AMOS Advanced Maui Optical and Space Surveillance Technologies Conference

2016 ABSTRACTS OF TECHNICAL PAPERS

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ADAPTIVE OPTICS AND IMAGING

Session Chairs: Lt Col Michael Martinez, Air Force Office of Scientific Research and Charles Matson, Air Force Office of Scientific Research

SPACE SITUATIONAL AWARENESS

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POSTERS

ADAPTIVE OPTICS AND IMAGING

Session Chairs: Lt Col Michael Martinez, Air Force Office of Scientific Research and Charles Matson, Air Force Office of Scientific Research

All-Sky Image Fusion for a Synoptic Survey Telescope in Arctic and Antarctic Domains

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Detection of Near-Earth objects (NEOs), Earth-orbiting space objects (SOs), and transient astronomical phenomena (meteors, supernovae) have motivated the design and construction of a large class of synoptic survey telescope systems. To support growing efforts in national and international Space Situational Awareness, this study will investigate potential for a new class of aggregated ultra-wide field-of view sensors wherein simultaneously captured images are fused to extract previously unavailable information.

The paper will present 1) the design of a testbed integrating three high performance All-Sky sensors that will be installed and operational at existing facilities on Svalbard, Norway, and Antarctica over the next year; 2) demonstration of effective resolution, bit depth and noise improvement of empirical data; 3) projected performance for each observation campaign; and 4) an analytical reduced-order sizing relationships between identified performance characteristics and constituent All-Sky sensor properties.

The paper will discuss the derivation and extension of theoretical framework for combined Super-Resolution (SR) and image stacking techniques on ultra-wide field-of-view images, and identify the computational complexity of the hybrid approach. Figures of merit are detection capabilities such as signal-to-noise ratio (SNR), angular resolution, and brightness resolution using post-measurement computing processing resources. Collected images from the designed All-Sky sensor array will be used in this effort to cleverly detect and track objects through improved image resolution.

This work is a collaboration between Georgia Institute of Technology/Georgia Tech Research Institute (GTRI), Fuerza Area de Chile (FACH)/Academica Politecnica Aeronautica (APA) and Universidad de Chile.

Daylight Operation of a Sodium Laser Guide Star for Adaptive Optics Wave-Front Sensing

Stuart Jefferies[1], Michael Hart[2]

[1]Georgia State University, [2]University of Arizona

We report contrast measurements of a sodium resonance guide star against the daylight sky when observed through a tuned magneto-optical filter (MOF). The guide star was created by projection of a laser beam at 589.16 nm into the mesospheric sodium layer, and the observations made with a collocated 1.5 m telescope. While MOFs are used with sodium LIDAR systems during the day to improve the signal-to-noise ratio of the measurements, they have not so far been employed with laser guide stars to drive adaptive optics (AO) systems to correct atmospherically-induced image blur. We interpret our results in terms of the performance of AO systems for astronomy, with particular emphasis on the next generation of extremely large telescopes now being built.

A Comprehensive Approach to High-Resolution Daylight Imaging for SSA

Michael Hart[1], Stuart Jefferies[2], Douglas Hope[3], James Nagy[4]

[1]University of Arizona, [2]Georgia State University, [3]US Air Force Academy, [4]Emory University

Current high-resolution ground-based optical observations of resident space objects (RSO) are largely limited to night-time because of the difficulty of seeing objects against the daylight sky. Atmospheric aberration correction becomes very challenging because photon noise from Rayleigh-scattered sunlight obscures the signal from all but the largest and brightest RSOs. The problem is particularly severe for LEO objects: their proximity to the Earth means that, even at night, they are observable only around dawn and dusk. The lack of access to round-the-clock observation has unfortunate consequences for space surveillance, by limiting the efficiency of sensors in collecting important data. To overcome this limitation, we propose a suite of techniques which collectively allow high-resolution imaging during daylight. First, a wave-front reference beacon is created with a sodium laser guide star (LGS). High contrast on the associated wave-front sensor (WFS) is assured by use of a very narrow-band atomic vapor filter. Second, we exploit the short-term temporal coherence of atmospheric turbulence to infer higher spatial frequencies of the wave front than are naively measured by the WFS. Third, we compute tomographic solutions to the wave-front aberration, taking advantage of the non-constant angular velocity of the LGS through the atmosphere. This allows us to mitigate the focus anisoplanatism inherent in the LGS signal. Finally, we construct point-spread functions from the reconstructed wave fronts and use them for numerical restoration of the image data. In this paper, we show results from daylight measurements of a sodium LGS through a magneto-optical filter and the formalism which allows tomographic wave-front estimation from a single beacon. We also show the results of simulations suggesting that the combined method will allow diffraction-limited resolution of objects at least as faint as mV = 8 on a 3-m class telescope at visible wavelengths during full daylight.

Developing Geostationary Satellite Imaging at Lowell Observatory

Gerard van Belle

Lowell Observatory

Lowell Observatory operates the Navy Precision Optical Interferometer (NPOI), and owns & operates the Discovery Channel Telescope; this combination of facilities uniquely positions Lowell to develop a robust program of observing geostationary and other high-altitude (>1000mi) satellites. The Navy Precision Optical Interferometer (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 operates every night of the year (except holidays) in the visible with baselines between 8 and 100 meters (up to 432m is available), conducting programs of astronomical research and 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, an ongoing program of facility upgrades will be outlined. 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. 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 a approach that tracks the low-resolution (and thus, high signal-to-noise), bright near-IR fringes between aperture pairs, allowing multi-aperture phasing for high-resolution visible light imaging. A complementary program of visible speckle and aperture masked imaging at Lowell's 4.3-m Discovery Channel Telescope, for constraining the low-spatial frequency imaging information, will also be outlined, including results from a pilot imaging study

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High Time Resolution Photon Counting 3D Imaging Sensors

Oswald Siegmund, Camden Ertley, John Vallerga

University of California

Novel sealed tube microchannel plate (MCP) detectors using next generation cross strip (XS) anode readouts and high performance electronics have been developed to provide photon counting imaging sensors for Astronomy and high time resolution 3D remote sensing. 18mm aperture sealed tubes with MCPs and high efficiency SuperGenII and GaAs photocathodes have been implemented to access the NUV/optical regimes for ground based and space sensing applications. Photoelectrons emitted by the cathode and multiplied (~ x10^6) by the MCPs, then the XS readout uses these signals detected on two orthogonal layers of conductive fingers to achieve charge cloud centroiding to encode event X-Y positions. Spatial resolution readout of the new XS detectors can be better than 25 microns FWHM, with good image linearity and stability. Relatively low MCP gain operation permits longer overall sensor lifetimes and high local counting rates. The new electronics system has integrated 2D position (anode) and timing (MCP) channels that can encode event rates of >6 MHz with event timing accuracy of <90ps. Furthermore, we are developing a high speed ASIC version of the electronics for low power/low mass spaceflight applications. Current demonstrations have achieved high resolution imaging in addition to ~2 cm 3D depth resolution. We will also discuss the implications of recent tests with Atomic Layer Deposited (ALD) MCPs which offer better overall sealed tube lifetime and gain stability and the ability to improve the overall device quantum efficiencies by improving photoelectron detection efficiencies. Initial tests of ALD MCPs in a Planacon device will be presented. We will discuss these detector system developments and their implications for ground based remote sensing instruments as well as implementation in satellite instruments to study transient and variable astronomical objects.

SPIDER: Next Generation Chip Scale Imaging Sensor Update

Alan Duncan[1], Sam Thurman[2], Danielle Wuchenich[1], Chad Ogden[1], Rick Kendrick[1], S. J. S. B. Yoo[3], Tiehui Su[3]

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The LM Advanced Technology Center and UC Davis are developing an Electro-Optical (EO) imaging sensor called SPIDER (Segmented Planar Imaging Detector for Electro-optical Reconnaissance) that provides a 10x to 100x Size, Weight, and Power (SWaP) reduction alternative to the traditional bulky optical telescope and focal plane detector array. The substantial reductions in SWaP will 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., CMOS fabrication). The standard EO payload integration and test process which 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 that substantially reduces associated schedule and cost. This paper provides an overview of performance data on the second generation PIC for SPIDER developed under DARPA SPIDER Zoom program funding. We also update the design description of the SPIDER Zoom imaging sensor and the second generation PIC (high and low resolution versions).

SPACE SITUATIONAL AWARENESS

Session Chairs: Stacie Williams, Air Force Office of Scientific Research and Thomas Cooley, Air Force Research Laboratory

Operational Implementation of a Pc Uncertainty Construct for Conjunction Assessment Risk Analysis

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Earlier this year the NASA Conjunction Assessment and Risk Analysis (CARA) project presented the theoretical and algorithmic aspects of a method to include the uncertainties in the calculation inputs when computing the probability of collision (Pc) between two space objects, principally uncertainties in the covariances and the hard-body radius. The output of this calculation approach is to produce rather than a single Pc value an entire probability density function that will represent the range of possible Pc values given the uncertainties in the inputs and bring CA risk analysis methodologies more in line with modern risk management theory. The present study provides results from the exercise of this method against an extended dataset of satellite conjunctions in order to determine the effect of its use on the evaluation of CA event risk posture. The effects are found to be considerable: a good number of events are downgraded from or upgraded to a serious risk designation on the basis of consideration of the Pc uncertainty. The findings counsel the integration of the developed methods into NASA CA operations.

Assessing the UN IADC Space Debris Mitigation Guidelines: A Case for Ontology-Based Data Management

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As the population of debris orbiting the Earth increases, so does the risk of damaging collisions. The UN Inter-Agency Space Debris Coordination Committee (IADC) has issued space debris mitigation guidelines including a key recommendation that before mission's end, spacecraft should move far enough from GEO so as not to be an operational hazard to other objects in active missions. It can be extremely difficult to determine if a spacecraft or operator is in compliance with this guideline, as it requires prediction of future actions based upon many data types. Furthermore, there has been no comprehensive assessment of the adequacy or validity of the IADC recommendations. The EU strives for a Code of Conduct in space, the UN-COPUOS strives for guidelines to ensure the Long Term Sustainability of Space Activities, the FAA is concerned with Space Traffic Management, etc. If rules, policies, guidelines, and laws are put in place, how can any entity know who and what is adhering to them, when we don't even know how to quantify and assess behavior of space objects? The University of Arizona aims to address this salient issue.

As part of its new Space Object Behavioral Science (SOBS) initiative, UA is developing an ontology-based system to support integration, use, and sharing of space domain data. As a first use case, we will test the system's ability to assess compliance with the IADC recommendation to move beyond GEO at the end of a mission and the adequacy and validity of recommendations. We describe the relevant data types gathered for this use case, present a prototype ontology, and outline methods for combining semantic analysis with astrodynamics modeling. Without loss of generality, we present this method as an approach that will form the foundation of SOBS and be used to address pressing challenges in Space Situational Awareness.

JSpOC SSA: A Year in Review

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[1]*Air Force,* [2]*Joint Space Operations Center,* [3]*SSA Sharing Lead*

This paper summarizes significant improvements and changes made by the JSpOC's Space Surveillance Division since the AMOS conference in 2015. It will focus on the areas of spaceflight safety, breakup and debris analysis, reentry processing, launch support, and SSA sharing. In relation to all of these topics, the paper will discuss how the JSpOC has worked with international and industry partners to address SSA challenges, citing current collaboration efforts, as well as specific events. Future initiatives will be presented to provide insight into where the JSpOC's SSA mission is headed in 2017.

Coordination of Ground- and Space-Based Optical Systems: Lessons from the SKYNET Observation and Relocation Experiment

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In 2015 Dstl became aware that Airbus Defence & Space (DS) were planning to relocate the military communications satellite SKYNET 5A from its position at 6E covering Africa and the Middle East to one at approximately 95E, covering the Asia-Pacific region to increase commercial capacity to this region. The relocation was eventually scheduled for 17 June to 26 August 2015. The SKYNET constellation is the carrier of long range communications to support UK deployed forces and operations. Whilst the UK Ministry of Defence (MOD) does not own SKYNET assets itself (services are provided by the commercial operator, Airbus DS), it has a vested interest in the relocation of a UK critical asset, especially during significant manoeuvres such as this. The SKYNET move provided an opportunity to assess the utility of space situational awareness (SSA) capabilities within the UK and as part of a wider coalition. Dstl took the lead in coordinating an observation campaign known as the SKYNET Observation and Relocation Experiment (SORE) which for the UK component included participation of civilian ground-based SSA assets, military SSA operators via the UK Space Operations and Coordination Centre (SpOCC), wider academia and industry (most notably Airbus DS). Under the auspices of the Combined Space Operations (CSPO) initiative, Dstl engaged with international partner organisations that possess assets capable of observing this move, namely Canada, the US and Australia. Participating SSA assets were tasked in conjunction with the respective space operations centres in UK, Canada, Australia and the US; this also helped to advise military users on issues associated with mission sharing issues related to GEO SSA. A key enabler of SORE was the UK Mission Planner SSA software suite developed in-house by Dstl. It performs orbit prediction and determination, coverage predictions, error analysis and space data fusion based around two orbit propagators: SGP4 and special perturbations. The Mission Planner software allows Dstl to explore potential long-term solutions to support the UK SpOCC and advise on the utility of third party models. It can also be used to assess the utility and potential contribution of differing sensors to SSA. For this experiment Mission Planner was successfully utilised to cue Canadian space-based assets from orbits generated based upon UK ground-based EO observations of SKYNET. This paper will discuss the design, execution and initial conclusions from SORE. Particular emphasis will be placed on the lessons learnt from the event in terms of the generation and provision of SSA data products, including the interaction between the military SSA hub and commercial operator during the experiment. This paper shall provide an overview and examples of the Mission Planner's capabilities and the interface with Canadian space-based assets. Emphasis shall be made of the utility of the sensors and software towards fulfilling the requirements of the commercial operator as identified during the planning and execution of the experiment. Inferences will be made to the wider SSA community to inform on improved coordination to provide GEO SSA capabilities.

A Novel Method for Satellite Maneuver Prediction

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[1]Aptima, Inc., [2]LEO Projects, LLC, [3]Air Force Research Laboratory, Space Vehicles Directorate

A space operations tradecraft consisting of detect-track-characterize-catalog is insufficient for maintaining Space Situational Awareness (SSA) as space becomes increasingly congested and contested. In this paper, we apply analytical methodology from the Geospatial-Intelligence (GEOINT) community to a key challenge in SSA: predicting where and when a satellite may maneuver in the future. We developed a machine learning approach to probabilistically characterize Patterns of Life (PoL) for geostationary (GEO) satellites. PoL are repeatable, predictable behaviors that an object exhibits within a context and is driven by spatio-temporal, relational, environmental and physical constraints. An example of PoL are station-keeping maneuvers in GEO which become generally predictable as the satellite re-positions itself to account for orbital perturbations. In an earlier publication, we demonstrated the ability to probabilistically predict maneuvers of the Galaxy 15 (NORAD ID: 28884) satellite with high confidence eight days in advance of the actual maneuver. Additionally, we were able to detect deviations from expected PoL within hours of the predicted maneuver (Shabarekh et al, 2016). This was done with a custom unsupervised machine learning algorithm, the Interval Similarity Model (ISM), which learns repeating intervals of maneuver patterns from unlabeled historical observations and then predicts future maneuvers. In this paper, we introduce a supervised machine learning algorithm that works in conjunction with the ISM to produce a probabilistic distribution of when future maneuvers will occur. The supervised approach uses a Support Vector Machine (SVM) to process the orbit state whereas the ISM processes the temporal intervals between maneuvers and the physics-based characteristics of the maneuvers. This multiple model approach capitalizes on the mathematical strengths of each respective algorithm while incorporating multiple features and inputs. Initial findings indicate that the incorporation of the SVM and orbit state information can increase accuracy and timeliness of predicted maneuvers over the ISM and astrometric observations only.

ORBITAL DEBRIS

Session Chairs: Tim Flohrer, ESA/ESOC Space Debris Office and Thomas Schildknecht, Astronomical Institute University of Bern

NASA's Orbital Debris Optical and IR Ground-Based Observing Program Utilizing the MCAT, UKIRT, and Magellan Telescopes

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Characterizing debris in Earth-orbit has become increasingly important as the growing population of debris poses greater threats to active satellites each year. Currently, the Joint Space Operations is tracking > 23,000 objects ranging in size from 1-meter and larger in geosychronous orbits (GEO) to 10-cm and larger at low-Earth orbits (LEO). Model estimates suggest that there are hundreds of thousands of pieces of spacecraft debris larger than 10 cm currently in orbit around the Earth. With such a small fraction of the total population being tracked, and new break-ups occurring from LEO to GEO, new assets, techniques, and approaches for characterizing this debris are needed.

With this in mind, NASA's Orbital Debris Program Office has actively tasked a suite of telescopes around the world. In 2015, the newly-built 1.3m optical Meter Class Autonomous Telescope (MCAT) came on-line on Ascension Island and is now being commissioned. MCAT is designed to track Earth-orbiting objects above 200km, conduct surveys at GEO, and work with a co-located Raven-class commercial-off-the-shelf system, a 0.4m telescope with a field-of-view similar to MCAT's and research-grade instrumentation designed to complement MCAT.

The 3.8m infrared UKIRT telescope on Mauna Kea, Hawaii has been heavily tasked to collect data on individual targets and in survey modes to study both the general GEO population and a break-up event. Data collected include photometry and spectroscopy in the near-Infrared (0.85 – 2.5um) and the mid-infrared (8-16um).

Finally, the 6.5-m Baade Magellan telescope at Las Campanas Observatory in Chile was used to collect optical photometric survey data in October 2015 of two GEO Titan transtage breakups, focusing on locations of possible debris concentrations as indicated by the NASA standard break-up model.

A summary of these programs will be presented.

The Population of Optically Faint GEO Debris

Patrick Seitzer[1], Juan Gomez[2], James Frith[3,4], Heather Cowardin[3,4], Andrew Burkhardt[5], Brent Buckalew[4], Ed Barker[6], Catherine Kaleida[7], Susan M. Lederer[8], Chris H. Lee[2]

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The 6.5-m Magellan telescope 'Walter Baade' at the Las Campanas Observatory in Chile has been used for spot surveys of the geosynchronous Earth orbit (GEO) regime to study the population of optically faint GEO debris. The goal is to estimate the population of GEO debris at sizes much smaller than can be studied with 1-meter class telescopes. Despite the small field of view of the Magellan instrument (diameter 0.5-degree), a significant population of objects fainter than R = 19th magnitude has been found with angular rates consistent with circular orbits at GEO. We compare the size of this population with the numbers of GEO objects found at brighter magnitudes by smaller telescopes.

The observed detections have a wide range in characteristics starting with those appearing as short uniform streaks. But there are a substantial number of detections with variations in brightness ("flashers") during the 5-second exposure. The duration of each of these flashes can be extremely brief: sometimes less than half a second. This is characteristic of a rapidly tumbling object with a quite variable projected product of size * albedo. If the albedo is of the order of 0.2, then the largest projected size of these objects is around 10-cm.

The data in this paper was collected over the last several years using Magellan's IMACS camera in f/2 mode. The analysis shows the brightness bins for the observed GEO population as well as the periodicity of the flashers. All detected objects are checked for possible correlation with known objects in the public catalog. The focus of the paper will be on all optically faint objects. The goal of this project is to better characterize the faint debris population in GEO that access to a 6.5-m optical telescope in a superb site can provide.

Optical Observations of Briz-M Fragments in GEO

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On January 21, 2016 the Joint Space Operations Center (JSpOC) of the US Strategic Command was informing about a possible breakup of a Briz-M upper stage in the geostationary ring. This upper stage with the International Designator 2015-075B is associated with the launch of the Russian Cosmos 2513 which took place only 6 weeks earlier on December 13, 2015. The same day, ESA together with the Astronomical Institute of the University of Bern (AIUB) prepared for a survey campaign using the 1-meter ESA Space Debris Telescope (ESASDT) on Tenerife and AIUB's sensors at the Zimmerwald Observatory. The selection of the survey strategy to search for fragments of this event was based on a synthetic debris cloud, assuming a hypothetical fragmentation epoch (the real fragmentation epoch was not known at this time). Observations with the ESASDT were performed on January 23 and 24, and in additional two nights in February. The uncorrelated objects found during this campaign were followed-up with the Zimmerwald sensors. We will present the observation results and the challenges related to the association of the candidate fragment tracklets with each other, the initial orbit determination, and the determination of the breakup epoch.

Application of Satellite Laser Ranging Techniques for Space Situational Awareness Efforts

Mark Shappirio[1], D.B. Coyle[1], J.F. McGarry[1], J. Bufton[2]. J.W. Cheek[3], S.M. Hull[1], P.R. Stysley[1], X. Sun[1], R.P. Young[1], T. Zagwodzki[4]

[1]NASA/GSFC, [2]Global Science and Technology, [3]Sigma SpaceCo., [4]Cybioms Inc.

With the numbers of conjunction avoidance maneuvers for the International Space Station and other Low Earth Orbit satellites rising and likely to continue to increase, the need to develop methods to produce accurate 72+ hour orbital predictions is becoming critical. One emerging solution is to utilize satellite laser ranging techniques to range to debris and refine the initial positions to improve the orbital predictions for objects predicted to experience a close approach. Some stations in Europe have already demonstrated that this technique is possible, but it has not been employed to refine the likelihood of collision. We will present a notional architecture for laser ranging to debris utilizing existing satellite laser ranging or visual tracking facilities. We will also discuss the capabilities of laser ranging for Space Situational Awareness and provide a direct comparison to current visual and radar tracking methods.

Optical Techniques for Space Environment Management

Ben Greene,

Space Environment Research Centre

The Space Environment Research Centre (SERC) is a fully-funded multi-national research collaboration for the management and mitigation of space debris using optical technologies. SERC is tasked with developing mitigation strategies for the many debris objects not amenable to space-based interventions.

SERC research leverages very accurate information and data from a new optical space tracking network to develop viable near-term strategies to manage debris using only ground-based infrastructure.

SERC has sufficient resources to conduct full-scale on-orbit testing of candidate approaches. We will report SERC progress in astrodynamics, precision catalogs, conjunction processing, adaptive optics and high power lasers as well as the architecture of the research effort.

Laser Remote Maneuver of Space Debris at the Space Environment Research Centre

Matthew Bold

Lockheed Martin Space Systems

Active satellites have the ability to maneuver to avoid collision with other space objects. Unfortunately, the majority of objects in space are debris objects that do not have the ability to maneuver. In the future the population of debris objects will grow and the probability of collision will increase. This paper will provide details on plans to use a ground based laser with uplink adaptive optics compensation to apply photon pressure to debris objects and maneuver them out of harm’s way. This work is ongoing at the Space Environment Research Centre at Mt. Stromlo Australia with collaborative efforts from Lockheed Martin, Electro-Optics Systems Inc. and the Australian National University.

Tracking Low Earth Orbit Small Debris with GPS Satellites as Bistatic Radar

Craig Benson, Sana Qaisar, Md. Sohrab Mahmud

UNSW Canberra

Space debris is a growing problem and collisions are potentially lethal. Trajectories for small objects are predicted based on infrequent measurements, and the scale of manoeuvre required to avoid collisions is a function of trajectory accuracy. Frequent and precise observations will improve trajectory accuracy In this paper, we extend on aspects of the feasibility of tracking space debris in Low Earth Orbit using emissions from GNSS satellites as bistatic radar illuminators. The wavelengths of GNSS signals are of order 20-30 cm and our primary focus is to track debris smaller than this, thereby maintaining phase stability of the scattered signals, enabling very long coherent processing intervals. However the signals scattered by debris will be very weak at a terrestrial receiver, requiring the computationally expensive integration of a large number of signals, over an extended duration and with a large phased-array. Detection of such weak signals in the presence of relatively strong direct-arrival signals is difficult, since sufficient cross-correlation protection is needed. We show that sufficient cross-correlation protection can be obtained due to the large and varying Doppler shift, and also illustrate a novel processing approach utilising downshifting of the collected signal to audio frequency. This technique dramatically reduces the cost and complexity of updating debris trajectories. The processing cost of preserving an uncertainty volume of many hundreds of meters around the predicted debris track is very modest, and searching within that uncertainty volume is undertaken at audio sampling rates. Further we explore search techniques that further lower the already modest search cost within the preserved uncertainty volume. We conclude with an outline of a system using these techniques that could provide centimetre level tracking of large quantities of small orbital objects at a modest cost.

Sub-Millimeter Size Debris Monitoring System with IDEA OSG 1

Masahiko Uetsuhara[1], Mitsunobu Okada[1], Yasunori Yamazaki[1], Toshiya Hanada[2]

[1]ASTROSCALE, [2]Kyushu University

Timely mapping and tracking capabilities for space debris in sub-millimeter size regime are essential to model the LEO environment and to improve spaceflight safety. This paper introduces the sub-millimeter size debris monitoring system, which consists of the in-situ monitoring of sub-millimeter size debris using impact sensors on board a microsatellite called IDEA OSG 1, and the ground-based data processing platform to communicate with the satellite and to process the impact data.

Sub-millimeter size debris is too small to detect using ground-based observation systems. Unlike trackable space debris, which are 10cm or larger, spacecraft cannot always make collision avoidance maneuvers. Despite its small size, due to its high velocity, sub-millimeter size debris has the capacity to cause lethal damages to operating spacecraft.

Sub-millimeter size debris data were originally gathered by scanning the surfaces of returned objects such as Long Duration Exposure Facility (LDEF) and the US space shuttles. After the end of the Shuttle program, there was no alternative to measure the sub-millimeter size debris environment. The data from returned objects is cumulated during the whole mission, therefore the accuracy of the collected data, time and location, is low.

IDEA project, initiated by Kyushu University, aims at developing in-situ debris environmental awareness by constructing a constellation of micro satellites carrying impact sensors. IDEA OSG 1, the first of the IDEA series, is expected to launch between the end of 2016 to early 2017. IDEA OSG 1 equips the impact sensor developed by JAXA, the Space Debris Monitor or SDM.

IDEA OSG 1 will detect sub-millimeter size debris in one of the most congested orbit and provide key data about the size, the time, and the precise location of sub-millimeter size debris. Data gathered from IDEA OSG 1 are transmitted to the ground-based data processing platform in near real time. The ground-based data processing platform identifies impacts of space debris from the satellite telemetry and transfers the information via the Internet. This information will contribute to update space debris models, provide space debris mapping capabilities, and eventually allow spacecraft manufacturers to use enhanced information for spacecraft shielding designs.

INSTRUMENTATION AND OPTICAL SURVEILLANCE

Session Chairs: Mark Ackermann, Sandia National Laboratories and Susan Lederer, NASA Johnson Space Center

Combined Space-Based Observations of Geostationary Satellites

Lauchie Scott[1], Dr Brad Wallace[1], Lt Kevin Bernard[1], Stefan Thorsteinson[2]

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Canada has launched the Sapphire and NEOSSat space surveillance satellites into a dawn-dusk low earth orbit performing both operational (Sapphire) and experimental (NEOSSat) Space Situational Awareness (SSA) observations. These small space telescopes feature visual-band instruments optimized to track Resident Space Objects (RSOs) in deep space orbits measuring both positional (metric) and brightness (photometric) characteristics of the RSOs. Both sensors achieve positioning accuracies on deep space resident space objects less than three arcseconds.

After a prolonged commissioning period, NEOSSat has joined Sapphire in collecting observations of deep space satellites and the NEOSSat SSA science activities have begun. One of the SSA science plan activities is to determine the benefits of combining space-based metric observations of NEOSSat with Sapphire to learn the practicalities of conducting combined operations of the two space-based platforms. To answer this question an experiment was devised to simultaneously observe Canadian geostationary satellites, such as Anik F2, with both Sapphire and NEOSSat. Both space-based tracking data were collected in a near simultaneous manner to augment both metric (orbit determination) and photometric (object state characterization) experiment needs.

This paper describes the characteristics of optical space-based space surveillance measurements of geostationary satellites collected by these orbiting sensors. We describe the orbit determination accuracies using experimental data for two different cases; a) single space-based sensor measurements alone and b) combined space-based measurements. We show the differences in orbital quality, the advantages and disadvantages of each sensor's data type and how combined space-based tracking data could be used to help reduce risk of orbital collisions on Canadian geosynchronous satellites.

Mission Design and Simulation Considerations for ADReS-A

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Space debris in general has become a major problem for modern space activities. Guidelines to mitigate the threat have been recommended, better prediction models are developed and an advanced observation of objects orbiting Earth is in progress. And still – without the implementation of active debris removal (ADR), the number of debris in space will exponentially increase. To support the ongoing research on ADR-missions, this paper presents the updated mission design of ADReS-A (Autonomous Debris Removal Satellite - #A) - one possible concept for the multiple active removal of large debris in Low Earth orbit, in this case especially of rocket bodies of the SL-8-type. ADReS-A as chaser satellite is supported by at least 5 de-orbit kits, allowing for the same number of targets to be removed. While ADReS-A is conceived for handling of the target, the kit's task is the controlled re-entry of the designated rocket body.

The presented mission design forms the basis for the simulation environment in progress. The simulation shall serve as testbed to test multiple scenarios in terms of approach and abort optimization or different tumbling modes of the target. The ultimate goal is the test of autonomous behaviors of the spacecraft in case of unforeseen failures during the approach phase. Considerations to create a simulation for the described mission are presented and discussed. A first visualization of pre-calculated aboard trajectories can be found at the end of this paper.

Matched Template Signal Processing for Coherent, Continuous Wave Laser Tracking of Space Debris

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We aim to develop a coherent detection scheme for ground-based laser tracking of space debris. In a coherent detection the signal is interfered with a bright local oscillator to amplify the signal at the photodetector. This can give a system the ability to distinguish weak signals reflected from the space debris, in the presence of background and photodetector noise.

The performance of current laser based debris ranging systems is typically limited by laser power. Due to the low effective reflectivity of debris targets as well as transmission losses, the return signal can be extremely weak and easily obscured by background light from the surroundings. This not only limits the tracking performance but also prevents the tracking of space debris during the day. In a coherent system, the reflected light from the target is interfered with a bright local oscillator. This local oscillator will amplify the detected signal above other noise sources, allowing the system to distinguish signal photons from background noise photons. This may allow laser-based tracking of space debris from the ground during the daytime.

In addition to a coherent optical layout, we are also utilizing a matched filter at the receiver to retrieve the orbital parameters of the space debris. The reflected signal is affected by both the range and velocity of the space debris. A template of the signal is generated at the receiver and a cross-correlation is carried out with the reflected signal. Therefore in order to match the template to the return signal, the right parameter values need to be used. The further these values are from the reflected signal received at the detector, the smaller the cross-correlation amplitude will be. A template bank will be generated for each orbit, covering the range of parameter uncertainties and where the best match can be used to obtain the orbital information of the debris.

We aim to present experimental and simulated results on the coherent system. The results will show how we plan to have a matched filter template bank to obtain the correct parameter values of both the velocity and range of the space debris target. We also aim to present the performance of the system in the presence of background noise. The authors would like to acknowledge the support of the Cooperative Research Center for Space Environmental Management (SERC Limited) through the Australian Government Cooperative Research Centre Programme.

GEO Satellite Characterization Through Polarimetry Using Simultaneous Observations from Nearby Optical Sensors

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Polarimetry has shown capacity for both geometry inference and material classification in recent years. By carefully selecting a polarimetric modality with higher contrast for the objects of interest, it becomes possible to discriminate those objects by leveraging the understanding of differing geometry, material characteristics, and its mapping into consequent polarisation measurements. Expansion of the measurement dimensionality increases the potential to discriminate unresolved objects, thereby widening the possible set of imaging tasks. The use of polarimetry as a technique to characterise non-resolved GEO satellites using telescopes of small aperture (less than 0.5 meters) is currently under study by the Space Research Group in UNSW Canberra. First experiments are currently being performed in order to evaluate the use of this technique to characterise GEO satellites. A comparison of both polarimetric and irradiance only acquisitions is being implemented.

Two telescopes separated by 500m are used for the experiments. One of them (USAFA funded Falcon Telescope Network) has the capability to be remote controlled and time tasks assigned, and the other can be operated on-site and is connected to a computer in a network which can control the former with known latency, both synchronised by the same GPS clock. A linear polariser is situated in a collimated beam section of the light path in one of the telescopes to capture polarised photometric measurements, while the other is acquiring the non-polarised photometric signature of the same GEO satellite under observation. The telescope detectors will be radiometrically calibrated to one another in order to evaluate the photometric data at the same scale.

We evaluate the polarised and non-polarised synchronous time photometric curves as a preliminary test to determine satellite signature and its variation over time. We will report on the discrimination of unresolved satellites and the merit of including polarisation sensing within the task.

Multiple Observing Modes for Wide-Field Optical Surveillance of GEO Space

John McGraw, Mark Ackermann, Peter Zimmer

J.T. McGraw and Associates, LLC

Very wide field of view optical sensors with silicon detectors are being used in multiple survey modes by J. T. McGraw and Associates to provide persistent, affordable surveillance of GEO space to faint limiting magnitudes. Examples include:

- classical staring mode with typical integration times of seconds provided by multiple co-directed sensors to provide a deep mosaic of tens of square degrees per exposure to faint limiting magnitude

- step-and-stare observations of several second integration time from which a continuous, overlapped, mosaicked image of GEO space can be provided

- time-delay and integrate (TDI) imagery obtained by driving the telescope in declination and stepping the telescope in the E-W direction, which produces repeated, overlapping (if desired), synoptic images of GEO space

With current 350 mm diameter optics, detection limits for concentrated observations (e.g. “neighborhood watch”) detection limits of magnitude 18 are achieved, and for uncued survey the detection limits are fainter than magnitude 16. Each of these techniques can employ multiple telescopes to obtain search rates in excess of 1000 square degrees per hour, allowing complete uncued CONUS GEO surveillance to +/- 15 degrees latitude every two nighttime hours. With appropriate placement, sensors could provide complete coverage of GEO to these limiting magnitudes at the same survey rate.

At each step of the development of this unique capability we discuss the fundamental underlying physical principals of optics, detectors, search modes and siting that enable this survey, a valuable adjunct to RF, GEODSS and other optical surveys of GEO space.

Affordable Wide-field Optical Space Surveillance using sCMOS and GPUs

Peter Zimmer, Mark Ackermann, John T. McGraw

J.T. McGraw and Associates, LLC

Recent improvements in sCMOS technology enable affordable, wide-field, and rapid cadence surveillance from LEO to beyond GEO using largely off-the-shelf hardware. sCOMS sensors, until very recently, suffered from several shortcomings when compared to CCD sensors – lower sensitivity, smaller physical size and less predictable noise characteristics. Sensors that overcome the first two of these are now available commercially and the principals at J.T. McGraw and Associates (JTMA) have developed observing strategies that minimize the negative effects, while leveraging the key features of sCMOS: fast readout and low average readout noise.

JTMA has integrated an sCMOS sensor into an existing COTS telescope system to develop and test new detection techniques designed for uncued optical surveillance across a wide range of apparent object angular rates – from degree per second for LEO objects to a few arcseconds per second for objects beyond GEO.

One major complication arises from the use of these fast, efficient detectors: increased useful frame rate means increased data volume. Fortunately, GPU technology continues to advance at a rate similar to detector technology, and we report on the results and performance of our new detection techniques implemented on new generation GPUs. Early results show detection significance within 20% of the expected theoretical limiting signal-to-noise using commodity GPUs in near real time across a wide range of object parameters, greatly closing the gap in sensitivity between moving object and tracked object detection techniques.

Automated Astrometric Analysis of Satellite Observations Using Wide-Field Imaging

Jovan Skuljan, John Kay

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An observational trial was conducted in the South Island of New Zealand from 24 to 28 February 2015, as a collaborative effort between the United Kingdom and New Zealand in the area of space situational awareness. The aim of the trial was to observe a number of satellites in low Earth orbit using wide-field imaging from two separate locations, in order to determine the space trajectory and compare the measurements with the predictions based on the standard two-line elements. This activity was an initial step in building a new space situational awareness capability at the Defence Technology Agency of the New Zealand Defence Force. New Zealand has an important strategic position as the last land mass that many satellites selected for deorbiting pass before entering the Earth's atmosphere over the dedicated disposal area in the South Pacific.

A preliminary analysis of the trial data has demonstrated that relatively inexpensive equipment can be used to successfully detect satellites at moderate altitudes. A total of 60 satellite passes were observed over the five nights of observation and about 2600 images were collected. A combination of cooled CCD and standard DSLR cameras were used, with a selection of lenses between 17 mm and 50 mm in focal length, covering a relatively wide field of view of 25 to 60 degrees. The CCD cameras were equipped with custom-made GPS modules to record the time of exposure with a high accuracy of one millisecond, or better. Specialised software has been developed for automated astrometric analysis of the trial data. The astrometric solution is obtained as a two-dimensional least-squares polynomial fit to the measured pixel positions of a large number of stars (typically 1000) detected across the image. The star identification is fully automated and works well for all camera-lens combinations used in the trial. A moderate polynomial degree of 3 to 5 is selected to take into account any image distortions introduced by the lens. A typical RMS error of the least-squares fit is about 0.1 pixels, which corresponds to about 4 to 10 seconds of arc in the sky, depending on the pixel scale (field of view). This gives a typical uncertainty between 10 and 25 metres in measuring the position of a satellite at a characteristic range of 500 kilometres.

The results of this trial have confirmed that wide-field measurements based on standard photographic equipment and using automated astrometric analysis techniques can be used to improve the current orbital models of satellites in low Earth orbit.

Intelligent Sensor Control for Autonomous Catalogue Building and Maintenance

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In order to safeguard the continued use of space-based technologies, effective monitoring and tracking of man-made resident space objects (RSOs) is paramount. The diverse characteristics, behaviours and trajectories of RSOs make space surveillance a challenging application of the discipline that is tracking and surveillance. When surveillance systems are faced with non-canonical scenarios, it is common for human operators to intervene while researchers adapt and extend traditional tracking techniques in search of a solution. A complementary strategy for improving the robustness of space surveillance systems is to place greater emphasis on the anticipation of uncertainty. Namely, give the system the intelligence necessary to autonomously react to unforeseen events and to intelligently and appropriately act on tenuous information rather than discard it.

In this paper, we describe our progress building a low-cost intelligent space surveillance system capable of autonomously cataloguing and maintaining track of RSOs. It currently exploits robotic electro-optical sensors, high-fidelity state-estimation and propagation as well as constrained initial orbit determination (IOD) to intelligently and adaptively manage its sensors in order to maintain an accurate catalogue of RSOs. In a step towards fully autonomous cataloguing, the system has been tasked with maintaining surveillance of a portion of the geosynchronous (GEO) belt. Using a combination of survey and track-refinement modes, the system is capable of maintaining a track of known RSOs and initiating tracks on previously unknown objects. Uniquely, due to the use of high-fidelity representations of a target's state uncertainty, as few as two images of previously unknown RSOs may be used to subsequently initiate autonomous search and reacquisition. To achieve this capability, particularly within the congested environment of the GEO-belt, we use a constrained admissible region (CAR) to generate a plausible estimate of the unknown RSO's state probability density function and disambiguate measurements using a particle-based joint probability data association (JPDA) method.

We also present the findings of a field trial of an experimental system that incorporates these techniques. The results demonstrate that such a system is capable of autonomously searching for an RSO that was briefly observed days prior in a GEO-survey and discriminating it from the measurements of other previously catalogued RSOs.

Enabling GEODSS for Space Situational Awareness (SSA)

Sam Wootton

The MITRE Corporation

The Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) System has been in operation since the mid-1980's. While GEODSS has been the Space Surveillance Network's (SSN) workhorse in terms of deep space surveillance, it has not undergone a significant modernization since the 1990's. This means GEODSS continues to operate under a mostly obsolete, legacy data processing baseline. The System Program Office (SPO) responsible for GEODSS, SMC/SYGO, has a number of advanced Space Situational Awareness (SSA)-related efforts in progress, in the form of innovative optical capabilities, data processing algorithms, and hardware upgrades. Each of these efforts is in various stages of evaluation and acquisition. These advanced capabilities rely upon a modern computing environment in which to integrate, but GEODSS does not have one—yet. The SPO is also executing a Service Life Extension Program (SLEP) to modernize the various subsystems within GEODSS, along with a parallel effort to implement a complete, modern software re-architecture. The goal is to use a modern, service-based architecture to provide expedient integration as well as easier and more sustainable expansion. This presentation will

describe these modernization efforts in more detail and discuss how adopting such modern paradigms and practices will help ensure the GEODSS system remains relevant and sustainable far beyond 2027.

Adapting a Planetary Science Observational Facility for Space Situational Awareness

Phil Bland[1], Martin Towner[1], Trent Jansen-Sturgeon[1], Hadrien Devillepoix[1], Eleanor Sansom[1], Mark Rutten[2]

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The Desert Fireball Network (DFN) is designed to track meteoroids entering the atmosphere, determine pre-entry orbits (their origin in the solar system), and pinpoint fall positions for recovery by field teams. Fireball observatories are sited at remote dark-sky sites across Australia - logistics for power, sensor platforms, and data connection are in place. Each observatory is a fully autonomous unit, taking 36MP all-sky images (with fisheye lenses) throughout the night, capable of operating for 12 months in a harsh environment, and storing all imagery collected over that period. They are intelligent imaging systems, using neural network algorithms to recognize and report fireball events. An automated data reduction pipeline delivers orbital data and meteorite fall positions. Currently the DFN stands at 50 observing stations covering ~2.5 million km2. A sub-set of the existing stations will be upgraded with a parallel camera package using prime lenses. Paired stations will allow triangulation. The high resolution array would deliver a ~Gpixel tiled image of the visible sky every 10 sec, at 20” resolution. There are benefits in transient astronomy (optical flashes associated with gamma-ray bursts; flares from sources that generate ultra-high energy cosmic rays), and space situational awareness. The hardware upgrade would extend the resolution of the DFN into the V=11-12 magnitude range for objects in LEO, allowing us to observe significant activity during the terminator period. The result would be a wide field array, capable of triangulation, with a 3500km baseline enabling a larger terminator observing ‘window’.

SSA ALGORITHMS

Session Chairs: Randall Alliss, Northrop Grumman Corporation and Ryan Coder, Integrity Applications Incorporated-Pacific Defense Solutions (IAI-PDS)

Uncued Low SNR Detection with Likelihood from Image Multi Bernoulli Filter

Timothy Murphy, Dr. Marcus Holzinger

Georgia Tech

Both SSA and SDA necessitate uncued, partially informed detection and orbit determination efforts for small space objects which often produce only low strength electro-optical signatures. General frame to frame detection and tracking of objects includes methods such as moving target indicator, multiple hypothesis testing, direct track-before-detect methods, and random finite set based multi-object tracking. This paper will apply the multi-Bernoilli filter to low signal-to-noise ratio (SNR), uncued detection of space objects for space domain awareness applications. The primary novel innovation in this paper is a detailed analysis of the existing state-of-the-art likelihood functions and a likelihood function previously proposed by the authors [Murphy, 2016]. The recently proposed likelihood function, which is based on a binary hypothesis test on the measured result of a matched filter, is shown to have superior low SNR space object detection qualities. The algorithm is first tested on simulated electro-optical images. This will demonstrate that multiple uncued and partially informed objects of varying photometric signal strength can detected and tracked in a very general framework and provide an environment for showing the limiting SNR. Preliminary results are promising for a total object photometric SNR of 1.0 to 2.0, depending on prior information. The algorithm is tested on electro-optical imagery obtained from a variety of sensors at Georgia Tech, including the GT-SORT 0.5m Raven-class telescope, and a ten degree field of view high frame rate CMOS sensor. In particular, a data set of an extended pass of the Hitomi Astro-H satellite approximately 3 days after loss of communication and potential break up is examined. This work will improve our understanding of applying likelihood functions directly on image data. Multi-Bernoulli filtering is a relatively efficient way to search through series of images blindly for space objects with extreme potential for parallelization

Utilizing Novel Non-Traditional Sensor Tasking Approaches to Enhance the Space Situational Awareness Picture Maintained by the Space Surveillance Network

Alex Herz[1], Ella Herz[1], Kenneth Center[1], Doug George[1], Penina Axelrad[2], Brandon Jones[3]

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The Space Surveillance Network (SSN) is tasked with the increasingly difficult mission of detecting, tracking, cataloging and identifying artificial objects orbiting the Earth, including active and inactive satellites, spent rocket bodies, and fragmented debris. Much of the architecture and operations of the SSN are limited and outdated. Efforts are underway to modernize some elements of the systems. Even so, the ability to maintain the best current Space Situational Awareness (SSA) picture and identify emerging events in a timely fashion could be significantly improved by leveraging non-traditional sensor sites.

Orbit Logic, the University of Colorado and the University of Texas are developing an innovative architecture and operations concept to coordinate the tasking and observation information processing of non-traditional assets based on information-theoretic approaches. These confirmed tasking schedules and the resulting data can then be used to “inform” the SSN tasking process. The ‘Heimdall Web’ system is comprised of core tasking optimization components and accompanying Web interfaces, are supported by a

secure, split architecture that for the first time allows non-traditional sensors to support SSA while improving SSN tasking.

Heimdall Web application components appropriately score/prioritize space catalog objects based on covariance, priority, observability, expected information gain, and probability of detect - then coordinate an efficient sensor observation schedule for non-SSN sensors contributing to the overall SSA picture maintained by the Joint Space Operations Center (JSpOC). The Heimdall Web Ops concept supports sensor participation levels of “Scheduled”, “Tasked” and “Contributing”. Scheduled and Tasked sensors are provided optimized observation schedules or object tracking lists from central algorithms, while Contributing sensors review and select from a list of “desired track objects”. All sensors are “Web Enabled” for tasking and feedback, suppling observation schedules, confirmed observations and related data back to Heimdall Web to complete the feedback loop for the next scheduling iteration.

OrbitOutlook Data Processing Algorithms: Multi-Modal Fusion for Autonomous Verification and Validation of Commercial and Crowdsourced Data

Larry Gunn[1], Channing Chow[2], Keric Hill[2], Daron Nishimoto[2], Mark Bolden[3], Jason Goldberg[3]

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OrbitOutlook Data Processing Algorithms: Multi-Modal Fusion for Autonomous Verification and Validation of Commercial and Crowdsourced Data Larry Gunn Defense Advanced Research Projects Agency, 675 North Randolph Street, Arlington, VA 22203 Channing Chow, Keric Hill, Jack Wetterer, Daron Nishimoto Integrity Applications Incorporated, Pacific Defense Solutions, LLC, 535 Lipoa Pkwy Suite 101, Kihei, HI 96753 Mark Bolden, Jason Goldberg Schafer Corporation, 3811N. Fairfax Drive, Arlington, VA 22203

As the space object population has rapidly grown, the data volume required to produce reliable orbital estimates has far surpassed the pace of the traditional government sensor acquisition process. Fortunately, over the last few years the commercial, academic, amateur, and government communities have stepped up to cost-effectively design sensor networks leveraging commercial off-the-shelf (COTS) and existing hardware. It is infeasible to follow the traditional sensor accreditation process to certify hundreds of sensors that are separately managed with a wide variety of configuration management practices. DARPA has been investing over the last three years in concepts to develop an autonomous process to parametrically assess quality of data originating from non-traditional sensors, and to fuse this information with certified sensors in near real time. Simulations have successfully demonstrated the viability of the autonomous software suite and DARPA is beginning the demonstration phase of the effort. The demonstration of this capability seeks to leverage real data from a global network of sensors including commercial, academic, amateur, and government sources. This paper will discuss progress to date and demonstrations to be completed through spring 2017.

Evidence-Based Sensor Tasking for Space Domain Awareness

Andris Jaunzemis[1], Moriba Jah[2], Marcus Holzinger[1]

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Space Domain Awareness (SDA) is the actionable knowledge required to predict, avoid, deter, operate through, recover from, and/or attribute cause to the loss and/or degradation of space capabilities and services. A main purpose for SDA is to provide decision-making processes with a quantifiable and timely body of evidence of behavior(s) attributable to specific space threats and/or hazards. To fulfill the promise of SDA, it is necessary for decision makers and analysts to pose specific hypotheses that may be supported or refuted by evidence, some of which may only be collected using sensor networks. While Bayesian inference may support some of these decision-making needs, it does not adequately capture ambiguity in supporting evidence; in other words, it struggles to rigorously quantify 'known unknowns' for decision makers. Over the past 40 years, evidential reasoning approaches such as Dempster-Shafer theory have been developed to address problems with ambiguous bodies of evidence. This paper applies mathematical theories of evidence using Dempster-Shafer expert systems to address the following critical issues: 1) How decision makers can pose critical decision criteria as rigorous, testable hypotheses, 2) How to interrogate these hypotheses to reduce ambiguity, 3) How to know when sufficient evidence has been gathered to confirm or refute specific hypotheses, and 4) How to task a network of sensors to gather evidence for large quantities of hypotheses.

A Sensor Tasking Reward Function Incorporating Target Priorities

Steven Gehly[1], James Bennett[2], Kingsley Oteng-Amoako[2], Kefei Zhang[1]

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One of the primary challenges in space situational awareness (SSA) is tracking a large number of objects using a limited number of sensors, which are further restricted in the times they are operational. The sensor limitation leads to sparse data scenarios, in which long gaps occur between measurements of individual objects. To maintain an accurate catalog, it is essential to collect measurements efficiently, in a manner to maximize use of the limited information available. A good sensor allocation scheme will yield accurate state estimates and a consistent representation of the uncertainty associated with each object, while additionally preventing the loss of known objects from the catalog.

Recent advances in information theoretic sensor tasking allow formulation of sensor allocation schemes in terms of information gain functionals computed from the multitarget state and hypothesized measurements. These reward functions quantify the difference between the prior and posterior PDF, and therefore account for the reduction in uncertainty for each object as a result of computing a measurement update. However, as currently formulated, they do not account for individual target priorities, which is a key requirement for the SSA problem.

The need for improved tracking of high priority targets may be driven by user requirements, or may arise from the state of the debris environment itself. For instance, if a collision is predicted between two objects, it is naturally important to schedule additional observations to refine the estimates and predicted probability of collision. This research seeks to employ a sensor allocation scheme driven by an information theoretic reward function, augmented by a tactical importance function (TIF) to specify target priorities. The TIF has been developed in conjunction with Finite Set Statistics (FISST)-based multitarget filters, and offers a mathematically sound approach to the sensor tasking problem including individual target priorities. This paper will focus on the application of such a scheme to the problem of tracking geosynchronous objects using angles-only measurements from ground based sensors. Simulated data will be used to establish the efficacy of the technique.

Resident Space Objects Characterization and Behavior Understanding via Machine Learning and Ontology-Based Bayesian Networks

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Over the past few years, Space Domain Awareness (SDA), which is concerned with acquiring and maintaining knowledge of Resident Space Objects (RSO) orbiting Earth, has become of critical to preventing the loss, disruption, or degradation of space capabilities and services. This is mostly due to the hazards to operational satellites caused by the growing number of RSOs including orbital debris. Whereas The U.S. Space Object Catalog currently lists approximately 22,000 trackable objects, the total population is thought to exceed 500,000 objects larger than 1 cm. Importantly, due to emerging capabilities of potential adversaries, threats to operational satellites are also increasing and need to be properly addressed. In order to protect valuable space assets, it is necessary to assess, quantify, and predict the behavior of objects in orbit around the Earth.

In this paper, we present an end-to-end approach that employs machine learning techniques and Ontology-based Bayesian Networks (OBN) to characterize the behavior of resident space objects. State-of-the-Art machine learning architectures (e.g. Extreme Learning Machines, Deep Networks) are trained on physical models to learn the RSO features in the energy and momentum states and parameters. The mapping from measurements to energy and momentum states and parameters enables behavior characterization via clustering in the features space and subsequent RSO classification. Additionally, Space Object Ontologies (SOO) are employed to define and capture the domain knowledge-base and OBN are constructed from the SOO in a semi-automatic fashion to execute probabilistic reasoning over conclusions drawn from trained classifiers and/or additional model-based filters (e.g. Multiple Model Adaptive Estimators). Such an approach enables integrating machine learning classifiers, model-based filters and probabilistic reasoning to support higher-level decision making for space situational awareness applications.

The innovation here is to use these methods (which have enjoyed great success in other domains) in synergy so that it enables a “from data to discovery” paradigm by facilitating the linkage and fusion of large and disparate sources of information via a Big Data Science and Analytics framework.

Dynamic Sensor Tasking for Space Situational Awareness via Reinforcement Learning

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This paper develops a Deep Reinforcement Learning (DRL) approach for sensor tasking and management applied to Space Situational Awareness (SSA). Reinforcement learning approaches define a Q-function which represents a cost of all possible actions at the current state. For the SSA problem, the agent is the telescope sensor and the possible actions are deciding to make an observations of a particular satellite. This paper develops a simulation environment where a DQN can be trained to preform a policy that will reduce the overall satellite catalog error. The reward model development is critical to the performance of the reinforcement learning policy and therefore this paper focuses on investigating different reward models. The primary model that is investigated is based on the Fisher information matrix, where the goal is to maximize the information gain of each observation. This approach rewards policies that take measurements that maximally reduce the overall catalog uncertainty. There are a number of ways of formulating the decision making problem under the reinforcement learning framework and therefore investigation of alternative reward functions are considered in this paper.

Stable methods for training reinforcement learning 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 paper leverages these results and applies this approach to decision making in SSA. The action space for the SSA problems can be high dimensional even for tasking of a single telescope. Since the number of SO in space is relatively high, each sensor will have a large number of possible actions that are possible at a given time. Therefore, efficient reinforcement learning approaches are required when solving the sensor tasking and management problem for SSA. This paper implements the Deep Q Neural network (DQN) reinforcement learning approach for SSA sensor tasking using experience replay. The Q-network is trained by randomly sampling mini-batches of experiences or past actions. Experience reply makes this approach more computationally efficient by reducing correlation in the data. It also enables reuse of past experiences for learning, thereby reducing sample costs. This paper investigates the use of experience replay and iterative updating for improving the efficiency of the reinforcement learning approach for SSA.

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False-Object Identification for Space Surveillance Catalog Maintenance

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A space object from a surveillance catalog of space objects that is predicted to be in the field of view of a tracking sensor may not be detected because of viewing conditions, or because either the estimated orbit of the space object has large error or the catalog object does not actually exist. In these two latter cases we call such a catalog object an invalid object (a false or lost track). Identification of false and lost catalog objects is an essential function for maintenance of a space surveillance catalog.

An invalid catalog object is not likely to be associable, with high probability, with any measurements (observations) in a sequence of data collects from tracking sensors. The sequential probability of association over multiple frames of data is cumulative evidence of whether the catalog object is valid or invalid. The catalog object is deemed to be an invalid object when the sequential probability of association is sufficiently close to zero.

The single-frame and sequential probabilities of validity of a catalog object are determined by first computing the maximum likelihood association of the tracks (the estimated orbits) and observations, and then by updating a sequential likelihood ratio test for each track. The probability that each track is valid is computed from likelihood ratios. The algorithm is simpler and computationally faster than the general Multiple Hypothesis Testing (MHT) algorithm that associates multiple measurements and multiple objects over multiple frames of data. The sequential data collects do not have to correspond to the same set of catalog objects, and the data collects can be separated in time and can come from tracking sensors that are geographically separated, have different views, and that report different types of measurements (angles, range, range rate, position vectors, or position and velocity vectors). The measurement data can include feature (attribute) data. The only condition is that the catalog object under consideration is predicted to be in or near the field of view of the tracking sensor in each data collect; whether or not there are any associable measurements in the data collects is determined by the algorithm.

High Performance Orbital Propagation Using a Generic Software Architecture

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Orbital propagation is a key element in many fields of space research. Over the decades, scientists have developed numerous orbit propagation algorithms, often tailored to specific use cases that vary in available input data, desired output as well as demands of execution speed and accuracy. Conjunction assessments, for example, require highly accurate propagations of a relatively small number of objects while statistical analyses of the (untracked) space debris population need a propagator that can process large numbers of objects in a short time with only medium accuracy. Especially in the latter case, a significant increase of computation speed can be achieved by using graphics processors, devices that are designed to process hundreds or thousands of calculations in parallel. In this paper, an analytical propagator is introduced that uses graphics processing to reduce the run time for propagating a large space debris population from several hours to minutes with only a minor loss of accuracy. A second performance analysis is conducted on a parallelised version of the popular SGP4 algorithm. It is discussed how these modifications can be applied to more accurate numerical propagators. Both programs are implemented using a generic, plugin-based software architecture designed for straightforward integration of propagators into other software tools. It is shown how this architecture can be used to easily integrate, compare and combine different orbital propagators, both CPU- and GPU-based.

ASTRODYNAMICS

Session Chairs: Moriba Jah, The University of Arizona and Paul Schumacher, Air Force Research Laboratory

Ground-Based Tracking of Geosynchronous Space Objects with a GM-CPHD Filter

Brandon Jones, Nicholas Ravago, Noble Hatten, Ryan Russell

The University of Texas at Austin

This paper presents a multi-target tracker for space objects near geosynchronous orbit using the Gaussian Mixture (GM) Cardinalized Probability Hypothesis Density (CPHD) filter. Given limited sensor coverage and over 1,000 objects near geosynchronous orbit, long times between measurement updates for a single object can yield propagated uncertainties sufficiently large to create ambiguities in observation-to-track association. Recent research considers various methods for tracking space objects via Bayesian multi-target filters, with the CPHD being one such example. In addition to handling ambiguities in data association, these Bayesian multi-target filters provide a mathematical framework to include models for new-target birth, probability of detection, and clutter measurements.

The implementation of the CPHD filter presented in this paper includes models for each of the previous elements in a manner consistent with the space-object tracking problem. Early tests demonstrate that most computation time is spent in the time update of the multi-target state, and the proposed CPHD filter combines parallelization with efficient models and propagation techniques to reduce the associated run time. To allow for instantiating new objects, the proposed filter uses a variation of the probabilistic admissible region that adheres to birth model assumptions in the derivation of the CPHD filter. Finally, to reduce filter computation time while mitigating the so-called "spooky action at a distance" phenomenon in the CPHD filter, we propose splitting the multi-target state into distinct, non-interacting populations based on the sensors' field of view (FOV). This also reduces filter complexity encountered as part of the multi-sensor fusion step. The paper presents a method for generating the parameterization of the multi-target state for each of these populations as a function of the CPHD multi-target state estimate and the sensor FOV.

This paper demonstrates the use of the proposed GM-CPHD filter when tracking both known and newly observed objects. The prior catalog estimate in the GM-CPHD is based on 700 objects randomly generated and representative of the public two-line element catalog. Simulated observations are generated via three, ground-based optical sensors. Additionally, the demonstration includes the instantiation and convergence on solutions for newly observed objects using the proposed birth model.

Schmidt-Kalman Filter with Polynomial Chaos Expansion for Orbit Determination of Space Objects

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Due to the rapid increase in the population of earth-orbiting objects, state estimation of these space objects for mission planning and collision avoidance is therefore of great significance. The Kalman filtering technique is widely used for orbit determination (OD), which combines both orbit prediction (OP) and observation update together in a sequential manner. However, non-gravitational perturbations, e.g., solar radiation pressure and atmosphere drag acting on the space objects, cannot be modeled precisely in the OP process due to the uncertainties associated with these parameters. This leads to the deterioration of OD reliability using the traditional Kalman filter. One approach to accounting for parameter errors in a dynamic system is to consider them in the so-called Schmidt-Kalman filter (SKF), by augmenting the state covariance matrix (CM) with additional parameter CM rather than additively estimating these so-called ‘consider’ parameters. This paper introduces a new SKF algorithm with polynomial chaos expansion (PCE) (PCESKF). The PCE approach has been proved to be more efficient than Monte Carlo method for propagating the input uncertainties onto the system response without experiencing any constraints of linear dynamics, or Gaussian distributions of the uncertainty sources. The state and covariance needed in the OP step are propagated using PCE. More specifically, the CM is computed from coefficients and samples of PCE instead of linear propagation by the state transition matrix (STM). The proposed PCESKF is applied to OD of space objects. An inclined Geosynchronous Earth Orbit scenario is set up. The satellite orbit is propagated based on numerical integration, with the uncertain coefficient of solar radiation pressure considered. Range observations from three ground stations are used in the measurement update step. The PCESKF solutions are compared with extended Kalman filter (EKF)?SKF and PCEEKF (EKF with PCE) solutions. It is found that the covariance propagation using PCE leads to more precise OD solutions in comparison with those based on linear propagation of covariance by STM.

Homotopy Particle Filter for Ground-Based Tracking of Satellites at GEO

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Ground telescopes enable low-cost tracking of multiple space objects or debris to perform characterization of meter-class objects. Since a telescope is typically tasked to collect observations from multiple space objects over one night, the frequency of observations of each object may vary between few seconds to tens of minutes. Due to long propagation times, the nonlinearity of both dynamics and measurement models will stress filtering solutions such as Extended Kalman Filter (EKF). Sampling-based filters, such as particle filters (PF), are suited for this nonlinear tracking problem. However, traditional PF solutions require very large number of particles, which could hamper tracking multiple targets simultaneously. In this work we evaluate the performance and effectiveness of a nonlinear filtering technique called homotopy particle filter (HPF), which requires orders of magnitude fewer particles. The performance of HPF is evaluated in a real-world scenario that involves detection and tracking of GEO satellites in images collected by a ground telescope at Lockheed Martin’s Space Object Tracking (SPOT) facility.

On the Confidence Region of Least Squares Solutions for Single-Arc Observations

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University of Southampton

The total number of active satellites, rocket bodies, and debris larger than 10 cm is currently about 20,000. Considering all resident space objects larger than 1 cm this rises to an estimated minimum of 500,000 objects. Latest generation sensor networks will be able to detect small-size object, producing millions of observations per day. Due to observability constraints it is likely that long gaps between observations will occur for small objects. Thus, it is required to determine the space object (SO) orbit and to accurately describe the associated uncertainty when observations are acquired on a single arc. The aim of this work is to revisit the classical least squares method taking advantage of the high order Taylor expansions enabled by differential algebra. In particular, the high order expansion of the residuals with respect to the SO state is used to implement an arbitrary order least squares solver, avoiding the typical approximations of differential correction methods. In addition, the same expansions are used to accurately characterize the confidence region of the solution, going beyond the classical Gaussian distributions. The properties and performances of the proposed method are discussed using optical observations of objects in LEO, HEO, and GEO.

Joint Target Detection and Tracking Filter for Chilbolton Advanced Meteorological Radar Data Processing

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Recently, the growing number of inactive Resident Space Objects (RSOs), or space debris, has provoked increased interest in the field of Space Situational Awareness (SSA) and various investigations of new methods for orbital object tracking. In comparison with conventional tracking scenarios, state estimation of an orbiting object entails additional challenges, such as orbit determination and orbital state and covariance propagation in the presence of highly non-linear system dynamics. In a cluttered environment, when multiple false alarms are possible and the number targets in the scene is variable, traditional single-target filtering solutions such as Kalman Filters fail to produce useful trajectory estimates. The recent Random Finite Set based Finite Set Statistical framework has yielded filters which are more appropriate for high clutter situations. The RFS based Joint Target Detection and Tracking (JoTT) filter, also known as the Bernoulli filter, is a single target, multiple measurements filter capable of dealing with cluttered and time-varying backgrounds as well as modeling target appearance and disappearance in the scene. Therefore, this paper presents the application of the Gaussian mixture-based JoTT filter for processing Chilbolton Advanced Meteorological Radar (CAMRa) measurements of both defunct and operational satellites. The CAMRa is a fully-steerable radar located in southern England, which was recently modified to be used as a tracking asset in the European Space Agency SSA program. The experiments conducted show promising results regarding the capability of such filters in processing cluttered radar data. The work carried out in this paper was funded by the EU Erasmus Mundus MSc Scholarship, Defense Science and Technology Laboratory (DSTL), U.K., and USAF Grant No. FA9550-15-1-0069.

KRATOS: Kollision Risk Assessment Tool in Orbital Element Spaces

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The Kollision Risk Assessment Tool in Orbital Element Spaces (KRATOS) provides a new approach to computing the probability of collision (PC) between space objects that supports the mission's goal of performing conjunction analysis screening further out into the future. Although applicable to all regimes of space, KRATOS was designed to treat objects in the challenging non-linear and non-Gaussian regimes by relaxing the Gaussian assumptions present in the traditional Foster method. In such challenging regimes, KRATOS is able to efficiently compute the PC over much longer screening intervals than what is currently possible, by leveraging Numerica's prior work in Gaussian mixture filters and orbital element coordinate systems, including the newly-developed J2 equinoctial orbital elements. These innovate features of KRATOS permit a robust computation of the PC integral without having to represent a space object's uncertainty as a potentially inaccurate Gaussian distribution in Cartesian space, as is needed in Foster's method.

In this paper, we provide an overview of the KRATOS algorithm and review the J2 elements. Using both real and simulated vector covariance message (VCM) data, we demonstrate scenarios in which the Foster method produces false alarms and misdetections, and hence would misinform the analyst. Use of KRATOS in these scenarios provides a reliable PC with accuracy that rivals more computationally expensive Monte-Carlo simulation, and hence would better inform the analyst. KRATOS is computationally viable, with runtimes that can be many orders of magnitude less than Monte-Carlo approaches. These runtime differences are especially pronounced in cases involving operational spacecraft when the PC is around the threshold value for which a decision to maneuver would be made, and for which a high number of Monte-Carlo trials would be needed to achieve sufficient accuracy. The computational efficiency of KRATOS is due, in part, to only having to propagate a single Gaussian in J2 element space to the nominal time-of-closest approach rather than an entire Gaussian mixture in Cartesian space. Evidence of this high performance is presented in this paper, and comparisons to other Gaussian-mixture-based approaches are made.

Spatial Density Maps from a Debris Cloud

Liam Healy, Christopher Binz, Scott Kindl

Naval Research Laboratory

A debris cloud from a fragmentation on orbit may be modeled by transformation of variables from the instantaneous velocity distribution at the fragmentation time to the spatial distribution at some elapsed time later. There are no Gaussian distributions assumed and the evolution map is quite nonlinear, being derived from the solution of the Lambert, two-point boundary value, problem and the state transition matrix for unperturbed propagation, so the traditional tools of analysis that assume these qualities fail dramatically. The transformation of variables technique does not suffer from any such assumptions, and unlike the Monte Carlo method, is not subject to sampling errors or approximations.

Structures and features are evident in the density maps, and these structures show promise for simplified approximation of the density map. Most prominent of the structures is the well-known pinch point at the fragmentation location in inertial space. The anti-pinch line, or wedge, is also observed. Bands on the opposite side of the fragmentation are very noticeable, and their existince may be motivated from simple orbit dynamics. These bands make the anti-pinch line actually more of a set of anti-pinch line segments.

By computing these density maps over time, the evolution may be studied. There is a density generator, a wave of density band at roughly the same altitude as the pinch point, that cycles around the earth and

appears a source of the bands, with newly created bands moving radially outward and diminishing in density. Although the initial velocity distribution affects the final spatial distribution, the Lambert solutions, which are the most time consuming to compute, need only be computed once. Therefore, different initial distributions may be changed and the results recomputed with relative speed. A comparison of the effects of initial distributions is shown in this paper.

When Does the Uncertainty Become Non-Gaussian?

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Texas A&M University

The orbit state covariance is used in the conjunction assessment/probability of collision calculation. It can also be a valuable tool in track association, maneuver detection and sensor tasking. These uses all depend on the uncertainty being Gaussian. Studies have shown that the uncertainty at epoch (time of last observation) is reasonably Gaussian, but the neglected nonlinearities in the covariance propagation eventually result in the uncertainty becoming non-Gaussian. Reference 1 showed that the effect of the nonlinearities is minimized when propagating in orbital elements and is maximized in Cartesian coordinates. The result is the covariance remains Gaussian the longest in orbital element space. Ref. 2 showed that in the catalog maintenance mode the covariance remains Gaussian for up to 10 days in element space but becomes non-Gaussian after 2-3 days in Cartesian coordinates for a typical LEO orbit. For calculations, such as the probability of collision, that have to be performed in Cartesian space propagating in orbital element space does not resolve the problem because the transformation into Cartesian space brings back in the nonlinearity effects. Ref. 3 presents a potential solution to that problem. The fundamental question is when does it become non-Gaussian and how can one given the state and covariance when it occurs. An equation that the operator can use to compute the approximate time when the neglected nonlinearities begin to have an impact would be a useful tool. This paper addresses this equation and develops an approach for providing that equation. The development and validation using simulations are presented in this paper.

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Unexplained Momentum Impulse Transfer Events (MITEs)

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Environment characterization is a fundamental component of Space Situational Awareness (SSA). In 2015, ExoAnalytic Solutions collected over 30 million astrometric measurements of active and inactive resident space objects (RSOs) in geosynchronous Earth orbit (GEO) and in the near-GEO region using a global network of ground-based telescopes. Orbit Determination (OD) of inactive RSOs in sub-synchronous (e.g., spent upper stages) and super-synchronous (e.g., retired satellites) orbits revealed numerous unexplained momentum impulse transfer events (MITEs) with detectable In-Track velocity changes of 0.5 to 10 mm/s with no preferred sign. MITEs were observed throughout the year; however, they were more prevalent during equinox periods for the RSOs analyzed. Details of identified MITEs include the RSO's NORAD ID and estimates of: time, implied impulse direction, delta velocity, and RSO's area to mass ratio (AMR). Critical to the MITE analysis is a high fidelity propagation and acceleration model which includes: Earth's gravitational moments, Sun and Moon gravitation, and Radiation Pressure (SRP) contributions. Consistency checks of the OD and the acceleration model were performed; no abnormalities were found. A velocity change in the In-Track direction causes an In-Track position drift seen as an In-Track residual that grows linearly over time allowing the MITE to be more readily detected and characterized using long time spans of data before and after the MITE. The number of observations per analyzed RSO ranged from 5,000 to 50,000, and most RSOs were seen by the entire sensor network as they drifted around the Earth. OD on these observations used data durations of 10 to 100 days, enabling an AMR fit and/or a characterization of MITEs. This collection and characterization of MITES aids the SSA mission of precision tracking of debris and observation of RSO phenomenology in the space environment.

Synthesis of Disparate Optical Imaging Data for Space Domain Awareness

Michael Schneider, William Dawson

Lawrence Livermore National Laboratory

We present a Bayesian algorithm to combine optical imaging of unresolved objects from distinct epochs and observation platforms for orbit determination and tracking. By propagating uncertainties we are able to optimally combine imaging of arbitrary signal-to-noise ratios, allowing the integration of data from low-cost sensors. Our Bayesian approach to image characterization also allows large compression of imaging data without loss of statistical information. With a computationally efficient algorithm to combine multiple observation epochs, we show statistically optimal orbit inferences and reachability volume predictions from a time stream of GEO streak images

Towards Relaxing the Spherical Solar Radiation Pressure Model for Accurate Orbit Predictions

Michael Lachut, James Bennett

Space Environment Research Centre Ltd.

The well-known “cannonball’’ model has been used ubiquitously to capture the effects of atmospheric drag and solar radiation pressure on satellites and/or space debris for decades. While it lends itself naturally to spherical objects, its validity in the case of non-spherical objects has been debated heavily for years throughout the space situational awareness community. One of the leading motivations to improve orbit predictions by relaxing the spherical assumption, is the ongoing demand for more robust and reliable conjunction assessments. In this study, we explore the orbit propagation of a flat plate in a near GEO orbit under the influence of solar radiation pressure, using a classical Lambertian BRDF model. Consequently, this approach will account for the spin rate and orientation of the object, which in practice is typically determined using a light curve analysis. Here, simulations will be performed which systematically reduces the spin rate to demonstrate the point at which the spherical model no longer reflects the orbital elements of the spinning plate. Further understanding of this threshold would provide insight into when a higher fidelity model should be used, thus yielding improved orbit propagations. The work presented here is therefore of particular interest to organisations and researches that maintain their own catalogue, and/or perform conjunction analyses.

Reconstructing Close Proximity Events in Geosynchronous Orbit Using Sparse, Multi-Aspect Observations

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Orbital ATK, USAF - 1SOPS

The number of close approaches between objects in geosynchronous orbits is increasing as the population of Geosynchronous orbit increases. It can be exceedingly difficult to quickly reconstruct these events using only ground or LEO (Low Earth Orbit) based optical observations due to the lack of angular diversity, sensor lighting constraints and sensor tasking limits. This problem is compounded objects are frequently maneuvering. This technique uses sets of space and ground based observations to estimate the range and range rate of an unknown object relative to a known RSO (Resident Space Object). The range and range rate can be estimated using the angular difference between observations of the unknown object and the RSO and using a basic set of assumptions about the orbit with as few observations as possible. As more observations are received, the full orbit solution can be determined. This technique can provide a first look characterization of high interest events in GEO in order to determine whether or not to task other sensors or increase coverage on unknown objects in proximity to know RSO’s. It can be used to evaluate potential risk to the RSO more quickly than a full orbit determination. Monte Carlo analysis will show the limits and results of this algorithm using simulated data.

NON-RESOLVED OBJECT CHARACTERIZATION

Session Chairs: Michael Duggin, Air Force Research Laboratory and Matthew Hejduk, Astrorum Consulting

Standardized Photometric Calibrations for Panchromatic SSA Sensors

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Panchromatic sensors used for Space Situational Awareness (SSA) have no standardized method for transforming the net flux detected by a CCD without a spectral filter into an exo-atmospheric magnitude in a standard magnitude system. Each SSA data provider appears to have their own method for computing the visual magnitude based on panchromatic brightness making cross-comparisons impossible. We provide a procedure in order to standardize the calibration of panchromatic sensors for the purposes of SSA. A technique based on theoretical modeling is presented that derives standard panchromatic magnitudes from the Johnson-Cousins photometric system defined by Arlo Landolt. We verify this technique using observations of Landolt standard stars and a Vega-like star to determine empirical panchromatic magnitudes and compare these to synthetically derived panchromatic magnitudes. We also investigate color-terms caused by differences in the quantum efficiency (QE) between the Landolt standard system and panchromatic systems. We evaluate calibrated panchromatic satellite photometry by observing several GEO satellites and standard stars using three different sensors. We explore the effect of satellite color terms by comparing the satellite signatures. In order to remove other variables affecting the satellite photometry, two of the sensors are at the same site using different CCDs. The third sensor is geographically separate from the first two allowing for a definitive test of calibrated panchromatic satellite photometry.

Open-Filter Optical SSA Analysis Considerations

John Lambert

Cornerstone Defense

Optical Space Situational Awareness (SSA) sensors used for space object detection and orbit refinement measurements are typically operated in an “open-filter” mode without any spectral filters to maximize sensitivity and signal-to-noise. These same optical brightness measurements are often also employed for size determination (e.g., for orbital debris), object correlation, and object status change. These functions, especially when performed using multiple sensors, are highly dependent on sensor calibration for measurement accuracy. Open-filter SSA sensors are traditionally calibrated against the cataloged visual magnitudes of solar-type stars which have similar spectral distributions as the illuminating source, the Sun. The stellar calibration is performed to a high level of accuracy, a few hundredths of a magnitude, by observing many stars over a range of elevation angles to determine sensor, telescope, and atmospheric effects. However, space objects have individual color properties which alter the reflected solar illumination producing spectral distributions which from those of the calibration stars. When the stellar calibrations are applied to the space object measurements, visual magnitude values are obtained which are systematically biased. These magnitudes combined with the unknown Bond albedos of the space objects result in systematically biased size determinations which will differ between sensors. Measurements of satellites of known sizes and surface materials have been analyzed to characterize these effects. The results have combined into standardized Bond albedos to correct the measured magnitudes into object sizes. However, the actual albedo values will vary between objects and represent a mean correction subject to some uncertainty. The objective of this presentation is to characterize the sensor spectral biases that are present in open-filter optical observations and examine the resulting brightness and albedo uncertainties that should accompany object size, correlation, or status change determinations, especially in the SSA analyses of individual space objects using data from multiple sensors.

A Discrimination Analysis of Sloan and Johnson Photometric Systems for Non-Resolved Object Characterization

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Accurate calibrations are critical to the ability to extract reliable features from the photometry such as albedo-Area and for fusion of data taken with different sensors. The new large stellar calibration catalogs produced by astronomers can be leveraged to improve the photometric calibrations of Resident Space Objects (RSOs). These catalogs use the Sloan filter set. In order to utilize these new catalogs, we need to evaluate the satellite discrimination capability of this filter set. Past research has shown that photometry taken in the Johnson-Cousins filter set and specialized filter sets such as SILC makes it possible to classify geosynchronous satellites by their bus type and uniquely identify them. In this work, we collect photometric signatures on a selected set of geosynchronous satellites in both Sloan and Johnson. With these measurements we compute the color indices and use the Mahalanobis distance as a metric of discrimination. We perform a statistical analysis on the metric to quantify the discrimination capability of each filter set.

Comparison of ENVISAT's Attitude Simulation and Real Optical and SLR Observations in Order to Refine the Satellite Attitude Model

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The population of space debris increased drastically during the last years. Catastrophic collisions involving massive objects produce large number of fragments leading to significant growth of the space debris population. An effective remediation measure in order to stabilize the population in Low Earth Orbit (LEO) is therefore the removal of large, massive space debris. Secondly, satellite malfunctions might lead to loss of contact with the spacecraft. Such scenarios are referred to as contingency cases. Currently, the Astronomic Institute of the University of Bern (AIUB) in cooperation with three partners is involved in an ESA study Debris Attitude Motion Measurements and Modeling? (ESA AO/1-7803/14/D/SR) dedicated to the attitude determination of large spacecraft and upper stages. Two major goals are defined for this project. First is the long term prediction of tumbling rates (e.g. 10 years) for selected targets for future Active Debris Removal (ADR) missions. Second goal is the attitude state determination in case of contingencies, when a short response time is required between the observations themselves and the attitude determination. One of the project consortium partners, Hypersonic Technology Goettingen (HTG), is developing a highly modular software tool IOTA to perform short- (days) to long-term (years) propagations of the orbit and the attitude motion of spacecraft in Earth orbit, taking into account all the relevant acting forces and torques. Furthermore, IOTA's post-processing modules will generate synthetic measurements, e.g. light curves, SLR residuals and Inverse Synthetic Aperture Radar (ISAR) images that can be compared with the real measurements. The strength of the approach is the combination of various attitude measurement types to cancel out ambiguities of the individual methods and to combine this with a dynamic model in order to establish attitude prediction. The validation of the attitude model will be done by comparison to real observations of targets with known attitude. In our paper we will shortly discuss the ESA project and IOTA software tool. We will present AIUB's ENVISAT attitude state determined from the SLR ranges acquired by the Zimmerwald SLR station. This state was used as the initial conditions within the IOTA software. Consequently the attitude of satellite was predicted by using IOTA and compared with the real SLR residuals, as well with the regular high frame-rate light curves acquired by the Zimmerwald 1-m telescope. Finally, we present a refined attitude state model of ENVISAT which was determined by searching for the best agreement between the simulated and the real measurements for both optical and SLR.

Non-Imaging Characterization Assessment of Shedding Events from Derelict Satellites in Near Geosynchronous Orbit (GEO)

Tom Kelecy, Mark Skinner

Applied Defense Solutions, Boeing

There is plausible speculation that retired satellites near geosynchronous orbit are the source of a debris population that was passively shed over time due to environmental effects. Recent initiatives intended to characterize these defunct satellites via analysis of non-imaging observations have established the ability to derive some of their physical and dynamic attributes. For long term observing of objects, what kinds of changes might one be able to detect that might be attributed to shedding? Are there any attributes common to both the shed piece of debris and the parent object that might allow one to tie the two together? The work presented attempts to shed some light on these questions by establishing several plausible shedding scenarios which include appropriate dynamics, shapes and materials, and uses appropriate bi-directional reflectance distribution functions and Long Wave Infrared (LWIR) models to create a simulated time history of observations that can be examined to analyze the shedding phenomenon. The goal of this work is to provide some insight into what characterization changes one might attribute to shedding when observing a parent object over an extended period. The results show that astrometric, photometric, albedo-area product, and multi-wavelength brightness observations each provide unique characterization attributes which, when combined, allow one to infer shedding phenomena.

Shape Estimation from Lightcurves including Constraints from Orbit Determination

Jay McMahon, Daniel Scheeres

University of Colorado

Space situational awareness doesn't end when a Resident Space Object's orbit is determined - in many cases we would also like to determine whatever we can about the shape and attitude state of the object. In many cases, the measurement type available to characterize this information is the optical lightcurve, which gives the observed brightness of the object over time. For most objects, the lightcurve varies in magnitude with time, and this periodicity is useful for determining the spin period and/or testing to see if an object is tumbling.

Unfortunately, estimating both the shape and attitude of the RSO from lightcurves is impossible - it has been rigorously proven that these features are unobservable in the literature. This is due to the fact that the brightness measurement is an integral of all of these parameters and states, so that an infinite number of possible combinations could produce the same measurements.

Although the inversion problem is technically ill-posed, and thus not uniquely solvable, people have still approached this problem and had success in characterizing different pieces of information from lightcurves by making certain assumptions. The most common and successful application of this theory is for estimating the shape and spin state of asteroids, using the method developed by Kaasalainen. This method assumes there is a fixed spin pole and spin rate and a simple diffuse BRDF that is constant for the entire surface, and under these assumptions will estimate the spin pole, spin rate, and shape. Even with these strong assumptions, this is a difficult non-linear optimization problem, and thus the answer is generally a non-unique local minima. Other methods have relied on posing various hypotheses which constrain the shape and spin state sufficiently to allow a neighboring solution to be found, however these results are clearly limited by the assumptions made when constructing the hypotheses.

However, there is extra information that can be leveraged to improve the situation due to the coupling of attitude and translation in the dynamics through solar radiation pressure perturbations. The SRP force at any given time is determined by the integral of the momentum exchange from all portions of the surface lit

by the Sun. Meanwhile, the observed brightness obtained at a telescope as part of a lightcurve is some component of the reflected light that contributed to the SRP force.

This relationship is extremely complicated due to the strong dependency on the shape definition, integrals over the shape, and the fact that the integrals are over different regions. However, there is coupling here, so using information gained about the SRP force necessarily provides more information about the body which simultaneously generates a given SRP force and lightcurve observation.

In this paper, we discuss the information content of lightcurves for estimating shape and attitude. Based on the information available, we will discuss what constraints on the shape can be determined. Furthermore, we will derive and discuss in detail how applying constraints from estimating solar radiation pressure changes the information content and the observable parameters available.

A High Fidelity Approach to Data Simulation for Space Situational Awareness Missions

Susan Hagerty, H. Benton Ellis, Jr.

Ball Aerospace & Technologies Corp.

Space Situational Awareness (SSA) is vital to maintaining our Space Superiority. Our high fidelity, time-based simulation tool (PROXOR™) supports this need by generating realistic mission scenarios including sensor frame data with corresponding truth. This is a unique and critical tool for supporting mission architecture studies, new capability (algorithm) development, current/future capability performance analysis, and mission performance prediction. PROXOR provides a flexible architecture for sensor and RSO orbital motion and attitude control that simulates space situational awareness and rendezvous and proximity operations scenarios. The major elements of interest are based on our ability to accurately simulate all aspects of the RSO model, the viewing geometry, the imaging optics, the sensor detector, and the environmental conditions. These capabilities enhance the realism of the generated data. As input, PROXOR uses an existing library of 3-D satellite models, including low-earth orbit (DMSP) and geostationary (Intelsat) spacecraft, where the spacecraft surface properties are those of actual materials and include Phong and Maxwell-Beard BRDF coefficients for accurate radiometry. We calculate the inertial attitude, the changing solar and Earth illumination angles of the satellite, and the viewing angles from the sensor as we propagate the RSO in its orbit. We render the satellite image at high resolution and aggregate to the focal plane resolution giving accurate radiometry even when the RSO is unresolved. Our sensor model includes optical effects from the imaging system (PSF includes aberrations, obscurations, support structures, defocus), detector effects (CCD blooming, left/right bias, fixed pattern noise, image persistence, shot noise, read noise, and quantization noise), and environmental effects (radiation hits with selectable angular distributions and 4-layer atmospheric turbulence model for ground based sensors). We have developed an accurate flash LIDAR model that supports reconstruction of 3-dimensional information on the RSO. PROXOR contains many subtle imaging effects such as intra-frame smear, which is realized by oversampling the image in time and captures target motion/jitter during the integration time.

POSTERS

Lens and Camera Arrays for Sky Surveys and Space Surveillance

Mark Ackermann[1], Pete Zimmer[2], John McGraw[2], Dave Cox[1]

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In recent years, a number of sky survey projects have chosen to use arrays of commercial cameras coupled with commercial photographic lenses to enable low-cost, wide-area, observation. Projects such as SuperWASP, Tortora, Raptor, Lotis, PANOPTES, and Dragonfly rely on multiple cameras with commercial lenses to image wide areas of the sky each night. The sensors are usually commercial astronomical CCDs or digital single reflex (DSLR) cameras while the lenses are large-aperture, high-end consumer items intended for general photography. While much of this equipment is very capable and relatively inexpensive, this approach comes with a number of significant limitations that reduce sensitivity and overall utility of the image data. The most frequently encountered limitations include lens vignetting, narrow spectral bandpass and relatively large point spread function. Understanding these limits helps to assess the utility of the data, and identify areas where advanced optical designs could significantly improve survey performance.

21st Century Atmospheric Forecasting for Space Based Applications

Randall Alliss, Billy Felton, Mary Ellen Craddock, Heather Kiley, Michael Mason

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Many space based applications from imaging to communications are impacted by the atmosphere. Atmospheric impacts such as optical turbulence and clouds are the main drivers for these types of systems. For example, in space based optical communications, clouds will produce channel fades on the order of many hundreds of decibels (dB) thereby breaking the communication link. Optical turbulence can also produce fades but can be compensated for by adaptive optics. The ability to forecast the current and future location and optical thickness of clouds for spaced to ground Electro Optical or optical communications are therefore critical in order to achieve a highly reliable system. We have developed an innovative method for producing such forecasts. These forecasts are intended to provide lead times on the order of several hours to days so that communication links can be transferred from a current clear ground location to another more desirable ground site. The system uses high resolution Numerical Weather Prediction (NWP) along with a variational data assimilation (DA) scheme to improve the initial conditions and forecasts. DA is the technique by which observations are combined with an NWP product or first guess field, and their respective error statistics to provide an improved estimate of the atmosphere state. Variational data assimilation achieves this through the iterative minimization of a prescribed cost function. Differences between the analysis and the observations/first guess are penalized (damped) according to their perceived error. 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 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. A series of DA experiments have been setup and conducted on the Maui High Performance Computing System, Riptide supercomputer. Initial results show a marked improvement of the cloud and optical turbulence forecasts over the control run without data assimilation. Detailed results will be presented at the conference.

The Critical Role of Experimentation to Further SSA Understanding

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Defence Science and Technology Laboratory (DSTL)

The UK has been an active partner and participant in international Space Situational Awareness (SSA) activities since the start of the space age utilising the radio telescope located at Jodrell Bank to track the first Sputnik satellite in 1957. Since that time the UK continues to support international SSA networks and organisations, focussed on the US Space Surveillance Network (SSN). UK research activities have centred on understanding the optimal utility of data sourced from these networks, with smaller investigations of the potential of non-traditional surveillance of space sensors to augment existing capabilities. However in the last few years this situation has substantially altered as UK government and industry becoming increasingly aware of the need to protect space assets in an ever more challenging situation as the space domain becomes increasingly congested, competitive and contested. This is particularly true with UK Ministry of Defence (MOD) as recognised in the recent Strategic Defence and Security Review (SDSR) 2015; as a consequence of which the recently formed space research programme within Dstl has recognised SSA as the top priority.

Technically it is recognised that comprehensive SSA can only be provided by international networks, encompassing sensors, Concept of Operations (CONOPS), data processing, communications, procedures, quality assurance and security elements. These elements must all be understood individually and collectively to provide SSA solutions; in particular the complex interactions within the network present significant coordination challenges that must be addressed to ensure effective SSA operations.

Dstl has developed an approach to explore these challenges through the design and execution of a series of national and international SSA experiments conducted since 2009. These have involved a number of nations to explore different multi-lateral constructs (such as Combined Space Operations [CSPO] and NATO), and have also served as test case scenarios in support of international SSA research collaboration. It has been found that this experimentally driven approach has been successful in linking government R&D activities to actual operations with UK MOD; as well as enabling enhanced cooperation with academia through the provision of access to sensors and data not usually available to these institutions. The experiences of the Dstl team over the past 7 years has yielded a number of lessons learnt that we believe the wider international community would benefit from in relation to effective SSA operations including how to generate closer relationships between communities across government, industry, academia and operators.

This paper describes the overall Dstl approach to this experiment series, including details of the participants, design, execution and major findings of each event to date. Lessons learnt pertinent to the AMOS and wider SSA community will be presented that will inform the audience on how this methodology may be adopted to meet other SSA scenarios. Finally it presents the UK roadmap for future experiments identified as possible activities under the Combined Space Operations initiative and the EU Space Surveillance and Tracking programme.

In-Situ Vis/NIR Measurements of Space Environment Effects on Spacecraft Surfaces

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Laboratory material characterization experiments have shown that passive observational techniques that measure the spectral energy distribution of reflected sunlight from spacecraft and space debris could potentially be used to determine an object's surface compositional make-up and even possibly its orientation. Such techniques, if proven to be reliable and consistent, would represent non-intrusive and cost effective tools that would benefit the overall space situational awareness (SSA) mission. However, to date, observations using either colour photometry or spectrophotometry to determine surface material characteristics of such objects have not produced encouraging results. One common problem that has plagued these attempts is the lack of understanding on how the spectral reflectance of the spacecraft surfaces evolves with time. There are a number of spacecraft materials whose spectral reflectance characteristics have been studied before and after spaceflight in LEO; there are no measurements on how the space environment gradually modifies the spectral scattering characteristics of these materials as a function of time. Furthermore, there are little or no in-situ observations of environmental effects on individually identifiable materials in MEO and GEO. This complicates the task of interpreting the spectral measurements of spatially unresolved spacecraft and orbital debris. This paper presents instrument concepts whose sole purpose will be to acquire on-orbit spectral reflectance measurements, at different observational geometries, of either witness samples or materials covering the surface of the host spacecraft. Such instruments could be flown as a hosted payload on an operational GEO satellite or as a dedicated payload on a microsatellite. Measurements would be acquired over the lifetime of the satellite and would observe how the spectral reflectance characteristics evolve during its lifetime. Furthermore, installation of one of the proposed instruments on multiple satellites would provide an opportunity to study the variation in space environment effects on the surfaces of spacecraft located in different orbital regimes, such as LEO, MEO, and GEO

Satellite Imaging with Adaptive Optics on a 1 M Telescope

Francis Bennet, Ian Price, Francois Rigaut, Michael Copeland

Research School of Astronomy and Astrophysics, Australian National University

The Research School of Astronomy and Astrophysics at the Mount Stromlo Observatory in Canberra, Australia, have been developing adaptive optic (AO) systems for space situational awareness applications. We report on the development and demonstration of an AO system for satellite imaging using a 1 m telescope.

The system uses the orbiting object as a natural guide star to measure atmospheric turbulence, and a deformable mirror to provide an optical correction. The AO system utilised modern, high speed and low noise EMCCD technology on both the wavefront sensor and imaging camera to achieve high performance, achieving a Strehl ratio in excess of 30% at 870 nm. Images are post processed with lucky imaging algorithms to further improve the final image quality. We demonstrate the AO system on stellar targets and Iridium satellites, achieving a near diffraction limited full width at half maximum. A specialised realtime controller allows our system to achieve a bandwidth above 100 Hz, with the wavefront sensor and control loop running at 2 kHz.

The AO systems we are developing show how ground-based optical sensors can be used to manage the space environment. AO imaging systems can be used for satellite surveillance, while laser ranging can be used to determine precise orbital data used in the critical conjunction analysis required to maintain a safe space environment. We have focused on making this system compact, expandable, and versatile. We are continuing to develop this platform for other space situational awareness applications such as geosynchronous satellite astrometry, space debris characterisation, satellite imaging, and ground-to-space laser communication.

Site Testing for Space Situational Awareness with Single Detector Stereo-SCIDAR

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Space situational awareness deals with gathering knowledge about the velocity and position of objects in orbit. Atmospheric turbulence presents an impediment to gathering high precision data of orbiting objects: adaptive optics systems are used to reduce the impact of this impediment. In order to track or image high speed orbiting objects, such as debris or satellites, a greater understanding of site-specific atmospheric turbulence is required. One path to this understanding is SCIntillation Detection And Ranging: SCIDAR. SCIDAR systems usually utilise one camera to image double stars whose images overlap on a detector. This method however can result in an underestimation of the Cn^2 profile due to the pupil patterns overlapping. Other SCIDAR systems make use of two cameras to image one star of a double star that have some angular separation: two cameras however come at twice the cost. The MSO SCIDAR system will image stars with an angular separation of between 10 and 20 arcseconds and therefore provide a good balance between resolution and altitude sampling. The detector to be used is a high-speed low-noise scientific CMOS camera with enough pixels to image two stars at once.

In conjunction with the Space Environment Research Centre (SERC), the Australian National University (ANU) and Electro Optic Systems (EOS) a SCIDAR system will be used to conduct the first site characterisation of atmospheric turbulence at Mount Stromlo astronomical observatory (MSO).

Elucidating More Orbital Information from Passive Optical Tracking Observations for Reliable Orbital Element Generation

James Bennett

Space Environment Research Centre Ltd.; and EOS Space Systems

This paper presents results from a new method for elucidating more orbital information from passive optical tracking data. An improvement in the accuracy of the observation data yields more accurate and reliable orbital elements.

A comparison between the orbit propagations from the orbital element generated using the new data processing method is compared with the one generated from the raw observation data for several objects.

Optical tracking data collected by EOS Space Systems, located on Mount Stromlo, Australia, is fitted to provide a new orbital element. The element accuracy is determined from a comparison between the predicted orbit and subsequent tracking data or reference orbit if available.

The new method is shown to result in a better orbit prediction which has important implications in conjunction assessments and the Space Environment Research Centre space object catalogue. The focus is on obtaining reliable orbital solutions from sparse data.

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

i1WFT: An Integrated 1-M Class Wide-Field Telescope

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[1]Officina Stellare, [2]EIE Group

We present a fully integrated system, based onto a 1-m aperture telescope, to perform fast-deployable, high-reliability, SSA deep observations. The optics is based onto a prime focus wide field configuration to increase target sensitivity and accuracy. Multi-spectral observations can perform target characterization. The system includes the telescope mount, the dome, the detector system, the dedicated softwares, to assist users in all the steps, from planning, scheduling, acquisition and data processing. The goal of the system is to evaluate collision probability based onto accurate orbital positional data, automatically generated by the system observations. User-customized solutions can be developed.

Towards a Network of Small Aperture Telescopes with Adaptive Optics Correction Capability

Manuel Cegarra Polo[1], Andrew Lambert[2]

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A low cost and compact AO system for a small aperture telescope (Meade LX200ACF 0.4 metres) has been developed at UNSW Canberra, where its performance is currently being evaluated. It is based on COTS components, with the exception of a real time control loop implemented in an FPGA, populated in a small form factor board which also includes the wavefront image sensor. A GUI running in an external computer connected to the FPGA imaging board provides the operator with control of different parameters of the AO system; results registration; and log of gradients, Zernike coefficients and deformable mirror voltages for later troubleshooting.

The U.S. Air Force Academy Falcon Telescope Network (USAFA FTN) is an international network of small aperture telescopes (0.5 meters) that provides raw imagery to FTN partners. The FTN supports general purpose use, including astronomy, satellite imaging and STEM support. Currently 5 nodes are in operation, operated on-site or remotely, and more are to be commissioned over the next few years. One of the network nodes is located at UNSW Canberra (Australia), where the ground-based space surveillance (SSA) team, part of the Space Research Group, is currently using it for research in different areas of SSA. Some current and future SSA goals include GEO satellite characterization through imaging modalities like polarimetry and real time image processing of LEO objects. The fact that all FTN nodes have the same configuration, facilitates the collaborative work between international teams of different nodes, so improvements and lessons learned at one site can be extended to the rest of nodes.

With respect to this, preliminary studies of the imagery improvement that would be achieved with the AO system developed at UNSW, installed on a second 0.4m Meade LX200ACF telescope and compared to the existing UNSW Canberra FTN telescope are reported. The ongoing, side-by-side test results of the AO system compared to those obtained without correction will be reported.

Orbit Determination with Angle-Only Data from the First Korean Optical Satellite Tracking System, OWL-Net

Jin Choi, Jung Hyun Jo

Korea Astronomy and Space Science Institute

The optical satellite tracking data obtained by the first Korean optical satellite tracking system, Optical Wide-field patrol – Network (OWL-Net), had been examined for precision orbit determination. During the test observation at Daejeon and Mongolia sites, we have successfully observed two satellites with Laser Retro Reflector (LRR) to calibrate the angle-only metric data. The OWL observation system is using a chopper equipment to get dense observation data in one-shot over 100 points for the low Earth orbit objects. After several corrections, orbit determination process was done with validated metric data. The TLE with the same epoch of the end of first arc was used for initial orbital parameter. One and two site observation case and sporadic observation case were experimented with over 600 point for each satellite.

Adaptive Optics for Satellite and Debris Imaging at LEO and GEO

Michael Copeland[1], Francis Bennet[2,3], Francois Rigaut[2,3], Celine d'Orgeville[2,3], Ian Price[2], Piotr Piatrou[2,3], Craig Smith[4,3]

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Ground based stations featuring adaptive optics (AO) can be an important component in the management of the space environment, in the effort to reduce the risk of a Kessler syndrome. The Research School of Astronomy and Astrophysics (RSAA) at the Australian National University (ANU) has developed an AO imaging system to be utilised with a 1.8m telescope located at Mount Stromlo Observatory. The AO system provides a capability of imaging satellites and debris in low Earth orbit (LEO) and geostationary Earth orbit (GEO). This system is developed as a part of the Space Environment Research Centre (SERC) framework for tracking and characterisation of orbiting objects.

The AO imaging system provides correction for atmospheric turbulence, giving the capability to resolve objects as small as 50cm in LEO. This provides opportunity for improved shape and orientation characterisation, which can identify suitable targets for orbit modification through photon pressure. Improved orbit predictions of objects in GEO can be made with AO corrected imaging through image centroiding and precision astrometry.

Imaging is preformed with reflected sunlight off a target, in LEO the targets are bright enough to serve as the guide star for the AO system. Objects in GEO are much dimmer, thus a natural guide star (NGS) or artificial laser guide star (LGS) is required, with a LGS offering increased sky coverage over a NGS.

The design and performance goals of the AO imaging system are presented. Wavefront measurements are performed with a Shack Hartmann wavefront sensor. Corrections to the measured wavefront are performed by a deformable mirror (DM) and images are taken with an EMCCD imaging camera capable of producing images at high frame rate and low noise, which allows for tip/tilt measurement and high signal to noise in images.

Implementing Operational Analytics Using Big Data Technologies to Detect and Predict Sensor Anomalies

Joseph Coughlin, Rohit Mital, Benjamin SanNicolas, Shashi Nittur, Christian Wolf, Rinor Jusufi

Stinger Ghaffarian Technologies, Inc.

Operational analytics when combined with Big Data technologies and predictive techniques have been shown to be valuable in detecting mission critical sensor anomalies that might be missed by conventional analytical techniques. Our approach helps analysts and leaders make informed and rapid decisions by analyzing large volumes of complex data in near real-time and presenting it in a manner that facilitates decision making. It provides cost savings by being able to alert and predict when sensor degradations pass a critical threshold and impact mission operations.

Operational analytics, which uses Big Data tools and technologies, can process very large data sets containing a variety of data types to uncover hidden patterns, unknown correlations, and other relevant information. When combined with predictive techniques, it provides a mechanism to monitor and visualize these data sets and provide insight into degradations encountered in large sensor systems such as the space surveillance network. In this study, data from a notional sensor is simulated and we use big data technologies, predictive algorithms and operational analytics to process the data and predict sensor degradations. This study uses data products that would commonly be analyzed at a site. This study builds on a big data architecture that has previously been proven valuable in detecting anomalies. This paper outlines our methodology of implementing an operational analytic solution through data discovery, learning and training of data modeling and predictive techniques, and deployment. Through this methodology, we implement a functional architecture focused on exploring available big data sets and determine practical analytic, visualization, and predictive technologies.

LEDsat: LEO Cubesats with LEDs for Optical Tracking

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We describe a project to launch 1U Cubesats equipped with Light Emitting Diodes (LEDs) into Low Earth Orbit (LEO) for optical tracking with ground-based telescopes. Active illumination on the satellites increases tremendously the number of passes where the LEO satellite is visible when the ground-based telescope is in darkness. The restriction that the satellite is in direct Sun is removed, and so tracking can take place all night long rather than just in twilight. The inspiration for this project came from the Japanese Cubesat FITSAT-1 that carried red and green high powered LED arrays, and was clearly visible from the ground with small telescopes.

There are two goals: 1) increase the accuracy and precision of LEO orbits by increasing the number of passes that satellite is visible, and 2) minimize the confusion between Cubesats in the case of multiple Cubesats being launched at the same time.

Technical issues to be discussed include the power level required for detection by small (20 - 40 cm) ground based telescopes, the optimum flash pattern for astrometry against star fields, and the timing of the flash pattern to millisecond or better accuracy and precision.

We propose to deploy two such LEDsats simultaneously from the International Space Station: the first to be built at the University of Michigan, and the second to be built at Sapienza University Rome. One experiment is to see how we can distinguish these two Cubesats shortly after deployment solely from optical tracking, and so the Cubesats will have different flash patterns

Orbit Outlook Data Archive

Michael Czajkowski, Andrew Shilliday, David Van Brackle, Asif Dipon, Nicholas Lofaso

Lockheed Martin

In this presentation, we describe and depict the Defense Advanced Research Projects Agency (DARPA)'s Orbit Outlook Data Archive (OODA) architecture. OODA is the infrastructure that the Orbit Outlook system uses to integrate diverse data from various academic, commercial, government, and amateur space situational awareness (SSA) telescopes.

At the heart of the OODA system is its World Model – a distributed data store built to quickly query big data quantities of information spread out across multiple processing nodes and data centers. The World Model applies a multi-index approach where each index is a distinct view on the data. This allows for analysts and analytics (algorithms) to access information through queries with a variety of terms that may be of interest to them. Our indices include: a structured global-graph view of knowledge, a keyword search of data content, an object-characteristic range search, and a geospatial-temporal orientation of spatially located data. In addition, the World Model applies a federated approach by connecting to existing databases and integrating them into one single interface as a "one-stop shopping place" to access SSA information.

In addition to the World Model, OODA provides a processing platform for various analysts to explore and analytics to execute upon this data. Analytic algorithms can use OODA to take raw data and build information from it. They can store these products back into the World Model, allowing analysts to gain situational awareness with this information. Analysts in turn would help decision makers use this knowledge to address a wide range of SSA problems.

OODA is designed to make it easy for software developers who build graphical user interfaces (GUIs) and algorithms to quickly get started with working with this data. This is done through a multi-language software development kit that includes multiple application program interfaces (APIs) and data model with SSA concepts and terms such as: Space Observation, Observable, Measurable, Metadata, Track, Space Object, Catalog, Expectation, and Maneuver.

Synthesis and Analysis of Custom Bi-Directional Reflectivity Distribution Functions in DIRSIG

Jeff Dank, David Allen, David W. Tyler

Integrity Applications Incorporated

The bi-directional reflectivity distribution function (BRDF) is a fundamental optical property of materials, characterizing important properties of light scattered by a surface. For accurate radiance calculations using synthetic targets and numerical simulations such as the Digital Imaging and Remote Sensing Image Generation (DIRSIG) model, fidelity of the target BRDFs is critical. While fits to measured BRDF data can be used in DIRSIG, obtaining high-quality data over a large spectral continuum can be time-consuming and expensive, requiring significant investment in illumination sources, sensors, and other specialized hardware. As a consequence, numerous parametric BRDF models are available to approximate actual behavior; but these all have shortcomings. Further, DIRSIG doesn't allow direct visualization of BRDFs, making it difficult for the user to understand the numerical impact of various models. We discuss the innovative use of "mixture maps" to synthesize custom BRDFs as linear combinations of parametric models and measured data. We also show how DIRSIG's interactive mode can be used to visualize and analyze both available parametric models currently used in DIRSIG and custom BRDFs developed using our methods.

Further Development of Automated Algorithms to Identify Geostationary Satellites, and to Detect Configuration Changes and Mistagging

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Automated detection of change of GEO satellites using photometry is fundamentally dependent on near real time association of non-resolved signatures and object identification. In the past, we decoupled the problem of correlation (with the catalog) from the photometry-based detection of change and mistagging. The technique under development addresses both problems simultaneously to take advantage of the fusion of information and to process all information concurrently in a single statistics-based framework. Non-statistical algorithms which rely on fixed positional boundaries for associating objects, such as the standard Report Observation Association (ROTAS) codes, work well with the uncongested space and small space objects catalog of the past. However, the catalog, as well as the population of objects not listed in the catalog, has grown in size substantially. To complicate the situation further, satellites in allocated GEO clusters are actively kept in slots and require frequent station-keeping. As a result, orbital information often becomes stale as soon as or soon after an ephemeris is generated, which may result in cross-tagging and corrupt reported metric and photometric data. In optical images taken by Las Cumbres Observatory Global Telescope Network (LCOGT), one telescope pointing may show multiple satellites, but identification cannot be done with certainty given only positional information derived from the most recent TLEs. The objective of this study is to demonstrate with LCOGT data that metric information, i.e. right ascension, declination, photometry and GP element set, can be used concurrently to associate (identify) GEO objects. Our tests were conducted on data taken at various cadences and focusing on the stressing scenario of GEO clusters and the occasional presence of uncorrelated tracks. Our use of metric data is different from techniques which rely on improving the ephemeris— the latter typically suffer from an inherent time lag from the last maintenance maneuver.

Blind Detection of Ultra-Faint Streaks with a Maximum Likelihood Method

William Dawson, Michael Schneider

Lawrence Livermore National Lab

We have developed a maximum likelihood source detection method capable of detecting ultra-faint streaks that are approximately an order of magnitude fainter than the detection threshold of canonical detection methods. Our maximum likelihood detection method is a blind model based approach that requires no a priori knowledge about the streak orientation, length, or surface brightness. This method increases the discovery space and enables the utilization of low cost sensors (i.e. higher noise data). The method also easily facilitates unbiased multi-epoch co-addition. We will present the results from the application of this method to simulations, as well as real LEO and GEO observations.

Recent Developments in Shadow Imaging of Geosynchronous Satellites

Dennis Douglas, Dr. Bobby Hint, Dr. David Sheppard, Dr. Channing Chow

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 shadow imaging of geosynchronous (GEO) satellites with near stationary orbits approximately 36,000 km from the Earth. Fundamental spatial resolution limits, post processing techniques, and the prediction of shadow trajectories are discussed in detail. Light collection methods pertaining to system aperture geometry, spectral binning, and detector types are examined over a range of observing scenarios. Results are shown using a radiometrically based numerical simulation taking into account stellar magnitude and angular extent as well as atmospheric factors including turbulence, transmission, and refraction/dispersion. Turbulence is shown to have little impact on shadow image quality and resolvable feature sizes of less than 1 m are shown to be readily achievable for stars with a visual magnitude brighter than mv = 11. Iterative phase retrieval image reconstruction techniques are evaluated leading to the development of a Fresnel propagation integral version of the Gerchberg-Saxton algorithm. GEO satellite sizes corresponding to shadows in the near (Fresnel) and far (Fraunhofer) fields are used to quantify the convergence rate and final image quality of the reconstruction algorithm. Both 1D and 2D reconstruction algorithms are evaluated. A prediction tool is developed to map the temporally varying density of shadows over the Earth's surface and quantify shadow trajectory errors based on stellar astrometric and satellite ephemeral uncertainties. Macroscopic shadow density maps as well as shadow track trajectories over localized regions are presented. This ongoing work is funded under a basic research grant by the Air Force Office of Scientific Research (AFOSR).

Satellite Type Estimation from Ground-Based Photometric Observation

Takao Endo, Hitomi Ono, Jiro Suzuki, Toshiyuki Ando, Takashi Takanezawa

Mitsubishi Electric Corporation

The optical photometric observation is potentially a powerful tool for understanding of the Geostationary Earth Orbit (GEO) objects. At first, we measured in laboratory the surface reflectance of common satellite materials, for example, Multi-layer Insulation (MLI), mono-crystalline silicon cells, and Carbon Fiber Reinforced Plastic (CFRP). Next, we calculated visual magnitude of a satellite by simplified shape and albedo. In this calculation model, solar panels have dimensions of 2 by 8 meters, and the bus area is 2 meters squared with measured optical properties described above. Under these conditions, it clarified the brightness can change the range between 3 and 4 magnitudes in one night, but color index changes only from 1 to 2 magnitudes. Finally, we observed the color photometric data of several GEO satellites visible from Japan multiple times in August and September 2014. We obtained that light curves of GEO satellites recorded in the B and V bands (using Johnson filters) by a ground-base optical telescope. As a result, color index changed approximately from 0.5 to 1 magnitude in one night, and the order of magnitude was not changed in all cases. In this paper, we briefly discuss about satellite type estimation using the relation between brightness and color index obtained from the photometric observation.

Optical and Chemical Characterization of Polyimide in a GEO-Like Environment

Daniel Engelhart[1], Dale Ferguson[1], Ryan Hoffmann[1], Elena Plis[2]

[1]Air Force Research Laboratory, [2]Assurance Technology Corporation

Ground- and space-based optical observations of space objects rely on knowledge about how spacecraft materials interact with light. However, this is not a static property. Each material's optical fingerprint changes continuously throughout a spacecraft's orbital lifetime. These changes in optical signature occur because energetic particles break bonds within a material and new bonds subsequently form. The newly formed bonds can be identical to the original bonds or different, resulting in a new material. The chemical bonds comprising the material dictate which wavelengths of light are absorbed. Understanding the processes of material damage and recovery individually will allow development of a predictive model for materials' optical properties as a function of exposure to the space environment. Toward that end, we have damaged samples of polyimide using high energy electrons comparable to those found in a geostationary earth orbit and characterized the resultant changes in the material's optical fingerprint in the wavelength range of 0.2 to 25 microns. The chemical modifications to the material that result in these optical changes have also been identified. After initial electron-induced damage, the rate and mechanism of material recovery have been monitored and found to be extremely sensitive to the exposure of the damaged material to air. The implications of that fact and experimental progress toward complete in-vacuo characterization will be discussed.

Realistic Sensor Tasking Strategies

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Efficient sensor tasking is a crucial step in building up and maintaining a catalog of space objects at the highest possible orbit quality. Sensor resources are limited; sensor location and setup (hardware and processing software) influence the quality of observations for initial orbit determination or orbit improvement that can be obtained. Furthermore, improved sensing capabilities are expected to lead to an increase of objects that are sought to be maintained in a catalog, easily reaching over 100 000 objects. Sensor tasking methods hence need to be computationally efficient in order to be successfully applied to operational systems, and need to take realistic constraints, such as limited visibility of objects, time-varying probability of detection and the specific capabilities in software and hardware for the specific sensors into account. This paper shows a method to formulate sensor tasking as an optimization problem and introduces a new method to provide fast and computationally efficient real time, near optimal sensor tasking solutions. Simulations are preformed using the USSTRATCOM TLE catalog of all geosynchronous objects. The results are compared to state of the art observation strategies.

Population Statistics for PHD Filter SSA Tracking

Carolin Frueh

Purdue University

Optical sensors equipped with CCD detectors are a popular configuration to collect astrometric observations of near Earth space objects, such as satellites or space debris. In ground based observations, for the majority of the objects only non-resolved imaging is available. This leads to the problem of observation association, which object image belongs to which object, cardinality, how many objects have been observed (and how many of the detections are due to clutter) and the state estimation, what is the full state determined with the observation of a subset of the state, e.g. two angles. These three problems are often solved together in a so-called multi-target tracking framework. A popular method of multi-target tracking that has gathered a lot of attention is an approach using random finite sets, with a popular implementation of e.g. the probability hypothesis filter (PHD). In order to apply such a filter the whole scene and detection scenario has to be accurately modeled. In this paper a twofold is shown. First, classical methods of sensor modeling are reviewed, such as the classical CCD equation. In a second step, improved modeling is offered, overcoming some of the classical limitations in the modeling assumptions. Solutions to noise modeling, and the probability of detection are offered. Subsequently, the uncertainty of the extracted object image centroid is quantified using Fisher information gain. In the filtering domain, this quantification is needed in order to determine the likelihood. Analytic expressions are offered. In a last step, the modeling assumptions of the classical PHD filter are shown and mismatches with the space situational awareness (SSA) tracking are shown. The precise sensor modeling, improved probability of detection and likelihood are compared with usual assumptions that are made in the PHD filter implementation. Performance is compared.

Time-Resolved CubeSat Photometry with a Low Cost Electro-Optics System

Forrest Gasdia, Aroh Barjatya, Sergei Bilardi

Embry-Riddle Aeronautical University

Once the orbits of small debris or CubeSats are determined, optical rate-track follow-up observations can provide information for characterization or identification of these objects. Using the Celestron 11" RASA telescope and an inexpensive CMOS machine vision camera, we have obtained time-series photometry from dozens of passes of small satellites and CubeSats over sites in Florida and Massachusetts. The fast readout time of the CMOS detector allows temporally resolved sampling of glints from small wire antennae and facets of rapidly tumbling objects. Because the shape of most CubeSats is known, these light curves can be used in a mission support function for small satellite operators to diagnose or verify the proper functioning of an attitude control system or deployed antenna or instrument. We call this telescope system and the accompanying analysis tools OSCOM for Optical tracking and Spectral characterization of CubeSats for Operational Missions. We introduce the capability of OSCOM for space object characterization, and present photometric observations demonstrating the potential of high frame rate small satellite photometry.

Real Time Phase Fluctuation Correction Using a Phased Array of Widely Separated Antennas

Barry Geldzahler

NASA

We present the results of two uplink phased array efforts at 8 GHz (X-band): (a) at NASA's Goldstone tracking station in California and (b) at the Kennedy Space Center. We show that the theoretical N2 power increase has been achieved and that atmospheric phase fluctuations have been compensated in real time. Next we present our progress toward similar demonstrations at Ka-band (30-31 GHz). We also discuss the limitation of the current systems and what is needed for an operational phased array of widely separated antennas. Finally, we show the results of our recent study to achieve high spatial resolution for GEO objects. These demonstrations and studies would then enable NASA to establish a high power, high resolution, 24/7 availability radar system (a) for tracking and characterizing observations of Near Earth Objects, (b) tracking, characterizing and determining the statistics of small-scale (?10cm) orbital debris, (c) to incorporate the capability into its space communication and navigation tracking stations for emergency spacecraft commanding in the Ka We then describe our visionary program to achieve similar results at Ka band in both communication and radar and how it compliments and supplements the Space Fence, MIT/LL's W-band efforts, and optical approaches.

Autonomous Processing of Satellite Streaks in Electro-Optic Imagery

Simon George, Grant Privett, William Feline

Defence Science & Technology Laboratory

In February 2015, the United Kingdom's Defence Science and Technology Laboratory (Dstl) and the Defence Technology Agency (DTA) of New Zealand undertook a collaborative Electro-Optical (EO) space surveillance activity using several items of low-cost, commercial off-the-shelf EO equipment.

Teams deployed to two sites separated by 160 km on the southern island of New Zealand, where they performed contemporaneous imaging using cooled CCD cameras fitted with consumer-level lenses, along with off-the-shelf Digital Single Lens Reflex cameras.

The aim was to determine whether data obtained using readily-deployable equipment and relatively unskilled operators could significantly enhance Space Situational Awareness (SSA) capability and support cross-cueing between two deployed systems. The data has also been employed to support and inform the development of a robust software suite for autonomous on-site processing and orbit determination which exploits existing tools such as Astrometry.Net and Source Extractor together with Dstl's existing model-based processor software and bespoke tools.

This paper presents a description of the scope of the campaign and presents an assessment of: (a) the collected data, (b) the ongoing development of Dstl's in-house research tool and (c) some preliminary results of the pragmatic approach to sensor hardware selection and software capability applied. The trial successes, limitations and implications for the use of deployable systems are discussed and recommendations made for follow-on activities.

Assessment for Operator Confidence in Automated Space Situational Awareness and Satellite Control Systems

Joe Gorman, Martin Voshell, Amy Sliva

Charles River Analytics

The United States is highly dependent on space resources to support military, government, commercial, and research activities. Satellites operate at great distances, observation capacity is limited, and operator actions and observations can be significantly delayed. Safe operations require support systems that provide situational understanding, enhance decision making, and facilitate collaboration between human operators and system automation both in-the-loop, and on-the-loop.

Joint cognitive systems engineering (JCSE) provides a rich set of methods for analyzing and informing the design of complex systems that include both human decision-makers and autonomous elements as coordinating teammates. While, JCSE-based systems can enhance a system analysts' understanding of both existing and new system processes, JCSE activities typically occur outside of traditional systems engineering (SE) methods, providing sparse guidance about how systems should be implemented. In contrast, the Joint Director's Laboratory (JDL) information fusion model and extensions, such as the Dual Node Network (DNN) technical architecture, provide the means to divide and conquer such engineering and implementation complexity, but are loosely coupled to specialized organizational contexts and needs.

We previously describe how Dual Node Decision Wheels (DNDW) extend the DNN to integrate JCSE analysis and design with the practicalities of system engineering and implementation using the DNN. Insights from Rasmussen's JCSE Decision Ladders align system implementation with organizational structures and processes. In the current work, we present a novel approach to assessing system performance based on patterns occurring in operational decisions that are documented by JCSE processes as traces in a decision ladder. In this way, system assessment is closely tied not just to system design, but the design of the joint cognitive system that includes human operators, decision-makers, information systems, and automated processes. Such operationally relevant and integrated testing provides a sound foundation for operator trust in system automation that is required to safely operate satellite systems.

Automated Space Surveillance Using the AN/FSY-3 Space Fence System

Peter Hack, Kameron Simon, Ken Carbaugh

Lockheed Martin

The AN/FSY-3 Space Fence System is a highly automated space surveillance system enabled by a service-oriented, net-centric architecture and an advanced situational awareness user interface. The large radar power aperture, coupled with mission processing, automation and advanced visualization, permits rapid space catalog build-up and provides space object event alerts to operators in near-real time. Operator burden is minimized with intuitive three-dimensional track displays, simplified radar tasking and control, and orbital mechanics processing driven by the US Air Force Space Command (AFSPC) Astrodynamic Standards Software.

Fast Optimization Schemes for Phase Recovery in Bispectral Imaging

James Herring, James Nagy

Emory University

Speckle interferometry is a common method used to obtain astronomical images using ground-based telescopes to image through a turbulent atmosphere-telescope system. However, when imaging more complicated astronomical objects such as satellites, speckle interferometry methods necessitate the separate recovery of the object's Fourier phase to obtain more detailed images. Bispectral methods are one approach to solving this complementary problem of phase recovery in speckle interferometry. They retrieve an object's Fourier phase by matching it to the object's bispectrum, a collectable statistical quantity from the speckle data. Mathematically, phase retrieval from the bispectrum can be formulated as a large-scale, non-linear inverse problem. We consider several optimization schemes from the literature for solving this phase retrieval problem. In particular, we focus on accelerating the speed and convergence of this optimization while maximizing the quality of the recovered image through efficient implementation, Hessian based optimization, and appropriate regularization.

Optimal Scheduling for Geosynchronous Space Object Follow-Up Observations Using a Genetic Algorithm

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Optical observations for space debris in the geosynchronous region have been performed for many years. During this time, observation strategies, processing techniques and cataloging approaches were successfully developed. Nevertheless, the importance of protecting this orbit region from space debris requires continuous monitoring in order to support collision avoidance operations. So-called follow-up observations providing information for orbit improvement estimations are necessary to maintain a high accuracy of the cataloged objects. Those serve a two-fold: For one the orbits have to be accurate enough to be able to re-observe the object after a time of no observations, that is keeping it in the catalog, secondly, the importance of protecting active space assets from space debris requires even higher accuracy of the catalog orbits. Due to the limited observation resources and because a space debris object in the geostationary orbit region can only be observed for a limited period of time per the observation night and telescope efficient scheduling of follow-up observations is a key element. This paper presents an optimal scheduling algorithm for a robotic optical telescope network using a genetic algorithm that has been applied providing optimal solutions for catalog maintenance. As optimization parameter the information content of the orbit has been used. It is shown that information content utilizing the orbit's covariance and the information gain in an expected update is a useful optimization measure. Finally, simulations with simulated data of space debris objects are used to study the effectivity of the scheduling algorithm.

Charged Geosynchronous Debris Perturbation Using Rapid Electromagnetic Force and Torque Evaluation

Joseph Hughes, Hanspeter Schaub

University of Colorado

Space objects experience perturbation torques and forces from their interaction with the local space environment. In the Geosynchronous orbit regime in particular objects have been shown to charge to 10's of kilo-Volts in the Earth's shadow, but also to kilo-Volt levels in sun-lit conditions if the object's surface is not continuously conducting.

This charging results in electrostatic torques and forces being produced due to the interactions with the local electric and magnetic fields. This paper investigates faster-than-realtime numerical methods such as Appropriate Fidelity Measures (AFMs) and the Multi-Sphere-Method (MSM) to approximate these forces and torques on uncontrolled HAMR space debris. Numerical simulations show how these electrostatic forces and torques couple to stronger perturbations such as SRP to create position differences of more than 50 km over periods of 12 hours.

A High Performance Computing Study of a Scalable FISST-Based Approach to Multi-Target, Multi-Sensor Tracking

Islam Hussein[1], Christopher W. T. Roscoe[1], Matthew P. Wilkins[1], Paul. W. Schumacher, Jr.[2]

[1]Applied Defense Solutions, [2]AFRL

Finite Set Statistics (FISST) is a powerful Bayesian inference tool for the joint detection, classification and tracking of multi-sensor, multi-target estimation. FISST is capable of handling phenomena such as clutter, misdetections, and object birth and death. Implicit within the approach are solutions to the data association and target label-tracking problems. Even for problems without object birth and death, i.e., just accounting for data association challenges and the associated misdetection and clutter errors, the full FISST filtering equations are intractable. While FISST-based methods such as the PHD and CPHD filters are tractable, they require heavy moment approximations to the full FISST equations that result in a significant loss of information contained in the collected sensor data. We have recently developed an approximation of the full FISST equations. These approximations do not require any moment approximations, hence retaining much of the information content of sensor data, yet they render the full FISST equations tractable and scalable. The key idea behind these approximations lies in the update step of the filter. While the prediction step is embarrassingly parallelizable, the update step is partially parallelizable. The bottleneck computation in the full FISST update step is the requirement to enumerate all possible observation-to-track associations. The core idea in rendering the FISST filter tractable is that instead of considering all associations, one can include only a subset of the associations. If the chosen subset contains the true association, only a small amount of irrelevant information is lost. If the true association is not among the chosen subset, while some tracking error will be introduced, the update step becomes essentially trivial in that the filter only weakly adjusts the multi-target probability density function. The subset of associations can be chosen in any one of various ways. For example, they can be selected uniformly randomly. Alternatively, one can select them according to a Markov Chain Monte Carlo (MCMC) technique partially developed by the authors, called Smart Sampling MCMC (SSMCMC). In SSMCMC one sets the number of selected associations M for inclusion in the update step and the method returns a subset of the associations of size M. In this paper we will review the FISST approximation as well as the SSMCMC approach. We will then study the effect of tuning the SSMCMC parameter M on tracking quality. The study will be performed on a representative space object catalog with varying numbers of RSOs ranging from a handful of objects to 2000 objects. We will implement the solution using the Scala computing language, which naturally lends itself to parallelism and distribution. The study will be conducted on AFRL's high performance computing facility. We expect to see that as the parameter M is increased the proposed FISST filter's performance improves tracking error wise, but worsens from the computational time perspective. We will also demonstrate the scalability of the developed solution as a function of the number of RSOs, the number of sensors, and consequently the number of observations.

Optimal SSN Tasking to Enhance Real-Time Space Situational Awareness

Islam Hussein[1], Robert Sivilli[2], John Ferreira[1]

[1]Applied Defense Solutions, [2]AFRL/RVSVC

In this paper we develop a scalable simulation environment that implements a finite set statistical (FISST) information-based centralized tasking of a modernized Space Surveillance Network (SSN) in order to improve Space Situational Awareness (SSA). The environment models a population of space objects and sensors representative of diverse types of SSN sensors. Observations collected by the sensors are used to maintain and update a probabilistic representation of the state (the “information state”) of the space objects. Currently, this state is the position and velocity of all objects. This state is then used by a centralized scheduler to task the sensors over a future finite horizon. In order to do this, the scheduler propagates this state into the future to predict the state using a candidate schedule over the scheduling horizon. The performance of a candidate schedule is evaluated based on the amount of information gained during the collection process. Because the information gain is based on FISST, the gain reflects phenomena such as miss-detections (e.g., due to space object dimness), and false alarms. To ensure a real-time schedule computation, we use a fast stochastic optimization algorithm called the Information State Receding Horizon Control (ISRHC). Current results demonstrate the performance improvement (in information gain and true tracking error) of the FISST/ISRHC solution. As one would expect, for example, tracking error grows as the schedule gets “older” (closer to the end of the scheduling horizon) and as each new schedule gets implemented, a significant drop in error occurs.

All-Sky Camera Calibration

Kevin Jim, Edward Pier, Peter Lewis, Robert Izuda, Allister Knox, Ishan Mons, Frank Price, Ian Wasnich

Oceanit

Oceanit has built an all-sky, thermal infrared imaging system for water vapor and cloud mapping. We discuss our methods for radiometric and geometric calibration of this system. Because the field of view is so wide, the standard method of filling the field of view with radiometric calibration sources cannot work. We also describe our purpose-built calibration instrumentation and results.

Automated RSO Stability Analysis

Thomas Johnson

Analytical Graphics, Inc.

A methodology for assessing the attitude stability of a Resident Space Object (RSO) using visual magnitude data is presented and then scaled to run in an automated fashion across the entire satellite catalog. Results obtained by applying the methodology to the Commercial Space Operations Center (COMSpOC) catalog are presented and summarized, including head counts of stable and unstable objects and their distribution in different orbit regimes. We also examine the timeline for detecting the transition from stable to unstable attitude.

Commercial SSA Catalog Performance

Thomas Johnson, Robert Hall

Analytical Graphics, Inc.

We present a summary over the last year of doing commercial SSA operations at AGI's Commercial Space Operations Center (COMSpOC) and examine some key performance statistics such as ephemeris accuracy, catalog completeness, and revisit rates, neighborhood watch, conjunction analysis, and maneuver detection and reconstruction performance.

Analysis of Specular Reflections off Geostationary Satellites

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Many photometric studies of artificial satellites have attempted to define procedures that minimise the size of datasets required to infer information about satellites. However, it is unclear whether deliberately limiting the size of datasets significantly reduces the potential for information to be derived from them. In 2013 an experiment was conducted using a 14 inch Celestron CG-14 telescope to gain multiple night-long, high temporal resolution datasets of six geostationary satellites. This experiment produced evidence of complex variations in the spectral energy distribution (SED) of reflections off satellite surface materials, particularly during specular reflections. Importantly, specific features relating to the SED variations could only be detected with high temporal resolution data.

An update is provided regarding the nature of SED and colour variations during specular reflections, including how some of the variables involved contribute to these variations. Results show that care must be taken when comparing observed spectra to a spectral library for the purpose of material identification; a spectral library that uses wavelength as the only variable will be unable to capture changes that occur to a material's reflected spectra with changing illumination and observation geometry. Conversely, colour variations with changing illumination and observation geometry might provide an alternative means of determining material types.

Ionospheric Impacts on UHF Space Surveillance

James Jones, Darvy Ceron Gomez

Northrop Grumman

Earth's atmosphere contains regions of ionized plasma caused by the interaction of highly energetic solar radiation. This region of ionization is called the ionosphere and varies significantly with altitude, latitude, local solar time, season, and solar cycle. Significant ionization begins at about 100 km (E layer) with a peak in the ionization at about 300 km (F2 layer). Above the F2 layer, the atmosphere is mostly ionized but the ion and electron densities are low due to the unavailability of neutral molecules for ionization so the density decreases exponentially with height to well over 1000 km. The gradients of these variations in the ionosphere play a significant role in radiowave propagation. These gradients induce variations in the index of refraction and cause some radiowaves to refract. The amount of refraction depends on the magnitude and direction of the electron density gradient and the frequency of the radiowave. The refraction is significant at HF frequencies (3-30 MHz) with decreasing effects toward the UHF (300-3000 MHz) range. UHF is commonly used for tracking of space objects in low Earth orbit (LEO). While ionospheric refraction is

small for UHF frequencies, it can cause errors in range, azimuth angle, and elevation angle estimation by ground-based radars tracking space objects. These errors can cause significant errors in precise orbit determinations. For radiowaves transiting the ionosphere, it is important to understand and account for these effects. Using a sophisticated radio wave propagation tool suite and an empirical ionospheric model, we calculate the errors induced by the ionosphere in a simulation of a notional space surveillance radar tracking objects in LEO. These errors are analyzed to determine daily, monthly, annual, and solar cycle trends. Corrections to surveillance radar measurements can be adapted from our simulation capability.

Season-Controlled Assimilated Thermospheric Mass Density Profiles for Solar Minimum and Solar Maximum Conditions

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It is well known that Earth’s atmosphere shows a high degree of variation to space weather and the 11-year sunspot cycle. This paper investigates the response of the thermosphere-ionosphere system during different space weather conditions using two satellite missions: Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) and Swarm. COSMIC is a constellation of six satellites at an average altitude of 800 km that can provide about 2000-3000 radio occultations per day. Swarm is a new mission that consists of three polar satellites (two satellites at 460 km, and the other at 530 km in altitude) designed for monitoring the entire magnetic field of the Earth.

Research on deriving atmospheric mass density using GNSS radio occultation data is a new arena with lots of potential. In this contribution, the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIE-GCM) developed by the High Altitude Observatory of the National Center for Atmospheric research, USA is incorporated into two data assimilation experiments. The first experiment is for year 2009, which is the most recent solar minimum and the second experiment is for 2014, which is a solar maximum year with the lowest recorded sunspot activity since accurate records began in 1750. Atmospheric mass density is analysed in six periods (perihelion, aphelion, two equinoxes and two solstices) where COSMIC measurements are used for solar minimum conditions while Swarm measurements are used for solar maximum conditions.

The atmospheric mass densities derived from GNSS precise orbit determination (POD) data and electron density measurements are compared. The experiment is arranged in such a way to obtain a wholistic view of the season-controlled assimilated data. In the second experiment accelerometer derived density is used as a benchmark to validate the data assimilation technique used in this work to take advantage of the measurements from high precision accelerometers onboard Swarm. Studies suggest that mass density derived from electron density of COSMIC satellites is more effective than mass density derived from GNSS POD data. Comprehensive investigation of mass density obtained through assimilation of precise orbit measurements and electron density will be carried out. It is expected that results will enhance our understanding of inferring total mass density from the more abundant electron density observations.

The forecasting capabilities of the TIE-GCM model during various space weather conditions through seasons and sunspot extremes will also be investigated. The experiments, given the wide coverage in both temporal and spatial domains, will be expected to retrieve valuable information to improve atmospheric mass density models and hence space situational awareness.

Space Fence System Support of Conjunction Assessment

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The Space Fence Radar System is designed to provide flexible scheduling of its power and aperture. Operations that use these capabilities in an efficient and effective manner will need to account for not only the radar's capabilities but also the dynamic space environment. This paper assesses the radar's flexible capabilities in support of an expanded conjunction assessment mission. Once activated, a massive amount of new objects will be cataloged. Therefore, conjunction assessment of the new catalog will flag more objects for possible collisions. These objects can be tasked to the radar to provide more accurate and timely information for better assessment of the probability of collision and collision avoidance analysis. The support Space Fence provides will help characterize space object interactions, prevent unnecessary satellite maneuvers, and minimize avoidable collisions.

Polish and European SST Assets: the Solaris-Panoptes Global Network of Robotic Telescopes and the Borowiec Satellite Laser Ranging System

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We present the assets of the Nicolaus Copernicus Astronomical Center, Space Research Center (both of the Polish Academy of Sciences), two Polish companies Sybilla Technologies, Cillium Engineering and a non-profit research foundation Baltic Institute of Technology. These assets are enhanced by telescopes belonging to the Open University (UK) and the Max Plank Institute for Extraterrestrial Physics. They consist of the Solaris-Panoptes global network of optical robotic telescopes and the satellite laser ranging station in Borowiec, Poland. These assets will contribute to the Polish and European Space Surveillance and Tracking (SST) program. The Solaris component is composed of four autonomous observatories in the Southern Hemisphere. Solaris nodes are located at the South African Astronomical Observatory (Solaris-1 and Solaris-2), Siding Spring Observatory, Australia (Solaris-3) and Complejo Astronomico El Leoncito, Argentina (Solaris-4). They are equipped with 0.5-m telescopes on ASA DDM-160 direct drive mounts, Andor iKon-L cameras and housed in 3.5-m Baader Planetarium (BP) clamshell domes. The Panoptes component is a network of telescopes operated by software from Sybilla Technologies. It currently consists of 4 telescopes at three locations, all on GM4000 mounts. One 0.36-m (Panoptes-COAST, STL-1001E camera, 3.5 BP clamshell dome) and one 0.43-m (Panoptes-PIRATE, FLI 16803 camera, 4.5-m BP clamshell dome, with planned exchange to 0.63-m) telescope are located at the Teide Observatory (Tenerfie, Canary Islands), one 0.6-m (Panoptes-COG, SBIG STX 16803 camera, 4.5-m BP clamshell dome) telescope in Garching, Germany and one 0.5-m (Panoptes-MAM, FLI 16803 camera, 4.5-m BP slit dome) in Mammendorf, Germany. Panoptes-COAST and Panoptes-PIRATE are owned by the Open University (UK). Panoptes-COG is owned by the Max Plank Institute for Extraterrestrial Physics and Panoptes-MAM by Baader Planetarium. Two additional Panoptes telescopes will be deployed in the near future. A double system 0.3-m f/1.44 TEC300VT-7DEG astrograph and a 0.5-m telescope (Panoptes-1AB) will be initially installed in Poland in mid 2017 and a 0.7-1.0-m class telescope will be installed at a yet not determined global location in 2018 (Panoptes-2). They will be co-owned and/or operated by Sybilla Technologies, Cillium Engineering and Baltic Institute of Technology. By 2018 the network will consist of 10

telescopes. In mid 2020 the first light of a 1.5-m f/4 telescope for SST is planned assuming that the feasibility study is approved by mid 2017. The 1.5-m telescope project is led by Nicolaus Copernicus Astronomical Center.

Borowiec Satellite Laser Ranging Station (BSLRS) belongs to the Space Research Center of the Polish Academy of Sciences (SRC PAS) and it is the only such device in Poland and one of the few ones in the world working since the mid-80's. The BSLRS entered the structures of International Laser Ranging Service (ILRS) on May 13, 1988 and represents the EUROpean LASer network (EUROLAS) consortium joining European laser stations in the frame of ILRS. The most important elements of the BSLRS system constitute two high-energy ND:YAG pulse laser modules (50 and 450 mJ pulse energy for 532 nm), both fully operational and a transmitting-receiving Cassegrain telescope with an aperture of 0.65 m, additionally equipped with 20 cm guiding Maksutov telescope. In the long history the BSLRS has tracked 71 different satellites (52 LEO and 19 MEO), providing more than 8 million good shots (single measurements) for more than 12 400 passes of satellites over the Borowiec station. The BSLRS is currently working in the frame of Space Debris Study Group (SDSG) ILRS and European SST program. In the last few months, station has participated in several campaigns of space debris objects like ENVISAT, TOPEX/Poseidon, JASON-1 and others with good results as presented in this publication.

Laser De-Spin Maneuvers for an Active Debris Removal Mission – A Realistic Scenario for Envisat

Daniel Kucharski[1], James Bennett[1], Georg Kirchner[2]

[1]Space Environment Research Centre, [2]IWF OEAW

The defunct Envisat satellite is considered to be a potential target for a future de-orbit mission. Before the removal from orbit, the massive satellite has to lose its rotational energy to present a stable attitude in the space. Laser tracking observations reveal that the satellite's spin energy is reducing slowly which can be explained by the electromagnetic radiation pressure acting on the surfaces of the large body. The spin analysis indicates that the torques exerted on the spacecraft by photon pressure from the direct solar irradiation, Earth's albedo and the Earth's IR emission (total up to 2.3•10-3 Nm) will slowly de-spin Envisat by 2031 (spin period equal to orbital period). In order to accelerate this process the additional laser photon pressure can be applied on the surfaces of the spacecraft. We employ the complete attitude model of Envisat and investigate the theoretical network of the 18 globally distributed 10 kW laser systems to produce an additional force on the satellite's body but only in the intervals when the resulting torque can act against the spin motion. The synchronization of the laser operation with the satellite's attitude model reduces the time required for an effective de-spin of Envisat by about 7 years. The presentation will explain the observed loss of the Envisat rotational energy, and will show the advantage of the synchronization between the laser operation intervals with the satellite's attitude model for the optimum de-spin maneuvers.

Comparison of Behavioral and Physical Ontologies for RSOs

Phillip Cunio, William Therien, Douglas Hendrix

ExoAnalytic Solutions Inc.

The population of resident space objects around the Earth is large and growing, and consists of a large number of artificial objects, both active and inactive, with a background flux of natural objects. The many sources of these objects over the course of multiple decades, together with the fact that partial breakup and surface wear events may generate subsidiary populations of debris fragments in crossing orbit regimes, means that the overall population may include objects that are nearly sui generis, as well as larger numbers of objects that bear close resemblances to one another.

In this paper, ExoAnalytic Solutions will present both behavioral (based on RSO activities or apparent activities) and physical (based on observable RSO features) ontologies for RSOs, and compare their capacity for performing meaningful classification of RSOs. This paper will also discuss the logic underlying the use of specific ontologies for RSOs, including the way that representations of categories for organizing knowledge may guide the definition of future research into a given technical regime.

The behavioral and physical ontologies developed will be applied to the problem of classifying actual RSOs as well. The extensive number of astrometric observations that ExoAnalytic Solutions has collected will be collated with a priori knowledge of the RSOs which produced these observations (where possible) to demonstrate example classifications, the utility of which will then be assessed.

Using Machine Learning for Advanced Anomaly Detection and Classification

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Recent advancements in Machine Learning (ML) applications have drastically changed the way we approach large, complex problems. ML has successfully been used in a wide variety of applications to automatically detect and potentially classify changes in activity or a series of activities by utilizing large amounts of seemingly-unrelated data. The amount of data being collected, processed, and stored in the SSA domain has grown at an exponential rate and is well suited for ML. ExoAnalytic Solutions is currently developing advanced algorithms to deliver significant improvements in characterization of deep space objects and Threat Indication and Notification (TIN) using a global network of telescopes collecting photometric data on a multitude of objects. The Phase II AFRL SBIR Autonomous Characterization Algorithms for Change Detection and Characterization (ACDC) effort is providing the ability to detect and identify photometric signature changes due to potential space object changes (e.g. stability, tumble rate, aspect ratio), and correlate the observed changes to potential behavioral changes using a variety of techniques, including supervised learning. Further, these algorithms run in real-time on data being collected and processed by the ExoAnalytic Space Operations Center (EspOC), providing timely alerts and warnings while dynamically creating collection requirements to the EspOC for the algorithms to provide higher fidelity TIN. This paper will discuss the recent algorithms being implemented in ACDC, including the general design approach and results to date. The usage of supervised algorithms (SVMs, Neural Networks, k-Nearest Neighbors, etc.) and unsupervised algorithms (k-means, PCA, Hierarchical clustering, etc.) and the implementations of these algorithms will be explored. Results of applying these algorithms to EspOC data both in an off-line "pattern of life" analysis as well as using the algorithms on-line in real-time will be presented. Finally, future work in applying ML for SSA using ACDC data and algorithms will be discussed.

Infrared Photometry of GEO Spacecraft with WISE

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NASA launched the Wide-field Infrared Survey Explorer (WISE) into orbit on December 2009 with a mission to scan the entire sky in the infrared in four wavelength bands: 3.4, 4.6, 12, and 22 microns. WISE acquired data in the four bands for 10 months until the solid hydrogen cryogen was depleted and then proceeded to operate in the two shorter wavelength bands for an additional four months in a Post-Cryo phase. In its trove of data, WISE captured many streaks that were artificial satellites in orbit around Earth. We have examined a subset of equatorial WISE images with |declination| < 2.0 degrees to find geosynchronous Earth orbit (GEO) station-keeping satellites. Furthermore, we require |galactic latitude| > 30 degrees in order to minimize contamination of the satellite streaks by stars in the galactic plane. At least one streak of the length appropriate for a GEO station-keeping satellite appears in over 10% of these images. In bands 1 through 3 (for images 1016x1016 in size), the streaks are approximately 100 pixels in length, and in band 4 (for images 508x508 in size), the streaks are approximately 50 pixels in length. Most, but not all, of these spacecraft appear in all 4 wavelength bands. Since WISE is in a Sun-synchronous orbit pointed radially away from the Earth at all times, all observations of GEO objects were obtained at a solar phase angle of approximately 90 degrees. We report on the color distributions of these detections and interpret the colors and compare the spacecraft colors with colors of other astronomical objects such as stars, galaxies, and asteroids that have appeared in previously published works on WISE data.

Creating Situational Awareness in Spacecraft Operations with the Machine Learning Approach

Zhenping Li

ASRC Technical Services

The spacecraft operation for maintaining the satellite health, safety, performance and accuracy involves data trending, data monitoring, and engineering analysis processes. The current concept of operations can no-longer meet the growing challenges from new mission with order of magnitude larger data volumes to trend, monitor and analyze. The focus of this talk is to present a machine learning approach for an automated and integrated approach to the spacecraft operations. The spacecraft data trending, monitoring, and engineering analysis are a natural fit to the operational concept of a machine learning system. The data training in the machine learning system obtains the time dependent trend for a dataset represented by its time dependent function and standard deviation, which moves beyond the statistical trending used in the most of existing spacecraft operations. The time dependent trend defines a dynamic limit so that it can predict what to expect for incoming data points. The potential anomalies or changes to the spacecraft can be detected and characterized in real time. Thus, the machine learning system not only automates the spacecraft operations for trending, monitoring and engineering analysis, it also provides a systematic approach in creating situational awareness in spacecraft operations. The real time detection and characterization of potential anomalies or sudden changes to the spacecraft create actionable information for an intelligent decision making system or engineers, which are crucial for a more proactive maintenance or an autonomous spacecraft operations. The general requirements for data training in a machine learning approach are discussed, and the data training strategy in spacecraft operations are presented. The neural networks are implemented in the machine learning algorithms. The application of the machine learning system to Geostationary Environment Operational Satellite(GOES) Imager data processing process is presented. It shows that the machine learning system enables the real-time monitoring of the instrument data calibration process that would have been impossible with the standard statistical trending approach. The machine learning provides a systematic approach in creating situational awareness, and it represents a significant advance toward an autonomous spacecraft operations.

System Design and Implementation of the Virginia Tech Optical Satellite Tracking Telescope

Daniel Luciani, Dr. Jonathan Black

Virginia Tech

The Virginia Tech optical satellite tracking telescope (VTOST) aims to test the feasibility of a commercial off-the-shelf (COTS) designed tacking system for Space Situational Awareness (SSA) data contribution. A novel approach is considered, combining two COTS telescopes, a high-powered telescope, built for astronomy purposes, and a larger field of view (FOV) telescope. Using only publicly available two-line element sets (TLEs), orbital propagation accuracy degrades quickly with time from epoch and is often not accurate enough to task a high-powered, small FOV telescope. Under this experimental approach, the larger FOV telescope is used to acquire and track the resident space object (RSO) and provide a real-time pointing update to allow the high-powered telescope to track the RSO and provide possible resolved imagery. VTOST is designed as a remotely taskable sensor, based on current network architecture, capable of serving as a platform for further SSA studies, including unresolved and resolved imagery analysis, network tasking, and orbit determination. Initial design considerations are based on the latest Raven class and other COTS based telescope research, including research by AFRL, ExoAnalytic Solutions, and other university level telescope projects. A holistic system design, including astronomy, image processing, and tracking methods, in a low-budget environment is considered. Method comparisons and results of the system design process are presented.

Reconstruction of the 1801 Discovery Orbit of Ceres via Contemporary Angles-Only Algorithms

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This paper employs contemporary angles-only methods of initial orbit determination (IOD) and differential correction (DC) to revisit how Gauss solved for the orbit of Ceres using observations taken more than two centuries ago. The solutions obtained with these angles-only algorithms are verified by accurate numerically-integrated ephemerides and published U.S. Naval Observatory (USNO) values. These angles-only IOD and DC algorithms are fully applicable to today's space situational awareness for both geocentric and heliocentric objects.

Giuseppe Piazzi's observations of the asteroid Ceres during 1801 were both the stimulus and a test case for Gauss's classic orbit determination method using three angles-only observations. While Gauss's method uses just three of Piazzi's observations during January-February 1801, there were actually 19 complete observations available. But to use all 19 observations would have been prohibitively difficult to accomplish with pen, ink, paper, and logarithm tables back in 1801, even if all of the necessary computational procedures had already been developed.

So this paper presents contemporary solutions that input all 19 complete observations to modern computer programs, and it assesses the quality of the observations and the orbital solutions that could have been obtained with them if contemporary algorithms and computers had been available in 1801. The contemporary solutions rely upon four computer algorithms developed by the two authors: HGM, Der IOD, ORBIT2, and Batch DC, as further described in the paper.

Laser Guidestar Satellite for Ground-based Adaptive Optics Imaging of Geosynchronous Satellites

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Real-time observation and monitoring of high value asset (HVA) GEO satellites with ground-based imaging systems is an attractive alternative to fielding high cost, long lead, space-based imaging systems, but ground-based observations are inherently limited by atmospheric turbulence. Adaptive optics (AO) systems help ground telescopes achieve diffraction-limited seeing. AO systems have relied on the use of bright natural guide stars or laser guide stars projected to the upper atmosphere by ground laser systems. There are several challenges with these traditional AO approaches, including the sidereal motion of GEO objects relative to natural guide stars and the inherent limitations of ground-based laser guide stars.

Inspired by previous work by Greenaway and Stewart (1994), we propose using space-based laser guide stars projected from nanosatellites orbiting Earth. We show that satellite guide star (SGS) systems meet the needs for high-quality imaging of GEO objects using low power lasers. They would be above atmospheric turbulence and provide small angular reference sources on the ground. CubeSats for SGS offer inexpensive, frequent access to space at very low relative cost. We present this enabling technology for potentially using the next generation of extremely large AO telescopes for SSA. SGS systems placed in GEO can enable visible-wavelength imaging of GEO HVAs potentially down to meter or sub-meter feature resolution and can supplement current SSA. The CubeSat bus unit of 10 cm cubed can be combined in multiple units and offers a common form factor for easy integration as auxiliary payloads on traditional launches. We describe a 6U CubeSat SGS measuring 10 x 20 x 30 cm with milliwatt-order laser power, and COTS based attitude determination and control system, among other subsystems. The 6U form factor allows for a propulsion system for navigating around many targets in the GEO belt for multiple SSA and HVA monitoring opportunities per satellite.

Pilot Production of Large Area Microchannel Plates and Picosecond Photodetectors

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Pilot production performance is reported for large area atomic layer deposition (ALD) coated microchannel plates (MCPs) and for Large Area Picosecond Photodetectors (LAPPD™) which incorporate them. "Hollow-core" glass capillary array (GCA) substrates are coated with ALD resistive and emissive layers to form the MCPs, an approach that facilitates independent selection of glass substrates that are mechanically stronger than conventional lead glass MCPs and that have lower levels of radioactive alkali elements compared to conventional MCP lead glass, reducing background noise. MCPs having competitive gain (~10^4), enhanced lifetime and gain stability (7 C cm-2 of charge extraction), reduced background levels (0.028 events cm-2 sec-1) and low gamma-ray detection efficiency are reported for large area (20cm X 20 cm) planar and curved MCPs suitable for use in high radiation environments applications, including astronomy, space instrumentation, and remote night time sensing. The LAPPD™ photodetector incorporates these MCPs in an all-glass hermetic package with top and bottom plates and sidewalls made of borosilicate float glass. Signals are generated by a bi-alkali Na2KSb photocathode, amplified with a stacked chevron pair of MCPs. Signals are collected on RF strip-line anodes integrated into to the bottom plates which exit the detector via pin-free hermetic seals under the side walls. Tests show that LAPPD™s have electron gains greater than 10^7, sub-millimeter spatial resolution for large (multi-photon) pulses and several mm for single photons, time resolution less than 50 picoseconds for single photons, predicted resolution less than 5 picoseconds for large pulses, high stability versus charge extraction, and good uniformity for applications including astrophysics, neutron detection, high energy physics Cherenkov light detection, and quantum-optical photon-correlation experiments.

Feasibility Study for a Near Term Demonstration of Laser-Sail Propulsion from the Ground to Low Earth Orbit

Edward Montgomery

MontTech, LLC

The concept of propellant-less in-space propulsion utilizing an external high energy laser (HEL) to provide momentum to an ultralightweight (gossamer) spacecraft has received attention since the late 1950's. The design, construction, and successful space missions by NASA, Japan's JAXA, and the non-profit Planetary Society has matured space flight hardware for small, yet capable spacecraft moved by photon momentum exchange. The results of recent achievements in high power solid state lasers, adaptive optics, and precision tracking have also made it possible to access the effectiveness and reduced cost of an entry level laser power source. Combined with renewed interest by the space science and space exploration communities in developing technologies that could eventually send a probe to the Kuiper Belt and beyond into interstellar space, a study team was formed to formulate near term mission concepts that would initiate the development of new propulsion methods needed for such a mission. This paper identifies potential key system characteristics and performance parameters available for near term mission applications.

Global Precipitation Measurement (GPM) and International Space Station (ISS) Coordination for CubeSat Deployments to Minimize Collision Risk

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The Global Precipitation Measurement Mission (GPM) is a joint U.S. and Japan mission to observe global precipitation, extending the Tropical Rainfall Measuring Mission (TRMM), which was launched by H-IIA from Tanegashima in Japan on February 28TH, 2014 directly into its 407km operational orbit. The International Space Station (ISS) is a international human research facility operated jointly by Russia and the USA from NASA’s Johnson Space Center (JSC) in Houston Texas. ISS executed a deboost from 415km to 400km a month prior to the GPM launch, effectively placing both vehicles into the same orbital regime. The ISS has been increasing a program of deployments of cost effective CubeSats from the ISS that allow testing and validation of new technologies. With a major new asset flying at the same effective altitude as the ISS, CubeSat deployments became a serious threat to the GPM Mission and a significant indirect threat to the ISS. This paper describes the specific problem and the coordination steps that the projects made to keep both missions safe from collision and maximize their project goals.

Synthetic-Aperture Silhouette Imaging (SASI)

Richard Paxman

MDA Information Systems

The problem of ground-based fine-resolution imaging of geosynchronous satellites continues to be an important unsolved space-surveillance problem. If one wants to achieve 10cm resolution at a range of 36,000km at a wavelength of 0.5um via conventional means, then a 180m diameter telescope with adaptive optics is needed (obviously prohibitively expensive). We are investigating a passive-illumination approach that is radically different from amplitude, intensity, or heterodyne interferometry approaches. The approach, called Synthetic-Aperture Silhouette Imaging (SASI), produces a fine-resolution silhouette image of the satellite. When plane-wave radiation emanating from a bright star is occluded by a GEO satellite, then the light is diffracted and a moving diffraction pattern (shadow) is cast on the surface of the earth. With prior knowledge of the satellite orbit and star location, the track of the moving shadow can be predicted with high precision. A linear array of inexpensive hobby telescopes can be deployed roughly perpendicular to the shadow track to collect a time history of the star intensity as the shadow passes by. According to Babinet's principle, the shadow is the complement of the diffraction pattern that would be sensed if the occluding satellite were an aperture. If the satellite is small, then the Fraunhofer approximation is valid and the collected data can be converted to the silhouette's Fourier magnitude. The method also accommodates Fresnel diffraction in the case of larger satellites. A phase-retrieval algorithm, using the strong constraint that the occlusion of the satellite is a binary-valued silhouette, allows us to retrieve the missing phase and reconstruct a fine-resolution image of the silhouette. Silhouettes are highly informative, providing diagnostic information about deployment of antennas and solar panels, enabling satellite pose estimation, and revealing the presence and orientation of neighboring satellites in rendezvous and proximity operations.

Improved Orbit Determination and Forecasts with an Assimilative Tool for Satellite Drag Specification

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Much as aircraft are affected by the prevailing winds and weather conditions in which they fly, satellites are affected by the variability in density and motion of the near earth space environment. Drastic changes in the neutral density of the thermosphere, caused by geomagnetic storms or other phenomena, result in perturbations of LEO satellite motions through drag on the satellite surfaces. This can lead to difficulties in locating important satellites, temporarily losing track of satellites, and errors when predicting collisions in space. As the population of satellites in Earth orbit grows, higher space-weather prediction accuracy is required for critical missions, such as accurate catalog maintenance, collision avoidance for manned and unmanned space flight, reentry prediction, satellite lifetime prediction, defining on-board fuel requirements, and satellite attitude dynamics.

We describe ongoing work to build a comprehensive nowcast and forecast system for specifying the neutral atmospheric state related to orbital drag conditions. The system outputs include neutral density, winds, temperature, composition, and the satellite drag derived from these parameters. This modeling tool is based on several state-of-the-art coupled models of the thermosphere-ionosphere as well as several empirical models running in real-time and uses assimilative techniques to produce a thermospheric nowcast. This software will also produce 72 hour predictions of the global thermosphere-ionosphere system using the nowcast as the initial condition and using near real-time and predicted space weather data and indices as the inputs. Features of this technique include: • Satellite drag specifications with errors lower than current models • Altitude coverage up to 1000km • Background state representation using both first principles and empirical models • Assimilation of satellite drag and other datatypes • Real time capability • Ability to produce 72-hour forecasts of the atmospheric state

In this paper, we will review the driving requirements for our model, summarize the model design and assimilative architecture, and present preliminary validation results. Validation results will be presented in the context of satellite orbit errors and compared with several leading atmospheric models. As part of the analysis, we compare the drag observed by a variety of satellites which were not used as part of the assimilation-dataset and whose perigee altitudes span a range from 200 km to 700 km.

Space Object Maneuver Detection Algorithms Using TLE Data

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An important aspect of Space Situational Awareness (SSA) is detection of deliberate and accidental orbit changes of space objects. Although space surveillance systems detect orbit maneuvers within their tracking algorithms, maneuver data are not readily disseminated for general use. However, two-line element (TLE) data is available and can be used to detect maneuvers of space objects.

Most of the published maneuver detection algorithms compute a least-squares fit of a sliding window of TLE data (typically semimajor axis and inclination) to a low-order polynomial. These algorithms require manual adjustment of parameters (window length, polynomial order, and threshold) for each space object to obtain acceptable results. They exhibit an inherent lag, low probability of detection, and high false alarm rate.

Three adaptive maneuver detection algorithms are developed and evaluated. The first is a fading-memory Kalman filter, which is equivalent to the sliding-window least-squares polynomial fit, but computationally more efficient and adaptive to the noise in the TLE data.

The second algorithm is based on a sample cumulative distribution function (CDF) computed from a histogram of the magnitude-squared |DV|^2 of change-in-velocity vectors (DV) computed from the TLE data. A maneuver detection threshold is computed from the median estimated from the CDF, or from the CDF and a specified probability of false alarm.

The third algorithm is a median filter. The median filter is the simplest of a class of nonlinear filters called order statistics filters, which is within the theory of robust statistics. The output of the median filter is insensitive to outliers, or large maneuvers. The median of the |DV|^2 data is proportional to the variance of the DV, so the variance is estimated from the output of the median filter. A maneuver is detected when the input data exceeds a constant times the estimated variance.

Optical Estimation of the 3D Shape of a Solar Illuminated, Reflecting Satellite Surface

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Knowledge of the shape and integrity of the surface of an earth orbiting satellite is important to understanding its overall condition and functionality. Surfaces that are optically reflecting can provide this knowledge passively via the detailed spatial distribution of sunlight reflected by them and received at a ground-based observatory. We shall consider here the exploitation of a small set of images of a given surface in reflected sunlight to infer its three-dimensional (3D) shape and roughness. Our present approach builds on a previous work reported three years ago at AMOS in which we utilized an efficient superquadric (SQ) parameterization of a smooth surface that has been slightly roughened over time, e.g., by space weather and other agencies such as micro-debris bombardment. A smooth, differentiable surface may be characterized either locally, one small patch at a time, as being a member of a low-order polynomial family of surfaces or more globally in terms of surface families such as triangular meshes, SQ and deformed SQ families. Of these, the SQ and low-order polynomial families employ the fewest parameters for surface description. For these two families of surfaces, we demonstrate our shape estimation approaches that utilize bi-directional reflectance distribution functions (BRDFs) acquired for as few as two views of the illuminated surface. Due to a high degree of nonlinearity and likely non-convexity of the estimation problem with respect to the parameters of the SQ family, the recovery of the SQ parameters is a highly complex global optimization problem rife with local minima that can trap the optimization from reaching the global minimum corresponding to the true values of the surface parameters. As in Ref. 1, the roughening of the surface is modeled in terms of randomly oriented microfacets that describe the surface imperfections locally, but our approaches are expected to work for more general models of roughening as well.

By contrast, the estimation of polynomial coefficients is a more robust inverse problem that converges well to the global minimum if we first extract the spatial distribution of unit normals of the mean, smooth surface by fitting the BRDF datasets with the BRDFs estimated from the vector field of unit normals, which we can then use to make an initial recovery ("guess") of the polynomial coefficients. The final refinement of the estimates of the surface roughness as well as the polynomial coefficients forms a third step of the process to achieve a reliable global minimization of the fit-to-BRDF-data cost function without need for any regularization.

The SQ parameter recovery is more complex because of the exponentially sensitive dependence of the surface shape on SQ shape parameters. We have made good progress on reliably recovering all nine of the SQ surface shape, size, and roughness parameters by breaking the full inverse problem into a smaller problem of estimating only four of these nine parameters based on the location of the glint point in each BRDF dataset on a spheroid starting surface, followed by the fuller problem of nine-parameter optimization that evolves the spheroid to the final surface shape starting from the values obtained from the smaller problem. Pattern search, combined with an alternating minimization protocol, seems to be quite effective as a global optimization tool, but other global searches are also being tested for a more efficient recovery of these parameters.

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[1] S. Prasad, Q. Zhang, and R. Plemmons, "Shape, Pose, and Material Recovery of Solar-Illuminated Surfaces from Compressive Spectral-Polarimetric Image Data," Proc. AMOS Tech. Conf., Maui, HI (2013)

Optimization of Observation Strategy to Improve Reentry Prediction of Objects in HEO

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In the last decade the number of space debris moving on high elliptical orbit (HEO) has grown fast. Many of these consist of medium and large objects, such as spent upper stages of launch vehicles, whose atmosphere re-entry might violate the constraint on casualty risk of 1/10000. In light of this, increasing the accuracy of the re-entry prediction is a key issue to manage on-ground casualty risk. Currently the only public data source available for re-entry prediction are represented by Two Line Elements (TLEs), provided by the United States Strategic Command (USSTRATCOM). However, these data are inaccurate and do not come with uncertainty information. Thus, the use of observational data coming from one or more Earth sensors might help to increase the accuracy on the re-entry estimation. Setting up an observation campaign is not an easy task, especially for HEO object class: a large number of observations coming from different type of sensors might be required to effectively improve the re-entry prediction, making the observation campaign complex and costly; in addition, to properly design a strategy for HEO object detection, an accurate dynamical model describing the effects of third-body perturbations and the Earth's oblateness, and capturing the intricacies of re-entry phase is needed. In light of the above, we propose an incisive method to determine the observation strategy which guarantees a low error on re-entry epoch and requires a low number of observations, i.e. an effective and low-cost observation campaign. More in details, the design of observation strategy is formulated as a multi-objective optimization problem solved by means of a multi-objective genetic algorithm (MGA). This approach allows minimizing both the number of total measurements and the uncertainty on re-entry epoch. The analyses carried out within this study show the effectiveness of the proposed approach.

Challenges in Physical Characterization of Dim Space Objects: What Can We Learn From NEOs

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Physical characterization of dim space objects in cis-lunar space can be a challenging task. Of particular interest to both natural and artificial space object behavior scientists are properties beyond orbital parameters that can uniquely identify them. These properties include rotational state, albedo, size, shape, density and composition. A wide range of observational and non-observational factors affect our ability to characterize dim objects in cis-lunar space. These include phase angle (angle between Sun-Target-Observer), temperature, rotational variations, and particle size (for natural objects). Over the last two decades, space object behavior scientists studying natural objects have attempted to quantify and correct for a majority of these factors to enhance our situational awareness. These efforts have been primarily focused on developing laboratory spectral calibrations in space-like environment. Calibrations developed to correct spectral data of natural dim objects could be applied when characterizing artificial objects, as the underlying physics is the same. The paper will summarize our current understanding of these observational and non-observational factors and present a case study showcasing the state of the art in characterization of natural dim objects.

Comparison of Phenomenology for Satellite Characterization

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Lockheed Martin

Techniques for improved characterization of Satellites have been an area of research for several years. Many of these approaches show great promise and have been validated using models and simulations. In this paper multiple phenomenology that support satellite characterization will be discussed to include: optical, radar, signals, and Infra-Red. The paper will identify satellite characteristics that could be gleaned from the various data types. Algorithms that support extracting the information will be referenced. Unique collection conditions that enable a phenomenology to yield desired data will be discussed. The paper will discuss the impact of changes to satellite characterization data types over the life of an on-orbit asset. The benefits of such information will be discussed, to include re-acquiring objects after a maneuver.

Performance Analysis and Control Design for a Small Robotic Telescope System

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Laser ranging and optical surveillance are integral parts of many space situation awareness programs. This especially applies for detection and observation of near-earth objects (NEOs). As the amount of space debris is growing, there is an increased need for accurate, continuous monitoring and cataloguing of such objects. The utilization of networks of small, robotic telescopes is key for achieving this goal in a cost efficient manner. However, commercially available telescope systems often lack the necessary pointing and tracking accuracy, especially at high tracking speeds.

This paper analyses the achievable precision of an equatorially mounted telescope system with two direct-drive permanent magnet synchronous motors. The analysis is done using a combination of physical system modeling, dynamic error budgeting and a kinematic description of the telescope system. The kinematic description is based on homogeneous transformations following the Denavit-Hartenberg convention and can be easily extended to a wide range of telescope systems.

The parameters of the physical system are obtained by system identification and parameter estimation for various telescope positions. Based on the identification of the system as well as the stochastic disturbances, a model based controller is designed and implemented. Using this system model and designed controller, the dynamic performance of the telescope system is simulated. The achieved performance is verified experimentally by measurements recorded at various tracking speeds. The experimental results are in good agreement with the performed simulations, verifying the proposed method. This provides a powerful tool to optimize the performance of robotic telescope systems for tracking of NEOs to improve space situation awareness.

High-Power Amplifier Compatible Internally Sensed Optical Phased Array for Space Debris Tracking and Maneuvering

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Optical phased arrays (OPAs) provide a way to scale optical power beyond the capabilities of conventional CW lasers via coherent beam combination. By stabilising the relative output phase of multiple spatially separate lasers, OPAs form a coherent optical wavefront in the far field. Since the phase of each laser can be controlled independently, OPAs also have the ability to manipulate the distribution of optical power in the far field, and therefore may provide the capability to compensate for atmospheric turbulence. Combined with their inherent scalability and high power handling capabilities, OPAs are a promising technology for CW space debris ranging and manoeuvring.

The OPA presented here is unique in its ability to sense the phase of each laser internally, without requiring any external sampling optics between it and the telescope. This allows the internally sensed OPA to be constructed entirely within fibre, utilising high-power fiber amplifiers to scale optical power beyond the limits of any conventional single lasers. The total power that can be delivered by each emitter in the OPA is limited only by the onset of stimulated Brillouin scattering, a non-linear effect that clamps the amount of power that can be delivered through a fiber waveguide.

A three element internally sensed OPA developed at the Australian National Univeristy has been demonstrated to coherently combine three commercial 15 Watt fiber amplifiers with an output phase stability of one 200th of a wavelength. We have also demonstrated the ability to dynamically manipulate the distribution of optical power in the far-field at a bandwidth of up to 10 kHz.

Since the OPA’s control system is implemented using field-programmable gate-array technology, the system may be scaled beyond 100 emitters, potentially reaching the kilowatt level optical powers required to perturb the orbit of space debris.

Satellite Catalog Renumbering Project

Timothy K. Roberts

HQ AFSPC/A5S

Air Force Space Command (AFSPC) has embarked on a project to expand the size of the United States Strategic Command Satellite Catalog. Several new space surveillance sensors will become operational in the next five years, greatly expanding the number of space objects that can be tracked and cataloged for military and civilian use. Space Fence and the Space Surveillance Telescope (SST) in particular will track thousands of new objects with the current Space Surveillance Network (SSN). The Satellite Catalog must be able to maintain the existing catalog and add these new objects. The catalog renumbering project expands all existing satellite numbers from five digits to nine while maintaining the current categories of satellites – cataloged satellites, recently launched objects, analyst satellites, and uncorrelated tracks. This major change will expand the size of each category by four orders of magnitude, increasing the overall satellite numbers available to almost a billion and providing added numbering supporting a wide variety of products and analyses.

Management of the satellite catalog renumbering project resides in the Space Superiority Division in Headquarters Air Force Space Command with direct support from the Space Superiority Systems Directorate at Space and Missile Systems Center and Strategic Warning and Surveillance Systems Division at Air Force Life Cycle Management Center. They are managing two major efforts underway to prepare

AFSPC-owned systems for the catalog expansion. One redefines the NORAD (or JSpOC) element set, moving from two lines to three. The other modifies data messages sent between the Joint Space Operations Center (JSpOC), SSN, and other AFSPC owned space systems. The approved changes to the NORAD element set and data message formats will be provided to system program offices and other satellite catalog users for use in adapting their systems to use the new, larger catalog.

The Orbital Space Environment and Space Situational Awareness Domain Ontology

Robert Rovetto

With the growing population of satellites and other space artifacts in the orbital and near-Earth space environment, there is greater potential for orbital debris formation. This hazard can be minimized by improving global space situational awareness (SSA). By sharing more SSA data and increasing observational coverage of the space environment we stand to achieve that goal, thereby making spaceflight safer and growing our understanding of orbital space.

To facilitate data-sharing among distinct orbital debris and SSA databases, space object catalogs, and space environment and weather information systems, I proposed the orbital debris ontology in (Rovetto)[1], and the broader space situational awareness domain ontology in (Rovetto & Kelso)[2]. I continue this effort toward an orbital space environment and SSA domain ontology to provide a unified formal representation that may serve to improve SSA and increase our scientific knowledge. Here, I explain the field of ontology, how it may be applied to this space domain; summarize work from [1] and [2]; and explain the overall project.

While in-progress, and in search of opportunities for the project, I develop the ontology of the orbital and SSA domain. Key domain entities to ontologically represent include: orbital debris and other space objects; their physical properties; orbits and orbital properties; astrodynamic and astronautical processes, including spacecraft maneuvers; observation, detection, tracking, propagation activities and events; satellite and general space operations; observational data (infrared, radar, visible, etc.); and domain science knowledge such as orbital dynamics.

With this ontology (or ontology suite), we can: computationally represent the domain, providing both a data-model for SSA data (e.g., orbital debris data) and a knowledge framework; offer one or more space domain vocabularies; and facilitate data-exchange between members of the orbital debris, satellite and general SSA community. There is great potential for international cooperation between space agencies, academia, and private sector organizations.

Conjunction Risks of Near-Earth Objects to Artificial Satellites: The Case of Asteroid 2016 VY105

William Ryan, Dr. Eileen V. Ryan

New Mexico Institute of Mining and Technology

Since the early 1990's, potentially hazardous asteroids have been monitored and catalogued through NASA's Spaceguard program. Based on current population models, objects 1 km and larger have an average impact interval on the order of about a million years. However, this population model has a power law behavior resulting in the prediction that meter-sized asteroids have impact intervals on the order of just one year. Fortunately, the Earth's atmosphere protects its surface from most objects less than ~25 meters in diameter. However, resident space objects (RSOs) do not benefit from this protective layer.

Although the risk to RSOs is low, it is not zero. Currently, there are procedures in place for NASA's Planetary Defense Office to inform JSpOC of any asteroidal bodies that have been identified to pose a risk to artificial objects. However, this procedure is still in development for recently discovered objects whose orbits have not been fully characterized. Unfortunately, many of the smaller objects that have impact intervals on the order of years fall into this category and are only discovered days or even hours before their closest approach.

The case of near-Earth object (NEO) 2015 VY105, which made its close approach less than 24 hours after discovery by the Catalina Sky Survey, will be discussed. Based on the discovery metric information and follow up data from the Magdalena Ridge Observatory, it was clear that this asteroid would pass through the geostationary satellite belt. In particular, data indicated that although 2015 VY105 would come within approximately 200 km of the DirectTV 11 and 14 satellites, it would not impact either. The details of this analysis as well as characterization results that were acquired will be presented. Further, examples of various other NEOs that have made close approaches within geostationary distances in the past will also be examined.

Multicolor Observations of Geostationary Satellites

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We present the results of B, V, R and I band observations of a sample of geostationary communications satellites with the U.S. Naval Observatory, Flagstaff Station 40-inch Ritchey telescope. The observations were done in July and 2015, and covered 68% of the targets observable from Flagstaff. The targets were observed with a solar phase angle smaller than 5 degrees, in an attempt to sample the satellite properties during the period where they are likely to be at peak brightness. We will present the distribution of magnitudes and colors, and interpret these results. We will also discuss the application of the results presented in this contribution to the design of future optical interferometers capable of imaging these targets.

Upgrades and Current SSA Activities at the Navy Precision Optical Interferometer

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We will describe the current status of the Navy Precision Optical Interferometer (NPOI), and current SSA related activities. The NPOI group has added three new stations in the inner array, which allow us to observe with baselines as short as 8.8 m, which have been instrumental in the detection of fringes from glinting geosats on multiple occasions. We will also describe efforts underway to install three 1m telescopes and a new optical/near-infrared beam combiner, and the application of these new capabilities for the observation of geosats over an extended time period outside the glinting season.

Influence of Observations on the Accuracy of the Semi-Analytical Least Squares Orbit Determination Process

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The present study is divided into two parts. The first part deals with the error analysis of a semi-analytical batch least square orbit determination process. The second part of the study evaluates common constrains and the requirements governing the mean element estimation using a batch least square orbit determination process.

The task of an orbit determination error analysis is to evaluate the error introduced by each considered parameter and to construct a more appropriate covariance matrix. The common error sources, such as modeling uncertainties (atmospheric and drag models, solar radiation pressure model, deviation in central body gravitational parameter, etc.), measurement uncertainties (systematic error and measurement noise in observations, biased station locations, etc.), Initial value uncertainty, and assumed statistics. The amount of error introduced by each variable can be quantized for a selected semi-analytical satellite theory.

Currently, we are conducting an error analysis on the orbit determination program which is using the Draper Semi-analytical Satellite Theory. The emphasis is to observe on why orbital errors behave as they do, and how well can we expect to determine orbits.

Later in the paper, we systematically investigate the following: 1. Minimum required observations arc length as a function of semi-major axis/mean motion in order to capture the model dynamics and to converge on 'right' mean element set. 2. Testing the behavior of mean element estimation using batch least squares filter against the sparsity or frequency of data (time difference between measurements and number of measurements in the arc) 3. A least square orbit determination program may not converge to the right value if the initial a-priori is outside the radius of convergence. We establish this "radius of a-priori" in order to estimate the right set of mean elements with BLSQ in different orbital regions.

Pixel-Remapping Waveguide and Microlens Array Additions to Internally Sensed Optical Phased Array

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The optical phased array (OPA) system with internal phase sensing architecture being developed at the Australian National University has direct applications in tracking and manoeuvring of space debris from a ground-based continuous wave laser. The future effectiveness of this system is dependent on providing a high fill-factor for the emitter array as well as a collimated output in the far field. This is especially important when aiming for high power density incident on space debris and is currently governed by an unmodified single mode fiber to air interface at the final stage of the system.

This research investigates the incorporation of a number of alternative optical head configurations, based on an output remapping waveguide and micro-lens array of varying dimensions. Addition of the waveguide allows for control over the emitter separation, a key parameter in controlling the beam overlap and increasing the emitter fill factor. The micro-lens array is used for collimation of individual emitter outputs, avoiding the degradation in beam collimation by misaligned outputs which would occur if a single collimation lens/mirror is used.

The influence of each optical head configuration is investigated in terms of the beam output intensity distribution, steering range (from changing the individual emitter phases), power loss and potential generation of waveguide crosstalk. Power loss in the waveguide is also particularly important due to the requirement of feeding high power through each emitter. The difference in the back reflection from each emitter returning to the system at the final air interface is also monitored as it is required for the internal phase sensing. Experimental results are compared with Gaussian beam calculations/simulations.

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Low Power Reflective Optical Communication System for Pico- and Nano-Satellites

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Pico- and nano-satellites (PNS) are promising options for cost-effective and rapid deployable satellite systems. Due to their small size, the available power and therefore the transmittable data volume is limited.

Optical communication by means of reflected laser light has the potential to solve this issue. The paper proposes the use of a modulating retro-reflector (MRR) for energy efficient optical communication with PNS. No laser source or beam steering assembly is necessary at the satellite, thus allowing a weight and energy efficient communication interface. Existing ground stations (GS) used for satellite laser ranging (SLR) provide all equipment required for this system, thereby enabling dual usage of such stations.

This paper investigates feasibility by providing a link budget for communication and tracking of LEO PNS. It is shown that an affordable GS based on small telescopes with diameters below 0.3m in combination with commercial mounts enables the targeted application.

A detailed analysis of LCD-MRR is shown, which denotes cost-efficient modulators for reflective optical communication. However, space readiness of LCD has not been demonstrated yet. In order to verify the application of LCD, vacuum and temperature tests are performed. A data-rate of 2.5kbps at an input power of less than 10mW is shown in a laboratory setup. Using a high performance sampling circuit and a laser power of only 1mW, a bit error ratio (BER) of below 10e-3 is achieved.

These results successfully demonstrate reflective optical communication as an alternative to current RF based systems. As secondary benefit the retro-reflector allows precise tracking of the satellite during and after its lifetime. Future work is targeted towards replacing the LCD modulator with faster MRRs and utilizing more powerful lasers, carrying the potential to increase the data-rate by 2 to 3 orders of magnitudes.

Parametric Excitation of Very Low Frequency (VLF) Waves and Wave-Particle Interaction in Radiation Belt

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Parametric excitation of VLF waves in the ionospheric plasma is analyzed. It is demonstrated that this mechanism is capable of exciting electromagnetic radiation fields, specifically the creation of whistler waves in the very low frequency (VLF) range, capable of propagating large distances away from the source region. The generation of whistler waves is parametric interaction of quasi-electrostatic low oblique resonance (LOR) oscillations excited by a conventional loop antenna. The conversion of LOR waves on quasi-neutral density perturbations in the near field of the antenna gives rise to whistler waves at combined frequencies. The amplitude of these waves can considerably exceed the amplitude of whistler waves directly excited by a loop or usual dipole antenna. PIC code LSP simulations demonstrating excitation and spatial structure of VLF waves excited by a loop antenna will be presented as well. Possible applications including wave-particle interactions in the radiation belt to mitigate performance anomalies of Low Earth Orbit (LEO) satellites, active space experiments, communication via VLF waves, and modification experiments in the ionosphere will be discussed.

Satellite-Based EMI Detection, Identification, and Mitigation

Richard Stottler

Stottler Henke Associates, Inc.

Commanding, controlling, and maintaining the health of satellites requires a clear operating spectrum for communications. Electro Magnetic Interference (EMI) from other satellites can interfere with these communications. Determining which satellite is at fault improves space situational awareness and can be used to avoid the problem in the future. The Rfi detection And Prediction Tool, Optimizing Resources (RAPTOR) monitors the satellite communication antenna signals to detect EMI (also called RFI for Radio Frequency Interference) using a neural network trained on past cases of both normal communications and EMI events. RAPTOR maintains a database of satellites that have violated the reserved spectrum in the past. When satellite-based EMI is detected, RAPTOR first checks this list to determine if any are angularly close to the satellite being communicated with. Additionally, RAPTOR checks the Space Catalog to see if any of its active satellites are angularly close. RAPTOR also consults on-line databases to determine if the described operating frequencies of the satellites match the detected EMI and recommends candidates to be added to the known offenders database, accordingly. Based on detected EMI and predicted orbits and frequencies, RAPTOR automatically reschedules satellite communications to avoid current and future satellite-based EMI. It also includes an intuitive display for a global network of satellite communications antennas and their statuses including the status of their EM spectrum. RAPTOR has been prototyped and tested with real data (amplitudes versus frequency over time) for both satellite communication signals and is currently undergoing full-scale development. This paper describes the TRACER technologies and results of testing.

Automated Terrestrial EMI Emitter Detection, Classification, and Localization

Richard Stottler

Stottler Henke Associates, Inc.

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 tracking down the source of EMI is extremely important to prevent it from occurring in the future. The Terrestrial RFI-locating Automation with CasE based Reasoning (TRACER) system is designed to automate terrestrial EMI emitter localization and identification, providing improved space situational awareness, realizing significant manpower savings, dramatically shortening EMI response time, providing capabilities for the system to evolve without programmer involvement, and offering increased support for adversarial scenarios (e.g. jamming). TRACER has been prototyped and tested with real data (amplitudes versus frequency over time) for both satellite communication antennas and sweeping Direction Finding (DF) antennas located near them. TRACER monitors the RTS and DF antenna signals to detect and classify EMI using neural network technology trained on past cases of both normal communications and EMI events. Based on details of the signal (its classification, its direction and strength, etc.) one or more cases of EMI investigation methodologies are retrieved, represented as graphical behavior transition networks (BTNs), which very naturally represent the flow-chart-like process often followed by experts in time pressured situations, are intuitive to SMEs, and easily edited by them. The appropriate actions, as determined by the BTN are executed and the resulting data processed by Bayesian Networks to update the probabilities of the various possible platforms and source types of the EMI. Bearing sweep of the EMI is used to determine if the EMI's platform is aerial, a ground vehicle or ship, or stationary. If moving, the Friis transmission equation is used to plot the emitter's location and compare it to current flights or moving vehicles. This paper describes the TRACER technologies and results of prototype testing.

Performance Comparison of Optimization Methods for Blind Deconvolution

Daniel Thompson, Brandoch Calef, Michael Werth

Boeing

There are many methods that will solve high-dimensional regression problems, and choosing an appropriate method can be challenging. For some problems, accuracy holds precedence over speed whereas in other instances speed is required for a large number of problem sets. In this paper we study the performance of several methods that solve the multiframe blind deconvolution problem by comparing speed and accuracy of each algorithm, highlighting the merits of each algorithm.

Sensor Network Scheduling Under Uncertainty: Models and Benefits

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Advances in space technologies continue to reduce the cost of placing satellites in orbit. With more entities operating space vehicles, the number of orbiting vehicles and debris has reached unprecedented levels and the number continues to grow. Sensor operators responsible for maintaining the space catalog face an increasingly complex scheduling status quo. Despite these trends, a lack of advanced tools continues to prevent sensor operators from fully utilizing space surveillance resources. One key challenge involves selecting sensors for missions with differing requirements from a network of sensors with varying capabilities. Another open challenge, the primary focus of our work, is building robust schedules that effectively plan for uncertainties associated with observational and occurrence uncertainties. Existing tools and techniques are not amenable to rigorous analysis of schedule optimality and do not adequately address the presented challenges.

Building on prior research, we have developed stochastic mixed-integer linear optimization models to address uncertainty due to weather and ad hoc activities. By making use of the open source Pyomo optimization software library, we have posed and solved sensor network scheduling models addressing both forms of uncertainty. The suitability of stochastic mixed-integer linear optimization for building sensor network schedules under different run-time constraints will be discussed.

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

Mark Vincent

Raytheon

This paper is a continuation and update of the paper presented last year which detailed the gaps between the academic research being carried out and the challenges faced by operators managing the risk from orbital debris. Some of the topics introduced in that paper, such as post-maneuver Probability of Collision (Pc) thresholds, have been addressed and are now in use for the Orbiting Carbon Observatory II (OCO-2) mission. Another topic of great interest to the A-Train Constellation is having realistic covariances associated with their satellites' future states for proper Pc calculations. This is a good example of where academic studies have helped in the calculations and testing involved in the various methods of scaling the covariance to be realistic. The dominant factor in these propagated covariances is due to the uncertainty in the future atmospheric drag, which is greatly exacerbated by geomagnetic storms. This is an example of a still-existing gap between getting the best atmospheric models, whether empirical or physics-based, implemented into the operations. Updates include further explanation of the Pc Forecasting Tool introduced last year. Results from the current spreadsheet version will be compared to those from a new computer program. Some of the useful algorithms presented in F.K Chan's textbook will be also be used as spot checks for the methods used in the tool.

Slitless Spectroscopy of Geosynchronous Satellites

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Cadets in the Department of Physics at the United States Air Force Academy are using the technique of slitless spectroscopy to analyze the spectra from geostationary satellites during glint season. In this paper, three seasons of glints for multiple satellites were observed using a diffraction grating on the Academy's 16-inch, f/8.2 telescope. It is clear from the visible spectra 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. We conduct a comparison of the glint spectra to determine a relative power capacity of the various spacecraft buses.

Harnessing Adaptive Optics for Space Debris Collision Mitigation

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Current error margins in conjunction predictions between operational satellites and space debris, together with the astronomical costs of adjusting satellite orbits, mean that it is common for satellite providers not to perform any orbital manoeuvres in response to a collision warning. Given that a single collision can generate thousands of new debris objects, higher-accuracy debris tracking is required. Adjusting the orbits of debris objects instead, however, would shift the responsibility of collision avoidance away from satellite providers altogether, thereby offering a superior solution.

The Research School of Astronomy and Astrophysics at the Australian National University, partnered with Electro Optic Systems Space Systems, Lockheed Martin Corporation and the Space Environment Research Centre Ltd., are developing the Adaptive Optics Tracking & Pushing (AOTP) system. AOTP will be used to perturb the orbits of debris objects using photon pressure from a 10kW IR laser beam launched from the 1.8m telescope at Mt. Stromlo Observatory, Australia. Initial simulations predict that AOTP will be able to displace debris objects ~10cm in size by up to 100m with several overhead passes. Currently in the conceptual design review stage, an operational demonstrator is planned for 2019.

Turbulence will distort the laser beam as it propagates through the atmosphere, effecting a lower photon flux on the target and reduced pointing accuracy. To mitigate these effects, AO will be used to apply wavefront correction to the beam prior to launch. A unique challenge in designing the AO system arises from the high slew rate needed to track objects in LEO, which in turn requires laser guide star AO to achieve satisfactory correction.

The requirements, design and results from simulations of estimated performance of AOTP will be presented. In particular, design considerations associated with the high-power laser, including beam alignment systems, optical design constraints and safety measures will be detailed.

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