Advancing Satellite Light Curve Glint Predictions Using Anisotropic Solar Cell BRDF Modeling

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Abstract

Space domain awareness (SDA) requires the ability to model satellites in radiometric simulations for predictive analysis and anomaly detection. Accurate satellite modeling makes use of computer-aided design (CAD) models with realistic material assignment. However, the choice of the right bidirectional reflectance distribution function (BRDF) model for each material is a significant determinant in the success or failure of the simulation. One of the main signal contributors for many satellites are the solar cells which make up the solar panels, often modeled using an isotropic, microfacet approach. However, these models ignore critical diffraction behavior produced by the anisotropic structure of solar cells. In this project, a new, anisotropic solar cell BRDF was implemented in satellite CAD model simulations and compared to real world geostationary (GEO) satellite visual magnitude collections, also known as light curves. The new BRDF model successfully captures the diffraction effects of the solar cell structure with a closed-form solution. The anisotropic model proved to be accurate in modeling strong, specular glints in a random sampling of GEO satellite collections. While the new model requires scaling to correct for overall magnitude, the slope and shape of the simulated light curves closely resemble real world collections. Further refinement of this anisotropic model will likely lead to even better agreement with observation

Simulating Spectral Observations Collected by the USAFA-Falcon of GEO Satellites using DIRSIG^{TM}.

Aryzbe Najera, Michael Gartley, Francis Chun, Miguel Velez-Reyes

Spectral remote sensing is an approach to extract quantitative information about Resident Space Objects (RSO) to support Space Domain Awareness (SDA). Measured spectral signatures collected in unresolved imaging of RSO contain information about its material composition, pose, spin rate, among other parameters even though it cannot be spatially resolved. Consequently, accurate spectral signature interpretation may allow us to understand and react appropriately to changing situations in the space domain. Modeling and understanding of spectral signatures behavior for URSOs can be used to generate algorithms to exploit these signatures for SDA. A challenge in this area is the limited availability of data to train, test and validate signature exploitation algorithms. Physics-based simulations can provide synthetic datasets to complement observations for this task.

The Digital Imaging and Remote Sensing Image Generation (DIRSIG^{TM}) model is a physics-based radiation propagation simulation tool used to generate synthetic imagery. We present simulation of ground-based observations of imagery for several satellites in GEO observed on 11 August 2022 and 7 August 2024 and compare with observations collected by the USAFA-Falcon telescope. We will also discuss the setting of the simulation model for this task and show how the modeling tool can be used to study the temporal and spectral variability of the signatures associated to the bus of the satellite.

Streaming Machine Learning Estimation of Satellite Shape using Non-Resolved Directional Reflectance Measurements

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Abstract

Space Situational Awareness (SSA) must advance beyond solely tracking the positions of satellites in order to adapt to growing congestion of near-Earth orbits. One method towards expanding operational SSA knowledge is via the development of algorithms for predicting satellite shape from light curves. The shape of a satellite can provide direct knowledge on design factors such as payloads and bus type, which thereby provides indirect insight into operations factors such as mission intent and system capabilities. In this work, we propose a streaming Machine Learning (ML) algorithm for classification of satellite shape that leverages a hemispherical reflectance model to capture the shape's non-resolved signature. This novel hemispherical reflectance model of non-resolved satellite signatures improves on current shape estimation approaches by leveraging the full observer-solar geometry rather than relying solely on phase angle to describe the angular reflectance of brightness measurements. We outline a simulation approach for producing shape hypotheses under this model and then discuss how the produced simulations can be utilized to infer satellite structure from sparsely collected telescope measurements. We then demonstrate how the hemispherical reflectance model can be deployed in the online ML framework to fuse brightness observations from geographically disparate observers to predict the probability of satellite shape in realtime.

Bayesian Approach to Light-Curve Inversion of Queqiao-2

[Presenter] Yael Brynjegard-Bialik (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Tanner Campbell (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Vinyas Bhat (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Roberto Furfaro (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), and Vishnu Reddy (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona)

On March 20, 2024, the relay satellite Queqiao-2 was launched from the Wenchang Space Launch Site along with two other scientific payloads for research in lunar orbit. We present analysis of the light curve of the second stage rocket body during its return to Earth and estimate reflective and dynamical properties using the data we collected from a 1-meter telescope between March 22, 2024 and April 14, 2024, before the rocket body splashed down back on Earth on April 24, 2024. Using a four parameter Fourier fit and least squares minimization, we found a period of 88.5951±0.0503 s at 1σ confidence level in the light curve of the rocket body before arriving at the moon. On its way back to Earth, we found periods of 88.6993±0.1039 s, 88.6763±0.0341 s, and 88.8232±0.0226 s, all at 1σ confidence level. The 95% Highest Posterior Density (HPD) region and Maximum A Posteriori (MAP) were estimated using Bayesian inversion and a predictive light-curve simulation based on an anisotropic Phong light reflection model. The estimated parameters were the primary body axis orientation (3), angular velocity vector (3), reflectivity parameters (3), and primary body axis inertia ratios (3). The parameter inversion process involved defining initial distributions for each variable, then repeatedly sampling from these distributions and applying the predictive model to assess how well the simulated outcomes matched the observed data.

Updates to Stingray: Photometric Survey of the GEO Belt

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ABSTRACT

The Stingray sensor system is a 15-camera optical array dedicated to an autonomous nightly astrometric and photometric survey of the Geosynchronous Earth Orbit (GEO) belt visible above Tucson, Arizona. After an extensive development phase including 220 nights of on-sky testing, results from an initial survey show an aggregate photometric uncertainty of 0.062 $\pm$ 0.008 magnitudes and astrometric accuracy consistent with theoretical sub-pixel centroid limits. There are approximately 200 near-GEO satellites on any given night that fall within the Stingray field of regard, and all those with a GAIA G magnitude brighter than approximately 15.5 are measured by the automated data reduction pipeline. The Stingray data products are astrometric and photometric measurements of these satellites, which allows the production of all-night phase curves of 3-axis stabilized satellites and periodic light curves for rotating/defunct objects. The period un-wrapping of the rotating object light curves also yields an analogous phase curve for the object. Approximately 7,200 images are collected on an ideal night, and the automated data processing pipeline takes an average of 18.5 minutes to analyze all the data. We present here results from the Stingray sensor system, published in Campbell et al. [2023], detailing the development and deployment of the system, as well as a look at recent updates and improvements to the performance.

REFERENCES

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H-G System Light Curve Representation for Artificial GEO Objects

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Modelling the light curves of artificial satellites is essential for space situational awareness, enabling the assessment of their visibility with optical instruments, such as telescopes, and contributing to the preservation and the safety of Earth's space environment. This study investigates the application of the H-G system, a method traditionally used in the study of asteroid light curves, to model the light curves of objects in the geostationary belt. The light curves, expressed in terms of magnitude and longitudinal phase angle, are modelled using a three-parameter (H-G_1-G_2) system. A nonlinear least-squares method is employed to estimate the optimal absolute magnitude H and slope parameters G by fitting theoretical models to real light curve data acquired from the Space4 Center at The University of Arizona. The modelled light curves are then compared with observed data to evaluate the feasibility and limitations of the proposed method. Analogous to asteroids, determining H and G parameters for artificial objects may offer valuable insights into their structural characteristics, such as bus architecture and size. The results indicate that adapting the H-G system to artificial satellite light curves is a promising technique for enhancing our understanding of these objects, though further refinement may be required to address specific challenges unique to the artificial objects environment.

Event-Based Cameras for Photometric Space Object Characterization

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The high temporal resolution and high dynamic range of Event-Based Cameras (EBCs) offer unique opportunities for Space Domain Awareness missions including photometric space object characterization. Unlike conventional cameras, EBCs do not produce images but instead a list of event detections indicating logarithmic changes in brightness. Each pixel in an EBC is an independent sensor that runs asynchronously with microsecond timestamp resolution producing a continuous data stream. EBCs offer a time resolution unmatched by most conventional sensors while producing significantly less data volume.

Performing photometric characterization with an EBC requires rethinking the processing and analysis techniques as conventional methods are not directly applicable. Using real-world data, we explore these challenges and consider possibilities for photometric characterization such as light curve creation.

Ionic liquids have garnered significant attention in electrospray propulsion applications due to their attractive physicochemical properties and growing relevance for small satellite platforms. They were successfully flight-tested on the ESA Laser Interferometer Space Antenna (LISA) Pathfinder mission as part of NASA'S ST7 Disturbance Reduction System (ST7 DRS). The onboard ionic liquid colloid thrusters exhibited station-keeping precision on the scale of the laser wavelength – a critical sensitivity requirement for gravitational wave measurements. Despite this success, there remain knowledge gaps regarding the effects of thruster exhaust plume contamination on spacecraft electronics and materials. Because ionic liquids are conductive, surface contamination from propellant deposition could cause arcing, impairing system performance and shortening mission lifetimes. To address these concerns, this study uses optical emission spectroscopy of laser-induced plasmas to analyze the chemical composition of ionic liquid coatings formed under various deposition conditions. Spectral data were evaluated using computational and machine-learning methods, including generalized linear models, partial-least squares (PLS) regression, and k-nearest neighbors (kNN) classification. Regression and predictive analyses investigated the relationships between spectral intensities (mass accumulation) and deposition parameters (time, substrate doping, substrate voltage, and emission mode). We revealed that deposition time and substrate doping significantly influenced spectral intensities, while thruster emission mode exhibited a weaker but measurable correlation. In contrast, applied voltage had no measurable effect. These findings enhance our understanding of ionic liquid deposition behavior and contribute to mitigating contamination risks in future spacecraft missions.

Supported by the Air Force Office of Scientific Research under award numbers 22RVCOR003 (Program Manager: Michael Berman) and 23RVCOR008. Partially supported by the Georgia Tech Research Institute Independent Research and Development (IRAD) program. The authors would like to acknowledge the Defense University Research Instrumentation Program (DURIP) for providing funding under Grant No. FA9550-23-1-0151. The views expressed are those of the author and do not necessarily reflect the official policy or position of the Department of the Air Force, the Department of Defense, or the U.S. Government. The DoD does not exercise any editorial, security, or other control over the information you may find at these locations. Public Affairs release approval AFRL-2025-0036.

Abstract for Poster Presentation – VOLTRON 2025

Title:

MOB BOSS, COPS, and SAFEGUARD: Explainable, Safe, and Accurate AI/ML Tools for Analyzing Hyperspectral Data and Optimally Designing Multispectral Instruments for SDA Missions

Authors:

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Abstract:

This poster will present an optimization procedure – called MOB BOSS (Mission-Oriented Bayesian Band Optimization for Spectral Systems) – that finds the minimal number of multispectral bands required for training high-performance machine-learning (ML) classifiers. The poster will show the results of a design study where MOB BOSS was applied to a notional space-domain-awareness (SDA) mission responsible for classifying three types of resident space objects: active payloads, rocket bodies, and space debris.

In addition to presenting these results, this poster will provide an overview of the AI/ML techniques undergirding the various components of the MOB BOSS procedure. For example, MOB BOSS relies heavily on the COPS (Classification Of Pixelwise Spectra) suite of tools for training, tuning, and testing the ML classifiers themselves. The ML classifiers produced by COPS are explainable, allowing the user to inspect whether the trained models are basing their classifications on appropriate wavelength ranges within the electromagnetic spectrum. The COPS suite of tools also allows for the processing of datacubes produced by multi-slit spectrometers – a capability facilitated by a mathematically grounded Bayesian-updating formula that can yield high-confidence detections even when using with a poorly trained ML classifier.

Lastly, the poster will describe recent work on a new set of AI/ML-based tools, collectively called SAFEGUARD (Spectral Analysis Framework for Embedding, Grouping, Unmixing, and Anomalous-Response Detection). The SAFEGUARD framework performs deep-learning-driven spectral unmixing and ML-based out-of-distribution detection. When used in conjunction with COPS, SAFEGUARD (a) reduces the risk of misclassification due to target-background mixing and (b) prevents the COPS models from classifying spectra that are far outside their training distribution. Taken together, these two capabilities of the SAFEGUARD framework result in higher prediction accuracy of the COPS classifiers, while imparting a degree of AI safety to the overall approach.

Space4 Center Spectroscopy Lab and Materials Spectra

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Confirmation of telescopic and remote spectroscopy observations with lab-based instruments is critical for correct identification and characterization of Resident Space Objects (RSOs). Spectral observations of RSOs are greatly improved with comparisons to laboratory data of known materials. To this end, we have created a spectral laboratory used for collecting reflectance spectra of common materials known to be used in spacecraft. Instrumentation available within the Space4 Center includes Avantes SensLine AvaSpec-ULS2048LTEC (0.2 – 0.45 µm), ASD Inc. Lab Spec 4 Hi-Res Analytical Instrument (0.35 – 2.5 µm), and Nicolet™ iS™ 50R Benchtop FTIR (1.5 – 25 µm). In total, the spectrometers cover a wavelength range of 0.2 – 25 µm with overlap between each sensor and can measure in both biconical reflectance and hemispherical reflectance. In addition, we possess a High Vacuum Chamber, with variable temperature of –196 °C to 520 °C and pressure conditions of ambient to 10 -7 mbar to simulate the near-Earth space environment. We are also developing the ability to measure variable phase angles within the High Vacuum Chamber. The Space4 Center has also created a novel space materials curation and preservation facility (Space Materials Curation Facility) that is rapidly growing. It is equipped with both humidity-controlled cabinets and nitrogen-purged cabinets. The curation facility is available for curating materials from our research collaborations. With these tools and facilities available, the Space4 Center team members plan to create a robust and accessible database that is lacking within the space situational awareness field.

Ground-Based Hyperspectral Speckle Imaging for Materials Identification and Aging Studies of Space-Based Targets

Fabien Baron

Ultra-broadband speckle imaging from ground-based telescopes provides spatially resolved spectral information of resident space objects that enable direct study of material aging. In our previous studies, we demonstrated via numerical simulations that ultra-broadband observations ($\Delta\lambda = 600$ nm) of resolved targets allow for the recovery of both high-resolution spatial information and low-resolution spectral information (~ 20 wavelengths). The reconstructions of our toy model satellite – containing different ages of Mylar, Kapton, and aluminized Mylar – suffer from significant spectral mixing which prevents direct identification of the spectrum of each material and characterization thereof.

Here we present two promising paths forward to solve the mixing problem. First, we explore a sparsity-based approach (Block-Simultaneous Method of Multipliers) that enables better extraction of the material spectra from the mixed hyperspectral reconstructions. Second, we investigate how to lift the mixing ambiguities using closure phases obtained from complementary interferometric observations.

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Infrared photometry and spectrometry of satellites and debris at UKIRT

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ABSTRACT

The characterization of deep space debris poses a significant challenge in Space Domain Awareness (SDA). Multi-color photometry and the resultant color indices offer the potential to rapidly discriminate between debris and intact space objects such as rocket bodies and satellites. These multi-color techniques can also identify anomalous members of objects in certain groups and cue higher fidelity data collections and studies. However, multi-color photometry can be difficult to interpret, as the effects of phase and rotation become conflated with the more fundamental material properties of the satellite. Additionally, the broad astronomical photometric bands may not identify key spectral features that can be diagnostic for SDA applications. With our recent observational campaign, we have been able to collect 5-color photometry in the near-IR with WFCAM on an additional suite of objects previously observed by other researchers from outside the United States. Many of the objects we have studied have significant orbital inclination or drift in the GEO belt. The interpretation of photometry of these objects is especially difficult as phase angle can no longer be considered simply as a single-dimensional quantity. During 2024, we have endeavored to expand our phase angle coverage of a handful of objects and comprehensively sample brightness and color in both components of phase angle. In this paper we present exemplary "phase-phase" diagrams demonstrating this technique and highlight some of the practical and observational difficulties in achieving comprehensive phase angle coverage and interpreting these results. We also show exemplar analyses of satellites using a color-color plot similar to techniques developed by the asteroid community to distinguish between different classes of satellites.

Event-Based Photometry for Non-Resolved RSOs

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Event cameras detect relative changes in brightness at the pixel level, outputting an asynchronous stream of pixel events with microsecond precision. This architecture provides both high spatial and temporal resolution as well as low data rates compared to high-speed, frame-based cameras. And unlike frame-based cameras with prescribed frame rates, event cameras dynamically react to brightness changes as they occur, facilitating "uncued" photometric studies for resident space objects (RSOs) with no *a priori* knowledge (e.g. unknown spin rates). Using event pixel dynamics models and real observations, we explore how stochastic photon arrivals allow for detection of motionless point sources with constant brightness. This is valuable for sidereally-tracked background star identification for astrometric applications (e.g. initial orbit determination for streaking RSOs). These stochastic events also enable estimation of an object's photometric brightness from the total event count across the event point spread function (PSF).

Using our campus observatory's Prophesee EVK3 Gen4.1 event camera and 0.2 m f/3 telescope, we obtain event curves (analogous to light curves) for several well-known spacecraft and extract spin rate information. These include NASA earth observation spacecraft with fast-rotating reflectors, spin-stabilized spacecraft whose spin rates exceed 70 rpm, and NASA's recently launched ACS3 solar sail mission. We track the two distinct fundamental periods of ACS3's time-varying, non-principal axis spin state and show clear consistency with downlinked attitude telemetry.

An Investigation of Material Resilience in Extraterrestrial Environments

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The environment near Earth's orbit remains a US critical active zone, making the protection of hardware and human assets in low Earth orbit (LEO) essential. While numerous space factors contribute to spacecraft degradation, atomic oxygen (AO) remains the primary threat, severely affecting spacecraft surfaces and astronaut space wear. Developing lightweight, robust, and AO-resistant materials is crucial to safeguarding US space infrastructure from extreme conditions in LEO.

However, the creation of AO-resistant materials is an intricate task. Despite persistent effort from research laboratories worldwide to develop such materials, the quest for superior performance, cost-effectiveness, and reduced weight remains ongoing. Commercially available products do not readily disclose detailed information about their structural and chemical composition, posing a challenge for full understanding of these materials' properties and ultimately restricting their effective integration into new spacecraft design.

This work details our efforts in developing novel AO-resistant materials using innovative post-polymerization modification techniques. These methods facilitate the incorporation of chemical functionalities known to enhance AO resistance. The materials, a series of Georgia Tech films based on Kapton CR®, were evaluated for stability after exposure to a simulated space AO environment. Measurements included average defect size, count, and coverage ratio, along with RMS roughness and color change. The most promising materials will be selected for the MISSE-22 mission, scheduled for launch in August 2025, providing a rare opportunity to test their performance in actual LEO conditions and validate their AO resistance.

This work was supported by GTRI's Independent Research and Development Program (IRAD).

A historical overview of the NASA Orbital Debris Program Office's Laboratory Optical Measurements

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The NASA Orbital Debris Program Office (ODPO) has used laboratory measurements to help bring ground-based measurements together with models to ascertain Earth-orbiting target parameters of interest to support various orbital debris models. In 2005, the Optical Measurement Center (OMC) was established to simulate space-based illumination conditions using equipment and techniques that recreate telescopic observations, particularly source-target-sensor orientations. The intent was to recreate light curves using known aspect angles of known targets and phase angles (angle is defined by the vertex between illumination source-object-detector) to complement telescopic observations that could be used to update the current optical size estimation model (OSEM) – a model that converts object brightness into size for orbital debris models.

To support the above goals, the laboratory has undergone several equipment upgrades to increase capabilities over almost 20 years of operation. The primary instrumentation acquires reflectance measurements and includes a solar-like light source, CCD camera with astrometric filters, and robotic arm. A rotary arm was added approximately five years after full operation to allow acquisition through a full 360° range of phase angles. Another part of the OMC instrumentation is a field spectrometer, predominately used for field operations to acquire pre- and post-flight spacecraft material spectral measurements. Additionally, reflectance spectroscopy of various materials is also of interest resulting from hypervelocity impact tests, pristine spacecraft materials, or samples of materials that are used in spacecraft design. These measurements are stored in NASA's Spectral Material Database, a resource that is still being populated today. The study of spectral measurements also enabled the development of spectral unmixing routines to support the identification of spacecraft materials from spectral data gathered by ground-based telescopes.

Preliminary OMC investigations focused on feasibility studies to acquire 360° rotation light curves of simple shapes at a single-phase angle and extended to measurements of representative fragments from ground-based explosion tests. To correlate the light curves with ground-based optical measurements, a focused study on high area-to-mass materials was conducted in support of a newly identified population (at the time) in geosynchronous orbit (GEO) consisting of multi-layered insulation. To further characterize orbital debris, a larger selection of materials was analyzed using laboratory photometric measurements that included representative targets from pristine spacecraft materials and ground-based impact tests.

Around 2012, an initiative was requested to understand the feasibility of active debris removal (ADR) of larger targets using grappling methods for spent rocket bodies. Using *a priori* information on selected targets, scaled-down versions of rocket bodies were generated thanks to improvements in 3D printing technology and machining. These targets were studied in the OMC to understand rotation characteristics. These were compared with telescopic data to determine if the tumble and rotation angles would allow ADR. In 2013, the OMC focused on combining spectral measurements with photometric data to characterize GEO orbital debris. Several years later, NASA acquired a Titan III Transtage test article from "The Boneyard" with a high-resemblance to on-orbit Titan III Transtage rocket bodies, allowing physical access to a representative rocket body that suffered fragmentations in GEO. This prompted the creation of 3D models using lidar technology and spectral measurements of the materials. Focused research also transitioned to specific materials (*i.e.*, solar cells) when telescopic surveys requested characterization of specific GEO targets.

In the different research products presented, the focus has been to understand the various parameters that influence optical size estimation, including albedo, phase functions, and brightness variations. Work in this area continues with newer sources of data, including DebriSat, a high-fidelity 56-kg spacecraft replica representative of a modern low Earth orbit (LEO) satellite subjected to a laboratory hypervelocity impact test to understand fragmentation events and to support updates to satellite breakup models and size estimation models. Utilizing the vast population of fragments from DebriSat and prior laboratory impact experiments, the ODPO has focused on acquiring bidirectional reflectance distribution function (BRDF) data to characterize targets in the laboratory, thus removing aspect angle dependencies. Additionally, the DebriSat project has provided improved processes for measuring size via image acquisition, such that a true fragment size can be directly compared to the derived size using the OSEM. The team continues to assess BRDFs and use spectral measurement data to investigate the parameters used in the OSEM, specifically magnitudes, albedo, and phase functions.

Laboratory Radar Measurements in Support of the NASA Orbital Debris Program Office's Size Estimation Model

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The NASA Orbital Debris Program Office (ODPO) relies on ground-based radar measurements from both the Haystack Ultrawideband Satellite Imaging Radar (HUSIR) and the Goldstone Solar System Radar (Goldstone) to characterize mm to cm debris population in low Earth orbit (LEO). Radar measurements help characterize the size of orbital debris objects, particularly fragmentation debris. However, debris size is not directly measured by radar but inferred from the measured radar cross section (RCS) which depends on several parameters in addition to physical size including electrical conductivity and polarization. To interpret the observed RCS of orbital debris objects detected by radar measurements as physical sizes, NASA uses an empirical size estimation model (SEM) based on laboratory RCS measurements of breakup fragments generated during hypervelocity impact tests as well as some pieces of non-impact-generated "artificial" debris-like objects expected to be representative of the debris population. Since the development of the ODPO SEM, many new materials have been introduced to spacecraft construction. Consequently, ODPO plans to update the radar SEM based on planned laboratory RCS measurements of debris fragments from DebriSat, a ground-based hypervelocity impact experiment conducted in 2014 that consisted of a high-fidelity spacecraft model characteristic of a modern LEO spacecraft.

Prior to measuring DebriSat fragments, a set of calibration targets with well-defined geometries and material compositions were measured at The Ohio State University's ElectroScience Laboratory (OSU-ESL) compact radar range. These calibration measurements help to validate, and understand any limitations of, laboratory measurements of RCS. Calibration targets include idealizations of typical shape categories seen in DebriSat fragments such as nuggets, flat plates, and cylinders. As with DebriSat, calibration target materials were chosen to represent typical modern-day spacecraft components and include stainless steel, aluminum, printed circuit board (PCB) substrate, and carbon fiber-reinforced polymer (CFRP). These materials also represent a wide range of electrical conductivities, which strongly influences measured RCS and inferred target size. The RCS calibration measurements were collected over a frequency sweep from 2 to 18 GHz and stepping through different azimuth angles from 0 to 360 degrees at an elevation of 0 degrees.

A second set of calibration measurements is in work consisting of more complex shapes such as bent rods and plates as well as different mounting options including epoxy and a 3D printed holder. These further measurements along with our initial calibration set will inform selection of representative DebriSat fragments for laboratory RCS measurements that will contribute to the planned update to the ODPO radar SEM. An appropriate subset of both the radar calibration and DebriSat samples will also be measured in the ODPO Optical Measurements Center to cross-calibrate size estimates over these different wavelength regimes.

Polariscopic Analysis of LEO Plasma-Induced Mechanical Property Changes in Novel Spacecraft Materials

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Space weathering impacts the outer materials of spacecraft, leading to physical degradation, changes in optical properties, and chemical alterations that can compromise the spacecraft's performance and longevity. This includes issues such as surface cracking, erosion, mechanical properties degradation, reduced reflectivity and transmissivity, and increased vulnerability to corrosion due to exposure to ionizing radiation, electrons, protons of varying energies, oxygen ions and atoms, as well as extreme temperature fluctuations. As a result, a thorough understanding of how material properties evolve over the course of a mission is crucial when designing long-duration space missions.

Accurately simulating the space environment on Earth is challenging due to the numerous factors that influence it, including orbit, solar conditions, and more. The controlled setting of the Materials International Space Station Experiment Flight Facility (MISSE-FF) aboard the International Space Station (ISS) enables scientists to closely monitor materials during their exposure to space. This environment allows for precise measurement of changes in material properties and provides an ideal platform to establish benchmark data for validating ground-based space weather simulation experiments.

This work provides an overview of the MISSE-22 project, launching in 2025, highlighting the project timeline, material selection, and ground testing data. The main goal of the orbital MISSE-22 experiment is to characterize LEO plasma-induced mechanical property changes in novel spacecraft materials and electronic system architectures using polariscopic measurements. Materials will be mounted on the ram face of the MISSE-Flight Facility science carrier, and exposed to neutral atomic oxygen, the primary degrading factor at ram face of the ISS. The experimental setup will use photoelasticity to detect changes in tensile stress-strain properties by inducing stress with mechanical deformation. Polariscopic images of stressed samples will help assess space environment-induced changes in material properties throughout the mission. Approved for public release; distribution is unlimited. Public Affairs release approval #AFRL-2024-6393.

Title:

The Magdalena Ridge Observatory Interferometer - A New Tool for Supporting SSA Inquiries

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Abstract:

The Magdalena Ridge Observatory Interferometer (MROI), located just outside Socorro, NM, is on the verge of producing “first fringes” – the initial system measurement that demonstrates the sensitivity and precision of a new interferometer. Operating in the optical and near-infrared, this facility will be capable of imaging astronomical targets down to the sub-milliarcsecond scale at brightnesses 100 times fainter than can be produced today by similar facilities. The architecture of MROI is also well-suited to imaging manmade objects in GEO orbit at angular resolutions equivalent to fractions of a meter. By employing fringe-tracking on targets and then making resolved measurements (both spectroscopically and spatially), MROI will be able to determine many details about the size, position, composition and stability over time of these GEO objects. I will present a brief overview of the MROI, current status of the array facility, and some examples of measurements that can be done in support of an SSA mission.

Aerospace Material Measurement, Modeling, and On-Orbit Observation Capabilities

Christopher Griffith (The Aerospace Corporation)

Over the past few years, The Aerospace Corporation has created an internal working group aimed at bridging measurement, modeling, and on-orbit satellite observations in response to the growing customer interest in Space Domain Awareness (SDA) characterization. The working group consists of material experts, physics-based modeling specialists, and astronomers all which play an equally important part in this SDA regime. In this talk, we will discuss numerous on-going efforts to study material measurement techniques (i.e. Bidirectional Reflectance Distribution Function (BRDF) measurements), modeling tools (BRDF fitting and modeling), and correlation with on-orbit observations. We will discuss Aerospace efforts in all three phases of study (measurement, modeling, observation) and highlight studies within the collaboration.

Comparing Modeled LCS1 VIS-NIR Spectra to Ground-Based Spectroscopy

As part of an internally funded study, the Aerospace Corporation used the Visible Near-Infrared Imaging Spectrograph (VNIRIS) at the 3.67m AEOS telescope to acquire signatures of LCS1, a polished aluminum calibration sphere launched in 1965, for comparison with physically motivated signature models produced by COAST/FIST. COAST/FIST is a software package focused on modeling observed RSO signatures via ray-tracing methodology. We compare VNIRIS spectra (0.4 – 2.5 µm) to simulated spectroscopic observations of LCS1 as an assessment of a simple test case for the proper measurement, modeling, and validation of satellite signatures. This comparison also serves as a preliminary investigation into the spectroscopic modeling of targets with more complex shapes and compositions. We find that the shape of observed VNIRIS spectra and COAST/FIST spectra match well, as both are representative of a shallow aluminum absorption feature (~0.845 µm) imposed onto the solar spectrum. However, we also see inconsistency in matching the intensity of observed and modeled spectra, with some spectra showing discrepancies in flux of up to 2-3x at shorter wavelengths. Possible explanations include an inaccurate assessment of the contribution of Earthshine, surface irregularities on LCS1 impacting observed spectra, or timing differences between LCS1 and calibration star observations. In general, it is encouraging that simulations can reasonably reproduce the shape of the observed spectrum of a simple RSO when significant object properties (shape and composition) are known. However, gaps still exist and will likely widen with increasingly complex targets (e.g solar cells).

Elucidating plasma-material interactions during atmospheric reentry in spacecraft thermal protection systems ***via*** *laser ablation and fast-gated optical emission spectroscopy*

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Abstract

Understanding the dynamic thermochemistry of the plasma sheath surrounding vehicles during atmospheric reentry is critical for applications of spacecraft thermal protection system material development and addressing concerns of the communications blackout phenomenon. To investigate the thermochemical dynamics present in these environments, we will use nanosecond pulsed laser-induced breakdown spectroscopy (LIBS) in conjunction with shadowgraphic measurements. This will be used to study the temporal evolution of the laser-produced plasma. We will focus on key parameters, including blast wave shock characteristics, rovibrational temperature, and relative concentrations of chemical species, as functions of laser pulse energy and gate delay. A high-resolution Echelle spectrometer will be used to resolve the discrete transitions of atomic and carbon-based molecular emissions from various types of TPS materials. These emissions are characteristic of those found in a hypersonic shock layer to enhance our understanding of reaction kinetics in high-enthalpy and shock environments. A Nedler-Mead fit of carbon-based molecular spectra will be used to determine plasma temperatures and analyze the thermal evolution of the plasma. Results will be evaluated through statistical error analysis and regression fitting, providing insights into plasma-material interactions of the reentry environment.

Public Release Statement

Distribution Unlimited; Approved for Public Release. Public Affairs Release # AFRL-2025-0038. The views expressed are those of the author and do not necessarily reflect the official policy or position of the Department of the Air Force, the Department of Defense, or the U.S. Government.

Acknowledgements

Supported by the Air Force Office of Scientific Research LRIR 24RVCOR005 and AFRL/RV Innovative Research Proposal funding.

Development of KESTREL System for Extending GEO Spectral Coverage

[Presenter] David Cantillo (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Adam Battle (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Tanner Campbell (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Vishnu Reddy (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona)

Artificial geostationary satellites are pivotal components of global communications networks and play crucial roles in military and weather surveillance. As the number of objects and maneuvers within this narrow orbital altitude range increases, so does the demand for methods to differentiate between them. Changes in visible (450 – 950 nm) spectroscopy and brightness measurements with longitudinal phase angle (LPA, East-West component of the Sun-target-observer angle) are two valuable observational parameters that can be simultaneously obtained using a single ground-based telescope. In this work, we expand upon the initial geostationary spectral atlas (-155° to -70° E long.) of Battle et al. (2024) by increasing our longitudinal coverage with a range centered over central Australia (+97° to +183° E long.). We utilize the KESTREL telescope (Keen-Eyed Spectroscopic Telescope for Reflections, Emissions, and Lightcurves), a 24-inch (0.61 m) f/4.29 corrected Dall-Kirkham telescope located in Moorook, Australia (MPC code D90). Like its RAPTORS I counterpart in Tucson, Arizona, KESTREL is equipped with an FLI CCD camera and a filter grating, enabling simultaneous photometry via the zeroth-order point source and visible spectroscopy via the first-order spectrum. We present the setup and calibration of the KESTREL system, including the derivation of its spectral resolution and validation using archival spectra of the main-belt asteroid (6) Hebe. Additionally, we provide comparative spectral analysis of two super-geosynchronous satellites, Gorizont 8 (14532) and Gorizont 24 (21759), observed by both RAPTORS I and KESTREL within a month and at comparable phase angles.

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A Battle, V Reddy, R Furfaro, T Campbell, 2024. The Planetary Science Journal, 5, 240. DOI: 10.3847/PSJ/ad76ab

Spectrally Dominated Satellite Buses as a Test-Case for Spectral Unmixing Algorithms

[Presenter] Rebecca Lersch (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Tanner Campbell (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Andrea D'Ambrosio (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Adam Battle (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Neil C. Pearson (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Roberto Furfaro (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Vishnu Reddy (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona)

We present our spectral unmixing analysis performed on telescopic data of the solar-cell-dominated HS-376 satellite bus type. This spin-stabilized bus type introduced by Hughes Space and Communication Company was a popular basis for communication satellites in the 1970s through the 1990s. There are over 40 satellites in the HS-376 standard model currently in orbit and most of these have been retired to a graveyard orbit. Visible wavelength (450 – 950 nm) spectra of nine satellites with HS-376 bus types were obtained using the RAPTORS I system (Battle et al. 2024) located in Tucson, Arizona, for comparison to spacecraft material spectra measured in our laboratory. Simultaneous brightness measurements are acquired as part of the spectral observations and these brightness measurements were used for rotational analysis of three out of the nine satellites. Spectral unmixing modeling was performed to estimate the ratios of different spacecraft materials needed to replicate a satellite's spectrum. Two methods were developed for estimating material compositions and for comparing the accuracy and efficiency of the different techniques. One algorithm is a brute-force grid search through ratios of user-identified potential materials. The second method is a genetic algorithm capable of searching all permutations in the user's library of material spectra. Estimated compositions and the ratio of each material – including solar cells, metals, and mylars – are presented for these observations. We discuss the importance of laboratory studies with representative spacecraft materials for providing context to observational studies.

REFERENCES:

A Battle, V Reddy, R Furfaro, T Campbell, 2024. The Planetary Science Journal, 5, 240. DOI: 10.3847/PSJ/ad76ab

Conclusions of the First Spectral Atlas of the GEO Belt

[Presenter] Adam Battle (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Tanner Campbell (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Neil Pearson (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Roberto Furfaro (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), David Cantillo (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona), Vishnu Reddy (Space Safety, Security, and Sustainability [Space4] Center, University of Arizona)

The characterization of geostationary Earth orbiting (GEO) satellites has historically been based on measuring lightcurves of satellite brightness as the longitudinal phase angle (East-West component of the Sun-target-observer angle) changes throughout the course of the night. The use of a diffraction grating allows these brightness measurements to be obtained simultaneously with the spectrum of the target, adding more information to the observations without increased observing time. The Robotic Automated Pointing Telescope for Optical Reflectance Spectroscopy (RAPTORS I) system is an automated 0.6-meter, f/4 telescope constructed by five engineering students at the University of Arizona. Data for a visible wavelength (450 – 950 nm) spectral survey of 96 GEO satellites observable from Tucson, AZ were collected between January 2020 and June 2022 using this system. The survey focused on GEO satellites with near-zero inclination to estimate phase variations expected on these types of objects and to establish a baseline of visible spectra of artificial objects for differentiating between natural and artificial targets. The data acquired for these objects is also ideal for machine learning techniques. Several early stages of machine learning algorithms have been developed to estimate the bus type of an observed satellite and to identify potential "eigenfeatures" in satellite spectra that can be correlated with known lightcurve features. The ultimate goal of this research is to "fingerprint" satellites with phase-resolved spectra so the target can be uniquely identified in future observations. We present the conclusions of the GEO spectral atlas and preliminary results from machine learning applications on this data set.

Photometric Characterization of AST Space Mobile Blue Bird Satellites

Owen Miller, Dr. Tanner Campbell, Neil Pearson, Dan Gray, Scott Tucker, Prof. Vishnu Reddy

AST SpaceMobile is a Houston-based satellite manufacturer that is designing a space-based telecommunication network with their SpaceMobile megaconsetllation of BlueBird satellites. In September of 2022 they launched their prototype "Blue Walker 3" into low Earth orbit. The press release that followed immediately sparked concerns over the potential brightness of their projected megaconstellation due to the abnormally large size of the prototype satellite (693 square feet). Concerns about the effects of this megaconstellation were reinvigorated with the September 12, 2024, launch of five new BlueBird satellites. We present photometric characterization of these five newest BlueBird satellites to continue our research on how megaconstellations affect ground-based astronomy. This is an extension of the work presented at Voltron 2022 in our presentation, "Characterizing Mega Constellations using a Multi-Aperture Optical Array (MOA)." To collect our data, we use an ASI 432 MM Pro Camera equipped on our MOA telescope system to obtain photometric data of the five BlueBird satellites that are currently in orbit. This research will help further our understanding of the impact of megaconstellations on ground-based astronomy and space situational awareness.