable. Under less favorable circumstances, one can median-combine the frames in the second stage to increase the rejection of non-sky pixels, but the SNR of the final sky flat will be reduced.
One motivation for the 2-stage approach was the realization that a median-combine followed by averaging in the second stage would produce a final sky flat with the same SNR as if all the images were median-combined in a single step. This seemed intuitive because the median-then-average approach applies the median operator once, and only once, to all of the data. A second Monte Carlo simulation was conducted to confirm this property. In the simulation, pixel values were combined in groups according to different methods (see Figure 4). The SNR ratio of the 2-stage median-then-average combination process is found to be 25 percent less than that for simple averaging of the images, which was the result seen previously for a 1-stage median combine (Figure 1). Applying the median operator twice in a median-then-median combination process results in another 25 percent reduction in the SNR of the final sky flat.

4. Conclusions

This paper has presented the considerations and analysis that led us to experiment with sky flats for our science program at Winer Observatory. Sky flats have the considerable practical advantage to us that they can be created from images already available without the need for additional equipment or manual intervention. With a research program that acquires a large number ($N = 100$ to 300) of 60- to 120-second exposures in an evening, it appears possible to achieve sufficiently high SNR values for unfiltered observations. We are also hopeful of obtaining satisfactory SNR values when images are taken in a few (2 or perhaps 3) broadband filters during a night. The color match of sky flats to the nighttime sky background should also be advantageous to the sky-limited detection of faint objects in NEO astrometry and for the differential photometry of relatively faint objects against the sky background, as in asteroid light-curve studies.
Figure 4. SNR Increase in a Two-Stage Image Combination Process (relative to a single image)

The information we present on the statistical properties of sky flats was developed using a simplified analytical treatment and is not a definitive treatment of the problem. It is intended to provide guidance on the selection of parameters to other amateurs whose observing programs might benefit from experimentation with sky flats. Because the treatment is not definitive, users of the results are encouraged to build in a safety margin on the number of images that will be combined. Those engaged in color filter photometry should also take care to achieve a satisfactory match to the colors of objects of interest and to ensure sufficient sample sizes in each passband so that reliable transformation coefficients and color terms can be derived.

Acknowledgements

The authors wish to acknowledge a fruitful discussion on the topic of sky flats with Dr. Mark Dickinson of the National Optical Astronomy Observatory. Author M. Trueblood wishes to thank the many generous supporters of the Winer Observatory listed on the observatory’s website Honor Roll of Donors.
Looking Forward in the Rearview Mirror

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Abstract: Work at the Palmer Divide Observatory in the past years has concentrated on asteroid lightcurves. However, there have been brief excursions into other areas that are of equal interest and importance. This paper takes a look back at recent research conducted at the observatory, some of the results, and possible future directions.

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References:
1. ScopeCraft, Inc. 4175 E. Red Cliffs Dr., Kanab, UT 84741.
7. The Minor Planet Bulletin, c/o Derald D. Nye, nye@kw-obsv.org
1. An Overview of the Palmer Divide Observatory

The PDO is located about 8 miles east of Monument, CO, and about 20 miles north of Colorado Springs, CO, at an elevation of 2304 meters. Telescopes seem to come and go, aperture fever being the primary cause. However, one scope has remained constant for the past several years: a 0.5m f/8.1 Ritchey-Chretien built in the 1980’s by Jerry Foote[1].

The buying of the scope could be a nice short story. Suffice it to say it involved a 36-hour round trip drive from Colorado Springs to Salt Lake City, UT, that included loading up the credit card to the maximum, renting a U-Haul trailer on-site, and driving back in the face of head winds that rivaled the Jet Stream.

The main camera, acquired specifically because of the 0.5m, is an FLI 1001E with a KAF-1001E chip (1024x1024x24um). The camera can be cooled to –50°C but is normally run at –30°C. This temperature can be maintained even during summer months, partly because the observatory is so high and so a good 10°F cooler than either Denver or Colorado Springs. The camera is also equipped with an FLI CFW-1 filter wheel that has Schuler-Bessell BVR filters as well as a Clear filter. Most observations are made in Clear, just to keep the signal-to-noise ratio high. 2x2 binning is the norm, giving 2.5” pixels. While this may seem a bit large by most standards, the average seeing at the PDO is rarely better than 4” and usually 5-6”. This makes the pixel size a better match. It also reduces the download time considerably, the camera being an older parallel port model and so having much longer download times than USB cameras.

The PDO includes a second telescope that has yet to be put into service, mostly because a suitable shed for it has not been built. A couple of iterations have been tried but they were not effective for protecting the scope from weather or passing neighbors. That scope is a 0.35m f/10 Meade LX-200 GPS. What little it has been put to service promises it to be a very useful scope for working bright to moderate asteroids and to do follow-ups on newly discovered variables. The camera is an SBIG ST-9E with an Optec MaxFilter that includes Schuler-Bessell VR filters as well as a Clear filter.

So, what’s to be learned from building several iterations of observatories along with buying and selling several scopes and camera? Plan ahead, devise some specific ideas of what you want to do, determine what equipment you really need, and be sure, if married, to build up a massive amount of “spousal permission units” (SPUs). Discovering an asteroid and naming it after that person goes a long ways towards building up the account, e.g., 70030 Margaretmiller in my case.

2. Asteroid Lightcurves – Smaller and Fainter

The almost exclusive focus of work at the Palmer Divide Observatory is asteroid lightcurves. Reasons for this type of work has been covered before [2][3]. What I’ll give here is a brief overview of some of the results that have been obtained in the past year or so and fields of research that are still wanting.

Approximately 85 lightcurves have been obtained at PDO and published in the Minor Planet Bulletin [4] since mid-1999. Between the 2003 and 2004 SAS meetings, nearly two-dozen new curves were added. Plots and data are available on the PDO lightcurves web page [5]. Most of the new curves were of general interest and served mainly to add to the statistical pool of rotation periods. In addition to the PDO site, results are posted on the CALL web site [6] and included in the list maintained by Alan Harris and the author [7]. The link provided in the references includes additional links to on-line references or publications of the original papers.
Fig. 1. Two lightcurves obtained at the Palmer Divide Observatory. The period for 301 Bavaria was found to be 12.24±0.01h. The period for Steins is 6.05±0.01h.

Given the advantage of having a larger scope than most amateurs, general lightcurve work at the PDO has started to focus on fainter asteroids, i.e., magnitude 15.0 and fainter. There is a considerable observational bias towards brighter asteroids that should be mitigated as much as possible so as to include the, presumably, smaller and/or more distant targets. In conjunction with this was developing a method to convert Clear measurements to the Johnson V band as closely as possible. Reducing to a standard band has many advantages. For example, it simplifies merging data sets from widely separated nights or a number of observers. Robert D. Stephens and the author worked on refining this method and presented their results [8]. Additional work at the PDO has shown that an accuracy on the order of 0.02m and better can be achieved.

3. Asteroids – Binaries

While radar observations often lead to the discovery of binary asteroids, optical observations have served nearly as well and had their share of discoveries. One the more famous cases occurred following the recovery of 1937 UB, Hermes in 2003 October. Many amateurs rushed to capture the prodigal asteroid, both for astrometry and photometry. The photometry efforts were coordinated in two camps, one being headed by Raoul Behrend at the Geneva Observatory and the other by Peter Pravec at Ondrejov Observatory, Czech Republic. The author worked with Dr. Pravec and submitted data from several runs in late October. The plot of that data is shown in Fig. 2.
Sometimes in astrometry work, an asteroid is over-observed. That’s rarely the case in photometry work and almost certainly never when a binary asteroid is suspected. This was reinforced when (65803) 1996GT was worked in 2003 November. Dr. Pravec reported that observations by Peter Kusnirak indicated a dual period, and so the possibility of being a binary asteroid [9]. The author and Donald Pray of Carbuncle Hill Observatory in Rhode Island began observing the asteroid in late November and the following lunation in late December. The combined observations taken at PDO are shown in Fig. 3.

Dr. Pravec used the combined data sets to confirm a period of $2.257\pm0.01\text{h}$ and amplitude of 0.1m. The mutual events of 0.03-0.07m depth suggest a satellite with size ratio of $\sim0.2$. Radar observations by Benner et al confirmed the binary nature of the asteroid [9]. There was some confusion about “first discovery rights” with the resolution being left by Dr. Pravec as “independent discoveries”

Again, radar observations can often confirm a binary asteroid. However, if a target is out of the coverage area of the larger radio telescope or something else prevents observations, it’s up to the optical observer to provide the necessary data. Given the small amplitude of the events, higher precision is required but is still within the reach of most amateurs. Collaboration with a professional is often essential since interpreting lightcurves with multiple periods is not easy. Using the data in Figure 3 as an example, one should never assume that “bad data” is really bad. Nor
should he jump to the conclusion he’s discovered a binary because of data such as in Figure 3. Careful work is required but the opportunity for studying a rare object is a great reward.

4. I See NOTHING!

It’s not often one is recognized for seeing nothing. The strange episode of AL0067 (2004 AS1) was an exception. The details of the night the Palmer Divide Observatory was involved in “saving the world” have been covered ad nauseum. However, the episode did demonstrate the importance of collaborations and the effectiveness of amateur participation. It was not just one amateur but several. Reiner Stoss of Germany first noticed the “impending impact” and Richard Miles of the U.K. gave initial indication the object was not on a collision course. The professional surveys may have taken over discovery but they are not quite yet complete masters of follow up.

5. YORP - The Effect of Sunlight on Asteroids

In a paper for Astronomy and Astrophysics [10], Vokrouhlicky et al proposed that proof of the YORP effect could be provided by monitoring the rotation of the asteroid 25143 Itokawa. They predicted that the maximum of the lightcurve would be delayed by approximately one hour, based on a period determined in 2001 and the elapsed time until 2004. Despite being near 18th magnitude, the author worked the asteroid in 2004 January on two nights to obtain the curve shown in Figure 4.

![Fig. 4. Lightcurve of 25143 Itokawa. The derived synodic period was 12.09±0.01h, which is in close agreement with the accepted sidereal period of 12.12h.](image)

Dr. Mikko Kaasalainen used the data to compare the time of maximum with the predictions. The results, while not conclusive because of the noise in the data, were suggestive that the prediction was correct [11]. However, Petr Pravec pointed out [12] that there was a possibility the asteroid could have non-principal axis tendencies, i.e., it was on the edge of being a “tumbler” and so additional observations were required. The asteroid is favorably positioned for Southern Hemisphere observers in 2004 June/July. At that time, it’s hoped that the data will confirm the theory one way or another.
This again points out the need for working closely with professional astronomers, the willingness of some professionals to build ties with the amateur community, and the need for pushing systems and technique to the limits. Not all targets of opportunity are going to burn holes in the CCD chip. This is true for the Karin family of asteroids, recently discovered by Nesvorny et al [13].

This family is believed to be the result of a breakup only 6MY ago. As such, it prevents a unique opportunity to study a newly formed family in light of dynamics, evolution, and the YORP effect on clustering of spin axis rates and orientation. The author created a special page on the Collaborative Asteroid Lightcurve Link (CALL) web site that provides the date of brightest in the current year as well as the daily magnitude and rise-set times for the known members of the family [14]. Most of the targets are out of reach of smaller amateur instruments but not of those in the 0.5m and larger range.

6. Second Chance Discoveries – Variable Stars

Stephens and Koff [15] outlined a program where they discovered variable stars using the images obtained for asteroid lightcurves. Since one has a large number of images of a given field, why not analyze them for something more than the original purpose? One never knows what might be discovered. Using the technique covered by those authors, three new variables were found in late 2003. Two appear to be W UMa stars, one possibly with a total eclipse, and the third is most likely an RR Lyrae [16]. The lightcurve for the last is shown in Figure 5.

![Plot for VS113624NC290754 JD - 2453056.0 (HJD Corrected)](Image)

**Fig. 5.** Raw data plot of variable star discovered among field stars during asteroid lightcurve work.

How many new variables might be waiting to be discovered? Since asteroid lightcurve images might go fainter than some gross surveys, e.g., TASS, it’s very likely there is much that can be done with images already being taken. Of course, data mining of the deeper catalogs, e.g., the Sloan Digital Sky Survey, might find many other targets. They still need follow up, a task for which amateurs are highly suited.
7. Pirates of the Caribbean – Orders from the Captains

I was fortunate enough to be invited to present a talk to a small gathering of professionals meeting held at the Arecibo Radio Observatory in Arecibo, Puerto Rico, in early 2004. The topics of the presentations centered on asteroid dynamics such as the Yorkovsky and YORP effects, structure, the newly discovered Karin family, and more. My talk pitched for professional-amateur collaborations and the quality of work of which amateurs are capable these days. I learned over the three days that there was considerable interest in tapping the pool of amateur observers, mostly because they are highly flexible with their time. That’s not always true, of course; many amateurs have “real jobs” that keep them busy. However, the community as a whole is certainly more capable of adjusting schedules on short notice than the professional community where it’s members must often schedule time months in advance only to be wiped out by a passing front. I went for marching orders and came back with directives from many generals to go in separate directions. In short, with far many more projects than a dozen amateurs could hope to achieve by themselves. Many more observers are required. Some of the projects mentioned have already been covered but here is a partial list.

◆ Build the pool of asteroid lightcurves for establishing relationships between rotation rate and size, taxonomic class, family grouping, etc.

◆ Observe asteroids over several apparitions to determine shape and spin axis characteristics. Some asteroids need only a few more observations to achieve the goal.

◆ In conjunction with the shape/spin studies are those in direct support for YORP effect research. Follow up on 25143 Itokawa was the first such project. There are others in the years to come.

◆ Multiple color photometry of asteroids to determine if they do change color during the rotation cycle. There is evidence using SDSS data that this might be the case [17]. However, there are studies that argue against it. This will take very careful work to assure values are placed with high precision and accuracy on standard bands. Brighter asteroids are likely the only targets of opportunity.

◆ Galaxy formation by stellar population studies. Some theories of galaxy formation depend on the distribution of RR Lyrae stars in the galactic halo. There are many variables discovered by the SDSS that need follow up to confirm their exact nature.
8. Summary

If you’re old enough, you remember a song about “countin’ flowers on the wall.” Another line in that song goes, “Now don’t tell me I’ve nothing to do.” Any amateur who thinks a clear sky can’t be used needs to expand his horizons. Professionals have long been in the practice of being experts in several fields. They must go where the funding is. One amateur recently lamented that since the MPC NEO page didn’t have any follow-ups he could do, a clear night had gone to waste. I hope the previous pages have shown that he had plenty to do in asteroid research. Even without working with other observers, there is always some reason to collect photons and analyze the numbers. The challenge comes in not trying to juggle too many plates in the air but to keep a few going for a long time.

9. Acknowledgments

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Most important, my wife Margaret J. Miller, for her patience and generosity over the years.
The MPC instituted the NEO Confirmation Page in 1996 as a means of confirmation/follow-up of newly “Discovered” NEO’s. The history of this web site and follow-up done at Grasslands and Sabino Canyon Observatories will be discussed.

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Contributions by Amateur Astronomers to Support Radar Imaging of Near-Earth Asteroids

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Abstract: Amateur astronomers can support radar observations of near-Earth asteroids (NEAs) principally by obtaining astrometry for objects with poorly-determined orbits and by obtaining lightcurves to estimate rotation periods and pole directions. The number of NEAs observed by radar has accelerated sharply in the last few years and the need for support has increased significantly.

Optical astrometry is necessary for radar targets when the 3-sigma plane-of-sky pointing uncertainty is larger than about 15 arcseconds because the Arecibo and Goldstone radar telescopes have narrow beam widths. Astrometry is particularly important for newly-discovered targets-of-opportunity, which often have large plane-of-sky, Doppler, and range uncertainties.

Photometric observations assist radar observations of asteroids in several important ways:

1. The rotation period and pole direction are very helpful for planning radar observations. We use the spin vector to estimate signal-to-noise ratios and to compute longitude and latitude coverage, which help justify requests for telescope time.
2. If the spin vector is available, it greatly facilitates inverting delay-Doppler radar data to construct an asteroid's three-dimensional shape. This is probably the most important way that photometry can support radar observations.
3. Lightcurves can be used with radar data (and independently) to reconstruct asteroid shapes and spin states.
4. Lightcurve observations can discover and characterize the orbital and rotation periods of binary NEAs and can complement sparse radar observations. Combined radar + lightcurve observations can yield binary NEA orbital parameters, masses, and bulk densities.
5. For asteroids with irregular shapes and well-determined spin states, photometric and radar observations during future close approaches may reveal changes in the spin state due to thermal torques caused by absorption and re-emission of sunlight (the "YORP" effect). If detected, the magnitude of the change can constrain the object's mass, density, and thermal conductivity.
6. For Doppler-only datasets, if the rotation period becomes available, the object's Doppler roadening (bandwidth) and rotation period yield its pole-on dimensions, which constrain the shape, radar and optical albedos, and composition.

To date, 147 near-Earth asteroids have been detected by radar at Arecibo and/or Goldstone. Rotation periods have been reported for only about one-half of those objects and pole directions are available for an even smaller percentage. If more rotation periods and pole directions were available, they would enable us to reconstruct more asteroid shapes and they would greatly increase the value of many unpublished radar observations. The need for photometric observations is great and we strongly encourage observations by amateur astronomers.

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Asteroid Occultation Observing Methods
Using Video and GPS Techniques

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Abstract: Observing asteroid occultations yields both location and size estimates with high precision. The poster displays a potpourri of methodologies involved in occultation observations and recordings by International Occultation timing Association (IOTA) members. Block diagrams of observing setups are shown for (a) a simple audio recorder setup, (b) video recorder with Short Wave radio (WWV timing), and finally, (c) Global Positioning Satellite (GPS)-based timing with time-inserted video. Typical results indicating asteroid shape determination and a double star occultation are shown. Along with the photos of field setups, the poster is a thought provoking collection of methodologies suitable for study by the beginning observer.

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