Advanced Maui Optical and Space Surveillance Technologies Conference

2015 ABSTRACTS OF TECHNICAL PAPERS

September 15-18, 2015

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POSTER PRESENTATIONS

ADAPTIVE OPTICS AND IMAGING

Session Chair: Glenn Tyler, the Optical Sciences Company

Anisoplanatic Imaging Through Turbulence Using Principal Component Analysis

Roberto Baena-Gallé, Royal Academy of Sciences and Arts of Barcelona

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The performance of optical systems is highly degraded by atmospheric turbulence when observing both vertically (e.g., astronomy, remote sensing) or horizontally (long-range surveillance). This problem can be partially alleviated using adaptive optics (AO) but only for small fields of view (FOV) described by the isoplanatic angle for which the turbulence-induced aberrations are considered constant. Additionally, this problem can also be tackled using post-processing techniques such as deconvolution algorithms which take into account the variability of the point spread function (PSF) in anisoplanatic conditions.

Variability of the PSF across the FOV in anisoplanatc imagery can be described using principal component analysis (Karhunen-Loeve transform). Then, a certain number of variable PSFs can be used to create new basis functions, called principal components (PC), which can be considered constant across the FOV and, therefore, potentially be used to perform global deconvolution.

Our aim is twofold: firstly, to describe the shape and statistics of the anisoplanatic PSF for single-conjugate AO systems with only a few parameters and, secondly, using this information to obtain the set of PSFs at positions in the FOV so that the associated variability is properly described. Additionally, these PSFs are to be decomposed into PCs. Finally, the entire FOV is deconvolved globally using deconvolution algorithms which account for uncertainties involved in local estimates of the PSFs. Our approach is tested on simulated, single-conjugate AO data.

Adaptive Optics for Satellite Imaging and Space Debris Ranging

Francis Bennet, Research School of Astronomy and Astrophysics, Australian National University

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Earth's space environment is becoming crowded and at risk of a Kessler syndrome, and will require careful management for the future. Modern low noise high speed detectors allow for wavefront sensing and adaptive optics (AO) in extreme circumstances such as imaging small orbiting bodies in Low Earth Orbit (LEO). The Research School of Astronomy and Astrophysics (RSAA) at the Australian National University have been developing AO systems for telescopes between 1 and 2.5m diameter to image and range orbiting satellites and space debris. Strehl ratios in excess of 30% can be achieved for targets in LEO with an AO loop running at 2kHz, allowing the resolution of small features (<30cm) and the capability to determine object shape and spin characteristics.

The AO system developed at RSAA consists of a high speed EMCCD Shack-Hartmann wavefront sensor, a deformable mirror (DM), and realtime computer (RTC), and an imaging camera. The system works best as a laser guide star system but will also function as a natural guide star AO system, with the target itself being the guide star. In both circumstances tip-tilt is provided by the target on the imaging camera. The fast tip-tilt modes are not corrected optically, and are instead removed by taking images at a moderate speed (>30Hz) and using a shift and add algorithm. This algorithm can also incorporate lucky imaging to further improve the final image quality.

A similar AO system for space debris ranging is also in development in collaboration with Electro Optic Systems (EOS) and the Space Environment Management Cooperative Research Centre (SERC), at the Mount Stromlo Observatory in Canberra, Australia. The system is designed for an AO corrected upward propagated 1064nm pulsed laser beam, from which time of flight information is used to precisely range the target. A 1.8m telescope is used for both propagation and collection of laser light. A laser guide star, Shack-Hartmann wavefront sensor, and DM are used for high order correction, and tip-tilt correction provided by reflected sunlight from the target. The system is expected to achieve a Strehl ratio of 30% at 1064nm, and enable ranging to targets in excess of 2000 km. The system is currently installed and is undergoing commissioning as a natural guide star AO system, before the system is upgraded for laser guide star AO and debris ranging.

This ranging system is aimed at demonstrating the capabilities of AO corrected laser ranging, and will be used as a platform to further develop space environment management techniques and strategies. SERC will continue this development and focus in particular on the development of a high power (>2kW) laser which can modify the orbit of debris using photon pressure.

The AO systems we are developing aim to show how ground based systems can be used to manage the space environment. AO imaging systems can be used for satellite surveillance, while laser ranging can be used to determine precise orbital data used in the critical conjunction analysis required to maintain a safe space environment.

Italian Air Force Radar and Optical Sensor Experiments for the Detection of Space Objects in LEO Orbit

Giovanni Marco Del Genio, Italian Air Force

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Italian Ministry of Defence is developing a sensor architecture for a national Space Surveillance & Tracking (SST) capability in order to protect its own space and satellite assets and infrastructure against the damage or destruction from collision with other space debris in LEO orbit. This national capability has recently joined the European Union SST Consortium, that is now facing the huge challenge of gradually becoming self-sufficient and independent in producing an integrated international space surveillance network. The national architecture will be composed of both radars and optical sensors since they have different capability and provide complementary type of information regarding targeted object. Collected data from networked sensors will be sent to an integration centre in order analyze it and make the orbit determination of the detected space debris using specific software tools. In this paper we briefly describe the potential capabilities of such architecture and the results of a preliminary radar-optical sensor data fusion experiment carried out with a monostatic long range radar and a telescope managed by Italian Air Force for the detection of a subset of space objects in LEO orbit. In particular, the optical sensor is a telescope properly designed for SST and is able to observe the portion of space above it with a coverage of 360°x90° in azimuth and elevation. The telescope is equipped with two CCD sensors: one with a wide field of view used for surveillance tasks and the second with a narrow field dedicated for tracking specific objects. The sensor is managed by an operating software system that allows user to remotely plan and schedule its daily activity and to make orbit determination and collision risk assessment in a completely automated way.

New Aperture Partitioning Element

Steven Griffin, Boeing

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Postprocessing in an optical system can be aided by adding an optical element to partition the pupil into a number of segments. When imaging through the atmosphere, the recorded data are blurred by temperature-induced variations in the index of refraction along the line of sight. Using speckle imaging techniques developed in the astronomy community, this blurring can be corrected to some degree. The effectiveness of these techniques is diminished by redundant baselines in the pupil. Partitioning the pupil

reduces the degree of baseline redundancy, and therefore improves the quality of images that can be obtained from the system. It is possible to implement the described approach on an optical system with a segmented primary mirror, but not very practical. This is because most optical systems do not have segmented primary mirrors, and those that do have relatively low bandwidth positioning of segments due to their large mass and inertia. It is much more practical to position an active aperture partitioning element at an aft optics pupil of the optical system. This paper describes the design, implementation and testing of a new aperture partitioning element that is completely reflective and reconfigurable. The device uses four independent, annular segments that can be positioned with a high degree of accuracy without impacting optical wavefront of each segment. This mirror has been produced and is currently deployed and working on the 3.6 m telescope.

Resolved Observations of Geosynchronous Satellites from the 6.5 m MMT

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We report observations of a number of geostationary spacecraft recorded in the J, H, and K bands (centered around 1.2 micron, 1.6 micron, and 2.2 micron) at the 6.5 m MMT telescope in January 2015. With adaptive optics, the satellites were resolved at close to the diffraction limit in each of the wavebands. True color images may be recovered from the multiple wavebands, while the large aperture allows accurate photometric calibration with excellent time resolution of even small, faint objects in these distant orbits. Of note are our observations of solar panels, which can only be satisfactorily imaged at wavelengths longer than their cutoff wavelengths. Since the cutoff is generally in the neighborhood of 1.5 – 2 micron, the panels will only be well resolved by telescopes larger than 4 m. In one case observed at the MMT, solar panels were seen to span approximately 25 m, twice the extent described in published data.

A Comprehensive Comparison of COMBAT Data to Wave-Optics Simulations

Richard Holmes, Boeing LTS

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An experiment called COMBAT collected data in 2010 along paths between Mauna Loa and Haleakala to investigate atmospheric effects in long horizontal paths. The data has proven difficult to interpret in terms of conventional analyses and wave-optics simulations. Recent modifications to the wave-optics simulations have shown better agreement with a subset of the COMBAT data that is available for comparison. These modifications include (a) alternative Cn2 profiles along the path from Mauna Loa to Haleakala, (b) non-Kolmogorov turbulence exponents, (c) anisotropy of turbulence, (d) turbulence inner and outer scale effects, (e) transmitter telescope jitter, (f) camera noise, (g) camera saturation, and (h) spatial averaging due to the finite extent of the pixels. The presence of transmitter telescope jitter helps provide additional agreement with the temporal data, contributing as much or more to full-aperture fades as turbulence. With the inclusion of these effects, the general trends were obtained, in which measured scintillation increased with wavelength, and the correct spatial and temporal structure were obtained as quantified by autocorrelations.

Fundamental Constraints on Imaging Geosynchronous Satellites

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Henrique Schmitt, Tom Armstrong
Naval Research Laboratory

Imaging objects in geosynchronous orbit is becoming an increasingly important topic in space situational awareness as evidenced by DARPA recently funding the Galileo program and sponsoring a "deep-space imaging workshop". Because of the required high-angular-resolution, an interferometer is the instrument of choice; there is, however, little consensus about what that system should look like. The DARPA workshop expanded the discussion to include heterodyne interferometry, telescopes mounted on steerable platforms and many more telescopes. However, it is not obvious how performance of these systems varies as a function of design parameters.

This paper presents quantitative relationships between system parameters and performance. Sensitivity, how faint an object can be imaged, can be improved by increasing the telescope diameters and the quality of the adaptive optics. Increasing the number of telescopes also helps because shorter baselines, which have higher fringe contrast, can be used to phase the array. Once fringes can be measured, the imaging time is determined by how many times the system has to be reconfigured to make observations at all the required spatial frequencies. The relationships presented here have been validated using detailed numerical models. They constrain the parameter space of workable designs and provide a basis for comparing the cost and feasibility of various designs. Low resolution interferometric observations of such satellites is needed in order to further refine the assumptions used in the calculations presented here.

Multiple-Baseline Detection of a Geostationary Satellite with the Navy Precision Optical Interferometer

Henrique Schmitt, Naval Research Laboratory

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Using the Navy Precision Optical Interferometer (NPOI), we have made the first multiple-baseline interferometric detection of a satellite. The observations, carried out during the March 2015 glint season, succeeded in detecting the DirecTV-7S satellite with interferometer baseline lengths of 8.8 m and 9.8 m and wavelengths from 850 nm to 550 nm, corresponding to a resolution of ~0.02 arcsec, or 4 m at geostationary altitude. This is the first multiple-baseline interferometric detection of a satellite.

Incorporating LWIR Data into Multi-Frame Blind Deconvolution of Visible Imagery

Michael Werth, Boeing

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The 3.6m telescope at the Air Force Maui Optical and Supercomputing (AMOS) site is able to send light to a Long Wave Infrared (LWIR) sensor and a visible imaging sensor for simultaneous recording in different wavebands. LWIR images suffer less from atmospheric blurring than visible images, therefore it should be possible to use LWIR information to provide a priori information to a Multi-Frame Blind Deconvolution (MFBD) algorithm that reconstructs visible images. This would result in better image reconstructions that are produced in less time. We describe techniques for fusing LWIR and visible data for MFBD processing, and we apply these techniques to a number of Low Earth Orbit satellite collections. Measured improvements in processing time and reconstructed image resolution are presented.

From Dye Laser Factory to Portable Semiconductor Laser: Four Generations of Sodium Guide Star Lasers for Adaptive Optics in Astronomy and Space Situational Awareness

Celine d'Orgeville, Australian National University

Gregory J. Fetzer, *Areté Associates*

This presentation recalls the history of sodium guide star laser systems used in astronomy and space situational awareness adaptive optics, analysing the impact that sodium laser technology evolution has had on routine telescope operations. While it would not be practical to describe every single sodium guide star laser system developed to date, it is possible to characterize their evolution in broad technology terms. The first generation of sodium lasers used dye laser technology to create the first sodium laser guide stars in Hawaii, California, and Spain in the late 1980’s and 1990’s. These experimental systems were turned into the first laser guide star facilities to equip medium-to-large diameter adaptive optics telescopes, opening a new era of LGS AO-enabled diffraction-limited imaging from the ground. Although they produced exciting scientific results, these laser guide star facilities were large, power-hungry and messy. In the USA, a second-generation of sodium lasers was developed in the 2000’s that used cleaner, yet still large and complex, solid-state laser technology. These are the systems in routine operation at the 8-10m class astronomical telescopes and 4m-class satellite imaging facilities today. Meanwhile in Europe, a third generation of sodium lasers was being developed using inherently compact and efficient fiber laser technology, and resulting in the only commercially available sodium guide star laser system to date. Fiber-based sodium lasers will be deployed at two astronomical telescopes and at least one space debris tracking station this year. Although highly promising, these systems remain significantly expensive and they have yet to demonstrate high performance in the field. We are proposing to develop a fourth generation of sodium lasers: based on semiconductor technology, these lasers could provide the final solution to the problem of sodium laser guide star adaptive optics for all astronomy and space situational awareness applications.

ASTRODYNAMICS

Session Chair: Moriba Jah, Air Force Research Laboratory

Orbital Element Generation for an Optical and Laser Tracking Space Object Catalogue

James Bennett, Space Environment Research Centre & EOS Space Systems

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In this paper results are presented from an analysis assessing the data requirements for orbit element generation for a new high-accuracy catalogue for the Space Environment Research Centre, Australia. The analysis is dedicated to obtaining a robust set of rules for orbit element generation using orbital data from optical and laser tracking of debris and satellites.

Optical and laser tracking data collected from several tracking campaigns carried out by EOS Space Systems, located on Mount Stromlo, Australia, is fitted to provide an updated orbital element. The element accuracy is determined for various data-availability scenarios, including: (1) fitting optical tracking data only; (2) fitting laser range data only; (3) fitting optical and laser tracking data. The orbit predictions from the new orbital element are compared with SGP4 propagation from two-line element data and accuracy is assessed by comparing with high accuracy ephemerides where available or subsequent accurate tracking data. The application of the catalogue to conjunction analyses is also discussed.

This work forms part of the collaborative effort of the Space Environment Management Cooperative Research Centre which is developing new technologies and strategies to preserve the space environment (www.serc.org.au).

Space-to-Space Based Relative Motion Estimation Using Direct Relative Orbit Parameters

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There has been an increasing interest in space-based space situational awareness around satellite assets and the tracking of orbital debris. Of particular interest is the space-based tracking of objects near critical circular orbit regimes, for example near the Geostationary belt or the International Space Station. Relative orbit descriptions such as the Clohessy-Wiltshire equations describe the motion using time-varying Cartesian or curvilinear coordinates. Orbit element differences describe the unperturbed motion using constant variations of inertial orbit elements. With perturbations these only vary slowly, but can be challenging to estimate. Linearized Relative Orbit Elements (LROEs) employ invariants of the linearized relative motion, are thus constant for the unperturbed linear case, and share the benefit of the CW equations in that they directly related to space-based relative motion measurements. The variational LROE equations enable the relative orbit to be directly propagated including perturbation forces. Utilization of the invariant-inspired relative motion parameters exhibits exciting applications in relative motion sensing and control. Many methods of relative motion estimation involve the direct estimation of time-evolving position and velocity variables. Developed is an angles-only relative orbit Extended Kalman filter (EKF) navigation approach that directly estimates these nominally constant LROEs. The proposed variational equations and filtering scheme enables direct estimation of geometric parameters with clear geometric insight. Preliminary numerical simulation results demonstrate the relative orbit insight gained and speed of convergence. EKF implementations often exhibit significant sensitivity to initial conditions, however, initial results show that the LROE filter converges within fractions of an orbit with initialization errors that exceed 100 percent. The manuscript presents the invariants of motion, develops the variational equations for propagation, and demonstrates the effectiveness in an EKF approach. This approach is applied to space-based relative motion sensing to demonstrate the flexibility and benefit of LROE estimation. Several examples of drift-by, periodic orbits, and lead-follower estimation are generated.

Coupled Simulations, Ground-Based Experiments and Flight Experiments for Astrodynamics Research

Russell Boyce, University of New South Wales

Dr. Melrose Brown, Dr. Philippe Lorrain, Mr. Christopher Capon, Dr. Andrew Lambert, Dr. Craig Benson, Dr. Sean Tuttle, Dr. Douglas Griffin
UNSW Canberra

Near-Earth satellites undergo complex and poorly understood interactions with their environment, leading to large uncertainties in predicting orbits and an associated risk of collision with other satellites and with space debris. The nature, evolution and behaviour of the growing cloud of space debris in that environment is even less well understood. Significant effort and expenditure is currently being made by governments in Australia, UK, USA, Europe and elsewhere in space surveillance and tracking, in order to mitigate the risk. However, a major gap exists with respect to the science of in-orbit behaviour.

Research is underway in Australia to enable the prediction of the orbits of near-Earth space objects with order(s) of magnitude greater fidelity than currently possible. This is being achieved by coupling together the necessary parts of the puzzle - the physics of rarefied space object “aerodynamics” and the space physics and space weather that affects it - and employing our capabilities in ground-based and in-orbit experiments, ground-based observations and high performance computing to do so.

As part of the effort, UNSW Canberra is investing $10M to develop a sustainable university-led program to develop and fly affordable in-orbit missions for space research. In the coming 6 years, we will fly a minimum of four cubesat missions, some in partnership with DSTO, which will include flight experiments for validating Space Situational Awareness astrodynamics simulation and observation capabilities. The flights are underpinned by ground-based experimental research employing space test chambers, advanced diagnostics, and supercomputer simulations that couple DSMC and Particle-in-Cell methods for modelling space object interactions with the ionosphere.

This paper will describe the research both underway and planned, with particular emphasis on the coupled numerical/experimental/flight approach.

Total Probability of Collision as a Metric for Finite Conjunction Assessment and Collision Risk Management

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The Probability of Collision (Pc) has become a universal metric and statement of on-orbit collision risk. Although several flavors of the computation exist and are well-documented in the literature, the basic calculation requires the same input: estimates for the position, position uncertainty, and sizes of the two objects involved. The Pc is used operationally to make decisions on whether a given conjunction poses significant collision risk to the primary object (or space asset of concern). It is also used to determine necessity and degree of mitigative action (typically in the form of an orbital maneuver) to be performed. The predicted post-maneuver Pc also informs the maneuver planning process into regarding the timing, direction, and magnitude of the maneuver needed to mitigate the collision risk. Although the data sources, techniques, decision calculus, and workflows vary for different agencies and organizations, they all have a common thread. The standard conjunction assessment and collision risk concept of operations (CONOPS) predicts conjunctions, assesses the collision risk (typically, via the Pc), and plans and executes avoidance activities for conjunctions as a discrete events.

As the space debris environment continues to increase and improvements are made to remote sensing capabilities and sensitivities to detect, track, and predict smaller debris objects, the number of conjunctions will in turn continue to increase. The expected order-of-magnitude increase in the number of predicted conjunctions will challenge the paradigm of treating each conjunction as a discrete event. The challenge will not be limited to workload issues, such as manpower and computing performance, but also the ability for satellite owner/operators to successfully execute their mission while also managing on-orbit collision risk. Executing a propulsive maneuver occasionally can easily be absorbed into the mission planning and operations tempo; whereas, continuously planning evasive maneuvers for multiple conjunction events is time-consuming and would disrupt mission and science operations beyond what is tolerable. At the point when the number of conjunctions is so large that it is no longer possible to consider each individually, some sort of an amalgamation of events and risk must be considered. This shift is to one where each conjunction cannot be treated individually and the effects of all conjunctions within a given period of time must be considered together. This new paradigm is called finite Conjunction Assessment (CA) risk management.

This paper considers the use of the Total Probability of Collision (TPc) as an analogous collision risk metric in the finite CA paradigm. TPc is expressed by the equation below and provides an aggregate probability of colliding with any one of the predicted conjunctions under consideration. TPc=1-?(1-Pc,i) While the TPc computation is straightforward and its physical meaning is understandable, the implications of its usage operationally requires a change in mindset and approach to collision risk management. This paper explores the necessary changes to evolve the basic CA and collision risk management CONOPS from discrete to finite CA, including aspects of collision risk assessment and collision risk mitigation. It proposes numerical and graphical decision aids to understand both the “risk outlook” for a given primary as well as mitigation options for the total collision risk. Both concepts make use of the TPc as a metric for finite collision risk management. Several operational scenarios are used to demonstrate the proposed concepts in practice.

Track-to-Track Data Association using Mutual Information

Islam Hussein, Applied Defense Solutions

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In this paper, we build on recent work to further investigate the use of mutual information to solve various association problems in space situational awareness. Specifically, we solve the track-to-track association (TTTA) problem where we seek to associate a given set of tracks at one point in time with another set of tracks at a different time instance. Both sets of tracks are uncertain and are probabilistically described using multivariate normal distributions. This allows for a closed-form solution, based on the unscented transform and on mutual information. Future work will focus on developing a similar solution when uncertainty is analytic but not Gaussian or when it is completely non-analytic –e.g., when the uncertainty is described using a particle cloud. The proposed solution is inspired by a similar solution based on the unscented transform and mutual information for the observation-to-observation association (OTOA) problem that was developed by the authors in the past. This solution can be adjusted to address the classical observation-to-track association problem (OTTA), which will be the focus of future research. We will demonstrate the main result in simulation for LEO, MEO, GTO, and GEO orbit regimes to show general applicability.

Towards Real-Time Maneuver Detection: Automatic State and Dynamics Estimation with the Adaptive Optimal Control Based Estimator

Daniel Lubey, University of Colorado Boulder

Daniel J. Scheeres, University of Colorado Boulder

Tracking objects in Earth orbit is fraught with complications. This is due to the large population of orbiting spacecraft and debris that continues to grow, passive (i.e. no direct communication) and data-sparse observations, and the presence of maneuvers and dynamics mismodeling. Accurate orbit determination in this environment requires an algorithm to capture both a system’s state and its state dynamics in order to account for mismodelings. Previous studies by the authors yielded an algorithm called the Optimal Control Based Estimator (OCBE) – an algorithm that simultaneously estimates a system’s state and optimal control policies that represent dynamic mismodeling in the system for an arbitrary orbit-observer setup. The stochastic properties of these estimated controls are then used to determine the presence of mismodelings (maneuver detection), as well as characterize and reconstruct the mismodelings. The purpose of this paper is to develop the OCBE into an accurate real-time orbit tracking and maneuver detection algorithm by

automating the algorithm and removing its linear assumptions. This results in a nonlinear adaptive estimator.

In its original form the OCBE had a parameter called the assumed dynamic uncertainty, which is selected by the user with each new measurement to reflect the level of dynamic mismodeling in the system. This human-in-the-loop approach precludes real-time application to orbit tracking problems due to their complexity. This paper focuses on the Adaptive OCBE, a version of the estimator where the assumed dynamic uncertainty is chosen automatically with each new measurement using maneuver detection results to ensure that state uncertainties are properly adjusted to account for all dynamic mismodelings. The paper also focuses on a nonlinear implementation of the estimator. Originally, the OCBE was derived from a nonlinear cost function then linearized about a nominal trajectory, which is assumed to be ballistic (i.e. the nominal optimal control policy is zero for all times). In this paper, we relax this assumption on the nominal trajectory in order to allow for controlled nominal trajectories. This allows the estimator to be iterated to obtain a more accurate nonlinear solution for both the state and control estimates.

Beyond these developments to the estimator, this paper also introduces a modified distance metric for maneuver detection. The original metric used in the OCBE only accounted for the estimated control and its uncertainty. This new metric accounts for measurement deviation and a priori state deviations, such that it accounts for all three major forms of uncertainty in orbit determination. This allows the user to understand the contributions of each source of uncertainty toward the total system mismodeling so that the user can properly account for them.

Together these developments create an accurate orbit determination algorithm that is automated, robust to mismodeling, and capable of detecting and reconstructing the presence of mismodeling. These qualities make this algorithm a good foundation from which to approach the problem of real-time maneuver detection and reconstruction for Space Situational Awareness applications. This is further strengthened by the algorithm’s general formulation that allows it to be applied to problems with an arbitrary target and observer.

Improving Space Object Catalog Maintenance Through Advances in Solar Radiation Pressure Modeling

Jay McMahon, University of Colorado Boulder

Daniel J. Scheeres, *University of Colorado Boulder*

This paper investigates the weaknesses of using the cannonball model to represent the solar radiation pressure force on an object in an orbit determination process, and presents a number of alternative models that greatly improve the orbit determination performance. These weaknesses are rooted in the fact that the cannonball model is not a good representation of the true solar radiation pressure force acting on an arbitrary object. Using an erroneous force model results in poor estimates, inaccurate trajectory propagation, unrealistic covariances, and the inability to fit long and/or dense arcs of data. The alternative models presented are derived from a Fourier series representation of the solar radiation pressure force. The simplest instantiation of this model requires only two more parameters to be estimated, however this results in orders of magnitude improvements in tracking accuracy.

This improvement is illustrated through numerical examples of a discarded upper stage in a geosynchronous transfer orbit, and more drastically for a piece of high area-to-mass ratio debris in a near-geosynchronous orbit. The upper stage example shows that using the proposed 3-parameter model can improve the orbit fit from 5 days of tracking data by 2-4 orders of magnitude over the cannonball model. Perhaps more importantly, over a 28 day propagation arc with the estimated models, the prediction errors with the 3-parameter model rarely exceed 2-sigma of the propagated covariance, whereas the cannonball prediction errors grow to over 70-sigmaof the propagated covariance.

Most significantly, we show that using the proposed Fourier model greatly improves estimation of HAMR debris orbits, where the cannonball model can struggle to fit the data at any level. In the most extreme case tested, fitting 3 short arcs of data each separated by 100 hours, the Fourier model fits the orbit to the centimeter level, while the cannonball model has errors on the order of 1000 km.

Implementation of the improved solar radiation pressure models can therefore help to alleviate track correlation, object identification, and sensor tasking issues that plague current catalog maintenance due to the standard inaccurate dynamic model.

Bridging the Gap between Academia and Operations for Orbital Debris Risk Mitigation

Mark Vincent, Raytheon

The operational aspects of mitigating the risks from orbital debris are increasing in complexity. The number of conjunctions for a typical satellite in Low Earth Orbit is increasing due to previous collisions and explosions. This will be exacerbated when tracking of secondaries with smaller diameters becomes functional in the future. Utilizing more frequent Risk Mitigation Maneuvers must be balanced to account for the negative consequences of doing the maneuvers. These consequences include possible interruptions to science observation, deviations from the desired orbit/groundtrack and the expenses involved in designing and executing the maneuver. Another complication of the maneuvers is the potential of post-maneuver conjunctions which have to be accounted for with the added factor of the maneuver execution error. Another complication of analyzing the original conjunction is the well-known dependence of the Probability of Collision (Pc) on the uncertainty in the orbit predictions of both primary and secondary and the conjunction geometry. The natural behavior is to have a low Pc when these uncertainties are large, then as the uncertainties decrease to first reach a maximum value of Pc and then decrease again to small values (assuming that there actually is not a collision). There has been a lot of academic study of methods to make these uncertainty predictions better match their true values. This paper will present a study of how these theoretical studies can best help the operational analysis and decision making processes, including comparisons to existing tools. The latter includes quantification of the confidence levels in the current Pc and how the range of future Pc values are a function of new tracking data and the de-weighting of old tracking data.

NON-RESOLVED OBJECT CHARACTERIZATION SESSION

Session Chairs: Doyle Hall, Boeing LTS and Matt Hejduk, Astrorum Consulting

IRTF SpeX Observations of Orbital Object

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Presented herein are the results of the Infrared Telescope Facility (IRTF) spectral observations of orbiting objects taken between 2006-2008. The data collected using the SpeX infrared spectrograph cover the wavelength range 1-8 ?m. Overall, data were collected on twenty different orbiting objects at or near the geosynchronous (GEO) regime. Four of the objects were controlled spacecraft, seven were non-controlled spacecraft, five were rocket bodies, and the final four were cataloged as debris pieces. The remotely collected data are compared to the laboratory-collected reflectance data on typical spacecraft materials thereby general materials are identified but not specific types. These results highlight the usefulness of observations in the infrared focusing on features from hydrocarbons due to paint, silicon, and the beginning of thermal emission from the debris itself. The spacecraft, both the controlled and non-controlled, show distinct features due to solar panels while the rocket bodies do not. The variations in signature between the types of rocket bodies show a presence of metals instead of solar panels showing that one can distinguish most spacecraft from rocket bodies through the infrared spectrum analysis. Finally, the debris pieces tend to show featureless, dark spectra. These results show that the laboratory data in its current state give an excellent idea as to the materials on the surface of the objects. Further remote data collection as well as updating the models to include noise, surface roughness, and material degradation is necessary to make a better assessment of material types. However, based on the current state of the comparison between the observations and the laboratory data, infrared spectroscopic data are adequate to classify objects in GEO as spacecraft, rocket bodies, or debris.

On-line Flagging of Anomalies and Adaptive Sequential Hypothesis Testing for Fine-feature Characterization of Geosynchronous Satellites

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The objective of on-line flagging in this paper is to perform interactive assessment of geosynchronous satellites anomalies such as cross-tagging of a satellites in a cluster, solar panel offset change, etc. This assessment will utilize a Bayesian belief propagation procedure and will include automated update of baseline signature data for the satellite, while accounting for the seasonal changes. Its purpose is to enable an ongoing, automated assessment of satellite behavior through its life cycle using the photometry data collected during the synoptic search performed by a ground or space-based sensor as a part of its metrics mission. The change in the satellite features will be reported along with the probabilities of Type I and Type II errors.

The objective of adaptive sequential hypothesis testing in this paper is to define future sensor tasking for the purpose of characterization of fine features of the satellite. The tasking will be designed in order to maximize new information with the least number of photometry data points to be collected during the synoptic search by a ground or space-based sensor. Its calculation is based on the utilization of information entropy techniques. The tasking is defined by considering a sequence of hypotheses in regard to the fine features of the satellite. The optimal observation conditions are then ordered in order to maximize new information about a chosen fine feature. The combined objective of on-line flagging and adaptive sequential hypothesis testing is to progressively discover new information about the features of a geosynchronous satellites by leveraging the regular but sparse cadence of data collection during the synoptic search performed by a ground or space-based sensor.

Automated Algorithm to Detect Changes in Geostationary Satellite’s Configuration and Cross-Tagging

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By characterizing geostationary satellites based on photometry and color photometry, analysts can evaluate satellite operational status and affirm its true identity. The process of ingesting photometry data and deriving satellite physical characteristics can be directed by analysts in a batch mode, meaning using a batch of recent data, or by automated algorithms in an on-line mode in which the assessment is updated with each new data point. Tools used for detecting change to satellite’s status or identity, whether performed with a human in the loop or automated algorithms, are generally not built to detect with minimum latency and traceable confidence intervals. To alleviate those deficiencies, we investigate the use of Hidden Markov Models (HMM), in a Bayesian Network framework, to infer the hidden state (changed or unchanged) of a three-axis stabilized geostationary satellite using broadband and color photometry. Unlike frequentist statistics which exploit only the stationary statistics of the observables in the database, HMM also exploits the temporal pattern of the observables as well. The algorithm also operates in “learning” mode to gradually evolve the HMM and accommodate natural changes such as due to the seasonal dependence of GEO satellite’s light curve. Our technique is designed to operate with missing color data. The version that ingests both panchromatic and color data can accommodate gaps in color photometry data. That attribute is important because while color indices, e.g. Johnson R and B, enhance the belief (probability) of a hidden state, in real world situations, flux data is collected sporadically in an untasked collect, and color data is limited and sometimes absent. Fluxes are measured with experimental error whose effect on the algorithm will be studied. Photometry data in the AFRL’s Geo Color Photometry Catalog and Geo Observations with Latitudinal Diversity Simultaneously (GOLDS) data sets are used to simulate a wide variety of operational changes and identity cross tags. The algorithm is tested against simulated sequences of observed magnitudes, mimicking both the cadence of untasked SSN and other ground sensors, occasional operational changes and possible occurrence of cross tags of in-cluster satellites. We would like to show that the on-line algorithm can detect change; sometimes right after the first post-change data point is analyzed, for zero latency. We also want to show the unsupervised “learning” capability that allows the HMM to evolve with time without user’s assistance. For example, the users are not required to “label” the true state of the data points.

Spatio-Temporal Scale Space Analysis of Photometric Signals with Tracking Error

Brien Flewelling, Air Force Research Laboratory/RVSVC

Steve Gregory, Air Force Research Laboratory/*RVSVC*

This paper will investigate the application of Scale-Space Theory to 1-Dimensional light curve signals generated by reducing imagery sequences taken from telescopes tasked in various modes. As an observed object with a variable light curve is viewed from a sensor achieving a perfect rate track mode, there is a trade between the time fidelity of the reconstructed signal and integration time required to make accurate detections. As the tracking error increases, a sensor in a step-stare con-ops for example may trade spatial samples for intensity information as a function of time. This is commonly seen in streak observations of tumbling resident space objects. The method presented here will demonstrate how consistent light curves with maximum time resolution can be generated from observation sequences with variable tracking error, and sensor integration times. Additionally, the sparse representation of these signals using 1-D Scale-Space feature trees will be investigated as a means for rapid correlation of light-curves against a large database. The proposed rapid correlations could be used to identify variable operating modes of a known object, or to identify an object as a member of a database.

NIR Color vs Launch Date: A 20-year Analysis of Space Weathering Effects on the Boeing 376 Spacecraft

James Frith, Univeristy of Texas El Paso

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The Boeing HS-376 spin stabilized spacecraft was a popular design that was launched continuously into geosynchronous orbit starting in 1980 with the last launch occurring in 2002. Over 50 of the HS-376 buses were produced to fulfill a variety of different communication missions for countries all over the world. The design of the bus is easily approximated as a telescoping cylinder that is covered with solar cells and an Earth facing antenna that is despun at the top of the cylinder. The similarity in design and the number of spacecraft launched over a long period of time make the HS-376 a prime target for studying the effects of solar weathering on solar panels as a function of time. A selection of primarily non-operational HS-376 spacecraft launched over a 20 year time period were observed using the United Kingdom Infrared Telescope on Mauna Kea and multi-band near-infrared photometry produced. Each spacecraft was observed for an entire night cycling through ZYJHK filters and time-varying colors produced to compare near-infrared color as a function of launch date. The resulting analysis shown here may help in the future to set launch date constraints on the parent object of unidentified debris objects or other unknown spacecraft.

Active Polarimetry for Orbital Debris Identification

Michael Pasqual, Massachusetts Institute of Technology

Kerri Cahoy, *Massachusetts Institute of Technology*

We present the results of polarimetric measurements that may help remotely identify orbital debris fragments, thereby extending current space surveillance capabilities. A bench-top polarimeter (wavelength 1064 nm) was used to experimentally determine the polarimetric Bidirectional Reflectance Distribution Function (BRDF) of several common spacecraft materials and coatings, including glossy white paint, matte black paint, black Kapton®, silver Teflon®, aluminum, and titanium. Analysis of these measurements allowed us to estimate each material's Mueller matrix and associated polarimetric properties as a function of the incident angle and (bistatic) in-plane scatter angle. Results revealed notable trends in the materials' polarimetric signatures. Specifically, the materials exhibited mostly weak diattenuation ($D < 0.5$) in all scatter directions, except for Kapton® and the two paints ($D > 0.5$ in the forward scatter direction). In terms of retardance (R), silver Teflon® exhibited a finite range of values ($R = 30$ to 120º) in all directions, while the other materials acted as mirrors ($R = 180º$) in the back scatter direction and had the full range of behavior ($R = 0$ to 180º) in the forward scatter direction. Finally, in terms of depolarization power (Delta), glossy white paint was a nearly perfect depolarizer (Delta = 1) in the back scatter direction, but sharply lost depolarization power (Delta = 0) at specular reflection. All other materials were mostly weak depolarizers (Delta < 0.5) in all scatter directions. These experimental findings may be used to develop requirements for a polarimetric laser radar that can interrogate debris fragments, identify their constituent materials, and infer their masses and other characteristics of interest.

Satellite Photometric Error Determination

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In this paper, we present analysis of the errors associated with optical photometry used in non-resolved object characterization for the Space Situational Awareness (SSA) community. We begin with an overview of standard astronomical techniques used to measure the brightness of spatially unresolved objects (point source photometry) in deep space. After discussing the standard astronomical techniques, we present the application of astronomical photometry for the purposes of space object characterization. Examples of filter photometry of geosynchronous satellites processed using the current techniques are shown. Next we advocate the adoption of new techniques based on in-frame photometric calibrations enabled by newly available all-sky star catalogs that contain highly accurate photometry.

Photometric Monitoring of Non-resolved Space Debris and Databases of Optical Light Curves

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The population of space debris increased drastically during the last years. Collisions involving massive objects may produce large number of fragments leading to significantly growth of the space debris population. An effective remediation measure in order to stabilize the population in LEO, is therefore the removal of large, massive space debris. To remove these objects, not only precise orbits, but also more detailed information about their attitude states will be required. One important property of an object targeted for removal is its spin period and spin axis orientation. If we observe a rotating object, the observer sees different surface areas of the object which leads to changes in the measured intensity. Rotating objects will produce periodic brightness variations with frequencies which are related to the spin periods. Photometric monitoring is the real tool for remote diagnostics of the satellite rotation around its center of mass. This information is also useful, for example, in case of contingency. Moreover, it is also important to take into account the orientation of non-spherical body (e.g. space debris) in the numerical integration of its motion when a close approach with the another spacecraft is predicted. We introduce the two databases of light curves: the AIUB data base, which contains about a thousand light curves of LEO, MEO and high-altitude debris objects (including a few functional objects) obtained over more than seven years, and the data base of the Astronomical Observatory of Odessa University (Ukraine), which contains the results of more than 10 years of photometric monitoring of functioning satellites and large space debris objects in low Earth orbit. AIUB used its 1m ZIMLAT telescope for all light curves. For tracking low-orbit satellites, the Astronomical Observatory of Odessa used the KT-50 telescope, which has an alt-azimuth mount and allows tracking objects moving at a high angular velocity. The diameter of the KT-50 main mirror is 0.5 m, and the focal length is 3 m. The Odessa's Atlas of light curves includes almost 5,5 thousand light curves for ~500 correlated objects from a time period of 2005-2014. The processing of light curves and the determination of the rotation period in the inertial frame is challenging. Extracted frequencies and reconstructed phases for some interesting targets, e.g. GLONASS satellites, for which also SLR data were available for confirmation, will be presented. The rotation of the Envisat satellite after its sudden failure will be analyzed. The deceleration of its rotation rate within 3 years is studied together with the attempt to determine the orientation of the rotation axis.

OPTICAL SYSTEMS

Session Chair: Jim Mayo, Tau Technologies

The MetaTelescope, a System for the Detection of Objects in Low and Higher Earth Orbits

Michel Boer, French National Centre for Scientific Research (CNRS)

We present an original design involving several telescopes for the detection of mobiles in space over a very wide field of view. The system uses relatively simple and cheap telescopes associated with commercial CCD cameras that can be placed either in a single location or in relatively close (100m – 10km) locations. This last set-up opens the possibility of detecting parallaxes, but sky conditions should remain almost identical. Areas on the order of 800 square degrees can be surveyed. The system is versatile, i.e. it can detect and follow up objects either in the LEO or higher orbits. We will present the system, how it can be operated in order to have a more efficient setup while using even less telescopes, and possible implementations for space surveillance activities.

SPIDER: Next Generation Chip Scale Imaging Sensor

Alan Duncan, Lockheed Martin

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The LM Advanced Technology Center and UC Davis are developing an Electro-Optical (EO) imaging sensor called SPIDER (Segmented Planar Imaging Detector for Electro-optical Reconnaissance) that provides a 10x to 100x size, weight, and power (SWaP) reduction alternative to the traditional bulky optical telescope and focal plane detector array. The substantial reductions in SWaP would reduce cost and/or provide higher resolution by enabling a larger aperture imager in a constrained volume. The SPIDER concept consists of thousands of direct detection white-light interferometers densely packed onto Photonic Integrated Circuits (PICs) to measure the amplitude and phase of the visibility function at spatial frequencies that span the full synthetic aperture. In other words, SPIDER would sample the object being imaged in the Fourier domain (i.e., spatial frequency domain), and then digitally reconstruct an image. The conventional approach for imaging interferometers requires complex mechanical delay lines to form the interference fringes. This results in designs that are not traceable to more than a few simultaneous spatial frequency measurements. SPIDER seeks to achieve this traceability by employing micron-=scale optical waveguides and nanophotonic structures fabricated on a PIC with micron-scale packing density to form the necessary interferometers. Prior LM IRAD and DARPA/NASA CRAD-funded SPIDER risk reduction experiments, design trades, and simulations have matured the SPIDER imager concept to a TRL 3 level. Current funding under the DARPA SPIDER Zoom program is maturing the underlying PIC technology for SPIDER to the TRL 4 level. This is done by developing and fabricating a second-generation PIC that is fully traceable to the multiple layers and low-power phase modulators required for higher-dimension waveguide arrays that are needed for higher field-of-view sensors. Our project also seeks to extend the SPIDER concept to add a zoom capability that would provide simultaneous low-resolution, large field-of-view and steerable high-resolution, narrow field-of-view imaging modes. A proof of concept demo is being designed to validate this capability. Finally, data collected by this project would be used to benchmark and increase the fidelity of our SPIDER image simulations and enhance our ability to predict the performance of existing and future SPIDER sensor design variations. These designs and their associated performance characteristics could then be evaluated as candidates for future mission opportunities to identify specific transition paths. This paper provides an overview of performance data on the first-generation PIC for SPIDER developed under DARPA SeeMe program funding. We provide a design description of the SPICER Zoom imaging sensor and the second-generation PIC (high- and low-resolution versions) currently under development on the DARPA SPIDER Zoom effort. Results of performance simulations and design trades are presented. Unique low-cost payload applications for future SSA missions are also discussed.

Early CAL/VAL Process for an Optical Tracking System by Korea

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An optical satellite tracking system has been developed and deployed by Korea Astronomy and Space Science Institute since 2010. The objectives of the system consist of acquiring ephemerides of domestic low Earth orbit satellites, monitoring domestic geosynchronous Earth orbit satellites and investigating the behavior of space debris. This system employs in-house software for image processing and operating system. Most of mount, observatory enclosure and control system was designed and manufactured domestically. A commercial 4k CCD camera was adopted for the back-end image sensor. And the broken satellite streak is generated by a chopper system in front of the CCD camera. The first observatory was built in Mongolia in September 2014. For the early calibration and validation phase, astrometric data of several bright low Earth orbit satellites has been collected from two observation sites in 2014. The preliminary results show the performance of system is close to the design specification.

Night and Daytime Detection of Orbital Objects and Filter Photometry at Short Infrared Wavelengths

Guillaume Langin, Artemis Observatoire de Côte d Azur

Boer Michel, Pyanet Marine
Artemis, Airbus Defence and Space

Observing orbital satellites/debris in low Earth orbit, and even higher orbits, is limited by the conditions of illumination of such objects. This need for specific angular configurations between the Sun, the object and the ground-based observer limits optical detection during the night. Moreover, during the day, the high atmospheric background limits observation at visible wavelengths.

We started a study and an experiment to assess and quantify the advantage of observing orbital objects in the near infrared (NIR) and short wave infrared (SWIR) ranges of the suns spectrum. Observing both during the night and daytime allows more favourable geometries and can extend the observing periods of time. Another advantage of the NIR-SWIR light is the extra information it contains about the material and the attitude of a reflecting space object. Performing filter photometry from the visible to the infrared regime can help characterizing satellites or debris.

Observations are now in progress using the 1m C2PU telescope (6.9°E, 43.8°N, alt. 1260m) at Observatoire de la Côte d Azur (OCA/CNRS). We are assessing the detectability and SNR of GEO objects and plan to extend the experiment to lower orbits. We observe at various times of the night and day and through five different optical filters, including J and H, in order to calibrate the simulations and validate our models.

We will present the early results from these series of observations and their interpretation.

The Fundamental Role of Wide-Field Imaging in Space Situational Awareness

John McGraw, J.T. McGraw and Associates, LLC

Mark R. Ackermann, Peter Zimmer
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Space Situational Awareness (SSA) is fundamentally based upon surveillance of the variety of objects moving in Earth orbital space: functioning satellites, derelicts, and space debris. Optical telescopes provide a significant fraction of all data for the surveillance of space, and virtually all data on GEO and related objects. Starting with an operational definition of surveillance of space (SoS), we discuss:

- The unique role of wide-field imaging in acquiring surveillance data
- The detector-driven optical design of small, wide-field telescopes that produce data capable of providing high signal-to-noise images and tracks in the presence of detector and complicated background noise
- Multiple sky tracking and detector readout combinations to optimize object detection from LEO through GEO
- The approach to real-time image data processing capable of enabling rapid analysis and decision-making, as needed.

Specifically, we describe the fundamental physics associated with the design of optical surveillance cameras based upon small aperture, wide field-of-view telescopes which we have designed. Critical performance issues include uncued detection of new and/or un-cataloged objects to faint limiting magnitudes (V > 18 at LEO), including initial orbit determination, and the capability to survey large areas of the sky (such as the CONUS GEO belt of approximately 1800 sq. degrees) to faint limiting magnitudes (V = 18) every two hours. The goal is to convert these data into actionable information in very near real-time.

Initial data demonstrating and supporting our surveillance of space system designs and design goals will be presented.

Developing Geostationary Satellite Imaging at the Navy Precision Optical Interferometer

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The Navy Precision Optical Interferometer (NPOI) is a six-beam long-baseline optical interferometer, located in Flagstaff, Arizona; the facility is operated by a partnership between Lowell Observatory, the US Naval Observatory, and the Naval Research Laboratory. NPOI operates every night of the year (except holidays) in the visible with baselines between 8 and 100 meters (up to 432m is available), conducting programs of astronomical research and technology development for the partners. NPOI is the only such facility as yet to directly observe geostationary satellites, enabling milliarcsecond resolution of these objects. To enhance this capability towards true imaging of geosats, a program of facility upgrades will be outlined. These upgrades include AO-assisted large apertures feeding each beam line, new visible and near-infrared instrumentation on the back end, and infrastructure supporting baseline-wavelength bootstrapping which takes advantage of the spectral and morphological features of geosats. The large apertures will enable year-round observations of objects brighter than 10th magnitude in the near-IR. At its core, the system is enabled by a approach that tracks the low-resolution (and thus, high signal-to-noise), bright near-IR fringes between aperture pairs, allowing multi-aperture phasing for high-resolution visible light imaging. A complementary program of visible speckle and aperture masked imaging at Lowell's 4.3-m Discovery Channel Telescope, for constraining the low-spatial frequency imaging information, will also be outlined, including results from a pilot imaging study.

ORBITAL DEBRIS

Session Chair: Tim Flohrer, European Space Agency

Environment Characterisation by Using Innovative Debris Detector

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The knowledge about small (> 100 µm) but abundant objects in space is low. To analyze the quantity of space debris and micrometeoroids in space, an innovative in-situ impact detection method has been developed at the German Aerospace Center (DLR) in Bremen, Germany. The Solar generator based Impact Detector, SOLID, uses solar panels for impact detection. Since solar panels provide large detection areas, this method allows the collection of large amounts of data. Such data enhances space debris and micrometeoroid population datasets and permits for related model validation. A ground verification of the detection method has been performed by Hypervelocity Impact (HVI) tests at Fraunhofer´s Ernst-Mach-Institut (EMI), Freiburg, Germany. The objective of this investigation was to test the applicability of the developed method concerning in-situ detection of space debris and micrometeoroids. The achieved test results are in agreement with ESA developed damage equations and the functionality of the detector has clearly been demonstrated. This paper presents the already manufactured hardware planned for on orbit test on the Technische Universität Berlin's TechnoSat mission in early 2016. The expected impact frequencies at corresponding probabilities and uncertainties regarding object size estimation are also outlined.

Statistical Track-Before-Detect Methods Applied to Faint Optical Observations of Resident Space Objects

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Toshifumi Yanagisawa, Masahiko Uetsuhara
Japan Aerospace Exploration Agency

Automated detection and tracking of faint objects in optical, or bearing-only, sensor imagery is a topic of immense interest in space surveillance. Robust methods in this realm will lead to better space situational awareness (SSA) while reducing the cost of sensors and optics. They are especially relevant in the search for high area-to-mass ratio (HAMR) objects, as their apparent brightness can change significantly over time. A track-before-detect (TBD) approach has been shown to be suitable for faint, low signal-to-noise ratio (SNR) images of resident space objects (RSOs). TBD does not rely upon the extraction of feature points within the image based on some thresholding criteria, but rather directly takes as input the intensity information from the image file. Not only is all of the available information from the image used, TBD avoids the computational intractability of the conventional feature-based line detection (i.e., "string of pearls") approach to track detection for low SNR data.

Implementation of TBD rooted in finite set statistics (FISST) theory has been proposed recently by Vo, et al. Compared to other TBD methods applied so far to SSA, such as the stacking method or multi-pass multi-period denoising, the FISST approach is statistically rigorous and has been shown to be more computationally efficient, thus paving the path toward on-line processing. In this paper, we intend to apply a multi-Bernoulli filter to actual CCD imagery of RSOs. The multi-Bernoulli filter can explicitly account for the birth and death of multiple targets in a measurement arc. TBD is achieved via a sequential Monte Carlo implementation. Preliminary results with simulated single-target data indicate that a Bernoulli filter can successfully track and detect objects with measurement SNR as low as 2.4.

Although the advent of fast-cadence scientific CMOS sensors have made the automation of faint object detection a realistic goal, it is nonetheless a difficult goal, as measurements arcs in space surveillance are often both short and sparse. FISST methodologies have been applied to the general problem of SSA by many authors, but they generally focus on tracking scenarios with long arcs or assume that line detection is tractable. We will instead focus this work on estimating sensor-level kinematics of RSOs for low SNR too-

short arc observations. Once said estimate is made available, track association and simultaneous initial orbit determination may be achieved via any number of proposed solutions to the too-short arc problem, such as those incorporating the admissible region. We show that the benefit of combining FISST-based TBD with too-short arc association goes both ways; i.e., the former provides consistent statistics regarding bearing-only measurements, whereas the latter makes better use of the precise dynamical models nominally applicable to RSOs in orbit determination.

Space Debris Attitude Simulation - IOTA (In-Orbit Tumbling Analysis)

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Today, there is little knowledge on the attitude state of decommissioned intact objects in Earth orbit. Observational means have advanced in the past years, but are still limited with respect to an accurate estimate of motion vector orientations and magnitude. Especially for the preparation of Active Debris Removal (ADR) missions as planned by ESA's Clean Space initiative or contingency scenarios for ESA spacecraft like ENVISAT, such knowledge is needed. The In-Orbit Tumbling Analysis tool (IOTA) is a prototype software, currently in development within the framework of ESA's "Debris Attitude Motion Measurements and Modelling" project (ESA Contract No. 40000112447), which is led by the Astronomical Institute of the University of Bern (AIUB). The project goal is to achieve a good understanding of the attitude evolution and the considerable internal and external effects which occur. To characterize the attitude state of selected targets in LEO and GTO, multiple observation methods are combined. Optical observations are carried out by AIUB, Satellite Laser Ranging (SLR) is performed by the Space Research Institute of the Austrian Academy of Sciences (IWF) and radar measurements and signal level determination are provided by the Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR). Developed by Hyperschall Technologie Göttingen GmbH (HTG), IOTA will be a highly modular software tool to perform short- (days), medium- (months) and long-term (years) propagation of the orbit and attitude motion (six degrees-of-freedom) of spacecraft in Earth orbit. The simulation takes into account all relevant acting forces and torques, including aerodynamic drag, solar radiation pressure, gravitational influences of Earth, Sun and Moon, eddy current damping, impulse and momentum transfer from space debris or micro meteoroid impact, as well as the optional definition of particular spacecraft specific influences like tank sloshing, reaction wheel behaviour, magnetic torquer activity and thruster firing. The meaning of IOTA is to provide high accuracy short-term simulations to support observers and potential ADR missions, as well as medium- and long-term simulations to study the significance of the particular internal and external influences on the attitude, especially damping factors and momentum transfer. The simulation will also enable the investigation of the altitude dependency of the particular external influences. IOTA's post-processing modules will generate synthetic measurements for observers and for software validation. The validation of the software will be done by cross-calibration with observations and measurements acquired by the project partners.

Deploying the NASA Meter Class Autonomous Telescope (MCAT) on Ascension Island

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NASA has successfully constructed the 1.3m Meter Class Autonomous Telescope (MCAT) facility on Ascension Island in the South Atlantic Ocean. MCAT is an optical telescope designed specifically to collect ground-based data for the statistical characterization of orbital debris ranging from Low Earth Orbit (LEO) through Middle Earth Orbits (MEO) and beyond to Geo Transfer and Geosynchronous Orbits (GTO/GEO). The location of Ascension Island has two distinct advantages. First, the near-equatorial location fills a significant longitudinal gap in the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) network of telescopes, and second, it allows access to objects in Low Inclination Low-Earth Orbits (LILO).

The MCAT facility will be controlled by a sophisticated software suite that operates the dome and telescope, assesses sky and weather conditions, conducts all necessary calibrations, defines an observing strategy (as dictated by weather, sky conditions, and the observing plan for the night), and carries out the observations. It then reduces the collected data via four primary observing modes ranging from tracking previously cataloged objects to conducting general surveys for detecting uncorrelated debris. Nightly observing plans, as well as the resulting text file of reduced data, will be transferred to and from Ascension, respectively, via a satellite connection. Post-processing occurs at NASA Johnson Space Center.

Construction began in September, 2014 with dome and telescope installation occurring in April through early June, 2015. First light was achieved in June, 2015. Acceptance testing, full commissioning, and calibration of this soon-to-be fully autonomous system commenced in summer 2015. The initial characterization of the system from these tests is presented herein.

GEO Collisional Risk Assessment Based on Analysis of NASA-WISE Data and Modeling

Capt Samantha Howard, AFRL Space Vehicles Directorate

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From December 2009 thru 2011 the NASA Wide-Field Infrared Survey Explorer (WISE) gathered radiometrically exquisite measurements of debris in near Earth orbits, substantially augmenting the current catalog of known debris. The WISE GEO-belt debris population adds approximately 2,000 previously uncataloged objects. This paper describes characterization of the WISE GEO-belt orbital debris population in terms of location, epoch, and size. The WISE GEO-belt debris population characteristics are compared with the publically available U.S. catalog and previous descriptions of the GEO-belt debris population. We found that our results differ from previously published debris distributions, suggesting the need for updates to collision probability models and a better measurement-based understanding of the debris population. Previous studies of collisional rate in GEO invoke the presence of a large number of debris in the regime of sizes too small to track, i.e. not in the catalog, but large enough to cause significant damage and fragmentation in a collision. A common approach is to estimate that population of small debris by assuming that it is dominated by fragments and therefore should follow trends observed in fragmentation events or laboratory fragmentation tests. In other words, the population of debris can be extrapolated from trackable sizes to small sizes using an empirically determined trend of population as a function of size. We use new information suggested by the analysis of WISE IR measurements to propose an updated relationship. Our trend is an improvement because we expect that an IR emissive signature is a more reliable indicator of physical size. Based on the revised relationship, we re-estimate the total collisional rate in the GEO belt with the inclusion of projected uncatalogued debris and applying a conjunction assessment technique. Through modeling, we evaluate the hot spots near the geopotential wells and the effects of fragmentation in the GEO graveyard to the collision with GEO objects.

Streak Detection Algorithm for Space Debris Detection on Optical Images

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Any image processing object detection algorithm somehow tries to integrate the object light (Recognition Step) and applies statistical criteria to distinguish objects of interest from other objects or from pure background (Decision Step). There are various possibilities how these two basic steps can be realized, as can be seen in the different proposed detection methods in the literature. An ideal detection algorithm should provide high recognition sensitivity with high decision accuracy and require a reasonable computation effort. In reality, a gain in sensitivity is usually only possible with a loss in decision accuracy and with a higher computational effort. So, automatic detection of faint streaks is still a challenge. This paper presents a detection algorithm using mean filters simulating the geometrical form of possible streaks on a CCD image. This is realized by image convolution. The goal of this method is to generate a more or less perfect match between a streak and a filter by varying the length and angle of the filters. The convolution answers are accepted or rejected according to an overall threshold given by the background statistics. This approach yields as a first result a huge amount of accepted answers due to filters partially covering streaks or remaining stars. To avoid this, a set of additional acceptance criteria has been included in the detection method. All criteria parameters are justified by background and streak statistics and they affect the detection sensitivity only marginally. Tests on images containing simulated streaks and on real images containing satellite streaks show a very promising sensitivity, reliability and running speed for this detection method. Since all method parameters are based on statistics, the true alarm, as well as the false alarm probability, are well controllable. Moreover, the proposed method does not create any extraordinary demands on the computer hardware and on the image acquisition process.

SPACE WEATHER

Session Chair: Randy Alliss, Northrop Grumman Corporation

Characterizing the Performance of Haleakala as a Ground Site for Laser Communications

Billy Felton, Northrop Grumman

Randall Alliss
Northrop Grumman

Radio Frequency (RF) signals have been relied on exclusively and successfully to communicate with spacecraft since satellite communications began nearly 60 years ago. However, missions now demand higher data rates to meet their data collection requirements. In response to this need, several organizations have begun to take steps to increase the data capacity of future missions by developing laser communications terminals and operational concepts for future missions. For example, NASA's Lunar Laser Communications Demonstration (LLCD) successfully demonstrated high data rate communications links to and from the LADEE satellite orbiting the moon during the Fall of 2013. As a next step, the Laser Communication Relay Demonstration (LCRD) will build upon the experience gained from LLCD and perform multi-year testing of Free-Space Optical Communications (FSOC) from geosynchronous orbit. Planning for these missions has included identifying candidate ground station locations, quantifying the impacts of the atmosphere on the data links, and developing operational concepts for mitigating transmission losses due to clouds, turbulence, and aerosols.

Since space-to-ground optical communications are adversely affected by the presence of clouds, turbulence, and other atmospheric phenomena, it is important to study the effects of the atmosphere on the communications link. To support this, Northrop Grumman is leading a campaign to measure and model the atmospheric effects on the link between a ground station on the summit of Haleakala and a satellite in geostationary orbit. Part of this effort involves using a modified version of the Weather Research & Forecast (WRF) model to generate long-term climatologies of optical turbulence parameters as well as to characterize the atmosphere along the line-of-sight (LOS) from the ground station to the satellite during operations to be used as a link diagnostic tool. While ground-based instruments can be used to measure the effects of turbulence integrated along the entire LOS, they cannot generally be used to identify the vertical structure of turbulence. In this work, WRF is used to generate a three-dimensional representation of Cn2 and other atmospheric parameters in both the planetary boundary layer and the free atmosphere. This allows for the characterization of Cn2 along the entire portion of the LOS below 20-km above mean sea level along with estimates of the Fried Coherence length (r0) and other seeing parameters along the LOS. In addition, a suite of ground-based sensors will be deployed, including a meteorological station, a whole-sky imager, and a ceilometer. Their measurements will be combined with output from WRF to support mission planning and the development of operational concepts for mitigating link outages. In particular, the in situ cloud data will be used along with multispectral Geostationary satellite imagery and WRF model soundings to characterize and predict cloud heights and cloud encroachment over the summit of Haleakala. For this work, the WRF model is configured to run at 1-km horizontal resolution over a domain that includes the major observatories on the Big Island of Hawaii as well as Haleakala on Maui. Results from this work will be used to quantify the effects of the atmosphere on FSOC communications, diagnose link disruptions, and to develop atmospheric mitigation strategies.

Research to Operations of Ionospheric Scintillation Detection and Forecasting

James Jones, Northrop Grumman

Kevin Scro[1], David Payne[2], Ryan Ruhge[2], Brandon Erickson[2], Sage Andorka[2], Catherine Ludwig[2], Jody Karmann[2], Drew Ebelhar[2]
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Ionospheric Scintillation refers to random fluctuations in phase and amplitude of electromagnetic waves caused by a rapidly varying refractive index due to turbulent features in the ionosphere. Scintillation of transionospheric UHF and L-Band radio frequency signals is particularly troublesome since this phenomenon can lead to degradation of signal strength and integrity that can negatively impact satellite communications and navigation, radar, or radio signals from other systems that traverse or interact with the ionosphere. Although ionospheric scintillation occurs in both the equatorial and polar regions of the Earth, the focus of this modeling effort is on equatorial scintillation. The ionospheric scintillation model is data-driven in a sense that scintillation observations are used to perform detection and characterization of scintillation structures. These structures are then propagated to future times using drift and decay models to represent the natural evolution of ionospheric scintillation. The impact on radio signals is also determined by the model and represented in graphical format to the user. A frequency scaling algorithm allows for impact analysis on frequencies other than the observation frequencies. The project began with lab-grade software and through a tailored Agile development process, deployed operational-grade code to a DoD operational center. The Agile development process promotes adaptive promote adaptive planning, evolutionary development, early delivery, continuous improvement, regular collaboration with the customer, and encourage rapid and flexible response to customer-driven changes. The Agile philosophy values individuals and interactions over processes and tools, working software over comprehensive documentation, customer collaboration over contract negotiation, and responding to change over following a rigid plan. The end result was an operational capability that met customer expectations. Details of the model and the process of operational integration are discussed as well as lessons learned to improve performance on future projects.

Predicting Space Weather Effects on Close Approach Events

Lauri Newman, NASA

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The NASA Robotic Conjunction Assessment Risk Analysis (CARA) team sends ephemeris data to the Joint Space Operations Center (JSpOC) for screening against the high accuracy catalog, then assesses risk posed to protected assets from predicted close approaches. Since most spacecraft supported by the CARA team are located in LEO orbits, atmospheric drag is a primary source of state estimate uncertainty, and drag is directly governed by space weather. At present the actual effect of space weather on atmospheric density cannot be accurately predicted because most atmospheric density models are empirical in nature.

The Jacchia-Bowman-HASDM 2009 atmospheric density model used at the JSpOC employs a solar storm active compensation feature that predicts storm sizes and arrival times, and thus the resulting neutral density alterations. With this feature, estimation errors can occur in either direction (i.e., over- or under-estimation of density and thus drag), giving rise to several questions. Does a change in space weather make a close approach safer or riskier? Might performing a maneuver make the approach worse due to uncertainty in predicted location at a given time? What if there are errors in the predicted timing or magnitude of the space weather event?

Although the exact effect of a solar storm on atmospheric drag cannot be determined, one can explore the effects of drag perturbations on conjuncting objects' trajectories to determine if a conjunction can become riskier or less risky. The CARA team has constructed a Space Weather Trade-Space tool that systematically alters the drag coefficient of the conjuncting objects and recalculates the probability of collision for each case to determine the effect is likely to have on the collision risk. In addition to a review of

the theory and the particulars of the tool, all of the observed output will be explained, along with statistics of their frequency.

MAMBA All-sky Camera

Edward Pier, Oceanit

Kevin T.C. Jim, Michael Hadmack
Oceanit

MAMBA is an actively calibrated, thermal, all-sky camera designed to measure the precipitable water vapor (PWV) column in any arbitrary direction. This has applications in the calibration of remote sensing, astronomy, radio frequency transmissions, meteorology, and climatology. MAMBA produces an all-sky cloud map, day or night, which is useful in astronomy and SSA for telescope aiming. The system is based on a new optical design and an extensive set of atmospheric radiative transfer models.

Sub-Auroral Ion Drifts as a Source of Mid-Latitude Plasma Density Irregularities

Vladimir Sotnikov, Air Force Research Laboratory

T. Kim[1], E. Mishin[1], I. Paraschiv[2], D. Rose[3]
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Ionospheric irregularities cause scintillations of electromagnetic signals that can severely affect navigation and transionospheric communication, in particular during space storms. At midlatitudes, such space weather events are caused mainly by subauroral electric field structures (SAID/SAPS) [1, 2]. SAID/SAPS – related shear flows and plasma density troughs point to interchange and Kelvin-Helmholtz type instabilities as a possible source of plasma irregularities. A model of nonlinear development of these instabilities based on the two-fluid hydrodynamic description with inclusion of finite Larmor radius effects will be presented. A numerical code in C language to solve the derived nonlinear equations for analysis of interchange and flow velocity shear instabilities in the ionosphere was developed. This code was used to analyze competition between interchange and Kelvin Helmholtz instabilities in the equatorial region [3]. The high-resolution simulations with continuous density and velocity profiles will be driven by the ambient conditions corresponding to the in situ Defence Military Satellite Program (DMSP) satellite low-resolution data [2] during UHF/GPS L-band subauroral scintillation events.

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SPACE SITUATIONAL AWARENESS (SSA)

Session Chair: Lt Col Elizabeth Campbell, SMC/SYAZ & Lt Col Larry Gunn, DARPA

Technique for GEO RSO Station-Keeping Characterization and Maneuver Detection

Jake Decoto, Orbital-ATK

Patrick Loerch, *Orbital-ATK*

As the Geosynchronous satellite population increases so too does the importance of accurate catalog maintenance for purpose of conjunction assessment and spacecraft operator situational awareness, particularly for operators in closely spaced regions or in collocated GEO slots. This paper presents the design, results, and limitations of an algorithm developed to aid these efforts by characterizing maneuver histories of geosynchronous satellites using published satellite TLE histories. Central to the algorithm is use of basic signal processing techniques to enhance the ability to detect small orbit changes amongst the noise in the raw data. After filtering out any single point inconsistent outliers the algorithm processes each orbit state with a temporal lead trail window of surrounding orbit states being propagated over a range of common epochs with key metrics being recorded. Potential maneuver events are then declared at any epoch where the comparison metrics between orbit states exceed several checks. Maneuver events are characterized as In-Plane or Out-of-Plane events, referring to the direction of the imparted change in velocity relative to the orbital plane of the satellite. Also characterized is the operational tempo of maneuvers including whether electric or chemical propulsion methods are being used. To illustrate this approach several examples from publicly available catalogs are processed with results provided.

Conceptual Design for Expert Centres Supporting Optical and Laser Observations in a Space Surveillance and Tracking System

Tim Flohrer, ESA/ESOC

One of the goals of ESA's SSA Programme in the Space Surveillance and Tracking (SST) segment is the successful establishment of expert centres for optical and laser observations. These centres will serve as the focal point for the interfacing with segment-external sensors and assets. They will also provide feedback on the provided data and will be able to request and manage observations. Benefits are expected in the coordination and monitoring of sensors and data providers, as well as through the expert support provision to the SST segment, such as in particular for sensor qualification and calibration. The establishment of the expert centres will have a strong technological focus on the complex networking and integration of heterogeneous sensors in a coherent SST segment, for which the enormous expertise that is available in Europe will be used. We report on the requirements analysis and the plans for the establishment of the centre,that is expected to start in 2015.

Integrated Space Asset Management Database and Modeling

Larry Gagliano, NASA/MSFC

Todd MacLeod[1], Shane Mason[2], Tom Percy[1], Jonathon Prescott[3]
[1]NASA/MSFC, [2]SRI International, [3]SRI International

The Space Asset Management Database (SAM-D) was implemented in order to effectively track known objects in space by ingesting information from a variety of databases and performing calculations to determine the expected position of the object at a specified time. While SAM-D performs this task very well, it is limited by technology and is not available outside of the local user base.

Modeling and simulation can be powerful tools to exploit the information contained in SAM-D. However, the current system does not allow proper integration options for combining the data with both legacy and new M&S tools.

A more capable data management infrastructure would extend SAM-D to support the larger data sets to be generated by the COI. A service-oriented architecture model will allow it to easily expand to incorporate new capabilities, including advanced analytics, M&S tools, fusion techniques and user interface for visualizations. Based on a web-centric approach, the entire COI will be able to access the data and related analytics. In addition, tight control of information sharing policy will increase confidence in the system, which would encourage industry partners to provide commercial data.

SIMON is a Government off the Shelf information sharing platform in use throughout DoD and DHS information sharing and situation awareness communities. SIMON providing fine grained control to data owners allowing them to determine exactly how and when their data is shared. SIMON supports a micro-service approach to system development, meaning M&S and analytic services can be easily built or adapted. It is uniquely positioned to fill this need as an information-sharing platform with a proven track record of successful situational awareness system deployments. Combined with the integration of new and legacy M&S tools, a SIMON-based architecture will provide a robust SA environment for the NASA SA COI that can be extended and expanded indefinitely.

First Results of Coherent Uplink from a Phased Array of Widely Separated Antennas: Steps Toward a Verifiable Real-Time Atmospheric Phase Fluctuation Correction for a High Resolution Radar System

Barry Geldzahler, NASA- HQ

NASA is pursuing a demonstration of coherent uplink arraying at 7.145-7.190 GHz (X-band) and 30-31 GHz (Ka-band) at using three 12m diameter COTS antennas separated by 60m at the Kennedy Space Center in Florida. In addition, we have used up to three 34m antennas separated by ~250m at the Goldstone Deep Space Communication Complex in California and at X-band 7.1 GHz incorporating real-time correction for tropospheric phase fluctuations. Such a demonstration would then enable NASA to establish a high power, high resolution, 24/7 availability radar system for (a) tracking and characterizing observations of Near Earth Objects, (b) tracking, characterizing and determining the statistics of small-scale (?10cm) orbital debris, (c) incorporating the capability into its space communication and navigation tracking stations for emergency spacecraft commanding in the Ka band era which NASA is entering, and (d) fielding capabilities of interest to other US government agencies. We present herein the results of our phased array uplink combining at near 7.17 and 8.3 GHz using widely separated antennas demonstrations at both locales, the results of a study to upgrade from a communication to a radar system, and our vision for going forward.

Operations Analysis of Australian-based Systems for Surveillance of Space

Mark Graham, Defence Science and Technology Group, Department of Defence

Due to increasing dependence on space-based capabilities, in recent years Australia has committed to making a greater contribution to generating space situational awareness (SSA). A natural first step has been to acknowledge Australia’s privileged geolocation and accept US invitations to host and jointly operate elements of the Space Surveillance Network (SSN), in particular a C-Band tracking radar to help maintain the Low Earth Orbit (LEO) region of the space object catalogue, and the Space Surveillance Telescope to maintain watch over the relatively crowded Geosynchronous sector above the Indian Ocean. The Australian government has also encouraged and supported increased investment by commercial and academic interests in SSA Research and Development capabilities.

Nevertheless, as Australia operates virtually no space systems itself, the Australian government has limited understanding of SSA. This can impact the ability to make informed decisions about participation in systems such as the SSN or further investments in Australian capability. Therefore Defence in Australia has sponsored ongoing work by the Defence Science and Technology (DST) Group to build up necessary understanding to support such decisions. This paper describes some of the operational analyses carried out to date in this program.

The program has centred on high-level modelling and simulation of the potential contribution sensors in Australia might make to maintain the unclassified LEO catalogue. This has involved calculating the ability of generic sensors to observe LEO objects, as a function of the sensors locations and key coverage

parameters such as range, elevation limits and operating hours which in turn depend on whether the sensors are active or passive. It has also required identification, computation and refinement of appropriate performance metrics to summarise the output of the simulations. This paper will outline work done, the results obtained and the conclusions drawn to date. In particular it notes findings so far and outstanding issues in carrying out perhaps the most difficult part of this work: assessing the difference new Australian systems might make to the overall performance of an enlarged SSN.

Space Fence Overview

Joseph Haimerl, Lockheed Martin

Gregory P. Fonder, *Lockheed Martin*

Space is no longer a vast, empty void. Unprecedented quantities of new satellites, derelict satellites, and debris litter the skies, posing an imminent threat to America's space assets.

The Space Fence System is a ground-based system of S-band radars designed to greatly enhance the Air Force Space Surveillance network. Space Fence provides unprecedented sensitivity, coverage and tracking accuracy, and contributes to key mission threads with the ability to detect, track and catalog small objects in LEO, MEO and GEO. Space Fence capabilities will revolutionize space situational awareness.

Space Fence includes up to two minimally-manned radar sites and the Space Fence Operations Center. Each radar site features a design with closely-spaced, but separate, Transmit and Receive Arrays that are mission-optimized for high availability and low lifetime support costs, including prime power. The radar architecture is based on Digital Beam-forming. This capability permits tremendous user-defined flexibility to customize volume surveillance and track sectors instantaneously without impacting routine surveillance functions.

Space Fence offers assured surveillance coverage for improved custody and features the capability to develop long arc tracks for accurate orbit determination, while simultaneously maintaining a persistent surveillance volume. Space Fence allows operators to reconstruct recent events such as collisions or satellite break-ups and accurately predict future events. For high-interest objects, a micro fence can be electronically constructed to gather more track data, focusing radar resources specifically on that object, providing more timely and accurate information.

The Space Fence System is net-centric and will seamlessly integrate into the existing Space Surveillance Network, providing services to external users such as JSpOC and coordinating handoffs to other SSN sites. Space Fence is a robust, flexible, advanced end-to-end system that will meet the warfighters operational needs and revolutionize Space Situational Awareness.

Heimdall System for MSSS Sensor Tasking

Alex Herz, Orbit Logic

Brandon Jones[1], Ella Herz[2], Doug George[2], Penina Axelrad[1], Steve Gehly[1]
[1]University of Colorado, [2]Orbit Logic

In Norse Mythology, Heimdall uses his foreknowledge and keen eyesight to keep watch for disaster from his home near the Rainbow Bridge. Orbit Logic and the Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado (CU) have developed the Heimdall System to schedule observations of known and uncharacterized objects and search for new objects from the Maui Space Surveillance Site.

Heimdall addresses the current need for automated and optimized SSA sensor tasking driven by factors associated with improved space object catalog maintenance. Orbit Logic and CU developed an initial baseline prototype SSA sensor tasking capability for select sensors at the Maui Space Surveillance Site (MSSS) using STK and STK Scheduler, and then added a new Track Prioritization Component for FiSST-inspired computations for predicted Information Gain and Probability of Detection, and a new SSA-specific Figure-of-Merit (FOM) for optimized SSA sensor tasking. While the baseline prototype addresses automation and some of the multi-sensor tasking optimization, the SSA-improved prototype addresses all of the key elements required for improved tasking leading to enhanced object catalog maintenance.

The Heimdall proof-of-concept was demonstrated for MSSS SSA sensor tasking for a 24 hour period to attempt observations of all operational satellites in the unclassified NORAD catalog, observe a small set of high priority GEO targets every 30 minutes, make a sky survey of the GEO belt region accessible to MSSS sensors, and observe particular GEO regions that have a high probability of finding new objects with any excess sensor time.

This Heimdall prototype software paves the way for further R&D that will integrate this technology into the MSSS systems for operational scheduling, improve the software's scalability, and further tune and enhance schedule optimization.

The Heimdall software for SSA sensor tasking provides greatly improved performance over manual tasking, improved coordinated sensor usage, and tasking schedules driven by catalog improvement goals (reduced overall covariance, etc.). The improved performance also enables more responsive sensor tasking to address external events, newly detected objects, newly detected object activity, and sensor anomalies. Instead of having to wait until the next day's scheduling phase, events can be addressed with new tasking schedules immediately (within seconds or minutes).

Perhaps the most important benefit is improved SSA based on an overall improvement to the quality of the space catalog. By driving sensor tasking and scheduling based on predicted Information Gain and other relevant factors, better decisions are made in the application of available sensor resources, leading to an improved catalog and better information about the objects of most interest.

The Heimdall software solution provides a configurable, automated system to improve sensor tasking efficiency and responsiveness for SSA applications. The FISST algorithms for Track Prioritization, SSA specific task and resource attributes, Scheduler algorithms, and configurable SSA-specific Figure-of-Merit together provide optimized and tunable scheduling for the Maui Space Surveillance Site and possibly other sites and organizations across the U.S. military and for allies around the world.

Dynamic Steering for Improved Sensor Autonomy and Catalogue Maintenance

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Neil Gordon, I. Vaughan L. Clarkson, Mark Rutten, Travis Bessell
The University of Queensland, Defence Science and Technology Group

A number of international agencies endeavour to maintain catalogues of the man-made resident space objects (RSOs) currently orbiting the Earth. Such catalogues are primarily created to anticipate and avoid destructive collisions involving important space assets such as manned missions and active satellites. An agencys ability to achieve this objective is dependent on the accuracy, reliability and timeliness of the information used to update its catalogue.

A primary means for gathering this information is by regularly making direct observations of the tens-of-thousands of currently detectable RSOs via networks of space surveillance sensors. But operational constraints sometimes prevent accurate and timely reacquisition of all known RSOs, which can cause them to become lost to the tracking system. Furthermore, when comprehensive acquisition of new objects does not occur, these objects, in addition to the lost RSOs, result in uncorrelated detections when next observed. Due to the rising number of space-missions and the introduction of newer, more capable space-sensors, the number of uncorrelated targets is at an all-time high. The process of differentiating uncorrelated detections caused by once-acquired now-lost RSOs from newly detected RSOs is a difficult and often labour intensive task. Current methods for overcoming this challenge focus on advancements in orbit propagation and object characterisation to improve prediction accuracy and target identification.

In this paper, we describe a complementary approach that incorporates increased awareness of error and failed observations into the RSO tracking solution. Our methodology employs a technique called dynamic steering to improve the autonomy and capability of a space surveillance networks steerable sensors. By co-situating each sensor with a low-cost high-performance computer, the steerable sensor can quickly and intelligently decide how to steer itself. The sensor-system uses a dedicated parallel-processing architecture to enable it to compute a high-fidelity estimate of the targets prior state error distribution in real-time. Negative information, such as when an RSO is targeted for observation but it is not observed, is incorporated to improve the likelihood of reacquiring the target when attempting to observe the target in future. The sensor is consequently capable of improving its utility by planning each observation using a sensor steering solution that is informed by all prior attempts at observing the target.

We describe the practical implementation of a single experimental sensor and offer the results of recent field trials. These trials involved reacquisition and constrained Initial Orbit Determination of RSOs, a number of months after prior observation and initial detection. Using the proposed approach, the system is capable of using targeting information that would be unusable by existing space surveillance networks. The system consequently offers a means of enhancing space surveillance for SSA via increased system capacity, a higher degree of autonomy and the ability to reacquire objects whose dynamics are insufficiently modelled to cue a conventional space surveillance system for observation and tracking.

A Fast Method for Embattling Optimization of Ground-Based Radar Surveillance Network

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Haowen Cheng, Yao Zhang, Jing Liu
National Astronomical Observatories, Chinese Academy of Sciences

A growing number of space activities have created an orbital debris environment that poses increasing impact risks to existing space systems and human space flight. For the safety of in-orbit spacecraft, a lot of observation facilities are needed to catalog space objects, especially in low earth orbit. Surveillance of Low earth orbit objects are mainly rely on ground-based radar, due to the ability limitation of exist radar facilities, a large number of ground-based radar need to build in the next few years in order to meet the current space surveillance demands. How to optimize the embattling of ground-based radar surveillance network is a problem to need to be solved.

The traditional method for embattling optimization of ground-based radar surveillance network is mainly through to the detection simulation of all possible stations with cataloged data, and makes a comprehensive comparative analysis of various simulation results with the combinational method, and then selects an optimal result as station layout scheme. This method is time consuming for single simulation and high computational complexity for the combinational analysis, when the number of stations increases, the complexity of optimization problem will be increased exponentially, and cannot be solved with traditional method. There is no better way to solve this problem till now.

In this paper, target detection procedure was simplified. Firstly, the space coverage of ground-based radar was simplified, a space coverage projection model of radar facilities in different orbit altitudes was built; then a simplified objects cross the radar coverage model was established according to the characteristics of space objects orbit motion; after two steps simplification, the computational complexity of the target detection was greatly simplified, and simulation results shown the correctness of the simplified results. In addition, the detection areas of ground-based radar network can be easily computed with the simplified model, and then optimized the embattling of ground-based radar surveillance network with the artificial intelligent algorithm, which can greatly simplifies the computational complexities. Comparing with the traditional method, the proposed method greatly improved the computational efficiency.

Collaborative Work Environment for Operational Conjunction Assessment

Francois Laporte, CNES

CHRISTY Stephane, *CNES*

Conjunction Messages (CM) provided by JSpOC are complete and valuable data to evaluate the level of risk of conjunctions, decide and choose avoidance actions. Nevertheless, conjunction assessment remains a difficult task which requires Middle Man between the CM provider (JSpOC) and Owner/Operators. Operational collision threat characterization is now an essential component of space mission operations. Most spacecraft operators have some sort of a process to evaluate and mitigate high-risk conjunction events. As the size of the space object catalog increases, satellite operators will be faced with more conjunction events to evaluate. Thus more sophisticated collision threat characterization and collision avoidance strategies must be implemented thought Middle Man entities.

CAESAR (Conjunction Analysis and Evaluation Service, Alerts and Recommendations) is the French Middle Man. CAESAR relies on a collaborative work environment between all members of CAESAR team and its subscribers. For CAESAR, the collaborative work environment is based on JAC software and a dedicated secure webserver SpOD Space Operational Data. JAC software is not the Main Flight Dynamics (FD) software used by CAESAR team, but it is a light friendly CM dedicated software to be used on a laptop by on-call teams or support dialogue between Middle Man and FD teams. The dedicated secure webserver is a key element to share data and information between actors.

This paper presents the main feedbacks from CAESAR team operational experience with regards to its collaborative work environment components: - JAC software which is not a classical Flight Dynamics software, its MMI is designed to be very quickly taken over (by teams not using it on daily basis) while also offering all the expertise levels required by the Middle Man team. JAC is used by CAESAR on-call team and all FD teams who subscribed to CAESAR. JAC is also distributed by CNES and therefore already used by some operational teams for Conjunction Assessment. - The secure webserver dedicated to CAESAR, SpOD, is used to offer operational security in combination with functions provided by JAC. For instance, JAC manages Team data such as operational procedures, templates, input data for analysis and so on. It garantees that each member of the operational team always uses the common last version of the operational procedures, templates or input data.

Collaborative work environment for Conjunction Assessment is essential to secure operations. CAESAR organization has been enriched and secured thanks to its declination of a collaborative work environment and is a concrete example of benefits in terms of security that can be achieved thanks to it.

Project UNITY: Cross Domain Visualization Collaboration

Jason Moore, Air Force Research Laboratory

Paul Havig, *Air Force Research Laboratory/RH*

UNITY is an International Cooperative Research and Development (ICR&D) project between the United States and Great Britain under the Research and Development Projects (RDP) Memorandum of Agreement (MOA). UNITYs objectives are to develop and evaluate the operational concepts and requirements for undertaking combined operations: a) pursuant to the interests of mission partners, b) develop, experiment, and demonstrate, transitionable emergent technologies, capabilities, or concepts, which facilitate the sharing of information and products between mission partners, and c) identify and define additional emerging technologies that may need to be developed to support current and future military information sharing. Collaboration between coalition partners is essentially for accurate and timely decision making in the ever increasing nature and tempo of global security. The purpose for this project is to develop engineering solutions in order to further investigate the human factors issues that arise while sharing information in a collaborative environment where security is an issue. The biggest difference between existing available solutions are in the presentation and interaction with the interface on both ends of the collaboration in order to preserve the expressed intent of shared situation awareness while also enabling markups and content on one screen that the other collaborator does not see and vice versa. The UNITY project stresses collaboration differently than all known realtime collaboration software in production, aka groupware, on the market today. The tradition of What You See Is What I See (WYSIWIS) as in typical implementations of shared whiteboards simply do not address the need for local and private information to be displayed in context with shareable data. This paper addresses the concerns, problems, and some solutions for shared 3D visualization and 2D tabular visualizations which are explored and presented within the space situation awareness problem set.

Application of a COTS Resource Optimization Framework to the SSN Sensor Tasking Domain – Part I: Problem Definition

Triet Tran, Braxton Technologies LLC

With the onset of the SmallSat era, the RSO catalog is expected to see continuing growth in the near future. This presents a significant challenge to the current sensor tasking of the SSN. The Air Force is in need of a sensor tasking system that is robust, efficient, scalable, and able to respond in real-time to interruptive events that can change the tracking requirements of the RSOs. Furthermore, the system must be capable of using processed data from heterogeneous sensors to improve tasking efficiency.

The SSN sensor tasking can be regarded as an economic problem of supply and demand: the amount of tracking data needed by each RSO represents the demand side while the SSN sensor tasking represents the supply side. As the number of RSOs to be tracked grows, demand exceeds supply. The decision-maker is faced with the problem of how to allocate resources in the most efficient manner.

Braxton recently developed a framework called Multi-Objective Resource Optimization using Genetic Algorithm (MOROUGA) as one of its modern COTS software products. This optimization framework took advantage of the maturing technology of evolutionary computation in the last 15 years. This framework was applied successfully to address the resource allocation of an AFSCN-like problem. In any resource allocation problem, there are five key elements: (1) the resource pool, (2) the tasks using the resources, (3) a set of constraints on the tasks and the resources, (4) the objective functions to be optimized, and (5) the demand levied on the resources. In this paper we explain in detail how the design features of this optimization framework are directly applicable to address the SSN sensor tasking domain. We also discuss our validation effort as well as present the result of the AFSCN resource allocation domain using a prototype based on this optimization framework.

POSTERS

Commercial Optics for Space Surveillance and Astronomy

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Since the first days of the space program, there have been both amateur and government satellite watchers. Large, expensive government systems with custom optics are still the most capable, but with modern sensors and high speed computers, amateur trackers are easily pushing the limits of what government systems achieved only a decade ago. A very recent trend in the space world is the emergence of commercial space operations centers. Once the exclusive purview of governments, corporations are now providing orbital environment awareness services to the operators of commercial satellites. The requirement for synoptic satellite observations has led to corporations developing world-wide observing networks.

A problem facing both amateur and corporate observers is the limited availability of suitable optical systems. Most observing efforts rely on long focus (f/8 or greater) optical systems with focal reducers, and a somewhat limited field of view. Often, the cameras in use are not ideally matched to the optical system. While there are a few exceptions, the choices are not many.

Celestron recently introduced the C-11 RASA optical system, with an 11-inch aperture and an f/2.2 focal ratio. This optical system is designed for dedicated imaging and is ideally suited for both wide-field astronomy and the detection and tracking of satellites. The larger C-14 RASA, to be introduced later this year, was specifically designed for wide-field imaging with large commercial CCDs. It offers greater sensitivity and a wider field of view than the smaller C-11 RASA and should prove to be the instrument of choice for both amateur and corporate satellite observers. We present data from satellite observations with a production model C-11 RASA and estimated performance for the new C-14 RASA.

Thermal Systems Engineering of a Highly Re-usable Host Spacecraft for Space Surveillance

Dr. Kevin Anderson, Cal Poly Pomona, Mechanical Engineering

Dr. Donald Edberg, Daniel Forgette, Matthew Devost
Cal Poly Pomona, Mechanical Engineering

Recent efforts have focused on low-cost opportunities to space [1] for scientific instruments (aka payloads to enable space surveillance missions) to study Earth's climate change [2] as well as astrophysics [3]. The days of large, flagship missions are out of favor for the foreseeable future. At the other extreme, Cubesats [4] are extremely economical, but are very limiting in the type of instruments they can accommodate due to restrictions on volume, mass, and power resources. Another one of the more economical ways for instruments to get to orbit is to join a scheduled mission that has the extra capacity to accommodate it. But such opportunities are hampered by incompatibilities with the orbit and spacecraft attitude scenarios as well as the available mass, volume, and power allocations. A low-cost spacecraft designed to maximize the opportunities for instruments would provide a significant benefit to the science community. Such a spacecraft would be designed for a given orbit range useful for both Earth science and astrophysics and would be capable of accommodating instruments requiring views ranging from Nadir to Earth limb to deep space. The payload or instrument is the element of the flight system that performs the science objectives of the mission Payloads have a wide breadth of technologies utilized to perform space surveillance. The most challenging to accommodate is the payload thermal subsystem needed to maintain science components within their operating temperature limits. Spatial gradients must often be kept within a fraction of a degree Celsius over large areas. The thermal subsystem is key to enabling such a spacecraft. The thermal design of the bus needs to consider the different environments associated with the orbit range, most importantly, the Sun to orbit plane, i.e., Beta, angle. What would enhance usability of the spacecraft from a thermal perspective is if it were able to absorb a payloads waste heat and maintain its interface with it to a stable temperature. Multiple mounting locations should be provided to allow for various observation views (Nadir,

limb, star) or to accommodate a single instrument with multiple components. Cryogenic payloads would be encouraged to utilize low-cost, tactical cryo-coolers where the compressor load could be dumped to the host interface. This AMOS poster will present the results of the design the thermal subsystem of a spacecraft that serves as a plug-and-play platform accommodating a variety of payloads. The design presented herein is a technology demonstration program and is allowed to use Technologies of Readiness Levels (TRL) 7 and above to accomplish the objectives. Simultaneously, the design should strive to minimize complexity, mass, power, and cost. The poster will present the results of thermal systems engineering trade studies and thermal modeling performed to demonstrate the feasibility of the re-usable host spacecraft with a generic payload which may accommodate a variety of space surveillance missions.

[1] Herrell, L. M., Peden, J. C., The Development of Small-Payload Rideshare Capabilities: A 2000-2008 Summary, IEEE Aerospace Conference, Big Sky, MT.

[2] http://science.nasa.gov/earth-science/focus-areas/

[3] http://science.nasa.gov/astrophysics/focus-areas/

[4] http://www.cubesat.org/

New Approach to Multiple Data Association Processing for Initial Orbit Determination using Optical Observations

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The proposed approach aims to develop a new method of forming and processing of multiple hypotheses for initial orbit determination using optical observations. This method allows us to generalize the existing 2-dimensional flat constrained admissible region (CAR) to a unique 3-dimensional (3D) manifold of points corresponding to the pairs of observed right ascension and declination. Another advantage of this method is that unlike the existing methods of initial orbit determination using CAR, the range, range rate and angular rates are computed analytically using the angle observations, the location coordinates of the observation station, the semi-parameter and semi-major axis corresponding to the CAR. Unlike the existing 2D CAR, the 3D manifold does not include the pairs of range and range rate that do not correspond to the observed angles and computed range rat and angular rates. Given the the semi-parameter and semi-major axis, the proposed approach allows us to analytically compute the orientation angles as the Keplerian orbital elements, including the longitude of ascending node, inclination and argument of perigee. The resulting method represents a new and computationally efficient procedure for multiple data association processing through multiple hypotheses filter and allows for an uncertainty quantification.

Flat-fielding in Very Wide-field of View Optical Systems: a Comparison between Twilight Sky and a Flat-fielding Box Approaches for the TFRM Baker-Nunn Camera

Roberto Baena-Gallé, Royal Academy of Sciences and Arts of Barcelona

Daniel del Ser[1], Albert Rosich[1], Octavi Fors[2]
[1]Royal Academy of Sciences and Arts of Barcelona, [2]Department of Physics and Astronomy, University of North Carolina at Chapel Hill

We present a comparative study of accuracy and effectiveness of flat-fielding strategies obtained from the sky twilight and those obtained from a taylor-made LED-driven flat-field box.

When photometric accuracy is a goal, this imposes critical requirements on the flat-fielding precision during data reduction. Twilight flat frames are often used in flat-fielding due to well-known uniformity of small regions of twilight sky. They also have the advantage spectral signature similar to the intended science images. However, in very wide field cameras it is proved the existence of a noticeable sky gradient that influences differential photometry when correcting science frames flat-fielding. The typical photometric

systematic error induced by the twilight flat-fielding strategy in a telescope with FoV of 4.4ºx4.4º, such as the TFRM, has been ~1%.

A flat-field box comprising an array of sixteen LEDs and a number translucent acrylic sheets has been built. By usual median averaging of several flat-fielding frames, a masterflat has been obtained and used for TFRM routine photometric observations. In this case the systematic photometric error induced by flat-fielding has been decreased down to ~0.1%.

Object Area-to-Mass Ratio Estimation for Better Orbit Predictions

James Bennett, Space Environment Research Centre & EOS Space Systems

Ben Greene[1], Craig Smith[2], Daniel Kucharski[1], Jizhang Sang[3]
[1]Space Environment Research Centre, [2]EOS Space Systems, [3]Wuhan University

In this paper results are presented from an analysis assessing the improvements in orbit prediction results for near-Earth objects when the area-to-mass ratio is estimated. These results form part of a new high-accuracy space object catalogue for the Space Environment Research Centre, Australia.

The area-to-mass ratio of the debris objects is estimated using long-term two-line element data. In data sparse situations where there is not enough data for a traditional least squares fit, the area-to-mass ratio is fixed and not estimated during the orbit determination process, leading to better orbit predictions. Otherwise, in these cases the least squares process is likely to diverge or worse, converge to an erroneous solution. The results of the sparse analysis are compared with results where more data is available for fitting to determine the transition between data-sparse fitting methods to regular fitting. This is an important aspect to the maintenance of the catalogue and creation of future orbital elements, i.e. whether to update an orbital element or postpone the calculation until more data is obtained.

This work forms part of the collaborative effort of the Space Environment Management Cooperative Research Centre which is developing new technologies and strategies to preserve the space environment (www.serc.org.au).

Comparison of BRDF-Predicted and Observed Light Curves of GEO Satellites

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Although the amount of light received by sensors on the ground from Resident Space Objects (RSOs) in geostationary orbit (GEO) is small, information can still be extracted in the form of light curves (temporal brightness or apparent magnitude). Previous research has shown promising results in determining RSO characteristics such as shape, size, reflectivity, and attitude by processing simulated light curve data with various estimation algorithms. These simulated light curves have been produced using one of several existing analytic Bidirectional Reflectance Distribution Function (BRDF) models. These BRDF models have generally come from researchers in computer graphics and machine vision and have not been shown to be realistic for telescope observations of RSOs in GEO. While BRDFs have been used for SSA analysis and characterization, there is a lack of research on the validation of BRDFs with regards to real data. In this paper, we compared telescope data provided by the Air Force Research Laboratory (AFRL) with predicted light curves from the Ashikhmin-Premoze BRDF and two additional popular illumination models, Ashikhmin-Shirley and Cook-Torrance. We computed predicted light curves based on two line mean elements (TLEs), shape model, attitude profile, observing ground station location, observation time and BRDF. The predicted light curves were then compared with AFRL telescope data. The selected BRDFS provided accurate apparent magnitude trends and behavior, but uncertainties due to lack of attitude information and deficiencies in our satellite model prevented us from obtaining a better match to the real data. The current findings present a foundation for ample future research.

Architecture Design for the Space Situational Awareness System in the Preparedness Plan for Space Hazards of Republic of Korea

Eun Jung Choi, Korea Astronomy and Space Science Institute

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The threat posed by asteroids and comets has become one of the important issues. Jinju meteorite discovered in March 2014 has expanded the interest of the people of the fall of the natural space objects. Furthermore, the growing quantity of space debris is a serious threat to satellites and other spacecraft, which risk being damaged or even destroyed. In May of 2014, Korea established the preparedness plan for space hazards according to the space development promotion act which is amended to take action with respect to hazards from space. This plan is largely composed of 3 items such as system, technology and infrastructure. System is included the establishment and management of national space hazards headquarters at risk situation. Korea Astronomy and Space Science Institute (KASI) was designated as a space environment monitoring agency under the ministry of science, ICT and future planning (MSIP). Technology is supposed to develop the space situational awareness system that can monitor and detect space objects. For infrastructure, research and development of core technology will be promoted for capabilities improvement of space hazards preparedness such as software tools, application and data systems. This paper presents the architectural design for building space situational awareness system. The trade-off study of space situational awareness system for the Korea situation was performed. The results have shown the proposed architectural design. The baseline architecture is composed of Integrated Analysis System and Space Objects Monitoring System. Integrated Analysis System collects the status data from Space Objects Monitoring System and analyzes the space risk information through a data processing. For Space Objects Monitoring System, the all-sky surveillance camera, array radar and meteoroid surveillance sensor networks were considered. This system focuses on not only the threat of a large artificial satellite and natural space objects such as asteroids that crashed to Earth but also the prediction of potential collisions between space objects. Especially, array radar aims to accurately track space objects. By analyzing performance for radar system and sensor networks, several feasible approaches for such a space objects monitoring system will be presented in this paper.

Adaptive Optics Testbed for the Visible High Resolution Imaging

Young Soo Choi, Agency for Defence Development

Jae Eun Yoo[1], Sung Soo Kim[1], Won Tae Park[2], Jong Kyu Jung[2], Soo Man Lee[2]
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We have developed Adaptive Optics testbed to obtain the visible high resolution imaging. Here, the various experimental performances of the AO testbed in the laboratory have been reported. The closed-loop AO system with real-time operations that is 1000Hz sampling frequency, has been compensated for both tip/tilt and high order disturbances induced by the rotating phase plates as the atmospheric turbulence simulators. A 277-element Deformable mirror(DM-277-15, ALPAO) with continuous membrane magnetic voice coils is matched with a 16x16 Shack-Hartmann wavefront sensor(Firstight). To evaluate the quality of the image, the average Strehl ratios have been measured as a function of object light levels and atmospheric seeing conditions.

Robust Wave-front Correction in a Small Scale Adaptive Optics System Using a Membrane Deformable Mirror

Young Soo Choi, Agency for Defence Development

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A small scale laboratory adaptive optics system using a Shack-Hartmann wave-front sensor (WFS) and a membrane deformable mirror (DM) has been built for robust image acquisition. In this study, an adaptive

limited control technique is adopted to maintain the long-term correction stability of an adaptive optics system. To prevent the waste of dynamic correction range for correcting small residual wave-front distortions which are inefficient to correct, the built system tries to limit wave-front correction when a similar small difference wave-front pattern is repeatedly generated. Also, the effect of mechanical distortion in an adaptive optics system is studied and a pre-recognition method for the distortion is devised to prevent low-performance system operation. A confirmation process for a balanced work assignment among deformable mirror (DM) actuators is adopted for the pre-recognition. The corrected experimental results obtained by using a built small scale adaptive optics system are described in this paper.

Spectral Measurements of Geosynchronous Satellites During Glint Season

Francis Chun, U.S. Air Force Academy, Department of Physics

Ryan M. Tucker, Evan M. Weld, Francis K. Chun, Roger D. Tippets,
U.S. Air Force Academy, Department of Physics

During certain times of the year, stable geosynchronous (GEO) satellites are known to glint or exhibit a very bright specular reflection, which is easily observed through broadband photometric filters. The glints are typically brighter in the Johnson red filter compared to the Johnson blue filter. In previous years, USAFA cadets have developed and refined techniques to take, calibrate and process satellite spectral data taken using a diffraction grating on the USAFA 16-inch, f/8.2 telescope (slitless spectroscopy). To the best of our knowledge, we have not seen any published research on observing glints across the visible spectrum. We present research from an Air Force Academy senior physics capstone project on observing glints off of GEO satellites using slitless spectroscopy. We discuss the calibration of the measurements using solar analog and solar twin stars, as well as results of the spectra of a glinting GEO satellite. A key question is whether a GEO satellite glint is localized in wavelength or equally observed across the entire spectra.

An Asteroid and its Moon Observed with LGS at the SOR

Jack Drummond, Air Force Research Laboratory

Robert Johnson, Odell Reynolds, Miles Buckman
Air Force Research Laboratory/RDSS

The faint moon, Romulus, around the main belt asteroid (87) Sylvia was detected and followed over 10 nights in March and May of 2015, using adaptive optics and a laser guide star on the 3.5 m telescope at the SOR. Romulus was some 80 times fainter than V=12.5 Sylvia at 1.2 μm. From these observations we are able to derive an orbit for the satellite, calculate the mass of Sylvia, and derive its density of 1.37±0.04 gm/cm^3. These observations closely mimic a small man-made geosynchronous satellite approaching a larger one, and make our 3.5 m telescope the smallest ground-based telescope to ever image any asteroid's moon.

Detecting GEO Debris via Cascading Numerical Evaluation for Lines in Image Sequence

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This paper presents a novel method to detect trajectories for Geosynchronous Earth Orbit (GEO) debris in image sequences. As far as Earth-based observation is concerned, detecting GEO debris is not so easy because debris often appear very faintly in image frames. A simple but effective way to detect such faint debris is decreasing a threshold value of binarization applied to an image sequence as preprocessing. However, a low threshold value of binarization leads to extracting a large number of image objects other than debris, which become obstacles to detect debris trajectories and cause high computational load. In order to detect debris from binarized image frames with a mass of obstacles, this work proposes a method that numerically evaluates the characteristics of a line segment connecting two image objects on different image frames or a candidate of debris trajectory. The proposed method adopts a cascading numerical

evaluation based on the physical properties of GEO debris image. In the first stage of the cascading evaluation, the candidates of debris trajectories are selected using a displacement between two image frames for each line segment. A Monte Carlo simulation of a target breakup event derives the threshold for the displacement, and the lines with displacements exceeding the threshold are removed. The second stage evaluates a direction of a line, i.e., a direction of motion in an image sequence. The lines with motion close to the horizontal direction are rejected, because they almost correspond to stars. The continuity of trajectories is utilized in the third stage. After the points of intersection of the selected lines on all image frames are computed, it is possible to check whether image objects can be found on the points. The continuity of each line is evaluated by the count of found image objects, and the lines are finally detected as debris trajectories if the count exceeds the threshold determined in proportion to the total number of image frames. Since the order of the numerical evaluation can adjust the performance to remove obstacles, the proposed cascading numerical evaluation efficiently detects GEO debris. The effectiveness of the proposed method is demonstrated by experiments using real observation image sequences obtained from the telescopes at Lulin Observatory in Taiwan.

Innovative Electrostatic Adhesion Technologies

Larry Gagliano, NASA/MSFC

Tom Bryan[1], Scott Williams[2], Brian McCoy[2], Todd MacLeod[1]
[1]NASA/MSFC, [2]SRI International

Developing specialized Electro-Static grippers (commercially used in Semiconductor Manufacturing and in package handling) will allow gentle and secure Capture, Soft Docking, and Handling of a wide variety of materials and shapes (such as upper-stages, satellites, arrays, and possibly asteroids) without requiring physical features or cavities for a pincher or probe or using harpoons or nets. Combined with new rigid boom mechanisms or small agile chaser vehicles, flexible, high speed Electro-Static Grippers can enable compliant capture of spinning objects starting from a safe stand-off distance. Electroadhesion (EA) can enable lightweight, ultra-low-power, compliant attachment in space by using an electrostatic force to adhere similar and dissimilar surfaces. A typical EA enabled device is composed of compliant space-rated materials, such as copper-clad polyimide encapsulated by polymers. Attachment is induced by strong electrostatic forces between any substrate material, such as an exterior satellite panel and a compliant EA surface.

When alternate positive and negative charges are induced in adjacent planar electrodes in an EA surface, the electric fields set up opposite charges on the substrate and cause an electrostatic adhesion between the electrodes and the induced charges on the substrate. Since the electrodes and the polymer are compliant and can conform to uneven or rough surfaces, the electrodes can remain intimately close to the entire surface, enabling high clamping pressures. Clamping pressures of more than 3 N/cm2 in shear can be achieved on a variety of substrates with ultra-low holding power consumption (measured values are less than 20 microW/Newton weight held). A single EA surface geometry can be used to clamp both dielectric and conductive substrates, with slightly different physical mechanisms. Furthermore EA clamping requires no normal force be placed on the substrate, as conventional docking requires.

Internally funded research and development has demonstrated that EA can function effectively in space, even in the presence of strong ultraviolet radiation, atomic oxygen, and free electrons. We created a test setup in an existing vacuum chamber to simulate low-Earth-orbit conditions. An EA mechanism was fabricated and installed in the chamber, instrumented, operated in a vacuum, and subjected to ultraviolet photons and free electrons generated by an in-chamber multipactor electron emitter.

Extensions to EA that can add value include proximity and contact sensing and transverse motion or rotation, both of which could enhance docking or assembly applications. Possible next steps include development of targeted applications for ground investigation or on-orbit subsystem performance demonstrations using low cost access to space such as CubeSats.

Small Orbital Stereo Tracking Camera Technology Development

Larry Gagliano, NASA/MSFC

Tom Bryan, Todd MacLeod
NASA/MSFC

On-Orbit Small Debris Tracking and Characterization is a technical gap in the current National Space Situational Awareness necessary to safeguard orbital assets and crew. This poses a major risk of MOD damage to ISS and Exploration vehicles. In 2015 this technology was added to NASAs Office of Chief Technologist roadmap. For missions flying in or assembled in or staging from LEO, the physical threat to vehicle and crew is needed in order to properly design the proper level of MOD impact shielding and proper mission design restrictions. Need to verify debris flux and size population versus ground RADAR tracking. Use of ISS for In-Situ Orbital Debris Tracking development provides attitude, power, data and orbital access without a dedicated spacecraft or restricted operations on-board a host vehicle as a secondary payload. Sensor Applicable to in-situ measuring orbital debris in flux and population in other orbits or on other vehicles. Could enhance safety on and around ISS. Some technologies extensible to monitoring of extraterrestrial debris as well

To help accomplish this, new technologies must be developed quickly. The Small Orbital Stereo Tracking Camera is one such up and coming technology. It consists of flying a pair of intensified megapixel telephoto cameras to evaluate Orbital Debris (OD) monitoring in proximity of International Space Station. It will demonstrate on-orbit optical tracking (in situ) of various sized objects versus ground RADAR tracking and small OD models. The cameras are based on Flight Proven Advanced Video Guidance Sensor pixel to spot algorithms (Orbital Express) and military targeting cameras. And by using twin cameras we can provide Stereo images for ranging & mission redundancy. When pointed into the orbital velocity vector (RAM), objects approaching or near the stereo camera set can be differentiated from the stars moving upward in background.

Spaceborne Laser Communication and the Space Data Highway - Enabling Near-Real-Time Surveillance For Earth Observation

David Germroth, PACE GS

The proposed presentation will demonstrate how, through the combination of novel technologies in Earth observation and telecommunication solutions for data latency and application areas that here-to-for have not been satisfactorily addressed. The combination of the next-generation space based X-Band radar systems with the SpaceDataHighway and airborne laser communication terminals will revolutionize the way we monitor and disseminate data. Each technology in its own right is game changing and offers advanced capabilities to users worldwide, however the combination of the two provides the much-needed solution for a continuous global surveillance like Open Ocean and Port Surveillance in near real time.

TerraSAR-X2-NG is the follow-on mission of TerraSAR-X and TanDEM-X providing long-term continuity with advanced capabilities. The TerraSAR-X2-NG mission will benefit from an advanced SAR sensor technology allowing among other things:

- Ground resolution down to 25 cm (best possible: 15 cm)
- Geo-location accuracy equal to resolution
- Full polarimetry
- Swath up to 400 km
- Synchronous AIS signal collection

The improved data quality and collection capability provided by TerraSAR-X2 will come into its own right when combined with the SpaceDataHighway that provides accelerated access to Spaceborne imagery and data from anywhere in the world. This constellation of geostationary satellites enables bi-directional high-speed data transfer from Low Earth Orbit satellites or UAVs and the ground. The unprecedented performance options for payload tasking and data download enabled by the SpaceDataHighway will make data available at the right time and the right place thus facilitating a near-real-time monitoring of the world. The new generation optical laser communication terminal used on the SpaceDataHighway provides end-to-end data relay capabilities of 2.8 Gpbs (raw). A laser terminal for use on UAVs is currently under production allowing UAVs to take advantage of forward tasking options and immediate broadband data transfer with a low probability of interception. Together these two systems inaugurate the first commercial global near-real-time Maritime Domain Surveillance Service capable of delivering actionable information in (less than) 20 minutes.

Space Situational Awareness Data Processing Scalability Utilizing Google Cloud Services

Dave Greenly, SpaceNav

Matt Duncan[1], Josh Wysack[1], Francesc Campoy Flores[2]
[1]SpaceNav, [2]Google

Space Situational Awareness (SSA) is a fundamental and critical component of current space operations. The term SSA encompasses the awareness, understanding and predictability of all objects in space. As the population of orbital space objects and debris increases, the number of collision avoidance maneuvers grows and prompts the need for accurate and timely process measures. The SSA mission continually evolves to near real-time assessment and analysis demanding the need for higher processing capabilities. By conventional methods, meeting these demands requires the integration of new hardware to keep pace with the growing complexity of maneuver planning algorithms. SpaceNav has implemented a highly scalable architecture that will track satellites and debris by utilizing powerful virtual machines on the Google Cloud Platform. SpaceNav algorithms for processing CDMs outpace conventional means. A robust processing environment for tracking data, collision avoidance maneuvers and various other aspects of SSA can be created and deleted on demand. Migrating SpaceNav tools and algorithms into the Google Cloud Platform will be discussed and the trials and tribulations involved. Information will be shared on how and why certain cloud products were used as well as integration techniques that were implemented. Key items to be presented are:

1.Scientific algorithms and SpaceNav tools integrated into a scalable architecture a) Maneuver Planning b) Parallel Processing c) Monte Carlo Simulations d) Optimization Algorithms e) SW Application Development/Integration into the Google Cloud Platform
2. Compute Engine Processing a) Application Engine Automated Processing b) Performance testing and Performance Scalability c) Cloud MySQL databases and Database Scalability d) Cloud Data Storage e) Redundancy and Availability

Efficient Photometry In-Frame Calibration (EPIC) Gaussian Corrections for Automated Background Normalization of Rate-Tracked Satellite Imagery

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Photometric processing of non-resolved Electro-Optical (EO) images has commonly required the use of dark and flat calibration frames that are obtained to correct for charge coupled device (CCD) dark (thermal) noise and CCD quantum efficiency/optical path vignetting effects respectively. It is necessary to account/calibrate for these effects so that the brightness of objects of interest (e.g. stars or resident space objects (RSOs)) may be measured in a consistent manner across the CCD field of view. Detected objects typically require further calibration using aperture photometry to compensate for sky background (shot noise). For this, annuluses are measured around each detected object whose contained pixels are used to estimate an average background level that is subtracted from the detected pixel measurements.

In a new photometric calibration software tool developed for AFRL/RD, called Efficient Photometry In-Frame Calibration (EPIC), an automated background normalization technique is proposed that eliminates the requirement to capture dark and flat calibration images. The proposed technique simultaneously corrects for dark noise, shot noise, and CCD quantum efficiency/optical path vignetting effects. With this, a constant detection threshold may be applied for constant false alarm rate (CFAR) object detection without the need for aperture photometry corrections. The detected pixels may be simply summed (without further correction) for an accurate instrumental magnitude estimate.

The noise distribution associated with each pixel is assumed to be sampled from a Poisson distribution. Since Poisson distributed data closely resembles Gaussian data for parameterized means greater than 10, the data may be corrected by applying bias subtraction and standard-deviation division.

EPIC performs automated background normalization on rate-tracked satellite images using the following technique. A deck of approximately 50-100 images is combined by performing an independent median calculation along the deck dimension for each image pixel. Because the images are rate-tracked, moving objects (such as background stars) are quickly eliminated. Stationary RSO signatures are removed from the resultant median combined image using a local area median filter that smoothes over the RSO responses. The result is an estimate of the background noise bias. The calculated bias estimate image is subtracted from each deck image, which effectively removes noise bias.

A variance correction is applied to address spatially varying noise by dividing each pixel by the square-root of its measured variance. This technique essentially uses the sky background noise (assumed to be uniform over the telescope aperture) to normalize the CCD quantum efficiency/optical path vignetting effects. Poisson distributed random variables have, by definition, equal mean and variance, which eliminates the need to estimate the variance explicitly. Simply dividing each pixel by the square-root of the measured bias effectively normalizes the imagery. The result after the bias and variance corrections are applied is a statistically stationary noise background appropriate for CFAR detection.

Additional techniques to address time-varying noise backgrounds (caused by atmospheric turbulence, clouds, and stray light) and hot-pixel / cosmic-ray mitigation are also explored.

10 Steps to Building an Architecture for Space Surveillance Projects

Eric Gyorko, Harris Corporation

Eric Barnhart, Howard Gans
Harris Corporation

Space surveillance is an increasingly complex task, requiring the coordination of a multitude of organizations and systems, while dealing with competing capabilities, proprietary processes, differing standards, and compliance issues. In order to fully understand space surveillance operations, analysts and engineers need to analyze and break down their operations and systems using what are essentially enterprise architecture processes and techniques. These techniques can be daunting to the first- time architect. This paper provides a summary of simplified steps to analyze a space surveillance system at the enterprise level in order to determine capabilities, services, and systems. These steps form the core of an initial Model-Based Architecting process. For new systems, a well defined, or well architected, space surveillance enterprise leads to an easier transition from model-based architecture to model-based design and provides a greater likelihood that requirements are fulfilled the first time. Both new and existing systems benefit from being easier to manage, and can be sustained more easily using portfolio management techniques, based around capabilities documented in the model repository. The resulting enterprise model helps an architect avoid 1) costly, faulty portfolio decisions; 2) wasteful technology refresh efforts; 3) upgrade and transition nightmares; and 4) non-compliance with DoDAF directives. The Model-Based Architecting steps are based on a process that Harris Corporation has developed from practical experience architecting space surveillance systems and ground systems. Examples are drawn from current work on documenting space situational awareness enterprises. The process is centered on DoDAF 2 and its corresponding meta-model so that terminology is standardized and communicable across any disciplines that know DoDAF architecting, including acquisition, engineering and sustainment disciplines. Each step provides a guideline for the type of data to collect, and also the appropriate views to generate. The steps include 1) determining the context of the enterprise, including active elements and high level capabilities or goals; 2) determining the desired effects of the capabilities and mapping capabilities against the project plan; 3) determining operational performers and their inter-relationships; 4) building information and data dictionaries; 5) defining resources associated with capabilities; 6) determining the operational behavior necessary to achieve each capability; 7) analyzing existing or planned implementations to determine systems, services and software; 8) cross-referencing system behavior to operational behavioral; 9) documenting system threads and functional implementations; and 10) creating any required textual documentation from the model.

Multi-sensor Observations of the SpinSat Satellite

Doyle Hall, Boeing - LTS

The Naval Research Laboratory developed and launched the spherical SpinSat satellite to accomplish two primary goals: 1) study the performance of a new class of micro-thrusters, and 2) provide a calibrated drag experiment to characterize Earth's upper atmosphere during the current period of relatively high solar activity. The 55.9 cm diameter aluminum sphere is equipped with a set of Electrically-Controlled Solid Propellant (ESP) thrusters, oriented to allow both translational and spin-up/spin-down maneuvers. To facilitate remote observations of the satellite's spin rate, the sphere's exterior features a reflectance pattern much like that of a beach-ball, as well as an ensemble of light-emitting diodes (LEDs) arranged along a meridian (i.e., a line of longitude) which can be turned on for brief periods. The Air Force Research Laboratory has conducted optical observations of SpinSat from several ground-based sensors, and more are planned. The observational goals include: 1) obtaining time-resolved, multi-band measurements of the satellite actively firing its micro-thrusters, 2) characterizing the detectability and spatial/temporal morphology of the ESP thruster plumes, 3) measuring the spin rate of the satellite with the LEDs turned on, ideally before and after a spin rate adjustment maneuver, and 4) measuring the spin rate of the satellite in its completely inactive mode, using only passive observations of reflected light and/or thermal emissions.

Changes of the Electrical and Optical Character of Polyimide Films Due to Exposure to High Energy GEO-like Electrons and the Chemistry that Drives it

Ryan Hoffmann, Air Force Research Laboratory/RVB

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As a result of the interaction between the spacecraft and its operational environment, the constituent materials begin to change. These changes are determined by a combination of: chemical reactions, contamination, and energy deposition. They can range in severity from negligible to total loss of the material. Virtually all properties of the material, the mechanical, optical/thermal, and electrical are altered in largely unknown ways from the pristine materials. This negatively impacts the ability of spacecraft operators to predict the behavior of a spacecraft as it ages its environment. For example, in the case of electrical conduction in polyimide, there is a three orders of magnitude decrease in the resistivity after only eight months of simulated GEO electron exposure. Optical changes in the material also dramatically impact the ability of ground based optical observations to identify and track both known and unknown spacecraft.

We will be presenting work done within the Spacecraft Charging and Instrument Calibration Lab at AFRL/RVB to quantify the changes in total reflection, BRDF, and electrical conduction of aluminized polyimide film after simulated aging in a GEO-like electron environment. We correlate these data with the chemical structure of the film as determined by XPS and NMR. A deeper, predictive understanding of how materials change will not only increase the operational lifetime of space assets by providing more accurate data to operators, it will improve SSA by allowing ground based observers to more accurately deduce component materials and determine how long a spacecraft has been in orbit.

Accurate Focus Correction for Large Telescope

Richard Holmes, Boeing LTS

Brett Sickmiller [1], Nicholas Steinhoff[2], Skip Williams[3], Andrew Whiting[4]
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A ubiquitous problem in observations with large telescopes is focus control. Typical auto-focus algorithms used in commercial cameras are not effective for the astronomical application due to the long range to the typical objects and the random focus caused by atmospheric turbulence. This problem can be mitigated with an adaptive optics system. However, adaptive optics systems are typically complex and costly. This paper discusses alternative approaches that are relatively low in cost and complexity. These options include two tracker/imager based means for focus control, and a dedicated focus sensor approach. The dedicated focus sensor is a simplified form of a Hartmann sensor. The specific implementation of such a focus sensor will be shown to provide significant benefits for focus correction. The tracker/imager-based implementations have an intrinsic plus/minus focus ambiguity, due to the nature of the focus sensed on an image plane. However, this ambiguity can be overcome with careful algorithm design. Two options are considered for tracker/imager-based focus control: an auto-focus metric that has been preferred in commercial cameras, and a spot-width estimation algorithm. It is found that the spot-width estimation algorithm works as well as a dedicated focus sensor when the plus/minus ambiguity is resolved, and that this ambiguity can be resolved in most cases. In addition to performance, cost and implementation issues are also considered for generic telescope systems with apertures greater than 0.5 meters.

Advantages of a Geographically Diverse Ground Based Architecture for SSA

Brendan Houlton, Analytical Graphics, Inc.

Bob Hall,
Analytical Graphics, Inc.

By employing a distributed optical ground architecture, AGI has demonstrated the ability to refine the orbital uncertainty for geostationary satellites. This refinement significantly enhances the ability to maintain custody and characterize the behavior and attributes of GEO satellites.

RSO Characterization from Photometric Data Using Machine Learning

Michael Howard, Charles River Analytics, Inc.

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Object characterization is the description of a resident space object (RSO), its capabilities and its behavior. While astrometric data has been used extensively for object detection, location, and characterization, photometric data has been less widely applied and remains a promising area for improving RSO characterization. RSO characteristics which may influence changes in light intensity with respect to changes in viewing angle or orientation signature include geometry, orientation, components material properties, stability and other characteristics. However, most RSO characterization is presently performed manually and on an individual basis by space analysts and there is a need for efficient and automated methods to perform characterization.

This paper discusses the application of machine learning techniques to characterization of RSOs in the geosynchronous altitude regime using photometric data. We develop simulated signatures in the visible spectral band of three basic RSO types, with variations in object orientation, material characteristics, size and attitude and attempt to recover these properties through object characterization techniques. We generate observations by sampling noisy measurements from the simulated signature. Next, we extract a set of features from the observations and train machine learning algorithms to classify the signatures. We consider the effectiveness of a set of binary classifiers trained to individually recognize separate cases. The results of each classifier are combined together to produce a final output characterization of an input observation. Experiments with varying levels of noise are presented, and we evaluate models with respect to classification accuracy and other criteria. The end result of this process is a unique methodology for exploiting the use usefulness and applicability of machine learning to an important space sensing and identification process.

This material is based upon work supported by the United States Air Force under Contract No. FA9453-14-M-0153.

Treemap Visualizations for Space Situational Awareness

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Zac Gorrell,
Valepro, LLC

Making sense of massive data sets is a problem for many military domains including space. With unwieldy big data sets used for space situational awareness (SSA), important trends and outliers may not be easy to spot especially not at-a-glance. One method being explored to visualize SSA data sets is called treemapping. Treemaps fill screen space with nested rectangles (tiles) of various sizes and colors to represent multiple dimensions of hierarchical data sets. By mapping these dimensions effectively with a tiling algorithm that maintains an appropriate aspect ratio, patterns can emerge that often would have gone unnoticed. The ability to interactively perform range filtering (in our case with sliders) and object drill-downs (hyperlinking the tiles) make this technology powerful for in-depth analyses in addition to at-a-glance awareness. For one SSA analysis, the tiles could represent satellites that are grouped by country, sized by apogee, and colored/shaded by the launch date. Filter sliders could allow apogee range or launch dates to be narrowed for better resolution of a smaller data set. The application of this technology for the Joint Space Operations Center (JSpOC) Mission System (JMS) is being explored on a DARPA Small Business Innovative Research (SBIR) effort as a plug-in to the existing User-Defined Operational Picture (UDOP). In addition, visualization of DARPA OrbitOutlook small telescope data will be demonstrated. This research will investigate what SSA analyses are best served by treemaps, the best tiling algorithms for these problems, and how the treemaps should be integrated into the existing JMS UDOP workflow. Finally, we introduce a variation of treemaps that help leaders allocate their time to tasks based on importance and urgency.

The Joint Space Operations Center (JSpOC) Mission System (JMS) and the Advanced Research, Collaboration, and Application Development Environment (ARCADE)

Kipp Johnson, Scitor Corporation

Richard Kim, Juan Echeverry
Scitor Corporation

The Joint Space Operations Center (JSpOC) is a command and control center focused on executing the Space Control mission of the Joint Functional Component Command for Space (JFCC-SPACE) to ensure freedom of action of United States (US) space assets, while preventing adversary use of space against the US. To accomplish this, the JSpOC tasks a network of space surveillance sensors to collect Space Situational Awareness (SSA) data on resident space objects (RSOs) in near earth and deep space orbits. SSA involves the ingestion of data sources and use of algorithms and tools to build, maintain, and disseminate situational awareness of RSOs in space. On the heels of emergent and complex threats to space assets, the JSpOC's capabilities are limited by legacy systems and CONOPs. The JSpOC Mission System (JMS) aims to consolidate SSA efforts across US agencies, international partners, and commercial partners.

The JMS program is intended to deliver a modern service-oriented architecture (SOA) based infrastructure with increased process automation and improved tools to remove the current barriers to JSpOC operations. JMS has been partitioned into several developmental increments. Increment 1, completed and operational in early 2013, and Increment 2, which is expected to be completed in 2016, will replace the legacy Space Defense Operations Center (SPADOC) and Astrodynamics Support Workstation (ASW) capabilities. In 2017 JMS Increment 3 will continue to provide additional SSA and C2 capabilities that will require development of new applications and procedures as well as the exploitation of new data sources. Most importantly, Increment 3 is uniquely postured to evolve the JSpOC into the centralized and authoritative source for all Space Control applications by using its SOA to aggregate information and capabilities from across the community.

To achieve this goal, Scitor Corporation has supported the JMS Program Office as it has entered into a partnership with AFRL/RD (Directed Energy) and AFRL/RV (Space Vehicles) to create the Advanced Research, Collaboration, and Application Development Environment (ARCADE). The ARCADE formalizes capability development processes that hitherto have been ad hoc, slow to address the evolving space threat environment, and not easily repeatable. Therefore, the purpose of the ARCADE is to: (1) serve as a centralized testbed for all research and development (R&D) activities related to JMS applications, including algorithm development, data source exposure, service orchestration, and software services, and provide developers reciprocal access to relevant tools and data to accelerate technology development, (2) allow the JMS program to communicate user capability priorities and requirements to developers, (3) facilitate collaboration among developers who otherwise would not collaborate due to organizational, policy, or geographical barriers, and (4) support market research efforts by identifying outstanding performers that are available to shepherd into the formal transition process.

Over the last several years Scitor Corporation has provided systems engineering support to the JMS Increment 3 Program Office, and has worked with AFRL/RV and AFRL/RD to create a high performance computing environment and SOA at both unclassified and classified levels that together allow developers to develop applications in an environment similar to the version of JMS currently in use by the JSpOC operators. Currently the ARCADE is operational in an unclassified environment via the High Performance Computing Modernization Program (HPCMP) Portal on DREN. The ARCADE also exists on SECRET and TOP SECRET environments on multiple networks.

This presentation will cover the following topics: (1) Scitors role in shaping the ARCADE into its current form, (2) ARCADEs value proposition for potential technology developers, and (3) ARCADEs value proposition for the Government. These topics will be discussed by way of several case studies: a JMS Prototype activity, integration of the Search and Determine Integrated Environment (SADIE) system into the ARCADE, and developer challenge opportunities using the ARCADE.

The contents of this presentation will be UNCLASSIFIED.

SSA Sensor Calibration Best Practices

Thomas M. Johnson, Analytical Graphics Inc.

Best practices for calibrating orbit determination sensors in general and space situational awareness (SSA) sensors in particular are presented. These practices were developed over the last ten years within AGI and most recently applied to over 70 sensors in AGI's Commercial Space Operations Center (ComSpOC) and the US Air Force Space Command (AFSPC) Space Surveillance Network (SSN) to evaluate and configure new sensors and perform on-going system calibration. They are generally applicable to any SSA sensor and leverage some unique capabilities of an SSA estimation approach using an optimal sequential filter and smoother. Real world results are presented and analyzed.

Multicolour Optical Photometry of Active Geostationary Satellites

Andrew Jolley, Royal Australian Air Force

Gregg Wade, Donald Bedard,
Royal Military College of Canada

Although broadband photometry has been used to infer information about artificial satellites since soon after the launch of Sputnik 1, the development of photometric techniques for non-resolved space object identification or characterisation has been hampered by the large number of variables involved. Many individual studies, and some long ongoing experiments, have used costly metre-class telescopes to obtain data despite other experiments demonstrating that much more flexible and affordable small aperture telescopes may be suitable for the task. In addition, due to the highly time consuming and weather dependent nature of obtaining photometric observations, many studies have suffered from data sets of limited size, or relied upon simulations to support their claims. With this in mind, an experiment was conducted with the aim of determining the utility of small aperture telescopes for conducting broadband photometry of satellites for the purpose of non-resolved space object identification and characterisation. A

14 inch Celestron CG-14 telescope was used to gain multiple night-long, high temporal resolution data sets of six active geostationary satellites. The results of the experiment cast doubt on the efficacy of some of the previous approaches to obtaining and analysing photometric data. It was discovered that geostationary satellite lightcurves can vary to a greater degree than has generally been recognised, and colour ratios vary considerably with changes in the illumination/observation geometry, making it difficult to use colour for satellite discrimination. Evidence was also detected of variations in the spectral energy distribution of sunlight reflected off satellite surface materials, which could have implications for surface material characterisation and techniques that aim to separate satellite body and solar panel contributions to the total observed spectra.

Imaging of Stellar Surfaces with the Navy Precision Optical Interferometer

Anders Jorgensen, New Mexico Institute of Mining and Technology, New Mexico Tech

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The Navy Precision Optical Interferometer (NPOI) has a unique layout which is particularly well-suited for high-resolution interferometric imaging. By combining the NPOI layout with a new data acquisition and fringe tracking system we are progressing toward a imaging capability which will exceed any other interferometer in operation. The project, funded by the National Science Foundation, combines several existing advances and infrastructure at NPOI with modest enhancements. For optimal imaging there are several requirements that should be fulfilled. The observatory should be capable of measuring visibilities on a wide range of baseline lengths and orientations, providing complete UV coverage in a short period of time. It should measure visibility amplitudes with good SNR on all baselines as critical imaging information is often contained in low-amplitude visibilities. It should measure the visibility phase on all baselines. The technologies which can achieve this are the NPOI Y-shaped array with (nearly) equal spacing between telescopes and an ability for rapid configuration. Placing 6-telescopes in a row makes it possible to measure visibilities into the 4th lobe of the visibility function. By arranging the available telescopes carefully we will be able to switch, every few days, between 3 different 6-station chains which provide symmetric coverage in the UV (Fourier) plane without moving any telescopes, only by moving beam relay mirrors. The 6-station chains are important to achieve the highest imaging resolution, and switching rapidly between station chains provides uniform coverage. Coherent integration techniques can be used to obtain good SNR on very small visibilities. Coherently integrated visibilities can be used for imaging with standard radio imaging packages such as AIPS. The commissioning of one additional station, the use of new data acquisition hardware and fringe tracking algorithms are the enhancements which make this project possible.

An FPGA-based High Speed Parallel Signal Processing System for Adaptive Optics Testbed

Hong Bong Kim, Hanwha Thales Co. Ltd.

Young Soo Choi, Yu Kyung Yang,
Agency for Defense Development

In this paper a state-of-the-art FPGA (Field Programmable Gate Array) based high speed parallel signal processing system (SPS) for adaptive optics (AO) testbed with 1 kHz wavefront error (WFE) correction frequency is reported. The AO system consists of Shack-Hartmann sensor (SHS) and deformable mirror (DM), tip-tilt sensor (TTS), tip-tilt mirror (TTM) and an FPGA-based high performance SPS to correct wavefront aberrations. The SHS is composed of 400 subapertures and the DM 277 actuators with Fried geometry, requiring high speed parallel computing capability SPS. In this study, the target WFE correction speed is 1 kHz; therefore, it requires massive parallel computing capabilities as well as strict hard real time constraints on measurements from sensors, matrix computation latency for correction algorithms, and output of control signals for actuators. In order to meet them, an FPGA based real-time SPS with parallel computing capabilities is proposed. In particular, the SPS is made up of a National Instrument's (NI's) real time computer and five FPGA boards based on state-of-the-art Xilinx Kintex 7 FPGA. Programming is done

with NI's LabView environment, providing flexibility when applying different algorithms for WFE correction. It also facilitates faster programming and debugging environment as compared to conventional ones. One of the five FPGA's is assigned to measure TTS and calculate control signals for TTM, while the rest four are used to receive SHS signal, calculate slops for each subaperture and correction signal for DM. With this parallel processing capabilities of the SPS the overall closed-loop WFE correction speed of 1 kHz has been achieved. System requirements, architecture and implementation issues are described; furthermore, experimental results are also given.

Parametric Excitation of Very Low Frequency (VLF) Electromagnetic Whistler Waves and Interaction with Energetic Electrons in Radiation Belt

Tony Kim, Air Force Research Laboratory

V. Sotnikov[1], D. Main[2], E. Mishin[1], I. Paraschiv[3], D. Rose[4]
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Concept of a parametric antenna in the ionospheric plasma is analyzed. Such antennas are capable of exciting electromagnetic radiation fields, specifically the creation of whistler waves generated at the very low frequency (VLF) range, which are also capable of propagating large distances away from the source region. The mechanism of whistler wave generation is considered a parametric interaction of quasi-electrostatic low oblique resonance (LOR) oscillations excited by conventional loop antenna. The transformation of LOR waves on quasi-neutral density perturbations in the near field of an antenna gives rise to whistler waves on combination frequencies. Amplitude of these waves can considerably exceed the amplitude of whistler waves directly excited by a loop. Simulation to demonstrate excitation and spatial structure of VLF waves excited by a loop antenna using a PIC code LSP will be presented as well. Possible applications including the wave-particle interactions to mitigate performance anomalies of Low Earth Orbit (LEO) satellites, active space experiments, communication via VLF waves, and modification experiments in the ionosphere will be discussed.

Real-time Astrometry Using Phase Congruency

Andrew Lambert, UNSW Canberra

Manuel Cegarra Polo, YongYi Tang
UNSW Canberra

Phase congruency is a computer vision technique that proves to perform well for determining the tracks of optical objects (Flewelling, AMOS 2014). We report on a real-time implementation of this using an FPGA and CMOS Image Sensor, with on-sky data. The lightweight instrument can provide tracking update signals to the mount of the telescope, as well as determine abnormal objects in the scene.

Reconstructing from Extended Imagery of Space Objects

Andrew Lambert, UNSW Canberra

Manuel Cegarra Polo
UNSW Canberra

Large resident space objects may be imaged using optical telescopes but as they traverse the sky in a matter of minutes their range from the telescope and associated size and aspect on the sensor change drastically. Traditional image stacking of images is not possible, so we address a volumetric reconstruction of the 3D object from the diverse observations. We report on this algorithm using observations of the ISS from the Canberra node of the Falcon Telescope Network.

Benefits of Applying Predictive Intelligence to the Space Situational Awareness (SSA) Mission

Ben Lane, Northrop Grumman

Brian Mann, Chris Millard
Northrop Grumman

Recent events have heightened the interest in providing improved Space Situational Awareness (SSA) to the warfighter using novel techniques that are affordable and effective. The current Space Surveillance Network (SSN) detects, tracks, catalogs and identifies artificial objects orbiting earth and provides information on Resident Space Objects (RSO) as well as new foreign launch (NFL) satellites. The reactive nature of the SSN provides little to no warning on changes to the expected states of these RSOs or NFLs. This paper will detail the use of the historical data collected on RSOs to characterize what their steady state is, proactively help identify when changes or anomalies have occurred using a pattern-of-like activity based intelligence approach, and apply dynamic, adaptive mission planning to the observables that lead up to a NFL. Multiple hypotheses will be carried along with the intent or the changes to the steady state to assist the SSN in tasking the various sensors in the network to collect the relevant data needed to help prune the number of hypotheses by assigning likelihood to each of those activities. Depending on the hypothesis and thresholds set, these likelihoods will then be used in turn to alert the SSN operator with changes to the steady state, prioritize additional data collections, and provide a watch list of likely next activities.

Robotic SLODAR Development for Seeing Evaluation at the Bohyun Observatory

Jun Ho Lee, Kongju National University, Department of Physics

Richard Wilson[1], Tim Butterley[1], Young Soo Choi[2], Sooman Lee[3],
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We had developed a robotic SLODAR (SLOpe Detection And Ranging) for characterization of the vertical profile of atmospheric optical turbulence at the Bohyun observatory, South Korea. The SLODAR had been developed in partnership between Kongju National Univ. South Korea and Durham Univ., U.K. The SLODAR instrument consists of a robotic 50 cm telescope feeding into a pair of Shack Hartmann wavefront sensors. SLODAR analysis of the wavefront sensor data yields turbulence profiles of the surface layer of turbulence, with the vertical resolution depending on the separation and elevation of the target stars.The total seeing (r0) is also measured, and by subtracting the directly measured turbulence from the total the unresolved strength (above the maximum sensing altitude) can also be determined. The instrument has two observing modes, "wide" and "narrow" depending on the angular sepration of pairs of stars. In wide mode regime, narrower targets are chosen (2 ~ 4 arcmin) such that the ground layer profile is measured up to ~500m. In narrow mode, very narrow targets (10 ~ 15 arcsec) are measured to provide the turbulence profile with coarse resolution up to ~6km. The automated SLODAR turbulence profiler at the Boyun Observatory is currently under remote and robotic operation since last June. We reports herein the development of the SLODAR with first observation results.

Orbit Determination and Maneuver Detection Using Event Representation with Thrust-Fourier-Coefficients

Daniel Lubey, University of Colorado Boulder

Hyun Chul Ko, Daniel J. Scheeres
University of Colorado, Boulder

The classical orbit determination (OD) method of dealing with unknown maneuvers is to restart the OD process with post-maneuver observations. However, it is also possible to continue the OD process through such unknown maneuvers by representing those unknown maneuvers with an appropriate event representation. It has been shown in previous work (Ko & Scheeres, JGCD 2014) that any maneuver performed by a satellite transitioning between two arbitrary orbital states can be represented as an equivalent maneuver connecting those two states using Thrust-Fourier-Coefficients (TFCs). Event

representation using TFCs rigorously provides a unique control law that can generate the desired secular behavior for a given unknown maneuver. This paper presents applications of this representation approach to orbit prediction and maneuver detection problem across unknown maneuvers.
The TFCs are appended to a sequential filter as an adjoint state to compensate unknown perturbing accelerations and the modified filter estimates the satellite state and thrust coefficients by processing OD across the time of an unknown maneuver. This modified sequential filter with TFCs is capable of fitting tracking data and maintaining an OD solution in the presence of unknown maneuvers. Also, the modified filter is found effective in detecting a sudden change in TFC values which indicates a maneuver. In order to illustrate that the event representation approach with TFCs is robust and sufficiently general to be easily adjustable, different types of measurement data are processed with the filter in a realistic LEO setting. Further, cases with mis-modeling of non-gravitational force are included in our study to verify the versatility and efficiency of our presented algorithm.
Simulation results show that the modified sequential filter with TFCs can detect and estimate the orbit and thrust parameters in the presence of unknown maneuvers with or without measurement data during maneuvers. With no measurement data during maneuvers, the modified filter with TFCs uses an existing pre-maneuver orbit solution to compute a post-maneuver orbit solution by forcing TFCs to compensate for an unknown maneuver. With observation data available during maneuvers, maneuver start time and stop time is determined

Comparison of IR and Visible Cloud Imagers

W. Jody Mandeville, MITRE Corporation

Tim McLaughlin, Steve Bygren, Chris Randell
MITRE Corporation

This paper presents a comparison between the Infrared Cloud Imager (IRCI) used at Ground-based Electro-Optical Deep Space Surveillance (GEODSS) sites and the Visible Cloud Imager (VCI) developed using a COTS all-sky camera. The cloud imagers are used to create exclusion maps for GEODSS observations based on detected cloud locations. Excluding observation attempts in obscured areas of the sky is done to improve the allocation of sensor resources. Estimates are made for atmospheric extinction across the entire sky by comparing known star brightness to measured brightness. Data for the comparison were collected at the GEODSS test site located in Yoder, Colorado for a variety of cloud conditions.

Moving into the Light: The AEOS Telescope in the Daytime Operating Environment

Jim Mayo, Tau Technologies LLC

Abstract for Coming into the Light: The AEOS Telescope in the Daytime Operating Environment” Interest in daylight operation for the AEOS 3.67-m Telescope first surfaced during the preparation of the AEOS specification documentation in 1991. The author and Lt Rich Elder prepared, edited and combined requirements inputs from AFRL technical staff to create the final RFP document. In this released specification, AEOS daylight performance was limited to best effort, although provisions for adding secondary mirror sky light baffling were to be provided. In 1993, during the AEOS construction phase, AFRL requested that the author prepare a report on special considerations for operating AEOS in the solar illuminated daytime environment. This report was published and briefed to AFRL and Space Command at that time. Interest in this topic at AMOS was rekindled in 2007 by Dr Joe Janni and Lt Col Scott Hunt. The author updated his 1993 report and in June 2007 presented AEOS 1993 Daylight Operation Study Revisited” at AMOS. Subsequently, Dr Stacie Williams spearheaded additional work in this critical technical area. Recent efforts at Tau Technologies LLC have focused on external AEOS telescope baffling and shielding options assessment, solar irradiation effects on optical components, especially the primary mirror, and on modeling the solar illumination on the entire telescope during daylight operation. Solid Works and Illustrator simulation models have been developed and exercised.

Using Big Data Technologies and Analytics to Predict Sensor Anomalies

Rohit Mital, SGT

Joseph Coughlin, Mike Canaday
SGT

A goal of big data analytics is to help leaders make informed and rapid decisions by analyzing large volumes of complex data, as well as other forms of data that may be untapped by conventional analyses, and presenting it in a form that facilitates decision making. Big data analytics is the process of examining large data sets containing a variety of data types to uncover hidden patterns, unknown correlations, and other useful information.

Sensors typically record significant amounts of data but it is often not exploited except in special cases and after historically large amounts of analysis time. Big data analytics provides a mechanism to routinely monitor these data sets while also providing insight into anomalous events, such as are encountered in large sensor systems such as those in the space surveillance network.

In this study, we simulate recorded data from a notional radar or optical sensor and use big data technologies and the analytics to process the data to analyze and predict sensor performance. This study focuses on data products that would commonly be analyzed at a site and how big data technologies can be used to detect anomalies.

This study shows how the ability to rapidly drill down into the data enables an analyst or decision maker to assess potential system anomalies. This study shows how current technologies and predictive analytical techniques can be used to view the data, detect and explain anomalies, and predict preventative maintenance actions in a timely manner.

An Imaging System for Satellite Hypervelocity Impact Debris Characterization

Matthew Moraguez, University of Florida

Dr. J.-C. Liou[1], Dr. Norman Fitz-Coy[2], Kunal Patankar[2], Dr. Heather Cowardin[3]
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This paper discusses the design of an automated imaging system for size characterization of debris produced by the DebriSat hypervelocity impact test. The goal of the DebriSat project is to update satellite breakup models. A representative LEO satellite, DebriSat, was constructed and subjected to a hypervelocity impact test. The impact produced an estimated 85,000 debris fragments. The size distribution of these fragments is required to update the current satellite breakup models. An automated imaging system was developed for the size characterization of the debris fragments. The system uses images taken from various azimuth and elevation angles around the object to produce a 3D representation of the fragment via a space carving algorithm. The system consists of N point-and-shoot cameras attached to a rigid support structure that defines the elevation angle for each camera. The debris fragment is placed on a turntable that is incrementally rotated to desired azimuth angles. The number of images acquired can be varied based on the desired resolution. Appropriate background and lighting is used for ease of object detection. The system calibration and image acquisition process are automated to result in push-button operations. However, for quality assurance reasons, the system is semi-autonomous by design to ensure operator involvement. This paper describes the imaging system setup, calibration procedure, repeatability analysis, and the results of the debris characterization.

Iteratively Reweighted Deconvolution through Subspace Projection

James Nagy, Emory University

Iteratively reweighted deconvolution algorithms can be used to incorporate sparse constraints and to account for outliers in measured data, such as glints. The reweighting process requires solving a sequence of deconvolution problems with different weighted convolution operators. This can be expensive, especially in the case of spatially varying blurs. In this work we describe a general framework to efficiently solve the sequence of deconvolution problems using Krylov subspace projection methods (i.e., conjugate gradient type methods). The projection approach allows much of the difficult work to occur on low dimensional subspaces, and thus significantly reduce the computational cost for large-scale problems.

Space Debris Measurements using the Advanced Modular Incoherent Scatter Radar

Michael Nicolls, SRI International

The Advanced Modular Incoherent Scatter Radar (AMISR) is a modular, mobile UHF phased-array radar facility developed and used for scientific studies of the ionosphere. The radars are completely remotely operated and allow for pulse-to-pulse beam steering over the field-of-view. A satellite and debris tracking capability fully interleaved with scientific operations has been developed, and the AMISR systems are now used to routinely observe LEO space debris, with the ability to simultaneously track and detect multiple objects. The system makes use of wide-bandwidth radar pulses and coherent processing to detect objects as small as 5-10 cm in size through LEO, achieving a range resolution better than 20 meters for LEO targets. The interleaved operations allow for ionospheric effects on UHF space debris measurements, such as dispersion, to be assessed. The radar architecture, interleaved operations, and impact of space weather on the measurements will be discussed.

Autonomous Object Characterization with Large Datasets

Mark Poole, ExoAnalytic Solutions

Dr. Jeremy Murray-Krezan
Air Force Research Laboratory/RV

Timely and effective space object (SO) characterization is a challenge, and requires advanced data processing techniques. Detection and identification of signature changes due to potential SO changes (e.g., stability, material aging) is a critical capability that is growing in importance. Unfortunately, better knowledge of more objects requires an infeasible investment of current technologies, or a change in collection methodology. A combination of large datasets and simulation technologies can help. Space object stability, methods for space object correlation, and material characterization are a few of the techniques explored via a combination of simulations and large datasets. This paper describes an approach for automating characterization techniques for RSOs using large photometric datasets from ExoAnalytics small telescope network.

Efficient Conjunction Assessment using Modified Chebyshev Picard Iteration

Austin Probe, Texas A&M University

Brent Macomber, Julie Read, Robyn Woollands, Abhay Masher, John L. Junkins,
Texas A&M University

Conjunction Assessment is one of the most important and computationally expensive components of modern SSA efforts. Timely warnings of potential conjunctions are critical for the protection of valuable space assets. Upgrades to the US Space Surveillance Network (SSN) such as the Space Surveillance Telescope and the new Space Fence become operational, the influx of newly trackable objects will exacerbate the current issues of computational tractability. Modified Chebyshev Picard Iteration (MCPI) is a numerical method for solving ordinary differential equations that can be utilized to efficiently proximate orbits with high accuracy. Unlike, more traditional stepping based integrators; MCPI uses recursive approximation using Chebyshev polynomials to estimate segments of an orbit. The end result of the propagation is orthogonal Chebyshev polynomial approximation of the orbital trajectory; this approximation is analytically differentiable and potentially accurate to machine precision. Once computed, these approximations provide an efficient method for evaluating and comparing the positions of space objects. The reduced cost of catalog propagation and subsequent conjunction probability analysis when using MCPI, allows for significant reduction in the cost to perform high fidelity conjunction assessment. A method for catalog propagation and conjunction assessment using MCPI is presented, along with results from implementation running in a compute cluster environment are presented.

Satellite Fingerprints

David Richmond, Lockheed Martin

Techniques for improved characterization of Satellites located at GEO have been an area of research for several years. Our team has begun a research activity to use multiple phenomenologies to establish a fingerprint of on-orbit assets located at GEO. Preliminary results have revealed that, in many cases, a single phenomenology (Optical, Radar, etc.) is not capable of positively characterizing deep space objects. The paper will identify the techniques used to gather data and will detail progress in establishing a fingerprint database. The paper will discuss the impact of changes in satellite characteristics over the life of an on-orbit asset to the fingerprint database. The benefits of such a database will be discussed, to include re-acquiring objects after a maneuver.

The Probabilistic Admissible Region with Additional Constraints

Christopher Roscoe, Applied Defense Solutions

Islam Hussein[1], Matthew Wilkins[1], Paul Schumacher, Jr.[2]
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The admissible region, in the space surveillance field, is defined as the set of physically acceptable orbits (e.g., orbits with negative energies) consistent with one or more observations of a space object. Given additional constraints on orbital semimajor axis, eccentricity, etc., the admissible region can be constrained, resulting in the constrained admissible region (CAR). Based on known statistics of the measurement process, one can replace hard constraints with a probabilistic representation of the admissible region. This results in the probabilistic admissible region (PAR), which can be used for orbit initiation in Bayesian tracking and prioritization of tracks in a multiple hypothesis tracking framework.

The PAR concept was introduced by the authors at the 2014 AMOS conference. In that paper, a Monte Carlo approach was used to show how to construct the PAR in the range/range-rate space based on known statistics of the measurement, semimajor axis, and eccentricity. An expectation-maximization algorithm was proposed to convert the particle cloud into a Gaussian Mixture Model (GMM) representation of the PAR. This GMM can be used to initialize a Bayesian filter. The PAR was found to be significantly non-uniform, invalidating an assumption frequently made in CAR-based filtering approaches. Using the GMM or particle cloud representations of the PAR, orbits can be prioritized for propagation in a multiple hypothesis tracking (MHT) framework.

In this paper, the authors focus on expanding the PAR methodology to allow additional constraints, such as a constraint on perigee altitude, to be modeled in the PAR. This requires re-expressing the joint probability density function for the attributable vector as well as the (constrained) orbital parameters and range and range-rate. The final PAR is derived by accounting for any interdependencies between the parameters. Noting that the concepts presented are general and can be applied to any measurement scenario, the idea will be illustrated using a short-arc, angles-only observation scenario.

Asteroid Detection Results Using the Space Surveillance Telescope

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MIT Lincoln Laboratory

From 1998-2013, MIT Lincoln Laboratory operated a highly successful near-Earth asteroid search program using two 1-m optical telescopes located at the MIT Lincoln Laboratory Experimental Test Site (ETS) in Socorro, N.M. In 2014, the Lincoln Near-Earth Asteroid Research (LINEAR) program successfully transitioned operations from the two 1-m telescopes to the 3.5-m Space Surveillance Telescope (SST) located at Atom Site on White Sands Missile Range, N.M. This paper provides a summary of first-year performance and results for the LINEAR program with SST and provides an update on recent improvements to the moving-object pipeline architecture that increase utility of SST data for NEO discovery and improve sensitivity to fast-moving objects. Ruprecht et al. (2014) made predictions for SST NEO search productivity as a function of population model. This paper assesses the NEO search performance of SST in the first 1.5 years of operation and compares results to model predictions.

This work is sponsored by the Defense Advanced Research Projects Agency and the National Aeronautics and Space Administration under Air Force Contract #FA8721-05-C-0002. The views, opinions, and/or findings contained in this article/presentation are those of the authors / presenters and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government. Distribution Statement A: Approved for public release, distribution unlimited.

Photometric Studies of Rapidly Spinning Decommissioned GEO Satellites

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A satellites general characteristics can be substantially influenced by changes in the space environment. Rapidly spinning decommissioned satellites provide an excellent opportunity to study the rotation-dependent physical processes that affect a resident space objects (RSO) spin kinematics over time. Specifically, inactive satellites at or near geosynchronous Earth-orbit (GEO) provide easy targets for which high quality data can be collected and analyzed such that small differences can be detected under single-year or less time frames.

Previous workers have shown that the rotational periods of defunct GEOs have been changing over time [1]. Further, the Yarkovsky-OKeefe-Radzievskii-Paddak (YORP) effect, a phenomenon which has been well-studied in the context of the changing the spin states of asteroids, has recently been suggested to be the cause of secular alterations in the rotational period of inactive satellites [2]. Researchers at the Magdalena Ridge Observatory 2.4-meter telescope (operated by the New Mexico Institute of Mining and Technology) have been investigating the spins states of retired GEOs and other high altitude space debris since 2007 [3]. In this current work, the 2.4-meter telescope was used to track and observe the objects typically over a one- to two-hour period, repeated several times over the course of weeks. When feasible, this is then repeated on a yearly basis. Data is taken with a 1 second cadence, nominally in groups of three 600 second image sets. With the current equipment, the cadence of the image sequences is very precise while the start time is accurate only to the nearest second. Therefore, periods are determined individually using each image sequence. Repeatability of the period determination for each of these sequences is typically on the order of 0.01 second or better for objects where a single period is identified.

Spin rate periods determined from the GEO light curves collected thus far have been found to range from ~3 sec to many tens of seconds. Based on these observed rotational characteristics, results will be presented on both the long- and short-term spin-rate variations of selected targets. The objective was to study a variety of satellites for rotational stability over time, and to discern how physical effects (such as YORP) might be dependent on the optical, thermal and geometrical parameters of the object.

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LEO Debris Ballistic Coefficients Estimated From TLE

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In cases of the LEO debris orbit determination (OD) and prediction (OP) using sparse tracking data, it has been found that the ballistic coefficient is a critical parameter affecting the convergence and quality of the OD process. In reality, the ballistic coefficients of most LEO debris are unknown. Methods of estimating them using long-archived TLEs have been developed, which all consume long computation time, and require TLEs spanning over several decades to obtain reasonably accurate estimates of the ballistic coefficients.

This paper reports the results of the current campaign of computing ballistic coefficients of all debris with perigee height below 1000km using TLEs. Techniques to improve the computation efficiency are presented in the paper. Applications of estimated ballistic coefficients in the debris OD and OP, TLE quality examination, and atmospheric mass density information retrieval from TLEs, are also discussed.

Semianalytic Orbit Propagation Using Multiple Scaling Perturbation Method

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This paper presents some early results of LEO orbit propagations with the semianalytic propagator developed at Wuhan University using the multiple scaling perturbation method. First, the basic principle of the multiple scaling method is introduced, followed by its application to the LEO orbit propagation problem. The first-order and second-order solutions considering the gravities, drag and solar radiation are obtained. The performance of the propagator for LEO orbits is assessed through simulations where true orbits are generated using the high-accuracy numerical orbit propagator. Propagation errors for various orbits at altitudes 300 - 2000km, inclinations 5 – 105 degrees, and area-to-mass ratios 0.001, 0.01, 0.1 and 0.5 are obtained by comparing with the “truth” orbits. For example, when the area-to-mass ratio is only 0.001, the 7-day orbit propagation error for orbit at altitude 700km is about 300m, it is increased to about 5000m when the area-to-mass ratio is 0.1. The computing time using the semianalytic propagator is only about 5% of that using the numerical integrator.

Exploiting Historical Photometric Data for 3 Axis Stabilized Geostationary Satellites

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This paper and presentation describe a successful multiyear effort to build-up reference signatures for geostationary spacecraft from archived historical photometric measurements which were taken nightly from diverse optical systems at diverse sites. A broad sampling of light curve data taken over large timespans was used to create detailed glint maps which are unique for each geostationary satellite. Using principles of bidirectional reflectance a map of surface normals was recovered for these objects in angle space and used to continually test the hypothesis that each geostationary satellite is maintaining nadir pointing with the same antenna pointing and solar panel offsets. Signatures of satellites from the same bus family show strong similarities indicating that generic bus typing may be possible yet unique features are detectable for almost all individual satellites as even identical satellites from the same production run show variations based on its exact solar panel offsets and antenna orientations. The diversity of illumination conditions at various solar declination angles and solar equatorial phase angles allowed for the detection of specular spikes or glints from small reflective features with surface normals spanning approximately 23.4 degrees of roll (north-south offset) and approximately 90 degrees of pitch (east-west offset). An automated photometric anomaly detection system has been built upon these reference signatures whereby new measurements are compared against the computed statistical photometric variance for the given solar illumination condition. Any measurements that fall outside the computed envelope are automatically flagged for analysis and indicate either bad photometric measurements, a detected change in satellite attitude, a change in satellite configuration or element articulation, or a cross tagging event. Examples will be given of how this technique has been successfully applied to detect attitude changes at GEO which were later verified.

High Speed Large Format Photon Counting Microchannel Plate Imaging Sensors

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Camden Ertley, John Vallerga
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The development of a new class of microchannel plate technology, using atomic layer deposition (ALD) techniques applied to a borosilicate microcapillary array is enabling the implementation of larger, more stable detectors for Astronomy and remote sensing. Sealed tubes with MCPs with SuperGenII, bialkali, GaAs and GaN photocathodes have been developed to cover a wide range of optical/UV sensing applications. Formats of 18mm and 25mm circular, and 50mm (Planacon) and 20cm square have been constructed for uses from night time remote reconnaissance and biological single-molecule fluorescence lifetime imaging microscopy, to large area focal plane imagers for Astronomy, neutron detection and ring imaging Cherenkov detection. The large focal plane areas were previously unattainable, but the new developments in construction of ALD microchannel plates allow implementation of formats of 20cm or more. Continuing developments in ALD microchannel plates offer improved overall sealed tube lifetime and gain stability, and furthermore show reduced levels of radiation induced background. High time resolution astronomical and remote sensing applications can be addressed with microchannel plate based imaging, photon time tagging detector sealed tube schemes. Photon counting imaging readouts for these devices vary from cross strip (XS), cross delay line (XDL), to stripline anodes, and pad arrays depending on the intended application. The XS and XDL readouts have been implemented in formats from 22mm, and 50mm to 20cm. Both use MCP charge signals detected on two orthogonal layers of conductive fingers to encode event X-Y positions. XDL readout uses signal propagation delay to encode positions while XS readout uses charge cloud centroiding. Spatial resolution readout of XS detectors can be better than 20 microns FWHM, with good image linearity while using low gain (<10^6), allowing high local counting rates and longer overall tube lifetime. XS tubes with electronics can encode event rates of >5 MHz and event timing accuracy of ~100ps. We will discuss how we are applying these detector system developments for devices in formats of 18mm and 25mm circular, and 50mm and 20cm square. The performance characteristics will be demonstrated along with lifetest data taken over the last year. Implications for ground based instruments to

study transient and variable astronomical objects, as well as implementation in satellite instruments for earth atmospheric, planetary and solar observations will be discussed.

Automatic, Rapid Replanning of Satellite Operations for Space Situational Awareness (SSA)

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Kyle Mahan
Stottler Henke Associates, Inc.

An important component of Space Situational Awareness (SSA) is knowledge of the status and tasking of blue forces (e.g. satellites and ground stations) and the rapid determination of the impacts of real or hypothetical changes and the ability to quickly replan based on those changes. For example, if an antenna goes down (either for benign reasons or from purposeful interference) determining which missions will be impacted is important. It is not simply the set of missions that were scheduled to utilize that antenna, because highly expert human schedulers will respond to the outage by intelligently replanning the real-time schedule. We have developed an automatic scheduling and deconfliction engine, called MIDAS (for Managed Intelligent Deconfliction And Scheduling) that interfaces to the current legacy system (ESD 2.7) which can perform this replanning function automatically. In addition to determining the impact of failed resources, MIDAS can also replan in response to a satellite under attack. In this situation, additional supports must be quickly scheduled and executed (while minimizing impacts to other missions). Because MIDAS is a fully automatic system, replacing a current human labor-intensive process, and provides very rapid turnaround (seconds) it can also be used by commanders to consider what-if questions and focus limited protection resources on the most critical resources. For example, the commander can determine the impact of a successful attack on one of two ground stations and place heavier emphasis on protecting the station whose loss would create the most severe impacts. The system is currently transitioning to operational use. The MIDAS system and its interface to the legacy ESD 2.7 system will be described along with the ConOps for different types of detailed operational scenarios.

Improved Space Surveillance Network (SSN) Scheduling using Artificial Intelligence Techniques

Dick Stottler, Stottler Henke Associates, Inc.

There are close to 20,000 cataloged manmade objects in space, the large majority of which are not active, functioning satellites. These are tracked by phased array and mechanical radars and ground and space-based optical telescopes, collectively known as the Space Surveillance Network (SSN). A better SSN schedule of observations could, using exactly the same legacy sensor resources, improve space catalog accuracy through more complementary tracking, provide better responsiveness to real-time changes, better track small debris in low earth orbit (LEO) through efficient use of applicable sensors, efficiently track deep space (DS) frequent revisit objects, handle increased numbers of objects and new types of sensors, and take advantage of future improved communication and control to globally optimize the SSN schedule. We have developed a scheduling algorithm that takes as input the space catalog and the associated covariance matrices and produces a globally optimized schedule for each sensor site as to what objects to observe and when. This algorithm is able to schedule more observations with the same sensor resources and have those observations be more complementary, in terms of the precision with which each orbit metric is known, to produce a satellite observation schedule that, when executed, minimizes the covariances across the entire space object catalog. If used operationally, the results would be significantly increased accuracy of the space catalog with fewer lost objects with the same set of sensor resources. This approach inherently can also trade-off fewer high priority tasks against more lower-priority tasks, when there is benefit in doing so. Currently the project has completed a prototyping and feasibility study, using open source data on the SSN's sensors, that showed significant reduction in orbit metric covariances. The algorithm techniques and results will be discussed along with future directions for the research.

Implementation of an open-scenario, long-term space debris simulation approach

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This paper provides a status update on the implementation of a flexible, long-term space debris simulation approach. The motivation is to build a tool that can assess the long-term impact of various options for debris-remediation, including the LightForce space debris collision avoidance scheme.

State-of-the-art simulation approaches that assess the long-term development of the debris environment use either completely statistical approaches, or they rely on large time steps in the order of several (5-15) days if they simulate the positions of single objects over time. They cannot be easily adapted to investigate the impact of specific collision avoidance schemes or de-orbit schemes, because the efficiency of a collision avoidance maneuver can depend on various input parameters, including ground station positions, space object parameters and orbital parameters of the conjunctions and take place in much smaller timeframes than 5-15 days. For example, LightForce only changes the orbit of a certain object (aiming to reduce the probability of collision), but it does not remove entire objects or groups of objects. In the same sense, it is also not straightforward to compare specific de-orbit methods in regard to potential collision risks during a de-orbit maneuver. To gain flexibility in assessing interactions with objects, we implement a simulation that includes every tracked space object in LEO, propagates all objects with high precision, and advances with variable-sized time-steps as small as one second. It allows the assessment of the (potential) impact of changes to any object. The final goal is to employ a Monte Carlo approach to assess the debris evolution during the simulation time-frame of 100 years and to compare a baseline scenario to debris remediation scenarios or other scenarios of interest. To populate the initial simulation, we use the entire space-track object catalog in LEO. We then use a high precision propagator to propagate all objects over the entire simulation duration. If collisions are detected, the appropriate number of debris objects are created and inserted into the simulation framework. Depending on the scenario, further objects, e.g. due to new launches, can be added. At the end of the simulation, the total number of objects above a cut-off size and the number of detected collisions provide benchmark parameters for the comparison between scenarios. The simulation approach is computationally intensive as it involves ten thousands of objects; hence we use a highly parallel approach employing up to a thousand cores on the NASA Pleiades supercomputer for a single run.

This paper describes our simulation approach, the status of its implementation, the approach in developing scenarios and examples of first test runs.

ArgusE: Design and Development of a Micro-Spectrometer used for Remote Earth and Atmospheric Observations

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In this paper we will discuss the design and development of the ArgusE. The ArgusE is a micro-spectrometer which has been developed for Earth and atmospheric monitoring purposes. The project is primarily focused on using the ArgusE micro-spectrometer in order to ascertain whether it is possible to obtain surface soil moisture content measurements from space using its short-wave infrared detector. The secondary objective of the project is to quantify greenhouse gases that could be studied within new spectral range.

The ArgusE is built on Argus 1000 micro-spectrometer design and spaceflight heritage. Currently, on the CanX-2 mission launched in 2008, the Argus 1000 micro-spectrometer observes the infrared solar radiation reflected by Earth surface targets as small as 1.5 km2 and the atmosphere (aerosols, clouds, and constituents). Over the past five years that Argus 1000 has been in operation, we have accumulated more than 200 observations from a series of land and ocean targets. It was followed by the SRMSAT, launched in 2011 (India). Currently all space-based Argus 1000s are collecting Earth and atmospheric observation data within the 0.9-1.7 micrometers spectral range, with special focus on CO2 and other greenhouse gases, and cloud and coastline detection.

GENSPECT, a line-by-line radiative Matlab-based toolbox is used to calculate gas absorption and emissivity for a custom grouping of atmospheric gases. Given gas types and amounts, temperature, pressure, path length and frequency range for an atmosphere or laboratory cell, GENSPECT computes the spectral characteristics of the gas mixture. The resulting models used to discover the potential monitoring of atmospheric greenhouse gases and topical soil moisture content will be discussed and displayed graphically.

In addition, this paper will showcase the chassis redesign and change of electronics which allow the ArgusE to now showcase the spectral region of 1.7 to 2.2 micrometers. It will also discuss the laboratory experimental procedures of the new instrument calibration and spectral collection of soil moisture , and will present a study surrounding a potential for a new chassis material to homopolymer acetal Delrin (150 SA). The results of ASTM-E 595 Outgassing Test will be discussed.

Mixed-Integer Formulations for Constellation Scheduling

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Remote sensing systems have expanded the set of capabilities available for and critical to national security. Cooperating, high-fidelity sensing systems and growing mission applications have exponentially increased the set of potential schedules. A definitive lack of advanced tools places an increased burden on operators, as planning and scheduling remain largely manual tasks. This is particularly true in time-critical planning activities where operators aim to accomplish a large number of missions through optimal utilization of single or multiple sensor systems. Automated scheduling through identification and comparison of alternative schedules remains a challenging problem applicable across all remote sensing systems. Previous approaches focused on a subset of sensor missions and do not consider ad-hoc tasking.

We have begun development of a robust framework that leverages the Pyomo optimization modeling language for the design of a tool to assist sensor operators planning under the constraints of multiple concurrent missions and uncertainty. Our scheduling models have been formulated to address the stochastic nature of ad-hoc tasks inserted under a variety of scenarios. Operator experience is being leveraged to select appropriate model objectives. Successful development of the framework will include iterative development of high-fidelity mission models that consider and expose various schedule performance metrics. Creating this tool will aid time-critical scheduling by increasing planning efficiency, clarifying the value of alternative modalities uniquely provided by multi-sensor systems, and by presenting both sets of organized information to operators. Such a tool will help operators more quickly and fully utilize sensing systems, a high interest objective within the current remote sensing operations community.

Preliminary results for mixed-integer programming formulations of a sensor scheduling problem will be presented. Assumptions regarding sensor geometry and sensing activity time constraints, durations, priorities, etc. will be outlined. Finally, solver speed and stochastic programming details for uncertain activities and scheduling impediments will be discussed.

Using Simplistic Shape/Surface Models to Predict Brightness in Estimation Filters

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The prerequisite for using brightness (radiometric flux intensity) measurements in an estimation filter is to have a measurement function that accurately predicts a space objects brightness for variations in the parameters of interest. These parameters include changes in attitude and articulations of particular components (e.g. solar panel east-west offsets to direct sun-tracking). Typically, shape models and bidirectional reflectance distribution functions are combined to provide this forward light curve modeling capability. To achieve precise orbit predictions with the inclusion of shape/surface dependent forces such as radiation pressure, relatively complex and sophisticated modeling is required. Unfortunately, increasing the complexity of the models makes it difficult to estimate all those parameters simultaneously because changes in light curve features can now be explained by variations in a number of different properties. The classic example of this is the connection between the albedo and the area of a surface. If, however, the desire is to extract information about a single and specific parameter or feature from the light curve, a simple shape/surface model could be used. This paper details an example of this where a complex model is used to create simulated light curves, and then a simple model is used in an estimation filter to extract out a particular feature of interest. In order for this to be successful, however, the simple model must be first constructed using training data where the feature of interest is known or at least known to be constant.

Light Curve Simulation Using Spacecraft CAD Models and Empirical Material Spectral BRDFS

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This paper presents a Matlab-based light curve simulation software package that uses computer-aided design (CAD) models of spacecraft and the spectral bidirectional reflectance distribution function (sBRDF) of their homogenous surface materials. It represents the overall optical reflectance of objects as a sBRDF, a spectrometric quantity, obtainable during an optical ground truth experiment. The broadband bidirectional reflectance distribution function (BRDF), the basis of a broadband light curve, is produced by integrating the sBRDF over the optical wavelength range. Colour-filtered BRDFs, the basis of colour-filtered light curves, are produced by first multiplying the sBRDF by colour filters, and integrating the products. The software package's validity is established through comparison of simulated reflectance spectra and broadband light curves with those measured of the CanX-1 Engineering Model (EM) nanosatellite, collected during an optical ground truth experiment. It is currently being extended to simulate light curves of spacecraft in Earth orbit, using spacecraft Two-Line-Element (TLE) sets, yaw/pitch/roll angles, and observer coordinates. Measured light curves of the NEOSSat spacecraft will be used to validate simulated quantities.

The sBRDF was chosen to represent material reflectance as it is spectrometric and a function of illumination and observation geometry. Homogeneous material sBRDFs were obtained using a goniospectrometer for a range of illumination and observation geometries, collected in a controlled environment. The materials analyzed include aluminum alloy, two types of triple-junction photovoltaic (TJPV) cell, white paint, and multi-layer insulation (MLI). Interpolation and extrapolation methods were used to determine the sBRDF for all possible illumination and observation geometries not measured in the laboratory, resulting in empirical look-up tables. These look-up tables are referenced when calculating the overall sBRDF of objects, where the contribution of each facet is proportionally integrated.

A Method for Improving Two-line Element Outlier Detection Based on a Consistency Check

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As the most complete source of orbital element information available to the public, the NORAD two-line element sets (TLEs) are used in a wide variety of orbit propagation tasks. Unfortunately, there is no error information provided for TLEs and therefore no measure of the data quality. Due to orbit manoeuvres, errors introduced during the TLE generation and unmodeled perturbations, there are inevitable outliers in the TLEs, which have a large deteriorative impact on orbit determination and propagation. Most of the current methods identify outliers using the three-sigma rule or a Mahalanobis distance-based detection method. However, in these methods the different perturbation characteristics of space objects in different altitudes are not taken into account. This study presents an improved method for detecting outliers in the TLEs based on a consistency check on pairwise differential residuals of adjacent TLEs. A filter based on the principle of locally weighted regression is applied on the pairwise differential residuals to investigate their underlying structure. The detection threshold is then determined by the variance of the filtered residuals in the moving window. Satellites from different altitudes with known manoeuvre histories were selected to assess the effectiveness of this improved method. Our results show that this method can achieve reliable detection of the manoeuvre events. The difference between the characteristics of TLE outliers of satellites and debris objects is also analysed to facilitate the application of the satellite-based method to debris to identify erroneous TLEs. Finally, a set of criteria for TLE outlier detection are proposed based on the different characteristics of space objects according to their altitudes. It is expected that this improved method will contribute to more robust orbit propagation and conjunction analysis using TLEs.

Real-Time Optical Surveillance of LEO/MEO with Small Telescopes

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J.T. McGraw and Associates, LLC operates two proof-of-concept wide-field imaging systems to test novel techniques for uncued surveillance of LEO/MEO/GEO and, in collaboration with the University of New Mexico (UNM), uses a third small telescope for rapidly queued same-orbit follow-up observations. Using our GPU-accelerated detection scheme, the proof-of-concept systems operating at sites near and within Albuquerque, NM, have detected objects fainter than V=13 at greater than 6 sigma significance. This detection approximately corresponds to a 16 cm object with albedo of 0.12 at 1000 km altitude. Dozens of objects are measured during each operational twilight period, many of which have no corresponding catalog object.

The two proof-of-concept systems, separated by ~30km, work together by taking simultaneous images of the same orbital volume to constrain the orbits of detected objects using parallax measurements. These detections are followed-up by imaging photometric observations taken at UNM to confirm and further constrain the initial orbit determination and independently assess the objects and verify the quality of the derived orbits. This work continues to demonstrate that scalable optical systems designed for real-time detection of fast moving objects, which can be then handed off to other instruments capable of tracking and characterizing them, can provide valuable real-time surveillance data at LEO and beyond, which substantively informs the SSA process.

Simpler Adaptive Optics using a Single Device for Processing and Control

Anna Zovaro, The University of Sydney and the Australian National University

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The management of low Earth orbit is becoming more urgent as satellite and debris densities climb, in order to avoid a Kessler syndrome. A key part of this management is to precisely measure the orbit of both active satellites and debris. The Research School of Astronomy and Astrophysics at the Australian National University have been developing an adaptive optics (AO) system to image and range orbiting objects. The AO system provides atmospheric correction for imaging and laser ranging, allowing for the detection of smaller angular targets and drastically increasing the number of detectable objects. AO systems are by nature very complex and high cost systems, often costing millions of dollars and taking years to design. It is not unusual for AO systems to comprise multiple servers, digital signal processors (DSP) and field programmable gate arrays (FPGA), with dedicated tasks such as wavefront sensor data processing or wavefront reconstruction. While this multi-platform approach has been necessary in AO systems to date due to computation and latency requirements, this may no longer be the case for those with less demanding processing needs. In recent years, large strides have been made in FPGA and microcontroller technology, with todays devices having clock speeds in excess of 200 MHz whilst using a < 5 V power supply. AO systems using a single such device for all data processing and control may present a far simpler, cheaper, smaller and more efficient solution than existing systems. A novel AO system design based around a single, low-cost controller is presented. The objective is to determine the performance which can be achieved in terms of bandwidth and correction order, with a focus on optimisation and parallelisation of AO algorithms such as wavefront measurement and reconstruction. The AO system consists of a Shack-Hartmann wavefront sensor and a deformable mirror to correct light from a 1.8 m telescope for the purpose of imaging orbiting satellites. The microcontroller or FPGA interfaces directly with the wavefront sensor detector and deformable mirror. Wavefront slopes are calculated from each detector frame and converted into actuator commands to complete the closed loop AO control system. A particular challenge of this system is to optimise the AO algorithms to achieve a high rate (> 1kHz) with low latency (< 1ms) to achieve a good AO correction. As part of the Space Environment Cooperative Research Centre (SERC) this AO system design will be used as a demonstrator for what is possible with ground based AO corrected satellite imaging and ranging systems. The ability to directly and efficiently interface the wavefront sensor and deformable mirror is an important step in reducing the cost and complexity of an AO system. It is hoped that in the future this design can be modified for use in general AO applications, such as in 1-3 m telescopes for space surveillance, or even for amateur astronomy.

Advanced Maui Optical and Space Surveillance Technologies Conference
A program of Maui Economic Development Board, Inc.
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