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ABSTRACTS OF TECHNICAL PAPERS
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ORBITAL DEBRIS

Session Chairs: Carolin Frueh, Purdue University and
Tim Flohrer, ESA/ESOC, Space Debris Office

Debris Albedo from Laser Ablation in Low and High Vacuum: Comparisons to Hypervelocity Impact

Gouri Radhakrishnan, Paul M. Adams, Christopher J. Panetta, Diana R. Alaan

The Aerospace Corporation

The albedo of orbital debris fragments in space is a critical parameter used in the derivation of their physical sizes from optical measurements. The change in albedo results from scattering due to micron and sub-micron particles on the surface. There are however no known hypervelocity collision ground tests that simulate the high-vacuum conditions prevailing during on-orbit optical measurements. While hypervelocity impact experiments at a gun range can offer a realistic representation of the energy of impact and fragmentation, and can aid the understanding of albedo, they are conducted in low-pressure air that is not representative of the very high vacuum of 10-8 Torr or less that exists in the Low Earth Orbit environment. Laboratory simulation using laser ablation with a high power laser, on the same target materials as used in current satellite structures, is appealing because it allows for well-controlled investigations that can be coupled to optical albedo (reflectance) measurements. This relatively low-cost laboratory approach can complement the significantly more elaborate and expensive field-testing of single-shot hypervelocity impact on representative satellite structures. Debris generated is optically characterized with UV-VIS-NIR reflectance, and particle size distributions can be measured. In-situ spectroscopic diagnostics (nanosecond time frame) provide an identification of atoms and ions in the plume, and plasma temperatures, allowing a correlation of the energetics of the ablated plume with resulting albedo and particle size distributions of ablated debris. Our laboratory experiments offer both a high-vacuum environment, and selection of any gaseous ambient, at any controlled pressure, thus allowing for comparison to the hypervelocity impact experiments in low-pressure air. Initial results from plume analysis and microstructure, and size distributions of debris collected on witness plates show that laser ablations in low-pressure air offer many similarities to the recent DebrisLV and DebriSat hypervelocity impact experiments, while ablations in high-vacuum provide critical distinctions.

A Search for Debris from Two Titan 3C Transtage Breakups at GEO with a 6.5-m Magellan Telescope

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There are two confirmed breakups of Titan 3C Transtage rocket bodies at GEO. The first was the breakup of 1968-081E (SSN03432) in 1992, resulting in a number of tracked objects in the public catalog. The second was 1969-013B (SSN03692) in 2014, which to date has no objects in the public catalog. The 6.5-m Magellan telescope, 'Walter Baade', at the Las Campanas Observatory in Chile has been used in an optical search for faint debris from these two breakups. All observations were rate tracked at the expected rate of debris. For 1968-081E, rates were generated using artificial TLEs using a range of mean anomalies from an average TLE for known objects from this breakup. For the search for 1969-013B, rates were generated from a simulated debris cloud produced using the NASA Standard Satellite Breakup Model. Based on the observed angular rates of detected objects, no objects brighter than 20th magnitude (approximately 10 cm) could be associated with the 1968-081E breakup, while one object brighter than 20th magnitude could be associated with 1969-013B

Characterizing the Survey Strategy and Initial Orbit Determination Abilities of the NASA MCAT Telescope for Geosynchronous Orbital Debris Environmental Studies

James Frith[1], Ed Barker[2], Heather Cowardin[1], Brent Buckalew[3], Mark Matney[4], Susan M. Lederer[4], Phillip Anz-Meador[3]

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The NASA Orbital Debris Program Office (ODPO) recently commissioned the Meter Class Autonomous Telescope (MCAT) on Ascension Island with the primary goal of obtaining population statistics of the geosynchronous (GEO) orbital debris environment. To help facilitate this, studies have been conducted using MCAT's known and projected capabilities to estimate the accuracy and timeliness in which it can survey the GEO environment. A simulated GEO debris population is created and sampled at various cadences and run through the Constrained Admissible Region Multi Hypotheses Filter (CAR-MHF). The orbits computed from the results are then compared to the simulated data to assess MCAT's ability to determine accurately the orbits of debris at various sample rates. Additionally, estimates of the rate at which MCAT will be able produce a complete GEO survey are presented using collected weather data and the proposed observation data collection cadence. The specific methods and results are presented here.

Precision Tracking of Decimeter Targets at GEO Distances Using the Magdalena Ridge Observatory 2.4-meter Telescope

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With the anticipated proliferation of cubesats reaching GEO in the coming years, the capability of detecting and tracking decimeter-sized targets at these distances will become increasingly important. In the present work, we report on efforts to develop this capability using the Magdalena Ridge Observatory (MRO) 2.4-meter telescope. Although the reported tests focus on small debris, these techniques will be equally applicable to active satellites.

Objects in or near geostationary orbit typically move approximately15 arc-sec per second with respect to sidereal motion. Therefore, exposure times are usually limited to half a second or less to avoid significant trailing of the field stars which are used as the metric fiducials. Using the MRO 2.4-meter, these exposure times permit detection to a visible magnitude of approximately V=20 when tracking at or near the target rates such that they appear as point sources. Assuming an albedo of 0.2, this implies the detection of decimeter-scale targets. This detection limit can be extended by increasing exposure times and then measuring the centroids of trailed images of the reference stars. However, the precision of this technique can be degraded by variable atmospheric conditions or uneven tracking during an exposure. An alternative method to extend exposure times is accomplished via the so-called synthetic tracking technique. In this case, multiple short exposures are shifted according to the anticipated motion of the target with the assumption that the reference stars will be sufficiently bright even in the short exposures. Then, the shifted images are co-added to build up the target signature.

In the present work, we present the results of the detection of decimeter sized targets in single exposures using the MRO 2.4-meter. We then explore the extension to deeper magnitudes resulting from the utilization of synthetic tracking. Finally, we discuss potential improvements that utilize alternative cameras and additional optics.

Characterizing GEO Titan IIIC Transtage Fragmentations Using Ground-based and Telescopic Measurements

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In a continued effort to better characterize the geosynchronous orbit (GEO) environment, NASA's Orbital Debris Program Office (ODPO) utilizes various ground-based optical assets to acquire photometric and spectral data of known debris associated with fragmentations in or near GEO. The Titan IIIC Transtage upper stage is known to have fragmented four times. Two of the four fragmentations were in GEO while the Transtage fragmented a third time in GEO transfer orbit. The forth fragmentation occurred in low Earth orbit. To better assess and characterize these fragmentations, the NASA ODPO acquired a Titan Transtage test and display article previously in the custody of the 309th Aerospace Maintenance and Regeneration Group (AMARG) in Tucson, Arizona. After initial inspections at AMARG demonstrated that it was of sufficient fidelity to be of interest, the test article was brought to NASA Johnson Space Center (JSC) to continue material analysis and historical documentation. The Transtage has undergone two separate spectral measurement campaigns to characterize the reflectance spectroscopy of historical aerospace materials. These data have been incorporated into the NASA Spectral Database, with the goal of using telescopic data comparisons for potential material identification. A Light Detection and Ranging (LIDAR) system scan also has been completed and a scale model has been created for use in the Optical Measurement Center

(OMC) for photometric analysis of an intact Transtage, including bidirectional reflectance distribution function (BRDF) measurements. An historical overview of the Titan IIIC Transtage, the current analysis that has been done to date, and the future work to be completed in support of characterizing the GEO and near GEO orbital debris environment will be discussed in the subsequent presentation

Exploiting Orbital Data and Observation Campaigns to Improve Space Debris Models

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The European Space Agency (ESA) has been developing the Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) software as the European reference model for space debris for more than 25 years. It is an event-based simulation of all known individual debris-generating events since 1957, including breakups, solid rocket motor firings and nuclear reactor core ejections.

In 2014, the upgraded Debris Risk Assessment and Mitigation Analysis (DRAMA) tool suite was released. In the same year an ESA instruction made the standard ISO 24113:2011 on space debris mitigation requirements, adopted via the European Cooperation for Space Standardization (ECSS), applicable to all ESA missions. In order to verify the compliance of a space mission with those requirements, the DRAMA software is used to assess collision avoidance statistics, estimate the remaining orbital lifetime and evaluate the on-ground risk for controlled and uncontrolled re-entries.

In this paper, the approach to validate the MASTER and DRAMA tools is outlined. For objects larger than 1 cm, thus potentially being observable from ground, the MASTER model has been validated through dedicated observation campaigns. Recent campaign results shall be discussed. Moreover, catalogue data from the Space Surveillance Network (SSN) has been used to correlate the larger objects. Alternative catalogues, like the bulletin provided by the JSC Vimpel Interstate Corporation and the Keldysh Institute of Applied Mathematics (KIAM) are currently being evaluated in an analogous correlation process and first results shall be presented.

In DRAMA, the assessment of collision avoidance statistics is based on orbit uncertainty information derived from Conjunction Data Messages (CDM) provided by the Joint Space Operations Center (JSpOC). They were collected for more than 20 ESA spacecraft in the recent years. The results of this analysis and the comparison of estimated manoeuvre rates with real manoeuvres from the operation of those spacecraft shall be compared.

ASTRODYNAMICS

Session Chairs: Marcus Holzinger, Georgia Institute of Technology and Paul Schumacher, Air Force Research Laboratory

Determining Type I and Type II Errors when Applying Information Theoretic Change Detection Metrics for Data Association and Space Situational Awareness

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Correlating new detections back to a large catalog of RSOs requires solving one of three types of data association problems: observation-to-track, track-to-track, or observation-to-observation. The authors' previous work has explored the use of various information divergence metrics for solving these problems: Kullback-Leibler divergence, mutual information, and Bhattacharrya distance. In addition to approaching the data association problem strictly from the metric tracking aspect, we have explored fusing metric and photometric data using Bayesian probabilistic reasoning for RSO identification to aid in our ability to correlate data to specific RSOs. In this work, we will focus our attention on the KL Divergence, which is a measure of the information gained when new evidence causes the observer to revise their beliefs. We can apply the Principle of Minimum Discrimination Information such that new data produces as small an information gain as possible and this information change is bounded by epsilon. Choosing an appropriate value for epsilon for both convergence and change detection is a function of your risk tolerance. Small epsilon for change detection increases alarm rates while larger epsilon for convergence means that new evidence need not be identical in information content. We need to understand what this change detection metric implies for Type I and Type II errors when we are forced to make a decision on whether new evidence represents a true change in characterization of an object or is merely within the bounds of our measurement uncertainty. This is unclear for the case of fusing multiple kinds and qualities of characterization evidence that may exist in different metric spaces or are even semantic statements. To this end, we explore the use of Sequential Probability Ratio Testing where we suppose that we may need to collect additional evidence before accepting or rejecting the null hypothesis that a change has occurred.

Sensitivity to Phase Angle for Reconciling Space Object Observed and Solar Pressure Albedo-Areas Via Astrometric and Photometric Data Fusion

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There are many Resident Space Objects (RSOs) in the GEO regime, both operational and debris. The primary non-gravitational force acting on these RSOs is Solar Radiation Pressure (SRP), which is sensitive to the RSO's area-to-mass ratio. Sparse observation data and mismodeling of non-gravitational forces has constrained the state of the art in tracking and characterizing RSOs. Accurate identification, characterization, tracking, and motion prediction of RSOs is a high priority research issue as it shall aid in assessing collision probabilities in the GEO regime.

Previous work in characterizing RSOs has exploited fusing astrometric and photometric data to estimate the RSOs mass, shape, attitude, and size. This technique works, in theory, since angles data are sensitive to SRP albedo area-to-mass ratio, and photometric data are sensitive to shape, attitude, and albedo area. By fusing the two data types, mass and albedo-area both become observable parameters and can be

estimated as independent quantities. However, current work in mass and albedo-area estimation has not rigorously analyzed the sensitivity to phase angle, which is the angle between the line of sight of the observer to the RSO and the vector between the RSO and the Sun. This paper shall study the sensitivity to phase angle on mass and albedo-area estimates of RSOs, with the goal of deriving a scaling factor that links observed albedo-area from photometric data to SRP albedo-area for a range of phase angles.

The RSO model used in this work will be a box-wing model with an MLI covered cube for the bus and a flat plate with solar panel material for the other surface, always sun-pointed. The SRP and observed albedo-areas will be identical only at a phase angle of zero degrees. The observed albedo-area is always a function of the solar pressure albedo-area. This work exploits this physical relationship.

Optical Initial Orbit Determination Using Polynomial Chaos Surrogate Functions

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Initial Orbit Determination (IOD) is an often overlooked, yet vital step in non-cooperative orbit tracking applications. When the observer has no initial information on the target's state, as occurs when a new target is detected or a new track of observations is not yet correlated with an existing track, IOD algorithms are necessary to obtain an initial state guess. This guess must be close enough to truth to use standard state estimation techniques, which typically either require an initial guess to linearize about or an initial estimate to use as a priori information.

A major problem with optical IOD, specifically, is that it can often fail to provide a solution. This lack of computational robustness is often rooted in the fact that these algorithms take two observation pairs as truth, and then they try to fit a trajectory that fits these exactly. Large underlying errors in these observation pairs result in either a poor fit or no solution can be determined.

This work seeks to introduce a new Polynomial Chaos-based optical IOD algorithm that does not constrain the system to exactly fit a given set of observations. Instead, it uses a Polynomial Chaos Expansion (PCE) in range, azimuth, and elevation at two different times to optimize a measurement-residual based maximum likelihood cost function while producing a full estimate of the target's position and velocity.

This algorithm takes, as input, a set of measurements associated with a single object and two constraints on its orbit: (1) minimum perigee and (2) maximum apogee. Using these constraints and observations the algorithm narrows the acceptable solution area, then generates the PCE as a surrogate for the cost function. This surrogate cost function is then optimized to provide an unconstrained state estimate based on all available observations. In summary, this algorithm provides an unconstrained batch estimate of a non-cooperative orbiting target without requiring an initial state guess.

Relative Orbit Determination of Multiple Satellites Using Double Differenced Measurements

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CU Boulder / CCAR

The location of operational space assets around the Earth is still of primary concern in the SSA community due to the ever increasing density of man-made objects and potential for collisions. Regions of particular interest are those with the highest spatial density. We propose a relative orbit determination method where we estimate the relative position and velocity between a primary (chief) and secondary (deputy) satellite. In this estimation scenario the chief satellite state is known to various levels of certainty. The uncertainty on the chief is considered when estimating the relative state to keep the covariance realistic. In this research we do not constrain the satellites to be within a certain region of each other. Consequently we use the full equations of motion rather than the Clohessy-Wiltshire relative equations of motion as the linearity assumption may no longer be valid.

The observables implemented are double differenced measurements including time difference of arrival (TDOA) and frequency difference of arrival (FDOA), also known as double differenced Doppler. The advantage of using these measurements is the mitigation of common errors resulting in a more accurate measurement. Double differenced observables eliminates satellite clock or delay errors, reduces orbit errors due to an insensitivity to dynamic mis-modeling in addition to diminished localized atmospheric and media errors, while canceling receiver clock biases as well. A disadvantage, however, is that the information about the state of each satellite is highly correlated with that of the other satellite. Due to this, the inertial estimation of the states of the satellites can be difficult, although not impossible. Therefore we leverage the relative information content of TDOA and FDOA for relative orbit determination while also reducing many common errors in the measurements.

Boundaries on Range-Range Constrained Admissible Regions for Space Situational Awareness

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We propose a new type of admissible-region analysis for track initiation in multi-satellite problems when apparent angles measured at known stations are the only observable. It takes at least three such observations to establish an orbit, thus one is faced with a problem that requires N-choose-3 sets of calculations to test every possible combination of the N observations. An alternative approach is to reduce the number of combinations by making hypotheses of the range to a target along the observed line-of-sight. If realistic bounds on the range are imposed, a pair of range possibilities can be evaluated via Lambert's method to find candidate orbits, which then requires N-choose-2 times M-choose-2 combinations, where M is the average number of range hypotheses per observation. The goal is to create an efficient and parallelizable algorithm for computing initial candidate orbits for a large number of new targets. The contribution of this work is a set of constraints that establish bounds on the range-range hypothesis region, thereby minimizing M. Two effective constraints are identified, which together, constrain the hypothesis region in range-range space to nearly that of the true admissible region based on an orbital partition. The first constraint is based on the geometry of the vacant orbital focus. The second constraint is based on time-of-flight and Lagrange's form of Kepler's equation.

Uninformative Prior Multiple Target Tracking Using Evidential Particle Filters

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Space situational awareness requires the ability to initialize state estimation from short measurements and the reliable association of observations to support the characterization of the space environment. The electro-optical systems used to observe space objects cannot fully characterize the state of an object given a short, unobservable sequence of measurements. Further, it is difficult to associate many such measurements generated through the observation of a cluster of satellites, debris, or from spurious detections of an object. The constrained admissible region multiple hypothesis filter (CAR-MHF) method is defined in the literature as a method to handle this association problem by initializing a bank of filters sampled from admissible regions. However, CAR-MHF is limited computationally by sampling of the admissible region and by the factorial nature of observation-to-observation association. Furthermore, CAR methods can impose constraints which are not always valid for a set of short-arc measurements.

An optimization based, probabilistic short-arc observation association approach coupled with a Dempster-Shafer based evidential particle filter in a multiple target tracking framework is developed and proposed to address these problems. The optimization based approach is computationally efficient and can produce probabilities of association, state estimates, and covariances while accounting for systemic errors. Rigorous application of Dempster-Shafer theory is effective at enabling ignorance to be properly accounted for in estimation by augmenting probability with belief and plausibility. The proposed multiple hypothesis framework will use a non-exclusive hypothesis formulation of Dempster-Shafer theory to assign belief mass to candidate association pairs and generate tracks based on belief. A high belief value indicates there is sufficient evidence to uniquely associate a set of observations to a single track whereas high plausibility indicates there are several consistent hypotheses. The proposed algorithm will be demonstrated using empirical observations of the ANIK cluster from the Georgia Tech Space Object Research Telescope.

Optical Data Association in a Multi-Hypothesis Framework with Maneuvers

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In Space Situational Awareness (SSA) one may encounter scenarios where the measurements received at a certain time do not correlate to a known Resident Space Object (RSO). Without information that uniquely assigns the measurement to a particular RSO there can be no certainty on the identity of the object. Typically, tracking methods tend to associate uncorrelated measurements to new objects or to clutter. In this paper, we consider the possibility that an uncorrelated measurement was produced by a previously known object that maneuvered away from its predicted location. Controlled RSOs have common maneuver constructs that can be accounted for in predictive models. For example, RSOs may need to maneuver with minimal time or minimal energy constraints. Other maneuvers such as orbit transfers or maintenance maneuvers can also be accounted for. The goal of this paper is to utilize a multiple hypothesis framework coupled with some knowledge of RSO maneuvers to develop an approach that allows one to maintain object custody of a maneuvered RSO in scenarios with uncorrelated optical measurement returns. We will use recent results from directional statistics that utilize the Fisher-Bingham-Kent probability density function for higher fidelity uncertainty representation when associating angles-only optical data. The key questions we will seek to answer are: (1) Given uncertainty in an object’s state and given that it can maneuver (under mild assumptions) can we correctly associate angles-only observations using the FBK association approach? (2) Based on that association, can we successfully update our tracking of the object and not lose

its track? In all, this paper will provide a framework for tracking maneuvered objects using a multiple hypothesis framework. In doing so it will increase capability of maintaining the identity of an object throughout a maneuver which in turn will provide better awareness in a maneuvering space object environment.

Limitations on Improving Orbit Prediction Accuracy through Machine Learning

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Current orbit predictions that are solely grounded on physics-based models may fail to achieve required accuracy for collision avoidance and have led to satellite collisions already. The failure is fundamentally arose from the lack of the required information such as the space environment condition and RSOs's body characteristics that are challenging to acquire in reality. One recently proposed remedy to overcome the limitation is to adopt the machine learning (ML) techniques, through which the models are learned based on large amounts of observed data and the prediction can be conducted without explicitly modeling space objects and space environment.

With the impressive capability that ML methods have demonstrated for various applications, crucial questions remain for applying such methods to orbital predication. The goal of the paper is to address the following three questions: 1) what are the assumptions in using the ML methods for orbital prediction? 2) What is the accuracy we can expect? 3) What are the requirements for the data sets?

We will first investigate the questions using a simulation-based approach. Recently, we have developed a space catalog model which will be used as a simulation environment for this study. The truth dynamic models include basic Newtonian two-body gravitational force, high fidelity non-spherical gravity model of the Earth, third-body perturbations, air drag force model with high-fidelity atmosphere model, solar radiation pressure model with high-fidelity solar activity model, with other parameters related with the specific RSO including the mass, inertia, geometry, material properties, etc. Ground-based measurements using radar or optical stations can also be generated.

Next, we will further explore the questions through a theoretical approach. We will start with the assumptions under the ML methods and then exploit those for the orbital prediction.

Strengthening the Bridge between Academia and Operations for Orbital Debris Risk Mitigation

Mark Vincent

Raytheon

The three-dimensional method of calculating the Probability of Collision developed by Coppola(1) is an elegant method of reducing the problem to integrations over a sphere and time. Horwood(2) extended this process to include J2 equinoctial elements. It is well known that the use of orbital elements can maintain the linearity in the propagation of the associated covariance matrices.(3) This paper will explore extending this to higher-order gravity terms using the semi-analytical (OSMEAN) and numerical methods (Morbiter) available at the Jet Propulsion Laboratory. The smaller uncertainty inherent in Mean orbital elements will be exploited, though as pointed out by Setty(4) the additional uncertainty in the conversion to Osculating elements must be taken into account since the actual conjunction geometry is dependent upon them. Nevertheless, the use of Mean elements can lead to the future inclusion of correlations between the two orbits involved. Examples of this include the common semi-major axis dependence on solar activity and the dependence on differential nodal precession presented by Vincent(5). The ultimate goal is to obtain a lower Pc, thus doing less risk mitigation maneuvers while maintaining the same maneuver thresholds.

1. Coppola, V.T., Including Velocity Uncertainty in the Probability of Collision between Space Objects, AAS Conference, Charleston SC, 2012
2. Horwood, J.T. et al, KRATOS: Kollision Risk Assessment Tool in Orbital Element Spaces, AMOS Conference, Maui HI, 2016
3. Alfriend, K.T. and I. Park When Does the Uncertainty Become Non-Gaussian? AMOS Conference, Maui HI, 2016
4. Setty, S.J., et al, Attributes affecting the Accuracy of a Batch Least Square Orbit Determination using Semi-analytical Satellite Theory, AMOS Conference Maui HI, 2016
5. Vincent, M., The Geometry of Repeating Conjunctions, Presented at SSA Workshop, Denver CO, 2016

Prediction Accuracy Analysis from Orbital Elements Generated for a New Space Object Catalogue

James Bennett, Michael Lachut

Space Environment Research Centre

The Space Environment Research Centre (SERC) is building a space object catalogue to provide accurate and reliable orbital information for a number of applications. Orbital elements are generated by fitting optical and laser tracking data from new tracking assets recently built in Australia.

This paper reports on the orbital prediction accuracy achieved. The data processing and fusion methodologies are described that improve accuracy and ensure the orbit determination process is not corrupted by erroneous data. More information from the data is generated by estimating the rates of change of the observation arcs. When the angles and range observation data is fused, the accurate 6-dimensional data is used to generate state vectors directly from the observations. The orbit predictions improvements form a critical component of the conjunction assessment capability being developed and progress is reported.

Conjunction Assessment for Commercial Satellite Constellations Using Commercial Radar Data Sources

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For companies with multiple orbital assets, managing the risk of collision with other low-Earth orbit (LEO) Resident Space Objects (RSOs) can amount to a significant operational burden. LeoLabs and Planet investigate the impact of a workflow that integrates commercial SSA data into conjunction assessments for large satellite constellations.

Radar measurements from LeoLabs are validated against truth orbits provided by the International Laser Ranging Service (ILRS) and to measurements from Planet's on-board GPS instrumentation. The radar data is then used as input for orbit fits in order to form the basis of a conjunction assessment. To confirm the reliability of the orbit determination (OD), the generated ephemerides are validated against ILRS and GPS-derived orbits. In addition, a covariance realism assessment is performed in order to check for self-consistency by comparing the propagated orbit and the associated covariance against later measurements.

Several cases are investigated to assess the benefits of integrating radar-derived products with Conjunction Data Messages (CDMs) received on Planet spacecraft. Collision probability forecasts for conjunctions are refined using onboard GPS measurements from Planet satellites along with tracking measurements of the secondary RSO by LeoLabs. The addition of commercial SSA data from LeoLabs has a positive impact on operations due to the reduced uncertainties in the state of the secondary RSO and increased confidence in any maneuver related decisions. Measurements from LeoLabs can also be used to improve conjunction assessment for commercial satellites that do not have any operator OD.

OPTICAL SYSTEMS

Session Chairs: Mike Dearborn, MITRE Corporation and Jim Shell, Novarum Tech

Event Based Sensing for Space Situational Awareness

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A revolutionary type of imaging device, known as a silicon retina or event-based sensor, has recently been developed and is gaining in popularity in the field of artificial vision systems. These devices are inspired by a biological retina and operate in a significantly different way to traditional CCD-based imaging sensors. Event-based sensors make use of asynchronous pixels and an event-based output with high temporal resolution, allowing these devices to offer a very high dynamic range independently for each pixel, high-speed operation, no need for fixed exposure times and a sparse spatio-temporal output. As a consequence, the data from these sensors must be interpreted in a significantly different way to traditional imaging sensors and some of the advantages that this offers are explored.

The applicability and capabilities of these devices for SSA applications are demonstrated in telescope field trials. Trial results have confirmed that the devices are capable of observing resident space objects from LEO through to GEO orbital regimes. Significantly, observations of RSOs were made during both day-time and night-time (terminator) conditions without modification to the camera or optics. The event based sensor's ability to image stars and satellites during day-time hours offers a dramatic capability increase for terrestrial optical sensors. This paper shows the field testing and validation of two different architectures of event-based imaging sensors.

An event-based sensor's asynchronous output has an intrinsically low data-rate. In addition to low-bandwidth communications requirements, the low weight, low-power and high-speed make them ideally suitable to meeting the demanding challenges required by space-based SSA systems. Results from these experiments and the systems developed highlight the applicability of event-based sensors to ground and space-based SSA tasks.

Image Reconstruction from Data Collected with an Imaging Interferometer

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The intensity distribution of an incoherent source and the spatial coherence function at some distance away are related by a Fourier transform, via the Van Cittert-Zernike theorem. Imaging interferometers measure the spatial coherence of light propagated from the incoherently illuminated object by combining light from spatially separated points to measure interference fringes. The contrast and phase of the fringe are the amplitude and phase of a Fourier component of the source's intensity distribution. The Fiber-Coupled Interferometer (FCI) testbed is a visible light, lab-based imaging interferometer designed to test aspects of an envisioned ground-based interferometer for imaging geosynchronous satellites. The front half of the FCI testbed consists of the scene projection optics, which includes an incoherently backlit scene, located at the focus of a 1 m aperture f/100 telescope. The projected light was collected by the back half of the FCI testbed. The collection optics consisted of three 11 mm aperture fiber-coupled telescopes. Light in the fibers was combined pairwise and dispersed onto a sensor to measure the interference fringe as a function of

wavelength, which produces a radial spoke of measurements in the Fourier domain. The visibility function was sampled throughout the Fourier domain by recording fringe data at many different scene rotations and collection telescope separations. Our image reconstruction algorithm successfully produced images for the three scenes we tested: asymmetric pair of pinholes, U.S. Air Force resolution bar target, and satellite scene. The bar target reconstruction shows detail and resolution near the predicted resolution limit.

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Stereo–SCIDAR System for Improvement of Adaptive Optics Space Debris-tracking Activities

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Research School of Astronomy and Astrophysics

The Research School of Astronomy and Astrophysics (RSAA) in conjunction with the Space Environment Research Centre (SERC) is developing a single-detector stereo-SCIDAR (SCIntillation Detection And Ranging) system to characterise atmospheric turbulence. We present the mechanical and optical design, as well as some preliminary results.

SERC has a vested interest in space situational awareness, with a focus on space debris. RSAA is developing adaptive optics systems to aid in the detection of, ranging to, and orbit propagation of said debris. These adaptive optics systems will be directly improved by measurements provided by the usage stereo-SCIDAR system under development.

SCIDAR is a triangulation technique that utilizes a detector to take short exposures of the scintillation pupil patterns (images) of a double star. There is an altitude at which light propagating from these stars passes through the same ‘patch’ of turbulence in earth’s atmosphere: this patch induces wavefront aberrations that are projected onto different regions of the scintillation pupil patterns. An auto-correlation function is employed to extract the height, at which the turbulence was introduced into the wavefronts. Unlike stereo-SCIDAR systems developed by other organisations—which utilise a dedicated detector for each of the pupil images—our system will use a pupil-separating refractive optic and a single detector to image both pupils. Using one detector will reduce cost as well as design and optical complexity. The system will be installed, tested and operated on the EOS Space Systems’s 1.8m debris-ranging telescope at Mount Stromlo, Canberra. Specifically, it will be used to observe a double star separated by 5 to 25 arcseconds with a greater magnitude difference tolerance than conventional SCIDAR, that conventional difference being roughly 2.5. We anticipate taking measurements of turbulent layers up to 15km in altitude with a resolution of approximately 1km. Our system will also be sensitive to ground layer atmospheric turbulence.

Plasma Spectroscopy CubeSat: A Demonstration of On-Orbit Electric Propulsion System Diagnostics

Jennifer Hudson, Kristina Lemmer

Western Michigan University

Electric propulsion (EP) systems on operational satellites may exhibit unexpected behaviors or failures on orbit. Determining the cause of these behaviors using onboard instruments and ground-based sensors can be challenging. Onboard instruments are located outside of the plasma plume, and most spacecraft will not be outfitted with them. Ground-based observations are hindered by the presence of the atmosphere and the timing and positioning of available telescopes. The Plasma Spectroscopy (P-Spec) mission aims to demonstrate a low-cost, responsive system for EP plasma plume diagnostics using a CubeSat platform. The P-Spec CubeSat is a technology demonstration satellite in development at Western Michigan University. P-Spec will demonstrate on-orbit optical emission spectroscopy of a plasma plume that is representative of an electric propulsion system. An optical emission spectrometer payload with a CMOS detector will measure light emission as a function of wavelength of the plasma source at distances up to 1 km to identify plasma composition, temperature, and energy distribution. The P-Spec satellite is a 6U CubeSat, which will separate into two independent CubeSats – Plasma-Sat and Detector-Sat – after deployment in low Earth orbit. Plasma-Sat will house a xenon feed system, propellant tank, and hollow cathode, which will emit a plasma plume representative of an ion thruster. Detector-Sat will contain the optical emission spectrometer system to measure light emission from Plasma-Sat. The P-Spec program has completed Preliminary Design Review and is preparing for Flight Selection Review in the Air Force Research Laboratory’s University Nanosatellite Program. This paper provides an overview of the satellite design and mission plan. It also discusses the data products that are expected from this mission and how they can be used to identify plasma plume composition and assess thruster performance.

QuadCam - A Quadruple Polarimetric Camera for Space Situational Awareness

Jovan Skuljan

Defence Technology Agency

A specialised quadruple polarimetric camera for space situational awareness, QuadCam, has been built at the Defence Technology Agency (DTA), New Zealand, as part of collaboration with the Defence Science and Technology Laboratory (Dstl), United Kingdom. The design was based on a similar system originally developed at Dstl, with some significant modifications for improved performance. The system is made up of four identical CCD cameras looking in the same direction, but in a different plane of polarisation at 0, 45, 90 and 135 degrees with respect to the reference plane. A standard set of Stokes parameters can be derived from the four images in order to describe the state of polarisation of an object captured in the field of view.

The modified design of the DTA QuadCam makes use of four small Raspberry Pi computers, so that each camera is controlled by its own computer in order to speed up the readout process and ensure that the four individual frames are taken simultaneously (to within 100-200 microseconds). In addition, a new firmware was requested from the camera manufacturer so that an output signal is generated to indicate the state of the camera shutter. A specialised GPS unit (also developed at DTA) is then used to monitor the shutter signals from the four cameras and record the actual time of exposure to an accuracy of about 100 microseconds. This makes the system well suited for the observation of fast-moving objects in the low Earth orbit (LEO).

The QuadCam is currently mounted on a Paramount MEII robotic telescope mount at the newly built DTA space situational awareness observatory located on Whangaparaoa peninsula near Auckland, New Zealand. The system will be used for tracking satellites in low Earth orbit and geostationary belt as well. The performance of the camera has been evaluated and a series of test images have been collected in order to derive the polarimetric signatures for selected satellites.

Towards Routine Uncued Surveillance of Small Objects at and near GEO with Small Telescopes

Peter Zimmer, John T. McGraw, Mark Ackermann

J.T. McGraw and Associates, LLC

There is considerable interest in the capability to discover and monitor small objects (d ~ 20cm) in geosynchronous (GEO) and near-GEO orbital regimes using small, ground-based optical telescopes (D < 0.5m). The threat of such objects is clear. Small telescopes have an unrivaled cost advantage and, under ideal lighting and sky conditions, have the capability of detecting such faint objects. This combination of conditions however is relatively rare, making routine and persistent surveillance more challenging.

In a truly geostationary orbit, a small object is easy to detect because their apparent rates of motion are nearly zero for a ground-based observer and signal accumulation occurs as it would for more traditional sidereal-tracked astronomical observations. In this regime, though, small objects are not expected to be in controlled or predictable orbits, thus a range of inclinations and eccentricities are possible. This results in a range of apparent angular rates and directions that must be monitored. This firmly establishes this task as uncued or blind surveillance. Detections in this case are subject to what is commonly called “trailing loss,” where the signal from the object does not accumulate in a fixed detection element, resulting in far lower sensitivity than for a similarly object optimally tracked.

We review the physics-based limits of detecting these objects across a range of observing conditions and orbits, subject further to the current limitations based on technological and operational realities. We demonstrate significant progress towards this goal using telescopes much smaller than normally considered viable for this task, using novel detection and analysis techniques. We compare these results to the limits imposed by fundamental physics and discuss some ways that telescopes, detectors and analysis can be improved to push ever closer to these limits.

Deep Space Wide Area Search Strategies

Michael Nayak, Michael Capps, Julian McCafferty

Air Force Research Laboratory

There is an urgent need to expand the space situational awareness (SSA) mission beyond catalog maintenance to providing near real-time indications and warnings of emerging events. While building and maintaining a catalog of space objects is essential to SSA, this does not address the threat of uncatalogued and uncorrelated deep space objects. The Air Force therefore has an interest in transformative technologies to scan the geostationary (GEO) belt for uncorrelated space objects. Traditional ground based electro-optical sensors are challenged in simultaneously detecting dim objects while covering large areas of the sky using current CCD technology. Time delayed integration (TDI) scanning has the potential to enable significantly larger coverage rates while maintaining sensitivity for detecting near-GEO objects. This paper investigates strategies of employing TDI sensing technology from a ground based electro-optical telescope, toward providing tactical indications and warnings of deep space threats. We present results of a notional "wide area search" TDI sensor that scans the Pacific region of the GEO belt. Deep space objects in the NASA 2030 debris catalog is propagated over multiple nights as an indicative data set to emulate notional uncatalogued near-GEO orbits which may be encountered by the TDI sensor. Multiple scan patterns are designed and simulated, to compare and contrast performance based on 1) efficiency in coverage, 2) number of objects detected, and 3) rate at which detections occur, to enable follow-up observations by other space surveillance network (SSN) sensors. A step-stare approach is also modeled using a dedicated, co-located sensor notionally similar to the Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) tower. Equivalent sensitivities are assumed. This analysis quantifies the relative benefit of TDI scanning for the "wide area search" mission.

NON-RESOLVED OBJECT CHARACTERIZATION

Session Chairs: Heather Cowardin, University of Texas El Paso, Jacobs-JETS and Matthew Hejduk, Astrorum Consulting

Debris Attitude Motion Measurements and Modeling - Observation vs. Simulation

Tobias Lips[1], Ronny Kanzler[1], Patrik Kaerraeng[1], Jiri Silha[2], Thomas Schildknecht[2], Daniel Kucharski[3], Georg Kirchner[4], Jens Rosebrock[5], Delphine Cerutti-Maori[5], Holger Krag[6]

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End of 2014, ESA initiated a research project named “Debris Attitude Motion Measurements and Modeling”. The main goal of this project was to combine space debris attitude state determination from observations with numerical simulations. Under the lead of AIUB, light curves and laser ranging residuals were obtained by AIUB and IWF, while FHR conducted radar observations. In parallel, HTG developed a 6 degrees-of-freedom – orbit and attitude – propagator. This tool called iOTA (In-Orbit Tumbling Analysis) takes into account all relevant external and internal perturbation sources (gravity, aerodynamics, solar radiation pressure, electro-magnetic, etc.).

The final phase of the project will be a critical comparison between observation data obtained for various space objects (e.g. ENVISAT, ERS-1/2, ADEOS-2, H2-A R/B, LAGEOS-2) and the corresponding simulation results. This comparison will also serve the purpose of software validation for iOTA.

The conversion of observation data into well-defined attitude states (i.e. rotation vector orientation and magnitude) can be quite difficult and sometimes resulting into multiple, non-unique solutions. Therefore, this comparison will use an inverse approach. iOTA is capable to convert its propagation results into synthetic observation results. This conversion takes into account the individual sensor type and relative perspective towards the observation target during the measurement campaign. This approach facilitates a direct comparison of real observation data (light curves, laser ranging residuals, and radar imaging) with the numerical propagation results.

This paper will present the attitude propagation methods of iOTA and the results of its software validation process showing a comparison between real and synthetic observation data.

Acoustic Imaging of Geosynchronous Satellites

Zachary Watson[1,2], Michael Hart[1]

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Identification and characterization of orbiting objects which are not spatially resolved is a non-trivial problem with no clear-cut present solution. Hyper-temporal imaging, enabled by fast-framing low noise detectors, is a new sensing modality which may allow the direct detection of acoustic resonances on satellites. Oscillations of solar panels and high-gain antennae, driven by fluctuations in solar radiation pressure, worn reaction wheels, or thrusters firing, may be observable by this technique. We present an analysis of observations of geostationary satellites conducted at the University of Arizona Kuiper 1.5 m telescope in January 2017. The instrument uses a dual detector reimaging system to capture both orthogonal linear polarizations of the light separately and synchronously, on the theory that the polarization amplitude and angle of sunlight reflected from non-metallic specular surfaces may yield a stronger signal than the total intensity alone. Data were recorded at sampling rates up to 1.5 kHz, where the rate was limited by object brightness. To date, three satellites have been observed; we see evidence of acoustic resonances in the polarization state of one of them. Further observations will reveal whether unique acoustic signatures may be attributed to each object. The technique is expected to support both object identification and characterization of on-board components as well as a discriminant between active satellites and junk or otherwise inactive objects.

Space Weathering Experiments on Spacecraft Materials

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A project to investigate space environment effects on specific materials with interest to remote sensing was initiated in 2016. The goal of the project is to better characterize changes in the optical properties of polymers and Mylar, specifically those found in multi-layered spacecraft insulation, due to electron bombardment. Previous analysis shows that chemical bonds break and potentially reform when exposed to high energy electrons. Among other properties these chemical changes altered the optical reflectance as documented in laboratory analysis. This paper presents results of the initial experiment results focused on the exposure of materials to various fluences of high energy electrons, used to simulate a portion of the geosynchronous space environment. The paper illustrates how the spectral reflectance changes as a function of time on orbit with respect to GEO environmental factors and investigates the survivability of the material after multiple electron doses. These results provide a baseline for analysis of aging effects on satellite systems used for remote sensing. They also provide preliminary analysis on what materials are most likely to encompass the high area-to-mass population of space debris in the geosynchronous environment. Lastly, the paper provides the results of the initial experimentation as a proof of concept for space aging on polymers and Mylar for conducting more experiments with a larger subset of spacecraft materials.

Probabilistic Analysis of Light Curves

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In this work, we advocate the view that a light curve, as a one-dimensional function as opposed to a time-series, is a realization of a functional random process. The random process is given by a light curve model, where uncertainty is present due to imperfect knowledge of space object, geometric and environment parameters. This view opens the door for a rigorous probabilistic analysis of light curves and can be used in applications such as space object identification and characterization, uncorrelated track analysis, and a rigorous use of light curves for attitude and position and velocity estimation. More specifically, after defining the notion of first and second probabilistic moments for a light curve population, we will use the notions of likelihoods and information gain to solve light-curve based object classification and association problems. In this paper, we will first use tools from machine learning, such as data clustering, to classify populations of light curves. Secondly, we will then use functional data analysis and its associated functional Principle Component Analysis (fPCA) to obtain first and second moment statistics (the equivalent of obtaining a Gaussian model for a point cloud in particle filtering). Next, given a new light curve, we will attempt to use an FDA-based Mahalanobis distance to assess whether the curve belongs to one of the available light curve classes. Such an analysis will help in answering questions like: (1) Is the new light curve generated from an object of a give class? And short of a decisive answer, (2) how much in common does this light curve have with a given class of objects? We will also use the Kullback-Leibler divergence to determine the degree of commonality between two classes of light curve populations.

Rapid Characterization of Geosynchronous Space Debris with 5-color Near-IR Photometry

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Adam D. Block[1], Kris Rockowitz[1]

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The characterization of deep space debris has posed a significant challenge in SSA. To be most operationally effective, characterization must be performed quickly and under non-ideal operational conditions, generally using non-resolved techniques. The use of multi-color photometry and the resultant color indices in the near and short-wave IR offer the potential to rapidly discriminate between debris and intact space objects such as rocket bodies and satellites. Specifically, the color indices surrounding the near IR Z band (0.83-0.925 µm) show promise to differentiate materials while providing a more realistic data collection opportunity when compared to spectroscopy. Similar techniques have been demonstrated in the astronomical community to discriminate between different classes of near Earth asteroids. The diagnostic attributes of the Z band are particularly compelling as similar diagnostic color indices can be measured using visible telescopes and the corresponding Sloan z’ band. Initial results of an extensive survey of cataloged debris, high area-to-mass ratio (HAMR) debris, rocket bodies, and intact satellites with the UK IR Telescope (UKIRT) Wide Field Camera (WFCAM) are presented to assess the efficacy of these techniques. As a test case, an ensemble of Russian SL-12 rocket bodies (SL-12 RB) discarded at in geosynchronous orbit has been studied. Using these techniques, one of these rocket bodies (2012-012D, SCN 38104) has been identified having anomalous near-IR spectral characteristics compared all others in the study. Additionally, this object experiences unusual secular perturbations in its post-mission orbital elements.

Development and Evaluation of New Methods for Estimating Albedo-Area for Stable GEOs

Tamara Payne[1], Adam Kruchten[1], Jeffrey Hollon[1], Markus Ernst[1], Anthony Dentamaro[1], Stephen A. Gregory[1], Phan D. Dao[2], Anil B. Chaudhary[1]

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Although direct measurements of the projected areas of various Geosynchronous Earth Orbit (GEO) satellite facets are impossible without high-resolution imaging, estimates of the albedo-Area (aA) product lead to the possibility of inferring the area. Such size estimates are an integral part of its identity. We are engaged in parallel development of two methods for calculating aA for the body/communication antennae structures and one method for the solar panels. We have previously reported on the Two Facet Model (2FM) method for body aA, and here we discuss a method based on differences between new observations and a baseline catalog that has been constructed from the GEO Observations with Longitudinal Diversity Simultaneously (GOLDS) data. We report on evaluations of the 2FM and differential method (DM) algorithm results. We also discuss a new method of estimating solar panel aA by fitting new data that include specular glints. All of these measurement methods are compared to models and simulations that serve as a proxy for ground truth. Because of the partially directional nature of the composite Bi-directional Reflectivity Distribution Function (BRDF) of all bus-mounted appendages, variance of body aA results is expected to be significant. Short term and long term variance of the derived aAs will be discussed.

TASKING

Session Chairs: Ryan Coder, AFRL, Air Force Maui Optical and Supercomputing Site and Tamara Payne, Applied Optimization

Sensor Tasking for Detection and Custody of HAMR Objects

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High-area-to-mass ratio (HAMR) objects are notoriously difficult to detect and upon detection to keep custody of in a catalog build up and maintenance scenario. HAMR objects is among the most susceptible space objects for orbital perturbations. Furthermore, orbit and attitude perturbations are highly coupled. Furthermore, it is suspected that these objects also act as flexible, non-rigid bodies, while in orbit. As a result, their orbits are hard to predict and even if initially detected, they are often 'lost', as they are not rediscovered in scheduled follow-up observations. This paper presents a new approach for the detection of HAMR objects and keeping custody of them in an optical sensor network. The method is fully based upon first principles without any a priori information. In a first step probability habitat regions are mapped out based upon the HAMR object response to dynamics. Those regions directly feed in an optimized sensor tasking algorithms, based upon optima observability in the most time efficient manner. Once objects are detected, the expected uncertainties and their growth is outlined, taking all sources of uncertainty, such as shape, reflection parameters, attitude and their unknown time evolution into account. Based upon those uncertainty maps, follow-up observations are scheduled in a fully automated manner. The performance of the method is shown in simulation and with optical observation data from the DLR SMARTnet telescope network.

Performance of Optimized Scheduled Follow-up Observations for Geosynchronous Space Object Using Different Genetic Algorithms

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The importance of protecting the geosynchronous region from space debris requires continuous monitoring in order to support collision avoidance operations. Accurate orbit information is prerequisite to avoid manoeuvres which might shorten the mission time. To gain this information, follow-up observations are necessary to maintain the accuracy of ephemeris data within certain limits of the catalogued objects. To perform these observations in the most efficient way, optimized scheduling is a key element. In this paper the performance of two optimal scheduling algorithms is compared for an optical telescope network. Both algorithms are based on genetic algorithms and have been utilized to provide optimal solutions for catalogue maintenance. The single-objective algorithm uses the expected information content of a new observation as optimization parameter. The multi-objective algorithm is based on the successful Non-dominated Sorting Genetic Algorithm II (NSGA-II) and uses as a further optimization parameter the detection probability given by the pre-estimated magnitude of the object. Both algorithms are introduced in detail and it is shown that the information content utilizing the orbit's covariance and the information gain in an expected update is a useful optimization measure. Since the information content of a follow-up observation depends also on the observation time and oscillates slightly during the night similar information gain values might be reached at different observation epochs. It is demonstrated that an optimized phase angle might not reduce the information content of a follow-up observation substantially. To prove the

concept, data of a simulated object catalogue is used to compare the effectiveness of the scheduling algorithms. Finally, first results of the performance of both algorithms using the optical telescope network are shown and analyzed.

Autonomous Space Object Catalogue Construction and Upkeep Using Sensor Control Theory

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The capability to track objects in space is critical to safeguard domestic and international space assets. Infrequent measurement opportunities, complex dynamics and partial observability of orbital state makes the tracking of resident space objects nontrivial. It is not uncommon for human operators to intervene with space tracking systems, particularly in scheduling sensors. This paper details the development of a system that maintains a catalogue of geostationary objects through dynamically tasking sensors in real time through the management of the uncertainty of objects state. As the number of objects in space grows the potential for conjunction grows exponentially. Being able to provide accurate assessment to operators regarding costly conjunction avoidance manoeuvres is paramount; the accuracy of which is highly dependent on how object states are estimated. The system represents object state and uncertainty using particles and utilises a particle filter for state estimation. Particle filters capture the model and measurement uncertainty more truthfully than typical filtering techniques, allowing for a more comprehensive representation of the state’s probability density function. Additionally, the number of objects in space is growing disproportionally to the number of sensors used to track them. Maintaining precise positions of all objects places large loads on sensors, limiting the time available to search for new objects or track high priority objects. Rather than precisely track all objects our system manages the uncertainty in orbital state for each object independently. The uncertainty is allowed to grow and only reduced when required, for example when data association issues may occur or the uncertainty grows to beyond a field of view. These control laws are formulated into a cost function, which is optimised in real time to task sensors. Using data from an optical telescope the system has been able to construct and maintain a catalogue in the order of 100 objects.

Time Optimal Search or Follow-up Tasking on Orbit Region for SSA

Timothy Murphy, Marcus Holzinger

Georgia Tech

This work proposes a methodology for tasking of a sensor to search an area of state space for objects in a time optimal manner. This work is, in particular, motivated by follow-up on a short arc observation and associated admissible region by a second sensor at an arbitrary place and time This will enable current space situational awareness programs to more efficiently locate a partially known object, defined by a UCT, and search for new objects.

In particular, this work assumes prior state knowledge in the form of a set, which can be defined through an admissible region or a high priority region of state space. The follow-up observations can occur from a different location at a different time, which often defines a large region of the sky which requires searching. This problem is a more complex variant of the travelling salesman problem and does not have an immediate solution. This work looks at instead analyzing the problem to provide an approximate, tractable solution.

To find a tractable solution, this work analyzes the area rate of change of a search region within the measurement space to locate areas of high divergence and therefore high priority. This work goes on to explore an approximate solution to the travelling salesman problem based an rigorous analysis of the search region's growth over time in order to solve the optimization problem. The solution presented is a solution that can be solved with reasonable computational efficiency.

Simulation work demonstrates the efficacy of this method to provide reasonable solutions in reasonable computation time. Further simulation work explores the effects of sensor geometry, initial detection uncertainty, and handoff delay time on total time and feasibility of follow-up. This work is vallidated on the GT SORT telescope.

An Autonomous Sensor Tasking Approach for Large Scale Space Object Cataloging

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The field of Space Situational Awareness (SSA) has progressed over the last few decades with new sensors coming online, the development of new approaches for making observations, and new algorithms for processing them. Although there has been success in the development of new approaches, a missing piece is the translation of SSA goals to sensors and resource allocation; otherwise known as the Sensor Management Problem (SMP). This work solves the SMP using an artificial intelligence approach called Deep Reinforcement Learning (DRL). Stable methods for training DRL approaches based on neural networks exist, but most of these approaches are not suitable for high dimensional systems. Reference 1 developed an effective approach for high dimensional systems and this work leverages these results and applies this approach to decision making in SSA. The decision space for the SSA problems can be high dimensional even for tasking of a single telescope. Since the number of SOs in space is relatively high, each sensor will have a large number of possible actions at a given time. Therefore, efficient DRL approaches are required when solving the SMP for SSA. This work develops policy gradient methods [1] for DRL applied to SSA sensor tasking. One of the key benefits of a DRL approach is the ability to handle high dimensional data such as image processing for the autonomous car applications. For example, a 256x256 RGB image has 196608 parameters (256*256*3=196608) which is very high dimensional, and deep learning approaches can take images like this as inputs. Therefore, when applied to the whole catalog the DRL approach offers the ability to solve this high dimensional problem. This work has the potential to, for the first time, solve the non-myopic sensor tasking problem for the whole SO catalog (over 22,000 objects) providing a truly revolutionary result.

ADAPTIVE OPTICS AND IMAGING

Session Chairs: Eric Pearce, University of Arizona Steward Observatory and Stacie Williams, Air Force Office of Scientific Research

High Resolution SSA Imaging Using Carbon Fiber Telescopes

Ryan Swindle[1], Douglas Hope[2], Michael Hart[2], Stuart Jefferies[3]

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High-resolution ground-based imagery of space satellites plays an important role in SSA. The current approach for obtaining this type of imagery requires a large aperture telescope equipped with adaptive optics. These requirements place limitations on AF surveillance capability by restricting coverage of the sky to that which can be achieved from the small number of geographical locations where the AF has a surveillance facility. However, recent advances in carbon reinforced polymer fiber (CFRP) telescopes offer the potential for field-deployable large aperture (>1m) telescopes for ground-based imaging of space objects. A major driver of cost of a CRFP telescope is the optical quality of the primary mirror, where the cost depends on the amount of polishing done to the mirror. Here we show, using both numerical simulations and real data, that a CFRP telescope with significant optical aberration can be used for high-resolution imaging if the telescope is equipped with a wave-front-sensor (WFS), and the recorded image and WFS data are processed using the Daylight Object Restoration Algorithm (DORA).

Developments in High Spatial Resolution Imaging of Faint, Complex Objects at Lowell Observatory

Gerard van Belle

Lowell Observatory

Lowell Observatory operates the Navy Precision Optical Interferometer (NPOI), and owns & operates the Discovery Channel Telescope (DCT); this unique combination of facilities is being leveraged by Lowell to develop a robust program of imaging faint, complex objects. NPOI is a six-beam long-baseline optical interferometer, located in Flagstaff, Arizona; the facility is supported by a partnership between Lowell Observatory, the US Naval Observatory, and the Naval Research Laboratory. NPOI is currently operational on-sky in the visible with baselines between 8 and 100 meters (up to 432m is available), conducting programs of astronomical research and imaging technology development. 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, progress on an ongoing program of facility upgrades will discussed. These upgrades include AO-assisted 1.0-m 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. First light for the large, relocatable apertures is expected in early 2018. The large apertures will enable year-round observations of objects brighter than 10th magnitude in the near-IR, corresponding to brighter than mag=12.5 in the visible. At its core, the system is enabled by an 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 DCT, for constraining the low-spatial frequency imaging information, will also be outlined, including pilot results.

Using Asteroids and their Moons for Closely Spaced Object Studies

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This past observing season (Oct 2016 - Feb 2017), employing two Toptica lasers to create a 40 w laser guide star, we imaged two asteroids (22) Kalliope and (317) Roxane and their moons with adaptive optics (AO) on our 3.5 m telescope on Kirtland AFB, NM. In both cases, the moons showed highly inclined orbits that ventured in and out of the point spread function of the parent asteroid over a period of 3.6 days for Kalliope's moon Linus, or 11.6 days for Roxane's unnamed moon. These two cases closely parallel our Closely Spaced Objects (CSO) study, being similar to geosynchronous satellites with potential nearby snugglers, since Kalliope ranged from V magnitude 10.9 to 10.3 and Roxane from 14.5 to 13.5, with their moons being some 25 times (Kalliope's moon) or 12 times (Roxane's moon) fainter than the asteroid in J-band (1.2 µm). We determined an orbit for Linus from our observations over 95 days that agrees quite nicely with the well-known orbit calculated from AO observations on 8-10 m telescopes over ten years. We also determined a first-ever orbit for Roxane’s moon; it has not been reported since its discovery in 2009.

Quantum Theory of Three-Dimensional Superresolution Using Rotating-PSF Imagery

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A recent paper [1] has shown that for a closely spaced pair of classical thermal sources like stars, it is possible to overcome the Rayleigh resolution limit by making spatial-mode demultiplexing (SPADE) measurements, rather than traditional imagery. The improvement seems to get better with decreasing pair separation at values below the minimum set by the Rayleigh criterion, which is a remarkably counter-intuitive result. Specifically, in the Poisson shot-noise limit appropriate to photon counting from thermal sources [2], the minimum photon number needed for resolving the pair can be made inversely proportional to the square of their separation, rather than to its fourth power [3] characteristic of direct imaging methods. This was proved in Ref. [1] by use of quantum Fisher information, which is the reciprocal of the quantum Cramer-Rao bound, the smallest variance of any unbiased estimator, whether classical or quantum mechanical.

In this paper, we will generalize the SPADE formalism for two-dimensional (2D) transverse resolution of a closely spaced source pair to the problem of their full 3D resolution. Such 3D resolution can be performed by a new imaging approach based on combining Bessel vortex beams in the imaging aperture that allows the range of a point source to be encoded in the angle of rotation of the imager point-spread function (PSF) and its transverse coordinates in the coordinates of the center of rotation in the 2D image plane.

This work has implications for 3D space-debris localization using a rotating-PSF imager that could be mounted on a space asset as part of an active optical surveillance system to rapidly monitor its 3D debris position and velocity fields in order to execute any avoidance or kill maneuvers. Some calculations of 3D snapshot debris-localization errors using a rotating-PSF telescope will be presented as motivation for the viability of such a surveillance system that could operate in conjunction with a radar-based surveillance system for extended 3D coverage.

[1] [1] M. Tsang, et al., “Quantum theory of superresolution of two incoherent point sources,” Phys. Rev. X, vol. 6, 031033 (2016). [2] J. Goodman, Statistical Optics (Wiley, 1985), Chap. 9. [3] S. Prasad, “Asymptotics of Bayesian error probability and 2D pair superresolution,'' Opt. Express, vol. 22, 16029-16047 (2014).

High-Fidelity Imaging Using Compact Multi-Frame Blind Deconvolution

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Multi-frame blind deconvolution (MFBD) has been a cornerstone for ground-based space situational awareness (SSA) of near-Earth satellites, since the early 2000's. In 2011, a variation of the classic MFBD algorithm was introduced that required solving for fewer variables than in the classic algorithm, but which still used all the available data to constrain the solution. The initial application of the new approach, referred to as compact multi-frame blind deconvolution (CMFBD), was found to be significantly faster than MFBD, and showed an indication that it may be able to provide restorations of higher quality (fewer artifacts). Since its introduction, the CMFBD approach has become the foundation of several next-generation MFBD-based algorithms that have been developed for applications such as high-accuracy wave front sensing from image plane data, and imaging through strong turbulence: both of which contribute to SSA by increasing the area of sky available for surveillance. Here we show, using real and simulated imagery, that the performance of the CMFBD approach can be improved through the addition of a new "internal consistency" constraint on the estimated point-spread functions. We discuss how this improved performance might contribute to an important advance in our ability to image satellites at high spatial resolution using ground-based assets.

Imaging Through Turbulence: A Light-Field Approach

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In contrast to traditional imaging techniques, light-field imaging systems record variations in intensity from points in a scene as a function of angle. In the context of computational photography, light-field processing allows for image reconstruction from multiple viewpoints and different depths of focus. It is increasingly recognized that certain wave front sensing techniques are essentially light-field capture techniques. In this work, we compare light-field processing techniques to traditional imaging in the context of imaging through turbulence. Our goal is to understand the effect of turbulence on captured light-field and if light field processing techniques may offer a way to overcome turbulence effects that are resistant to traditional processing techniques. Specifically, we aim to understand how light field techniques may provide angular diversity to overcome the effects of extreme anisoplanatism.

High-Altitude Airborne Platform Characterisation of Adaptive Optic Corrected Ground Based Laser

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Adaptive optics can be used for more than astronomical imaging with large telescopes. The Research School of Astronomy and Astrophysics (RSAA) and the Space Environment Management Research Centre (SERC) at the Mount Stromlo Observatory in Canberra, Australia, have been developing adaptive optics (AO) for space environment management.

Turbulence in the atmosphere causes optical signals to become degraded during propagation, which reduces the effective aperture of your transmitting or receiving telescope. An AO system measures and corrects for the turbulence in the atmosphere, allowing for greater resolution of optical signals. AO can be used to correct a laser beam propagating from the ground into space, or high-altitude airborne platform. The AO system performance depends heavily on the chosen site and system design. In order to properly design and implement a cost-effective AO system to propagate a laser into orbit, we propose using high-altitude platforms to measure AO system performance directly as precursor in-orbit measurements.

SERC plan on demonstrating remote manoeuvre of an orbiting object using photon pressure from an AO corrected high power ground based laser. The manoeuvre target will be a cubesat which is instrumented and tracked to measure the applied photon pressure and resulting orbit perturbation. High-altitude airborne platforms such as weather balloons or UAVs enable us to efficiently de-risk elements of this program by validating our numerical simulations of AO system performance with actual measurements. We are then able to confidently move towards in-orbit measurement of an AO corrected ground based laser, and remote manoeuvre with photon pressure. We present simulations along with experimental results for the development of array detectors which can be used to directly measure AO system performance.

SPACE SITUATIONAL AWARENESS

Session Chairs: James "Chris" Higgins, SMC/SYGO and Robert "Lauchie" Scott, Defence R&D Canada

ESA's SSA Programme: Activities in Space Surveillance and Tracking

Tim Flohrer, Holger Krag

European Space Agency

Today, satellites and space-based systems are indispensable for the provision of critical services. Understanding and forecasting the space environment, especially space weather, near-Earth objects, space debris is needed to protect the space-based infrastructure. Space debris is among the major risks to our critical infrastructure in space. The rapidly growing number of smaller satellites and plans for deploying large constellations increase further the need for information on the space object population. Since 2009 the European Space Agency (ESA) has been undertaking a Space Situational Awareness (SSA) Program with three segments Space Weather (SWE), Near Earth Objects (NEO) and Space Surveillance and Tracking (SST). Period 3 of the program has been approved at the ESA Ministerial Council in December 2016 for the period 2017 to 2020. A total of 19 member states of ESA participate in the SSA program, of which 11 subscribed to the SST segment. In SST, the development of the technologies for detection, cataloging and follow-up of space objects, and of the derived applications for conjunction event prediction, re-entry predictions, and fragmentation event detection are considered as the first important steps towards an European SST capability. To achieve this goal, ESA is focusing on research and development, supporting national initiatives, and staying complementary with other European approaches in SST. It is expected that in Europe a demand for larger, cross-national SST components and technology developments arises to ensure interoperability of systems. Examples of planned activities are space-based SST sensors, sensor and data center processing software facilitating data exchange mechanisms, and common data processing techniques and formats. With the activities of the SSA program ESA's expertise will be further exploited in supporting the research, development, and coordination of space-related technologies in a multinational environment, and in assessing and maturing the relevant emerging technologies. We report on status and plans of ESA's SSA program in its SST domain with focus on applications and developing new technologies.

AN/FSY-3 Space Fence System – Sensor Site One/Operations Center Integration Status and Sensor Site Two Planned Capability

Peter Hack, Matt Hughes, Greg Fonder

Lockheed Martin

This paper covers two topics related to Space Fence System development: Sensor Site One/Operations Center construction and integration status – including risk reduction integration and test efforts at the Moorestown, NJ Integrated Test Bed (ITB), and the planned capability of Sensor Site Two.

The AN/FSY-3 Space Fence System is a ground-based system of S-band radars integrated with an Operations Center designed to greatly enhance the Air Force Space Surveillance network. 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 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. The 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.

Sensor Site One construction on the Kwajalein Atoll is in progress and nearing completion. The Operations Center in Huntsville, Alabama has been configured and will be integrated with Sensor Site One in the coming months. System hardware, firmware, and software is undergoing integration testing at the Mooretown, NJ ITB and will be deployed at Sensor Site One and the Operations Center. The preliminary design for Sensor Site Two is complete and will provide critical coverage, timeliness, and operational flexibility to the overall system.

Detection of Faint Companions in the Vicinity of Geostationary Satellites

Henrique Schmitt, Ellyn K. Baines, J. Thomas Armstrong, Sergio R. Restaino

Naval Research Laboratory

The detection of faint companions in the vicinity of geostationary satellites, either debris or controlled spacecraft, is an outstanding issue in the field of Space Situational Awareness. The main challenges related to the detection of these companion objects is related to their proximity to the target of interest and brightness ratio. We will discuss a novel interferometric fringe nulling technique being developed at the Navy Precision Optical Interferometer. This technique uses baseline phase observations of the target around the null crossing, where the presence of a companion manifests itself as large phase fluctuations. We will present the results of observation of binary stars, which are being used to develop the technique, as well as simulations of observations of satellites with companions, which are being used to determine the limitations of the technique and as a guide for the development of future instruments.

Empirical Real-time Dynamic Data Driven Detection & Tracking Using Detectionless and Traditional FiSSt Methods

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Autonomous search and recovery of resident space object (RSO) tracks is crucial for decision makers in SSA. This paper leverages dynamic data driven approaches to improve methodologies used in real-time detection and tracking of RSOs with a low signal-to-noise ratio (SNR). Detected RSOs are assigned to be tracked using one of two simultaneously operating algorithms. The Generalized Labeled Multi-Bernoulli filter (GLMB) tracks all RSOs above a certain SNR threshold, while a Detectionless Multi-Bernoulli filter (DMB) detects and tracks low SNR objects. The DMB filter uses a matched filtering technique to detect low SNR signals which requires filter templates. The templates for known RSOs passing through the field of view are generated using the public space object catalog. Unknown RSOs are detected using a blind matched filter by constraining the length and orientation of the templates based on the dynamics of the space objects in a given orbit regime. For dim objects, the likelihood function of the DMB can be highly non-Gaussian. Hence, the DMB filter is particle based which leads to higher computational complexity. The primary idea proposed in this paper is to balance the computational efficiency of GLMB and high sensitivity of the DMB likelihood computation by dynamically switching tracks between the two filters using a Poisson modulated Markov process for the SNR model; allowing for real-time detection and tracking. These algorithms are implemented and tested on real data of objects in the geostationary (GEO) belt using a wide field-of-view

camera (18.2 degrees). A star tracking mount is used to inertially stare at the GEO belt and data are collected for 2 hours corresponding to RSOs being observed in 48.2 degrees of the GEO belt. Preliminary results show 14-16 objects being tracked per frame, of which only half are visually observable by a human carefully examining each frame.

An Autonomous Data Reduction Pipeline for Wide Angle EO Systems

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Defence Science and Technology Laboratory

The UK's National Space and Security Policy makes it clear that the identification of potential on-orbit collisions and re-entry warning over the UK is of high importance, and is driving requirements for indigenous Space Situational Awareness (SSA) systems.

To meet these requirements several options are being examined within the UK, including the creation of a distributed network of simple, low cost commercial–off-the-shelf electro-optical sensors to support survey work and catalogue maintenance.

This paper outlines work being undertaken at Dstl to examine whether data obtained using readily-deployable equipment could significantly enhance UK SSA capability and support cross-cueing between multiple deployed systems.

To effectively exploit data from this distributed sensor architecture, a data handling system is required to autonomously detect satellite trails in a manner able to pragmatically handle highly variable target intensities, periodicity and rates of apparent motion. The processing and collection strategies must be tailored to specific mission sets to ensure effective detections of platforms as diverse as stable geostationary satellites and uncontrolled low altitude cubesats.

Data captured during the ATV-5 de-orbit trial and images captured of a rocket body break up have been employed to inform the development of a prototype processing pipeline for autonomous on-site processing. The approach taken employs tools such as Astrometry.Net and DAOPHOT from the astronomical community, together with Dstl's bespoke software and the existing Dstl model-based processor.

Interim results from the automated analysis of data collected from wide angle sensors are described, together with the current perceived limitations of the proposed system and our plans for future development.

Small and Medium Aperture Speckle Interferometry for Geostationary On-Orbit-Servicing Space Situational Awareness

Lauchie Scott

Defence R&D Canada – Ottawa

On-Orbit-Servicing (OOS) in geostationary (GEO) orbit is likely to become a space mission reality provoking new problems for the optical space surveillance community. OOS' close-proximity flight of servicer and client satellites with separations less than 1 kilometer in GEO challenge the metric measurement capabilities of medium and small aperture space surveillance instruments. This paper describes an OOS monitoring technique based on Cross-Spectrum speckle interferometry to compensate for atmospheric turbulence and measure the OOS satellites' differential relative position. Cross-Spectrum speckle interferometry, an astronomical technique developed to measure the astrometric positions of binary stars, was adapted to the geostationary OOS problem and was tested using Sloan i' observations of co-located geostationary satellites. Medium (1.6m) and small (0.35m) aperture telescopes were used to observe these satellites undergoing optical conjunctions where their apparent line-of-sight separation narrowed within 5 arcseconds. During the initial development of the Cross-Spectrum approach some weaknesses were identified where particle strikes, faint background stars, anomalous fringe orientation angles and high relative angular rates corrupt the relative position measurement process. In this paper, newly adjusted compensation techniques to remedy these issues are described and the data is reprocessed. The Cross-Spectrum's performance is shown to work well on closely-spaced GEO satellites with separations less than 3 arcseconds and evidence is shown suggesting the technique can measure satellite separations within 1.8 arcseconds.

The Ultimate Big Data Enterprise Initiative: Defining Functional Capabilities for an International Information System (IIS) for Orbital Space Data (OSD)

Robert Raygan

Integrity Applications Incorporated

Global collaboration in support of an International Information System (IIS) for Orbital Space Data (OSD) requires a global enterprise. As with many information technology enterprise initiatives attempting to corral the desires of business with the budgets and limitations of technology, Space Situational Awareness (SSA) includes many of the same challenges. 1) Adaptive / Intuitive Dash Board that facilitates User Experience Design for a variety of users. 2) Asset Management of hundreds of thousands of objects … moving at thousands of miles per hour … hundreds of miles in space. 3) Normalization and integration of diverse data in various languages, possibly hidden or protected from easy access. 4) Expectations of near real-time information availability coupled with predictive analysis to affect decisions before critical points of no return, such as Space Object Conjunction Assessment (CA). 5) Data Ownership, management, taxonomy, and accuracy. 6) Integrated metrics and easily modified algorithms for "what if" analysis. This paper proposes an approach to define the functional capabilities for an IIS for OSD. These functional capabilities not only address previously identified gaps in current systems, but also incorporate lessons learned from other big data, enterprise, and agile information technology initiatives that correlate to the space domain.

The Role of Impacts and Momentum Transfer for the Evolution of Envisat's Attitude State

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The currently proposed space debris remediation measures include the active removal of large objects and "just in time" collision avoidance by deviating the objects using, e.g., ground-based lasers. These techniques require precise knowledge of the attitude state and state changes of the target objects. In the former case, e.g. to devise methods to capture the target with a tug spacecraft, in the latter, to precisely propagate the orbits of potential collision partners, as disturbing forces like air drag and solar radiation pressure depend on the attitude of the objects. The long-term evolution of the attitude motion is, among many other causes, depending on the effects of possible impacts of debris and meteoroid, while momentum transfer from reaction wheels or other moving internal components may contribute to the root cause of the initial attitude motion. Impacts of small particles like meteoroids and space debris pieces on compact space objects are unavoidable events, which were already observed several times, e.g., on International Space Station, or rather recently on the Sentinel-1A on August 23, 2016. This paper will discuss a detailed analysis of the effects of momentum transfer from the reaction wheels and of debris and meteoroid impacts for the particular case of Envisat. Based on the physical model of Envisat and the MASTER environment model, the likelihood to have an impact-related attitude rate increase in ten years larger than selected threshold rates was determined.

Space Objects Maneuvering Detection and Prediction via Inverse Reinforcement Learning

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As space is becoming more congested and contested, inferring behavior of Space Objects (SO) from observed data (e.g. detecting and predicting adversarial SOs intention of restricting the operational space) is a critical aspect of space domain awareness. In this paper, we propose and develop a method based on inverse Reinforcement Learning (RL) to learn the behavior of SO from observed orbital motion. The behavior of SO is estimated using inverse RL to determine the reward function that each operator is using to control the spacecraft. Since SO with the capability of maneuvering are controlled to achieve a particular goal which is mission driven, maneuvering can be very subjective. Consequently, a data-driven learning approach can reveal the true goal. Additionally, it is important to determine what type of behavior SO is using and if this behavior changes. Given a set of observations, inverse RL approaches uses optimal control principles to learn what reward function is being used. The latter is intimately related to the behavior of the particular controlled spacecraft. The simplest inverse RL methodology solves for the reward function using features and weighted sum of these feature vectors. The weights determined from the inverse RL calculation are the representation for the reward function the expert is using. The estimated reward function weights can be used to determine the type of behavior mode the unit is following and to classify the model based on libraries of behavior models. In this work, we investigate the classification of behavior using the weight vectors for maneuver prediction and classification. Importantly, such weight vectors can be added to the state of SOs as a way to represent the policy that the SO is currently following and allow for the change of this policy over time and the behavior changes.

Attaining Situational Understanding in the Space Domain

Jim Foster

Lockheed Martin

The information available today in the space domain consists primarily of basic positional, mission, and status data for ground and space based assets. This data provides a necessary, but not sufficient, basis for understanding the true situation of the overall space domain. Experts analyze this information, put it into context with other ongoing events, and then make assessments of the risks posed to allied assets. The potential for unknown, unexpected, and unprecedented situations to overwhelm this manual process is increasing as the number of space faring nations and orbiting objects increases. This presentation will describe a product family called iSpace that Lockheed has created, and continues to invest in, to help tackle the problems of attaining space information more timely, deriving deeper space situational understanding from the data, and integrating components and tools generated throughout the world-wide industry to contribute towards a comprehensive space solution. We will also update the group on iSpace's usage in the Space Situational Awareness (SSA) Table Top Exercises (TTX), used to explore future SSA cooperation concepts and procedures among allied nations.

A Cloud-Based, Open-Source, Command-and-Control Software Paradigm for Space Situational Awareness

Ryan Melton, Jason M. Thomas

Ball Aerospace

With the rapid growth in the number of space actors, there has been a marked increase in the complexity and diversity of software systems utilized to support SSA target tracking, indication, warning, and collision avoidance. Historically, most SSA software has been constructed with "closed" proprietary code, which limits interoperability, inhibits the code transparency that some SSA customers need to develop domain expertise, and prevents the rapid injection of innovative concepts into these systems. Open-source aerospace software, a rapidly emerging, alternative trend in code development, is based on open collaboration, which has the potential to bring greater transparency, interoperability, flexibility, and reduced development costs. Open-source software is easily adaptable, geared to rapidly changing mission needs, and can generally be delivered at lower costs to meet mission requirements.

This paper outlines Ball's COSMOS C2 system, a fully open-source, cloud-based, command-and-control software architecture which provides several unique capabilities to move the current legacy SSA software paradigm to an open source model that effectively enables pre- and post-launch asset command and control. Among the unique characteristics of COSMOS is the ease with which it can integrate with diverse hardware. This characteristic enables COSMOS to serve as the command-and-control platform for the full life-cycle development of SSA assets, from board test, to box test, to system integration and test, to on-orbit operations. The use of a modern scripting language, Ruby, also permits automated procedures to provide highly complex decision making for the tasking of SSA assets based on both telemetry data and data received from outside sources. Detailed logging enables quick anomaly detection and resolution. Integrated real-time and offline data graphing renders the visualization of the both ground and on-orbit assets simple and straightforward.

Evaluating Options for Civil Space Situational Awareness

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In recent years, the number of active satellites and human-made orbital space debris has increased dramatically. An expansion of activities in space, as is currently being proposed by many commercial and international entities, is expected to further exacerbate the challenge of safe operations. International and commercial operators in space demand better SSA service than is currently feasible, and this demand comes at a time when the current provider of SSA services, US Strategic Command (USSTRATCOM), is under pressure to better prepare for and respond to growing space-based threats to national security. Concerned about the possibility of overextending across conflicting missions in a fiscally constrained environment, some DOD officials have publicly noted a desire to move non-national security-related SSA services out of its purview.

Responding to a request from the Federal Aviation Administration (FAA) Office of Commercial Space Transportation (AST), researchers at the IDA Science and Technology Policy Institute identified and evaluated potential approaches for providing SSA services for civil and commercial operations in space. In this paper, we present findings from a representative survey of US and international operators, as well as a survey of vendors and other providers of SSA services. Building on these surveys, we present four approaches to the provision of civil SSA services in the United States: (1) maintaining the status quo through continued provision by USSTRATCOM; (2) provision by a civil government entity; (3) industry self-provision; and (4) provision by an international organization. For each approach, we summarize the cost, if feasible to estimate, and strengths and weaknesses of the approach. We end with a recommendation on a way forward.

An Imagineering Approach to the Future of Space Situational Awareness

Rick Luce

Stellar Solutions, Inc.

It is widely accepted that space is becoming a more congested, contested, and competitive domain. This drives a need not only to track space objects but also to have a clear and constant picture of what the objects are and how they are being operated.

Space situational awareness, like most mission areas, suffers from the need to maintain aging, increasingly fragile legacy infrastructure and at the same time acquire increasingly complex materiel solutions that often fall behind schedule and over budget. Imagineering, the name for both the process by which Disney creates new theme park experiences and the corporate division that does the work, offers some new ways of thinking about balancing these needs and providing better bang-for-the-buck.

Through a series of personal anecdotes that illustrate key concepts of Imagineering, this paper supports a conclusion that a new way of thinking about the space situational awareness mission area will be needed to ensure mission success moving forward.

POSTERS

Characterization of Hypervelocity Impact Debris from the DebriSat Tests

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The DebriSat program consisted of 3 hypervelocity impact tests conducted in 2 Torr of air with 7 km/s, 600 g aluminum projectiles. In the first test, Pre Preshot, the target consisted of multiple layers of fiberglass, stainless steel and Kevlar fabric. No soft catch foam was used. The subsequent two tests, DebrisLV and DebriSat, were designed to simulate hypervelocity impacts with a launch vehicle upper stage and a modern LEO satellite, respectively. The interior of the chamber was lined with soft catch foam to trap break-up fragments. In all three tests, witness plates were placed near the target to sample impact debris and determine its reflectance, composition and spectral properties. Reflectance measurements are important for calculating the size of orbital hypervelocity impact fragments. The debris from the Pre Preshot test consisted of a two phase mixture formed from solidified molten silicate and steel droplets. Individual droplets ranged from 100 μm to 10 nm. The reflectance of witness plates dropped from 95% to 20-30% as a result of the debris. Debris collected on witness plates in the DebrisLV and DebriSat tests consisted of μm to nm-sized solidified molten metallic droplets in a matrix of condensed vaporized soft catch. Disordered graphitic carbon was also detected. The reflectance of debris-covered witness plates dropped from 95% to 5%. The dramatic decrease in reflectance for hypervelocity impact debris is attributed to the effect of scattering from μm to nm sized solidified molten metallic droplets and the presence of graphitic carbon, when organics are present. The presence of soft catch in the later tests and the high organic content with graphitic carbon in the debris appear to be responsible for this much lower post-test reflectance. Understanding orbital debris reflectance is critical for estimating size and determining debris detectability.

A Deep Machine Learning Algorithm to Optimize the Forecast of Atmospherics

Randall Alliss

Northrop Grumman

Space based applications from imaging to optical communications are impacted by the atmosphere. Specifically the occurrence of optical turbulence and clouds impact whether an imaging or optical communication mission will be a success. For example, for space based imaging applications, clouds will produce atmospheric transmission losses rendering an electro-optical platform unable to image its target. It is desirable to accurately predict the occurrence of negative atmospherics on such systems so alternative resource scheduling can be made.

The present study seeks to revolutionize our understanding of and our ability to predict such atmospheric events through the mining of output from a high resolution numerical weather prediction model. Since atmospherics are inherently a spatial-temporal phenomenon, mining such data requires an efficient model capable of representing and reasoning about complex spatial-temporal dynamics. This study investigates the potential of the random forecasts (RF) ensemble classification and regression technique to improve cloud forecasts based on physical properties of the atmosphere including temperature, humidity, winds and pressure. RF models contain a combination of characteristics that make them well suited for its application in cloud forecasting. One of the key characteristics of the RF is the ability to capture non-linear association of patterns between predictors (the physical quantities of the atmosphere described above) and the predictand (clouds), which becomes critical when dealing with the complex non-linear occurrence of clouds. The development of an RF model for the prediction of clouds takes place in three steps. First, a tuning

study is performed to customize each of the RF models. For example, the diurnal variation in clouds has to be treated differently due to the different dynamical and thermo dynamical processes that occur as a function of time of day. Second, The RF models are trained using the optimum values for the number of trees and number of randomly chosen predictor variables found during the tuning phase. Finally, the RF models are used to predict the occurrence of clouds using an independent validation dataset so as to prevent the hindsight bias. The results are validated against in situ observations of clouds.

The input dataset is derived from a year of cloud forecasts generated using a high resolution Numerical Weather Prediction (NWP) Model over Maui including Haleakala. The NWP model is a fully 3D physics based model of the atmosphere initialized with atmospheric gridded data obtained from a global scale model. The global model input data has a horizontal resolution of approximately 25km, which is insufficient for the desired atmospheric forecasts required at near 1km resolution. Therefore, a variational data assimilation (DA) system is used to improve in quality and resolution the initial conditions first prescribed by the global model. Data used by the DA system are local surface observations of temperature, pressure, winds and moisture (also known as the Standard Meteorological Variables, SMV), local vertical soundings of SMV and local radar reflectivities from the National Weather Service NEXRAD radar network. The validation dataset is derived from a high resolution satellite remote sensed cloud dataset augmented by surface observations of clouds from Haleakala, HI. The RF model will be trained and tuned on approximately one-half the input dataset and evaluated on the remaining six months. Results from this study will be presented at the conference.

SPIDER: First Extended Scene Images

Katherine Badham[1], Alan L. Duncan[1], Richard L. Kendrick[1], Chad Ogden[1]. Danielle Wuchenich[1], Guy Chriqui[1], Samuel T. Thurman[1], Tiehui Su[2], S. J. B. Yoo[2]

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The Lockheed Martin Advanced Technology Center (LM ATC) and the University of California at Davis (UC Davis) are developing an electro-optical (EO) imaging sensor called SPIDER (Segmented Planar Imaging Detector for Electro-optical Reconnaissance) that seeks to provide 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.

Our SPIDER imager replaces the traditional optical telescope and digital focal plane detector array with a densely packed interferometer array based on emerging photonic integrated circuit (PIC) technologies that samples the object being imaged in the Fourier domain (i.e., spatial frequency domain), and then reconstructs an image. Our approach replaces the large optics and structures required by a conventional telescope with PICs that are accommodated by standard lithographic fabrication techniques (e.g., complementary metal-oxide-semiconductor (CMOS) fabrication). The standard EO payload integration and test process that involves precision alignment and test of optical components to form a diffraction limited telescope is, therefore, replaced by in-process integration and test as part of the PIC fabrication, which substantially reduces associated schedule and cost. In this paper we describe the photonic integrated circuit design and the testbed used to create the first images of extended scenes. We summarize the image reconstruction steps and present the final images. We also describe our next generation PIC design for a larger (16x area, 4x field of view) image.

A Space Object Detection Algorithm Using Fourier Domain Likelihood Ratio Test

David Becker, Dr. Stephen Cain

Air Force Institute of Technology

Space object detection is of great importance in the highly dependent yet competitive and congested space domain. Detection algorithms employed play a crucial role in fulfilling the detection component in the situational awareness mission to detect, track, characterize and catalog unknown space objects. Many current space detection algorithms use a matched filter or a spatial correlator to make a detection decision at a single pixel point of a spatial image based on the assumption that the data follows a Gaussian distribution. This paper explores the potential for detection performance advantages when operating in the Fourier domain of long exposure images of small and/or dim space objects from ground based telescopes. A binary hypothesis test is developed based on the joint probability distribution function of the image under the hypothesis that an object is present and under the hypothesis that the image only contains background noise. The detection algorithm tests each pixel point of the Fourier transformed images to make the determination if an object is present based on the criteria threshold found in the likelihood ratio test. Using simulated data, the performance of the Fourier domain detection algorithm is compared to the current algorithm used in space situational awareness applications to evaluate its value.

Simultaneous Hyperspectral Measurements of Space Objects with a Small Format System

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Under an AFRL/RYMT effort, Sensing Strategies, Inc. is developing a small format system for collecting spectral data from satellites to support space situational awareness missions. The system uses a slitless spectrometer and a modified pan/tilt stage to point the spectrometer. The system's goal is to collect signatures with significantly higher spectral resolution than traditional methods that use astronomical filters for multi-spectral measurements. In addition, the spectra are collected simultaneously rather than collecting multi-spectral data sequentially in different bandpasses. The spectral data is being evaluated for its utility to uniquely classify or categorize satellites. This paper will present preliminary measurements of satellites and discuss observations on how the spectral data can improve SSA functions.

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Rotation State Evolution of Retired Geosynchronous Satellites

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With the growing value of geosynchronous orbit for communications and observation, understanding the motion of retired geosynchronous satellites is all the more important. While their orbital evolution has been extensively studied, little is understood about their rotational dynamics. However, many retired geosynchronous satellites are known to have fast or evolving spin states. Albuja et al. hypothesized that the observed evolution is largely driven by solar radiation through the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect and that satellites alternate between periods of uniform and tumbling motion. We aim to explore this hypothesis through analysis of light curve observations. Better knowledge of retired satellite

rotational motion stands to improve attitude dependent solar radiation pressure modeling and aid on-orbit debris mitigation and recycling efforts.

Here we conduct tumbling light curve rotation state analysis for several retired geosynchronous satellites. These particular satellites have been observed periodically at the Maui Research and Technology Center as well as Magdalena Ridge and Lowell Observatories since 2013. Two fundamental periods define tumbling motion, one corresponding to rotation around an extremal principal axis and the second to precession of this axis about the rotational angular momentum vector. To extract tumbling periods from the light curves, Fourier transforms and two-dimensional Fourier series fits were used. Torque-free dynamics and the satellites' known moments of inertia were then leveraged to filter and validate candidate periods. Finally, simulated light curves were generated using representative shape models for further validation. Analysis of several tumbling light curves shows that the GOES-8 satellite has transitioned from uniform rotation with a period of 16.83 seconds in 2013 to increasingly complex tumbling motion with fundamental periods of 5-20 minutes in 2016. These findings agree with the YORP predictions of Albuja et al., supporting their hypothesis that the YORP effect drives retired geosynchronous satellite rotation state evolution.

Australian Space Situational Awareness Capability Demonstrations

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Australia is increasing its contribution to the global space situational awareness (SSA) problem by committing to acquire and operate SSA sensors. Over the last year, a series of collaborative SSA experiments have been executed to demonstrate the capabilities of indigenous Australian sensors in the optical and radar regimes. These experiments aimed to demonstrate Australian SSA assets and prove passive radar's capability to observe LEO satellites and perform SSA handoffs to optical sensors. Furthermore, the trials established a data sharing and communications protocol that bridged defense, academia, and industry partners. Geographically dispersed optical assets, including the Falcon telescope (Canberra), Raven telescopes (Exmouth, West Australia), and DST Telescopes (Adelaide), collected on LEO satellites and established cueing protocols. The Murchison Widefield Array (MWA) located in Western Australia, demonstrated the capability of passive radar as an SSA asset after successful observing LEO satellites based on reflected FM radio and Digital TV signals. The combination of radar and optical SSA assets allows for the exploitation of each sensors unique advantages and a diversity of locations across the Australian continent. This paper outlines the capabilities and diversity of indigenous Australian optical and radar sensors as demonstrated by field trials in 2016 and 2017. It also suggests future potential for harnessing novel radar and optical integration techniques to supplement high-value assets such as the SST as part of the Space Surveillance Network.

Larger Optics and Improved Calibration Techniques for Small Satellite Observations with the ERAU OSCOM System

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OSCOM, Optical tracking and Spectral characterization of CubeSats for Operational Missions, is a system capable of providing time-resolved, high frame rate satellite photometry using commercial-off-the-shelf (COTS) hardware and custom tracking and analysis software. This system has acquired photometry of objects as small as CubeSats using a Celestron 11" RASA and an inexpensive CMOS machine vision camera. For satellites with known shapes, these light curves can be used to verify a satellite's attitude and the state of its deployed solar panels or antennae. While the OSCOM system can successfully track satellites and produce light curves, there is on-going improvement towards increasing its automation and efficiency while supporting additional mounts and telescopes. A newly acquired Celestron 14" Edge HD can be used with a Starizona Hyperstar to increase the SNR for small objects as well as extend beyond the limiting magnitude of the 11" RASA. OSCOM currently corrects instrumental brightness measurements for satellite range and site average atmospheric extinction, but calibrated absolute brightness is required to determine information about satellites other than their spin rate, such as surface albedo. A calibration method that automatically detects and identifies background stars can use their catalog magnitudes to determine the absolute brightness of the satellite in the image. We present photometric light curves from both the 14" Edge HD and 11" RASA optical systems as well as plans for a calibration method that will perform background star photometry to efficiently determine absolute satellite brightness in each frame

Satellite Characterization Data Collection and Analysis

David Richmond, Jeff Brennan

Lockheed Martin

Techniques for improved characterization of Satellites have been an area of research for several years. Our team evaluated Optical characterization techniques in 2015 and expanded to radar, signals and infra-red phenomenology 2016. In this paper our efforts to collect optical, radar and signal data for satellite characterization and Pattern of Life understanding will be covered. Algorithmic approaches to fuse data from multiple phenomenology will be identified to include rapidly re-acquiring objects after a maneuver, estimation of available fuel, and power profile considerations. Tip and Queue points between collectors necessary to implement the multi phenomenology data fusion algorithms will be identified. The benefits of such information will be discussed, to include anomaly resolution, and positional understanding.

Optical Ground Based Space Surveillance Obscured Sky Mitigation

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Space Situational Awareness (SSA), especially in deep space, has long relied on the contribution from ground based optical sensors. It is, also, widely recognized that terrestrial based astronomical and space track telescopes are subjected to weather constraints. Consequently, the Ground Based Electro Optical Deep Space Surveillance (GEODSS) telescope constellation is limited in its mission capability by impacting atmospheric circumstance and subsequently implemented weather restrictions on telescope operations. While it is recognized that weather will always play a limiting role to the GEODSS mission, site personnel

have initiated efforts to reduce the impact of these conditions. Working with Air Force Space Command and its C2 interface, a collaborative effort has been directed at this liability. As a result, strategies have been developed and implemented through extensive testing that have resulted in measures that can be imposed to minimize the space track mission impact of weather. Currently, weather is factored in three areas of consideration, humidity, winds and visibility. When completely clouded in or, 0% star visibility is perceived in the field of regard, the domes are closed and the telescopes sit idle in a condition referred to as red weather operations capability (RED OPSCAP). This state is determined based on input from an infrared sensor located in the center of the facility roof and through the perception of the human eye in the form of an onsite crew member. Two issues exist within which visibility is defined. The first is the sensitivity of the GEODSS optical system in comparison to the infrared sensor. Both look at an entirely different spectrum of light. The second is the human eye and its limited collection surface as opposed to the light collection ability of the GEODSS telescope. Testing has, so far, revealed that the GEODSS telescopes are extremely adept at detecting the reflected sun light off of orbital bodies in a completely cloud obscured environment. Thus, by continuing to collect satellite tracks until the cloud density precludes any such activity, versus, terminating data collection when complete cloud coverage occurs, the GEODSS telescope provides a significant increase in data to the SSA community. While it is very difficult to determine the vertical cloud stratification, thus far, data collected in these circumstances has always proven useable. In fact, as the Air Force C2 user evaluates the accuracy of the data collected through the obscure sky testing, it is finding surprisingly accurate metric collections. All factors considered, this augmented operational availability will improve SSA through increased satellite detection and catalog updates.

Looking Down Through Clouds

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Detecting and identifying nuclear explosions in the atmosphere and on the surface of the Earth is important for the Air Force Technical Applications Center (AFTAC) treaty monitoring mission. Optical signals, detected by satellite sensors, from surface or atmospheric nuclear explosion are attenuated by real-time atmosphere and clouds. For this study, the source used is lightning, which has a rapid initial rise time and is a reasonable surrogate for a nuclear explosion. Determining the attenuation for each optical ray-path is uniquely dependent on the source geolocation, the specific optical transmission characteristics along that ray path, and sensor detection capabilities. Determining that optical ray-path attenuation is the topic of this presentation. We will discuss an AFTAC and AFIT team effort to fuse worldwide weather data, from a variety of sources, to provide the wavelength dependent optical attenuation from the source to the satellite. Of particular interest for this study is in measuring attenuation due to clouds, in near real-time and with high spatial resolution. AFIT has developed a means to model global clouds using “Weather Cubes”. Meteorological models to be included range from global-scale models loosely coupled with attenuation codes to regional scale weather forecast models that are tightly integrated with attenuation models. Results evaluating attenuation algorithms with a suite of meteorological forecast models will be presented. Expected final products of this work include validation of received optical signal characteristics and source geolocation solutions

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Can LEO Conjunction Warnings Become a Viable Business?

Joseph Carroll

Tether Applications, Inc.

It is hard to create a commercially viable conjunction warning service if a government agency gives away a similar service paid for out of general funds. But it is possible, especially if the commercial service has much higher value.

One can add value by providing more accurate warnings. Conjunction warnings do not actually warn of collisions, but rather tiny chances of collisions. If 2D conjunction uncertainties are 100-1000X larger than typical satellite dimensions, then chances of collisions are in the 1-100 ppm range. The main payoff of smaller uncertainties is reducing how many conjunctions operators should react to. In fact, “actionable conjunction warnings” might best be defined as warnings accurate enough that ignoring them will on average cost more than acting on them. The cost of an avoidance maneuver may be ~10-100 ppm the cost of losing a satellite, so making warnings actionable may require substantial reductions in conjunction uncertainties.

One can even multiply the value of warnings by a factor of up to 100, by warning of collisions with far more objects. The US tracks and catalogs most LEO objects >10 cm, including ~9000 tracked LEO fragments. Its new S-band fence may drop this threshold to ~5 cm. But most LEO satellite losses will come from hypervelocity impacts by ~1E6 now-untracked cm-class objects.

This paper argues that it appears feasible to use ground-based telescopes to find and track most cm-class LEO objects and provide actionable conjunction warnings, and that observation and prediction services might provide enough value to operators to be commercially viable. It also argues that observation and prediction services should be distinct organizationally for liability reasons, that object discoveries can be “crowd-sourced” and paid for by bounty payments, and that pricing of both discovery bounties and update observations can be automated.

Combined SSA Sensor Tasking for Space-to-Space and Ground-to-Space

Ken Center, Alex Herz, Ella Herz,Josh Neel, Marc Simpson

Orbit Logic

Comprehensive and persistent Space Situational Awareness is best achieved when the sensors employed for observations and searches are coordinated to eliminate duplication of effort and to maximize the utility of the information that can be extracted from the resulting data products. The desired results of sensor tasking optimization is; 1) to better maintain custody of objects of interest, 2) to detect object changes as quickly as possible, and 3) to maximize the discovery and tracking of new uncorrelated objects. All objectives must be balanced for overall SSA efficacy.

Effective approaches toward achieving the objectives summarized above frequently involve both ground-based and space-based sensors. Each of these sensor categories has inherent strengths and weaknesses (each is subject to its own operational constraints), but a well-planned utilization of both can result in a highly effective overall capability.

Orbit Logic has developed a unique system that solves the difficult problem of optimizing the tasking schedules of ground-to-space and space-to-space SSA sensors. The framework is highly configurable using web-based interfaces, allowing models of ground- or space-resident sensors to be parameterized, orbital objects to be specified, search areas to be defined, and an SSA-specific figure of merit (FOM) to be dynamically tuned to mission operational needs. The latter allows the generated sensor tasking schedules to best meet the current operational priorities.

The system has recently received enhancements to its advanced planning algorithms to optimize the distribution of tasks over all assets of a specific sensor class (space or ground), resulting in significant improvement of the FOM results, especially for large numbers of custody objects and search cells. The validated schedules honor not just access constraints, but factor in ground site weather, object observability relative to the selected sensor, sensor performance limitations, and (when possible) serendipitous collections of multiple objects.

Non-traditional Sensor Tasking for SSA: A Case Study

Alex Herz[1], Ella Herz[1], Ken Center[1], Isabel Martinez[1], Nick Favero[1], Clint Clark[2], Mark Jeffries[2]

[1]Orbit Logic, [2]ExoAnalytic

Industry has recognized that maintaining SSA of the orbital environment going forward is too challenging for the government alone. Consequently, there are a significant number of commercial activities in various stages of development standing-up novel sensors and sensor networks to assist in SSA gathering and dissemination. Use of these systems will allow government and military operators to focus on the most sensitive space control issues while allocating routine or lower priority data gathering responsibility to the commercial side.

The fact that there will be multiple (perhaps many) commercial sensor capabilities available in this new operational model begets a common access solution. Absent a central access point to assert data needs, optimized use of all commercial sensor resources is not possible and the opportunity for coordinated collections satisfying overarching SSA-elevating objectives is lost.

Orbit Logic is maturing its Heimdall Web system - an architecture facilitating “data requestor” perspectives (allowing government operations centers to assert SSA data gathering objectives) and “sensor operator” perspectives (through which multiple sensors of varying phenomenology and capability are integrated via machine-machine interfaces). When requestors submit their needs, Heimdall’s planning engine determines tasking schedules across all sensors, optimizing their use via an SSA-specific figure-of-merit.

ExoAnalytic was a key partner in refining the sensor operator interfaces, working with Orbit Logic through specific details of sensor tasking schedule delivery and the return of observation data. Scant preparation on both sides preceded several integration exercises (walk-then-run style), which culminated in successful demonstration of the ability to supply optimized schedules for routine public catalog data collection – then adapt sensor tasking schedules in real-time upon receipt of urgent data collection requests.

This paper will provide a narrative of the joint integration process - detailing decision points, compromises, and results obtained on the road toward asset of interoperability standards for commercial sensor accommodation.

Design and Efficiency Analysis of Operational Scenarios for Space Situational Awareness Radar System

Eun Jung Choi, Sungki Cho, Jung Hyun Jo, Jang-Hyun Park

Korea Astronomy and Space Science Institute

The need to secure technology for space situational awareness is on the rise to protect the safety of the people and space assets from space hazards. According to the “Preparedness Plan for Space Hazards”, the main mission is to build the surveillance and tracking capacity of space objects that are likely to re-enter the Earth, or space objects that are likely to collide with the domestic satellites. Building up this capability is possible with optical and radar sensors, which are the technical components for space situation awareness system. Especially, radar system in combination with optical sensors network plays an outstanding role for space situational awareness system. At present, OWL-Net (Optical Wide-field patroL Network) optical system which is the only one space situational awareness infrastructure in Korea is very limited in all-weather and observation time. Therefore, development of radar system capable of continuous operation is becoming an essential space monitoring element. Therefore, for an efficient space situational awareness system at the current state of our own technology, radar development strategy should be considered. The purpose of this paper is to analyze the efficiency of radar system for detection and tracking of space objects as the operational scenarios. Through the efficiency analysis and trade-off study, the key parameters of the radar system are designed. The radar detection and tracking characteristics with system level modeling and simulation according to the trajectory of the space objects are investigated. As a result, this research will provide the guideline for the development of the national space situational awareness system and it is expected to be used for the conceptual design of radar system.

Orbit Determination Results and Space Debris Test Observation of the OWL-Net

Jin Choi, Jung Hyun Jo, Myung-Jin Kim, Dong-Goo Roh, Hong-Suh Yim

Korea Astronomy and Space Science Institute

Korea Astronomy and Space Science Institute has developed the Optical Wide-field patroL-Network (OWL-Net) for maintaining the domestic Low Earth Orbit satellites’ ephemeris and monitoring Geostationary Earth Orbit region. It also can be used to observe space debris or natural space objects. The orbit determination process was planned with batch least square orbit estimator for every week. We attempted to compare the test operation results with Two Line Elements and CPF files to validate the system. This results can be used to estimate the performance of the OWL-Net operations. And also we present the photometric analysis result for observation of the Astro-H debris. We got the dozens of photometric data of the Astro-H debris main part for a few seconds with the chopper system last year. We calculated the main rotation period and compared it with other’s result.

Determining Relative Power Capacities of Geosynchronous Satellites

Daniel Weisz, Francis Chun

USAF Academy

Cadets and faculty in the Department of Physics, United States Air Force Academy have been refining the technique of slitless spectroscopy as a means to analyze the spectra from geostationary satellites. In this paper, four seasons of glints were observed and analyzed for multiple stable communication satellites, as measured across the visible spectrum using a 100 lines per millimeter diffraction grating. It is clear from the results that the glint maximum wavelength decreases relative to the time periods before and after the glint, and that the spectral reflectance during the glint is less like a blackbody. This is consistent with the presumption that solar panels are the predominant source of specular reflection. The glint spectra are also quantitatively compared to different blackbody curves and the solar spectrum by means of absolute differences. We believe that spectral measurements of satellite glints offer us the opportunity to determine the relative power capacity of a variety of satellite manufacturers and their spacecraft buses.

Joint Estimation of Sensor Drift and Space Object Tracking with Single-cluster PHD Filters

Mark Campbell, Emmanuel Delande, Isabel Schlangen, Daniel Clark,

Heriot Watt University

With the increasing reliance on space-based infrastructure, there is a commensurate increasing demand for methods for tracking objects in orbits to prevent damage from collisions. Methods for target tracking require some knowledge of models for the motion of a target, the projection of its state onto the sensor, and the related uncertainty in these models. The problem is compounded when there is a drift in the sensor co-ordinate frame. This paper presents applications of multi-object filtering algorithms, known as single-cluster PHD filters, for jointly estimating the drift of the sensor and the motion of moving objects.

Training the Next Generation in Space Situational Awareness Research

Sameep Akhil Arora, Ryan Scott Bronson, Damon Colpo, Evelyn Hunten, Lindsie Jeffries, Scott Tucker, Doug May, Vishnu Reddy

University of Arizona

Traditional academic SSA research has relied on COTS systems for collecting metric and lightcurve data. COTS systems have several advantages over a custom built system including cost, easy integration, technical support and short deployment timescales. We at the University of Arizona took an alternative approach to develop a sensor system for space object characterization. Five engineering students designed and built two 0.6-meter F/4 electro-optical systems for collecting lightcurve and spectral data. All the design and fabrication work was carried out over the course of two semesters as part of their senior design project that is mandatory for the completion of their bachelors in Engineering degree. The students designed over 200 individual parts using three-dimensional modeling software (SolidWorks), and conducted detailed optical design analysis using raytracing software (ZEMAX), with oversight and advice from faculty sponsor and Starizona, a local small business in Tucson. The components of the design were verified by test, analysis, inspection, or demonstration, per the process that the University of Arizona requires for each of its design projects. Methods to complete this project include mechanical FEA, optical testing methods (Focault Knife Edge Test and Couder Mask Test), tests to verify the function of the thermometers, and a final

pointing model test. A surprise outcome of our exercise is that the entire cost of the design and fabrication of these two EO systems was significantly lower than a COTS alternative. With careful planning and coordination we were also able to reduce to the deployment times to those for a commercial system. Our experience shows that development of hardware and software for SSA research could be accomplished in an academic environment that would enable the training of the next generation with active support from local small businesses.

Satellite and Debris Characterisation in LEO and GEO Using Adaptive Optics

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Australian National University & Space Environment Research Centre

Space debris poses a significant risk to space operations due to the potential of Kessler Syndrome. The Research School of Astronomy and Astrophysics (RSAA) at the Australian National University (ANU) is developing ground based adaptive optics (AO) systems for satellite and debris imaging. A ground based optical system featuring AO can allow detailed characterisations of objects in low Earth orbit (LEO) and accurate positional measurements of objects in geostationary Earth orbit (GEO). We have developed an AO system for imaging satellites and debris on a 1.8 m telescope at Mt Stromlo Observatory. We will present the final optical design of the system and results of initial lab testing.

The AO system gives the capability to resolve objects 50 cm in size at a range of 800 km and imaging wavelength of 800 nm. This resolution allows specific features such as satellite bodies and solar panels can be observed, which can be used to improve models of satellite and debris orbits for improved collision predictions. The system is capable of operating in natural guide star (NGS) or laser guide star (LGS) modes. Operating in the LGS mode allows for fainter and thus smaller objects to be imaged as a wider wavelength range can be used by the imaging camera.

Photometric Analysis of Small Momentum Impulse Transfer Events

Phillip Cunio, Michael Bantel, Brien Flewelling, Douglas Hendrix, William Therien

ExoAnalytic Solutions

Precise orbit determination (OD) is essential for Space Situational Awareness (SSA) and Space Traffic Management. OD models directly impact propagated orbit accuracy, which drives collision assessments (COLAs) and impels responses to potential collisions. To improve tracking of Resident Space Objects (RSOs), ExoAnalytic Solutions uses a global network of ground-based telescopes annually to collect 80+ million correlated astrometric and photometric measurements of active and inactive RSOs in geosynchronous Earth orbit (GEO) and the near-GEO region.

Precision OD analysis reveals occasional momentum impulse transfer events (MITEs) with detectable in-track velocity changes as small as 1 mm/s. In several cases, observed MITEs were explained by using a two-parameter asymmetric radiation pressure acceleration that significantly improved the OD fit to observations during and after equinox seasons when the RSO traversed Earth's umbra.

Using this 9-parameter model, OD applied over 700 days of observations yielded orbit residuals of 1-3 km. Interestingly, there was discernible structure in the residuals, possibly attributable to an incomplete or a slowly-varying solar radiation pressure model. Perhaps recently-defunct RSOs have more pronounced residual structure, as their initial spin characteristics are equilibrating to the space environment; whereas

older RSOs (e.g., rocket bodies from prior decades), may have closer fits as they no longer evolve in response to exposure in space.

This hypothesis is examined by analyzing changes in photometric measurements of RSOs in order to drive dynamic updates to the radiation pressure model. A small suite of RSOs with extensive data are assessed as to whether they exhibit a changing orientation or surface features, and then these alterations (if any) are correlated to observable effects in the orbit-fit residuals over long durations. The correlation provides a verification for likely long-term evolution of orbits for RSOs which transition from alive states to inactive states as a natural part of their lifecycles.

Satellite Articulation Characterization from an Image Trajectory Matrix using Optimization

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Autonomous on-orbit satellite servicing and inspection benefits from an inspector satellite that can autonomously gain as much information as possible about the primary satellite. This includes performance of articulated objects such as solar arrays, antennas, and sensors. This paper presents a method of characterizing the articulation of a satellite using resolved monocular imagery. A simulated point cloud representing a nominal satellite with articulating solar panels and a complex articulating appendage is developed and projected to the image coordinates that would be seen from an inspector following a given inspection route. A method is developed to analyze the resulting trajectory matrix. The developed method takes advantage of the fact that the route of the inspector satellite is known to assist in the segmentation of the points into different rigid bodies, the creation of the 3D point cloud, and the identification of the articulation parameters. Once the point cloud and the articulation parameters are calculated, they can be compared to the known truth. The error in the calculated point cloud is determined as well as the difference between the true workspace of the satellite and the calculated workspace. These metrics can be used to compare the quality of various inspection routes for characterizing the satellite and its articulation.

Improved Orbit Determination of LEO CubeSats: Project LEDsat

James Cutler[1], Patrick Seitzer[1], Chris H. Lee[1], Robert Gitten[1], Fabrizio Piergentili[2], Fabio Santoni[2], Alice Pellegrino[2], Tommaso Cardona[2], Donald Bedard[3], Thomas Schildknecht[4], Heather Cowardin[5]

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Project LEDsat is an international project (USA, Italy, and Canada) designed to improve the identification and orbit determination of CubeSats in low Earth orbit (LEO). The goal is to fly CubeSats with multiple methods of measuring positions on the same spacecraft: GPS, optical tracking, satellite laser ranging (SLR), and radio tracking. These satellites will be equipped with light emitting diodes (LEDs) for optical tracking while the satellite is in Earth shadow. It will be possible to compare the orbits determined from different methods to examine the systematic and random errors associated with each method. Furthermore, if each LEDsat has a different flash pattern, then it will be possible to distinguish closely spaced satellites shortly after deployment. The Sapienza University of Rome 3U CubeSat URSA MAIOR with LEDs and retro-reflectors was launched in June 2017 and is working on orbit. Sapienza has designed a 1U CubeSat follow-on mission dedicated to LED tracking, which was selected for possible launch in 2018 in the European Space Agency's (ESA) 'Fly Your Satellite' program. The University of Michigan is designing a 3U version with LEDs, GPS receiver, SLR, and radio tracking. The Royal Military College of Canada (RMC) is leading a Canadian effort for a LEDsat mission as well. All three organizations have a program of testing LEDs for space use to predict the effects of the LEO space environment.

GEO Optical Data Association with Concurrent Metric and Photometric Information

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Data association in a congested area of the GEO belt with occasional visits by non-resident objects can be treated as a Multi-Target-Tracking (MTT) problem. For a stationary sensor surveilling the GEO belt, geosynchronous and near GEO objects are not completely motionless in the earth-fixed frame and can be observed as moving targets. In some clusters, metric or positional information is insufficiently accurate or up-to-date to associate the measurements. In the presence of measurements with uncertain origin, star track residuals and other sensor artifacts, heuristic techniques based on hard decision assignment do not perform adequately. In the MMT community, Bar-Shalom [1] was first in introducing the use of measurements to update the state of the target of interest in the tracking filter, e.g. Kalman filter. Based on Shalom's idea, we use the Probabilistic Data Association Filter (PDAF) but to make use of all information obtainable in the measurement of three-axis-stabilized GEO satellites, we combine photometric with metric measurements to update the filter. Therefore, our technique Concurrent Spatio-Temporal and Brightness (COSTB) has the stand-alone capability of associating a track with a unique identity, if the tracked object is resident. That is possible because the light curve of a stabilized GEO satellite changes minimally from night to night. We exercised COSTB on the high-cadence and decimated cadence data, collected with a COTS camera wide field sensor, to associate measurements, correct mistags and detect non-residents in a simulated near real time cadence. Data on GEO clusters were used. (1) Yaakov Bar-Shalom, Fred Daum and Jim Huang, The probabilistic data association filter, IEEE Control Systems, Volume: 29 Issue: 6, 2009.

Autonomous Orbit Propagation for GPS Equipped Cubesats

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This paper presents the computational performance and implementation of the analytic Vinti algorithm for autonomous orbit propagation for GPS equipped CubeSats. Since the Vinti7 orbit propagator (Vinti7 OP) predicts directly with the GPS ECI state vector as input, orbit propagation is much simplified. Also periodic uplinks of the NORAD TLEs, which consume a relatively large amount of Cubesat power and incur costly ground operations, are no longer needed. The problematic conversion of osculating orbital elements (ECI state vectors) to mean orbital elements, which is required only for SGP4, is also not needed. If the time between two GPS locks is two days or less, then Vinti predictions are on average just as accurate as, if not better than, those of SGP4 for most satellites in the TLE catalog. However, the Vinti7 OP is extremely robust, which is essential for autonomous orbit propagation and unmatched by any other analytic orbit propagator.

This paper discusses the capabilities, inputs and outputs requirements of the TLE/SPG4 and GPS/Vinti7 with special attention paid to singularity, convergence issues and practicalities when applied to small satellite operations. Comparison of OP position errors for two days between SGP4 and Vinti7 for a range of orbit regimes is presented. Also comparison of OP position errors between GPS locks with real GPS data over multiple days for a typical Cubesat orbit using the two-body, AGIJ2, SGP4 and Vinti7 algorithms is included.

We document an implementation of the Vinti7 OP in the flight software (FSW) of the JPL-Stanford LMRST-Sat CubeSat. We characterize the code size and complexity of the Vinti7 OP as implemented on a typical nanosatellite-class single-chip 16-bit MCU, and show how the LMRST-Sat FSW acquires occasional GPS locks, applies the appropriate transformations and feeds them to the Vinti7 OP for state vector predictions. The power consumed by the GPS receiver to achieve GPS lock and that required by the Vinti7 implementation to propagate an orbit are also compared.

Recent Developments in Shadow Imaging

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Integrity Applications Incorporated

Shadow imaging is a technique to obtain highly resolved silhouettes of resident space objects (RSOs) which would otherwise be unattainable using conventional terrestrial based imaging approaches. This is done by post processing the measured irradiance pattern (shadow) cast onto the Earth as the RSO occults a star. The research presented here focuses on recent developments in shadow imaging of geosynchronous (GEO) satellites with near stationary orbits approximately 36,000 km from the Earth. A high fidelity shadow prediction tool is presented and verified using data collects taken by small aperture Raven class telescopes. The morphology of shadow densities on the Earth is shown in the context of the local galactic orientation over the course of a year, and is used to explore advantageous collection system location.

Spectroscopic Characterization of GEO Satellites with Gunma LOW Resolution Spectrograph

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The spectroscopic observation is potentially a powerful tool for understanding the Geostationary Earth Orbit (GEO) objects. We present here the results of an investigation of energy spectra of GEO satellites obtained from a ground-based optical telescope. The spectroscopic observations were made from April to June 2016 with the Gunma LOW resolution Spectrograph and imager (GLOWS) at the Gunma Astronomical Observatory (GAO) in JAPAN. The observation targets consist of eleven different satellites: two weather satellites, four communications satellites, and five broadcasting satellites. All the spectra of those GEO satellites are inferred to be solar-like. A number of well-known absorption features such as H-alpha, H-beta, Na-D, water vapor and oxygen molecules are clearly seen in the wavelength range of 4,000 - 8,000A. For comparison, we calculated the intensity ratio of the spectra of GEO satellites to that of the moon which is the natural satellite of the earth. As a result, the following characteristics were obtained. 1) Some variations are seen in the strength of absorption features of water vapor and oxygen originated by the telluric atmosphere, but any other characteristic absorption features were not found. 2) For all observed satellites, the intensity ratio of the spectrum of GEO satellites decrease as a function of wavelength or to be flat. It means that the spectral reflectance of satellite materials is bluer than that of the moon. 3) A characteristic dip at around 4,800 A is found in all observed spectra of a weather satellite. Based on these observations, it is indicated that the characteristics of the spectrum are mainly derived from the solar panels because the apparent area of the solar cell is probably larger than that of the satellite body

Implementation of High Power, High Resolution Radar System

Barry Geldzahler

NASA

NASA is pursuing a high precision (<5cm), high power (10PW), deep space tracking and characterization radar at Ka-band. Towards this end, NASA has demonstrated coherent uplink arraying with real-time compensation for atmospheric phase fluctuations at 30-31 GHz and 7.145-7.190 GHz using three 12m diameter COTS antennas separated by 60m at the Kennedy Space Center (KSC) in Florida. With this *final* demonstration of the Ka Band Objects: Observation and Monitoring (KaBOOM) project, NASA has transitioned into the upgrade of the KSC system to high power, high resolution demonstration.

NASA has also conducted studies and concept validation activities towards manufacturing precision RF and optical components – both active and passive – using digital manufacturing (e.g. "3D printing") techniques. These validations include the production and verification of a dual X-band RF feed horn, a rectangular to circular waveguide transition, and a 30cm dual optical/RF telescope reflector suitable for in-space or terrestrial applications. NASA has demonstrated the in-space applicability of this technique by "printing" a geometrically identical feed horn onboard the International Space Station. Each of these advances are aimed at NASA's eventual goal of significantly decreasing logistics challenges and increasing operability of large arrays of monolithic antennas for deep space radar and communications, with an eventual goal of "printing" complete 12m class antennas and their associated high power precision RF systems and optics.

Debris Manoeuver with Ground-Based Laser

Ben Greene, Dr Craig Smith, Dr James Bennett

Space Environment Research Centre

The Space Environment Research Centre (SERC) is a multi-national research collaboration tasked with developing mitigation strategies for debris objects not amenable to space-based interventions. SERC is leveraging accurate orbit and conjunction information from a new laser space tracking network to develop strategies to manage some types of debris using only ground-based infrastructure.

The ultimate objective is to manoeuver space debris away from collisions and towards re-entry. The technique is potentially applicable to debris with high surface-area-to-mass (SAM) ratio in any aspect.

We report on progress in debris orbit determination and SAM characterization, high-precision special-purpose catalogs, conjunction processing, high power lasers, adaptive optics for effective beam delivery and flight hardware for system qualification.

Aperture Partitioning Element Results

Steven Griffin, Brandoch Calef

Boeing

Partitioning the pupil reduces the degree of baseline redundancy, and therefore improves the quality of images that can be obtained from the system. A practical realization of this approach uses an aperture partitioning element at an aft optics pupil of the optical system. This paper describes on-sky 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. A comparison to a non-partitioned image will illustrate the utility of the hardware in improving image quality.

Laser Propogation through Deep Turbulence Characterization

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Laser beam can get weakened and defocused after its propagation through a long path if the refractive index of the medium fluctuates vigorously. A dominant cause for the index fluctuations of the atmosphere is presence of atmospheric turbulence. We present preliminary results on new metrics designed to effectively characterize the turbulent effects on laser beam propagation. The metrics are investigated for plane wave propagation through a 10km medium using phase screen approach. The turbulent effects are modeled using non-Kolmogorov descriptions by varying power law exponent and examining its impacts on intensity variance and number of zero intensity. The exponent is based on fractal dimension arguments which incorporates space filling concepts for the eddies in the inertial turbulence ranges.

Simulations for Improved Imaging of Dim Objects at Maui Space Surveillance Site

Richard Holmes[1], Michael Werth[1], Michael Roggemann[2], Jacob Lucas[1], Daniel Thompson[1]

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A detailed wave-optics simulation is used in conjunction with advanced post-processing algorithms to explore the trade space between image post-processing and adaptive optics for improved imaging of low signal-to-noise ratio (SNR) targets. Target-based guidestars are required for imaging of most active Earth-orbiting satellites because of restrictions on using laser-backscatter-based guidestars in the direction of such objects. With such target-based guidestars and Maui conditions, it is found that significant reductions in adaptive optics actuator and subaperture density can result in improved imaging of dimmer objects. Simulation indicates that elimination of adaptive optics produces sub-optimal results for all of the dim-object cases considered.

Image Restoration from Limited Data

Douglas Hope[1], T. Ryan Swindle[2], Michael Hart[1], Stuart M. Jefferies[3], James Nagy[4]

[1]Hart Scientific Consulting International, [2]AFRL, [3]Georgia State University, [4]Emory University

Ground-based imagery of satellites is a cornerstone of SSA. The resolution of this type of imagery is fundamentally limited by turbulence in the atmosphere. This limit in resolution can be overcome using advanced multi-frame blind deconvolution algorithms, which estimate the object scene and point spread functions (PSFs) that characterize the turbulence. In the regime of limited data, e.g. a satellite with a rapidly changing pose, estimation of the object and PSFs can be an ill-posed problem with current MFBD methods yielding poor quality restorations. The Daylight Object Restoration Algorithm (DORA) overcomes this problem, by using additional measurements from a wave-front sensor, along with a frozen flow model of the atmosphere, to achieve high-resolution estimates of space objects from limited data sets. The improvement in image resolution achieved by DORA when compared to current state of the art MFBD algorithms will be demonstrated using data from the AEOS and SOR telescopes.

A Validation Method of ESA's MASTER 1 cm Population in Low Earth Orbit

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[1]TU Braunschweig, [2]Space Debris Office, ESOC/ESA

ESA's Meteoroid And Space Debris Terrestrial Environment Reference (MASTER) allows to assess the debris and meteoroid flux imparted on a spacecraft in Earth orbit. In addition, spatial densities of artificial satellites in altitudes up to 1000 km above Geostationary Earth Orbit (GEO) can be evaluated. The most recent version is based on the reference population May 1st, 2009. It includes space debris with diameters down to 1 micrometer. PROOF-2009 is a complementary software to validate the MASTER population by simulating observation campaigns. This paper explains the validation phase within the MASTER model for the large object population in LEO (diameter > 1 cm). It answers three questions: 1) How is the MASTER population calibrated against observation results 2) Do recent fragmentation events affect the validation phase and 3) Does the space debris model represent reality sufficiently? Since all on-orbit fragments are modeled event-based, one of the main calibration parameters for each fragmentation is the number of objects that are tracked by the Space Surveillance Network (SSN). However, to further calibrate the LEO population, radar surveys such as the TIRA Beampark experiments (Fraunhofer Institute/FHR, Germany) and EISCAT observations (three radar systems in northern Scandinavia) are performed within dedicated observation campaigns. These space debris observation campaigns can detect objects in LEO down to 1 cm in diameter. For the validation, the observation campaigns are simulated with PROOF-2009 using the MASTER population. The results are compared against those from the observation campaigns. One important aspect during the validation is that observation campaigns can be susceptible to recent fragmentation events due to the sensors' detection sensitivity. This is shown by comparing radar observations, which were performed shortly after a fragmentation event, and a state-of-the-art MASTER population snapshot at the same epoch. Evaluations are based on the Fengyun-1C fragmentation event and the contemporary radar observations.

Design and Commissioning of the Transportable Laser Ranging Station STAR-C

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German Aerospace Center, Institute of Technical Physics (DLR)

A fast growing population of nano and micro satellites, space debris, as well as plans of installing mega constellations drives the demand for the development of new ground station technologies. The Institute of Technical Physics of the German Aerospace Center (DLR) focuses its research on optical methods in order to track and range orbital objects for precise orbit determination. Laser ranging is an inherently accurate method to determine an object's distance where sub-mm accuracy is achieved by the contributing stations within the International Laser Ranging Service (ILRS). Usually the orbits of space debris are determined with radar based observations and maintained in catalogues, for example the TLE data by NORAD. Multiple optical ground stations can contribute significantly to support catalogue maintenance or to refine orbits of particular orbital objects. Laser ranging data does not only measure the slant range to an object, but also allows to determine the state of propagation, if the single shot accuracy of the laser pulse is shorter than the apparent dimension of the object. Currently there is work in progress to build a transportable laser ranging station into a standard 20ft-ISO container, which takes up its initial operation during the second half of this year. A platform raises two telescopes configured in a bi-static set-up on an alt-azimuth mount above the roof of the container. Each axis of the alt-azimuth mount is driven with direct drive motors, where absolute encoders give a theoretical angular resolution of 1/50arcsec. One telescope with an aperture of 10cm is used for the transmit channel of a pulsed infrared laser and including active beam stabilization. In other telescope, the receive channel, with an aperture of 43cm a beam-splitter separates the visible light on a camera for tracking and the infrared light on a fiber-coupled single photon detector for ranging.

Application of Multi-Hypothesis Sequential Monte Carlo for Breakup Analysis

Weston Faber[1], Islam I Hussein[1], Waqar Zaidi[1], Matthew Wilkins[1], Christopher Roscoe[1], Paul Schumacher[2]

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In 2014 it was reported [1] that, since 1996, there had been 10 confirmed debris events such as a breakups, collisions, or intercepts. Increased debris may lead to cascading debris events otherwise known as the Kessler Syndrome. The aim of this research is to aid in preventing such a scenario by increasing debris and breakup analysis capabilities. The space object tracking problem, in general, is nonlinear in both state dynamics and observations. Additionally, given the multi-object, multi-scenario nature of the problem, space situational awareness requires multi-hypothesis tracking and management that is combinatorically challenging in nature. In practice, it is often seen that assumptions of underlying linearity and/or Gaussianity are used to provide tractable solutions to the multiple space object tracking problem. However, these assumptions are, at times, detrimental to tracking data and provide statistically inconsistent solutions. The goal of this paper is to provide a tractable solution to the multiple space object tracking problem that is statistically rigorous in the fact that simplifying assumptions of the underlying probability density function are relaxed and heuristic methods for hypothesis management are avoided. This paper employs the SMC approach introduced in [2] and expands to multi-object scenarios. Object birth is implemented using a Probabilistic Admissible Region (PAR) analysis introduced in [3]. In doing so it will provide a solution to the multi-object tracking problem applicable to RSO breakup scenarios that will enable the tracking of the post-breakup debris. By taking advantage of the mentioned SMC-based methods the solution will maintain statistical consistency and computational tractability. An SMC-based Particle Gaussian Mixture (PGM) approach presented in [4] is used to perform filtering.

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Shape and Orbit Estimation Technique for Space Debris Observation Using MU Radar

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The number of space debris is rapidly increasing and this is becoming an obstacle for space exploration. Therefore, we have to expand and improve observation method for space debris in order to reduce the risk of collision with spacecraft. The aim of our study is to develop a method of estimating the shape and orbit of space debris using the Middle and Upper atmosphere (MU) radar, which is basically used for atmospheric observation. This can lead to expansion of the observation network for space debris without constructing a new observation facility. In previous research, the Single Range Doppler Interferometry (SRDI) method has been proposed to observe space debris using MU radar. The SRDI method can image the shape of space debris using a fluctuating Doppler spectrogram caused by the spin motion of space debris, but the image has a bit poor resolution. In order to obtain higher resolution spectrogram, we introduced Smoothed Pseudo Wigner Distribution (SPWD) to SRDI method. We will present results of the shape estimation using the improved SRDI method, for both numerical simulation and observed value. As for orbit estimation, we developed the technique which uses Gauss-Newton method to decide orbital elements from plural position vectors of space debris estimated from observation. To improve the accuracy of the estimation, we also investigated the method using values from several times observation on a given space debris. We applied both methods and confirmed that the several times observation certainly improves the estimation error.

Applying Cognitive Fusion to Space Situational Awareness

Steven Ingram, Margaret Shaw, Moses Chan

Lockheed Martin

Space security is critical to United States national security. Maintaining a state-of-the-art Space Situational Awareness model is key to ensure our ability to observe, orient, decide, and act in response to on-orbit and ground events. We propose fusion of a real-time, natural language processing capability provided by IBM Cognitive Services with analysis of ground-based sensor data of positions and trajectories of satellites in geostationary orbit. We expect insight derived from unstructured textual data will provide previously untapped context to missile launches, help predict when a satellite of interest could be in danger (either by accident or by intent), and could alert interested parties to the perceived threat.

We seek to implement an improved Space Situational Awareness model by developing a probabilistic graphical model informed by the fusion of ground-based "structured" sensor data with "unstructured" data from the public domain, such as news articles, blogs, and Twitter, in real time. To this end, we employ IBM's Cognitive services, specifically, Watson Discovery. These services allow real-time natural language processing of text including entity extraction, keyword search, taxonomy classification, concept tagging, relation extraction, sentiment analysis, and emotion analysis.

We present various scenarios that demonstrate the utility of this new Space Situational Awareness model, each of which combine past structured information with related open source data. In these scenarios, should the model come to estimate a satellite is in danger, it will indicate it as so, based on the most pertinent data, such as a reading from a sensor or by information available online. We also present and discuss a model encompassing many satellites in a more general scenario.

Dynamic Aperture Diversity

Stuart Jefferies

Georgia State University

Our recent research has shown that the technique of aperture diversity has the potential to facilitate high-resolution, ground-based, imaging of low-Earth orbit satellites through strong atmospheric turbulence. This capability opens the door for imaging both during daylight hours and at low elevation angles and provides a significant step towards the goal of uninterrupted, full sky, monitoring for space situational awareness.

Our initial studies were performed for a single set of aperture sizes. This was because we originally envisioned a multi-telescope application of the technique to the current suite of telescopes atop Mount Haleakala. This is an unnecessary restriction as the technique is equally applicable to a single large aperture telescope (e.g. the Air Force’s 3-meter class telescopes in Hawaii and New Mexico).

Here we extend the aperture diversity technique to a dynamically variable set of aperture sizes and investigate how the set of apertures should change as observing conditions change.

Space Object Classification Using Fused Features of Time Series Data

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In this paper, a fused feature vector is proposed for space object classification which incorporates raw time series and texture feature information of the time series. The texture feature of the time series is obtained via the recurrence plot which describes the essential structure of the time series. Instead of using simulated data, two realistic time series data of historical orbit trajectories and asteroid light curves, are used. Both unsupervised learning and supervised learning algorithms using different feature vectors are compared to test the resident space object (RSO) classification performance of the proposed feature fusion for RSO classification. The simulation results show that the classification algorithms using the fused feature vector achieve better performance than those using raw time series or texture features only.

Research to Operations Transition of an Auroral Specification and Forecast Model

James Jones

Northrop Grumman

Aurorae are generally caused by collisions of high-energy precipitating electrons and neutral molecules in Earth’s polar atmosphere. The electrons, originating in Earth’s magnetosphere, collide with oxygen and nitrogen molecules driving them to an excited state. As the molecules return to their normal state a photon of energy is released resulting in the aurora. Aurora can become troublesome for operations of UHF and L-Band radars since these radio frequencies can be scattered by these abundant free electrons and excited molecules. The presence of aurorae under some conditions can lead to radar clutter or false targets. It is important to know the state of the aurora and when radar clutter is possible. For this reason models of the aurora have been developed and used in an operational center for many decades. Recently, a data-driven auroral precipitation model was integrated into the DoD operational center for space weather. The auroral precipitation model is data-driven in a sense that solar wind observations from the Lagrangian point L1 are used to drive a statistical model of Earth’s aurorae to provide nowcasts and short-duration forecasts of auroral activity. The project began with a laboratory-grade prototype and an algorithm theoretical basis document, then through a tailored Agile development process, deployed operational-grade code to a DoD operational center. The Agile development process promotes adaptive planning, evolutionary development, early delivery, continuous improvement, regular collaboration with the customer, and encourages rapid and flexible response to customer-driven changes. The result was an operational capability that met customer expectations for reliability, security, and scientific accuracy. Details of the model and the process of operational integration are discussed as well as lessons learned to improve performance on future projects.

A Simulation Environment to Determine the Performance of SSA Systems

Christopher Kebschull, Enrico Stoll

TU Braunschweig/Institute of Space Systems

Many states in Europe are participating in the build-up of an independent Space Situational Awareness (SSA) programme. One goal is to combine national assets like RADAR and telescope stations and share the data amongst the participating states. Within the EU and the ESA SSA programs have been setup to enable the collaboration between the different nation states. In order to get an idea of the capabilities of the different SSA system configurations the Institute of Space Systems (IRAS) has been developing a simulation software suite. Its main goal is to evaluate the performance of a given SSA system configuration. The paper outlines the architecture of the simulation software. Each integrated module necessary to achieve the complex simulation is described. A focus lies on the module to generate artificial RADAR measurements, which are modelled on the microsecond time scale and the orbit determination (OD) module. The measurement generation module is able to generate noisy data. Based on variations like the noise level, the frequency of observation and the type of observed objects a sensitivity analysis is performed. The OD module is able to use different initial or statistical orbit determination algorithms and configurations. Given the different levels of noise in the artificial measurements the achieved accuracies of OD configurations are analysed. The paper concludes with best practice recommendations for the use of different OD settings based on the chosen scenario.

Geosynchronous Patrol Orbit for Space Situational Awareness

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Applying a small amount of eccentricity to a geosynchronous orbit produces both longitudinal and radial motion when viewed in Earth-fixed coordinates. An interesting family of orbits emerges, useful for ‘neighborhood watch’ space situational awareness and other missions. The basic result is a periodic (daily), quasi-elliptical, closed path around a fixed volume of the geosynchronous (GEO) orbit belt, keeping a sensor spacecraft in relatively close vicinity to designated GEO objects. The motion is similar, in some regards, to the relative motion that may be encountered during spacecraft proximity operations, but on a much larger scale. The size and shape of the patrol orbit is determined by the eccentricity, while the general orientation of the quasi-ellipse and the direction of relative motion around the path is controlled by the argument of perigee. The patrol orbit does not occupy a fixed slot in the GEO belt, and the east-west motion can be combined with the north-south motion caused by orbital inclination, leading to even greater versatility. Multiple satellites can operate on the same patrol orbit simultaneously with different phase and direction of motion. Multiple, complimentary patrol orbits with multiple spacecraft can also be employed.

Some of the practical uses of the GEO patrol orbit include space surveillance (including catalog maintenance), and general space situational awareness. The patrol orbit offers improved, diverse observation geometry for angles-only sensors, resulting in faster, more accurate orbit determination compared to simple inclined GEO orbits. It also offers unique ground tracks and coverage for Earth observing and communications missions. In this paper, we analyze the requirements for putting a spacecraft in a patrol orbit, the unique station keeping requirements to compensate for perturbations such as maintaining argument of perigee, repositioning the patrol orbit to a different location along the GEO belt, maneuvering into, around, and out of the volume for proximity operations with spacecraft within the volume, and safe end-of-life disposal requirements.

Integrating Machine Learning into Space Operations

Kevin Kelly

US Air Force

There are significant challenges with managing activities in space, which for the scope of this paper are primarily the identification of objects in orbit, maintaining accurate estimates of the orbits of those objects, detecting changes to those orbits, warning of possible collisions between objects and detection of anomalous behavior. The challenges come from the large amounts of data to be processed, which is often incomplete and noisy, the limitations on the ability to influence objects in space and the overall strategic importance of space to national interests.

The focus of this paper is on defining an approach to leverage the improved capabilities that are possible using state of the art machine learning in a way that empowers operations personnel without sacrificing the security and mission assurance associated with manual operations performed by trained personnel. There has been significant research in the development of algorithms and techniques for applying machine learning in this domain, but deploying new techniques into such a mission critical domain is difficult and time consuming. Establishing a common framework could improve the efficiency with which new techniques are integrated into operations and the overall effectiveness at providing improvements.

DVD-COOP: Innovative Conjunction Prediction Using Voronoi-filter Based on the Dynamic Voronoi Diagram of 3D Spheres

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Conjunction prediction is one of the critical operations in space situational awareness (SSA). For the objects in geospace, common practices of the conjunction prediction are either all pairwise checks, geometric hashing, or kd-tree of objects. The object set is usually reduced through filters to reduce computational burden. However, there still exists a good possibility of missing potential collisions between space objects. We present a novel algorithm which both guarantees no missing conjunction case and facilitates to answer to a variety of important problems other than the common conjunction prediction one. The algorithm takes only O(k log N) time, in the worst case, to answer to conjunctions where k is a constant which is linear to prediction time length. The proposed algorithm, named DVD-COOP (dynamic Voronoi diagram-based conjunctive orbital object predictor) is based on the dynamic Voronoi diagram of moving spherical balls in 3D space. The algorithm has a preprocessing which consists of two steps: the construction of an initial Voronoi diagram (taking O(N) time on average) and the construction of a priority queue for the events of topology changes of the Voronoi diagram and conjunctions (taking O(N log N) time in the worst case). The scalability of the proposed algorithm is also discussed. We anticipate that the proposed Voronoi-approach could lead to a revolutionary approach to collision avoidance, optimal maneuver path planning for satellites, etc.

Publicly Available Geosynchronous (GEO) Space Object Catalog for Future Space Situational Awareness (SSA) Studies

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Previously, there have been many commercial proposals and extensive academic studies regarding ground and space based sensors to assist a space surveillance network in obtaining metric observations of satellites and debris near Geosynchronous Orbit (GEO). Most use physics based models for geometric constraints, lighting, and tasker/scheduler operations of sensor architectures. Under similar physics modeling assumptions, the space object catalog is often different due to proprietary standards and datasets. Lack of catalog commonality between studies creates barriers and difficulty comparing performance benefits of sensor trades. To solve this problem, we have constructed a future GEO space catalog from publicly available datasets and literature. The annual number of new payloads and rocket bodies is drawn from a Poisson distribution while the growth of the current GEO catalog is bootstrapped from the historical payload, upper stage, and debris data. We adopt a spherically symmetric explosion model and couple it with the NASA standard breakup model to simulate explosions of payloads and rocket bodies as they are the primary drivers of the debris population growth. The cumulative number of fragments follow a power-law distribution. Result from 1,000 random catalog growth simulations indicates that the GEO space object population in the year 2050 will include over 3,600 objects, nearly half of which are debris greater than 10 cm spherical diameter. The number of rocket bodies and dead payloads is projected to nearly double over the next 33 years. For comparison, the current Air Force Space Command catalog snapshot contains fewer than 50 pieces of debris and coarse Radar Cross Section (RCS) estimates which include: small, medium, and large. The current catalog may be sufficient for conjunction studies, but not for analyzing future sensor system performance. The 2050 GEO projected catalog will be available online for commercial/academic research and development.

Utilizing Cubesatellites for Characterization of the AN/FSY-3 Space Fence System and Other Sensors

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In 2018, a ground-based S-band radar system named Space Fence will undergo operational testing. This radar is designed to discover and frequently track tens of thousands of satellites and debris objects in orbit around Earth. It is challenging to calibrate and test a system meant for discovering small objects, because the only calibration objects in orbit are large. To alleviate this, the Air Force Operational Testing and Evaluation Center is working with the US Air Force Academy and the Space Fence System Program Office to develop a cubesatellite to characterize the radar's ability to expand the space object catalog's fidelity. The cubesatellite will eject two small calibration spheres in low Earth orbit to be tracked by the Space Fence System and other sensors. The radar cross sections of the spheres are precisely measured to support calibration of sensors that will track them in orbit. This paper discusses the cubesatellite's design and on-orbit mission.

The cubesatellite will also benefit optical sensors. The larger sphere will have an optically-measured iridite coating, and the cubesatellite bus will contain LEDs in frequencies that support testing of selected optical sensors. This cubesatellite's design can be further adapted for use with other new sensor acquisitions and their individual capabilities. Different sized objects could be released at various speeds in any point in the cubesatellite's orbit to cater to the test requirements. This cubesatellite platform has the ability to provide real-world on-orbit characterization of billion-dollar assets built to protect the USA and its allies, as well as to expand space situational awareness.

The Solaris-Panoptes Global Network of Robotic Telescopes and the Borowiec Satellite Laser Ranging System for SST: A Progress Report

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We present an update on the preparation of our assets that consists of a robotic network of eight optical telescopes and a laser ranging station for regular services in the SST domain. We discuss the results of the first observational campaigns carried out with the sensors, including joint laser-optical observations. We report the development of new optical assets that include a double telescope system, Panoptes-1AB, and a new astrograph on our Solaris-3 telescope at the Siding Spring Observatory, Australia. Progress in the software development necessary for smooth SST operation includes a web based portal and an XML Azure Queue scheduling for the network giving easy access to our sensors. Astrometry24.net our new prototype cloud service for fast astrometry, streak detection and measurement with precision and performance results is also described. In the laser domain, for more than a year, Space Research Centre Borowiec laser station has regularly tracked space debris cooperative and uncooperative targets. The efforts of the stations' staff have been focused on the tracking of typical rocket bodies from the LEO regime. Additionally, a second independent laser system fully dedicated to SST activities is under development. It will allow for an increased pace of operation of our consortium in the global SST laser domain.

Technical Description of a Novel Sensor Network Architecture and Results of Radar and Optical Sensors Contributing to a UK Cueing Experiment

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DSTL, STFC, CL2 and NERC have recently participated in a campaign of satellite observations, with both radar and optical sensors, in order to demonstrate an initial network concept that enhances the value of coordinated observations. STFC and CL2 have developed an SST server/client architecture to slave one sensor to another. The concept was originated to enable the Chilbolton radar (an S-band radar on a 25 m diameter fully-steerable dish antenna called CASTR – Chilbolton Advanced Tracking Radar) which does not have an autotrack function to follow an object based on position data streamed from another cueing sensor. The original motivation for this was to enable tracking during re-entry of ATV-5, a highly manoeuvrable ISS re-supply vessel. The architecture has been designed to be extensible and allows the interface of both optical and radar sensors which may be geographically separated. Connectivity between the sensors is TCP/IP over the internet. The data transferred between the sensors is translated into an Earth centred frame of reference to accommodate the difference in location, and time-stamping and filtering are applied to cope with latency. The server can accept connections from multiple clients, and the operator can switch between the different clients. This architecture is inherently robust and will enable graceful degradation should parts of the system be unavailable. A demonstration was conducted in 2016 whereby a small telescope connected to an agile mount (an EO tracker known as COATS - Chilbolton Optical Advanced Tracking System) located 50m away from the radar at Chilbolton, autonomously tracked several objects and fed the look angle data into a client. CASTR, slaved to COATS through the server followed and successfully detected the objects. In 2017, the baseline was extended to 135 km by developing a client for the SLR (satellite laser ranger) telescope at the Space Geodesy Facility, Herstmonceux. Trials have already demonstrated that CASTR can accurately track the object using the position data being fed from the SLR.

Automated Cloud Observation for Ground Telescope Optimization

Ben Lane, Mark W. Jeffries Jr, Bill Therien

ExoAnalytic Solutions

As the number of man-made objects placed in space each year increases with advancements in commercial, academic and industry, the number of objects required to be detected, tracked, and characterized continues to grow at an exponential rate. Commercial companies, such as ExoAnalytic Solutions, have deployed ground based sensors to maintain track custody of these objects. For the ExoAnalytic Global Telescope Network (EGTN), observation of such objects are collected at the rate of over 8 million unique observations per month. Currently, the EGTN does not optimally collect data on nights with significant cloud levels. However, a majority of these nights prove to be partially cloudy providing clear patches in the sky for the EGTN sensors to observe between clouds. It proves useful for a telescope to utilize these clear patches to continue object observation. By dynamically updating the tasking as the cloud position changes, the number of observations could potentially increase dramatically, with increased persistence, cadence, and revisit. This paper will discuss the recent algorithms being implemented within the EGTN, including the motivation, need, and general design. The use of automated image processing as well as various edge detection methods, including Canny, Sobel, and Marching Squares, on real-time large FOV images of the sky enhance the tasking and scheduling of a ground based telescope. Implementations of these algorithms on single and expanding to multiple telescopes, will be explored. Results of applying these algorithms to the EGTN in real-time and comparison to non-optimized EGTN tasking will be presented. Finally, future work in applying these throughout the EGTN as well as other optical telescopes will be discussed.

Cloud Services for Space Situational Awareness

Sarah Law, Jared Dorny, Jared Stallings

Raytheon

On Feb. 14, 2017 the Indian Space Research Organization launched 104 satellites with a single rocket. This single launch illustrates the increasingly difficult problem of maintaining space situational awareness. Space based constellations are becoming much larger, with some in current design planned to be in the thousands. In addition, the number of countries and organizations that are participating in space is growing at an unprecedented rate, creating difficulties with maintaining the satellite ancillary data including intended use and ownership.

To manage this difficult problem, Raytheon has developed a scalable distributed data repository for entity state information along with cloud services to generate orbit events. These orbit events including ascending node, descending node, perigee, apogee, umbra, and penumbra are critical for mission and contact planning, as well as situational awareness. In legacy systems the orbit event data is based on position data which is frequently single-sourced, generated, and stored as the ephemeris is generated. This data is then presented to the user for all satellites in the system, which is generally only a few satellites. However, in this new system, use of cloud scalability patterns, together with dynamic features of micro services provides for a highly scalable and distributable orbit event service which can handle datasets for thousands of vehicles in near real time and allows for distribution to many users.

Beyond just ephemeris, the Entity State Information Service will store information gathered from a variety of sources, together with its relationships to other entities. Examples of source data include Space-track.org, AGI COMSPOC, and Gunter's Space Page. Not surprisingly, data from these sources may have varied accuracy and are in a variety of formats. As such this repository provides linkages to other data stores, or to the source of such data. Changes in the data, as well as the time when they occurred, are also tracked.

NASA's Optical Program on Ascension Island: Bringing MCAT to Life as the Eugene Stansbery-Meter Class Autonomous Telescope (ES-MCAT)

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In June 2015, the construction of the Meter Class Autonomous Telescope was completed and MCAT saw the light of the stars for the first time. In 2017, MCAT was newly dedicated as the Eugene Stansbery-MCAT telescope by NASA's Orbital Debris Program Office (ODPO), in honour of his inspiration and dedication to this newest optical member of the NASA ODPO. Since that time, MCAT has viewed the skies with one engineering camera and two scientific cameras, and the ODPO optical team has begun the process of vetting the entire system.

The full system vetting includes verification and validation of: (1) the hardware comprising the system (e.g. the telescopes and its instruments, the dome, weather systems, all-sky camera, FLIR cloud infrared camera, etc.), (2) the custom-written Observatory Control System (OCS) master software designed to autonomously control this complex system of instruments, each with its own control software, and (3) the custom written Orbital Debris Processing software for post-processing the data. ES-MCAT is now capable of autonomous observing to include Geosyncronous survey, TLE (Two-line element) tracking of individual catalogued debris at all orbital regimes (Low-Earth Orbit all the way to Geosynchronous (GEO) orbit), tracking at specified non-sidereal rates, as well as sidereal rates for proper calibration with standard stars.

Ultimately, the data will be used for validation of NASA's Orbital Debris Engineering Model, ORDEM, which aids in engineering designs of spacecraft that require knowledge of the orbital debris environment and long-term risks for collisions with Resident Space Objects (RSOs).

Distinguishing Active Box-Wing and Cylindrical Geostationary Satellites Using IR Photometry with NASA's WISE Spacecraft

Chris Lee[1], Patrick Seitzer[1], Roc Cutri[2], Carl Grillmair[2], Thomas Schildknecht[3], Jeremy Murray-Krezan[4], Donald Bédard[5]

[1]University of Michigan, [2]California Institute of Technology, [3]University of Bern, [4]Air Force Research Laboratory, [5]Royal Military College of Canada

Observations of 245 box-wing (BW) and 18 cylindrical (C) active geostationary satellites (GEOsats) have been extracted from the thousands of Resident Space Objects (RSOs) serendipitously detected by NASA's Wide-field Infrared Survey Explorer (WISE). In 2010, WISE performed an all-sky 4-band infrared (IR) survey at 3.4, 4.6, 12, and 22 microns simultaneously from Low Earth Orbit. All observations were obtained near quadrature. The 3.4 micron band is dominated by GEOsat reflected sunlight, the 12 and 22 micron bands are dominated by GEOsat thermal emission, and the 4.6 micron band can have significant contributions from both reflected sunlight and thermal emission. We present our analyses of differences in IR photometric signatures between BW and C GEOsats and those of other satellite types. Our primary results include:

1.) BW and C satellites have separate distributions in the 4.6 - 12 and 4.6 - 22 micron color indices, where C satellites appear generally redder by almost 1 magnitude.
2.) BW and C satellites do not appear distinctly different in any other color index.
3.) Eurostar-2000+ BW satellites are most similar to C satellites in the 4.6 - 12 micron color index, whereas HS/BSS-601 BW satellites are most different from C satellites in the same color index.
4.) BW satellites show clustering in the 3.4 - 4.6 micron color index, whereas C satellites show a more uniform distribution, indicating no preference in reflected sunlight colors.

WENESSA, Wide Eye-Narrow Eye Space Situational Awareness

Paul LeVan[1], Ouail Albarait[2], Don Payne[2], Khahn Luu[2]

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In an effort to achieve timelier indications of anomalous object behaviors in geosynchronous earth orbit, a Planning Capability Concept (PCC) for a “Wide Eye-Narrow Eye” (WE-NE) telescope network has been established. The PCC addresses the problem of providing continuous and operationally robust, layered and cost-effective, Space Situational Awareness (SSA) that is focused on monitoring deep space for anomalous behaviors. It does this by first detecting the anomalies with wide field of regard systems, and then providing reliable handovers for detailed observational follow-up by larger aperture assets. WENESSA will explore the added value of such a system to the existing space surveillance network. The study will assess and quantify the degree to which the PCC completely fulfills, or improves or augments, these deep space knowledge deficiencies relative to current operational systems.

In an effort to improve organic simulation capabilities, we will explore options for the federation of diverse community simulation approaches to evaluate the efficiencies offered by a network of small and larger aperture, ground-based telescopes. Existing Space Modeling and Simulation (M&S) tools designed for evaluating WENESSA-like problems will be taken into consideration as we proceed in defining and developing the tools needed to perform this study, leading to the creation of a unified Space M&S environment for the rapid assessment of new capabilities. The primary goal of this effort is to perform a Military Utility Assessment (MUA) of the WE-NE concept. The assessment will explore the mission utility of various WE-NE concepts in discovering deep space anomalies in concert with the Space Surveillance Network (SSN). The secondary goal is to generate an enduring M&S environment to explore the military utility of future proposed concepts. Ultimately, our validated simulation framework would support the inclusion of other ground- and space-based SSA assets through integrated analysis. Options will be explored using at least two competing simulation capabilities, but emphasis will be placed on reasoned analyses as supported by the simulations.

Applications of Photometric Stereopsis for Shape Estimation of RSOs

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[1]Texas A&M University, [2]University at Buffalo, SUNY, [3]Ford Motor Company

Photometric models for image formation are utilized to devise stereopsis approaches to esti- mate the surface geometry of naturally illuminated resident space objects (RSOs). Relative pose estimates of the RSOs as a function of the image features are utilized to aid the stereopsis process in both orthography and perspective projection geometries. As opposed to traditional methods of stereo photogrammetry, the approach uses illumination variations to estimate the shape of natural and man-made objects. It is shown that the proposed approach is more robust to lack of texture. Linear covariance analysis of the surface es- timation process is utilized as a measure of observability of the surface geometry. This analysis is slated to ultimately provide a data driven framework to schedule more measurements to improve the attribute estima- tion process, ultimately facilitating effective space situational awareness (SSA). Synthetic and hardware in the loop experiments are used to demonstrate the efficacy of the approaches presented in the paper.

Ever Wonder What's in Molniya? We do.

John McGraw, Peter Zimmer, Mark Ackermann

J.T. McGraw and Associates, LLC

What happens when you combine curious astronomers and fast, wide-field optical systems designed for blind surveillance of LEO, MEO, GEO, GTO, and HEO?

The answer involves lots of image data -- many terabytes in fact. Fortunately these same curious astronomers also have state-of-the-art detection algorithms and powerful GPU-based computing systems to run them on. These resources allow them to reduce these data from a terrifyingly large volume to one that is merely daunting.

These curious astronomers use these results to examine the limits of using small optical telescopes to discover HEO objects, such as Molniyas, and those in other similarly less well-monitored regimes.

Modular Mount Control System for Telescopes

John Mooney, Richard Cleis, Trent Kyono, Matthew Edwards

The Boeing Company

The Space Observatory Control Kit (SpOCK) is the hardware, computers and software used to run small and large telescopes in the RDS division of the Air Force Research Laboratories (AFRL). The system is used to track earth satellites, celestial objects, terrestrial objects and aerial objects. The system will track general targets when provided with state vectors in one of five coordinate systems. Client-to-server and server-to-gimbals communication occurs via human-readable s-expressions that may be evaluated by the computer language called Racket. Software verification is achieved by scripts that exercise these expressions by sending them to the server, and receiving the expressions that the server evaluates.

This paper describes the adaptation of a modular mount control system developed primarily for LEO satellite imaging on large and small portable AFRL telescopes with a goal of orbit determination and the generation of satellite metrics.

Harnessing Orbital Debris to Sense the Space Environment

Shaylah Mutschler, Dr. Tomoko Matsuo, Dr. Penina Axelrad

University of Colorado Boulder

A key requirement for accurate SSA is knowledge of the non-conservative forces that act on space objects. These effects vary and are driven by the dynamical behavior of space weather. Existing SSA algorithms adjust space weather models based on observations of calibration satellites. However, lack of sufficient data and mismodeling of non-conservative forces cause inaccuracies in space object motion prediction. The uncontrolled nature of debris makes it particularly sensitive to the variations in space weather. Our research takes advantage of this behavior by inverting observations of debris objects to infer the space environment parameters causing their motion. In addition, this research will produce a more accurate prediction of the motion of debris objects.

The premise of this research is that it is possible to utilize a "cluster" of debris objects, objects within relatively close proximity of each other, to sense their local environment. We focus on deriving parameters of an atmospheric density model to more precisely predict the drag force on LEO objects. An Ensemble Kalman Filter (EnKF) is used for assimilation; the prior ensemble to the posterior ensemble is transformed during the measurement update to circumvent the inversion of large matrices. A prior ensemble is utilized to empirically determine the nonlinear relationship between measurements and density parameters. The filter estimates an extended state that includes position and velocity of the debris object, and atmospheric density parameters. We parameterize the density as a grid of values, distributed by latitude and local sidereal time over a spherical shell encompassing Earth. This research focuses on LEO object motion but it can also be extended to additional orbital regimes for refinement of magnetic field and solar radiation models. An observability analysis of the proposed approach will be presented in terms of the measurement cadence necessary to estimate the local space environment.

Fuel Optimal, Finite Thrust Guidance Methods to Circumnavigate with Lighting Constraints

Eric Prince[1], Dr. Richard Cobb[2]

[1]Air Force Institute of Technology, [2]Advisor

This paper details improvements made to the authors' most recent previous work to find fuel optimal, finite-thrust guidance to inject an inspector satellite into a prescribed natural motion circumnavigation (NMC) orbit about a resident space object (RSO) in geosynchronous orbit (GEO). Better initial guess methodologies are developed for the low-fidelity model nonlinear programming problem (NLP) solver to include using Clohessy-Wiltshire (CW) targeting, a custom particle swarm optimization (PSO), and MATLAB's genetic algorithm (GA). These initial guess solutions may then be fed into the NLP solver as an initial guess, where a different NLP solver, IPOPT, has been used. More lighting constraints are also taken into account in addition to the Sun vector, ensuring that the resulting NMC also adheres to Moon and Earth lighting constraints. The guidance is initially calculated given a fixed final time, and then solutions are also calculated for fixed final times before and after the original fixed final time, allowing mission planners to choose the lowest-cost solution in the resulting range which satisfies all constraints. The developed algorithms provide computationally fast methods for determining fuel optimal guidance for NMC establishment while also adhering to multiple lighting constraints.

TC4 Observing Campaign: An Operational Test of NASA Planetary Defense Network

Vishnu Reddy[1], Dr. Michael S. Kelley[2], Dr. Kelly Fast[2], Dr. Lindley Johnson[2]

[1]University of Arizona, [2]NASA Headquarters

Impacts due to near-Earth objects (~90% near-Earth asteroids, or NEAs, and ~10% comets) are one of the natural hazards that can pose a great risk to life on Earth, but one that can potentially be mitigated, if the threat is detected with sufficient lead-time. While the probability of such an event is low, the outcome is so catastrophic that we are well justified in investing a modest effort to minimize this threat. Historically, asteroid impacts have altered the course of evolution on the Earth. In 2013 the Chelyabinsk meteor over Russia, which injured over 1600 people and caused ~$30M in damages, reinforced the importance of detecting and characterizing small NEAs that pose a greater threat than most large NEAs discovered so far. The NASA Planetary Defense Coordination Office (PDCO) was established to ensure the early detection, tracking and characterization of potentially hazardous objects (PHOs) and is the lead body for providing timely and accurate communications and coordination of U.S. Government planning for response to an actual impact threat. In an effort to test the operational readiness of all entities critical to planetary defense, the NASA PDCO is supporting a community-led exercise. The target of this exercise is 2012 TC4, a 20-meter diameter asteroid that is currently expected to pass by the Earth on Oct. 12, 2017 at a distance of only 2.3 Earth radii over Antarctica. The goal of the TC4 Observing Campaign is to recover, track, and characterize 2012 TC4 as a potential impactor in order to exercise the entire Planetary Defense system from observations, modeling, prediction, and communication. The paper will present an overview of the campaign and summarize early results from the exercise.

Space Surveillance Using TAROT Telescopes Network

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The TAROT telescope network is composed of three telescopes which primary mission is observation of transient celestial phenomena following gamma ray bursts or gravitational waves alerts. CNES uses this network for space surveillance as it can observe 70% of the geostationary belt.

The poster will present the recent evolutions of the image processing and astrometric reduction system; OSMOSE, the CNES system for space objects orbit determination and cataloguing; then recent space surveillance achievements CNES obtained using the TAROT telescope network.

Single Photon Counting Large Format Imaging Sensors with High Spatial and Temporal Resolution

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High time resolution astronomical and remote sensing applications have been addressed with microchannel plate based imaging, photon time tagging detector sealed tube schemes. Recent developments include large detectors with high spatial and temporal resolution. These are being realized with the advent of cross strip readout techniques with high performance encoding electronics and atomic layer deposited (ALD) microchannel plate technologies. Sealed tube devices up to 20 cm square have now been successfully implemented with sub nanosecond timing and imaging. New developments include 50 mm format Planacons with UV/visible photocathodes, ALD MCPs, and the readout has been implemented with a cross strip anode. The objective is to provide sensors with large areas (50mm to 200mm) with spatial resolutions of <20 micron FWHM and timing resolutions of <100ps for dynamic imaging. New high efficiency photocathodes for the visible regime are discussed which also allow response down below 150nm for UV sensing. Borosilicate MCPs are providing high performance, and when processed with ALD techniques are providing order of magnitude lifetime improvements for microchannel plate performance and photocathode stability. The first flat panel sealed tubes with 20cm square formats have been successfully constructed with ALD MCPs for uses including large area focal plane imagers for Astronomy, to neutron detection and Cherenkov ring imaging. Tests with 50mm format cross strip readouts for Planacon devices show spatial resolutions better than 20 microns FWHM, with good image linearity while using low gain (<10^6). Current cross strip encoding electronics can accommodate event rates of >5 MHz and event timing accuracy of ~100ps. We have also just implemented an ASIC version of this electronics with higher event rate performance in a low power and mass package that is suitable for spaceflight and ground based instruments to study transient and variable astronomical objects.

Preliminary CubeSat Design for Laser Remote Maneuver of Space Debris at the Space Environment Research Centre

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[1]Lockheed Martin, [2]Space Environment Research Centre, [3]Georgia Institute of Technology

The Space Environment Research Centre (SERC) endeavors to demonstrate the ability to maneuver high area to mass ratio objects using ground based lasers. Lockheed Martin has been leading system performance modeling for this project that includes high power laser propagation through the atmosphere, target interactions and subsequent orbital maneuver of the object. This paper will describe a CubeSat that could be used as a potential target to demonstrate the maneuver system as well as the model assumptions and performance estimates for laser maneuver demonstration. Additionally it will discuss how the choice of models has impacted design considerations for the demonstration.

Automated Terrestrial EMI Emitter Detection, Classification, and Localization

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[1]Stottler Henke Associates Inc., [2]Data Fusion & Neural Networks, [3]Air Force Research Lab, RVSV

Clear operating spectrum at ground station antenna locations is critically important for communicating with, commanding, controlling, and maintaining the health of satellites. Electro Magnetic Interference (EMI) can interfere with these communications, so it is extremely important to track down and eliminate sources of EMI. The Terrestrial RFI-locating Automation with CasE based Reasoning (TRACER) system is being implemented to automate terrestrial EMI emitter localization and identification to improve space situational awareness, reduce manpower requirements, dramatically shorten EMI response time, enable the system to evolve without programmer involvement, and support adversarial scenarios such as jamming. The operational version of TRACER is being implemented and applied with real data (power versus frequency over time) for both satellite communication antennas and sweeping Direction Finding (DF) antennas located near them. This paper presents the design and initial implementation of TRACER's investigation data management, automation, and data visualization capabilities.

TRACER monitors DF antenna signals and detects and classifies EMI using neural network technology, trained on past cases of both normal communications and EMI events. When EMI events are detected, an Investigation Object is created automatically. The user interface facilitates the management of multiple investigations simultaneously. Using a variant of the Friis transmission equation, emissions data is used to estimate and plot the emitter's locations over time for comparison with current flights. The data is also displayed on a set of five linked graphs to aid in the perception of patterns spanning power, time, frequency, and bearing. Based on details of the signal (its classification, direction, and strength, etc.), TRACER retrieves one or more cases of EMI investigation methodologies which are represented as graphical behavior transition networks (BTNs). These BTNs can be edited easily, and they naturally represent the flow-chart-like process often followed by experts in time pressured situations.

Automatic Satellite Telemetry Analysis for SSA using Artificial Intelligence Techniques

Richard Stottler, Jay Mao

Stottler Henke Associates, Inc.

In April, 2016, General Hyten, commander of Air Force Space Command, announced the Space Enterprise Vision (SEV), http://www.af.mil/News/Article-Display/Article/719941/hyten-announces-space-enterprise-vision/. The SEV addresses threats to space-related systems, including an integrated approach across all mission areas, emphasizing improved access to data across the entire enterprise and the ability to protect space capabilities. "The future space enterprise will maintain our nation's ability to deliver critical space effects throughout all phases of conflict," Hyten said. Satellite telemetry will become available to a new audience. While that information should be valuable for achieving Space Situational Awareness (SSA), these new telemetry consumers will be inexperienced.

We are applying AI techniques to build an infrastructure to process satellite telemetry into higher abstraction level symbolic space situational awareness and to initially populate that infrastructure with useful data analysis methods. We are working with three organizations (Montana State University (MSU), the Air Force Academy, and Space and Missile Systems Center (SMC)'s RDT&E Support Complex Support Complex (RSC) who control satellites and analyze satellite telemetry to assess the health and circumstances of their satellites. The design is a hybrid approach which combines symbolic processing techniques of Case-Based Reasoning (CBR) and Behavior Transition Networks (BTNs) with current Machine Learning approaches. BTNs are used to represent the process and associated formulas to check telemetry values against anticipated problems and issues. CBR is used to represent and retrieve BTNs that represent an

investigative process that should be applied to the telemetry in certain circumstances. Machine Learning is used to learn normal patterns of telemetry, learn pre-mission simulated telemetry patterns that represent known problems, and detect both pre-trained known and unknown abnormalities in real-time. The operational system is being implemented and applied to real satellite telemetry data. This paper presents the design, examples, and results from the first version as well as planned future work.

Sohbrit: Autonomous COTS System for Satellite Characterization

Nicholas Blazier, Samuel Tarin, Mitchell Wells, Nathanael Brown, Prabal Nandy, Drew Woodbury

Sandia National Laboratories

As technology continues to improve, driving down the cost of commercial astronomical products while increasing their capabilities, manpower to run observations has become the limiting factor in acquiring continuous and repeatable space situational awareness data. Sandia National Laboratories set out to automate a testbed comprised entirely of commercial off-the-shelf (COTS) hardware for space object characterization (SOC) focusing on satellites in geosynchronous orbit. Using an entirely autonomous system allows collection parameters such as target illumination and nightly overlap to be accounted for habitually; this enables repeatable development of target light curves to establish patterns of life in a variety of spectral bands.

The system, known as Sohbrit, is responsible for autonomously creating an optimized schedule, checking the weather, opening the observatory dome, aligning and focusing the telescope, executing the schedule by slewing to each target and imaging it in a number of spectral bands (e.g., B, V, R, I, wide-open) via a filter wheel, closing the dome at the end of observations, processing the data, and storing/disseminating the data for exploitation via the web. Sohbrit must handle various situations such as weather outages and focus changes due to temperature shifts and optical seeing variations without human interaction. Sohbrit can collect large volumes of data nightly due to its high level of automation. To store and disseminate these large quantities of data, we utilize a cloud-based big data architecture called Firebird, which exposes the data out to the community for use by developers and analysts. Sohbrit is the first COTS system we are aware of to automate the full process of multispectral geosynchronous characterization from scheduling all the way to processed, disseminated data. In this paper we will discuss design decisions, issues encountered and overcome during implementation, and show results produced by Sohbrit.

Network Enabled Unresolved Residual Analysis Learning

Dwight Temple

Exoanalytic Solutions

Since the advent of modern computational capacity, machine learning algorithms and techniques have served as a method through which to solve numerous challenging problems. However, for machine learning methods to be effective and robust, sufficient data sets must be available; specifically, in the space domain, these are generally difficult to acquire. Rapidly evolving commercial space-situational awareness companies boast the capability to collect hundreds of thousands nightly observations of resident space objects (RSOs) using a ground-based optical sensor network. This provides the ability to maintain custody of and characterize thousands of objects persistently. With this information available, novel deep learning techniques can be implemented. The technique discussed in this paper utilizes deep learning to make distinctions between nightly data collects with and without maneuvers. Implementation of these techniques will allow the data collected from optical ground-based networks to enable well-informed and timely the space domain decision making.

Daytime Sky Brightness Characterization for Persistent GEO SSA

Grant Thomas

Air Force Institute of Technology

Space Situational Awareness (SSA) is fundamental to operating in space. SSA for collision avoidance ensures safety of flight for both government and commercial spacecraft through persistent monitoring. A worldwide network of optical and radar sensors gather satellite ephemeris data from the nighttime sky. Current practice for daytime satellite tracking is limited exclusively to radar as the brightening daytime sky prevents the use of visible-band optical sensors. Radar coverage is not pervasive and results in significant daytime coverage gaps in SSA. To mitigate these gaps, optical telescopes equipped with sensors in the near-infrared band (0.75-1.1um) may be used. The diminished intensity of the background sky radiance in the near-infrared band may allow for daylight tracking further into the twilight hours. To determine the performance of an near-infrared sensor for daylight custody, the sky background radiance must first be characterized spectrally as a function of wavelength. Using a physics-based atmospheric model with access to near-real time weather, we developed a generalized model for the apparent sky brightness of the Geostationary satellite belt. The model results are then compared to measured data collected from Dayton, OH through various sun angles for model validation and spectral sky radiance quantification in the visible and near-infrared bands.

Optical In-Situ Monitor – A Step Towards European Space-Based Debris Observations

Jens Utzmann[1], Luis Ferreira[2], Gerard Vives[1], Lionel Métrailler[2], Thomas Schildknecht[2], Nicolas Lièvre[3], Tim Flohrer[4]

[1]Airbus DS GmbH, [2]AIUB, [3]Micos, [4]ESA

The goals of the ESA project "Optical In-Situ Monitor" are to design and integrate a breadboard of a space-based space debris camera and to develop and test its end-to-end processing chain. The corresponding future flight model shall be used for the detection of small-sized (down to 1 mm) space debris in LEO as well as larger objects in GEO. It is intended to be flown on a platform in sun-synchronous orbit near the terminator plane.

The activity's breadboard system is comprised of the following three main elements:

- Breadboard Instrument: Acquires images of space debris scenes generated by the Test Set-Up with the characteristics of the future flight model instrument.
- Image processing pipeline: On-board debris detection & data reduction, on-ground astrometry & photometry.
- Test Set-Up: Scene generator for space debris observation scenarios.

The breadboard system will constitute a unique facility to perform realistic tests of the end-to-end chain for debris observations within a controlled environment. This chain starts from signal generation via the scene generator, is followed by the acquisition of images via the breadboard instrument and finally performs the data processing until the astrometric and photometric reduction step. High accuracy is required for the scene generation part regarding motion and photometric accuracy because it serves as ground-truth for the system. As prime contractor, Airbus DS is responsible for project management, system and performance engineering, the breadboard instrument, and on-board data processing hardware issues. The required image processing software is being developed at the Astronomical Institute of the University of Bern (AIUB). Micos provides the space debris scene generator, emulating both debris and star background. The paper will provide details on requirements and design of the three main elements. The current status of the project will be presented.

LauncherOne: Virgin Orbit's Dedicated Launch Vehicle for Small Satellites & Impact on the Space Enterprise Vision

Mandy Vaughn, Barry Matsumori

VOX Space

Virgin Orbit is developing a space transportation service to provide an affordable, reliable, and responsive dedicated ride to orbit for smaller payloads. No longer will small satellite users be forced to make a choice between accepting the limitations of flight as a secondary payload, paying dramatically more for a dedicated launch vehicle, or dealing with the added complexity associated with export control requirements and international travel to distant launch sites. Virgin Orbit has made significant progress towards first flight of a new vehicle that will give satellite developers and operators a better option for carrying their small satellites into orbit. This new service is called LauncherOne (See the figure below). LauncherOne is a two stage, air-launched liquid propulsion (LOX/RP) rocket. Air launched from a specially modified 747-400 carrier aircraft (named “Cosmic Girl”), this system is designed to conduct operations from a variety of locations, allowing customers to select various launch azimuths and increasing available orbital launch windows. This provides small satellite customers an affordable, flexible and dedicated option for access to space.

In addition to developing the LauncherOne vehicle, Virgin Orbit has embarked in worked with US government customers and across the new, emerging commercial sector to refine concepts for resiliency, constellation replenishment and responsive launch elements that can be key enables for the Space Enterprise Vision.

This presentation will summarize technical progress made on LauncherOne in the past year and extend the thinking of how commercial space, small satellites and this new emerging market can be brought to bear to enable true space system resiliency.

Passive Optical Link Budget **for LEO Space Surveillance**

Paul Wagner, Thomas Hasenohr, Daniel Hampf, Fabian Sproll, Leif Humbert,
Jens Rodmann, Wolfgang Riede

DLR

The rising space debris population is becoming an increasing risk for space assets. Even objects with the size of 10 mm can cause major damages to active spacecraft. Especially the orbit around 800 km high is densely populated with space debris objects. To assess the risk of collisions with active satellites, the Earth orbits need to be surveyed. Such space surveillance using wide angle optical sensors followed by laser optical measurements can deliver highly accurate positional data, allowing for an increase of orbit precision. Space debris laser ranging stations need initial orbit information to initiate laser tracking. The Institute of Technical Physics at the German Aerospace Center in Stuttgart runs an observatory to perform passive as well as laser optical measurements to LEO objects. In order to detect unknown objects, a wide-angle imaging system with a field of view in the range of 5° to 15° equipped with an astronomical CCD camera and a commercial of the shelf (COTS) lens was designed to observe the night sky for LEO objects continuously. This paper presents the passive optical link budget to show the benefits and limits of the physical performance of an optical surveillance system. A compact COTS system is able to detect objects with a couple of decimeters in size while large aperture telescope can detect objects below 10 cm. Additionally, data captured by a passive optical staring system with a 10 cm aperture was analyzed. It is shown that 90% of all objects with a radar cross section larger than 2 m^2 are detected with such a system. The smallest detected LEO object with this system has a size of 0.2 m x 0.2 m x 0.3 m. These measurements are compared to the developed link budget which allows an adjustment of the theoretical performance to fit realistic results.

Dynamics Observation of Space Objects Using Adaptive Optics Simulation and Light Curve Analysis

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This paper gives a thought of combining an adaptive optics simulation and light curve analysis in order to observe the attitude motion of space object in GEO.

Previous studies have analyzed light curve data to estimate the attitude motion and shape of space objects using Unscented Kalman Filter(UKF) and Multiple-Model Adaptive Estimation(MMAE). The attitude and shape estimation using the Kalman filter is required to give the initial attitude of the space object and the initial angular velocity, and this method assume that the initial values required for the Kalman Filter is already known. However, it is difficult to obtain its initial values when carrying out actual optical observation. Therefore, it is necessary to give initial values of posture and shape using some method.

Based on the above, this study aims to improve the accuracy of the estimation by determining the initial value using imaging data obtained from adaptive optics simulation, and aims to determine the imaging system that is required to perform the actual optical observation. In the simulation of adaptive optics, an adaptive optics software "Soapy" is used to obtain Point Spread Function (PSF) depending atmospheric conditions and imaging system.

Automation of a Wave-Optics Simulation and Image Post-Processing Package on Riptide

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Detailed wave-optics simulations and image post-processing algorithms are computationally expensive and benefit from the massively parallel hardware available at supercomputing facilities. We created an automated system that interfaces with the Maui High Performance Computing Center (MHPCC) Distributed Matlab Portal interface to submit massively parallel wave-optics simulations to the IBM iDataPlex (Riptide) supercomputer. This system subsequently post-processes the output images with an improved version of physically-constrained iterative deconvolution (PCID) and analyzes the results using a series of modular algorithms written in Python. With this architecture, a single person can simulate thousands of unique scenarios and produce analyzed, archived, and briefing-compatible output products with very little effort.

The views, opinions, and/or findings expressed are those of the author(s) and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

Improved Anomaly Detection Using Integrated Supervised and Unsupervised Processing

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There are two broad technologies of signal processing applicable to space object feature identification when resolved image data is not available, e.g., GEO space objects. Supervised processing uses training algorithms to analyze a large set of data for common characteristics that can be then used to identify, transform, and extract information from new data collected of the same given class. The pattern recognition technique of support vector machine is such a state-of-the-art algorithm. Unsupervised processing utilizes detailed physics-based models that generate comparison data that is then used to estimate parameters presumed to be governed by the same physical models. The Kalman filter exemplifies such techniques. Both processes have been used in non-resolved space object identification for Space Situational Awareness (SSA) and yield similar results, though arrived at using very different processes. The goal of integrating these two technologies is to achieve an improved performance by building on the diversity of the processes. We report herein a system that integrates Supervised and Unsupervised Processing for non-resolved SSA scenarios. Specifically, both supervised processing (support vector classification) and unsupervised processing (Kalman filter) jointly process brightness (radiometric flux intensity) measurements reflected by space objects. The system acts to determine whether measurements, made on a particular day, conform to a nominal operating mode (as determined from a baseline training set), or exhibits anomalous behavior because a particular parameter (e.g. object attitude, solar panel articulation angle) has changed in some way. The system demonstrates in several different scenarios that the integrated processing achieves performance that is superior to the separate processes acting alone for SSA detection of space object anomalies.

Debris Object Orbit Initialization Using the Probabilistic Admissible Region with Asynchronous Heterogeneous Observations

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One of the most challenging problems in treating space debris is the characterization of the orbit of a newly detected and uncorrelated observation. The admissible region 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 semi-major axis, eccentricity, etc., the admissible region can be constrained, resulting in the constrained admissible region. Based on known statistics of the measurement process, one can replace hard constraints with a probabilistic admissible region (PAR).

The PAR concept was introduced in 2014 [1]. In that paper, a Monte Carlo approach was used to construct the PAR in the range/range-rate space. 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. Using the GMM or particle cloud representations of the PAR, orbits can be prioritized for propagation in a multiple hypothesis tracking framework such as Finite Set Statistics [2]. In a recent paper, the PAR was adapted to enable the processing of radar range data [3].

In all the work on the PAR to date, observations were collected concurrently and by the same sensor. In this paper, we allow observations to have different time stamps. We also allow for non-collocated sensor collections; optical data can be collected by one sensor at a given time and range radar data collected by another sensor located elsewhere. We explore scenarios including mixed and unmixed optical and radar synchronized and asynchronous observations. Lack of observation synchronicity adds a new element to the

analysis, namely that the orbit may change from one observation time to another due to orbital perturbations. Thus, we also explore the impact of perturbations on the construction of the PAR.

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Event-Driven Site Controller for Distributed Optical SSA

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Lockheed Martin

The Space Situational Awareness (SSA) and amateur astronomy communities have experienced a rise in the number of observatory management software systems that enable remote, or autonomous operation of telescopes. Many of these systems use a scheduler that allocates observation time in blocks.

The Lockheed Martin Advanced Technology Center has developed the Distributed Observatory Manager for Enhanced SSA (DOMES) over the past five years. DOMES enables remote and autonomous operation of several optical observatories, and has been designed specifically for the purpose of collecting SSA data. This paper will analyze the limitations of time-block schedulers used by the SSA community, and discuss the novel capabilities that have been implemented in the DOMES software.

Orbital Resonances in the Vinti Solution

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As space becomes more congested, contested, and competitive, high-accuracy orbital predictions become critical for space operations. Current orbit propagators use the two-body solution with perturbations added, which have significant error growth when numerically integrated for long time periods. The Vinti Solution is a more accurate model than the two-body problem because it also accounts for the equatorial bulge of the Earth. Unfortunately, the Vinti solution contains small divisors near orbital resonances in the perturbative terms of the Hamiltonian, which lead to inaccurate orbital predictions. One approach to avoid the small divisors is to apply transformation theory, which is presented in this research. The methodology of this research is to identify the perturbative terms of the Vinti Solution, perform a coordinate transformation, and derive the new equations of motion for the Vinti system near orbital resonances. An analysis of these equations of motion offers insight into the dynamics found near orbital resonances. The analysis in this research focuses on the 2:1 resonance, which includes the Global Positioning System. The phase portrait of a nominal Global Positioning System satellite orbit is found to contain a libration region and a chaotic region. Further analysis shows that the dynamics of the 2:1 resonance affects orbits with semi-major axes ranging from -5.0 to +5.4 kilometers from an exactly 2:1 resonant orbit. Truth orbits of seven Global Positioning System satellites are produced for 10 years. Two of the satellites are found to be outside of the resonance region and three are found to be influenced by the libration dynamics of the resonance. The final satellite is found to be influenced by the chaotic dynamics of the resonance. This research provides a method of avoiding the small divisors found in the perturbative terms of the Vinti Solution near orbital resonances.

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