2008 AMOS CONFERENCE

ABSTRACTS OF TECHNICAL PAPERS

September 16-19, 2008

Wailea Marriot Resort & Spa
Maui, Hawaii

SSA & SSA ARCHITECTURE

INSTRUMENTATION DESIGN

ATMOSPHERICS/SPACE WEATHER

ADAPTIVE OPTICS

IMAGING

NON-RESOLVED OBJECT CHARACTERIZATION

ASTRONOMY

ASTRODYNAMICS

ORBITAL DEBRIS

POSTER PRESENTATIONS

TUTORIAL

Surveillance of Space in Australia

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Defence Science and Technology Organisation, Australia

Australia's geography and technology base got it off to a flying start in the early days of surveillance of space, starting with CSIRO's first radio telescope in the 1940's and climaxing in NASA's establishment of station 43 in the Deep Space Network at Tidbinbilla in 1965. But Britain's exit from space and the subsequent closure of the Woomera launch range and associated space tracking facilities in the early 1970's saw the start of a long draw-down of capability. Programs such as CSIRO's radio astronomy telescopes, Electro-Optic Systems' adoption of laser technology for satellite laser ranging and tracking system, and the exploration of the use of technology developed in Australia's over-the-horizon-radar program for surveillance of space, kept some interest in the problem alive, but there has been no serious national investment in the area for the last thirty years.

Recently, however, increased awareness of the vulnerability of space systems and the need to include potential opponents' space capabilities in operations planning has led to a revival of interest in space situational awareness within the Australian Defence Organisation. While firm commitments to new systems must wait on the next Defence White Paper due out at the end of 2007 and the policy directions it formally endorses, discussions have already started with the US on participating in the Space Surveillance Network (SSN) and developing a comprehensive space situational awareness capability. In support of these initiatives the Defence Science and Technology Organisation (DSTO) is drawing up an inventory of relevant Australian capabilities, technologies and activities: the paper will describe the findings of this inventory, and in particular local technologies and systems that might be deployed in Australia to contribute to the SSN.

In the optical regime the available options are rather limited; they centre primarily on the satellite laser ranging technology developed by Electro-Optic Systems and operating in stations at Yarragadee, Western Australia and Mt Stromlo, Australian Capital Territory. Recently, however, Australia has also agreed to host a node of AFRL's Extended HANDS telescope network in Learmonth, Western Australia, and discussions are underway with researchers in Australian academia about also participating in this research program.

In the RF regime, however, DSTO has substantial HF and microwave radar programs, elements of which could be readily adapted to surveillance of space. Proposals have already been developed internally within both programs for various forms of space surveillance systems including both broad area surveillance and imaging along with some very initial technology concept demonstrator systems. Recently proposals have also been floated to substantially increase Australia's civilian space surveillance programs including the Ionospheric Prediction Service's longstanding program to monitor the ionosphere and space weather, meteor radars and other systems. Finally Australia's bid to host the international Square Kilometer Array radio telescope has already generated concrete commitments to establish several very substantial RF arrays in Western Australia that may also provide instruments of unprecedented sensitivity and resolution for surveillance of space. The paper will survey these technology development programs and associated progress on integrating them into some sort of national program for space situational awareness.

A Simulation and Modeling Framework for Space Situational Awareness

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This paper describes the development and initial demonstration of a new, integrated modeling and simulation framework, encompassing the space situational awareness enterprise, for quantitatively assessing the benefit of specific sensor systems, technologies and data analysis techniques. This framework includes detailed models for threat scenarios, signatures, sensors, observables and knowledge extraction algorithms. The framework is based on a flexible, scalable architecture to enable efficient simulation of the current SSA enterprise, and to accommodate future advancements in SSA systems. In particular, the code is designed to take advantage of massively parallel computer systems available, for example, at Lawrence Livermore National Laboratory. We will describe the details of the modeling and simulation framework, including hydrodynamic models of satellite intercept

and debris generation, orbital propagation algorithms, radar cross section calculations, optical and infra-red brightness calculations, generic radar system models, generic optical and infra-red system models, specific Space Surveillance Network models, object detection algorithms, orbit determination algorithms, and visualization tools. The specific modeling of the Space Surveillance Network is performed in collaboration with the Air Force Space Command Space Control Group. We will demonstrate the use of this integrated simulation and modeling framework on specific threat scenarios, including space debris and satellite maneuvers, and we will examine the results of case studies involving the addition of new sensor systems, used in conjunction with the Space Surveillance Network, for improving space situational awareness.

Space Situational Awareness Research Findings

David Richmond

Lockheed Martin

Space Situational Awareness (SSA) is the foundation for space superiority and has become a national priority. Providing full SSA requires knowledge of space and ground assets along with communication links between these assets. It also requires an understanding of potential event/threats that may affect these assets. This paper summarizes the findings resulting from a research environment established to explore SSA issues. Non-traditional data sources available on the internet are identified along with methods used to mine the data. Algorithms to augment this data with value added processing were evaluated and key features are presented to include All-on-All conjunction analysis utilizing analytical distributed processing approaches and maneuver detection utilizing an approach described in the AMOS 2007 paper Satellite Maneuver Detection Using Two-line Elements'. Data fusion techniques are presented which were utilized to evaluate space launches, enhance maneuver detection capabilities, characterize events and determine possible intent. Several visualization approaches were explored and the key features/limitations are discussed to include performance consideration, event models between visualization components, and data needs at the tactical, operational, and strategic levels. Data dissemination approaches utilizing a Service Oriented Architecture (SOA) are highlighted along with challenges such as Multiple Levels of Security associated with the data. Dependencies between visualization and dissemination that impact the system's performance are discussed. Alternatives to balance system performance and application of a User Defined Operational Picture (UDOP) are explored.

Space-Based Visible End of Life Experiments

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The Space-Based Visible (SBV) sensor was launched to orbit on 24 April 1996 as part of the Midcourse Space Experiment (MSX) satellite. As the only optical space surveillance sensor in space, it has provided a unique space surveillance capability and has paved the way for future systems such as SBSS. After more than 12 years of operations, SBV and the MSX satellite are being permanently shut down by June 2008. This provides a unique opportunity to perform several experiments that were deemed too risky during SBV's operational lifetime. These experiments will be conducted through May 2008. Depending on spacecraft performance we plan to conduct several tests of advanced space situational awareness data collection modes including reduced target motion data collection for geosynchronous targets, high phase angle observations of geosynchronous targets, and discrimination of closely-spaced geosynchronous targets. We also plan several experiments for sensor characterization that will yield insight into how the CCD sensors have been affected by 12 years of radiation in space. These include observing well calibrated star fields to assess CCD sensitivity and charge transfer efficiency degradation, and Earth and moon limb observations to assess stray light rejection and optical cleanliness. We will also attempt to close the telescope cover, a procedure that has not been performed since 1998 due to fears that the cover may not reopen. If the cover successfully closes, we will acquire dark current and flat field data to compare with historical values for this sensor and we will acquire data during transit through the South Atlantic Anomaly to characterize the interaction between the focal plane and high-energy particles. Finally, we will attempt to warm the focal plane to determine whether annealing will improve the charge transfer efficiency that has significantly degraded since launch due to damage from high-energy protons.

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Sapphire: Canada's Answer to Space-Based Surveillance of Orbital Objects

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The Canadian Department of National Defence is in the process of developing the Canadian Space Surveillance System (CSSS). The CSSS consists of two major elements: the Sapphire System and the Sensor System Operations Centre (SSOC). The space segment of the Sapphire System is comprised of the Sapphire Satellite - an autonomous spacecraft with an electro-optical payload which will act as a contributing sensor to the US Space Surveillance Network (SSN). It will operate in a circular, sun-synchronous orbit at an altitude of approximately 750 kilometers and image a minimum of 360 space objects daily in orbits ranging from 6,000 to 40,000 kilometers in altitude. The ground segment of the Sapphire System is comprised of a Spacecraft Control Center (SCC), a Satellite Processing and Scheduling Facility (SPSF), and the Sapphire Simulator. The SPSF will be responsible for data transmission, reception, and processing while the SCC will serve to control and monitor the Sapphire Satellite. Surveillance data will be received from Sapphire through two ground stations. Following processing by the SPSF, the surveillance data will then be forwarded to the SSOC.

The SSOC will function as the interface between the Sapphire System and the US Joint Space Operations Center (JSpOC). The JSpOC coordinates input from various sensors around the world, all of which are a part of the SSN. The SSOC will task the Sapphire System daily and provide surveillance data to the JSpOC for correlation with data from other SSN sensors. This will include orbital parameters required to predict future positions of objects to be tracked. The SSOC receives daily tasking instructions

from the JSpOC to determine which objects the Sapphire spacecraft is required to observe. The advantage of this space-based sensor over ground-based telescopes is that weather and time of day are not factors affecting observation. Thus, space-based optical surveillance does not suffer outage periods of surveillance as is the case with ground-based optical sensors; thus, a space-based sensor can collect more data and from a more flexible vantage point.

The Sapphire launch is planned for July 2011. The Sapphire spacecraft is designed to operate for a minimum of five years. It will contribute considerably to establishing a significant space capability for Canada. This, and other current Canadian space initiatives, will have wide-ranging benefits in the area of national defence.

Hosting Sensors on Commercial Communication Satellites to Meet Space Surveillance Requirements

Timothy Deaver

Americom Government Systems

The majority of USSTRATCOM detect and track requirements in the geosynchronous regime could be met via strategic placement of medium grade optical sensors on select geosynchronous satellites at relatively low cost in less than 48 months. An architecture which includes hosting SSA sensors on six to eight commercial communication satellites could provide for highly accurate, timely and relatively inexpensive detect and track capabilities that exceed those of the Space-based Surveillance System (SSBS) currently under development. The major factors considered when hosting any sensor on a commercial communications satellite are size, power, mass, data rate, and mounting constraints. These factors directly impact the cost of hosting such a sensor. By choosing a relatively light weight, low power consumption sensor which requires a small amount of bandwidth to transmit its data, the cost of hosting the sensor is kept low. Once the type of sensor or sensors is identified, the next step is to identify idea geosynchronous locations for the “hosted” sensors. Once these locations are identified, then one would identify a potential host which needs to be replaced within the desired timeframe. Once the host is identified, then the satellite owner / operator should be approached about hosting a “neighborhood” watch sensor aboard their spacecraft. Commercial satellites are routinely replaced based on age and available station keeping fuel. Each commercial communication satellite operator maintains a plan of replacing spacecraft. Between the two largest commercial SATCOM providers, INTELSAT and SES, six to eight spacecraft will be replaced each year. (90 plus spacecraft with 15 year avg life). The satellites are usually procured, designed, built, launched and operational within 36 months. In order for the US Government to adapt to this timeline, a sensor specification would need to be established as well as a sensor procurement pipeline. The sensors would then be provided to the satellite bus manufacturer for integration into the bus. The spacecraft would then be launched and operated by the commercial SATCOM operator for the life of the spacecraft. Based on this approach, it is highly conceivable that a complete geosynchronous “neighborhood” watch program could be completed within 48 months of initiation.

Site Testing for a Far-North Optical/IR Telescope

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Earth-observing satellites are often placed in sun-synchronous, polar orbits. There are numerous reasons for this, including consistent solar illumination of the ground, and near-constant exposure to the sun for power. The orbits of such spacecraft converge near the poles; a high latitude space surveillance sensor is thus able to observe these spacecraft nearly every orbit. Such a site is thus ideal for high-cadence monitoring of the orbit, and potentially status, of these spacecraft. Such monitoring could be of significant potential interest in dealing with sovereignty and operational concerns of high-latitude countries.

A Far-North optical sensor would be complementary to existing space surveillance radar sensors. Such a sensor has not been serious consideration in the past due to the lack of a potential site. However, recent modeling – based on low-resolution, satellite-based environmental sensors – have identified a small number of sites in Canada and Greenland that may be suitable for placement of optical and IR sensors. Over the past two years a number of Canadian government and academic scientists have been conducting an initial assessment of three potential sites located on ridges on Ellesmere Island (located at a latitude of 82 degrees north). These sites have altitudes of up to 1700m, above the expected inversion layer in these locations. Basic environmental sensors and all-sky imaging cameras have been put at each of the sites, using local winds to power the sensors.

This paper will describe the activities conducted over the last two years, present the initial results and discuss future plans. The potential of these sites for both astronomy and space surveillance will be introduced and a comparison with Antarctic sites made. Specific emphasis will be made to the site testing results, and the challenges inherent in both the site testing and any possible future system at these remote sites.

Human System Interface Research for Space Cognitive Awareness

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AFRL/RHC

Satellites are critical to our national security thus making them targets for adversaries. However, it is difficult for space analysts to recognize threatening situations with the current suite of tools available to them [Ianni, 2004]. As indicated by Gen. Robert Kehler (AFSPC/CC), the most effective, rapid improvements that can be made are in exploiting existing information [Simpson, 2008]. The Air Force Research Laboratory (AFRL) is conducting research focused on the human analyst to address this situation. The goal is to more effectively use available information for timelier, more informed decisions.

Based on interviews of space professionals, there are several issues that need to be addressed. These issues range from improved sensor visualization to better human-to-human collaboration. However we feel that a major issue that needs to be addressed is work flow. More specifically, the issue is how the tools used by space analysts and their collaborations affect the decision process. If the analyst spends too much time on tool management or overhead tasks, fewer cognitive processes will be available for the fundamental tasks involved in decision making.

An approach, advocated by the AFRL Human Effectiveness Directorate (AFRL/RH), is to develop a unified work environment that harnesses the power of these specialized tools without exceeding the analyst's cognitive limitations. The concept seems simple but developing such a system benefits greatly from a structured scientific approach and human factors expertise. Separate computer applications are unified into a holistic work environment that flows with the decision process. Such an environment, referred to as a Work-Centered Support System [Scott, et al, 2005], has been shown to reduce time required to make decisions and a reduction in erroneous conclusions [Wampler, 2004]. We hypothesize that these results can be attributed to a reduction in work complexity. Specifically, we notice improved information transfer and a reduction in the demands on the analyst's limited cognitive resources.

This paper will outline the space situational awareness research being conducted in AFRL/RH and explain how each is envisioned to fit into a work-centered construct. A possible approach will be provided for human-system interface design that integrates seemingly dissimilar information sources and services such as orbital analysis, intelligence, space weather, fused sensor data, telemetry link protection, and human expertise. Human expertise, in particular, is often overlooked as an input source yet a significant portion of the knowledge across the enterprise is only available from human sources.

SSA Building Blocks – Transforming Your Data and Applications into Operational Capability

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The Electronic System Center's 850 Electronic Systems Group (ELSG) is currently using a Service Oriented Architecture (SOA) to rapidly create net-centric experimental prototypes. This SOA has been utilized effectively across diverse mission areas, such as Global Strike air operations and Direct Ascent anti-satellite missile response. The 850 ELSG has deployed a working, accredited, SOA on the SIPRNET and provided real-time space information to five separate distributed operations centers. The 850 ELSG has learned first-hand the power of SOAs for integrating DoD and non-DoD SSA data in a rapid and agile manner, allowing capabilities to be fielded and sensors to be integrated in weeks instead of months. This opens a world of opportunity to integrate University data and experimental or proof-of-concept data with sensitive sensors and sources to support developing an array of SSA products for approved users in and outside of the space community. This session will identify how new capabilities can be proactively developed to rapidly answer critical needs when SOA methodologies are employed and identifies the operational utility and the far-reaching benefits realized by implementing a service-oriented architecture. We offer a new paradigm for how data and application producer's contributions are presented for the rest of the community to leverage.

Iao: The New Adaptive Optics Visible Imaging and Photometric System for AEOS

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The Iao camera is a totally new upgraded camera system that will be replacing the existing visible imager (VisIM) camera. It functions as the science camera, and is capable of collecting uncompensated, as well as adaptive-optics compensated images. Iao offers a number of improvements over the existing system, including higher speed, greater sensitivity, as well as improved flexibility in control of the imaging system. We will describe the Iao camera system, the current state of progress, as well as the plans for integration of the new system into AEOS.

Spectrum Tunable Quantum Dot-in-a-well Infrared Detector Arrays for Thermal Imaging

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The Center for High Technology Materials at the University of New Mexico has been investigating quantum dot and quantum well detectors for thermal infrared imaging applications. Recent advances in manufacturing have led to the development of a hybrid quantum dot-in-a-well configuration, allowing many of the benefits of each type of detector in addition to multiple transition energies. These transition energies (and thus wavelengths of detection) are also bias tunable providing the capability of spectrum tunability. These devices have been manufactured in 300 x 256 pixel arrays and can be adjusted to obtain a maximum responsivity to wavelengths ranging from 3 micrometers to nearly 30 micrometers 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. This paper reports on the device specifications, spectral response measurements, noise characterization and reduction techniques, and discusses suitable applications in the field of thermal surveillance. It also reports on the most recent advances in manufacturing that have led to dramatic increases in quantum efficiency and joint work with other fabrication facilities that have led to the manufacture of mega-pixel (1200 x 1024) arrays.

The ISON Subsystems for GEO and HEO Surveying on the Base of Small Telescopes

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New instrument for global monitoring of space objects in high orbits, the International Scientific Optical Network (ISON), is developed during the last three years under auspices of the Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences. Three ISON subsystems are under development for observations of bright object (15m-16m) at GEO-region, high-orbit faint fragments (17m-18m) and HEO-objects, and the series of dedicated small telescopes with large FOV and automated mounts were elaborated for them. Ten 22-cm aperture instruments with FOV of 4° on 36-mm size CCD chip with EQ6Pro mounts are installed in observing facilities around the world in order to provide surveying capability for the GEO region in global scale both in longitude (0°-360°) and inclination (0°-20°). The first units of 40-cm and 50-cm aperture instruments with FOV of 2.4° and 1.8° on 36-mm size CCD chip are produced along with mounts with 80 kg and 150 kg payload capability and installed in a few facilities in order to provide the long-time continuous tracking of faint objects. Four 125-mm aperture instruments with FOV of 15° on 50-mm size CCD chip with EQ6Pro mounts for HEO-objects observations will be installed in four facilities in order to cover all longitudes. It is elaborated and tested a few survey

modes as well as special algorithms permitting to find correlation between short non-correlated tracks in order to discovery the new objects and to establish their orbits. The methods of discovering and follow up observations of faint fragments at high orbits are adjusted. The ways of application of telescopes with FOV of 15° are investigated. The main principles of coordination of large network of optical sensors are explained, the samples of results obtained with large FOV instruments are presented.

Modeling the Imaging Performance of Ground-Based Telescopes

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Over the past year, the Air Force Space Superiority Systems Wing (SYSW) has conducted conceptual design work on a transportable meter-class telescope system to support Space Situational Awareness. Trex Enterprises of San Diego CA and Maui HI was the prime contractor, and the Aerospace Corporation in El Segundo CA supported SYSW in conducting the work. One of the missions will be to image LEO satellites during the daytime and near terminator to determine position and attitude along some portion of its orbit. The telescope could be deployed in locations with poor seeing, such as in the desert during daytime with strong turbulent boundary layers. The goal of the simulation was to assess the feasibility of using a one meter-class telescope in locations with these harsh seeing conditions with post-processing in the absence of adaptive optics, and determine if the resulting image quality is sufficient to measure its attitude. To support the assessment, Trex and Aerospace each developed the end-to-end modeling capabilities that are the subjects of this paper. Both models integrate previously-developed AFRL tools for satellite modeling (TASAT) and atmospheric transmission and sky backgrounds (PLEXUS), with different implementations of turbulence, image formation, and image post-processing simulations. The end-to-end results of the two codes have been compared and were found to agree very closely. Subsequently, the tools were used to shape the telescope conceptual design. Results indicate that the system should perform adequately in conditions of moderate turbulence to obtain a reasonably accurate estimate of the attitude over a sufficient portion of the orbit, but would have difficulty in more severe turbulence or on parts of the orbit with inadequate radiometry. Efforts are underway to validate the codes using experimental data from existing telescopes, and both companies are continuing to develop their models to provide capability for subsequent and related studies.

Improved Field Corrector for Large Telescopes

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We present the design for an improved design spherical aberration corrector for large aperture telescopes with spherical primary and spherical secondary mirrors. This corrector design is very short and compact when compared with other approaches seen in the literature and operates a moderate focal ratio of f/6. It results in very high image quality over fields of 5 to 20 arc-minutes and could be adapted to driving a large integral field unit spectrograph for characterization and identification of space objects.

Simulations of Optical Turbulence for Use in Optical Communication Studies

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Northrop Grumman – TASC

Optical turbulence (OT) acts to distort light in the atmosphere, degrading imagery from large astronomical telescopes and possibly reducing data quality of laser communication links. Some of the degradation due to turbulence can be corrected by adaptive optics. However, the severity of optical turbulence, and thus the amount of correction required, is largely dependent upon the turbulence at the location of interest. Therefore, it is vital to understand the climatology of optical turbulence at such locations. In many cases, it is impractical and expensive to setup instrumentation to characterize the climatology of OT, so simulations become a less expensive and convenient alternative.

The strength of OT is characterized by the refractive index structure function Cn2, which in turn is used to calculate atmospheric seeing parameters. While attempts have been made to characterize Cn2 using empirical models, Cn2 can be calculated more directly from Numerical Weather Prediction (NWP) simulations using pressure, temperature, thermal stability, vertical wind shear, turbulent Prandtl number, and turbulence kinetic energy (TKE). In this work we use the Weather Research and Forecast (WRF) NWP model to generate Cn2 climatologies in the planetary boundary layer and free atmosphere, allowing for both point-to-point and ground-to-space seeing estimates of the Fried Coherence length (ro) and other seeing parameters. Simulations are performed using the Maui High Performance Computing Centers Jaw's cluster.

The WRF model is configured to run at 1km horizontal resolution over a 60km by 60km domain. The vertical resolution varies from 25 meters in the boundary layer to 500 meters in the stratosphere. The model top is 20 km. The Mellor-Yamada-Janjic (MYJ) TKE scheme has been modified to diagnose the turbulent Prandtl number as a function of the Richardson number, following observations by Kondo and others. This modification de weights the contribution of the buoyancy term in the equation for TKE by reducing the ratio of the eddy diffusivity of heat to momentum. This is necessary particularly in the stably stratified free atmosphere where turbulence occurs in thin layers not typically resolvable by the model. The modified MYJ scheme increases the probability and strength of TKE in thermally stable conditions thereby increasing the probability of optical turbulence. Over twelve months of simulations have been generated. Results indicate realistic values of the Fried Coherence Length (ro) are obtained when compared with observations from a Differential Image Motion Monitor (DIMM) instrument. Seeing is worse during day than at night with large ro's observed just after sunset and just before sunrise. Three-dimensional maps indicate how seeing varies as a function of location and elevation. This study has shown that urban heat islands can greatly influence the production of optical turbulence as well as nighttime low level jets. Detailed results of this study will be presented at the conference.

Refractive Turbulence, Transient Propagation Disturbances, and Space Situational Awareness

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This paper examines the proposition that mission limiting space situational awareness (SSA) has important and fundamental turbulence and propagation physics issues to be investigated. We propose to call these aspects, propagation situational awareness (PSA). Transient disturbances can be present in communication to and from ground stations and satellites and in the performance of ground based and space based optical and infra-red imaging and tracking systems. Propagation frequency is important in characterizing whether the source of the disturbance lay in the electron density fluctuations of ionosphere or the refractive turbulence of the neutral atmosphere. Over the past ten years high altitude airborne measurements of clear air and refractive turbulence were made in Australia to support design and performance evaluations of the Airborne Laser. More recently in collaboration with the Australian Defence Science & Technology Organization (DSTO) smaller aircraft were used to investigate the effect of ducting layers on the signal strength of an airborne emitter as a low cost simulation of potential for loss of track in the coverage pattern of an airborne radar. From 2002 onward we were also tasked to do fundamental investigations of clear air turbulence for flight safety evaluations of both manned and unmanned high altitude surveillance aircraft. These investigations covered a wide spread in frequency, from infra-red to microwave. Most of these investigations were confined to measurement days and altitudes where strong turbulence was expected. The decision to measure was based on predictions of the location of jet streams relative to the measurement area as well as bulk gradient Richardson (Ri) vertical profiles derived from radio sound measurements from stations surround the potential measurement location. We will show how all these analyses and decision aids, including the Ri profiles, can be used to estimate potential for propagation disturbances to SSA. Current DOD interest in net-centric communications, airborne networks, and joint space and airborne networks all can have critical Space Situational Awareness aspects under disturbed propagation conditions.

Two- aircraft combined propagation measurements at 10 GHz and refractive and clear air turbulence measurements are planned jointly with DSTO in Australia in their winter season in 2008 and 2009. These two-aircraft measurements are fundamental to developing a PSA analysis scheme and supporting progress in propagation modeling through strong and weak turbulence. It will also be interesting to apply the results of these measurements to the assessment of the role that Kolmogorov and non-Kolmogorov scaling play in interpreting interstellar scintillation and the power law behavior at scales between what astronomers call refractive and diffractive scintillation and its ultimate relevance for ionospheric scintillation.

The Los Alamos Dynamic Radiation Environment Assimilation Model for Space Weather Specification and Forecasting

Geoffrey Reeves

Los Alamos National Laboratory

The Dynamic Radiation Environment Assimilation model was developed at Los Alamos National Laboratory to predict the natural space radiation environment, the artificial radiation belts produced by high altitude nuclear explosions (HANE), and the risks to space-based systems.

The space radiation environment produces a variety of effects in space systems ranging from penetrating backgrounds that degrade system performance, to false signals in mission-critical detectors, to component failures that completely disable spacecraft. The natural space environment near the Earth is dominated by the Earth's radiation belts which vary in size, intensity and structure in response to solar activity. The belts typically show variations of intensity by factors of 1,000 on time scales from years down to minutes. For this reason, models that represent average conditions without dynamics can specify only a limited range of hazardous conditions – primarily those associated with long-term accumulated dose. New, data-driven, dynamic models are required for spacecraft design, anomaly assessment, and reliability/survivability forecasting.

Unsurprisingly, the high-altitude nuclear environment produces similar effects to the natural environment but can be substantially more intense. However, the intensity, the spatial distribution, and the temporal evolution of HANE-produced belts can vary substantially with source characteristics, geographic location, burst altitude, and with subsequent geomagnetic activity.

The techniques of data assimilation have a long history and have been applied with great success to problems of navigation, weather forecasting, process control and many other areas. It is only recently, however, that data assimilation has been applied to space weather. DREAM combines physical models of the Earth's magnetosphere with observations from spacecraft in GPS, GEO, and HEO orbits to specify the global space radiation environment at any satellite, any orbit, and any time. The DREAM model does not simply use data statistically or as deterministic input. Rather, it determines a "state vector" that optimizes the combination of observations and physical dynamics of the radiation belts consistent with the uncertainties in both. Version 1 of DREAM, using a relatively simple physical model and only a subset of available observations, predicts out-of-data set satellite observations with errors ten times less than standard radiation belt models. The model can be run in retrospective, specification, and forecasting modes. We will describe the model and the techniques that it uses and discuss applications to other space weather requirements including HANE-produced environments.

Ground-layer Adaptive Optics with Multiple Laser Guide Stars

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We report the first closed-loop results obtained from an adaptive optics system with multiple laser guide beacons. The system is mounted on the 6.5 m MMT in Arizona, and is designed to explore advanced altitude-conjugated techniques for wide-field image compensation. Five beacons are made by Rayleigh scattering of laser beams at 532 nm integrated over a range from 20 to 29 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 sub apertures, and wavefront correction is applied with the telescope's unique deformable secondary mirror. The first application of the system is to correct boundary-layer turbulence, resulting in image quality of 0.2 arcsec in the near infrared bands from 1.2 to 2.5 microns. In this mode we do not try to reach the diffraction limit of the 6.5 m aperture, but instead aim for improved seeing over a field of view much larger than the isoplanatic patch. In this paper we present images of the central 2 arcmin region of a number of globular clusters in the halo of the Milky Way, where correction is almost uniform across the full field. The system has particular scientific application to extragalactic survey work, typically done in dark fields where guide stars are very faint, and where large samples of objects are required.

Solar Multi-Conjugate Adaptive Optics at the DST

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Solar observations are performed over and extended field of view and the isoplanatic patch over which conventional adaptive optics (AO) provides diffraction limited resolution is a severe limitation. The development of multi-conjugate adaptive optics (MCAO) for the next generation large aperture solar telescopes is thus a top priority. The Sun is an ideal object for the development of MCAO since solar structure provides “multiple guide stars” in any desired configuration. The first successful on-the-sky MCAO experiments were performed at the Dunn Solar Telescope (DST) and at the VTT on Tenerife, Canary Islands. However, further development is needed before operational solar MCAO can be implemented at future large aperture solar telescopes such as the Advanced Technology Solar Telescope (ATST).

At the DST we recently implemented a dedicated MCAO bench with the goal of developing well-characterized, operational MCAO. The MCAO system uses 2 deformable mirrors conjugated to the telescope entrance pupil and a layer in the upper atmosphere, respectively. DM2 can be placed at conjugates ranging from 2km to 10km altitude. For our initial experiments we have used a staged approach in which the 97 actuator, 76 sub-aperture correlating Shack-Hartmann solar adaptive optics system normally operated at the DST is followed by the second DM and the tomographic wavefront sensor, which uses three “solar guide stars”. We use modal reconstruction algorithms for both DMs. We have successfully and stably locked the MCAO system on artificial objects (slides), for which turbulence screens are generated directly in front of the DMs, as well as solar structure. We varied the height of the upper conjugate between 2km and 7 km. We recorded strictly simultaneous images after the pupil DM and after the upper layer DM. Comparing these images allows us to evaluate the performance of the MCAO stage and directly compare to the conventional AO. In addition we recorded wavefront sensor telemetry data for closed and open loop. We present preliminary results and discuss future plans.

Measuring Tilt and Focus for Sodium Beacon Adaptive Optics on the Starfire 3.5 Meter Telescope

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Adaptive optics systems can measure high-order aberrations using an artificial laser beacon without the need for a relatively bright object near the object being imaged. Unfortunately, tilt and focus measurements are difficult to obtain from a laser beacon. One solution is to use light from the object being imaged to measure tilt and focus. Through analysis, we estimate the performance of using a Shack-Hartmann wavefront sensor with 2 by 2 sub-apertures for measuring tilt and focus. Specifically, we discuss implementing this scheme for the sodium beacon adaptive optics upgrade to the Starfire Optical Range (SOR) 3.5 m telescope. We use wave-optics simulation tools to evaluate the performance of the tilt and focus sensor in the SOR sodium beacon system.

Curvature Adaptive Optics and Low Light Imaging Goals

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Institute for Astronomy

We review the basic approach of curvature adaptive optics (AO) and show how its many advantages arise. Adaptive correction with a curvature wave front sensor (WFS) that measures exactly what a curvature deformable mirror (DM) generates offers computational and operational simplicity of a nearly diagonal control matrix. The DM automatically reconstructs the wave front based on WFS curvature measurements. Thus, there is no formal wave front reconstruction. This poses an interesting challenge to post-processing of AO images since PSF reconstruction is not directly possible from WFS data.

Physical continuity of the DM and the reconstruction of phase from wave front curvature data assure that each actuated region of the DM corrects local phase, tip-tilt and focus. This gain in per-channel correction efficiency, combined with the need for only one pixel per channel detector reads in the WFS, allow the use of photon counting detectors for wave front sensing. We note that the use of photon counting detectors implies penalty-free combination of correction channels either in the WFS or on the DM. This effectively decouples bright and faint source performance in that one no longer predicts the other. In fact, for curvature systems, all curves of performance with guide star magnitude are essentially identical for the faintest guide stars regardless of the number of channels.

We also consider the application of curvature AO to the low light moving target detection problem, and explore the resulting challenges to components and control systems. Rapidly moving targets generally impose high speed operation which can pose new requirements unique to curvature components. On the plus side, curvature wave front sensors, unlike their Shack-Hartmann counterparts, are continuously tunable for optimum sensitivity to seeing and we are examining autonomous optimization of the WFS to respond to rapid changes in seeing.

Snapshot Wavefront Distortion Characterization Using Compressive Spectral Imagers

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Duke University

We propose the use of a snapshot spectral imager for snapshot characterization of wavefront distortions and a blurred image.

Spectral imaging is a method to capture a three dimensional data cube of information where the two dimensional spatial image obtained from a monochrome camera is complemented with spectral information at every pixel. DISP has developed coded aperture snapshot spectral imagers (CASSI) that can recover a data cube by measuring a snapshot, coded, spatio-spectral projection of the data cube. The CASSI utilizes a coded aperture and one or more dispersive elements to modulate the optical field from a scene and the detector array makes just N2 multiplexed measurements of N3 voxels in the data cube. The nature of the multiplexing performed depends on the relative position of the coded aperture and the dispersive elements with the instrument. A reconstruction algorithm is used to infer an estimate of the three dimensional data cube from the two dimensional measurements and relies on a crucial property of natural scenes, namely that they tend to be sparse on some multi-scale basis.

Atmospheric turbulence produces variations in the index of refraction of air, which leads to wavelength dependent wavefront distortions in the pupil plane. These distortions degrade the quality of images of distant objects. The wavefront distortions scale the point spread function across the detector as a function of wavelength. The knowledge of the nature of these distortions can be used to minimize their impact on image quality. A CASSI can measure distorted images of the scene at multiple wavelengths in a snapshot. We analyze the use of CASSI to characterize the distortion in the point spread function induced by the wavelength dependent wavefront distortions and recover an undistorted estimate of the object distribution in the scene. The snapshot capability of the instrument may allow imaging of a dynamic scene through a turbulent medium.

RytovProp

David Fried

RytovProp is a new approach to the task of generating a large number of random realizations manifesting some aspect(s) of the effect of turbulence on optical propagation. This method has been applied to the evaluation of Up-Link performance——delivery of laser power from a simple ground transmitter to a satellite. This computational method allows the development of hundreds of thousands of statistically independent random realizations of the laser power density at the satellite in just one or two minutes on an ordinary PC.

The RytovProp method is based on use of analytic results for the phase structure function, the log-amplitude covariance, and the phase: log-amplitude cross-covariance, that have been developed using the Rytov approximation, the assumption that turbulence induced phase and log-amplitude perturbations are jointly Gaussian random variables, and a “little trick” from statistics/matrix-theory that allows a realization of a set of random variables to be very easily/quickly developed given the covariance matrix relating all of the random variables with each other.

The “little trick” is the following. Given a covariance matrix, and using the fact that for any covariance matrix it is possible to generate a real matrix which when multiplied by its transpose will be equal to the covariance matrix—a matrix which may be considered to be the square root of the covariance matrix, then it can be shown that this square root matrix when it multiplies a column vector of normally distributed, statistically independent random values will produce a column vector of Gaussian random values for which the covariance between any pair of elements of this column vector will be equal to the corresponding element of the original covariance matrix.

This means that if the covariance matrix is one relating the turbulence perturbed phases and log-amplitudes of the contributions to the optical held at the satellite from each of an array of points covering the transmitter aperture, then these elements of the product column vector (plus any applicable mean values) can be taken as suitably chosen random realizations of these turbulence perturbed phases and log-amplitudes of the contributions to the optical held at the satellite from each of an array of points covering the transmitter aperture. From these random phase and log-amplitude values the laser power density at the satellite can be calculated.

With suitable modifications this computational method can be made to incorporate the effect of rapid tip/tilt adjustment of the transmitted laser beam——these adjustments being based on tracking of the satellite. Such modifications of the method can be made to incorporate the effects of both anisoplanatism and of the nite tip/tilt tracking servo bandwidth.

The relevant theory will be presented as will sample results comparing probability distributions developed using the RytovProp method and using the (orders of magnitude slower) split-step wave optics propagation method——the comparisons generally showing good agreement. What discrepancies are observed appear to be due to the smallness of the number of wave optics propagation samples that were generated and to the sample-to-sample correlation in the wave optics propagation results.

The Implementation of RytovProp in Matlab

Michael Oliker

Science Applications International Corporation

RytovProp.m is a single file of Matlab Code which implements David Fried's new RytovProp method. Its use and the issues in applying it are discussed along with the implementation by which its results were compared to the ACS Wave Propagation Results.

An Experimental Laser Guide Star Wavefront Sensor Simulator

Colin Bradley, Olivier Lardiere, Rodolphe Conan, Kate Jackson

University of Victoria

Sodium laser guide stars (LGSs) allow, in theory, Adaptive Optics (AO) systems to reach full sky coverage, but they have their own limitations. The artificial star is elongated due to the sodium layer thickness, and the temporal and spatial variability of the sodium atom density induces changing errors on wavefront measurements, especially with Extremely Large Telescopes (ELTs) for which the LGS elongation is larger. In the framework of the Thirty–Meter–Telescope project (TMT), the AO–Lab of the University of Victoria (UVic) has built an LGS–simulator test bed in order to assess the performance of new centroiding algorithms for LGS Shack-Hartmann wavefront sensors (SH–WFS). The design of the LGS–bench is presented, as well as laboratory SH–WFS images featuring 29x29 radially elongated spots, simulated for a 30–m pupil. The errors induced by the LGS variations, such as focus and spherical aberrations, are characterized and discussed. This bench is not limited to SH–WFS, but can also serve as an LGS–simulator test bed for any other LGS–AO projects for which the sodium layer fluctuations are an issue. The paper presents the design and implementation of the bench top system and, in particular, the utilization of a deformable mirror to create the LGS elongation and impart the Na-layer fluctuation. The bench utilizes data containing the sodium profiles from a time series of 88 real profiles measured. The implementation of two centroiding algorithms is under process and the experimental performance of

these centroiding algorithms, using a dithering signal, are described in the paper. Some residual turbulence is also added in the simulator. Although the initial goal of the bench is focused on the matched filter centroiding algorithm, the test bench can also serve as a LGS–source simulator for the other AO systems. The LGS simulator bench is certainly a useful research tool to understand the origins of LGS aberrations, and to validate experimentally the models elaborated by other authors. The bench can reproduce the LGS aberrations for any sodium layer time series, any telescope diameter, any field-stop sizes and shapes, any laser launch telescope positions.

Target-in-the-loop Wavefront Sensing and Control

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It is well known that atmospheric turbulence can severely degrade performance of various optical systems including the laser beam projection systems for directed energy applications discussed here. These systems are designed to create and maintain a laser spot (target hit-spot) of the smallest possible size on a remotely located object (target) in the atmosphere. Compensation (mitigation) of turbulence effects in the laser beam projection systems is typically performed using adaptive optics (AO) wavefront correctors. In the directed energy applications the outgoing beam scattering off an extended target rough surface results in strong speckle modulation of the return wave. This speckle modulation is the major problem for the existing AO wavefront control techniques. In this paper we consider a new approach for speckle-effect mitigation in adaptive laser beam projection systems by creating a target-surface incoherent beacon (Collett-Wolf beacon) using either the projected beam itself or a single auxiliary laser illuminator beam. Using numerical simulations and bench-top experiment we show that using the Collett-Wolf beacon it is possible to mitigate speckle effects and achieve a high degree of turbulence compensation and increase of the laser hit-spot brightness.

Real Time Processing for the ATST AO System

Kit Richards, Thomas Rimmele
National Solar Observatory

The real time processing requirements for the 4m Advanced Technology Solar Telescope (ATST) extended source high order adaptive optics system will be approximately 15 times that of the Dunn Solar Telescope AO systems on which the ATST AO system is based. The ATST AO, with its approximately 1300 subapertures, will use massively parallel processing and is based on TigerSharc DSPs as the central processing units. We will discuss the requirements for processing and data handling and the architecture of the correlating Shack-Hartmann and reconstructor processing unit and present the results of bench-mark testing of the DSP hardware that was selected for the ATST AO system.

Three-Dimensional Imaging and Satellite Attitude Estimation Using Pulse Laser Illumination and a Remote Ultra-Low Light Imaging Sensor for Space Situational Awareness

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The remarkable temporal resolution of the Remote Ultra-Low Light Imaging (RULLI) sensor developed by Los Alamos National Laboratory has lead to interest in exploiting this capability to perform 3-D imaging of satellites for improved Space Situational Awareness (SSA). Such a system would require a pulsed laser illuminator combined with an adaptive optics system. We have developed a simulation of such a system, and present a discussion of the model, and present preliminary results. These results show that 3-D imaging is a potentially powerful tool for understanding the orientation and configuration of satellites.

Local Minima Analysis of Phase Diverse Phase Retrieval Using Maximum Likelihood

David Gerwe, Brandoch Calef, Michael Johnson

The Boeing Company

Abstract: Phase diversity techniques infer wavefront phase aberrations of an imaging system directly from the image data by processing of a set of two or more images with deliberately induced additional aberrations (usually defocus). This is a non-linear inverse problem that is typically solved by iteratively determining the aberration that maximizes an objective function or by iteratively applying a set of constraints. The robustness of these techniques can be severely degraded by local minima that start to appear and increase in density with increasing wavefront aberration strength. Local minima severely limit the dynamic range of wavefront aberration levels for which diversity techniques can serve as a reliable wavefront sensing method using the processing approaches currently in practice. This paper explores mechanisms behind the local minima and characterizes their density and spacing as dependent on SNR and wavefront aberration level. The performance of a global optimization method is compared to a single gradient search for robust WF estimation accuracy.

Development of a Sparse Aperture Test-bed Utilizing Pupil-plane Imaging

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Sparse aperture imaging provides the opportunity to achieve high resolutions with groups of smaller apertures rather than large single apertures. Eliminating these large monolithic apertures provides both a cost and weight reduction among other possible benefits. Imaging with sparse apertures requires that both amplitude and phase of the incident field be captured so that an effective larger aperture can be synthesized. Amplitude is easily captured using traditional imaging systems however capturing phase requires more advanced methods such as interferometry or phase retrieval algorithms. The design of these sparse aperture imaging arrays has previously been discussed theoretically and through computer simulations however experimental verification is still needed. A sparse aperture test bed is proposed and initial designs are discussed. The test bed provides the ability to experiment with various sparse aperture array patterns as well as sub-aperture spacing and to compare the results with theory. The first step in construction of the test beds is the design of individual telescopes which will allow the field to be recorded at each of the sub-apertures by utilizing digital holography, a method referred to as pupil plane imaging. Pupil plane imaging (using spatial heterodyne techniques) is described and theory presented which will allows for the recovery of the target field from a recorded interference pattern. It is demonstrated how pupil plane imaging telescopes can be used to perform lens-less imaging, effectively forming the image digitally. Expressions, which simplify focusing the resulting image on the target, are derived and experimental results are provided. Compact telescopes are developed which will provide the foundation of a sparse aperture test bed and image results are given for a prototype telescope.

Automatic Reconstruction of Spacecraft 3D Shape from Imagery

Harry Voorhees, Robert Radke, Conrad Poelman

Stellar Science, Ltd. Co.

We describe a system that we have implemented to compute the three-dimensional (3D) shape of a spacecraft from a sequence of uncalibrated, two-dimensional images. Our task is to apply shape-from-motion computer vision algorithms to space surveillance imagery. While the mathematics of multi-view geometry is well understood, building a system that accurately recovers 3D shape from real imagery remains an art. To illustrate the process, we demonstrate how spacecraft models are computed from imagery taken by the Air Force Research Laboratory's XSS-10 inspector satellite and DARPA's Orbital Express satellite.

A novel aspect of our approach is the combination of algorithms from photogrammetry, computer vision, and computer graphics. Using feature tie points (each identified in two or more images), we compute the relative motion of each frame and the 3D location of each feature using iterative linear factorization followed by non-linear bundle adjustment. The point cloud that results from this traditional shape-from-motion approach, however, is typically too sparse to generate a detailed 3D model.

Instead, we use the computed motion solution as input to a volumetric silhouette-carving algorithm, which constructs a solid 3D model based on viewpoint consistency with the image frames. The resulting voxel model is then converted to a facet-based surface representation and is texture-mapped, yielding realistic images from arbitrary viewpoints.

We also illustrate some other applications of the algorithm, including 3D mensuration and stereoscopic 3D movie generation.

Implementation of Estimation Theoretic Image Restoration Algorithms on OPERA: 2D FFT Benchmarking

Carlos Luna[1], Jesse Foldbaum[1], David Gerwe[1], Dagim Seyoum[2]

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Image quality degradations arising from atmospheric turbulence often limit the utility of ground-based observations of space objects for Space Situational Awareness (SSA). This situation has motivated the development of many image restoration techniques to improve image quality by post-processing. Diversity imaging techniques based on estimation theory such as Phase Diversity and Multi-Frame Blind De-convolution (MFBD) have proven very successful and specific instantiations such as PCID are being deployed for operational use.

Estimation theoretic techniques for image restoration require the application of iterative non-linear optimization algorithms to produce a restored image. Several two-dimensional Fast Fourier Transform (2D-FFT) computations are required per iteration which results in very high computational complexity requirements. These computational complexity requirements have precluded the deployment of these image restoration techniques from situations with strict delay requirements in which high-performance computing facilities are not available.

The OPERA (On Board Processing Expandable Reconfigurable Architecture) program is developing a high-performance multi-core embedded processor and software development tools to enable the deployment of complex algorithms on board a sensing platform. Multi-core embedded processors combine a large number of computing elements on a single chip effectively providing cluster parallel

computers with very high-performance interconnects. The suitability of the OPERA processor for supporting estimation theoretic image restoration algorithms is studied by benchmarking the performance of a distributed memory 2D-FFT algorithm.

A distributed memory implementation of the 2D-FFT algorithm based on the row-column decomposition method is presented. This method consists of performing the 1-D FFT for each image row, followed by a matrix transpose and performing the 1-D FFT for each row of the transposed matrix, and a final matrix transpose to obtain the correct ordering of the coefficients. The 1-D FFT stages are performed independently on each row and thus very amenable to parallelization. Performing a matrix transpose in a distributed memory environment limits performance because it requires all-to-all communication among the processors, i.e. O(N^2) data transfers are needed for N processors. The proposed implementation addresses this problem in two ways: First, a parallel out-of core matrix transpose algorithm requiring only O(Nlog(N)) data transfers is used. Second the OPERA processor features a very efficient mesh network interconnecting all the processor cores. Full benchmarking results for the 2D FFT algorithm are presented in the conference.

Improving Large-telescope Speckle Imaging with Phase Masks

Brandoch Calef, Eric Therkildsen

The Boeing Company

When images are collected through the atmosphere, they are corrupted by sensor noise (shot noise, read noise, etc.) and by distortions induced by refractive index fluctuations along the turbulent path. The former effect may be overcome by using a better camera and a larger aperture. However, due to the latter effect, increasing aperture size beyond a certain point will actually decrease the quality of the images. This phenomenon may be understood in terms of the bi-spectrum SNR, which drops as the number of redundant atmospheric baselines in the pupil increases. We demonstrate that this problem can be solved by introducing a suitable pupil phase mask that spatially separates the redundant baselines.

The Super-resolution of Linear Structures in Image Data

Michael Egan

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Super-resolution of images, particularly the separation of point sources within the Rayleigh limit of an optical system, has been empirically and theoretical proved. Issues remain however around the ability to perform true super-resolution of structure within extended objects. Puschmann and Kneer (2005) conclude that “super-resolution cannot be achieved for extended objects which are not band limited.” They do find that sharpening by contrast enhancement was possible in extended images. Examination of the theoretical work of Donoho (1991) suggests the possibility of resolving linear structures under certain conditions. The resolution enhancement is only possible in the direction normal to the feature’s length vector. This paper will discuss the required conditions for super-resolution of these objects and propose a modification of the Magain, Courbin, and Sohy (MCS) method that allows super-resolved reconstruction of linear features.

Imaging Geo-synchronous Satellites with the AEOS Telescope

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The USA has significant civilian and military assets in geostationary orbit. High-resolution, ground-based imaging of these assets enables us to monitor in detail their health and safety and to detect the presence of any foreign micro-satellites that might be in proximity. Although adaptive optics compensation of ground-based imagery imparts some level of mitigation of the deleterious effects due to the Earth's turbulent atmosphere, the correction is far from optimal and there is significant room for further improvement in resolution through image post processing.

Here we show that significant gains in image fidelity and detection sensitivity can be achieved during the image post processing by the injection of prior information on the wave-front phases via wave-front sensing data and wave/phase-diverse data. The gains are such that it is possible that AEOS could become a practical resource for high-fidelity imaging and detection of GEO targets.

Shadow Imaging Efforts at MIT Lincoln Laboratory

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MIT Lincoln Laboratory

The technique of shadow imaging allows one to take pictures of distant objects that are beyond the reach of the current largest ground-based astronomical telescopes. The technique relies on the fact that stars are nearly ideal point sources and are conveniently located behind man-made deep space objects, such as satellites. As a space object passes in front of a star (an "occultation event"), the object casts a shadow on the ground -- diffraction pattern that can be inverted to reveal the silhouette of the object. This idea of reconstructing the image from the shadow on the ground was first proposed by Burns et al. (2005, Proc. SPIE 5896), but the idea has never been implemented nor has its feasibility been studied in detail. There is no doubt that the technique is very challenging: the ability to predict the location of and capture meter-size shadows (roughly the size of the space object) that travel at 0.5 km/s across the surface of the Earth has never been demonstrated experimentally; furthermore, effects such as turbulence, background light, non-monochromatic light, and atmospheric refraction have not been addressed or even considered. We have addressed these issues and our simulations show that, among other capabilities, the technique offers near diffraction-limited "imaging" from the ground, with the resolution limited only by the angular size of the occulted star. The technique is also remarkably robust against atmospheric turbulence. We are thus proposing shadow imaging as an alternative method to image deep space objects that elude ground-based optical telescopes and radars, such as non-spinning geosynchronous satellites. Most man-made satellites can be imaged with centimeter resolution by existing radars, but geosatellites that display very little motion cannot be imaged by radar and there is still no good solution for this problem. Shadow imaging can fill this imaging gap, and compares very favorably to current capabilities in both capability and cost. We are setting up an experiment to capture the first geosynchronous satellite occultation in order to prove the feasibility of shadow imaging.

Observations of a Geosynchronous Satellite with Optical Interferometry

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We report a tentative interferometric detection of an earth-orbiting artificial satellite using optical interferometry. We targeted four geosynchronous communications satellites with the Navy Prototype Optical Interferometer (NPOI) near Flagstaff, AZ, and obtained interferometric fringes on one of them, DIRECTV-9S. We used an east-west 15.9-meter baseline of the NPOI and took data in 16 spectral channels covering the 500-850 nm wavelength range. Observations took place during the "glint season" of 28 February to 3 March 2008, when the geometry of the solar panel arrays and the Sun's position creates glints as bright as 2nd magnitude of a few minutes' duration each night. We detected fringes on the satellite at approximately the 2 sigma level on 1 March at magnitude 4.5. Subsequent analysis shows that the fringe amplitudes are consistent with a size scale of 2 meters (50 nanoradians at GEO) in an east-west direction. This detection shows that interferometric detection of satellites at visual wavelengths is possible, and suggests that a multi-baseline interferometer array tailored to the angular size and brightness of geosynchronous satellites could lead to images of these satellites.

Satellite Characterization Using Small Aperture Instruments at DRDC Ottawa

Brad Wallace, Robert Lauchie Scott

Defence Research and Development Canada

Small aperture telescopes used to obtain metric information can also provide a wealth of photometric detail on Deep Space satellites. Photometry of stabilized geostationary satellites as a function of phase angle can be used to classify objects based on bus type, and can be useful in identifying objects that have been cross-tagged in the satellite catalog. Photometric measurements sampled at rates faster than the spin rates of tumbling or spinning objects can provide additional detail about the objects. We present two cases of measurement on Canadian geostationary satellites. Once case is to differentiate operational Canadian satellites from their cluster peers. The other is to seek information about the configuration and shape of the decommissioned spacecraft.

Space Object Temperature Determinations from Multi-Band Infrared Measurements

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We describe a technique to determine the temperature of a Resident Space Object (RSO) from multiple infrared (IR) bands. The characteristic temperature of an object is the temperature of the Planck function that has the closest least squares fit to the observed irradiance in at least three infrared bands. The characteristic temperature and the effective solid angle are free parameters in a formulation that requires simultaneous minimization, across all bands, of chi-square expressions using modeled irradiances and the measured irradiances and their errors. Solutions are determined from a multi-dimensional Levenberg-Marquardt fitting algorithm. The advantage of this approach is that it provides a single, best-fit solution to the RSO modeled as a gray body radiator. In contrast, a 2-band (color) temperature approach using three or more bands produces different solutions for different band combinations with no objective way of determining which solution is best.

We apply this technique to IR measurements of RSOs obtained by the Midcourse Space Experiment (MSX) satellite. Our MSX database of serendipitous RSO observations contains multi-band IR measurements for hundreds of objects, including payloads, rocket bodies, and debris. Using this technique, we have obtained object characteristic temperatures and InfraRed Cross Sections (IRCS) under a large variety of phase angle and solar illumination conditions, including eclipse. We examine specific cases in detail. We also compare and contrast results for population groups based on orbit type (LEO, MEO, and GEO) and other parameters of interest. In addition, we look at a number of cases where color and characteristic temperatures and solid angles have been determined for the same object measurements and show that the characteristic parameters are more consistent with the Planck function model when expressed as their equivalent isophotal emissions.

Optical CubeSat Discrimination

Doyle Hall[1], Paul Kervin[2]

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The numbers and capabilities of small cubical satellites have increased significantly during the past few years. Built by a variety of US and non-US University, commercial and military organizations, such CubeSats typically occupy low-Earth orbits (LEO) and have mission lifetimes spanning from weeks to years. Most are nearly perfectly cubical, although some have elongated shoebox shapes. They are often

launched in groups inserted into LEO almost simultaneously from the same launch vehicle. This creates a significant need for remote methods of discriminating one from another. Each of the eight edges of a typical CubeSat spans 10 to 30 cm, subtending 0.1-0.3 urad (0.02-0.06 arcsec) when viewed by a sensor at a range of 1000km too small to be resolved by even the most advanced ground-based optical and radar imaging instrumentation. This work discusses non-imaging methods of optical CubeSat discrimination, focusing specifically on using temporal photometry of reflected sunlight. Different CubeSats launched within a group often have many similarities in structure. For instance, solar arrays typically cover all or most of the six cube faces, so gross photometric differences from main-face reflections generally cannot be used to distinguish one CubeSat from another. However, our analysis indicates that these objects often deploy wire antenna and/or cylindrical boom structures after orbital insertion. Because, each satellite's specific mission drives the exact configuration of such structures, they can serve as unique identifiers for these otherwise nearly identical objects. Furthermore, because such cylindrical structures readily glint sunlight, they create tell-tale photometric patterns that can reveal their specific orientation with respect to the main cubical body, thereby providing a means of using temporal reflected-sunlight photometry as a means of CubeSat discrimination.

Resolving Rotational Ambiguities for Spin-stabilized Satellites

Keith Knox

Boeing LTS

The rotation rates of asteroids can be determined by analyzing the periodic frequencies of time-varying photometric signatures from unresolved images of the asteroid. Due to the random nature of the asteroid, in terms of shape and albedo, a unique period can be determined. Because the various sides of an asteroid are different, the smallest repeat cycle of the photometric curve is directly related to the rotation rate of the asteroid.

When this method is applied to spin-stabilized satellites, an ambiguity arises. Spin-stabilized satellites are often constructed in the shape of a cylindrical regular polygon. Unless the various sides of the satellite have different albedos or otherwise reflect the light differently, the period of the rotation of the satellite will be an integral multiple of the smallest period in the signature. In other words, the rotational period of the satellite will be N times bigger than the smallest period in the signature, where N is the number of identical sides on the satellite. With this ambiguity, one has to know a priori the number of sides on the satellite to measure the rotation rate. This talk will present an analysis of the photometric signatures of a diffuse, rotating cylindrical regular polygon and relate it to the periodicity in the signature. The analysis will show that the modulation of the periodic signal decreases as the number of sides on the cylindrical polygon increases. The modulation of the periodic curve is defined as the difference between the maximum and minimum values divided by the sum of the maximum and minimum values. For a large number of sides, this modulation falls off roughly as the inverse of the cube of the number of sides.

Photometric signatures of actual satellites in orbit are complicated and will not be adequately represented by a diffuse regular polygon model, but this analysis does provide insight into the problem of the multiple-side satellite rotation rate ambiguity.

Unmixing the Materials and Mechanics Contributions in Non-resolved Object Signatures

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Temporal behavior of a non-resolved object signature is a function of the fractional abundance content of its contributing materials. These abundances are, in turn, a function of the orbital behavior of the space object. For example, in case of a spinner, the fractional abundances will display a cyclic behavior. The present work uses a positive matrix factorization technique to extract the temporal variation of material fractional abundances, or material loci, from non-resolved object signatures. As a result, the signature is replaced by a set of material loci, which are further condensed into one or more 1-D signals. A time-frequency analysis of these 1-D signals provides information about the orbital character of the space object. This paper describes the abundance calculation and time-frequency analysis that, taken together, extract information about materials and mechanics from non-resolved object signatures.

Noise-Tolerant Hyperspectral Signature Classification in Unresolved Object Detection Using Adaptive Tabular Nearest Neighbor Encoding

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Accurate spectral signature classification is key to the non-imaging detection and recognition of space borne objects. In classical hyper spectral 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 tend 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 non-imaging 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 non-ergodicities, 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 hyper spectral images of space borne 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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The Magdalena Ridge Observatory's 2.4-meter Telescope: A New Facility for Follow-up and Characterization of Near-Earth Objects

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The Magdalena Ridge Observatory's (MRO) state-of-the-art 2.4-meter telescope is contributing to the Near-Earth Object (NEO) effort by working in partnership with existing NASA telescopic survey programs to provide the astrometric and physical characterization follow-up required to meet the congressional directive to identify bodies 140 meters in diameter or larger that have the potential to impact the Earth. The 2.4-meter's large primary mirror size allows the observatory researchers to acquire accurate astrometry and important characterization data (colors, lightcurves, and spectra) on the faintest objects detected. The system is capable of doing 2% photometry on bodies having a V (visual) magnitude of ~20.5 with 60 second exposures. The working limit for astrometric follow-up is V~24-25 under ideal observing conditions. The objective of the program is to characterize the small end of the NEO size distribution and ensure that newly discovered objects are not lost (maximizing the chance that their orbits are accurately catalogued). A significant advantage of a large-aperture telescope is the ability to work effectively in less than photometric conditions, resulting in a high productivity rate.

The resulting information acquired on these potentially hazardous asteroids and comets (e.g., absolute magnitudes, sizes, rotation rates and orientations, binary or tumbling objects) should considerably improve our understanding of the NEO population down to its smallest members. Characterization studies that determine physical properties such as spin rates and orientations, shapes, material type and internal structure/strength are important for properly addressing and mitigating any potential threats from dangerous Earth-crossing objects.

A recent example of the facility's contribution to NEO studies was its participation in an observing campaign to improve the astrometric accuracy of the orbit of a recently discovered V~24 magnitude asteroid (2007 WD5) with the potential to impact Mars on January 30, 2008. Orbital data acquired by the 2.4-meter telescope on December 18, 2007 through January 3, 2008 was used by NASA to increase the precision of the asteroid's orbit and constrain the impact probability (the likelihood of a collision was eventually derived to be 1 in 10,000, i.e., it missed Mars).

Reference-less Detection, Astrometry, and Photometry of Faint Companions with Adaptive Optics at 1, 2 and 5 microns

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We propose a new post-processing technique for the detection of faint companions from a sequence of adaptive optics corrected exposures. The algorithm exploits the difference in statistics between the on-axis and off-axis intensity and in principle it does not require the signal to be above the noise level in surrounding pixels. We show that the method is particularly useful in dealing with static speckles which are the greatest obstacle in detecting faint companions and exoplanets.

The classification algorithm produces a map of statistical properties of pixels. This map has a maximum at the location of a faint companion. Accurate differential astrometry is obtained by over-sampling this map and searching for maximum.

We call the new approach to differential photometry "distribution deconvolution". Two-dimensional image deconvolution is replaced by a one-dimensional time-series deconvolution. The intensity distributions at the location of a star and a companion are scaled and shifted versions of the same statistical distribution.

This fact is exploited in a one-dimensional, "blind", iterative deconvolution scheme with the speckle distribution as the convolution kernel.

To test the accuracy of our "speckle discrimination" methods we use adaptive optics short-exposure data from three observing campaigns: 20% Strehl ratio I-band observations with the 5m telescope at the Palomar Observatory, moderate Strehl ratio (50%) K-band data from the Lick Observatory's 3m telescope, and very high quality (Strehl ratio above 80%) M-band images from the MMT Observatory's 6.5m telescope.

For companions located less than 0.5 arcsec away from the bright star and being 10-100 times fainter, differential astrometry is accurate to within 0.05 arcsec. For separations larger than 1 arcsec astrometric error is less than 0.01 arcsec. Errors in differential magnitude range from 0.01 to 0.5 magnitudes for separations less than 0.5 arcsec and contrasts as large as 6 magnitudes. The accuracy of new algorithms compares favorably to the standard procedure of PSF-fitting when the calibration PSF matches the science image. In the more probable case of mismatch in calibration, "speckle discrimination" yields results which are an order of magnitude more accurate.

We predict that the described techniques could be applied to images with exposures as long as 0.5 sec in K-band and even longer in M-band. All three proposed algorithms are self-calibrating, i.e. they do not require observation of a calibration star after the science target thus improving the observing efficiency.

CRBLASTER: A Fast Parallel-Processing Program for Cosmic Ray Rejection in Space-Based Observations

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National Optical Astronomy Observatory

Many astronomical image analysis tasks are based on algorithms that can be described as being embarrassingly parallel--- where the analysis of one sub image generally does not affect the analysis of another sub image. Yet few parallel-processing astrophysical image-analysis programs exist that can easily take full advantage of today’s fast multi-core servers costing a few thousands of dollars. One reason for the shortage of state-of-the-art parallel-processing astrophysical image-analysis codes is that the writing of parallel codes has been perceived to be difficult. I describe a new fast parallel-processing image-analysis program called CRBLASTER which does cosmic ray rejection using van Dokkum's L.A.Cosmic algorithm. CRBLASTER is written in C using the industry standard Message Passing Interface library. Processing a single 800x800 Hubble Space Telescope Wide-Field Planetary Camera 2 (WFPC2) image takes 1.87 seconds using 4 processors on an Apple Xserve with two dual-core 3.0-GHz Intel Xeons; the efficiency of the program running with the 4 cores is 82%. The code has been designed to be used as a software framework for the easy development of parallel-processing image-analysis programs using embarrassing parallel algorithms; all that needs to be done is to replace the core image processing task (in this case the C function that performs the L.A.Cosmic algorithm) with an alternative image analysis task based on a single-processor algorithm. I describe the design and implementation of the program and then discuss how it could possibly be used to quickly do time-critical analysis applications such as those involved with space surveillance or do complex calibration tasks as part of the pipeline processing of images from large focal plane arrays.

AO Images of Asteroids, Inverting their Lightcurves, and SSA

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In a program to study asteroids with large telescopes, we have recently obtained images of Main-Belt asteroids with adaptive optics (AO) on the Keck II 10 meter telescope, the world's largest. Although generally featureless as expected, these images show irregular asteroid outlines, and by following the changing size and orientation we have been able to deduce full tri-axial ellipsoid dimensions and spin axis direction in less than one night for individual asteroids. Even before the first such AO images, Kaasalainen and his colleagues made attempts to deduce the shape of asteroids from their light curves. We compare our AO images to these light curve inversion (LCI) models, and show the excellent agreement. Similar techniques can be applied to satellite light curves.

Determination and Prediction of Satellite Orbits

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University of Texas at Austin

During the last 30 years, considerable progress has been made in the area of precision orbit determination for earth orbiting satellites. The geodetic satellites have been used to support studies of the Earth, including its rotation and shape, gravity field, tidal variations, surface topography and the accurate determination of the location and motion of the tracking stations. In the case of the current GRACE mission, repeat measurements of gravity field allow determination of the time variable Gravity signal at a level of concern in the orbit fit and prediction problem. The requirements of the current geodetic missions vary, but orbit accuracy is always a high priority. The ability to determine the satellite orbit with sufficient accuracy to fully exploit the centimeter level precision of contemporary satellite laser ranging, GPS phase measurements and radar altimeters requires high fidelity force models to describe the satellite motion and well distributed temporally and geographically distributed data. The ability to predict accurate orbits dictates an even greater challenge. An accurate fit during an observation interval does not ensure an accurate prediction. For non-thrusting satellites, the prediction of the satellite orbits is limited by errors in the gravity model, the atmospheric density model and the solar and earth-reflected radiation pressure models. The relative importance of these three error sources will depend on the satellite altitude. The prediction accuracy is also influenced by such decisions as the orbit fit interval, from which the prediction evolves. In these presentations, advancements in the force models and data processing methodology will be reviewed. Particular attention will be given to the improvement in the model for the Earth's gravity field accomplished with the results from the current GRACE mission. Finally the implications for improvements in the orbit prediction accuracy will be considered.

Orbit Determination of Space Debris

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When a piece of space debris is observed by optical telescopes, angular and angular-rate information can be estimated from the track with a low uncertainty using basic kinematic relations. However range and range-rate information is to a large extent undetermined, other than by a few weak physical constraints. The standard approach in performing an orbit determination between two separate tracks of data is the least squares approach. This approach, however, presupposes a nominal estimation of the true orbit that is later corrected by the least squares algorithm. Since such an initial estimate is not known, this approach in practice is manually intensive and ill-suited to deal with the torrents of data expected when new high power telescopes come online within the next few years. The approach we present here, on the other hand, takes a more global perspective. After computing the admissible region, the set of all points possible belonging to a given track, for each of the two tracks, we then dynamically evolve or regress these two-dimensional regions into a common coordinate system and finally search for possible intersections. By utilizing this type of process, large reductions can be made to the uncertainty in the topocentric range, range-rate space. Errors in the angular measurements can now be included and a standard least squares approximation can refine the initial guess orbit produced by our method. This paper discusses some of the complications and advantages associated with performing these intersections.

Algorithms for Calculating KAM Tori

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The prediction by Kolmogorov, Arnold, and Moser that most lightly perturbed orbits will lie on tori has lain fallow for over 50 years. Unlike a perturbation solution, their frequencies are already known to high accuracy. Also, instead of proceeding in an analytic development of literal series, as in a perturbed two body approach, the torus is obtained directly as a Fourier series with numerical coefficients. KAM tori introduce a new set of canonical elements that are unique to the particular Hamiltonian system involved, and differ from a perturbation solution in that they are the actual solution to the problem.

They allow much more of the underlying dynamics to be incorporated in the solution. For example, an earth satellite may have the entire geo-potential included in its torus dynamics, with only air drag left to be handled by a perturbation approach. They offer simplicity of implementation for a user, who need only sum a Fourier series.

Since orbits lying within the same torus do not drift apart, they are also the natural solution to the formation flight problem in orbital mechanics.

However, the calculation of KAM tori has proven to be somewhat of a challenge. It is critical to have knowledge of the systems' frequencies to moderate accuracy before torus fitting can succeed. In this paper we investigate and compare the achievable accuracy of three methods of calculating a KAM torus. These are 1) direct least squares fitting of the torus to a numerical integration, 2) numerical integration and least squares fitting of a finite - time Fourier transform, and 3) least squares fitting to the underlying equations of motion, with constrained initial conditions.

Once the torus is in hand, we show how to obtain the corresponding action momenta, and to describe local motion near (but not quite on) the baseline torus. This is essential if tori are to be used for orbit determination and themselves to serve as the basis of further perturbation work, for, e.g. air drag.

Examples will include the restricted problem of three bodies, and (hopefully) the earth satellite / geo-potential problem. We develop methods for estimating the accuracy of the torus.

Improved Conjunction Analysis via Collaborative Space Situational Awareness

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With recent events such as the Chinese ASAT test in 2007 and the USA 193 intercept in 2008, many satellite operators are becoming increasingly aware of the potential threat to their satellites as the result of orbital debris. However, to be successful at conjunction monitoring and collision avoidance requires accurate orbital information for as many space objects (payloads, dead satellites, rocket bodies, and debris) as possible.

Given the current capabilities of the US Space Surveillance Network (SSN), approximately 18,500 objects are now being tracked and orbital data (in the form of two-line element sets) is available to satellite operators for 11,400 of them (as of 2008 April 1). The capability to automatically process this orbital data to look for close conjunctions and provide that information to satellite operators via the Internet has been continuously available on CelesTrak, in the form of Satellite Orbital Conjunction Reports Assessing

Threatening Encounters in Space (SOCRATES), since May 2004. Those reports are used by many operators as one way to keep apprised of these potential threats.

However, the two-line element sets (TLEs) are generated using uncooperative tracking via the SSN's network of radar and optical sensors. As a result, the relatively low accuracy of the data results in a large number of false alarms that satellite operators must routinely deal with. Yet, satellite operators typically perform orbit maintenance for their own satellites, using active ranging systems. This data is often an order of magnitude more accurate than that available using TLEs. When combined (in the form of ephemerides) with maneuver planning information, the ability to maintain predictive awareness increases significantly. And when satellite operators share this data, the improved space situational awareness, particularly in the crowded geosynchronous belt, can be dramatic and the number of false alarms is reduced considerably.

Working with Intelsat, Inmarsat, and EchoStar, CelesTrak now offers a new service--SOCRATES-GEO--which takes advantage of the availability of satellite operator-supplied orbital data, along with other improved sources of orbital information, to provide improved conjunction monitoring and automatic notification of potential threats based on user-defined criteria. This paper will discuss the SOCRATES-GEO process and demonstrate the potential improvements possible using satellite operator-supplied orbital data.

Angles and Range: Initial Orbital Determination with the Air Force Space Surveillance Telescope

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The institution of a robust, comprehensive program of Space Situational Awareness (SSA) necessarily includes observations by ground-based optical and infrared (OIR) telescopes. The Air Force Space Surveillance Telescope (AFSST) has been proposed as a system of telescopes designed to address the ground-based component of comprehensive SSA. A hallmark of our definition of AFSST is that it be composed of inexpensive, replicable telescopes programmed to accomplish multiple surveillance programs, but designed to achieve the difficult design-driving task of accomplishing an un-cued search for small objects in Low Earth Orbit (LEO).

We discuss the configuration of AFSST and describe one technique by which AFSST simultaneously acquires angle and range data for accurate real-time determination of LEO orbital elements, even upon first detection of the object.

Space Debris - Birth to Death

David Finkleman

Center for Space Standards and Innovation

This paper will present a process and tools for predicting events that might generate orbital debris, estimating the distribution of debris that would be created, assessing the evolution of the debris, inferring consequences, and planning mitigations. We will also describe how these techniques contribute to establishing and technical and operational environment for debris management and mitigation through international standards.

Orbital debris research has focused on estimating the distribution and evolution of the Earth's man made debris environment in order to estimate long term risk. We have applied several widely used collision and explosion models to predict the prompt debris environment, short term moderation of the debris cloud through reentry, mid-term assessment of conjunctions with operational satellites, and identification of the long term persistent aftermath. We trace the contribution of specific events from birth of the debris cloud to its final state. We provide distributions of fragment sizes, masses, and radar cross sections which we use to identify the trackable population and the remaining population which is either imperceptible to space surveillance radars or which eludes surveillance coverage. This is important for planning operational launches, transition trajectories, and orbit selection to minimize risk.

We will present assessments of the Feng Yun and USA 193 events, exploring alternative conjunction geometries that might have minimized risk. We will explore hypothetical test cases for planning intercepts that minimize or completely avoid creating persistent debris.

We will also describe the international initiative to develop standards, tools, and techniques that form the operational and collaborative environment for debris management and minimization. This environment includes standards for disposal of geostationary and low Earth orbit satellites, approaches to passivating space vehicles at end of life, approaches to gauging remaining propellant to assure sufficient energy for safe end of mission disposal, and schemes for exchanging orbit data from diverse sources for collaborative conjunction avoidance or to develop surveillance campaigns to catalog and monitor new debris.

Space debris, birth to death, begins with standards and design techniques specifically to minimize debris and extend to predicting potential debris events and assessing the spectrum of consequences from prompt phenomena to long term orbit lifetimes.

Survey Strategies for Detection of GEO Debris

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Since January, 2002, the Orbital Debris Program Office (ODPO) at NASA/JSC has undertaken an optical wide field telescopic survey to better define the GEO debris environment, specifically to obtain photometric and orbital information on faint targets that are not tracked by the Space Surveillance Network. The survey has been carried out on the University of Michigan's 0.6/0.9 m Curtis-Schmidt telescope, called the Michigan Orbital DEbris Survey Telescope (MODEST), located at Cerro Tololo Inter-American Observatory (CTIO) near La Serena, Chile. Optimum coverage of the GEO environment requires sampling the multi-dimensional space of orbital elements of GEO objects in a uniform manner. A typical survey observation of a potential GEO object includes eight detections in a 5 minute time-span. This is not enough time in the orbital arc to determine a full six-parameter orbit, and so we have to assume a circular orbit. The orbital element space defined by inclination (INC) and right ascension of the ascending node (RAAN) provides insight into the distribution of both the cataloged (CT) and un-catalogued (UCT) objects. Based on MODEST's actual observational coverage between 2004 and 2006, the detection probability plot for the INC - RAAN space shows a detection probability of greater than one for most objects in GEO orbits. These probability mappings aid in identifying the orbital space that needs better coverage or is over-sampled, as well as showing the likelihood of detecting debris in the observed fields.

Various observing scenarios based on different spatial, diurnal, and seasonal samplings will be compared and ways to improve the probability of detection for future GEO surveys will be discussed. In particular, optimum observing strategies will be developed for NASA's meter class autonomous telescope (MCAT), scheduled for deployment on the Kwajalein Atoll in 2010, as well as for future MODEST observations.

Color Photometry and Light Curve Observations of Space Debris

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The ESA debris surveys at high altitudes revealed a significant population of small-size debris in GEO and GEO-like orbits. For a sub-set of the discovered objects high area-to-mass ratios were determined. The nature and the origin of most of this debris are currently unknown. There are several ways to identify possible progenitors or parent objects. Studies of the dynamical properties of the objects are one way; another possibility is to acquire more information on the sizes, shapes and possibly the material of the debris pieces. Non-resolving observation techniques like color photometry, light curves, and spectrometry are the only ground-based optical methods applicable for objects at the given distances.

Multi-color observations of small-size space debris including high area-to-mass ratio debris were obtained with the ZIMLAT 1-meter telescope. We will discuss the techniques used to obtain colors for objects with considerable brightness variations over short time intervals. The colors of the small-size debris are compared with measurements from large ‘known’ debris objects like abandoned upper stages.

Light curves of a variety of space debris were obtained over different time spans. The data set in particular contains observations of high area-to-mass ratio debris at high altitudes (in GEO-like orbits), but also some observations of high area-to-mass fragments of the Fengyun-1C breakup in LEO. Large debris objects show distinct signatures and periods in their light curves. These features seem to be stable over long time intervals and may thus be used to identify the objects. The observed small-size debris, on the other hand, show highly variable light curves with strongly changing amplitudes and periods, indicating complex shapes and scattering properties.

Classification and Characterization of GEO Population Based on Results of the ISON Observations

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The ISON international observation network developed in the last few years continues to produce new results in the field of studying of high altitude (though mainly GEO for a while) orbits population of artificial objects. During the last 3 years of the work 143 bright (9th-15th magnitude) and 353 faint (fainter than 15th magnitude) earlier unknown objects are discovered, including high area-to-mass ratio (AMR) ones. Population of continuously tracked objects in GEO region is increased more than 30 per cent compared to the officially issuing the U.S. SSN catalogue data. New discovery of 15th-16th magnitude uncorrelated short tracks continues to happen in every GEO survey. Specially developed algorithm permits to find correlation between such tracks that in turn results in discovery of new objects with well established orbits. In addition, the ISON obtained the large amount of data for almost all previously known GEO objects. Collected data for the first time represents deterministic picture of the bright part of the whole GEO population with the high level of completeness. Examples of the most interesting discoveries and overall statistics will be given. Importance of studying the GEO population step by step in terms of brightness will be shown.

Fragments in GEO region are discovered on different types of orbits both drifting and librating. That means there are different GEO debris creation processes involved into the generation of the fragments. Possible events and sources of the observed space debris will be discussed.

We will also discuss observed and calculated properties of studied GEO population (physical and orbital), including distribution of the AMR, orbital parameters, observed brightness. Extended classification of GEOs by orbital motion type will be presented. There will be given examples of analysis of the discovered unexpected changes in orbital motion of old passive GEO objects which can not be explained by natural forces like gravity or solar radiation pressure.

Prediction and Tracking Analysis of a Class of High Area-to-mass Ratio Debris Objects in Geosynchronous Orbit

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A subset of the population of deep space objects is thought to be high area-to-mass ratio (A/m) debris having origins from sources within the geosynchronous orbit (GEO) belt. The typical A/m values for these have been observed to range anywhere from 1s to 10s of m2/kg, and hence, are susceptible to significant solar radiation pressure effects which result in long-term migration of eccentricity (0.1-0.6) and inclination over time. However, the nature of the debris orientation-dependent dynamics also results time-varying solar radiation forces about an average value over shorter time scales which complicate the short-term orbit determination (OD) processing and prediction. In November of 2007, several of these objects were acquired and tracked from the 0.9 m telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile using prediction products derived from the orbit determination of optical angles tracking data. The estimated states computed using the Orbit Determination Tool Kit (ODTK) included dynamic estimation of the area-to-mass ratio, the variations of A/m relative to an average value. The work presented in this paper assesses the OD, prediction and tracking performance using the ODTK derived predictive products that were utilized during the survey, the CTIO tracking data that was collected, and the post-fit orbit products resulting from additional data collected after the observations. The OD and A/m estimation performance for the selected objects tracked is presented, and the derived prediction performance is also analyzed by comparison with the CTIO 0.9 m telescope acquisition metrics. The post-fit prediction assessments of 10s of kilometers positional accuracy over 24-48 hour prediction spans is consistent with the arc-minute level tracking offsets that were observed.

Assessment and Categorization of TLE Orbit Errors for the US SSN Catalogue

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ESA/ESOC Space Debris Office (OPS-GR)

Based on Two-Line element (TLE) data obtained from the US Space Surveillance Network, the Space Debris Office at ESA predicts conjunction events. Currently two ESA missions, the Low-Earth orbiting satellites ERS-2 and Envisat, are covered. For all conjunction events that passed a so-called smart sieve filtering the related collision risk is assessed and provided in a bulletin that is distributed by email daily. In case a high-risk conjunction event is forecast external tracking data of the chaser are acquired. Orbit determination using these data gives improved state and covariance information of the chaser. A subsequent re-assessment of the collision risk allows to decide on the necessity of collision avoidance maneuvers and to support the planning of necessary maneuvers. At ESA's Space Debris Office the central tools for analyzing conjunction events are the collision risk assessment software CRASS and the orbit determination software ODIN.

The risk assessment faces the problem that no covariance information is available for the TLE data set. CRASS copes with this issue by introducing pre-defined look-up tables for the initial covariance that are sorted by eccentricity, perigee height and inclination. Through ODIN the covariance information was obtained from comparing states derived directly from the TLE data with states resulting from an orbit determination using pseudo-observations derived from TLE data. The obtained covariance information reflects the insufficiencies of the TLE (SGP4) orbit model combined with limitations in the orbit determination and orbit propagation accuracy. Until now the CRASS look-up table contained only a limited number of exemplary objects.

Recently, a new command-line version of ODIN has been developed, allowing repetitive, fully automated analyses. Thus, the application of the covariance estimation procedure to the entire TLE catalogue becomes feasible. We address the effect of orbit determination and orbit propagation accuracy of ODIN by comparing orbits obtained from precise radar tracking with orbits from TLE data, and by comparing propagated TLE-based Envisat orbits with those obtained from laser-tracking and Doppler ranging, which are of cm-accuracy. For a current catalogue we assess the TLE orbit errors in along-track, cross-track, and out-of-plane coordinates (i.e. as function of eccentricity, inclination and perigee height). This analysis not only provides a more realistic look-up table for the collision risk assessment with CRASS. Insights into the applicability of the TLE theory to certain classes of orbits will be helpful in particular for the selection of data product formats for the European SSA system that is under study. Finally the presented approach may be the basis for comparisons of snapshots of the TLE catalogue of past epochs.

Comparison of Re-entry Prediction Using MSISE-00 and Jacchia 1971

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Japan Aerospace Exploration Agency

Japan Aerospace Exploration Agency has monitored the re-entry of rather large space debris on daily basis since 2000. The prediction of the re-entry time and location depends on atmospheric density deeply and the timing to choose the best atmospheric density model at the best timing is also the key factor for the better prediction. Two famous and mostly used atmospheric densities among each space agency are MSISE-00 and Jacchia 1971 these days. The comparison between these two models has conducted among several agencies so far. However there are still few comparisons for re-entering space debris, such as at the altitude of 100 – 200km. In this paper we would like to discuss the comparison result of re-entering prediction analyzed by two atmospheric densities, MSISE-00 and Jacchia 1971.

PERCS, the 10-meter Diameter Laser Imaging Calibration Sphere in Low-Earth-Orbit

Paul Bernhardt, Andy Nicholas, Linda Thomas

Naval Research Laboratory

A unique resource in low-earth-orbit (LEO) will be available in a few years to determine the accuracy of ground based systems for satellite laser imaging. The Precision Expandable Radar Calibration Sphere (PERCS) is a spherical wire frame with 360 vertex points. Corner-cube reflectors will be located at each vertex in the sphere at a radial distance of 5 meters from the center of the sphere. The distance between adjacent vertices is exactly 116 cm in a uniform distribution around the surface of the sphere. The rigid frame will be deployed from a rocket as an expanding Hoberman sphere with torsion springs located at the centers of 810 scissors that deploy the PERCS structure. The primary use of PERCS is calibration of HF radars but the addition of retro-reflectors on each vertex makes is useful for validation of the metric capabilities with ground laser imaging telescopes. The preliminary design for the retro-reflector placement has a 1-cm diameter corner cube reflectors placed in a triangle at each vertex. The small diameter of the reflectors is used to spread the laser return so that velocity aberration from the orbital motion of the satellite does not prevent laser beam from being reflected back to the source. Larger diameter spoiled-reflectors or multiple 1-cm reflectors at each vertex are under consideration to increase the reflected photon flux for improved signal to noise at the observation telescope. The large number of separate reflectors around a large 3-dimensional object both enhances the total return light intensity from long (> 100 ns) pulses and allows determination of pulse reflection time delay from a variety of ranges to the sphere surface. The altitude of PERCS is chosen to be 500 to 800 km. The open frame structure of PERCS and large density from the steel struts provide a 10-meter diameter satellite with very low drag area and large mass (200 kg). PERCS will remain in LEO for at least 5 years. Ground observations of PERCS with laser imaging systems will be used to measure the effects of electromagnetic forces on the rotation and motion of the PERCS sphere. The current status of the design, construction and launch of PERCS will be described.

Validation of MODTRAN(TM) for Planetary Atmospheres

Alexander Berk, Lawrence Bernstein

Spectral Sciences, Inc.

At last year’s AMOS conference we presented a new version of MODTRAN(TM) for radiative transfer in planetary atmospheres. The initial application was to Neptune and demonstrated good agreement with remotely obtained spectral data from the near UV through the far IR. This year, we describe upgrades to the model and demonstrate its application to a wider variety of moons and planets in our solar system, including Titan, Triton, Saturn, and Jupiter. Comparisons will be made to spectra from many different sources, including, for example, the Cassini-Huygens probe that landed on Titan. Some of the model upgrades include extending the spectral data bases to higher temperatures and adding new aerosol and haze models.

The Utility of Time-varying Spectral Similarity Analyses Using Multispectral and Hyperspectral Imagery in Diagnosing Satellite Anomalies

Joseph Coughlin

Master Solutions, LLC

Correctly determining satellite health and status is an important aspect in ascertaining satellite anomalies. Spectral data has often been proposed as having the potential to provide one part in the larger puzzle of determining satellite status. This paper presents the results of our study to clarify the utility of spectral data in ascertaining satellite anomalies, as compared to conventional broad-band imagery, using spectral similarity techniques.

This study focuses on the extraction of time varying signature distributions for non-resolved images using spectral similarity techniques. Analysis of the time varying distributions has potential to show the rough material similarities as a function of time without requiring a thorough material end-member extraction for each spectral image. We model time-varying multispectral and hyperspectral satellite signature images for different satellite models, configurations, and lighting conditions in the VIS/NIR spectral region for a realistic sensor system. We analyze the resultant spectral signatures to determine spectral similarities and material distributions. By varying the model configurations we analyze the presence and distribution of different materials, reflectivity changes, rotation rates, and temporal changes to ascertain the effects of potential anomalies, such as incomplete or improper solar panel deployments.

To clarify the utility of spectral data, we compare the broad-band time variability in the signatures to the spectral similarity time variability. Our initial results indicate that spectral similarity derived from the spectral signatures can yield relevant information to determine satellite anomalies. This paper presents the results of our internal study to clarify the utility of spectral data in ascertaining satellite anomalies.

Space Object Characterization with 16-Visible-Band Measurements at Magdalena Ridge Observatory

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Data was collected at the Magdalena Ridge Observatory (MRO) with the Multi Lens Array (MLA) camera coupled to the MRO 2.4 m telescope. MRO is located at 33.985oN, 252.811oE at an altitude of 3193 m, approximately 30 miles West of Socorro, NM and its use is intended for both astronomical research and resident space object (RSO) characterization. The purpose of the measurement campaign was to collect Resident Space Objects' (RSO) resolved images and unresolved signatures in the 16 spectral bands, ranging from 414 nm to 845 nm. During the campaign, observations were made over five sessions for the period 21-27 September 2007. During that time, we succeeded in observing and collecting data for a total of 18 different calibration stars and 40 different RSO's, mostly those in low Earth orbit (LEO). A major objective of the measurement campaign is to collect RSO data that can be used to select spectral bands optimized for estimating surface material composition. The analysis results help us determine the nominal spectral differences for typical RSO materials. The paper will discuss the potential of using a multi-band camera for RSO identification and characterization.

Space Object Modeling: Some Examples

Michael Duggin[1], William Glass[1], Jim Riker[1], Meiling Kline[2], Deith Bush[3], Chris Sabol[1]

[1]AFRL, [2]Northrop Grumman, [3]Schafer Corp

Over the course of many years, the Air Force has developed a modeling capability to characterize space objects. This consists of a facet model which may be oriented in three directions to positionally and radiometrically match observations. Characteristics of the model have been described elsewhere, but will be summarized. The output of the model may be used to generate multiband data sets in order to test analytical algorithms used for design and monitoring questions. Examples involving the Hubble Space Telescope are presented.

Simultaneous Single Site Color Photometry of LEO Satellites

James Frith, Russell Knox, Brooke Gibson, Kawailehua Kuluhiwa

Oceanit

Several Low Earth Orbit (LEO) satellites were observed simultaneously using three identically configured telescopes from the High-Accuracy Network Determination System (HANDS) at the Remote Maui Experiment (RME) observing site. Each telescope observed the satellites using a different Johnson filter (B,V, or R). In this way we acquired simultaneous color photometry of multiple LEO objects, and color indices were produced. We believe this approach will yield promising results in the field of Non-Resolved Satellite Characterization. We present our data, results, and conclusions.

The Joint Milli-Arcsecond Pathfinder Survey Mission: Application for Space Situational Awareness

Ralph Gaume

US Naval Research Laboratory

Rapid and accurate threat assessment and characterization are key elements in the quest for space superiority. These often depend on rapid orbit determination, accurate orbit propagation and object characterization. Threat scenarios involving new launches or vehicle maneuvers demand rapid and precise position metrics to determine and propagate new orbital elements. Existing and planned ground and space-based optical surveillance systems are optimized for the detection of Resident Space Objects (RSOs), which unfortunately, compromises their ability to determine position metrics at the highest possible accuracy levels. An SSA architecture would potentially benefit from supplementing existing and planned detection assets with a dedicated high metric accuracy orbit determination asset or assets, with the potential for 24/7 taskability and near-real time capability. By optimizing an instrument to perform position measurement rather than detection, significant improvement may be realized in rapid orbit determination vs. current and envisioned systems, enabling rapid and accurate threat assessment and characterization. The United States Naval Observatory (USNO) is developing the space-based J-MAPS mission to support current and future star catalog and star tracker requirements. By its very nature, USNO's J-MAPS mission, a microsatellite designed to take very high precision measurements of star positions (astrometry), is ideally suited to make high metric accuracy measurements for brighter GEO RSOs. The J-MAPS mission will demonstrate novel and innovative measurement techniques and technologies, including new focal plane technologies such as CMOS-Hybrid active pixel sensors. The J-MAPS baseline also includes a novel filter-grating wheel, of interest in the area of non-resolved object characterization. We will discuss the status of the J-MAPS mission, including the current mission baseline, and discuss Space Situational awareness applications of the J-MAPS mission, including RSO orbit determination and SOI.

MEMS Segmented Deformable Mirror for Adaptive Optics

Michael Helmbrecht, Min He, Carl Kempf, Nathan Doble

Iris AO, Inc.

Microelectromechanical system (MEMS) technology has long been touted as a way to fabricate compact, high-performance deformable mirrors (DMs). The MEMS technology has the ability to build large-actuator-count DMs in a compact form factor. After over ten years of development by university researchers and private companies, the technology is coming to fruition. Recently, researchers and MEMS DM manufacturers have demonstrated DMs with large stroke, fast response times, actuation with no hysteresis, and good open loop control.

This paper will introduce the Iris AO segmented DM to the AMOS community by discussing recent developments and development directions. The Iris AO DM is a high-stroke (4-10µm), 37-segment DM capable of piston/tip/tilt (PTT) motions. Relatively thick mirror segments assembled onto actuator arrays provide a robust optical surface that stays flat over large temperature ranges (0.56 nm PV bow/°C) yet allow the DM to operate at kilohertz update rates (2.3 kHz response). Excellent linear open-loop control has been demonstrated with a factory-calibrated PTT controller. Over the majority of the operating space, the DM can be positioned to better than 30 nm rms residual surface figure error. Furthermore, the factory-calibrated controller allows the user to position the DM with meaningful coordinates (piston/tip/tilt) positions rather than nonlinear voltage values. Calibration values for the DM are stored on the printed circuit board the DM is mounted to.

To operate the DM, Iris AO has developed compact (6.5” x 6.5” x 2”) high-resolution drive electronics. The electronics are factory calibrated to compensate for gain and offset errors. As with the DM, calibration values are stored on board the electronics.

The paper will also present latest development results of protected aluminum and protected silver coatings as well as progress towards building larger DM arrays.

Space-Based Space Situational Awareness with Guaranteed Orbit Coverage

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Worcester Polytechnic Institute

In this paper we propose a space-based system for the surveillance of Earth-orbits. The proposed design will have the capability of completely covering spatial tubes (whose widths depends on the sensor ranges) spanning a range of Earth orbits. While the literature on ground-based surveillance is large, the problem we study in this paper (space-based surveillance of Earth orbits) is rarely studied in the past.

A surveillance satellite placed in orbit about Earth will only be able to detect objects of interest within its sensors' footprints. Objects of interest on the same orbit but outside the sensors' footprints will not be detected due to a difference in angular positions between the satellite and objects of interest. Hence, for that satellite to scan an entire orbit and ensure the detection, with probability one, of any objects on that orbit, it will have to apply control forces to march along the orbit. Hence, in this paper, we develop a simple (and cheap) orbital maneuver to effect the marching of the satellite along the orbit. The maneuver depends on the sensor range and nominal orbit size. This basic design is then extended to multiple satellite systems.

Once the basic design is introduced, we investigate the interdependence of three basic design variables: number of satellites used, fuel usage, and time to mission completion. The proposed design starts with two extreme cases: a system design that uses a single satellite but maximum fuel usage and time to mission completion; and a system design with (an analytically computable) maximum number of satellites but with zero fuel usage and time to mission completion. Each of the cases has the ability to detect, with probability one, any objects of interest in orbit within a given range of space orbits. With J2 effect taken into account, the proposed system design will guarantee complete coverage, not only of a tube in space, but of an entire shell containing a wide range of orbits with varying inclination angles.

Detailed numerical examples are given for the coverage of Low Earth Orbits and Geostationary Orbit. This paper lays the basis for future work where the authors will consider questions of resource allocation for cases with limited resources (especially severe constraints on the number of satellites used in the mission), and a formal formulation of a multi-objective optimal design problem and solutions where the design parameters are: number of satellites used in the system, fuel-usage and time to mission completion.

The Extended Hands Characterization and Analysis of Metric Biases

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The Extended High Accuracy Network Determination System (Extended HANDS) consists of a network of low cost, high accuracy optical telescopes designed to support space surveillance and development of space object characterization technologies. Comprising off-the-shelf components, the telescopes are designed to provide sub arc-second astrometric accuracy. The design and analysis team are in the process of characterizing the system through development of an error allocation tree whose assessment is supported by simulation, data analysis, and calibration tests. The metric calibration process has revealed 1-2 arc-second biases in the right ascension and declination measurements of reference satellite position, and these have been observed to have fairly distinct characteristics that appear to have some dependency on orbit geometry and tracking rates. The work presented here outlines error models developed to aid in development of the system error budget, and examines characteristic errors (biases, time dependence, etc.) that might be present in each of the relevant system elements used in the data collection and processing, as well as the metric calibration processing. The relevant reference frames are identified, and include the sensor (CCD camera) reference frame, Earth-fixed topocentric frame, topocentric inertial reference frame, and the geocentric inertial reference frame. The errors modeled in each of these reference frames, when mapped into the topocentric inertial measurement frame, reveal how errors might manifest themselves through the calibration process. The error analysis results that are presented use satellite-sensor geometries taken from periods where actual measurements were collected, and reveal how modeled errors manifest themselves over those specific time periods. These results are compared to the real calibration metric data (right ascension and declination residuals), and sources of the bias are hypothesized. In turn, the actual right ascension and declination calibration residuals are also mapped to other relevant reference frames in an attempt to validate the source of the bias errors. These results will serve as the basis for more focused investigation into specific components embedded in the system and system processes that might contain the root source of the observed biases.

Space Shuttle Plume Transport: Evidence that the Great Siberian Impact of 1908 was due to a Comet

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During the northern hemisphere summer of 1997 and again in the southern hemisphere summer of 2003, satellite and ground-based observations indicated that the water vapor plume from the main engine of the Space Shuttle rapidly expanded and quickly moved to the summer pole. Once in the polar region, the water vapor plume condensed into large noctilucent cloud displays. Here we provide what we believe to be the first explanation for both the transport and the anomalously rapid horizontal diffusion of the plume. In addition, and coincidentally in the 100th year anniversary of the largest earth impact event in recorded history, we apply these results to the aftermath of the Great Siberian Impact event of 1908. This event included observations of an extremely bright night sky in Great Britain on the days following the impact. We argue that the impacting object must have contained considerable ice and thus was very likely a comet with a stony interior.

Optimization of the PCID Multi-frame Blind Deconvolution Algorithm for Multi-core High Performance Computers

Richard Linderman[1], Scott Spetka[2], Charles Matson[3], Major David Strong[3]

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The parallelization strategy of the Physically-Constrained Iterative Deconvolution (PCID) algorithm has been optimized to enhance performance on emerging multi-core architectures. PCID processes sets of blurred image frames into highly resolved reconstructed images through multi-frame blind deconvolution (MFBD). MFBD runtime is dominated by two dimensional Fast Fourier Transform (FFT) calculations which can be parallelized effectively across multi-core architectures given their high bandwidth, low latency intercommunications. The next higher level of parallelization is to disseminate image frames across a clique of multi-core processing nodes. Finally, multiple cliques can be employed to parallelize the formation of multiple reconstructed images. These three levels of parallelization allow PCID to make effective use of large multi-core HPC resources in the 50 TFLOPS class.

This paper reports results from porting PCID to multi-core architectures including the JAWS supercomputer at MHPCC (60 TFLOPS of dual-dual Xeon nodes) and the Cell Cluster at AFRL in Rome, NY (45 TFLOPS of dual-quad Xeons and Playstation 3 nodes with IBM Cell Broadband Engine multi-cores). Sustained floating point performance as a percentage of machine peak performance is analyzed. Multi-core architectures programmed with multiple threads delivered significantly better performance on parallelization the low level image convolution operations compared to earlier parallelization across cluster nodes with MPI.

The PS3 port required mixing single and double precision arithmetic to optimize performance. The IBM Cell Broadband Engine processor within the PS3 presently has a 14x performance preference for single precision. A selected portion of the PCID algorithm was converted from double to single precision, to increase performance while controlling numerical precision effects. Numerical precision results are discussed.

A final attribute of the PCID multi-core effort was to move from MPI message passing to a publish-subscribe approach to information flow and management. The publish-subscribe infrastructure was optimized for large scale machines, such as JAWS, and features a loose coupling of publishers to subscribers through intervening brokers that make runs on large HPCs with thousands of intercommunicating cores both more flexible and more fault tolerant. Performance comparisons between the MPI and Pub-Sub approaches are presented.

Analysis of USA-193 Breakup and Resulting Debris Characteristics with Public TLEs

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As we know breakup is main source of space debris which almost account for one half even more of all catalog objects. So studying the breakup events is very meaningful for understanding the future debris environments. This thesis analyzed the characteristics of UAS-193 breakup with tles data before and soon after the breakup. Resulting debris mass and size distribution were calculated and compared with public RCS data and some breakup models. A method of analyzing the breakup events and fragmentation characteristic was formed, which was applied to other breakup events in 2008. However it is a reliable means for analyzing breakup events and fragmentation characteristics later.

Plans for Tomographic Wavefront Sensing with a Hybrid Laser Guide Star System at the 6.5 m MMT

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The 6.5 m MMT telescope in Arizona is presently equipped with a unique adaptive optics system that uses a constellation of five Rayleigh laser guide beacons. First results, presented separately at this conference, demonstrate wide-field ground-layer compensation. In this paper, we describe plans to upgrade the system to diffraction-limited imaging in the near IR, 1.2 to 2.5 micron wavelength. In the first phase, signals from the five Rayleigh beacons will be analyzed tomographically to estimate the integrated atmospheric wavefront aberration along a particular line of sight toward a chosen science object. This mode requires no changes to the existing system hardware or software; merely the replacement of the ground-layer reconstructor matrix by the tomographic matrix. We present closed-loop performance estimates with the MMT's single deformable mirror showing that the diffraction limit will be achieved, but with image quality in the field suffering from the usual effects of anisoplanatism. A second more extensive upgrade to the AO system will see the addition of a 20 W sodium laser which the AFRL's Starfire Optical Range has kindly agreed to make available. The beam will be launched along the telescope axis and placed in the center of the Rayleigh constellation, creating a hybrid beacon system. This arrangement, with beacons at more than one altitude, has unique strength in determining the instantaneous vertical distribution of the aberration, breaking mathematical degeneracies that are present in information from beacons at just one altitude. The technique therefore is of particular value to multi-conjugate AO, where two or more deformable mirrors conjugated to different ranges in the atmosphere are used to correct aberrated light over a field substantially bigger than the conventional isoplanatic angle. We present further simulations estimating the performance of the hybrid laser system when combined with a corrector using two deformable mirrors.

Active Optical Zoom for Tracking

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In order to optically vary the magnification of an imaging system, continuous mechanical zoom lenses require multiple optical elements and use fine mechanical motion to precisely adjust the separations between groups of lenses. By incorporating active elements into the optical design, imaging systems that are capable of variable optical magnification with no macroscopic moving parts are possible. Changing the effective focal length and magnification of an imaging system can be accomplished by positioning two or more active optics in an optical design. In this application, the active optics (deformable mirrors) serve as variable focal-length lenses and steering mirrors making an active optical zoom system that can zoom in on off-axis points on the image and therefore track objects in the field of view of the system. We will present results from a bench top system.

SiC Technology for Lightweighted Aerospace Mirrors

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The use of monolithic glass and beryllium to produce lightweighted aerospace mirror systems has reached its limit due to the long lead times, high processing costs, environmental effects and launch load/weight requirements. New material solutions and manufacturing processes are required to meet DoD's directed energy weapons, reconnaissance/surveillance, and secured communication needs. Over the past several years the Air Force, MDA and NASA has focused their efforts on the fabrication, lightweighting and scale-up of numerous silicon carbide (SiC) based materials. It is anticipated that SiC can be utilized for most applications from cryogenic to high temperatures. This talk will focus on describing the SOA for these technologies for making mirror structural substrates, figuring and finishing technologies being used to reduce cost and time and non-destructive evaluation methods being investigated to reduce risk.

First Proper Motions from Pan-STARRS PS1

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The Pan-STARRS PS1 telescope on Haleakala began taking astrometrically useful data during the summer of 2007. At the 2007 AMOS Technical Conference and the 2008 American Astronomical Society Meeting in Austin, we presented astrometric results from the analysis of a sequence of dithered frames. At this conference, we expect to have sufficient observational data and a sufficient epoch difference to search (and possibly discover) stars with relative proper motions of about 0.1 arcseconds per year. Details of the astrometric analysis will be presented, and the results will be compared with the expectations for the PS1 AP survey.

An Investigation of Global Albedo Values

M.K. Mulrooney[1], M.J. Matney[1], M.D. Hejduk[2], E.S. Barker[1]

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Mulrooney and Matney [1] developed a technique for estimating the intrinsic size distribution of orbital fragmentation debris and among the conclusions of their study was the recommendation of a global albedo value of 0.13 for these debris objects. In 2008 this value was revised upward to 0.175 [2] after revisions were made to the basis set of supplied brightness data (NASA-Liquid Mirror Telescope photometry data [3-5]). These revisions primarily involved uniform application of Lambertian phase function correction as opposed to the specular/Lambertian mixture in the original dataset. While these two studies demonstrated the soundness of their approach, uncertainties in the optical and radar data used for the calculations led the studies to produce only a provisional, rather than definitive, global albedo value for fragmentation debris. Calculations using alternate photometric and RCS (Radar Cross Section) data is required to support the use of their albedo in a truly global context. As a first step in this vetting process we perform an albedo consistency check by utilizing RCS values from an alternate source - the United States Air Force Space Command Studies and Analysis Division (AFSPC/A9A) high-precision RCS catalogue. As with prior work, these values will be passed through NASA's Size Estimation Model which primarily provides a diameter correction (downward) for objects in the Rayleigh scattering regime. Analysis using other photometric sources, such as the GEODSS visual magnitude data repository, will be performed in future.

In addition to fragmentation debris, there is utility in exploring the albedo distribution of non-fragmentation objects including intact rocket bodies, payloads, and mission related objects. Queries about space object size are often tendered against object types other than merely fragmentation debris; frequently, full-catalogue size profiling is desired, which includes payloads and rocket bodies. When published size information about these objects is available, these actual measurements can be used for such profiling; but since they are often unavailable, it would be helpful to have an expansion of the Mulrooney and Matney technique available for this class of objects. As a first step in this process, we will determine the character of the albedo distribution for non-fragmentation targets based on LMT photometry and available data from the A9 high-precision RCS catalogue. Since the size distribution for this object class does not follow a simple power-law, a suitable subset will be extracted whose behavior is approximated by a weak power-law and a bias corrected albedo will be derived.

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Automated Image Quality Assessment for Ground Based Space Surveillance Optical Sensors

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Clouds can degrade the capabilities of ground based space surveillance optical sensors by occluding targets of interest. With the increasing field of view (FOV) and search rates of future optical sensors, cloud impact increases. However, at the same time, cloud structure and temporal variability becomes discernable in the surveillance telescope data, and gross estimates of cloud cover can be replaced with a finer assessment and extraction of usable data. The impact is two-fold. First, photometric and astrometric inaccuracies can be identified and linked to specific data sets. Second, data can be further segmented, identifying portions that are cloud covered prior to processing, to improve detection and tracking performance.

We investigate two approaches that exploit the optical imagery data from space surveillance telescopes for data image quality assessment and generation of cloud maps. The first approach leverages stellar extinction to generate cloud masks. Flux from star detections are compared to estimated average fluxes on cloud free nights. Areas with significant flux change are identified as locations of potential clouds. The second approach takes advantage of structural and temporal variability to discriminate clouds from the stellar background. Three algorithms for automated cloud map generation were developed. The first algorithm uses texture discrimination to discriminate cloud from stellar background. A Gabor wavelet decomposition is used to derive a multi-dimensional feature vector for each pixel in a frame. Matched filtering using a stellar background centroid feature vector derived from a training set is used to identify cloud regions. The second algorithm leverages multi-frame data to generate a statistical background model of the stellar field. Pixels that vary significantly from the expected background model are identified as clouds. Finally, an optical flow algorithm was employed to assess per pixel relative frame to frame motion. Non-stationary pixels are identified as clouds.

Evaluation results will be presented from data from the Lincoln Near-Earth Asteroid Research (LINEAR) Ground-based Electro-optical Deep Space Surveillance (GEODSS) telescope and from a wide FOV camera deployed alongside the Experimental Test Site (ETS)-B in Socorro, New Mexico.

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Silicon Carbide Optics for Space Situational Awareness and Responsive Space Needs

Joseph Robichaud, Chris Ullathorne

L-3 Communications SSG- Tinley Inc

Over the past 10 years the application of Silicon Carbide (SiC) materials to space based imaging systems has expanded. The aerospace community has long recognized the technical, cost, and schedule benefits associated with the material, and adoption of the technology is facilitated as more successful flight systems are demonstrated. SiC provides a number of technical advantages, as a result of superior material properties. The material can also be manufactured using near-net-shape fabrication processes which provide significant cost and schedule advantages compared with competing material technologies. These technical and manufacturing advantages make SiC uniquely well suited to address the needs associated with Space Situational Awareness (SSA) and Responsive Space (RS) applications. The material has a low coefficient of thermal expansion, and a high thermal conductivity, allowing visible quality imaging in the presence of stressing, and changing, thermal loads. The material's specific stiffness is high, approximately 70% of Beryllium, allowing stiff, lightweight optical systems to be produced. Passively athermal systems have been produced, demonstrating the ability of the material to provide visible quality imaging, without the need for actively controlled focus adjust mechanisms. In addition, SiC structural elements do not outgas, and have no issues with moisture absorption, allowing rapid on-orbit data acquisition. From the manufacturing perspective the material offers dramatic schedule benefits, these come primarily from L-3 SSG's near-net-shape manufacturing process which allows complex, lightweighted optical and structural elements to be produced without the need for costly/time-consuming machining processes. These schedule advantages become more dramatic as the aperture of the system increases, and/or as the number of units increases. In this paper we provide an overview of the technical and manufacturing advantages associated with SiC, provide background with respect to the material's flight heritage, and illustrate the advantages that can be obtained in applying the material to SSA and RS mission scenarios.

Precision Orbit Determination, Validation and Orbit Prediction for ICESAT

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Center for Space Research

The NASA Ice, Cloud and land Elevation Satellite (ICESat) was launched on 13 January 2003 00:45 UTC into a 600 km altitude, 94 degree inclination, frozen orbit. The primary payload was the Geoscience Laser Altimeter System (GLAS), an instrument intended to detect changes in the polar ice sheets. Change detection is accomplished by determination of the GLAS illuminated spot coordinates on the Earth s surface, a process referred to as spot geolocation. This geo-location requires determination of both the spatial position and the orientation of the GLAS instrument. This paper will focus on the precision orbit determination (POD) aspects of ICESat, which is the process for determination of the spatial position of the GLAS instrument. To support POD, ICESat carries two JPL BlackJack GPS receivers and a laser retro-reflector array (LRA) to operate with ground-based satellite laser ranging (SLR) systems. GPS Flight Model (FM) #1 was powered on shortly after launch and has been in continuous operation since that time (FM#2 has not been powered on). This receiver is the primary input to the POD process. Using the high precision carrier phase measurements recorded by FM#1, these data are double-differenced with measurements collected by the global receiver network of the International GNSS Service (IGS). A quick-look orbit determination is performed in near real-time and a preliminary POD solution is performed with a 3-day latency using the IGS Rapid ephemerides for the GPS satellites and a final POD solution is performed with a latency of approximately 30 days using the IGS Final ephemerides. The POD methodology uses 30-hour periods (arcs) in which the epoch position/velocity is determined, plus double-difference ambiguity parameters, empirical orbit force parameters, usually characterized as once per revolution parameters, and other parameters. The satellite force model uses an Earth gravitational model based on GRACE, solid Earth and ocean tides, luni-solar forces and non-gravitational force models. The mission geo-location requirement is < 5 cm accuracy in the radial component of the orbit. Although several methods are used to assess the accuracy of the radial component of the orbit, the most robust is to use SLR measurements. The SLR measurements are not used in the POD process, but the GPS-determined orbit is used to generate SLR residuals. High elevation residuals are a close approximation to the radial direction and these residuals typically show < 2 cm, hence it is concluded that the POD process has exceeded the mission requirement. For some applications, predicted satellite positions are required, and the well-known influence of atmospheric drag is an important factor. Based on five years of operation, the quality of the predicted ephemerides will be described. With the prospect of follow-on missions, considerations of improvement in the POD and prediction accuracies will be summarized.

Optical Studies of Orbital Debris at GEO Using Two Telescopes

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We present a status report on optical observations of debris at geosynchronous orbit (GEO) using two telescopes simultaneously at the Cerro Tololo Inter-American Observatory (CTIO) in Chile. This program commenced in March 2007.

The University of Michigan's 0.6/0.9-m Schmidt telescope MODEST (for Michigan Orbital DEbris Survey Telescope) was used in survey mode to find objects that potentially could be at GEO. Because GEO objects only appear in this telescope's field of view for an average of 5 minutes, a full six-parameter orbit can not be determined. Interrupting the survey for follow-up observations leads to incompleteness in the survey results. Instead, as objects are detected on MODEST, initial predictions assuming a circular orbit are done for where the object will be for the next hour, and the objects are reacquired as quickly as possible on the CTIO 0.9-m telescope. This second telescope then follows-up during the first night and, if possible, over several more nights to obtain the maximum time arc possible, and the best six parameter orbit.

Our goal is to obtain an initial orbit for all detected objects fainter than R = 15th in order to estimate the orbital distribution of objects selected on the basis of two observational criteria: magnitude and angular rate. Objects fainter than 15th are largely un-cataloged and have a completely different angular rate distribution than brighter cataloged objects. Combining the information obtained for both faint and bright objects yields a more complete picture of the debris environment rather than just concentrating on the faint debris. One objective is to estimate what fraction of objects selected on the basis of angular rate are not at GEO. A second objective is to obtain magnitudes and colors in standard astronomical filters (BVRI) for comparison with reflectance spectra of likely spacecraft materials.

This paper reports on results from 35 nights of observations in March 2007, November 2007, and March 2008:

* A significant fraction of objects fainter than R = 15th have eccentric orbits (e > 0.1)

* Virtually all objects selected on the basis of angular rate are in the GEO and GTO regimes.

* Calibrated magnitudes and colors in BVRI were obtained for many objects fainter than R = 15th magnitude.

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High Spatial Resolution GaN and Optical Photon Counting Detectors with Sub-nanosecond Timing for Astronomical and Space Sensing Applications

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Microchannel plate (MCP) detectors can meet many of the challenging imaging and timing demands of applications, including astronomy of transient and time-variable sources, time resolved X-ray fluorescence spectroscopy, LIDAR, airborne and space situational awareness, and optical night-time/reconnaissance (LANL-ASPIRE). We have implemented a variety of high-resolution, photon-counting MCP detectors in space instrumentation for satellite FUSE, GALEX, IMAGE, SOHO, HST-COS, rocket, and shuttle payloads as well as sensors for ground based Astronomy, reconnaissance and biology. Our recent work on efficient UV/optical photocathodes, ceramic MCPs and high performance photon counting imaging readouts enables significant advancements over previous detector systems used for these applications. Gallium Nitride (GaN, AlGaN, InGaN) photocathodes, cross strip image readouts, and ceramic MCPs show great promise for future detector applications in Astrophysical and other instruments. GaN in sealed tube detectors offers high QE across the UV (above 110 nm), with tailored cutoffs around 400 nm. Development efforts have yielded considerable advancement, with opaque GaN photocathode efficiencies up to 70% at 120 nm and cutoffs at ~380 nm, with low out of band response, and high stability. Previous work with semitransparent GaN photocathodes produced relatively low QE (3%), however our recent data shows that QE of 15% to 25% can be achieved over a well defined band from 230nm to 360nm. We have also used 25mm active area semitransparent GaN photocathodes in an MCP two dimensional photon counting detector. The performance is quite good with low intrinsic background (below 1 event/sec/cm2), reasonable image uniformity and high spatial resolution. As the multiplication stage of the detector, ceramic MCPs offer the possibility to produce devices with small pores, excellent uniformity, high temperature capability, long lifetimes and low background compared with conventional glass MCPs. We have tested a number of Al2O3 MCPs with sizes of 8mm, 18mm, 25mm and pore sizes from 1um to 35um with good results. To obtain the highest event rates and spatial resolution at low MCP gain we have developed the Cross Strip (XS) anode. This anode uses charge division, and centroiding, of microchannel plate charge signals detected on two orthogonal layers of sense strips to encode event X-Y position, event time and signal amplitude. We have developed novel XS anode structures that can, in combination with small pore MCPs perform at the highest spatial resolution levels with self triggered ~1 ns timing accuracy and encode photons and particles at greater than 1 MHz rates. For time of flight applications the individual events can also be time tagged to 100ps accuracy. Our development the XS charge division scheme has been demonstrated with circular, square, and rectangular formats, with sizes of 22mm, 32mm, and 45mm. Using custom parallel channel encoding electronics with FIR centroiding algorithms excellent resolution (better than 10 um FWHM) has been achieved using MCP gain less than 5 x 10^5. Various aspects of these developments are being used to produce open face and sealed tube imaging detectors for a wide range of photon and particle sensing tasks. Applications include the next generation of space astronomy imaging and spectroscopy missions (NASA SFO & USO), neutron imaging and time of flight spectroscopy, ground based astronomical transient detection and variable source observations (NSF), optical night-time/reconnaissance (LANL-ASPIRE, and DOE-NNSA) and time resolved X-ray fluorescence spectroscopy (LBNL-ALS).

Orbital Debris from the Collision of USA 193

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On February 21 (UT), 2008, the US Navy intercepted the USA 193 spacecraft prior to the satellite's uncontrolled reentry into the atmosphere. By intercepting the spacecraft when it was in a low-altitude, nearly-circular orbit, it ensured that the resulting debris would be in short-lived orbits which would not significantly affect the future debris population. By mid-March, more than 165 debris from this collision had been cataloged by the US Space Surveillance Network (SSN). Of those, more than 60 had already decayed. In addition to data from the SSN, the Haystack radar, which can detect debris smaller than 1-cm diameter, collected data as the debris orbit planes passed overhead within hours after the collision. Haystack has continued to collect data at intervals over the ensuing months as the debris cloud continued to decay and reenter the atmosphere. This paper presents the results of the publically available SSN data and the results of Haystack measurements. The measured size distribution and the time evolution of the debris cloud will be presented.

A Modular Control Platform for a Diode Pumped Alkali Laser

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Many of the difficulties of creating compact, high power laser systems can be overcome if the heat dissipating properties of chemical lasers can be combined with the efficiency of diode lasers. Recently, the novel idea of using solid state diode lasers to pump chemical gain media or diode pumped alkali laser (DPAL) systems has been proposed and early experiments have shown promising results, however, a number of technical issues need to be overcome to realize high output power from these lasers. In order to achieve higher power, the efficiency of coupling between pump laser energy and the chemical cell must be increased, and eventually multiple high power diode pumps must be combined and synchronized so that their energy can pump the chemical cell. An intercavity adaptive optics system can be effectively integrated into the DPAL system to propagate these lasers with high efficiency.

DPAL systems are complex and require a significant amount of data fusion and active feedback to control and optimize their performance. As well, there are a wide range of pump lasers, chemical cells and monitoring points needed to compare and refine the systems. In support of this dynamic development environment, we have developed a hardware framework using commercial off the shelf (COTS) components which supports the rapid assembly of functional system blocks into a cohesive integrated system. Critical to this system are a simple communication protocol, industry standard communication pipes (USB, Bluetooth, etc), and flexible high level scripting. Simplifying the integration process has the benefit of allowing flexible "on the fly" modifications to adapt the system as needed and enhance available functionality. The modular nature of the architecture allows scalability and adaptability as more pieces are added to the system. Key components of this system are demonstrated for selected portions of a DPAL system using a USB backbone including the integrated adaptive optics subsystem.

Application of the Iterative Methods to Sparse 3D Satellite Images

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Image data collected by observing orbiting spacecraft from ground-based observatories is subject to various image blurring phenomena. Where adaptive optics or post-processing can be used to minimize the effects of atmospheric and optical aberrations, the object itself can present interesting motions such as tumble or intentional maneuvers. Laser radar systems provide 3D data that is additionally subject to geometry-induced distortions (which can be removed analytically) at the object frame of reference. A 3D model from laser radar can be starved for returns and requires a long integration period for maximizing model statistics, yet a short integration period is required for minimizing both geometry-induced distortions and tumble/maneuver distortions. Two algorithms have been identified to iteratively establish the distortions on short-exposure (sparse) 3D models and mitigate the effect of combining the models to form a long-exposure model: the iterative Hough transform (IHT) and iterative closest-point (ICP) algorithms. The IHT is here used to register short-exposure 3D models by integrating over flat surfaces and tracking the rotational differences in the models; de-rotating prior to a buildup model. It relies upon the quality of the structural information with the dataset. The ICP algorithm registers adjacent 3D images by minimizing the mean-square error (MSE) between the closest points between the short-exposure models based upon breaking down the geometry-induced distortions into scaling, azimuth/elevation rotation, and object whole-body motion relative to the observation reference frame. We resolve to compare and contrast both of these techniques in application to sparse 3D data with the purposes of measuring body dynamics and registering successive 3D images to produce a clearer 3D image.

Autonomous Global Sky Surveillance with Real-Time Robotic Follow-Up

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We discuss the development of prototypes for a global grid of advanced “thinking” sky sentinels and robotic follow-up telescopes that observe the full night sky to provide real-time SSA for LEO, MEO, HEO, and GEO objects by autonomously recognizing anomalous behavior, selecting targets for detailed investigation, and making real-time, follow-up observations. The layered, fault-tolerant, surveillance network uses relatively inexpensive robotic EO sensors to provide persistent autonomous surveillance and real-time anomaly detection to enable rapid recognition and a swift response to SSA threats and opportunities as they emerge. This T3 global EO grid avoids the limitations imposed by geography and weather to provide timely space control information to the war-fighter.

Development of an Architecture of Sun-Synchronous Orbital Slots to Minimize Conjunctions

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Sun-synchronous orbit (SSO) satellites serve many important functions, primarily in the areas of Earth reconnaissance and weather. The orbital parameters of altitude, inclination and right ascension which allow for the unique utility of Sun-sync orbit limit these satellites to a very specific region of space. The popularity of these satellite missions combined with the use of similar engineering solutions has resulted in the majority of current Sun-sync satellites within this region having very similar inclinations and altitudes while also spaced around the Equator in right ascension, creating the opportunity for conjunctions at the polar crossing points and a serious safety issue that could endanger long-term sustainability of SSO. This paper outlines the development of a new architecture of SSO zoning to create specific slots separating

SSO satellites in altitude, right ascension and time at all orbital intersections while minimizing the limitations on utility. A methodical approach for the development of the system is presented along with the work-to-date and a software tool for calculating repeating ground track orbits. The slot system is intended to allow for continued utility of and safe operation within SSO while greatly decreasing the chance of collisions at orbital intersections. This architecture is put forward as one possible element of a new Space Traffic Management (STM) system with the overall goal of maintaining the safe and continued used of space by all actors.

Update on the MAUI Experiment

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The MAUI experiment (Maui Analysis of Upper atmospheric Injections) provides needed knowledge applicable to current issues in space situational awareness and space weather. Spacecraft thruster injection effects can be divided into three categories that are distinguished by their spatial and temporal extent. The vacuum core emission emanates from the hot exhaust gases in the vicinity of the nozzle and only exists while the thruster is firing. Further downstream the plume appears extending up to kilometers from the nozzle, as the now cooled exhaust interacts with the neutral atmosphere in hyper thermal collisions and with the solar and earthshine radiation. Condensed phases scattering of sunlight is also prominent. The third category involves the chemical interaction of the molecular components of the exhaust with the ambient ionosphere. This occurs over larger areas and persists for a longer time, of the order of minutes. For relatively large orbital adjusting burns this interaction produces emissions that can be observed from ground-sites using all-sky imaging equipment. In this presentation we will focus on:

(1) An update of the 2007 analysis of STS-115 sunlit PRCS engine burns from the Maui Space Surveillance Site. We will center discussion on the transients caused by sunlight scattering on condensed phases of the propellant and how they can yield information of importance to maneuver characterization.

(2) Examination of a time series of all-sky images taken during STS-122 NC2 burn that were observed by the AFRL ground system in Kwajalein around 12:43 UT on February 8, 2008. Images were taken in two wavelength bands arising from the atomic oxygen metastables O (1D) (red line at 630nm) and O(1S) (green line at 557.7nm). The 630nm images are brighter but have its structure smeared out due to the 110 second radiative lifetime as opposed to the images at 557.7nm, emission with radiative lifetime of 0.7 seconds. This case is unique in that it occurred during a period when the ionosphere was dominated by natural north-south aligned equatorial plasma depletions. The large shuttle-induced enhancement in emissions was bounded to some degree by the pre-existing ionospheric structure, and the affected region was seen to drift eastward with the background ionosphere for 15-20 minutes after the burn. Small-scale (~10 km) field-aligned structure was also observed immediately after the burn. This provides insights into space environment conditions that are essential to predicting the quality of communications and navigation operations under stressing conditions.

AMOS Site Capabilities Tutorial

Arthur Hassall

AMOS, AFRL/RDSM

The Maui Space Surveillance Complex (MSSC), located at the summit of Haleakala, is a national resource providing support to various government agencies and the scientific community. The tutorial summarizes MSSC 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).

Technically Speaking: Bringing Excitement and Clarity to Technical Presentations Tutorial

Brad Wallace

Technical presentations don't have to be boring or confusing! Whether you're an engineer, a scientist, or a programmer, giving presentations is an integral part of your career. Learn how to more effectively share your ideas and get support for your projects or proposals. The AMOS Conference is pleased to present a tutorial designed to help you do just that. Help your organization leverage your expert knowledge and experience by presenting complex, sophisticated material in an engaging way that other people can understand and act on.