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Historical Trends in Ground-Based Optical Space Surveillance System Design

Michael Shoemaker, Lewis E. Shroyer

The Boeing Company

In the spirit of the 50th anniversary of the launch of the first man-made satellite, an historical overview of ground-based optical space surveillance systems is provided. Specific emphasis is given on gathering metrics to analyze design trends. The subject of space surveillance spans the history of spaceflight: from the early tracking cameras at missile ranges, the first observations of Sputnik, to the evolution towards highly capable commercial off-the-shelf (COTS) systems, and much in between. Whereas previous reviews in the literature have been limited in scope to specific time periods, operational programs, countries, etc., a broad overview of a wide range of sources is presented.

This review is focused on systems whose primary design purpose can be classified as Space Object Identification (SOI) or Orbit Determination (OD). SOI systems are those that capture images or data to determine information about the satellite itself, such as attitude, features, and material composition. OD systems are those that produce estimates of the satellite position, usually in the form of orbital elements or a time history of tracking angles.

Systems are also categorized based on the orbital regime in which their targets reside, which has been simplified in this study to either Low Earth Orbit (LEO) or Geosynchronous Earth Orbit (GEO). The systems are further classified depending on the industry segment (government/commercial or academic), and whether the program is foreign or domestic. In addition to gathering metrics on systems designed solely for man-made satellite observations, it is interesting to find examples of other systems being similarly used. Examples include large astronomical telescopes being used for GEO debris surveys and anomaly resolution for deep-space probes. Another interesting development is the increase in number and capability of COTS systems, some of which are specifically marketed to consumers as satellite trackers.

After describing the results of the literature review and presenting further information on various systems, we gather specific metrics on the optical design. Technical specifications, such as aperture and field of view (FOV), are plotted with time to ascertain trends in ground system design. Aperture is a useful metric because it gives insight into the light-gathering capability, as well as the overall size and complexity of the system. The size of the FOV can indicate user priorities or system performance, such as tracking capability of the mount for SOI systems and star detection ability in OD systems that use celestial references for position measurements.

The review is restricted to systems that use natural sunlight to illuminate targets, for the simple reason of having commonality between systems that span half a century, particularly recent COTS systems.

The DRDC Ottawa Space Surveillance Observatory

Brad Wallace, Robert (Lauchie) Scott, Aaron Spaans

Defence Research and Development Canada

DRDC Ottawa has recently developed a small optical sensor to serve as an R&D tool for Surveillance of Space (SofS); the sensor is referred to as the DRDC Ottawa Space Surveillance Observatory (SSO). This paper will describe the SSO, its philosophy and architecture, the automated data reduction software system, and the initial testing performance. In addition, this paper will describe how the SSO is supporting the Canadian Surveillance of Space Project's Concept Demonstrator (CD), the NEOSSat space-based SofS microsatellite, and DRDC's future R&D directions.

The SSO is regularly observing in star stare mode (SSM), and is automatically producing metric and photometric data for deep-space RSOs; track-rate mode (TRM) has also been implemented. Observations of GPS satellites demonstrate that the system can regularly produce metric data with an accuracy of better than 3.5 arcseconds in SSM, and ~1 arcsecond in TRM. The sensor, located at a decidedly non-optimal site, is sensitive to objects having intrinsic magnitudes down to about 13 in SSM, and below 14 in TRM.

Carbon Fiber Reinforced Polymer Telescope Program at the Naval Research Laboratory

Sergio Restaino¹, Ty Martinez¹, Jonathan Andrews¹, Christopher Wilcox¹, Scott Teare²,
Robert Romeo³, Robert Martin³, David Wick⁴

¹Naval Research Laboratory, ²New Mexico Tech., ³CMA, ⁴Sandia National Laboratories

The Naval Research Laboratory (NRL) has been investigating the possibility of developing meter class telescopes using Carbon Fiber Reinforced Polymer (CFRP) material. In conjunction with Composite Mirror Applications (CMA), for the past three years such a program has proceeded from conceptual phase to prototype development. In this paper we will review that various stages of this program. We will also present the status of our 0.4 meter and 1.4 meter telescopes. Experimental results from these developments and testing will be shown.

A 1.2m Deployable, Transportable Space Surveillance Telescope Designed to Meet AF Space Situational Awareness Needs

John McGraw¹, Mark R. Ackermann²

¹University of New Mexico, ²Sandia National Laboratories

Recent years have seen significant interest in optical-infrared (OIR) space surveillance capabilities to complement and supplement radar-based sensors. To address this legitimate need for OIR sensors, the Air Force Research Laboratory has been working on several projects intended to meet SSA requirements in practical, fieldable and affordable packages. In particular, while the PanStarrs system is primarily an astronomy project, their well-designed telescope(s) will have substantial SSA capability, but the system, based on four 1.8m apertures on the same mount, will be a fixed location asset. For world-wide deployment, we are studying a smaller "PanStarrs derived" system which would be replicable and inexpensive. A fixed set of telescope arrays would provide substantial SSA search and monitor capability. These telescopes are also designed to be deployed in pairs in a standard cargo container package for theater SSA.

With a 1.2m aperture and a 4.5deg FOV, each telescope would have the same etendue as its big brother PanStarrs telescope, but with image quality optimized for space surveillance rather than astronomy. The telescope is even scaled to use production PanStarrs focal plane arrays. A single 1.2m system has almost the same search rate for dim targets as any other system in development. Two such telescopes working together will exceed the performance of any SSA asset either in production or on the drawing boards. Because they are small they can be designed to be replicable and inexpensive and thus could be abandoned in place should the political climate at their deployment sites change for the worse.

Measurement Astrophysics and the AF Space Surveillance Mission

John McGraw¹, Mark R. Ackermann¹, Tom Williams¹, Peter C. Zimmer¹, Walter Gerstle¹, M. Suzanne Taylor¹, Jon Turner¹, Julie Smith¹, Justin Linford¹, G. Fritz Benedict², plus nine other authors³

¹University of New Mexico, ²The University of Texas at Austin, ³USAF, Georgia Tech, AFRL, USNO, NOAO, SSI, SNL

As part of the AFRL-funded Near Earth Space Surveillance Initiative (NESSI) the University of New Mexico's Measurement Astrophysics (MAP) Research Group has defined, designed and implemented several atmospheric measurement techniques to complement and supplement the observations of the CCD/Transit Instrument with Innovative Instrumentation (CTI-II). The principal idea driving the creation of atmospheric sensing and telescope metrology ancillary instrumentation is that these instruments produce data relevant to the reduction and analysis of astronomical data in the quest for quantitatively more precise and accurate photometric and astrometric observations of the night sky.

Instruments and techniques relevant to optical-infrared (OIR) space surveillance include:

" The Astronomical Lidar for Extinction (ALE) to measure precisely the time-dependent total atmospheric extinction

" A spectrophotometric telescope for measuring wavelength-dependent atmospheric extinction

" A differential microbarograph array to measure anomalous atmospheric refraction

" A multi-baseline microthermal array for measuring atmospheric turbulence on multiple spatial scales.

When implemented in support of the stationary, meridian-pointing CTI-II, designed to be the most precise ground-based photometric and astrometric telescope, these instruments operated together provide near real-time measurements of wavelength-dependent total atmospheric extinction caused by scattering and absorption by molecules and aerosols. They also characterize the time-dependent vertical atmospheric pressure and density above the telescope and measure the large-scale (degrees) tilt induced by atmospheric gravity waves, the apparent source of anomalous refraction.

Imaging, photometry and spectrophotometry of satellites can be dramatically enhanced by use of these low-cost deployable instruments. Applications relative to CTI-II will be described. The network of faint photometric and astrometric standard stars always observable in the northern hemisphere resulting from multi-year CTI-II observations and the utility of this network to sky surveys will be discussed and demonstrated.

Large-Aperture, Three-Mirror Telescopes for Near-Earth

Mark Ackermann¹, John T. McGraw²

¹Sandia National Laboratories, ²University of New Mexico

In this era when Space Situational Awareness (SSA) is a national priority and optical-infrared telescopic sensor development is underway, cost-benefit analyses of competing approaches are necessary and appropriate. The DOD is presently investing in a new three-mirror telescope for SSA. At the same time, the Air Force, various universities and private research organizations are either studying or building wide-field telescopes with similar capabilities, but in most cases, at a significantly lower cost. Much of the expense for the DOD system appears driven by certain design choices which were advertised as necessary to fulfill the mission. Design details which would allow an independent analysis have not been published and no public comparison with other approaches is known to exist. Most telescope designs however, can be closely approximated from their optical configuration and imaging performance specifications.

An optical designer will tell you that field curvature is one of the five monochromatic aberrations which they try to eliminate. The fact that one DOD development effort considers field curvature a design feature immediately draws attention to the project. This coupled with the paucity of published information and the very high development cost makes this program irresistible for comparison with competing approaches.

This paper examines the likely design and performance of a proxy telescope intended to find NEOs, compares and contrasts that telescope with similar, but lower cost on-going projects, and examines the predictable impacts of reproducing such a telescope and placing multiple copies around the globe. The study primarily concentrates on performance measured in terms of search rate in square degrees per hour vs. object visual magnitude. Other considerations such as cost, transportability, availability of replacement components and ease of installation are also considered.

Tunable Wide Band Infrared Detector Array for Space Situational Awareness

Jonathan Andrews¹, Sergio Restaino¹, Scott Teare², Sanjay Krishna³, Christopher Wilcox¹, Ty Martinez¹

¹Naval Research Laboratory, ²New Mexico Tech, ³University of New Mexico

The Center for High Technology Materials at the University of New Mexico has been investigating tunable quantum well/dot detectors for infrared detection. These devices have been manufactured in 300 x 256 pixel arrays and can be adjusted to obtain a maximum responsivity to wavelengths ranging from 1 mm to 10 mm by applying an external bias voltage. This detector has the capability of expanding the field of hyperspectral imaging by allowing real-time tunability over a very wide spectrum without switchable filters. Additionally, devices can be manufactured in a linear array and coupled with a grating to produce a spectrometer with a maximum sensitivity that is tunable over a wide range of frequencies. This paper reports on the device specifications, laboratory results, and discusses suitable applications in the field of space surveillance

USAF Academy Fast-tracking Telescope

Geoff Andersen, Derek Buzasi, Maj Brian Bailey

USAF Academy

The United States Air Force Academy is building a 2m ground-based optical telescope for experiments in space situational awareness. The new telescope will be a fast-slewing instrument suitable for both sidereal and low-Earth object tracking down to altitudes of 200km. The telescope will have a 25 arcminute field of view with instruments located at two possible Nasmyth locations. Construction of the new truss, mount and dome is due to begin in early 2008, with first light scheduled at the beginning of 2010.

This telescope facility will be unique in its access to optical equipment and operational flexibility. In conjunction with the Laser and Optics Research Center at the Academy, we can leverage an extensive range of laser wavelengths, powers and temporal profiles. This will make it possible to conduct a wide range of experiments involving optical ranging, communications and characterization of satellites. Plans are also being considered to use the telescope to improve the capabilities of a pre-existing thermometric lidar as well as developing innovative lidars for atmospheric analysis and relativistic studies. Future telescope research will also incorporate adaptive optics technologies being developed in the Department of Physics.

The telescope will greatly enhance the astronomical studies of cadets and faculty. Beyond our mission as a teaching facility for future Air Force officers, we also anticipate a flexibility in access of this telescope to other agencies. This includes availability as a test-bed for instruments as well as participation in time-critical projects where last-minute scheduling of other facilities may not be possible. In our presentation we will discuss the opportunities for other organizations to access time on this instrument, as well as suggesting joint projects with similar telescopes around the world.

The Pan-STARRS Survey Telescope Project

Nick Kaiser

University of Hawaii Institute for Astronomy

The Institute for Astronomy at the University of Hawaii is developing a large optical/near-IR survey telescope system; the Panoramic Survey Telescope and Rapid Response System. Pan-STARRS will employ 1.8m optical imagers very large (7 square degree) field of view and revolutionary 1.4 billion pixel CCD cameras with low noise and rapid read-out to provide broad band imaging from 400-1000nm wavelength. The project is proceeding in two phases: PS1 is a single aperture system that has been deployed on Haleakala on Maui and the full 4-aperture system PS4 will be sited on Mauna Kea and is scheduled to become operational in late 2010. The data from Pan-STARRS will be reduced in near real time to produce both a cumulative image of the static sky and difference images, from which transient, moving and variable objects can be detected. Pan-STARRS will be able to scan the entire visible sky to approximately 24th magnitude in less than a week, and this unique combination of sensitivity and cadence will open up many new possibilities in time domain astronomy. A major goal for the project is to survey potentially dangerous asteroids, where Pan-STARRS will be able to detect most objects down to 300m size, much smaller than the km size objects accessible to existing search programs. In addition, the Pan-STARRS data will provide a dramatic leap in data quality and extent over existing wide-field image survey data that will be used to advance our understanding of the formation of the Solar System, the Galaxy, and the Cosmos at large. In this talk I will describe the science drivers for the project; review the technical design and performance metrics for various scientific goals; and give an update on the current status and future time-line of the project.

Autonomous Low Earth Orbit Satellite and Orbital Debris Tracking Using Mid Aperture COTS Optical Trackers

Brad Ehrhorn, Dan Azari

RC Optical Systems

Low Earth Orbit (LEO) and Orbital Debris tracking have become considerably important with regard to Space Situational Awareness (SSA). This paper discusses the capabilities of autonomous LEO and Orbital Debris Tracking Systems using commercially available (mid aperture 20-24 inch) telescopes, tracking gimbals, and CCD imagers.

RC Optical Systems has been developing autonomous satellite trackers that allow for unattended acquisition, imaging, and orbital determination of LEOs using low cost COTS equipment. The test setup from which we are gathering data consists of an RC Optical Systems Professional Series Elevation over Azimuth Gimbal with field de-rotation, RC Optical Systems 20 inch Ritchey-Chretien Telescope coupled to an e2v CCD42-40 CCD array, and 77mm f/4 tracking lens coupled to a KAF-0402ME CCD array.

Central to success of LEO acquisition and open loop tracking is accurate modeling of Gimbal and telescope misalignments and flexures. Using pro-TPoint and a simple automated mapping routine we have modeled our primary telescope to achieve pointing and tracking accuracies within a population standard deviation of 1.3 arc-sec (which is 1.1 arc-sec RMS). Once modeled, a mobile system can easily and quickly be calibrated to the sky using a simple 6-10 star map to solve for axis tilt and collimation coefficients.

Acquisition of LEO satellites is accomplished through the use of a wide field imager. Using a 77mm f/4 lens and 765 x 510 x 9μm CCD array yields a 1.28 x 0.85 degree field of view in our test setup. Accurate boresite within the acquisition array is maintained throughout the full range of motion through differential Tpoint modeling of the main and acquisition imagers. Satellite identification is accomplished by detecting a stationary centroid as a point source and differentiating from the background of streaked stars in a single frame. We found 100% detection rate of LEO with radar cross sections (RCS) of > 0.5 meter*meter within the acquisition array, and approximately 90% within 0.25 degrees of center. Tests of open loop tracking

revealed a vast majority of satellites remain within the main detector area of 0.19 x 0.19 degrees after initial centering

Once acquired, the satellite is centered within the main imager via automated adjustment of the epoch and inclination using non-linear least square fit. Thereafter, real time satellite position is sequentially determined and recorded using the main imaging array. Real time determination of the SGP4 Keplerian elements are solved using non-linear least squares regression. The tracking propagator is periodically updated to reflect the solved Keplerian elements in order to maintain the satellite position near image center.

These processes are accomplished without the need for user intervention. Unattended fully autonomous LEO satellite tracking and orbital determination simply requires scheduling of appropriate targets and scripted command of the tracking system.

Design of an Imaging Infrared Spectrograph Using Compact Dyson Lenses

David Gutierrez¹, Richard J. Rudy¹, Ray W. Russell¹, David K. Lynch¹, Dee Pack¹, David W. Warren¹, Mark A. Skinner²

¹The Aerospace Corporation, ²The Boeing Company

We describe a concept for a new imaging spectrograph operating in the mid-wave and long-wave infrared. The instrument is proposed as an upgrade to The Aerospace Corporation's Broadband Array Spectrograph System (BASS), a 3-13 micron sensor currently in use on the Advanced Electro-Optical System (AEOS) 3.67 meter telescope. The primary tasks of the instrument would be to generate precise spectrophotometry of stars, and to characterize resident space objects. The core of the design features two ultra compact spectrographic modules, each utilizing a concentric Dyson lens and concave diffraction grating. We will describe the considerable advantages that result for this design as well as the implementation of the instrument on the AEOS telescope and similar facilities.

Fast Holographic Wavefront Sensor

Geoff Andersen¹, Fassil Ghebremichael², Ken Gurley²

¹USAF Academy, ²Lockheed Martin

There are several different types of wavefront sensors that can be used to measure the phase of an input beam. While they have widely varying modes of operation, they all require some computational overhead in order to deconstruct the phase from an optical measurement which greatly reduces the sensing speed. Furthermore, zonal detection methods, such as the Shack-Hartmann wavefront sensor (SHWFS) are not well suited to temporal changes in pupil obscuration such as can occur with scintillation. Here we present a modal detector that incorporates a multiplexed hologram to give a full description of wavefront error without the need for any calculations.

The holographic wavefront sensor (HWFS) uses a hologram that is "pre-programmed" with all desired Zernike aberration components. An input beam of arbitrary phase will diffract into pairs of focused beams. Each pair represents a different aberration, and the amplitude is obtained by measuring the relative brightness of the pair of foci. This can be easily achieved by using conventional position sensing devices. In this manner, the amplitudes of each aberration components are directly sensed without the need for any calculations. As such, a complete characterization of the wavefront can be made at speeds of up to 100 kHz in a compact device and without the need for a computer or sophisticated electronics.

In this talk we will detail the operation of the holographic wavefront sensor and present results of a prototype sensor as well as a modified design suitable for a closed-loop adaptive optics system. This new wavefront sensor will not only permit faster correction, but permit adaptive optics systems to work in extremely turbulent environments such as those encountered in fast-tracking systems and the Airborne Laser project.

Space Surveillance One Photon at a Time

Jeffrey Bloch¹, Richard Rast²
¹Los Alamos National Laboratory, ²AFRL/DE

Large format photon counting imaging sensors with high time resolution provide a unique capability for astrometry and object tracking from a moving or scanning observation platform. These sensors produce an output list of photon event data in X, Y, and Time which can be transformed in a distortion-less manner to any fixed or co-moving coordinate system. In this presentation we will discuss how this capability enables new approaches to space object detection and metric observation over traditional framing sensors such as CCDs using a specific, serendipitous set of observations as an example.

NASA's Galaxy Explorer (GALEX) ultraviolet astrophysics mission provides this unique opportunity to explore the utility of high time precision imaging photon counting sensors for SSA. The 280 kg GALEX satellite was launched in 2003 by a Pegasus XL rocket into a 690 km circular orbit. GALEX contains a 50 cm NUV/FUV telescope with a field of view of 1.2 degrees and a 5 arcsecond spatial point spread function. Each UV photon detected by GALEX is time stamped to a precision of 5 milliseconds and telemetered to the ground. In this talk we will discuss the results of a study to utilize GALEX X-Y-Time photon list data to explore methods of data analysis to detect and characterize space objects that serendipitously crossed its field of view. We will show the results of how the high precision angle-angle-time GALEX photon data combined with the GALEX satellite's ephemeris can be used to detect a space object and derive a state vector for the object from a single field-of-view crossing in ways very different from traditional framing sensors such as CCDs. Such analysis methods can be applied in general to any photon counting imaging detector system working at any wavelength on any ground, airborne, or space platform.

Initial Lab and Sky Test Results for the Teledyne Imaging System's H4RG-10 CMOS-Hybrid 4k Visible Array for Use in Ground- and Space-based Astronomical and SSA Applications

Bryan Dorland¹, Greg Hennessy¹, Norbert Zacharias¹, Ralph Gaume¹, Peter Shu², Laddawan Miko²,
Chris Rollins³, Augustyn Waczynski⁴

¹US Naval Observatory, ²NASA/GSFC, ³RSI, Inc., ⁴GST, Inc.

We report on the first set of laboratory and telescope tests of the Teledyne Imaging System's (TIS) H4RG-10 CMOS-Hybrid visible focal plane array (FPA). This family of detectors has been chosen as the baseline for USNO's proposed J-MAPS space astrometry mission to close a number of capability gaps. While this FPA has been designed for precision astrometry, it has potentially significant Space Situational Awareness (SSA) applications. Because of the hybrid design, which consists of separate readout and detector layers connected by Indium bump-bonds, this FPA has the readout flexibility of advanced CMOS readout integrated circuits (ROICs), including non-destructive readout, random access windowing and selective reset, and near-CCD performance in terms of fill factor, quantum efficiency, read noise and dark current. Our laboratory testing, performed at Goddard Space Flight Center's Detector Characterization Lab, includes measures of absolute spectral quantum efficiency, flat-field response uniformity, read noise, dark current as a function of operating temperature, inter-pixel crosstalk, and persistence. Sky testing, performed at Naval Observatory Flagstaff Station, consists of astrometric and photometric performance characterization. We discuss implications for the use of this detector in future ground- and space-based astrometric, astronomical and SSA applications.

Advanced Integrated Multi-Sensor System - An Integrated Approach for Space SurveillanceVladimir Markov¹, Shiang Liu², Anatoliy Khizhnyak¹, Roberta Ewart³, Douglas Craig⁴¹*MetroLaser, Inc.*, ²*The Aerospace Corporation*, ³*LAAFB*, ⁴*Space Vehicle Directorate, Kirtland AFB*

Robust and reliable space surveillance requires enhanced capabilities in tracking, characterization and discrimination of the space objects. The operational characteristics of existing system are insufficient in desired tracking accuracy, imaging resolution, detailed object characterization, and do not provide an adequate responsiveness. With the majority of the space surveillance systems (SSS) based on either passive single-sensor based design or architecture based on an assemblage of the distinct class of sensors, further improvement in their performance is limited by a selection of the sensors console. In this report, we present the architecture, operational concept and design of an advanced, integrated multi-sensor system (AIMS) that should be able to alleviate these deficiencies. The proposed AIMS configuration incorporate on a single platform both active laser tracking and passive sensing modules operating synchronously through a single optical train. When fully developed and integrated, the AIMS should provide real-time reliable tracking capabilities, with detection of 3D (and potentially 9D) state vector of the space object, as well as its extensive characterization, including imaging, calorimetric, multi-spectral and vibrational parameters. In addition, laser illumination with sufficient energy on the target can result in reactive signatures for active object discrimination.

In this presentation we report on the recent results with AIMS integration, its laboratory performance and initial data of the field-test experiments with ground-based target, and a plan for field-test demonstration and operability of a prototype AIMS with airborne target. Potential applications of AIMS to support new space control concepts and other missions are also discussed.

Digital Signal Processing Techniques for the GIFTS SM EDUJialin Tian¹, Robert A. Reisse², Michael J. Gazarik²¹*SSAI*, ²*NASA Langley Research Center*

The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) Sensor Module (SM) Engineering Demonstration Unit (EDU) is a high resolution spectral imager designed to measure infrared (IR) radiance using a Fourier transform spectrometer (FTS). The GIFTS instrument employs three Focal Plane Arrays (FPAs), which gather measurements across the long-wave IR (LWIR), short/mid-wave IR (SMWIR), and visible spectral bands. The raw interferogram measurements are radiometrically and spectrally calibrated to produce radiance spectra, which are further processed to obtain atmospheric profiles via retrieval algorithms. This paper describes several digital signal processing (DSP) techniques involved in the development of the calibration model. In the first stage, the measured raw interferograms must undergo a series of processing steps that include filtering, decimation, and detector nonlinearity correction. The digital filtering is achieved by employing a linear-phase even-length FIR complex filter that is designed based on the optimum equiripple criteria. Next, the detector nonlinearity effect is compensated for using a set of pre-determined detector response characteristics. In the next stage, a phase correction algorithm is applied to the decimated interferograms. This is accomplished by first estimating the phase function from the spectral phase response of the windowed interferogram, and then correcting the entire interferogram based on the estimated phase function. In the calibration stage, we first compute the spectral responsivity based on the previous results and the ideal Planck blackbody spectra at the given temperatures, from which, the calibrated ambient blackbody (ABB), hot blackbody (HBB), and scene spectra can be obtained. In the post-calibration stage, we estimate the Noise Equivalent Spectral Radiance (NESR) from the calibrated ABB and HBB spectra. The NESR is generally considered as a measure of the instrument noise performance, and can be estimated as the standard deviation of calibrated radiance spectra from multiple scans. To obtain an estimate of the FPA performance, we developed an efficient method of generating pixel performance assessments. In addition, a random pixel selection scheme is developed based on the pixel performance evaluation. This would allow us to perform the calibration procedures on a random pixel population that is a good statistical representation of the entire FPA. The design and implementation of each individual component will be discussed in details.

MSSS/AMOS Overview

Air Force Research Laboratory, Detachment 15

The Maui Space Surveillance System (MSSS), located at the summit of Haleakala, is a national resource providing support to various government agencies and the scientific community. The tutorial summarizes MSSS systems, capabilities, and support procedures and includes a description of the telescopes and sensors. It will also include a brief overview of the Maui High Performance Computing Center (MHPCC).

A Tutorial on Imaging through Turbulence

Michael Roggemann

Michigan Technological University

This paper is a brief tutorial on the "forward problem" of image formation in the presence of atmospheric turbulence, and various strategies for mitigating the effects of turbulence on imaging systems. The talk begins with a brief review of the history of the field, followed by a discussion of the origins of turbulence. The optical effects of turbulence are then reviewed. Finally, mitigation strategies including speckle imaging, blind deconvolution, and adaptive optics are presented. This presentation is intended for an audience which already has some knowledge and experience in the imaging and image processing areas.

Application of Improved LEO Scattering Physics to Modeling Radiant Emission from Spacecraft Emanations

William Dimpfl¹, Lawrence S. Bernstein², Matthew Braunstien²

¹The Aerospace Corporation, ²Spectral Sciences, Inc.

Direct Simulation Monte Carlo (DSMC) refinements for applications relevant to modeling chemiluminescent radiant emission resulting from gases emanating from spacecraft in LEO were reported at the AMOS Technical Conference in 2005. These refinements, which include improved velocity dependence of total scattering cross sections at hyperthermal energies and forward biased versus isotropic elastic scattering distributions, have been applied to improved modeling of ultraviolet chemiluminescence from Space Shuttle Orbiter engine burns. The ultraviolet emission modeled is from the 190-250 nm Cameron band system of carbon monoxide, CO(A->X), which has been found to result from two and three-step sequences of reactions of atmospheric atomic oxygen with a minor amount of methane (~1% mole fraction) in the engines' exhaust. Well-resolved images of steady-state chemiluminescent radiant emission fields were acquired from the Midcourse Space Experiment (MSX) Shuttle Plume Observations experiment. The Space Test Program (STP) facilitated collaboration with NASA for the MSX satellite to acquire band pass images and spectrographic images from dedicated burns of Space Shuttle Orbital Maneuvering System (OMS) and Primary Reaction Control System (PRCS) engines. Earlier analysis of those data using conventional DSMC scattering treatment indicated the needs for the refinements. The new analysis with the refinements is compared with the originally analysis to demonstrate the validity of the refinements.

SATELLITE MANEUVER DETECTION USING TWO-LINE ELEMENTS DATA

Thomas Kelecy¹, Doyle Hall¹, Kris Hamada¹, Maj Dennis Stocker²

¹Boeing-LTS, ²AFRL

This paper summarizes the methods and limitations of deriving satellite maneuver information from historical two-line element (TLE) data. Each TLE contains the orbital information of an earth-orbiting object at a particular epoch time, and is used to calculate object state vectors. A TLE "time-history" comprises a list of TLEs measured over an extended period of time, and therefore contains information on orbital perturbation effects, both environmental and non-environmental. The non-environmental perturbations of interest for active satellites are thrusting maneuvers. This paper describes the design, implementation and performance of a TLE-based maneuver detection algorithm. Algorithm performance is measured relative to several spacecraft with known maneuver histories. TLE time-histories may also be used to estimate satellite masses, because the recorded environmental perturbations depend on a satellite's area-to-mass ratio (A/m). Estimates of a "best-fit" A/m value for a satellite can be derived by performing a least-squares comparison of the orbital elements taken from the TLE history with analytically-derived orbital elements. However, in order for the least-squares analysis to yield an accurate A/m estimate, all forces that significantly perturb the orbit need to be appropriately modeled, including maneuver thrusting for active satellites. The focus of this work is on the development and assessment of techniques that allow maneuvers to be detected from the historical TLE data, and thus support trending of the A/m ratio. The results show surprisingly reliable detection of maneuvers down to delta-velocity magnitudes at the centimeter-per-second level or less, provided the algorithm parameters are "tuned" appropriately.

Assessing Space and Satellite Environment and System Security

Gary Haith, Steven C. Upton

Referentia Systems Incorporated

Satellites and other spacecraft are key assets and critical vulnerabilities in our communications, surveillance and defense infrastructure. Despite their strategic importance, there are significant gaps in our real-time knowledge of satellite security. One reason is the lack of infrastructure and applications to filter and process the overwhelming amounts of relevant data. Some efforts are addressing this challenge by fusing the data gathered from ground, air and space based sensors to detect and categorize anomalous situations. The aim is to provide decision support for Space Situational Awareness (SSA) and Defensive Counterspace (DCS). Most results have not yielded estimates of impact and cost of a given situation or suggested courses of action (level 3 data fusion). This paper describes an effort to provide high level data fusion for SSA/DCS through two complementary thrusts: threat scenario simulation with Automatic Red Teaming (ART), and historical data warehousing and mining. ART uses stochastic search algorithms (e.g., evolutionary algorithms) to evolve strategies in agent based simulations. ART provides techniques to formally specify anomalous condition scenarios envisioned by subject matter experts and to explore alternative scenarios. The simulation data can then support impact estimates and course of action evaluations. The data mining thrust has focused on finding correlations between subsystem anomalies on MightySat II and publicly available space weather data. This paper describes the ART approach, some potential correlations discovered between satellite subsystem anomalies and space weather events, and future work planned on the project.

Satellite Survivability Module

Patrick Buehler, Joshua Smith

Ball Aerospace & Technologies Corporation

The Satellite Survivability Module (SSM) is an end-to-end, physics-based, performance prediction model for directed energy engagement of orbiting spacecraft. SSM was created as an add-on module for the Satellite Tool Kit (STK). Two engagement types are currently supported: laser engagement of the focal plane array of an imaging spacecraft; and Radio Frequency (RF) engagement of spacecraft components. This paper will focus on the laser engagement scenario, the process by which it is defined, and how we use this tool to support a future laser threat detection system experiment. For a laser engagement, the user creates a spacecraft, defines its optical system, adds any protection techniques used by the optical system, introduces a laser threat, and then defines the atmosphere through which the laser will pass. SSM models the laser engagement and its impact on the spacecraft's optical system using four impact levels: degradation, saturation, damage, and destruction. Protection techniques, if employed, will mitigate engagement effects. SSM currently supports two laser protection techniques. SSM allows the user to create and implement a variety of "what if" scenarios. Satellites can be placed in a variety of orbits. Threats can be placed anywhere on the Earth or, for version 2.0, on other satellites. Satellites and threats can be mixed and matched to examine possibilities. Protection techniques for a particular spacecraft can be turned on or off individually; and can be arranged in any order to simulate more complicated protection schemes. Results can be displayed as 2-D or 3-D visualizations, or as textual reports. A new report feature available in version 2.0 will allow laser effects data to be displayed dynamically during scenario execution. In order to test SSM capabilities, the Ball team used SSM to model several engagement scenarios for our future laser threat detection system experiment. Actual test sites, along with actual laser, optics, and detector characteristics were entered into SSM to determine what effects we can expect to see, and to what extent. We concluded that SSM results are accurate when compared to actual field test results. The work is currently funded by the Air Force Research Laboratory, Space Vehicles directorate at Kirtland AFB, New Mexico, under contract number FA9453-06-C-0371.

Time Domain Performance Simulations of Active Tracking Developments at SOR and MSSSEdwin Pease¹, John Klosterman¹, Robin Ritter¹, Victor Gamiz²¹*Tau Technologies*, ²*AFRL/DESA*

The authors have exercised AFRL's Time Domain Analysis System for Advanced Tracking to study the performance of Active Tracking experiments developing at SOR and MSSS. We present the range and jitter performance of simulated systems and observe expected performance. We compare our performance predictions to measured data. The comprehensive simulations provide the community with a very powerful tool for making design trades on laser power, beam divergence and track control bandwidth.

Nonlinear Optical Phase Conjugation Amplifier for Remote Object tracking, Imaging and DiscriminationVladimir Markov¹, Frank Wu¹, Anatoliy Khizhnyak¹, Shiang Liu², Roberta Ewart³¹*MetroLaser, Inc.*, ²*The Aerospace Corporation*, ³*LAAFB*

Laser pointing, tracking, imaging/discrimination and engaging (PTIE) of a remote target, such as high-altitude aircraft, satellite, or reentry vehicle, requires for a sufficient level of energy density on surface of the target. Satisfactory laser systems performance has been demonstrated at relatively short distances and low optical aberration and distortion conditions. However, longer range and deep atmospheric turbulence introduce serious challenges for an efficient PTIE function. Solution to the two key technical challenges: (a) very low intensity in a returned signal, and (b) compensation of optical aberrations along the beam path, become critical issues in designing of an efficient PTIE laser system (PTIELS).

Reliable detection of a low intensity return signal requires for a narrow bandwidth high-gain, practically thresholdless amplifier. An extensive analysis of this problem allows to conclude that optimal solution to low intensity signal detection can be achieved by using phase-conjugating amplifiers (PCA). Moreover, the PCA as the mirror in a laser system leads to compensation of optical wavefront aberrations in real time. Optimal performance of such a system can be attained with the PCM operating in the Brillouin-Enhanced Four-Wave Mixing (BEFWM) scheme.

We report on the results of the analysis and experimental studies of the PTIELS brassboard design with the BEFWM. The system allows coherent thresholdless detection and amplification of an ultra-low intensity target-scattered signal with the gain (up to 100 db) with complete phase conjugation of its wavefront. As result, the PTIELS output is the amplified signal beam that holds the information that is essential for target characterization, i.e. its speed and scattering characteristics of its surface. Moreover, because of the coherent nature of signal detection, this technique enables for measuring the atmosphere-introduced aberrations of the transmitted wavefront and their real-time compensation with adaptive optics methods.

The presented results of an extensive theoretical analysis and experimental studies illustrates that the BEFWM-based approach allows for an end-to-end solution to the problem of a remote target pointing, tracking, imaging and engaging and outlines roadmap for its practical implementation.

Measurements of the Short Term Variability of r_0

L. William Bradford, Lewis C. Roberts, Jr.

Boeing LTS Inc

We have made measurements with the AEOS Visible Imager camera and with the AEOS adaptive optics wavefront sensor that allow us to estimate the value of Fried's parameter r_0 which can be directly related to the seeing. Wavefront sensor slope data is analyzed using Fried's differential angle of arrival equations, and the Visible Imager data is analyzed using the relationship between the Full Width at Half Maximum of a star's "seeing disk" and r_0 . The wavefront sensor data sets will typically have 2000 measurements in 2 seconds. The Visible Imager measurements are about 100 images at intervals of 0.5 to 2 seconds.

We examine the variability and the probability distributions of r_0 at multiple time scales. We are particularly interested in how much one measurement may differ from the preceding or the next measurement and in how much that variability varies with the seeing itself. This is of interest to modelers of adaptive optical systems, who in the past relied on models that use fixed values of r_0 over the entire time history of a simulation. The data may also prove useful for setting error bounds on image processing algorithms that assume a fixed seeing over a data set. For a very large telescope, the time variability such as we observe is usually then translated into a spatial variability over the aperture, using Taylor's frozen flow hypothesis. The implication of our data is that that spatial variability must be different than would be found using only a single value of r_0 over the full aperture.

Measurement of Atmospheric Turbulence over a Horizontal Path Using the Black Fringe Wavefront Sensor

Richard Tansey, H.M. Chan, M. Virgen, A. Phenis

Advanced Technology Center, Lockheed Martin

The black fringe wavefront sensor (bfwfs) uses the peak of a visibility function, or the location of the maximum contrast fringe center as obtained in a self reference interferometer, to identify the zero optical path difference (opd) and resultant phase of a wavefront. The bfwfs is described in two previous papers (1, 2) and only a brief description will be described in this report. In the current work the first use of the the bfwfs for the measurement of atmospheric turbulence will be described. The drive voltage of a scanner mirror is synchronized to a max peak detector circuit to provide a real time voltage output which is equivalent to the phase (opd) at an array of subapertures. The surface height of a test object, or equivalently the opd due to atmospheric turbulence, is thus obtained.

An argon laser acts as a point source beacon for the sensor. Using a self-reference interferometer, the heterodyne beat from the dominant 514.5nm and 488nm lines produces a visibility function with minimum to minimum separations of 9470nm. Results of measurements of phase over an array of detectors will be shown, at several horizontal ranges. In addition, a complete closed loop adaptive optics system will be described using the black fringe wavefront sensor and a Mems mirror to correct atmospheric turbulence.

1. R.J. Tansey, H. Chan, A.A. Honkan, "The Black Fringe Wavefront Sensor: Real Time Adaptive Optics with Minimum Computation", AMOS 2007, Adaptive Optics Session 2. R.J. Tansey, A.A. Honkan, H.M.Chan, "The Black Fringe Wavefront Sensor: White Light Real Time Analog Phase Measurement", SPIE, Photonics West 2007

LIDAR System for Monitoring Atmospheric Turbulence Profiles

Gary Gimmestad, David W. Roberts, John M. Stewart, Jack W. Wood

Georgia Tech Research Institute

The Georgia Tech Research Institute (GTRI) has developed a new type of LIDAR system for monitoring the vertical profile of atmospheric refractive turbulence. The ground-based system makes real-time measurements by projecting a laser beam to form a laser beacon at several successive altitudes from 250 m to 15 km. The beacon is observed with a four-aperture telescope and the differential motions of pairs of the beacon images from each altitude are statistically characterized as variances. The measurement technique is similar to the astronomical instrument known as the Differential Image Motion Monitor (DIMM), which uses natural stars as sources. Whereas the DIMM only provides one number, σ_0 , to characterize the entire atmosphere, the LIDAR uses beacons at a range of altitudes, along with an inversion algorithm that we have developed, to retrieve the turbulence profile. GTRI has developed and tested a brassboard version of the turbulence LIDAR. The brassboard system transmits 300 mJ pulses of 355 nm laser light at 50 pulses per second, (15 W) and receives backscattered light with a 40-cm telescope. Altitude ranges are selected by using an electro-optical shutter based on two Pockels cells, and image data is recorded with a specialized CCD camera manufactured by SciMeasure (this type of camera is normally used in wavefront sensors for adaptive optics systems). The LIDAR provides turbulence profiles at 10-minute intervals during both day and night, and it also has a separate receiver for a conventional aerosol LIDAR in order to characterize aerosol and cloud layers. Tests will be conducted at the White Sands Missile Range during a two-week period in June, 2007. The tests will include truth data obtained with micro-thermal probes carried aloft by a tethered blimp. Turbulence profiles provided by the LIDAR will be compared with the truth data, and overall system performance will be discussed.

Cross-path LIDAR for Turbulence Profile Determination

Mikhail Belenkii¹, Don Bruns¹, Kevin Hughes¹, Vincent Rye¹, Frank Eaton²

¹*Trex Enterprises Corporation*, ²*Air Force Research Laboratory*

Knowledge of the turbulence profile is important for various applications including directed energy systems such as Airborne Laser and Tactical Airborne Laser, ground-based adaptive optics telescopes, and laser communication systems. The known methods for turbulence profile determination have various limitations. We present a concept of a cross-path LIDAR that overcomes these shortcomings. Our sensor system uses laser guide star technology combined with a cross-path wavefront sensing technique. This sensor has several advantages as compared with the known approaches. A cross-path LIDAR has high spatial and temporal resolution, can operate along arbitrary atmospheric paths in the presence of strong turbulence both at daytime and night, and does not depend on the availability of binary stars. We evaluated the feasibility of this approach by carrying out a performance and error budget analysis, developing an analytical model for the wavefront slope cross-correlation and validating this model using wave optics code, examining the sensitivity of the wavefront slope cross-correlation to the variations of the turbulence profile, and developing and testing an inversion algorithm for reconstruction of the turbulence profile from the optical measurements, as well as developing conceptual LIDAR design. The performed study confirmed that the cross-path LIDAR is feasible.

Observational and Modeling Study of Mesospheric BoresPamela Loughmiller¹, M.P. Hickey¹, S.J. Franke², M.C. Kelley³*¹Embry-Riddle Aeronautical University, ²University of Illinois at Urbana-Champaign, ³Cornell University*

In mid-latitude studies of the dynamics of the mesosphere and lower thermosphere, some of the most intriguing phenomena observed high over the Hawaiian night skies are internal bores. These events affecting chemiluminescence are documented in monochromatic airglow images taken by high performance all-sky CCD imaging systems operating at the Maui Space Surveillance Site on top of Haleakala Crater. Data continues to be collected as part of the ongoing, collaborative Maui - Mesosphere and Lower Thermosphere (MALT) campaign, jointly sponsored by the National Science Foundation and the Air Force Office of Scientific Research. Bolstered by the Maui-MALT dataset, several theories now exist for mesospheric bores, agreeing in principle that they are likely nonlinear structures spawned by gravity waves and propagating within ducted waveguide regions. We investigate these plausible theories using a multi-instrument 2 approach, looking for correlation between bores and thermal inversion layers or wind shears, both potential guiding structures for lateral, geographic bore propagation.

Astrometric Support for Space Situational Awareness and Space Control: The U.S. Naval Observatory

Captain Jonathan White

United States Naval Observatory

The United States Naval Observatory (USNO), founded in 1830 as the progenitor of warfighting Position, Time and Navigation (PNT) operations, is the DoD agency mandated by the Joint Chiefs to establish, maintain, and coordinate Precise Time (such as for GPS) and Astronomical Reference Frames used by all components for navigation, precise positioning and orientation, space operations, and command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR). Specifically, the USNO-charged astrometric programs address fundamental needs gaps in several key aspects of Space Situational Awareness (SSA), Space Control (SC), and space-borne Target Location Error/CEP - reduction systems. As part of its responsibility, the USNO is the developer and synthesizer of all astronomical catalogs, surveys, and databases used by the DoD. USNO then produces the products needed to satisfy both broad and mission-specific needs gaps for the warfighter in the field, the air, at sea, or on the high frontier of Space. USNO DoD programs specifically applicable to the latter include space object tracking, extreme accuracy/rapid orbit determination, offensive/defensive counterspace (OCS/DCS), multi-waveband non-resolved object characterization, space sensor calibration, and astrometric reference frame and stellar catalog definition, maintenance, and improvement. Indeed, USNO's unique capability to produce milli-arcsecond guidance data is foundational to SSA/SC, and precision targeting and munitions. USNO capabilities will be discussed, and a vision presented of how advancements in astrometric programs will close need gaps, enable future capabilities in Space Situational Awareness, Space Control and spaceborne ISR.

Preliminary Astrometric Results from PS1

David Monet, PS1 Team

US Naval Observatory

As the AMOS Conference Abstract deadline closes, first light for the Pan-STARRS PS1 telescope and Gigapixel Camera (GPC1) is scheduled for August 23/24. Even in the pessimistic case that only a small portion of the field has good images, astrometric processing can commence. The key observables are (1) the astrometric uncertainty for a single measure of a single star bright enough to have its error set by seeing and not photon statistics, and (2) the size of the patch of sky over which the local seeing can be modeled by a low-order polynomial. As the data collections continue, we will improve our understanding of PS1 astrometry, but the first few First Light images will give us the preliminary data needed to update the astrometric expectations of the PS1 survey.

Application of MODTRAN to Planetary Atmospheres

Lawrence Bernstein, Robert L. Sundberg, Alexander Singer-Berk

Spectral Sciences, Inc.

MODTRAN(TM) is a widely used radiative-transfer (RT) code for computing the transmission, emission and scattering in the Earth's atmosphere. However, the RT algorithms used in MODTRAN(TM) are generally applicable to any layered atmosphere, and, in principle, can be applied to any planetary atmosphere. The primary required modification required for this application is the development of the appropriate spectral properties data bases for the particular species associated with a given planetary atmosphere. We will show the application of MODTRAN(TM) to Neptune for which the primary atmospheric species are H₂, CH₄, C₂H₆, and C₂H₂. For the carbon-containing species, we have developed molecular band model parameters, and for H₂ we have utilized continuum parameters computed by others. Additionally, we have developed a new cloud model to account for the CH₄ clouds which form in the extremely cold upper atmosphere of Neptune. We will show calculations both for the solar reflective spectral region and the thermal IR emission region, ~0.4-20 microns. Comparisons will be made with archival data.

Photometric Color Conversions for Space Surveillance Sensors

Joseph Scott Stuart

MIT Lincoln Laboratory

In order to maximize sensitivity, optical space surveillance sensors use detectors that have good sensitivity over a wide region of the spectrum. For example, the CCD detectors for the Lincoln Near-Earth Asteroid Research (LINEAR) Project, which are nearly identical to the detectors of the Ground-based Electro-Optical Deep Space Surveillance System, have good sensitivity over the visible spectrum from 380 nanometers to beyond 1000 nanometers. However, photometric calibration of the intensities of objects (stars, satellites, asteroids, etc.) measured by these systems must be referenced to astronomical star catalogs that were measured over much narrower portions of the available spectrum. For example, the Sloan Digital Sky Survey (SDSS) Photometric Database contains photometric measurements in five bandpasses that are each about 150 nanometers wide. This paper will present a method for converting between photometric systems with different bandpasses. The method uses the measured response functions of the detectors of interest along with a model of the spectral transmissivity of the atmosphere (Stone, 1996), and a catalog of stellar spectra (Pickles, 1998) to derive polynomial functions that allow for the conversion of brightness measurements from astronomical catalogs to the bandpass of the sensor. The method has been extensively tested using data from the Lincoln Near-Earth Asteroid Research project in comparison with catalog measurements from the USNO B1.0 astrometric catalog, and the SDSS Photometric Database. Through OPAL (Optical Processing Architecture at Lincoln), this technique is being applied to ground-based and space-based sensors including the Space-Based Visible (SBV) system, the Space-Based Space Surveillance (SBSS) system, and the Space Surveillance Telescope (SST).

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Enhancing the Science Return of the Spitzer Warm Mission

Kenneth Mighell

National Optical Astronomy Observatory

Planning is underway for the post-cryogenic ("warm") operation of the Spitzer Space Telescope which will start around April 2009 after all of the liquid helium has been depleted. Only channels 1 and 2 (3.6 and 4.5 microns) of Spitzer's Infrared Array Camera (IRAC) will be operational at full sensitivity at that time -- providing an unmatched sensitivity from 3 to 5 microns until the James Webb Space telescope is launched. The other channels of all remaining instruments will not operate at the elevated temperatures (25-30K) of Spitzer will experience during its warm mission phase. Last year at AMOS 2006, I showed how the recorded flux of bright point sources observed with IRAC Ch1 is corrupted by lossy detectors which have large intrapixel quantum efficiency variations. During the past year, I have worked closely with members of Spitzer's IRAC Instrument Team to demonstrate that my NASA-funded MATPHOT algorithm for precision stellar photometry and astrometry can yield an improvement in the precision of stellar photometry obtained from IRAC Ch1 observations of bright stars of more than 100% over the best results obtained with aperture photometry corrected with the radial correction recommended in the IRAC Data Handbook. I will describe results of an ongoing effort to develop new calibration procedures for IRAC Ch1 and Ch2 which have the potential of significantly improving the precision of IRAC bright point-source photometry. This timely research effort is intended to not only enhance the science return of existing IRAC Ch1 and Ch2 observations in the Spitzer data archive but also those that will be made during the Spitzer Warm Mission.

SAMM-2: A Rapid, Modular and Extensible All-Altitude VIS-IR Background Scene Generator

Raphael Panfili¹, H. Dothe¹, J. Gruninger¹, J. W. Duff¹, J. H. Brown²

¹*Spectral Sciences, Inc.*, ²*Air Force Research Laboratory*

This talk describes recent upgrades to SAMM-2, a background radiance and transmission code. SAMM-2 incorporates all of the major components necessary for background scene generation at all altitudes: atmospheric characterization, solar irradiance, molecular chemical kinetics and molecular spectroscopic data. In addition, it seamlessly combines MODTRAN, a standard low-altitude local thermodynamic equilibrium model (LTE), with SAMM-1 and SHARC, standard high-altitude non-local thermodynamic equilibrium models (NLTE) to form a single, unified code with comprehensive coverage in the .4 to 40 micron (250 to 25,000 wavenumber) wavelength region for arbitrary lines-of-sight in the 0 to 300 kilometer altitude regime.

Efforts are currently underway to upgrade SAMM-2 from a code primarily used for line-of-sight computations to an efficient scene generator. The inclusion of new, high-efficiency radiation transport (RT) algorithms is central to this upgrade. To this end, Spectral Sciences, Inc. (SSI) has developed an NLTE correlated-k RT model which provides a factor-of-100 speed increase over the existing line-by-line model (QBL) in SAMM-2. This model is able to simulate atmospheric stochastic structure as defined by a temperature and density fluctuation model in addition to clear atmosphere radiance and transmission. In addition, a new NLTE band model developed by SSI provides a factor-of-1000 speed increase over the QBL model.

The proliferation of RT algorithms within SAMM-2 provides the impetus to open SAMM-2 to a wider developer community. SAMM-2 will communicate with its RT algorithms through a well-defined interface. This interface will guarantee inter-operability while allowing for independent development of SAMM-2 and the third-party algorithms in the future. This approach will allow cutting-edge RT algorithms can be rapidly incorporated without the need to develop new atmospheric characterization and molecular chemistry components.

Analysis of the 2007 Chinese ASAT Test and the Impact of its Debris on the Space Environment

T.S. Kelso

Center for Space Standards & Innovation

On 2007 January 11, the People's Republic of China conducted a successful direct-ascent ASAT test against one of their own defunct polar-orbiting weather satellites. The test produced at least 1,337 pieces of debris large enough to be routinely tracked by the US Space Surveillance Network and the NASA Orbital Debris Program Office estimated it generated over 35,000 pieces of debris down to 1 centimeter in size.

While this event captured worldwide attention in the weeks and months after the test was revealed, much of the information provided in the press was inaccurate or misleading and did not appear to be based on scientific analysis of the data available to the public. In order to help the public and key policy makers more fully understand the nature of the event and its impact on the existing satellite population, the Center for Space Standards & Innovation developed a series of animations, images, and graphical analyses to more clearly portray this event and provide a factual foundation for the subsequent debate. Those materials were all made publicly available via the Internet without restriction and have appeared in numerous publications.

This paper will summarize the primary areas of analysis of this event, to include a confirmation of the basic facts initially reported in *Aviation Week & Space Technology*, a visualization of the initial spread of the debris cloud in the first couple of hours after the attack, analysis of the impact of the debris on the LEO space environment including the number of satellites potentially affected and the increase in the number of conjunctions, a look at the current debris environment, and an assessment of the orbital lifetimes that shows that these impacts will last not for years but for centuries. The visualization techniques used to portray these analyses played a substantial role in helping the scientific community to quickly and easily convey important aspects of this event to policy makers and the public at large.

LEO Observation and Orbit Determination by Optical Telescope and Radar

Chikako Hirose, Takehisa Ohmura, Nobuo Kudoh

Japan Aerospace Exploration Agency

In 2000, Japan Aerospace Exploration Agency (JAXA) started to observe space debris with the optical system. In 2004, JAXA started debris observation also with a radar system. Japan Space Forum built these systems in cooperation with JAXA. These systems are located in two separate sites in Okayama Prefecture in the west mainland of Japan. The optical systems, located at the Bisei Spaceguard Center (BSGC), has three optical telescopes and is operated by Japan Spaceguard Association (JSGA). The radar is at the Kamisaibara Spaceguard Center (KSGC) and is automatically operated according to observation requests JAXA sends in a determined format. BSGC focuses on observations of Geostationary Orbit (GEO) or Geotransfer Orbit (GTO) objects and KSGC mainly observes Low Earth Orbit (LEO) objects. At the BSGC, a 1m and a 50cm telescopes are mainly used. Both are Cassegrain telescopes with equatorial mounts. The 1m telescope is designed to observe GEO, GTO and NEO objects and does not rotate fast enough to observe LEO objects. On the other hand, the 50cm telescope is designed to track LEO objects in actual operation and rotates at more than 5 [deg/sec] in both right ascension and celestial declination. The KSGC radar is 3m x 3m active phased arrays with 1395 transmit/receive modules, which transmits 70kW at a peak power level. The radar is designed to observe LEO and detects up to 10 space debris simultaneously with a detection capability of 1m-diameter sphere at a slant range of 577km. JAXA conducted a campaign in cooperation with the JSGA to observe small LEO objects with the 50cm telescope from January to March in 2007. We observed 13 LEO objects out of 50 objects we intended to observe. Although it is usually difficult due to weather restrictions to perform optical observations on consecutive days to determine the orbit, we successfully observed one object for three consecutive nights during five days and determined its orbit. In this paper, we tried to see if there is a relation between 13 LEO objects we could observe and their orbit characteristics and compared our optically-determined orbit with SpaceTrack information. On the other hand, radar observation is not affected by the weather condition and is very useful to determine the orbit. We also describe the orbit determination using radar as a useful tool to observe space debris with limited facilities.

Space Debris Observation Programs in JAXA

Atsushi Nakajima, Hirohisa Kurosaki

Japan Aerospace Exploration Agency

Japan Aerospace Exploration Agency(JAXA) has the facility of ground-based space debris optical observation at Nyukasayama observatory for the R&D on observation technology and also offered the data collections for the GEO debris to Japan Spaceguard Association(JSGA) at Bisei Spaceguard Center(BSGC). For the LEO debris radar observation, JAXA has operated Kamisaibara Spaceguard Center(KSGC). Because of the limiting observation capability of the facilities, the developments of the detection technologies and also the improvements of the facilities are necessary for the faint debris observation and orbit determination. Institute of Aerospace Technology(IAT) of JAXA has been developing the faint debris detection technologies and evaluating them by using the data obtained from the small aperture telescopes at Nyukasayama observatory, which was finished its construction last autumn. The facility has two domes, in which a 35cm Newtonian optical telescope with 2K2K CCD camera and a 25cm BRC optical telescope with 2K2K CCD camera are installed. The optical circumstances in this area was already proved by detecting faint asteroids, about 22nd magnitude, which is equivalent to the detection capability of one meter telescope. One of the most important study items in our R&D is to develop an automatic small size GEO debris detection software. We have proposed a stacking method for detecting noise level faint GEO debris to accumulate the signals by using a number of images. The standard exposure time is 10 seconds and the limiting magnitude is about 17.5 by using a single shot image. By using stacked images, the limiting magnitude will be improved to 19, which is equivalent to 20cm size GEO debris. The Nyukasayama observatory is used to develop optical observation technologies and also to cooperate with the related organizations for space debris observation. The overview of space debris observation program in JAXA and some details of the detection method are described in this paper.

Optical Studies of Space Debris at GEO - Survey and Follow-up with Two Telescopes

Patrick Seitzer¹, Kira Abercromby², Ed Barker³, Heather Rodriguez²

¹University of Michigan, ²ESCG, ³NASA

For 14 nights in March 2007, we used two telescopes at the Cerro Tololo Inter-American Observatory (CTIO) in Chile to study the nature of space debris at Geosynchronous Earth Orbit (GEO).

In this project one telescope was dedicated to survey operations, while a second telescope was used for follow-up observations for orbits and colors. The goal was to obtain orbital and photometric information on every faint object found with the survey telescope. Thus we concentrate on objects fainter than $R = 15$ th magnitude.

MODEST (Michigan Orbital DEbris Survey Telescope, the University of Michigan's 0.6/0.9-m Schmidt telescope at CTIO) was used in survey mode every night to scan a strip of sky 1.3-deg wide in declination by over 100 degrees long in hour angle. Five second exposures were obtained every 37.9 seconds, reaching a limiting R magnitude of 18.0 for a S/N of 10. With a field-of-view (fov) of 1.3-degrees, an average of 8 detections are made of an individual object at GEO during a 5.2 minute timespan.

A real-time processing pipeline detects objects and provides positions and magnitudes to the CTIO 0.9-m equipped with CCD imager with a fov of 0.22 degrees. Predictions of future rates and positions for the first recovery observation with the 0.9-m were made by fitting an assumed circular orbit (ACO) to the observed MODEST positions.

The recovery rate with the 0.9-m of objects found by MODEST was over 85%. The average time between the last detection on MODEST and acquisition on the 0.9-m was 17 minutes. The quickest hand-over was 4 minutes.

The 0.9-m was used to determine:

1. full 6 parameter orbits (including eccentricity). An initial orbit was determined based on observations during one night, and then refined with observations on subsequent nights. One challenge of studying these objects with periods close to 23h56m is that frequent observations are required to refine and update the orbit so the object can be recovered later.
2. magnitudes and colors in the standard astronomical BVRI system. Sequences of 10 observations in each filter were obtained to measure brightness variations.

In this paper we will summarize the results obtained and outline future work.

An Attempt to Observe Debris from the Breakup of a Titan 3C-4 Transtage

Ed Barker¹, M. J. Matney¹, T. Yanagisawa², J.-C. Liou³, K. J. Abercromby³, H.M. Rodriguez³, M. F. Horstman³, P. Seitzer⁴

¹*National Aeronautics and Space Administration, Johnson Space Center*, ²*Japan Aerospace Exploration Agency*, ³*ESCG*, ⁴*University of Michigan*

In February 2007 dedicated observations were made of the orbital space predicted to contain debris from the breakup of the Titan 3C-4 transtage back on February 21, 1992. These observations were carried out on the Michigan Orbital DEbris Survey Telescope (MODEST) in Chile with its 1.3^m field of view. The search region or orbital space (inclination and right ascension of the ascending node (RAAN) was predicted using NASA's LEGEND (LEO-to-GEO Environment Debris) code to generate a Titan debris cloud. Breakup fragments are created based on the NASA Standard Breakup Model (including fragment size, area-to-mass (A/M), and delta-V distributions). Once fragments are created, they are propagated forward in time with a subroutine GEOPROP. Perturbations included in GEOPROP are those due to solar/lunar gravity, radiation pressure, and major geopotential terms. Barker, et. al, (Proceedings of AMOS 2006 Technical Conference, pp. 596-604) used similar LEGEND predictions to correlate survey observations made by MODEST in February 2002 and found several possible night-to-night correlations in the limited survey dataset.

One conclusion of the February 2002 survey search was to dedicate a MODEST run to observing a GEO region predicted to contain debris fragments and actual Titan debris objects (SSN 25000, 25001 and 30000). Such a dedicated run was undertaken with MODEST between February 17 and 23, 2007 (UT dates). MODEST's limiting magnitude of 18.0 (SN~10) corresponds to a size of 22cm assuming a diffuse Lambertian albedo of 0.2. However, based on observed break-up data, we expect most debris fragments to be smaller than 22cm which implies a need to increase the effective sensitivity of MODEST for smaller objects. MODEST's limiting size could not be lowered by increasing the exposure time from 5 to 20 seconds due to trailing of the image. However, special image processing did allow the detection of smaller debris. Special processing combined several individual CCD images to detect faint objects that were invisible on a single CCD image. Sub-images are cropped from six consecutive CCD images with pixel shifts between images being consistent with the predicted movement of a Titan object. A median image of all the sub-images is then created leaving only those objects with the proper Titan motion. Limiting the median image in this manner brings the needed computer time to process all images taken on one night down to about 50 hours of CPU time.

Successful observations were carried out over 6 consecutive nights. Positions for each of the 62 detected targets on individual nights were fit under the assumption of circular orbits (ACO). Those targets that were observed on other nights and that had similar ACO orbital parameters will be combined and their observed positions fit to a full 6 parameter orbit. Combinations of targets having RMS fits less than ~10 arcseconds were considered to be the same target. Six combinations were correlated to cataloged targets (CTs). Cataloged Titan debris (SSNs 25000, 25001, 30000) were not detected because they were not observable during nighttime hours. Nine combinations could not be correlated to cataloged targets, hence they were defined as UCTs. These UCTs have orbital elements very similar to those predicted by LEGEND and thus are strong candidates for Titan debris.

Challenges Related to Discovery, Follow-up, and Study of Small High Area-to-mass Ratio Objects at GEO

Thomas Schildknecht, Reto Musci, Tim Flohrer

Astronomical Institute, University of Bern

A significant population of faint debris with high area-to-mass ratios (AMR) in the range of 1 to 50 m²/kg exists in GEO. The team of the authors discovered the population several years ago using the ESA 1-m Space Debris Telescope in Tenerife. Individual groups, partly in the context of internationally coordinated projects, have undertaken significant observational effort to investigate the properties of this new class of debris objects during the past two years. The current consensus is that these objects may be fragments of multi-layer insulation blankets. The orbital elements of these high AMR objects heavily vary mainly due to solar radiation pressure. In particular the eccentricity and the inclination change significantly on time scales of a few days. It became moreover evident, that even the effective AMR of some individual objects is changing considerably. The study of the characteristics of high AMR objects is supported by immediate follow-up observations shortly after the discovery, as well as by regular re-observation (tracking). Both are mandatory tasks, which involve some technical and practical challenges. This paper describes challenges related to discovering and to following-up high AMR objects using several observing sites and coordinated telescopes. We will in particular address the near real-time orbit determination and scheduling of follow-up observations and the hand-over of objects between the ESA 1-m telescope in Tenerife and the 1-m ZIMLAT telescope of the Astronomical Institute of the University of Bern (AIUB) in Zimmerwald, Switzerland. The discussion will also include the data exchange with international co-operating partners like the Keldysh Institute of Applied Mathematics (KIAM) in Moscow and NASA. The continuous monitoring of high AMR objects allows further studies using technologies and approaches that imply the availability of accurate and up-to-date sets of orbital elements. As an example of recent studies, the investigation of optical properties by acquiring color photometry and light curves is presented. The paper concludes by summarizing additional recent results from the ESA and the AIUB telescopes.

Phase Functions of Deep-Space Orbital Debris

Matt Hejduk

AFSPC/A9L (RABA Technologies)

Because most work on deep-space orbital debris has been in the form of debris surveys, relatively little effort has been directed to the photometric characterization of these debris objects. The present abundance of well-calibrated GEODSS satellite photometric data, however, can enable the beginnings of such an investigation. The brightness versus phase response of some 250 debris objects was studied and compared to the response for approximately 1000 payloads and 750 rocket bodies. Debris brightness response remains better circumscribed than that for payloads or rocket bodies, but with increased "retrograde" brightness-vs-phase behavior. Straight-line brightness versus phase response, typical for most payloads and rocket bodies, is not nearly so prevalent for debris but still constitutes the substantial majority of the debris cases. For brightness prediction, a straight-line phase function is a better predictor than the diffuse sphere approximation in about 80% of the cases, a figure similar to that for the other object types.

With the general behavior of the debris objects characterized, such objects were subdivided into three broad response categories, with further subdivisions into a total of nine categories, as a function primarily of the linear slope (or lack thereof) of the phase function and the spread about the fit line (or mean value). The categories were assigned by visual examination of brightness-versus-phase-angle plots, and the goal was to determine statistical quantities that could reliably separate both the larger and smaller categories. Fitted slope is a poor discriminator and t-test p-value a substantially better one, but the p-value at which discrimination is most reliable is much smaller than what would generally be used for hypothesis testing. Statistical discrimination among the smaller sub-categories is much less successful, but some of the natural groupings of the results are surprising.

The Space-Based Calibration of Optical Systems and HF Radars Using the Precision Expandable Radar Calibration Sphere

Paul Bernhardt

Naval Research Laboratory

The Precision Expandable Radar Calibration Sphere (PERCS) is designed to provide a relatively simple target in space that can be used to determine the operational parameters of both ground Imaging systems and HF radars. PERCS is a 10 meter diameter wire frame in low earth orbit with corner cube reflectors placed at 60 or more vertices around the wire frame. For optical system calibration, PERCS will provide precisely spaced reflection points on the vertices of a large polyhedron. For HF radar calibration, PERCS will have a known radar cross section that is independent of observation direction within 0.5 dB. Laser satellite tracking will provide accurate orbital position and velocity of PERCS. The PERCS will orbit at 600 km altitude in a high inclination. Because of the wire frame construction, atmospheric drag will be low and the large spherical structure is expected to be available for more than five years. The PERCS satellite will be launched in a stowed configuration that has less than one meter in diameter. After launch, the PERCS will expand to a diameter of almost 10 meters. Hoberman Sphere technology will be used to produce a stable wire-frame to act as a radar scatter target. The sphere is based on a truncated icosahedron commonly known in chemistry as a "buckyball". The 60 vertices (V60) are hinged to be joined to 90 rigid segments. Each segment is hinged so that the PERCS can be folded into a compact package for launch.

Remote and Ground Truth Spectral Measurement Comparisons

Kira Abercromby¹, Kris Hamada², Michael Guyote², Jennifer Okada², Edwin Barker³

¹ESCG / Jacobs, ²Boeing LTS, ³NASA Johnson Space Center

FORMOSAT III are a set of six research satellites from Taiwan that were launched in April 2006. The satellites are in 800 km, 71 degree inclination orbits and separated by 24 degrees in ascending node. Laboratory spectral measurements were taken of outer surface materials on FORMOSAT III. From those measurements, a computer model was built to predict the spectral reflectance accounting for both solar phase angle and orientation of the spacecraft relative to the observer. However, materials exposed to the space environment have exhibited spectral changes including a darkening and a "reddening" of the spectra. This "reddening" is characterized by an increase in slope of the reflectance as the wavelength increases. Therefore, the model of pre-flight materials was augmented to include the presumed causative agent: space weathering effects.

Remote data were collected on two of the six FORMOSAT satellites using the 1.6 meter telescope at the AMOS (Air Force Maui Optical and Supercomputing) site with the Spica spectrometer. Due to the separation in ascending node, observations were acquired of whichever one of the six satellites was visible on that specific night. Three nights of data were collected using the red (6000 - 9500 angstroms) filter and five nights of data were collected using the blue (3200 -6600 angstroms) filter. A comparison of the data showed a good match to the pre-flight models for the blue filter region. The absorption feature near 5500 angstroms due to the copper colored Kapton multi-layer insulation (MLI) was very apparent in the remote samples and a good fit to the data was seen in all satellites observed. The features in the red filter regime agreed with the pre-flight model up through 7000 angstroms where the reddening begins and the slope of the remote sample increases. A comparison of the satellites showed similar features in the red and blue filter regions, i.e. the satellite surfaces were aging at the same rate.

A comparison of the pre-flight model to the first month of remote measurements showed the amount by which the satellite had reddened. The second month of data observed a satellite at a higher altitude and was therefore, not compared to the first month. A third month of data was collected but of satellites at the lower altitude regime and can only be compared to the first month. One cause of the reddening that was ruled out in early papers was a possible calibration issue.

Monitoring Variations to the Near-Earth Space Environment during High Solar Activity Using Orbiting Rocket Bodies

Van Romero, William H. Ryan, Eileen V. Ryan

New Mexico Institute of Mining and Technology

A space object's general characteristics can be substantially influenced by changes in the magnetosphere, ionosphere, and thermosphere environments. These space weather effects can vary according to the space object's orbit, position relative to certain regions in space, the severity of solar activity, and many other factors. Outcomes can range from minor and easily recoverable to total breakdown. Further, technology has advanced such that satellite components have become smaller and smaller, and these micro-systems are increasingly more susceptible to the highly energetic solar particles associated with intense activity. Therefore, additional study of the significance of space weather events on Earth-orbiting objects would be beneficial.

A rotating rocket body in orbit experiences a magnetic torque due to the Earth's magnetic field that results in an exponential decay of its rotational frequency and a variation on the axis of rotation. The Photometric Periods of Artificial Satellites (McCants, 2007) database consists of over 60,000 period measurements, mostly visually acquired, dating back to 1958. Although this database validates this predicted exponential decay in rotation rate, many anomalies have been observed, including increased rotational frequencies. Theories for the causes of these anomalies range from leaking fuel tanks to interaction with the local space environment.

Our program aims to complement the current visual database through CCD and video photometric observations of rotating rocket bodies using a portable 0.35-meter telescope and the Magdalena Ridge Observatory's 2.4-meter telescope. The goal is to generate a detailed astrometric and photometric database for a small set of targets at different orbital altitudes in order to study the variability in orbital motion and the rotational angular momentum vector, particularly during times of high solar activity. The National Oceanic and Atmospheric Administration (NOAA) provides daily information and forecasts of solar variations, so correlation of ground-based observations with enhanced periods of activity is immanently feasible. By studying these effects for the somewhat simplistic case of a rocket body, we hope to provide the necessary data required to predict the effects on working satellites of a more complex shape.

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First Light from the MAUI Space Experiment

Rainer Dressler¹, Paul F. Sydney², Lewis Roberts², Kris Hamada², Paul Kervin³, Capt Albert F. Meza⁴, Darrin T. Walker⁴, James C. McLeroy⁴, Lawrence S. Bernstein⁵, Matthew Braunstein⁵, Benjamin Hester⁶

¹*Air Force Research Laboratory*, ²*Boeing Corporation*, ³*AFRL/DESM*, ⁴*DoD Space Test Program*,
⁵*Spectral Sciences Inc.*, ⁶*AFRL/VSBXT*

The objective of MAUI (Maui Analysis of Upper Atmospheric Injections) is to measure the spatial and spectral properties of Shuttle engine exhaust interactions with the low-Earth orbit environment and to validate the chemical kinetics and transport physics implemented in a direct simulation Monte Carlo (DSMC) computer model, SOCRATES-P. The code is a research tool that can be applied towards the development of a future maneuver characterization capability. MAUI was manifested during the past 4 Space Shuttle missions. STS-115 resulted in a unique MSSS observation opportunity at conditions where the orbiter was in sunlight while the optical station was in darkness (terminator pass). The crew was ready to conduct a series of burns per MAUI request. The experiment was scrubbed due to concern related to an unidentified object in the vicinity of the orbiter. Instead, MSSS was tasked to image the tail section of the orbiter to ensure the object was not the parachute door. STS-115 passed over MSSS in an attitude in which the Shuttle axis was locked to the MSSS line-of-sight. This required a large number of attitude maneuvers. Unfortunately, the optical station had to reconfigure its telescopes on very short notice, and the fact that the new mission represented an interesting burn observation opportunity, did not register with the ground crew, so only unfiltered images were taken. Nevertheless, the 0.33 deg field-of-view LAAT

acquisition scope of the 3.6 m adaptive optic tracking telescope, AEOS, provided extremely interesting unfiltered imagery. A total of 22 attitude control pulsed firings were recorded at very good lighting conditions. Each firing involved 2 or 3 PRCS engines firing bursts between 80 and 320 ms long. In every case, the thrust axis was perpendicular to the line of sight, providing a unique and optimal viewing geometry. By far the most interesting white-light features were transients observed at engine start up and shut-down. These transients are due to droplets, or frozen particles, of un-burnt propellant or condensed exhaust that effectively scatter sunlight. The imagery is such that the velocity of the transients can be accurately determined, thereby providing an excellent opportunity to validate state-of-the-art two-phase flow models implemented in SOCRATES-P. An analysis of the transient speeds based on known PRCS engine start-up and shutdown information will be presented.

IR Spectrophotometric Observations of Geosynchronous Satellites

Mark Skinner¹, Tamara E. Payne¹, Ray W. Russell², David Gutierrez², Kirk Crawford², David Harrington³, Daryl Kim², David K. Lynch², Richard J. Rudy²

¹Boeing, ²The Aerospace Corporation, ³University of Hawaii, Institute for Astronomy

We have observed several geosynchronous satellites at the Advanced Electro-Optical System (AEOS) 3.6 meter telescope, utilizing The Aerospace Corporation's Broadband Array Spectrograph System (BASS) 3-13 micron sensor, as well as the site's Hi-VIS 1-2.5 micron spectrograph. The various satellites show different trends with phase angle, which may allow satellite identification based on observables. Data were collected on several nights, on multiple satellites, and at various phase angles for each satellite. We describe our methods, our data, our analysis, and our results.

Algorithms for Hyperspectral Signature Classification in Non-resolved Object Characterization Using Tabular Nearest Neighbor Encoding

Mark Schmalz¹, Gary Key²

¹University of Florida, ²Frontier Technology, Inc.

Accurate spectral signature classification is key to the nonimaging detection and recognition of spaceborne objects. In classical hyperspectral recognition applications, signature classification accuracy depends on accurate spectral endmember determination [1]. However, in selected target recognition (ATR) applications, it is possible to circumvent the endmember detection problem by employing a Bayesian classifier. Previous approaches to Bayesian classification of spectral signatures have been rule-based, or predicated on a priori parameterized information obtained from offline training, as in the case of neural networks [1,2]. Unfortunately, class separation and classifier refinement results in these methods tends to be suboptimal, and the number of signatures that can be accurately classified often depends linearly on the number of inputs. This can lead to potentially significant classification errors in the presence of noise or densely interleaved signatures.

In this paper, we present an emerging technology for nonimaging spectral signature classification based on a highly accurate but computationally efficient search engine called Tabular Nearest Neighbor Encoding (TNE) [3]. Based on prior results, TNE can optimize its classifier performance to track input nonergodicities, as well as yield measures of confidence or caution for evaluation of classification results. Unlike neural networks, TNE does not have a hidden intermediate data structure (e.g., the neural net weight matrix). Instead, TNE generates and exploits a user-accessible data structure called the agreement map (AM), which can be manipulated by Boolean logic operations to effect accurate classifier refinement algorithms. This allows the TNE programmer or user to determine parameters for classification accuracy, and to mathematically analyze the signatures for which TNE did not obtain classification matches. This dual approach to analysis (i.e., correct vs. incorrect classification) has been shown to significantly strengthen analysis of classifier performance in support of classifier optimization.

We show that AM-based classification can be modified to include dynamic tracking of input statistical changes, to achieve accurate signature classification in the presence of noise, closely spaced or interleaved signatures, and simulated optical distortions. In particular, we examine two critical cases: (1) classification of multiple closely spaced signatures that are difficult to separate using distance measures, and (2) classification of materials in simulated hyperspectral images of spaceborne satellites. In each

case, test data are derived from a NASA database of space material signatures. Additional analysis pertains to computational complexity and noise sensitivity, which are superior to Bayesian techniques based on classical neural networks.

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A New Spin on Spin Polarimetry

Mark Pesses¹, Eileen Ryan²

¹SAIC, ²New Mexico Institute of Technology

Polarimetric observations of space objects can provide information on shape, surface roughness and electrical conductivity that are very difficult or impossible to obtain from non-polarimetric data. This polarization information has the potential to enhance non-resolved imaging identification techniques by offering improved discrimination between objects as a valuable complement to hyperspectral and temperature signatures. Nature does not give up this extra information freely, as polarimetric data acquisition is more complicated and cumbersome than acquisition of intensity-only data. Stokes' original paper reports that six separate observations are required to measure the four Stokes parameters. Researchers at AFRL/Kirtland recently showed that all four Stokes parameters can be measured via the Fourier analysis of the modulation of the intensity observed behind a rotating quarter-wave plate and a stationary linear polarizer. We present three new methods for measuring Stokes parameters that require a spinning polarizer and/or a spinning achromatic quarter-wave plate. Several applications of these new methods are discussed for obtaining spectropolarimetric data from space object-tracking telescopes. One application is "upgrading" multispectral sensors to spectropolarimeters

Space Object Characterization Studies and the Magdalena Ridge Observatory's 2.4-meter Telescope

Eileen Ryan, William H. Ryan

New Mexico Institute of Mining and Technology

The Magdalena Ridge Observatory's (MRO) fast-tracking 2.4-meter telescope is located at 10,612 feet atop the Magdalena Mountains in Central New Mexico, and is presently transitioning to an operational status. The MRO 2.4-meter is one of the largest telescopes in the world that has as its primary mission the physical characterization of small bodies (both natural and artificial) in the Solar System. The 2.4-meter's control system is designed to provide convenient and accurate non-sidereal tracking, and the telescope is capable of rapid movement (slew rates are up to 15 degrees/sec) making it an ideal instrument for non-resolved imaging of low-Earth orbit (LEO) space objects. The 2.4-meter telescope can accommodate a wide variety of instrument systems, and support the fabrication, integration, and operation of new instrumentation as well as the development of new and innovative techniques in space object identification studies. Currently, we are investigating various methods to enhance and improve existing capabilities for unique discrimination of resident space objects. The temporal brightness variations (i.e., lightcurves) of unresolved targets such as artificial satellites can be used to develop a powerful tool for general characterization studies. Analysis of these temporal signatures permits the extraction of pertinent distinguishing features, and may also be an indicator for a change in general health status of a satellite. Payne (2005) and Gregory (2005) have demonstrated what can be obtained by adding multi-color information to traditional photometric intensity measurements for geosynchronous satellites. Our current focus is to introduce supplementary discriminators, including polarization data and simultaneously obtained spectral and temporal data. We will discuss new methods for incorporating such data, with a specific emphasis toward LEOs as our target objects. Our observing strategy will be to choose a statistically robust target set with known properties, obtain standard lightcurve intensity

information, and then analyze the utility of adding the additional discerning information. We will also employ predictive modeling for assessing the usefulness of the obtained data for satellite classification and for the identification and interpretation of any anomalous signatures.

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Satellite Characterization: Angles and Light Curve Data Fusion for Spacecraft State and Parameter Estimation

Moriba Jah¹, Ron Madler²

¹*Oceanit Laboratories, Inc.*, ²*Embry-Riddle Aeronautical University*

One of the challenges of satellite characterization is the ability to not only determine the spacecraft orbit but also the spacecraft orientation, size, and material properties. A substantial amount of research has been conducted in using photometry and spectroscopy to give insight into these spacecraft properties, but this work has been traditionally decoupled from the orbit determination process. Data fusion is an eventual goal in the spacecraft characterization community. The reality is that the spacecraft non-gravitational dynamics are influenced by the effects of solar radiation pressure, which are precisely a function of the heliocentric spacecraft position and orientation with associated material properties. By using data types that are sensitive to spacecraft position, attitude, and material properties, not only should orbit determination be possible, but this may constrain the estimates of spacecraft properties yielding more realistic results. Another benefit of the data fusion in the estimation process is that the correlations between spacecraft states and associated properties are captured within the covariance matrix. Hence, the uncertainties in these parameters are readily available. Errors in the spacecraft modeling are able to be mapped into spacecraft state errors and vice versa. This work describes the capability of satellite characterization achieved by fusing angles and light curve data in a sigma-point filter framework. Since this filter strategy is a current-state filter, this capability reflects what can be achieved in near-real time.

Satellite Monitoring, Change Detection, and Characterization Using Non-Resolved Electro-Optical Data from a Small Aperture Telescope

Tamara Payne¹, Stephen Gregory¹, Jill Tombasco², Kim Luu², Laura Durr³

¹*Boeing LTS Inc.*, ²*AFRL/DESM*, ³*AFRL/DES*

The Air Force Research Laboratory has been pursuing development of the exploitation of passive reflectance signatures collected from electro-optical sensors to obtain information on man-made satellites. Recent data collection campaigns have acquired filter photometric signatures in the visible regime from satellites in a variety of orbits and under a variety of operating conditions. The orbits include semi-synchronous, geosynchronous, geosynchronous transfer, and supersynchronous. The operating conditions include active, inactive, stable, and unstable. These satellites pose unique challenges because many times they are too distant or too small or both to image using conventional means. Therefore, they are ideal candidates to use to develop techniques that exploit non-resolved photometric intensity measurements to determine status, detect changes, identify, and characterize.

The data were collected using a Raven-type sensor system. The telescope has a 16-inch aperture and the optical path includes a filter wheel and a CCD. In this paper, we present the data collected from these recent campaigns, the exploitation techniques used, and the results of the analyses. The results will compare signatures from satellites in different orbit regimes under different operating conditions and illustrate the robustness of the techniques.

Separating Attitude and Shape Effects for Non-resolved Objects

Doyle Hall

Boeing, LTS

Time-resolved photometric measurements provide a means of constraining the attitude and/or shape of on-orbit objects that are too small or distant to be imaged by ground-based optical or radar facilities. At the most general level, a detailed inversion of photometric data to determine attitude and shape entails the solution of a multivariate numerical optimization problem involving two classes of variables: attitude and body parameters. Attitude parameters specify the object orientation at the times of the observations and provide a means to convert between the inertial reference frame and the body-centered and body-fixed reference frame. Body or "shape" parameters provide the information required to calculate the flux reflected from the object within the body reference frame. Our analysis indicates that the most basic requirement for the analysis is an extensive set of photometric observations, ideally gathered from multiple perspectives and under multiple illumination conditions. Given such a rich data-set, a complete attitude/shape inversion analysis requires supercomputer resources to address in a timely fashion, even for relatively simple convex objects. The basic reason for this is that the inversion approach requires solving for a large number object attitude and shape parameters simultaneously. A significantly more computationally efficient means of addressing the problem would be to separate the attitude and body parameter determination analyses, if at all possible. In this regard, we present a variety of theoretical approaches for both shape-independent attitude analysis and attitude-independent shape analysis for non-resolvable objects.

Super Resolved Harmonic Structure Function for Space Applications

Richard Dikeman¹, Eric Stanko², John Reagan³

¹*Lockheed Martin Hawaii*, ²*Photon Research Associates/Raytheon*, ³*Lockheed Martin Space Systems*

Lockheed Martin Hawaii presents the application of the combination of two novel signal processing algorithm for non-resolved object characterization. We introduce the Super Resolved Harmonic Structure Function (SR-HSF) and demonstrate its utility in providing "fingerprints" for space based objects. The work presented here is making a major impact in the Missile Defense Agency's Project Hercules group but the results presented here are shown in an unclassified form. First, the SR-HSF algorithm is detailed. The SR-HSF is shown to pull out key space situational awareness fingerprints from a minimal set of observations. Next, the mathematical definition of the SR-HSF is detailed. SR-HSF is shown to be both optimal, and also applicable in the real-time sense. Then, applications to both simulations and unclassified data collected at AMOS of space based bodies are used for analysis. The SR-HSF is then used to analyze these fidelity simulations. It is shown that the SR-HSF is capable of "tagging" an object with a minimal set of observations - a previously impossible result. This analysis yield important considerations for sensor developers, SSA systems, and operators.

Diversity Image Restoration with Dynamically Changing Magnification, Rotation, and Translation

David R. Gerwe, Brandoch Calef, Carlos E. Luna

Boeing

A generalization of diversity algorithms for image restoration and wavefront sensing is presented that allows joint processing of image sets in which the sampling geometry may be different for each frame. The sampling relations are assumed to be well approximated by affine transformations. This embraces translations, rotations, skew, and magnification, which may differ in x- and y-axis directions but not higher order distortions such as pincushion or as resulting from 3D parallax issues. This work extends superresolution processing with affine distortions to blind deconvolution and phase diversity in which the wavefront or PSF is jointly estimated with the object allowing these algorithms to be applied to collection engagement with 3D dynamic motion between the sensor and target. Simulations demonstrate the approach for ground-to-space and air-to-ground applications. A regularization approach is shown to balance image sharpening against noise amplification and handle spatial variations in effective sample density.

Accelerating Convergence of Iterative Image Restoration Algorithms

James Nagy

Emory University

Many methods are available to restore an image from blurred and noisy data. In some cases simple filtering techniques, such as the Wiener filter, can be very effective. For more difficult problems, such as for spatially variant blurs or when enforcing physical constraints (e.g., non-negativity), iterative methods must be used. The cost of an iterative scheme depends on the amount of computation needed per iteration, as well as on the number of iterations needed to reach a good restoration of the image. Much work has been done to optimize cost per iteration, for both serial and parallel implementations. However, very little work has been done to develop robust schemes to accelerate convergence.

Preconditioning is a classical approach used in many areas of scientific computing to accelerate convergence of iterative methods. However, if not done carefully for image restoration (which is an ill-posed problem), preconditioning can lead to erratic convergence behavior that results in fast convergence to a poor approximate solution. In this paper we show how to overcome these difficulties. Specifically, we describe a robust preconditioning scheme for image restoration problems, where the preconditioner is constructed from the PSF and noise properties. To avoid erratic convergence behavior, regularization is naturally incorporated into the construction of the preconditioner. We show that with proper implementation, the overhead of using preconditioning for typical iterative methods, such as conjugate gradients, is about 1.5 times that of using no preconditioning, but that number of iterations can be reduced dramatically, resulting in a substantial reduction in overall cost of the iterative scheme. We show that our preconditioning scheme can be applied to spatially invariant and spatially variant blurs, to multi-frame deconvolution problems, as well as to algorithms that enforce non-negativity constraints. Several examples will be given to illustrate the performance of our preconditioning scheme.

Numerical Studies of the Value of Including Pupil Intensity Information in Multi-frame Blind Deconvolution Calculations for Data Measured in the Presence of Scintillation

Michael Roggemann¹, Paul Billings², Jeff Houchard¹

¹*Pacific Defense Solutions*, ²*Textron*

Under most situations where it is appropriate to use multi-frame blind deconvolution (MFBD) image reconstruction, defects in the point spread function (PSF) are dominated by phase errors attributed to atmospheric turbulence. However, under extreme conditions, such as horizontal imaging, or imaging at low elevation angles, scintillation can also arise, and these amplitude errors also contribute to the degradation of the PSF. MFBD algorithms which parameterize the phase aberrations in the pupil generally neglect pupil intensity information. The key issue addressed in this paper is whether incorporating information about the pupil intensity in an MFBD algorithm improves the accuracy of the reconstruction. We used a numerical simulation approach to address this issue. The results of this study show that incorporating pupil intensity information improves the quality of the reconstructed images only slightly.

High-resolution Imaging through Strong Turbulence

Douglas Hope¹, Stuart M. Jefferies², Cindy Giebink²

¹*University of Hawaii*, ²*University of Hawaii, Institute for Astronomy*

Random fluctuations in the index of refraction, caused by differential heating and cooling of the atmosphere, can severely limit the quality of ground-based observations of space objects. Techniques such as adaptive optics can help compensate for the deleterious effects that such turbulence has on the images by deforming the telescope mirror and thus correcting the wave-front. However, when imaging through strong turbulence such techniques may not adequately correct the wave-front. In such cases blind restoration techniques - which estimate both the atmospheric turbulence characterized by the atmospheric point-spread-function and the object that is being observed - must be used. We demonstrate high quality blind restorations of object scenes, obtained when observing through strong turbulence, by using a sequence of images obtained simultaneously at different wavelengths and prior information on the distribution of the sources of regions of low spectral power in the data.

Evaluation of a Maximum-likelihood Based Multi-frame Blind Deconvolution Algorithm Using Cramer-rao Bounds

Charles C. Beckner Jr., Charles L. Matson

Air Force Research Laboratory

Recently, Cramer-Rao bound (CRB) theory for support-constrained multi-frame blind deconvolution has been developed. In this paper, this CRB theory is employed as a metric to evaluate the performance of a multi-frame blind-deconvolution (MFBD) imaging algorithm developed at the Air Force Maui Optical and Supercomputing Site, a site operated by the Air Force Research Laboratory. Sample variances from the MFBD algorithm named PCID (physically constrained blind deconvolution) and CRB lower bounds to variances are compared for a baseline imaging scenario that employs an object, blurring, and noise model. The variance reduction effects produced by imposing support constraints on the object and on the point spread function (PSF) are analyzed. Pixel-by-pixel sample variance maps are compared to CRB maps for the case of perfect and loose object support constraints. The PCID sample variance maps are evaluated against CRBs both to determine the relative magnitude of these variances as opposed to CRB lower bounds and to assess overall morphology differences. For the baseline imaging scenario, the PCID pixel-by-pixel sample variance magnitudes match their associated CRBs, and the PCID sample variances and CRBs share the same overall morphology. Additionally, PCID sample variance results are presented for cases where the baseline imaging and post-processing scenario above is extended beyond where CRB theory has been developed. Extensions to the model scenario include the use of: positivity in the imaging algorithm, Fourier-domain and Tikhonov regularization, and the addition of photon noise in the imaging model. The matching PCID and CRB results from above are used as a basis for comparison with these sample variance results.

High Contrast Imaging at 3-5 microns

Philip Hinz, Matt Kenworthy, Ari Heinze, John Codona, Roger Angel

Steward Observatory

The 6.5 m MMT, with its integrated deformable secondary, is an ideal platform for carrying out high contrast diffraction-limited imaging in the 3-5 micron wavelength regime. We have developed a dedicated camera for this purpose that can operate with high efficiency at both the L' and M atmospheric windows. In addition we have demonstrated an approach to diffraction suppression, using a relatively simple apodizing phase plate (APP) that allows improved sensitivity to faint objects at several resolution elements away. These techniques are currently being used to search for extrasolar Jupiter-like planets around nearby stars.

Recovering Saturated Pixels Blurred by CCD Image Smear

Keith Knox

Boeing LTS

When a pixel has saturated, its value has exceeded the dynamic range of the analog-to-digital converter. All that is recorded is that the value of the individual pixel exceeded the maximum value of the A/D converter. The actual value of the pixel is lost. There is one circumstance, however, in which the pixel value can be recovered, and that is when the image has been blurred by frame transfer smear.

Frame-transfer CCD sensors make an exposure and then transfer the charge image to a readout buffer. During the time it takes to transfer the charge to the readout buffer, the light-sensitive array continues to be exposed to the image. This exposure during the motion of the charge causes a linearly-smear component to be added to the image, which is roughly proportional to the ratio of the transfer time to the exposure time.

Ordinarily, this smear would be considered a defect that needs to be avoided, but it actually opens an opportunity to recover the values of any saturated pixels. Because the image has been smeared across the CCD array, the brightest areas of the image that saturated in the exposed image have also been imaged all across the array in regions where it is not saturated.

This paper will analyze the effects of saturation in individual pixels on the smear correction algorithm. The analysis shows that a residual streak in the readout transfer direction remains after the smear correction is performed. The value of the streak is proportional to the loss in pixel value due to the saturation. By measuring the amount of the residual streak, a correction value to the saturated pixels can be determined.

The analysis of the effects of saturated pixels on the smear correction algorithm will be given and the conclusions will be illustrated with examples from saturated images of unresolved stars.

PCID And ASPIRE 2.0 - The Next Generation Of AMOS Image Processing Software

Charles Matson¹, Tom Soo Hoo², Maria Murphy³, Brandoch Calef², Charles Beckner¹, Shihyo You²
¹USAF/AFRL, ²Boeing LTS, ³SAIC/MHPCC

One of the missions of the Air Force Maui Optical and Supercomputing (AMOS) site is to generate high-resolution images of space objects using the Air Force telescopes located on Haleakala. Because atmospheric turbulence greatly reduces the resolution of space object images collected with ground-based telescopes, methods for overcoming atmospheric blurring are necessary. One such method is the use of adaptive optics systems to measure and compensate for atmospheric blurring in real time. A second method is to use image restoration algorithms on one or more short-exposure images of the space object under consideration. At AMOS, both methods are used routinely. In the case of adaptive optics, rarely can all atmospheric turbulence effects be removed from the imagery, so image restoration algorithms are useful even for adaptive-optics-corrected images. Historically, the bispectrum algorithm has been the primary image restoration algorithm used at AMOS. It has the advantages of being extremely fast (processing times of less than one second) and insensitive to atmospheric phase distortions. In addition, multi-frame blind deconvolution (MFBD) algorithms have also been used for image restoration. It has been observed empirically and with the use of computer simulation studies that MFBD algorithms produce higher-resolution image restorations than does the bispectrum algorithm. MFBD algorithms also do not need separate measurements of a star in order to work. However, in the past, MFBD algorithms have been factors of one hundred or more slower than the bispectrum algorithm, limiting their use to non-time-critical image restorations. Recently, with the financial support of AMOS and the High-Performance Computing Modernization Office, an MFBD algorithm called Physically-Constrained Iterative Deconvolution (PCID) has been efficiently parallelized and is able to produce image restorations in only a few seconds. In addition, with the financial support of AFOSR, it has been shown that PCID achieves or closely approaches the theoretical limits to image restoration quality for a variety of scenarios. For these reasons, PCID is now being transitioned to being the site-wide image restoration algorithm. Because the algorithm can be complicated to use, a GUI is being developed to be the front end to the PCID algorithm. This interface, called the Advanced SPeckle Image Reconstruction Environment (ASPIRE) version 2.0, is the next generation of the current ASPIRE GUI used as a front end to the bispectrum algorithm. ASPIRE 2.0 will be the front-end GUI to PCID, the bispectrum algorithm, and the AMOSphere database. In this presentation we describe ASPIRE 2.0 and PCID and how to use them to obtain high-resolution images.

Laboratory Imaging of Satellites and Orbital Appearance Estimation

David Wellems¹, David Bowers¹, Jim Boger¹, Capt Neal Kleinschmidt²
¹Applied Technology Associates, ²AFRL/VSSS

For an increasingly cluttered space environment, having detailed pre-launch image information that can be used to predict space object appearance is essential. Both laboratory and extrapolated imagery may provide important diagnostic information in the event of a satellite malfunction or assist in space object discrimination. In the visible and NIR wavelength ranges, simple setups that reduce unwanted background light and that mimic solar glint and diffuse earth shine are described. Numerical methods for extrapolating either high resolution laboratory satellite imagery or unresolved spectral data to space-like scenarios are presented. Image extrapolation, which is performed in the spatial frequency and spectral domains, requires that the camera modulation transfer function (MTF), and that source and sensor characteristics be known. Image data would be referenced to a known reflectance standard and realistic laboratory illumination geometries would be investigated.

Advanced Adaptive Optics for Detection of Extrasolar Planets

Bruce Macintosh¹, Gemini Planet Imager team, TMT Planet Formation Instrument team

¹*Lawrence Livermore National Laboratory*

The next major frontier in the study of extrasolar planets is direct imaging detection of the planets themselves. To achieve this with ground-based telescopes will require advanced adaptive optics systems capable of achieving Strehl ratio > 0.9 on 8-m telescopes, combined with coronagraphy to control diffraction and ultraprecise control of systematic wavefront errors at the nanometer level. Such direct detection is sensitive to planets inaccessible to current radial-velocity surveys and allows spectral characterization of the planets, shedding light on planet formation and the structure of other solar systems.

I will discuss two such "extreme" adaptive optics systems. The first is the Gemini Planet Imager (GPI), which should be deployed in 2010 on the Gemini South telescope. It combines a 2000-actuator MEMS-based AO system, an apodized-pupil Lyot coronagraph, a precision infrared interferometer for calibration at the nanometer level, and a infrared integral field unit for detection and characterization of the target planets.

The second, more speculative instrument is designed for the future Thirty Meter Telescope (TMT), currently planning "first light" in 2016. TMT's high angular resolution offers the unique opportunity to study planets in distant star- and planet-forming regions 130 parsecs away, allowing astronomers to see entire planetary systems in the process of formation. The proposed TMT planet-finder is PFI, the Planet Formation Instrument (PFI). It will require a 2-stage AO system with 10000-actuator deformable mirrors, interferometric infrared wavefront sensing, and a coronagraph optimized for the finely-segmented TMT primary mirror. If constructed, PFI will provide capabilities an order of magnitude beyond even GPI.

Focal Plane and Non-linear Curvature Wavefront Sensing for High Contrast Coronagraphic Adaptive Optics Imaging

Olivier Guyon

Subaru Telescope

Wavefronts can be accurately estimated directly from either focal plane images or defocused pupil plane images, in schemes similar to phase diversity. These wavefront sensing techniques offers fundamental advantages over more traditional techniques for high contrast Adaptive Optics. When combined with a high performance coronagraph, these techniques enable efficient detection of exoplanets.

High-contrast Adaptive Optics on the 200-in. Telescope at Palomar Mountain

Richard Dekany¹, Antonin Bouchez¹, Jennifer Roberts², Mitchell Troy², Ed Kibblewhite³, Ben R. Oppenheimer⁴, Anna Moore¹, Chris Shelton², Roger Smith¹, Thang Trinh², Viswa Velur¹

¹*Caltech Optical Observatories*, ²*Jet Propulsion Laboratory*, ³*University of Chicago*, ⁴*American Museum of Natural History*

The top science priorities for the PALM-3000 adaptive optics system are precision photometry and astrometry, and high-contrast observations at both visible and infrared wavelengths. PALM-3000 will build upon its unprecedented 3,675 active deformable mirror actuators and 5.1 meter collecting aperture with auxiliary systems designed to optimize end-product science return. Chief among these are the use of real-time Cn2(h,t) monitoring equipment, already in regular use at Palomar Observatory, and the potential combination of PALM-3000 with a nanometer-level calibration system and a state-of-the-art coronagraphic infrared speckle suppression integral field spectrograph and polarimeter. Using our existing sodium laser guide star as the AO beacon, PALM-3000 is expected to achieve contrast levels of $\sim 10^{-6}$ at an angular target offset of 1.0 arcsec with SNR = 10 sensitivities down to apparent companion magnitude of $m_V \sim 24.5$ in a 300 second exposure in median seeing conditions.

Progress with Adaptive Optics Testbeds at the UCO/Lick Observatory Laboratory for Adaptive Optics

Donald Gavel

UCO/Lick Observatory, UC Santa Cruz

We report on experimental results with adaptive optics testbeds at the UCO/Lick Observatory. One testbed is dedicated to high contrast AO imaging and is a prototype for a ground-based extrasolar planet imager. The second testbed is dedicated to developing concepts and architectures for multi-laser guidestar tomography in wide-field AO applications. Concurrent with the testbed experiments we are evaluating the new components and key technologies applicable to the next generation of AO systems including MEMS deformable mirrors, high speed low noise detectors, wavefront sensing methods, and fast wavefront control processors. The high contrast testbed has achieved its contrast goal of better than 10^{-6} in a 5 to 15 λ/d region around the central star, the "discovery region," using a 1024 actuator MEMS deformable mirror correcting typical atmospheric aberrations. A new section of the testbed has been added recently which will contain an advanced concept apodized pupil Lyot coronagraph for which some initial results will be attained in time for this conference. We now progressing with the design phase of the Gemini Planet Imager instrument for which we are developing a 4096 actuator MEMS device. The Multi-guidestar Tomography testbed has been configured to analyze MCAO and MOAO architectures under consideration for the Keck and proposed Thirty Meter Telescope AO systems. These configurations will consist of from 5 to 9 laser guidestars spread out on a field of between 2 and 5 arcminutes diameter. Testbed results are clearly showing the extension of the high-Strehl correction field out to these wide fields, which are much larger than the isoplanatic angle. As part of this project, we have developed high-speed tomography algorithms for efficient minimum-variance estimation and control of wavefronts. We have also scoped and prototyped the specialized compute hardware necessary to implement them in real-time. In the component development area we are investigating the use of MEMS deformable mirrors for open-loop control of wavefronts. This will enable the multi-object AO (MOAO) configuration that is suited to simultaneous multi-object spectroscopy, an architecture that multiplies the efficiency of science observing on large telescopes. Since the actuation of MEMS deformable mirrors is based on a very repeatable and low hysteresis electrostatic deflection process, they show great promise for this their use in this approach. Present go-to accuracies have been demonstrated to on the order of 15nm rms. MEMS are also small and lower in cost than current generation piezo actuator DMS, which implies that they have potential for additional applications throughout the AO optical system. We are investigating applications in the high-order wavefront and tip/tilt sensors.

Closed-loop Results from the MMT's Multi-Laser Guide Star Adaptive Optics System

Michael Lloyd-Hart¹, Christoph Baranec¹, N. Mark Milton¹, Thomas Stalcup², Miguel Snyder¹

¹*The University of Arizona,* ²*MMT Observatory*

Key advances in adaptive optics (AO) for both astronomical and military applications will be enabled through the deployment of multiple laser guide stars on a single large-aperture telescope. Wider compensated fields of view than are now seen with conventional AO systems, even those equipped with single laser beacons, will be achieved with less field dependence of the delivered point-spread function. Correction to the diffraction limit over 2 arcminute fields with multi-conjugate AO and partial correction over 10 arcminutes with ground-layer AO are anticipated. In this paper, we will describe the first closed-loop results from an adaptive optics system deploying multiple laser guide stars, anticipated from a telescope run in early July 2007. The system operates on the 6.5 m MMT in Arizona. Five beacons are made by Rayleigh scattering of laser beams at 532 nm integrated over a range from 20 to 30 km by dynamic refocus of the telescope optics. The return light is analyzed by a unique Shack-Hartmann sensor that places all five beacons on a single detector, with electronic shuttering to implement the beacon range gate. The wavefront sensor divides the 6.5 m telescope pupil into 60 subapertures, with correction possible up to 54 modes using the telescope's unique deformable secondary mirror. Image compensation at wavelengths of 1.5 microns and longer is anticipated from analysis of previously recorded open-loop data. Global image motion, not sensed by the lasers, is measured from a natural star imaged onto a photon-counting CCD camera. In tests of the real-time tilt loop conducted in April 2007, the limiting magnitude of the system was found to be $V=17$ for full correction, with some correction remaining down to $V=19$.

The Sodium LGS Brightness Model Over the SOR

Jack Drummond¹, Craig Denman¹, Paul Hillman¹, John Telle¹, Mark Eichkoff², Steve Novotny¹

¹AFRL/DES, ²Boeing LTS

Reviewing the now nearly five years worth of sodium laser guide star (LGS) measurements over the Starfire Optical Range (SOR), we present a comprehensive model to predict its brightness as a function of time of year and direction, taking into account the effect of the Earth's magnetic field. Furthermore, by overlapping two lasers slightly offset in frequency we have enhanced the brightness of the LGS by a factor of 2 (and possibly more) over the simple sum of the two. The brightest LGS we have produced has been of V magnitude 4.5, one hundred times brighter than currently being produced at astronomical observatories.

The First Light of the Subaru Laser Guide Star Adaptive Optics System

Hideki Takami, Yutaka Hayano, Shin Oya, Masayuki Hattori, Makoto Watanabe, Olivier Guyon, Michael Eldred, Stephen Colley, Yoshihiko Saito, Meguru Itoh, Matt Dinkins

Subaru Telescope, National Astronomical Observatory of Japan

Subaru Telescope has been operating 36 element curvature sensor AO system for the Cassegrain focus since 2000. We have developed a new AO system for the Nasmyth focus. The AO system has 188 element curvature wavefront sensor and bimorph deformable mirror. It is the largest format system for this type of sensor. The deformable mirror has also 188 element with 90 mm effective aperture and 130 mm blank size. The real time controller is 4 CPU real time Linux OS computer and the update speed is now 1.5 kHz. The AO system also has laser guide star system. The laser is sum frequency solid state laser generating 589 nm light. We have achieved 4.7 W output power with excellent beam quality of $M^2=1.1$ and good stability. The laser is installed in a clean room on the Nasmyth platform. The laser beam is transferred by photonic crystal optical fiber with 35 m to the 50 cm laser launching telescope mounted behind the Subaru 2ry mirror. The field of view of the low order wavefront sensor for tilt guide star in LGS mode is 2.7 arcmin in diameter. The AO system had the first light with natural guide star in October 2006. The Strehl ratio was > 0.5 at K band under the 0.8 arcsec visible seeing. We also has projected laser beam on the sky during the same engineering run. Three instruments will be used with the AO system. Infrared camera and spectrograph (IRCS), High dynamic range IR camera (HiCIAO) for exosolar planet detection, and visible 3D spectrograph.

An Operations and Maintenance Overview of the Gemini North Artificial Guide Star Laser

Robert Wyman, Maxime Boccas, Celine d'Orgeville, Kevin White

Gemini Observatory

This is an overview of technical issues, and operational and maintenance activities for the Gemini North Guide Star Laser system that are specific to the laser itself, which currently operates in support of Laser Guide Star Adaptive Optics (LGS AO) science observations.

Discussion will detail various issues with laser pump diode failures, failure analysis and reliability as well as techniques in spectral temperature tuning and laser diode procurements. Wavelength stability has been a major issue for operation of the laser and continuous monitoring of the laser is required to maintain power and wavelength within specification. Current investigation in to the problem will be reviewed along with the methods of managing the issue. The sum frequency generation PPSLT crystal will be discussed with respect to performance, maintenance and future testing plans to commission spare crystals in the laser system should they be needed. Various improvements in software and hardware will be briefly discussed along with an overview of diagnostics tools that are in place or being developed.

Since the completion of science commissioning the operations model we follow to prepare and maintain the laser for LGS AO science observations has allowed for very good uptime. During this time it has been an intensive training for those operating the system and some of the experience will be discussed along with the current laser operations support model.

Adaptive Optical System Atmospheric Turbulence Generator Test-bed

Christopher Wilcox¹, Jonathan Andrews¹, Sergio Restaino¹, Ty Martinez¹, Scott Teare², Don Payne³

¹Naval Research Laboratory, ²New Mexico Tech., ³Narrascope

At the Naval Research Laboratory (NRL), we have developed a testbed for simulating atmospheric turbulence using Kolmogorov statistics for testing the correctability of an Adaptive Optical System (AOS). In this testbed, a Liquid Crystal Spatial Light Modulator is being used to induce the atmospheric turbulence and a MEM deformable mirror is being used in the AOS to correct it. This atmospheric turbulence generator can be used to simulate the atmospheric effects on light viewed by an AOS for any telescope aperture with either very poor or very good seeing conditions. This dynamic and expandable system is being used to characterize performance and optimization parameters of our AOS at NRL.

Open Loop Performances of a High Dynamic Range Reflective Wavefront Sensor

Jonathan Andrews¹, Scott Teare², Sergio Restaino¹, David Wick³, Christopher Wilcox¹, Ty Martinez¹

¹Naval Research Laboratory, ²New Mexico Tech, ³Sandia National Laboratories

Sandia National Laboratory has constructed segmented Micro-Electro-Mechanical deformable mirrors that are under investigation for their suitability in experimental Adaptive Optics systems for the Naval Research Laboratory. These mirrors are fabricated in a hexagonal array and can be constructed with flat surfaces, or with optical power allowing each mirror to bring its subaperture of light to a focus similar to a Shack-Hartman array. Each mirror can use the tip, tilt and piston function to move the focused spots to the reference location, and the measurement of the applied voltage can be used directly to power a similar flat MEMS deformable mirror. Unlike the Shack-Hartman array, this wavefront sensor can detect large magnitude aberrations up to and beyond where the focused spots overlap, due to the ability to dither each focused spot. Previous publications reported on this novel new technique and the electrical specifications, while this paper reports on experiments and analysis of the open-loop performance, including repeatability and linearity measurements.

Compensating Atmospheric Turbulence Effects at High Zenith Angles with Adaptive Optics Using Advanced Phase Reconstructors, and Post-detection Image Reconstruction

Michael Roggemann, Grant H. Soehnel, Glen E. Archer

Michigan Technological University

Atmospheric turbulence degrades the resolution of images of space objects far beyond that predicted by diffraction alone. Adaptive optics telescopes have been widely used for compensating these effects, but as users seek to extend the envelopes of operation of adaptive optics telescopes to more demanding conditions, such as daylight operation, and operation at low elevation angles, the level of compensation provided will degrade. We have been investigating the use of advanced wave front reconstructors and post detection image reconstruction to overcome the effects of turbulence on imaging systems in these more demanding scenarios. In this paper we show results comparing the optical performance of the exponential reconstructor, the least squares reconstructor, and two versions of a reconstructor based on the stochastic parallel gradient descent algorithm in a closed loop adaptive optics system using a conventional continuous facesheet deformable mirror and a Hartmann sensor. The performance of these reconstructors has been evaluated under a range of source visual magnitudes and zenith angles ranging up to 70 degrees. We have also simulated satellite images, and applied speckle imaging, multi-frame blind deconvolution algorithms, and deconvolution algorithms that presume the average point spread function is known to compute object estimates. Our work thus far indicates that the combination of adaptive optics and post detection image processing will extend the useful envelope of the current generation of adaptive optics telescopes.

Atmospheric Turbulence Compensation of Point Source Images Using Asynchronous Stochastic Parallel Gradient Descent Technique on AMOS 3.6 m Telescope

Mikhail Voronstov¹, Jim F. Riker², G. Carhart¹, V.S. Rao Gudimetla², L. Berensev¹, T. Weyrauch³

¹US Army Research Laboratory, ²US Air Force Research Laboratory, Directed Energy Directorate, Optics Division, ³University of Maryland

Stochastic Parallel Gradient Descent Technique-based Adaptive Optics (SPGD-AO) system described in this presentation doesn't use conventional wave front sensor. It uses a metric signal collected by a single pixel detector placed behind a pinhole in the image plane to drive three deformable mirrors (DMs). The system is designed to compensate the image for turbulence effects. The theory behind this method is described in detail in J. Opt. Soc. Am. A, 15,2745-2758,1998. However, this technique, while widely simulated and tested, was not verified so far in astronomical field site experiments. During the month of May 2007, a series of experiments using SPGD-AO compensation on stars at several elevation angles and turbulence levels, were conducted successfully at US Air Force Maui Optical and Supercomputing Site (AMOS) using 3.6 m telescope. Some of the results of these experiments will be described. This is the first time SPGD-AO systems have been tested and verified in astronomical field site experiments.

Adaptive Optics Performance over Long Horizontal Paths: Aperture Effects in Multi-conjugate Adaptive Optical Systems

Miao Yu¹, Mikhail Vorontsov², Svetlana Lachinova¹, Jim Riker³, V.S. Rao Gudimetla³

¹University of Maryland, ²US Army Research Laboratory, ³AFRL/DESM

Propagation of optical waves over along horizontal path through continuously distributed or layered phase-distorting medium results in the development of intensity scintillations and phase singularities in the optical receiver system pupil. Both effects are highly undesirable for the traditional (based on phase conjugation) adaptive optics (AO) technique which requires direct reconstruction of the phase aberration function based on data obtained from a wavefront sensor. The intensity scintillations "propagate" to the wavefront sensor output resulting in a parasitic modulation of the sensor's output and phase reconstruction errors. Wavefront phase singularities (branch-points) add an additional complexity to phase reconstruction computations. In this paper, we consider both the traditional adaptive optics technique and an alternative model-free control strategy (e.g., wavefront control based on a decoupled stochastic gradient descent (D-SPGD) technique). The latter does not require reconstruction of the phase. It is demonstrated in this paper that the model-free technique is more robust to intensity scintillations.

Optimization of adaptive compensation efficiency includes not only optimization of control algorithm parameters, but also identifying the optimal position for the wavefront corrector in the adaptive system wave-train. The recipe widely used in the multi-conjugate AO approach for wavefront corrector position suggests positioning the wavefront corrector in the conjugate (image) plane of the phase-distorting layer that the corrector intends to compensate. In this paper, both receiver system aperture diffraction effects and the impact of wavefront corrector position on phase aberration compensation efficiency are analyzed. As shown in the presented study, this recipe on multi-conjugate AO approach indeed results in optimal closed-loop compensation performance, but only if aperture-induced diffraction effects can be neglected. In the presence of aperture-induced diffraction and/or for the case of multiple phase-distorting layers separated by short distances, the optimal corrector position for both closed-loop phase conjugation and D-SPGD control algorithms corresponds to the conjugate pupil-plane. Any advantage that may arise from relocation of the wavefront corrector from the plane conjugate to pupil-plane disappears in the presence of aperture diffraction effects.

Because in most cases the geometry of the phase-distorting layers location is unknown or known with some degree of uncertainty, the results presented in this paper suggest that there is no compelling reason for relocating the wavefront corrector from the conjugate plane of the telescope pupil, unless phase aberrations are the result of a single phase-distorting layer with an accurately defined location and aperture diffraction effects neglected. These results and analyses are expected to provide important insight for the development of high performance adaptive optic systems over long horizontal paths.

Spectral Imaging of Mercury's Sodium Exosphere Using AEOS

Jeff Baumgardner, Jody K. Wilson, Michael Mendillo

Boston University / Center for Space

Unlike other planetary exospheres, Mercury's sodium exosphere is highly non-uniform spatially, and temporally variable on daily time scales. The exosphere is sometimes dominated by localized, bright regions of sodium emission at high latitudes near each pole, and the exact location and origin of these spots is still controversial.

Mercury's exosphere is also one of the most difficult to observe with groundbased telescopes, since Mercury is visible in a dark sky only on rare occasions, and even then it must be observed through a high airmass at low elevations.

The need to resolve the small exospheric enhancements during high airmass observations presents a unique challenge. Potter et al. (e.g. 2007) prefer daytime observations at low airmass, and have recently developed a tip-tilt correction scheme to improve their resolution (Potter et al. 2006), but they have not yet attempted full Adaptive Optics (AO) correction in their observations.

In June 2006 we used the AO system on the AEOS telescope to observe Mercury's sodium exosphere in evening twilight. The AO system was able to "lock" on Mercury's disk, and we obtained spectral images of the exospheric sodium emission using our own 20x20 fiber optic image slicer and medium-resolution spectrograph.

The resulting images of the sodium exosphere are arguably the best ever obtained. Both high latitude spots were clearly visible, and an additional sodium enhancement along Mercury's morning terminator was also obvious. These images thus provide the best opportunity yet to precisely locate Mercury's exospheric enhancements and identify their origins. This data set may very well mark the new standard for groundbased observations of Mercury's exosphere.

Potter, A.E., R.M. Killen, and T.H. Morgan, Solar Radiation Acceleration Effects on Mercury Sodium Emission, *Icarus*, 186, 571-580, 2007.

Potter, A.E. et al., Mapping sodium distribution in the exosphere of Mercury with tip-tilt image stabilization, *Advances in Space Research*, 38, 599-603, 2006.

ESC Track Fusion Demonstration Tool for Distributed Environments

Christopher Cox¹, Erik DeGraaf¹, Robert A Perry¹, Raul Diaz²

¹Raytheon Integrated Defense Systems, ²USAF ESC 850 ELSG/NSA

A key requirement of future net-centric Space Situational Awareness systems development and operations will be decentralized operations, including multi-level distributed data fusion. Raytheon has developed a demonstration for ESC 850 ELSG/NS that fuses sensor-supplied tracks in a dense resident space object (RSO) environment. The demonstration use the state vector and covariance input data from single pass orbit solutions and applies track-to-track correlation algorithms to fuse the individual tracks into composite orbits. Platform independent Java technology and an agent-based software design using asynchronous inter-process communications was used in the demonstration tool development.

The tool has been tested against a simulated scenario corresponding to the future 100,000+ object catalog environment. Ten days of simulated data from Fylingdales, Shemya, Eglin, and a future Space Fence sensor were generated for a co-orbiting family of 122 sun-synchronous objects between 700 and 800 km altitude from the NASA simulated small debris for 2015. The selected set exceeds the average object densities for the 100,000+ RSO environment, and provides a scenario similar to an evolved breakup where the debris has had time to disperse.

The demo produced very good results using fast and simple astrodynamical models. A total of 16678 input tracks were fused, with less than 1.6% being misassociated. Pure tracks were generated for 65% of the 122 truth objects, and 97% of the objects had a misassociation rate <5%. This was achieved in a hands-off process on a single Windows XP laptop running about 240 times faster than real-time. This successful demonstration shows the ability to perform autonomous multi-track data fusion using an approach that is scalable and will support operation in a distributed heterogeneous computing environment, as well as providing a tool that can be used to assess current breakups such as the Chinese ASAT event.

Laboratory Demonstration of a Multiple Beam Fourier Telescope

Louis Cuellar, Justin Cooper, Paul Fairchild

TREX Enterprises Corporation

A detailed laboratory experiment has been completed which models a simultaneous multiple beam Fourier telescope (FT) technique capable of imaging rapidly changing targets such as LEO satellites. Fourier telescope uses multiple beams that illuminate the target with a complex fringe pattern that sweeps across it due to frequency differences between beams. Using this method, the target spatial frequency components are encoded in the temporal signal that is reflected from the target. Previous work has concentrated on system designs where the target is illuminated with 3 individual beams in order to use a standard phase closure process, which is not suitable to image LEO satellites. Data processing and image reconstruction for the laboratory experiment invoked a novel reconstruction algorithm that has been developed under the Satellite Active Imaging National Testbed (SAINT) program. The algorithm compensates for atmospheric phase fluctuations affecting the large number of beams transmitted simultaneously and includes a new type of global phase closure which allows image reconstruction from the time history of measured total reflected intensity from the target. The reconstruction algorithm also solves for hundreds of image Fourier components simultaneously, permitting rapid reconstruction of the image. This multiple beam laboratory experiment includes effects from realistic photon and speckle noise. Additional effects have been expanded to include uplink turbulence, piston jitter, and beam scintillation on the target, which will be encountered in an actual FT imaging system. Experimental results have obtained reconstructed image Strehl values which are greater than 0.9 under scaled system conditions.

Testing the MCS Deconvolution Algorithm on Infrared Data

Michael Egan

NGA/IB

Magain, Courbin and Sohy (MCS 1998, AJ, 494, 472) proposed a two-channel (separable point source and extended background) method for astronomical image deconvolution. Unlike the two-channel Richardson-Lucy algorithm, the MCS method does not require prior knowledge of the point source amplitudes and positions. MCS have claimed that their method produces accurate astrometry and photometry in crowded fields and in the presence of variable backgrounds. This paper compares MSX 8 micron Galactic plane images deconvolved via the MCS method with Spitzer Space Telescope IRAC 8 micron images of the same regions. The improved sampling and final image PSF for the deconvolved MSX image is chosen to match the Spitzer observation. In the parlance of MCS, this determines the light distribution for an 85 cm telescope (Spitzer) by deconvolving data taken with a 33 cm space telescope (MSX). Deconvolution of both the Spitzer and MSX data are also presented that reconstruct the image at resolution consistent with that expected from the 6.5 meter aperture James Webb Space Telescope. I will present results for varying degrees of background complexity and examine the limitations of the MCS method for use on infrared data in regions of high source density and bright, complex backgrounds.

LBD Resurrection

Timothy Georges¹, Bob Lercari¹, Bob Nolan¹, Dan O'Connell², Terry Born², Laura Ulibarri³,
Lt. Steve Mawhorter³

¹Textron Systems, ²HnuPhotonics, ³Air Force Research Laboratory

The 0.64m Laser Beam Director (LBD) was one of the first telescopes on Haleakala when AMOS meant "ARPA Maui Optical Station". The LBD was used for many experiments including Relay Mirror Experiment (RME) and Atmospheric Compensation Experiment (ACE). Originally there was a Ruby Laser for illumination and ranging. Later experiments utilized a HICLASS CO2 laser. With the construction of other larger mounts, (the BDT and AEOS), use of the LBD to support experiments waned in the late 90's, with only HICLASS using it until 2002, and essentially no use there after. Maintenance of the LBD optics became a minimal effort and electronic components (mainly computers) were scavenged by other mounts, rendering the LBD non-operational. In 2006, the HICLASS laser system was crated for removal with the idea of resurrecting the LBD to support bistatic low energy laser programs due to limited space on the BDT. To accomplish this, AFRL has contracted with Textron to perform restoration of the basic LBD optics and the computer systems and software controlling the mount. In addition, Textron has been tasked with integrating lasers supporting two upcoming programs, the Single Photon Detection Sensor System (SPDSS) based on Los Alamos National Laboratory's RULLI Detector, and the LOS Satellite Tracking and Surveillance System (STSS) program.

This paper summarizes the LBD optics and computer systems refurbishments and upgrades. The optics metrology and performance are addressed as well as the Mount Control System performance. Preliminary results from validation tests are reviewed. Validation testing is scheduled to be completed by 1 November. The program specific optics to integrate the SPDSS laser and STSS laser are briefly summarized as well as their layout in the LBD Coude Room. The potential to integrate other low power laser programs into the LBD is also discussed.

TASAT Simulations of NASA Image Satellite to Predict the Spin Rate

V. S. Rao Gudimetla¹, Eric Reinhart², Chris Hart³

¹AFRL/DESM, ²AFRL, ³Northrop Grumman

TASAT simulations of an approximate model of NASA Image Satellite have been conducted and the resulting time domain data of the passive cross section was collected. FFT of this data shows a clear significant peak at the frequency corresponding to the spin rate of the satellite. The spin rate of the satellite has been varied in the simulations and the corresponding change in the frequency location of peak has been correctly recovered. However, there are other significant peaks at various low frequencies, caused by high reflectivity glint like objects on the surface of the satellite, cross talk due to interference of the glints and the mixing of the time returns from various parts of the satellite.

The Laser Guide Star System for Adaptive Optics at Subaru Telescope

Yutaka Hayano¹, Yoshihiko Saito¹, Meguru Ito², Norihito Saito³, Kazuyuki Akagawa⁴, Akira Takazawa⁴,
Mayumi Ito⁴, Satoshi Wada³, Hideki Takami¹, Masanori Iye⁵

¹Subaru Telescope, National Astronomical Observatory of Japan, ²The University of Tokyo,
³RIKEN (The Institute of Physical and Chemical Research), ⁴MegaOpto Co. Ltd.,
⁵National Astronomical Observatory of Japan

We report on the current status of developing the new laser guide star (LGS) system for the Subaru adaptive optics (AO) system. We have three major subsystems: the laser unit, the relay optical fiber and the laser launching telescope.

A 4W-class all-solid-state 589nm laser has been developed as a light source for sodium laser guide star. We use two mode-locked Nd:YAG lasers operated at the wavelength of 1064nm and 1319nm to generate sum-frequency conversion into 589nm. The side-LD pumped configuration is used for the mode-locked Nd:YAG lasers. We have carefully considered the thermal lens effect in the cavity to achieve a high beam quality with TEM₀₀; M₂ = 1.06. The mode-locked frequency is selected at 143 MHz. We obtained the output powers of 16.5 W and 5.0 W at 1064nm and 1319 nm. Sum frequency generated by mixing two synchronized Nd:YAG mode-locked pulsed beams is precisely tuned to the sodium D2 line by thermal control of the etalon in the 1064nm Nd:YAG laser by observing the maximum fluorescence intensity of heated sodium vapor cell. The maximum output power at 589.159 nm reaches to 4.6 W using a PPMgOSLT crystal as a nonlinear optical crystal. And the output power can be maintained within a stability of +/- 1.2% for more than 3 days without optical damage.

We developed a single-mode photonic crystal fiber (PCF) to relay the laser beam from laser clean room, in which the laser unit is located on the Nasmyth platform, to the laser launching telescope mounted behind the secondary mirror of Subaru Telescope. The photonic crystal fiber has solid pure silica core with the mode field diameter of 14 micron, which is relatively larger than that of the conventional step-index type single mode fiber. The length of the PCF is 35m and transmission loss due to the pure silica is 10dB/km at 589nm, which means PCF transmits 92% of the laser beam. We have preliminary achieved 75% throughput in total. Small mode-locked pulse width in time allows us to transmit the high-power laser beam with no suffer from the non-linear scatter effect, i.e. stimulated Brillouin scatter, in the PCF.

The laser launching telescope (LLT) has an output clear aperture as 50 cm. It is classical Cassegrain type optical configuration with tertiary mirror to insert the laser beam from the side. The wavefront error is designed to be 60 to 70nm. The LLT is a copy product what European Southern Observatory has been designed for the laser guide star system at Very Large Telescope.

We succeeded to launch the laser beam to the sky on October 12, 2006. After several tests on the sky, we succeeded to get an image of the laser guide star with the size of more than 10 arc second. The larger size of the laser guide star is caused by the large optical aberration on the primary mirror of LLT due to the heat stress generated at the trigonal support points. We are making a plan to repair this problem during June and the second laser launching test will start around this summer.

Image Reconstruction by Aperture Diversity Blind Deconvolution

Mario Ivanov, Donald McGaughey

Royal Military College of Canada

Phase diversity is a well known method to estimate a phase aberration and undistorted object. In this paper we present a new method of collecting diverse images called aperture diversity. This technique involves forming images through different shaped apertures. Incoming wavefronts are collimated and beam-split into two or more paths to ensure the wavefront in each path have the same aberrations. Images are then formed for each path using apertures with different sizes. Since the optical transfer function of the system is an autocorrelation of the generalized pupil function, the transfer functions for each path are different but related, thus giving a strong constraint for minimization. We use two circular apertures - the first being un-obscured, the second having a central circular obscuration. The radius of the central obscuration varies in different experiments but typical values are between 0.4 and 0.7 of the whole aperture. Blurred images are simulated following the Kolmogorov model of atmospheric turbulence. For each frameset an independent phase screen is constructed. The pupil phase is calculated for each of the two channels and two sets of simulated images are produced. Different magnitudes of the simulated turbulence are investigated, ranging from mild to severe. A combination of two minimizing algorithms is used to obtain the set of Zernike weight estimates - the Simplex algorithm and Genetic algorithm. The weight estimates are then used to construct object intensity estimates using a Wiener filter. The object estimates are compared visually and quantitatively to the initial undisturbed object and the blurred input images. Different radii of the central obscuration are investigated in searching of the best results. The method is described and initial results for real images collected with an imaging system and a static phase screen are presented.

Missing in Action? Evaluating the Putative Absence of Impacts by Large Asteroids and Comets during the Quaternary Period

W. Bruce Masse¹, Robert P. Weaver¹, Dallas H. Abbott², Viacheslav K. Gusiakov³, Edward A. Bryant⁴

¹*Los Alamos National Laboratory*, ²*Lamont Doherty Earth Observatory*, ³*Russian Academy of Sciences, Tsunami Laboratory, Novosibirsk*, ⁴*University of Wollongong*

The Quaternary period represents the interval of oscillating climatic extremes (glacial and interglacial periods) beginning about 2.6 million years ago to the present. Based on modeling by the Near Earth Object (NEO) community of planetary scientists, the known and validated record of Quaternary impact on Earth by comets and asteroids is seemingly depauperate in terms of larger impactors of 10,000+ Mt (roughly equal to or larger than about 500 m in diameter). Modeling suggests that an average of between 2-3 and perhaps as many as 5 globally catastrophic (ca. 1,000,000+ Mt) impacts by asteroids and comets could have occurred on Earth during this period of time, each having catastrophic regional environmental effects and moderate to severe continental and global effects. A slightly larger number of substantive but somewhat less than globally catastrophic impacts in the 10,000-100,000 Mt range would also be predicted to have occurred during the Quaternary. However, databases of validated impact structures on Earth, contain only two examples of Quaternary period impacts in the 10,000-100,000 Mt range (Zhamanshin, Bosumtwi), dating to around a million years ago, while no examples of Quaternary period globally catastrophic impact structures have been yet identified. In addition, all of the 27 validated Quaternary period impact structures are terrestrial--no Quaternary period oceanic impacts have been yet validated. Two likely globally catastrophic probable oceanic impacts events, Eltanin (ca. 1,000,000 Mt at around 2.5 mya), and that associated with the Australasian tektite strewn field (> 1,000,000 Mt at around 0.8 mya), are known due to their debris fields for which craters have not yet been identified and validated. These and the 8-km diameter Bolivian Iturralde candidate impact structure (ca. 10,000 Mt at around 20 kya) round out our list of likely large Quaternary impact structures. This suggests that one or more Quaternary period globally catastrophic impacts and several events in the 10,000-100,000 Mt range occurred in oceanic settings and have not yet been identified. At issue here is the default position of the NEO community that no large impacts have occurred during the past 15,000 years and that there is little evidence for human death by impacts during the past 5000 years of recorded history. This bias, deriving largely from reliance on stochastic models and by selectively ignoring physical, anthropological, and archaeological evidence in support of such impacts, is apparent in the messages being given to the media and general public, and in the general lack of grant support and other assistance to scientists and scholars wishing to conduct fieldwork on impacts that may date to the past 15,000 years. Such a position has a chilling effect on what should otherwise be an important arena of inquiry into the risks and effects of cosmic impact on human society. It potentially limits advancement in our understanding of the recent record and flux of cosmic impact, and diverts attention away from significant research questions such as the possible role of impact in Quaternary period climate change and biological and cultural evolution and process. LA-UR-07-2526.

An algorithm-independent Analysis of the Quality of Images Produced Using Multi-frame Blind Deconvolution Algorithms

Charles Matson, Alim Haji

USAF/AFRL

In many imaging applications, it is desired to reconstruct a high-resolution image of an object from one or more blurred and noisy measured data frames. A key component of the reconstruction process is deconvolving the blurring point spread functions (PSFs) from the measured data frames. When the blurring PSFs are known a priori or can be measured separately to the desired degree of accuracy, the deconvolution process is straightforward. However, in many situations, the blurring PSFs are both not known a priori and there are no separate measurements of them. One such situation is imaging through atmospheric turbulence where the measured data frames are a sequence of one or more short-exposure images and the atmospheric turbulence blurring is not known and is different for each data frame. For these situations, the blurring PSFs must be estimated jointly with the object from the measured data

frames. Algorithms that carry out this joint estimation process are known as multi-frame blind deconvolution (MFBD) algorithms. It is of interest to determine the fundamental limits (i.e., algorithm-independent limits) to the achievable resolution and noise reduction in MFBD reconstructions. Cramér-Rao lower bound (CRB) theory can be used to generate these limits. In this presentation we give results from applying CRB theory to the single-frame and multi-frame blind deconvolution problem. We calculate these fundamental limits for a variety of scenarios, including Zernike versus pixel-based PSF estimation, the number of frames used, the texture of the object and PSFs, photon versus read noise, and the sizes of the support constraints. Some of the results we show include the fact that Zernike-based PSF estimation produces higher-quality images than does pixel-based PSF estimation, the amount of noise reduction is an increasing function of PSF texture, and the benefit of adding just a few frames of data is greater for highly-textured PSFs but is independent of PSF texture when more than ~ five frames are used.

Derivation and Application of a Global Albedo Yielding an Optical Brightness to Physical Size Transformation Free of Systematic Errors

Mark Mulrooney¹, Mark Matney²

¹NASA-JSC/MEI Tech, ²NASA-JSC

We have developed a technique for estimating the intrinsic size distribution of orbital debris objects via optical measurements alone. The process is predicated on a priori knowledge of the power-law size distribution of debris (as indicated by radar RCS measurements) and the log-normal distribution of optical albedos. Since the observed distribution of optical brightness is the convolution of the parent [size] population with the albedo distribution, it is a straightforward matter to transform a given distribution of optical brightness back to a size distribution by appropriate choice of a single albedo value. This is true because the integration of a power-law with a log-normal distribution yields a Gaussian-blurred power law distribution with identical power-law exponent. Application of a single albedo to this distribution recovers a simple power-law which is linearly offset from the original distribution by a constant whose value depends on the choice of the albedo. Significantly, there exists a unique weighted-average albedo which when applied to an observed brightness distribution yields zero offset and therefore recovers the original size distribution. For physically realistic power-laws of negative slope, the proper choice of weighted albedo effectively removes the biases caused by the large number of small objects that look anomalously large (bright) and the lower number of large objects looking anomalously small (dim). Based on this comprehensive analysis a global value of 0.13 should be applied to all orbital debris albedo-based brightness-to-size transformations of debris objects regardless of data source. This represents a modification to the canonical value of 0.1 widely employed. Herein we present the empirical and mathematical arguments for this approach and by example apply it to a comprehensive set of photometric data acquired via NASA's Liquid Mirror Telescopes during the 2000 observing season.

Atmospheric Neutral Density Experiment Mission Update

Andrew Nicholas¹, B. Bruninga², J.M. Picone¹, J. Emmert¹, G. C. Gilbreath¹, L. Healy¹, L. Wasiczko¹, R. Burris¹, T. Finne³, M. Davis⁴, C. Cox⁵

¹Naval Research Laboratory, ²USNA, ³Praxis, Inc. ⁴Honeywell, TSI, ⁵Raytheon

The Atmospheric Neutral Density Experiment (ANDE) Risk Reduction flight was launched on Dec 9, 2006 and deployed into orbit by the Space Shuttle Discovery on December 21, 2006. The primary mission objective is to test the deployment mechanism from the Shuttle for the ANDE flight in mid 2009. Scientific objectives of the ANDE risk reduction flight include; monitor total neutral density along the orbit for improved orbit determination of resident space objects, monitor the spin rate and orientation of the spacecraft, provide a test object for polarimetry studies using the HI-CLASS system.

Each of the two ANDE missions consists of two spherical spacecraft fitted with retro-reflectors for satellite laser ranging (SLR). The ANDE risk reduction mission spacecraft each contain a small lightweight

payload designed to determine the spin rate and orientation of the spacecraft from on-orbit measurements and from ground based observations. The follow-on ANDE mission scheduled for launch in 2009 will consist of two spherical spacecraft also fitted with retro-reflectors for SLR. One of these spacecraft will also carry instrumentation to measure the in-situ atmospheric density, composition and winds.

This paper presents a mission overview and emphasis will be placed on the scientific results from the risk reduction mission and a brief overview of the follow-on mission.

Anuenue: A New Tool for Studying Unresolved Objects

Lewis Roberts, Eric Therkildsen, Shawn Haar

The Boeing Company

The standard instrument for collecting photometry data on unresolved objects at the Maui Space Surveillance System (MSSS) is the Visible Imager, which is the science camera for the AEOS adaptive optics (AO) system. Being embedded in the AO system comes at a high cost. The Visible Imager is unable to collect light shorter than 700nm, in addition the large number of optics in the AO system steals light from Visible Imager and makes it fairly inefficient.

The Anuenue sensor avoids all of these problems by being a dedicated to collecting photometry of unresolved objects. It is located on the B29 rear Blanchard of the 1.2 m telescope at MSSS. It is capable of collecting data from 400 nm to 1000 nm at a variety of frame seeds. Even though it is located on a smaller telescope, it is more sensitive than the Visible Imager and is capable of collecting more accurate data. In addition to an overview of the sensor, we detail the operational characteristics of the sensor.

Optical Properties of Multi-Layered Insulation

Heather Rodriguez¹, Kira J. Abercromby¹, Mark Mulrooney², Edwin Barker³

¹ESCG/Jacobs Sverdrup, ²ESCG/MEI Technologies, ³NASA Johnson Space Center

Multi-layer insulation (MLI) is a material used on rocket bodies and satellites primarily for thermal insulation. MLI is comprised of a variety of materials, layer numbers, and dimensions to satisfy specific design requirements. Typically, it is a sandwich of outward facing copper-colored Kapton layers with inward facing aluminized backing. The inner layers consist of alternating DACRON or Nomex netting and aluminized Mylar. From an orbital mechanics perspective, if this material becomes separated from a spacecraft or rocket body, its orbit will vary greatly in eccentricity due to both its high area-to-mass ratio (A/m) and its susceptibility to solar radiation pressure perturbations. Recently, a debris population was found with high A/m which could be MLI.

Laboratory photometric measurements of one intact piece and three different layers of MLI are presented in an effort to ascertain the characteristics of MLI light curves and aid in identifying the source of the new population. For this paper, the layers used will be consistent with the aforementioned common MLI. Using a robotic arm, the piece was rotated from 0-360 degrees in 10° increments along the object's longest axis. Laboratory photometric data was recorded with a CCD camera and a 300 W Xenon arc light source selected to approximate the solar spectrum. The measurements were taken in white light and using various filters (Johnson Blue (B), Visible (V), and Bessell Red (R)), all taken at an 18 degree (light-object-camera) phase angle selected to closely match typical GEO observations which follow the anti-solar point. As expected, the MLI pieces exhibited characteristics similar to a bimodal magnitude plot of a flat plate, but with photometric features dependent upon the layer composition. To minimize highlight saturation (and consequent loss of intensity information), exposure times were selected empirically based on layer type and filter.

In addition to photometric laboratory measurements, laboratory spectral measurements were acquired for each MLI sample. Spectral data will be combined to match the wavelength region of photometric data to

establish a fiducial reference for the photometric measurements. Not only will this help validate the color photometry, but it will also assist interpretation and analysis of telescopic data. As an example, copper-colored Kapton shows a strong absorption feature near 4800 angstroms. If the observed debris is MLI and the outer layer of copper coloring of Kapton is present, evidence of this material should be seen spectroscopically by the specific absorption feature as well as photometrically (eg. by using R-B (red-blue) light curves).

Using laboratory photometric and spectroscopic measurements an optical property database is provided for a representative high A/m object. These results should directly aid the accurate interpretation of telescopically acquired optical orbital debris photometry of both high A/m targets as well as satellites and spacecraft that incorporate MLI.

Hawaiian Atmospheric Forecasting Utilizing the Weather Research and Forecast Model

Kevin Roe¹, Duane Stevens²

¹Maui High Performance Computing Center, ²University of Hawaii at Manoa

The Hawaiian Islands consist of large terrain changes over short distances, which results in a variety of microclimates in a very small region. Some islands have rainforests within a few miles of deserts; some have 10,000+ feet summits only a few miles away from the coastline. Because of this, weather models must be run at a much finer resolution to accurately forecast weather changes in these regions. NCAR's Weather Research and Forecast Model (WRF) is run, on a nightly basis, using a coarse 54 km resolution grid (encompassing an area of approximately 7000 by 7000 km) nested down to a 2 km grid over each Hawaiian county. Since the computational requirements are high to accomplish this in a reasonable time frame (as to still be a forecast) WRF is run in parallel on MHPCC's Cray 2.4 GHz Opteron based Linux system, "Hoku". Utilizing 32 nodes (64 processors) the WRF model is run over the above conditions in approximately 4 hours. Although WRF forecast have been in place for over a year now, a lot of experience has gone behind its setup. MHPCC has been running NCAR's Mesoscale Model version 5 (MM5) since 2000, which continues to be utilized by operators at the telescope facilities on Haleakala, Maui. Currently, the forecast produced is for a 48-hour simulation, but will most likely be extended to a 72-hour simulation; this forecast is available to operators by 8 AM and produces forecasts out until the next day at 8 PM. This is enough time to give operators and managers time to reschedule their operations if unacceptable conditions are predicted. The products we currently provide are: temperature, wind speed & direction, relative humidity, and rainfall. Additional products to be produced over Haleakala, include clear air turbulence, the Richardson number, and a measure of optical turbulence for the telescope operators using the Dewan and Jackson models.

The Effects of Gray Scale Quantization and Saturation on MFBD and Bispectrum SSA Image Reconstructions

Michael C. Roggemann^{1,2}, Paul Billings³, Michael Reiley³, Jeff Houchard¹

¹Pacific Defense Solutions, ²Michigan Technological University, ³Textron Systems

The bispectrum and MFBD algorithms were developed to overcome the effects of turbulence and measurement noise in astronomical and space situational awareness systems. However, two non-ideal, but highly practical aspects of the measurements are not explicitly handled in the derivation of either of these algorithms: gray scale quantization, and the possibility of saturation. Minimizing the number of gray levels recorded allows the amount of data which must be recorded, stored, and processed to be minimized. However, gray scale quantization reduces the quality of the image reconstructions. Additionally, part of an image may occasionally saturate, causing a non-linear effect in the measurement, and also resulting in artifacts in the image reconstructions. We have investigated both of these issues, and report the results in this paper. Here we show that the effects of gray scale quantization are smaller for the MFBD technique than for the bispectrum technique. We have also modified an implementation of the MFBD algorithm to account for saturation, and present the results.

Ultra-lightweight CFRP Optical/IR Telescopes for Deployable Applications

Robert Romeo¹, RN Martin¹, SR Restaino², T Martinez², CC Wilcox², JR Andrews², SW Teare³, DM Payne⁴, FE Penado⁵

¹*Composite Mirror Applications, Inc.*, ²*Naval Research Laboratory*, ³*New Mexico Tech*, ⁴*Narrascope, Inc.*,
⁵*Northern Arizona University*

Deployable Optical/IR telescopes must be lightweight and rugged enough to withstand being placed from one location to another, in mostly adverse environments. This requires unique materials that are light, stiff and dimensionally stable in most any environment including a space environment. Continuous fiber reinforced polymer (CFRP) composite materials have been used to produce ultra-lightweight optical telescopes. Their thermal/mechanical properties offer advantages over conventional materials in terms of thermal expansion, stiffness and strength. The anisotropic nature of the material allows for weight and stiffness-optimized designs of dimensionally stable structures, ideal for telescopes. Optical mirrors can be produced from CFRP composites as well; yielding 1m diameter rigid primary mirrors weighing 27 lbs. Presented will be unique telescope and mirror fabrication leading to extremely lightweight OTA systems up to 1.4m for the Navy Prototype Optical Interferometer, NPOI. The 1.4m NPOI Telescope, being produced by CMA, is required to be deployable along the baselines of the interferometer. We present the design of this system and how it extrapolates to various deployable concepts for optical telescopes.

Efficient Velocity Matched Filter for Optical Detection of Faint Satellites

Brian Shucker, Ronald Sayer

MIT Lincoln Laboratory

We present an efficient approach to optical detection of faint satellites when observing in sidereal stare mode. Our approach is based on a velocity matched filter. By generating a series of hypotheses about the velocity of potential targets, we create a set of highly sensitive velocity-specific filters, the results of which are combined to achieve complete coverage of the search space. Each filter consists of a "shift-sum" stage, which collapses a set of sidereal frames into a single frame, followed by a convolution stage, which optimizes for the detection of streaklets in the sum frame. The entire set of filters may be run in parallel, and individual operations within each filter are easily parallelized as well. This fact, along with other optimizations, makes our algorithms computationally efficient enough to deploy. We present the specific algorithms behind our implementation, the gains in signal-to-noise ratio, and the computational cost. We also compare detection performance of our algorithm to a standard signal processing approach, using simulated data as well as datasets from the Space-Based Visible (SBV) experiment. Our analysis shows that with a feasible investment in computational resources, we can detect targets that are significantly dimmer than those detected by conventional methods.

Narrow Line-width, High-energy, 2-micron Laser for Coherent Wind Lidar

Upendra Singh, Jirong Yu

NASA Langley Research Center

2 micron solid-state lasers are the primary choice for coherent Doppler wind detection. As wind lidars, they are used for wake vortex and clear air turbulence detection providing air transport safety. In addition, 2 micron lasers are one of the candidates for CO₂ detection lidars. The rich CO₂ absorption line around 2 micron, combined with the long upper state lifetime, has made Ho based 2 micron lasers a viable candidate for CO₂ sensing DIAL instrument. As a transmitter for a coherent wind lidar, this laser has stringent spectral line width and beam quality requirements.

The laser architecture is composed of a seed laser, a ring oscillator, and a double pass amplifier. The seed laser is a single longitudinal mode with a line width of 13 KHz. The 100mJ class oscillator is stretched to 3 meters to accommodate the line-width requirement without compromising the range resolution of the instrument. The amplifier is double passed to produce greater than 300mJ energy. This system is hardened for ground as well as airborne applications.

An Assessment of the January 2007 Chinese ASAT Test on the LEO Environment

David Talent

Oceanit Laboratories, Inc.

Over the past several decades there has been increasing concern regarding the growth of the orbital debris population in the Low Earth Orbit (LEO) environment. Even under the best of circumstances the debris population may be expected to increase under conditions of ambient use by the space-faring nations of the world. It is easy to see that such a situation will obtain since the operational lifetimes of most on-orbit systems are typically less than a decade, while their orbital lifetimes may be many decades to hundreds of years or more. Historically, very little has been done regarding the removal of defunct orbital systems. Making matters worse, there have been many cases of spontaneous explosion of derelict upper stages on orbit. In such an event, a single large "hazard to navigation" becomes hundreds to thousands of pieces of orbiting shrapnel. As the numbers of debris objects increases, for whatever reason, so does the threat of collision with high-value operational assets. Thus, given the importance of minimizing orbital debris in LEO, it is obvious that any nation conducting anti-satellite (ASAT) tests should do so in a responsible fashion - minimizing the long-term deposition of large numbers of orbital debris objects at operational LEO altitudes. It is the thesis of this paper that the January 2007 ASAT test conducted by the Chinese government was particularly careless in this regard. In support of this statement, Oceanit's LEO environment model, PODEM (patented in 2004), was employed. The Chinese ASAT test was conducted successfully at an altitude of about 850 km producing large numbers of debris objects. Results, based on an approximation to this recent event, utilizing the PODEM model, suggest that meter-size debris pieces may remain in the LEO environment for hundreds of years. By contrast, debris ranging in size from one to several centimeters may be expected to drift down, due to drag, through lower LEO altitudes producing a transient spike in hazard within a few years to a decade. The International Space Station (ISS) is a particular concern. By comparison and in contrast, several hypothetical cases of debris deposition in LEO at lower altitudes are illustrated. The current research concludes that the Chinese ASAT test has unnecessarily exposed valuable LEO systems to an enhanced hazard over a long time scale.

The Generation of a Tsunami from the Impact of a Massive Comet Impact in the Indian Ocean

Robert Weaver¹, Lori Pritchett¹, Bruce Masse¹, Galen Gisler², Michael Gittings³

¹*Los Alamos National Laboratory*, ²*University of Oslo*, ³*Science Applications International Corporation*

Calculations with the LANL multiphysics hydrocode SAGE of tsunamis produced by a massive Comet impact in the Indian Ocean is studied with 2D and 3D simulations. We examine the extent of the ejected material from the initial impact and whether that ejecta could be entrained in a distant tsunami, such as the one that left crescents on Madagascar.

Current astrophysical models indicate that globally catastrophic cosmic impacts occur on the average of once per million years, and suggest that no human has been demonstrably killed by impact during recorded history. A review of data from the Quaternary period of the past 2.6 million years indicates instead that several cosmic impacts had significant consequences for ancestral human populations, including during the past 5,000 years. Regrettably, the study of recent impacts is obfuscated by questionable methodologies and poor reporting, and by neglect from archaeologists and anthropologists. One of us (BM) provides in a separate paper an anthropological and geomythology perspective by noting that mythology contains structured observations of major witnessed natural processes and events, including possible impacts, which may be amenable to detailed environmental analysis and chronometric reconstruction. According to the authors' interpretation of mythology, airbursts in South America apparently generated lethal mass fires, and details contained in worldwide "great flood" myths may relate to a catastrophic oceanic comet impact 4,813 years ago. Reasons are provided for why these modeled impact events have not been previously recognized. If these interpretations are confirmed by future archaeological and geological research, then current models of hazards and risks are based on an incomplete understanding of the cosmic impact record.

The Militarily Critical Technologies Program's Space Systems Technologies

Raymond Wick

Institute for Defense

The major objectives of the Militarily Critical Technologies Program (MCTP) are to identify and characterize technologies by specific parameters including quantitative values and to assess worldwide technology capabilities. The MCTP program, which is sponsored by the office of the Deputy Under Secretary/ITS vice Under Secretary, develops the Militarily Critical Technologies List (MCTL) through the support of the Institute for Defense Analyses. This paper describes the MCTL and its Space Systems Technologies. It outlines the unique TWG process developed by the Institute for Defense Analyses (IDA) to support the MCTP. It also outlines the approach used to determine which technologies are included as well as how worldwide technology capability assessment for each technology is determined. Each TWG has a broad membership that includes representatives from government, industry and academia who are subject matter experts in their respective fields. Therefore, the TWG process provides a systematic, ongoing assessment and analysis of goods and technologies to determine technologies that are being developed worldwide that significantly enhance or degrade military capabilities.

Spectral Imaging of Io's Neutral Cloud Source Region using AEOS

Jody Wilson, Jeff Baumgardner, Michael Mendillo

Boston University, Center for Space Physics

Jupiter's volcanic moon Io is the primary source of the heavy ions in Jupiter's magnetosphere. Gases from Io's volcanoes (sulfur dioxide, NaCl) form a tenuous atmosphere around Io, and these atmospheric molecules are dissociated, ionized, and ejected from Io via collisions with plasma in Jupiter's magnetosphere. Molecules and atoms which are ejected from Io as neutrals can form extended neutral clouds near Io and around Jupiter, and the morphologies of these neutral clouds can be used to infer details of the interaction between Io's atmosphere and the plasma in Jupiter's magnetosphere.

Global maps of Io's patchy atmosphere have been made during spacecraft encounters and by groundbased observations of mutual eclipses between Io and other satellites. On a much larger spatial scale, the neutral clouds formed by Io's atmospheric escape have been well characterized by groundbased observations.

On an intermediate spatial scale, encompassing Io's upper atmosphere and neutral cloud source region, emission from neutrals is too close to Io for most groundbased telescopes to resolve from Io's disk. It is also a difficult target for spacecraft, as the Galileo orbiter managed to glimpse this intermediate region only once. (Burger et al. 1999)

In May 2006 we used the adaptive optics capability of AEOS to spatially resolve the emission from escaping sodium atoms near Io. We obtained spectral images of the sodium using our own 20x20 fiber optic image slicer and medium-resolution spectrograph.

Two features are seen in the data. In all of the images we see a spatially uniform corona of sodium around Io, which we interpret to be the isotropic source of the banana cloud. At Io orbital phases near 45 degrees, a second, smaller region of emission is seen extending either ahead of Io or in the anti-Jupiter direction. We interpret this to be the source region of the NaCl⁺ stream feature. This latter feature contradicts observational results of Burger et al. (2001) who measured higher concentrations of sodium over Io's Jupiter-facing hemisphere.

Burger, M.H., N.M. Schneider and J.K. Wilson, Galileo's close-up view of the Io sodium jet, *Geophysical Research Letters*, 26, 3333-3336, 1999.

Burger, M.H. et al., Mutual Event Observations of Io's Sodium Corona, *Astrophysical Journal*, 563, 1063-1074, 2001.