Sustainability of Outer Space

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October 18, 2019
Sustainability of Outer Space

Avoiding a Tragedy of the Commons
Outline

- Satellites: So What?
- What’s on Orbit?
- What’s the Problem?
- Space Situational Awareness: Why, What, How?
- Challenges
- Example of Research
Satellites: So What?
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What if Satellites Disappeared?
Assumed Space Object Population

- ~1200 “Live” objects
- ~20,000 objects >10cm
- ~3-600,000 objects >1cm

Space participants are proliferating – 43 countries today

Sources

- New Live objects/satellites
- All space object weathering leads to flaking, chipping, erosion
- Mission/deployment related debris
- Gravity fatigue and torqueing self destruction
- Dead objects/debris and explosions
- Fretting fatigue causing structural failure

Sinks

- De-orbiting objects: Space environment and/or gravitationally induced perturbations about 1-3 per day

Sources and sinks of space debris.
Space Object Population Growth Over Time
Example: Iridium vs Cosmos Collision
Currently Tracked Resident Space Object Population

Legend
- Active satellite
- Inactive satellite
- Rocket body
- Debris
- Uncategorized
## Planned US Sources to the Space Object Population

<table>
<thead>
<tr>
<th>Constellation name</th>
<th>number of satellites</th>
<th>Altitude (km)</th>
<th>Launch year (start)</th>
<th>Owner</th>
</tr>
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<tbody>
<tr>
<td>Starlink Phase A</td>
<td>1584</td>
<td>550</td>
<td>2019</td>
<td>SpaceX</td>
</tr>
<tr>
<td>Starlink Phase B1</td>
<td>1600</td>
<td>1110</td>
<td>2020</td>
<td>SpaceX</td>
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<td>Starlink Phase B2</td>
<td>400</td>
<td>1130</td>
<td>2023</td>
<td>SpaceX</td>
</tr>
<tr>
<td>Starlink Phase B3</td>
<td>375</td>
<td>1275</td>
<td>2024</td>
<td>SpaceX</td>
</tr>
<tr>
<td>Starlink Phase B4</td>
<td>450</td>
<td>1325</td>
<td>2024</td>
<td>SpaceX</td>
</tr>
<tr>
<td>OneWeb</td>
<td>648</td>
<td>1200</td>
<td>2019</td>
<td>OneWeb</td>
</tr>
<tr>
<td>Telesat 45° inclination</td>
<td>150</td>
<td>1000</td>
<td>2021</td>
<td>Telesat</td>
</tr>
<tr>
<td>Telesat 98° inclination</td>
<td>150</td>
<td>1150</td>
<td>2022</td>
<td>Telesat</td>
</tr>
<tr>
<td>Kuiper Phase 1</td>
<td>1156</td>
<td>630</td>
<td>2022</td>
<td>Blue Origin</td>
</tr>
<tr>
<td>Kuiper Phase 2</td>
<td>1296</td>
<td>610</td>
<td>2023</td>
<td>Blue Origin</td>
</tr>
<tr>
<td>Kuiper Phase 3</td>
<td>784</td>
<td>590</td>
<td>2024</td>
<td>Blue Origin</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>8593</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Courtesy Prof. Marek Ziebart, UCL*
Planned US Sources to the Space Object Population

- Starlink Phase A
- Starlink Phase B1
- Kuiper Phase 2
- Kuiper Phase 1
- Kuiper Phase 3
- OneWeb
- Starlink Phase B4
- Starlink Phase B2
- Starlink Phase B3
- Telesat \( i = 45^\circ \)
- Telesat \( i = 98^\circ \)

Courtesy Prof. Marek Ziebart, UCL
What’s The Problem?
The Space Frontier: Wild West!

• Little-to-no Rules, no real-estate deeds: What should be regulated? “Lawlessness of the West”
• Potential to make lots and lots of money near term: “Gold Rush” Bonanza!
• Easier and cheaper access to space seen as the biggest barrier: “Transcontinental Railroad”
• “New Space” not following the paradigm of traditional space actors. Where is cost cut?
There are no Space Traffic rules!
Traditional Ecological Knowledge (for Space)

- **Factual Observations**
  - Development of a taxonomy, knowledge graph, models, etc.
- **Sustainable Use of Resources: Management Systems**
  - Registries and databases, data sharing, coordination, etc.
- **Past and Current Uses**
  - Geopolitical, types of missions, military/civil/commercial, etc.
- **Ethics and Values**
  - Norms of Behavior, UN COPUOS, UN PAROS, etc.
- **Cultural Relationships**
  - Apollo missions, International Space Station, etc.
- **Cosmology (Anthropological)**
  - Societal relationship with space, obligations, beliefs, existential interpretations, etc.
Space Events and Processes Venn Diagram

The Set of ALL Space Domain Processes and Quantities

Beliefs
- Hypothesized Knowledge
  - Epistemic Addition
- Inferred Knowledge
  - Aleatory
- Targeted Information
  - Tasking

Evidence
- Latent Knowledge
  - Epistemic Reduction
- Multi-Source Information
  - Fusion, AI/ML

Arcana
- Ignorance
  - Epistemic
Traditional Ecological Knowledge

Practice
- Data Sharing
- Traffic Management
- Skills
- Respect
- Techniques

Knowledge
- Empirical Observations
- Astrodynamics
- Space Environment
- Models
- Causal Relationships
- Human Impacts and Effects

Ethics
- Norms of Behavior
- Moral Code
- Judgements
Space Situational Awareness and Space Traffic Management
## SSA: The "Why"

<table>
<thead>
<tr>
<th><strong>Space Hazard</strong></th>
<th><strong>Space Hazards</strong></th>
<th><strong>Space Threats</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;A Harsh Environment&quot;</td>
<td>&quot;The Safety of Flight&quot;</td>
<td>&quot;The Adversary&quot;</td>
</tr>
</tbody>
</table>

The space environment is hostile and hazardous
- Electronics upset
- Materials age
- Radio waves degrade

The space environment affects the dynamic behavior of objects

| The environment needs to be understood and managed |

There are many space objects—many dead, some not
- Paths only approximately known
- Space is more crowded today

Space objects are hazardous to each other
- The probability is low, but the consequences are very high!

| Traffic management of space congestion needs to assure safe operations, security, and sustainability |

Space is contested by adversaries today
- The required methods to address the threat are new
- The methods cross many phenomenologies and disciplines
- As long as we do not fully understand and measure the space domain, there will be places to hide and an ability for us to be deceived!!!

The threat is real, and growing
- We must be able to attribute cause of behavior: intentional vs unintentional

| The threat must be detected, understood, and addressed |

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To Know it, you MUST Measure it; to Understand it, you MUST Predict it!
SSA: The “What” it should provide

- **Transparency**
  - Open and accessible space object and event data sharing

- **Accountability**
  - We must be able to monitor all behavior and given the evidence, come to common conclusions and infer similar causal relationships

- **Predictability**
  - Communication
    - Preemptive sharing of details (registering events) for planned events like maneuvers, launches, deployments, etc.
  - Cultural Competency
    - What is Sharia interpretation of the UN LTS Guidelines?
    - Do Israeli satellites maneuver on Shabbat?
    - Bottom Line: Can we predict what any space actor will do for any given space event?
  - Accurate and precisely modeled astrodynamics and space events
    - Ephemerides and related parameters
    - Space weather predictions
Essential Ingredients For Success

• Independent Space Object and Event Behavior Quantification, Monitoring, and Assessment
  - Collectively produce the evidence upon which to measure orbital safety, space security, and operational sustainability

• Sustainability Metrics
  - Space Traffic Footprint (STF)
  - Orbital Capacity
  - Space Sustainability Rating

• Development and Implementation of Best Practices and Standards
  - UN COPUOS
  - IADC
  - ISO
  - AIAA

You MUST Measure It to Know It; you MUST Predict It to Understand It!
Space Traffic Footprint

• Impact or risk to space services, capabilities, and activities by quantifying any specific space object’s burden upon space safety, security, and environmental/operational sustainability.

• It impacts the cost to the operational and user segments of space domain services.

• What is the effect of any given object’s existence in space upon the operational calculus of other users and space operators? How much orbital capacity does any given object take?
Space Traffic Footprint

- Must be independently measurable

- Must be spatio-temporally assessed and updated (i.e. dynamically computed and updated)

- Algorithm/process must be transparent and accepted as a community standard

- Must be repeatable, consistent, and unbiased

- Must be individual and cumulative, and people must be able to actively minimize it
Space Traffic Footprint

- Is a calculation risk based on Weighted Variables which parameterizes the possibility of loss, disruption, or degradation of space activities, services, or capabilities of other resident space objects given the existence and behavior of any given RSO. Example:

<table>
<thead>
<tr>
<th></th>
<th>Maneuverability</th>
<th>Trackability</th>
<th>Robust Design</th>
<th>Design for Demise</th>
<th>Neighborhood Population</th>
<th>Size</th>
<th>Event Coordination</th>
<th>Natural Removal Regime</th>
<th>STF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ISS</strong></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>10</td>
<td>2</td>
<td>3</td>
<td>2.875</td>
</tr>
<tr>
<td><strong>Flock 1C 10</strong></td>
<td>9</td>
<td>5</td>
<td>2</td>
<td>7</td>
<td>8</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4.875</td>
</tr>
<tr>
<td><strong>WorldView1</strong></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>3.875</td>
</tr>
<tr>
<td><strong>Fengyun 1C Deb</strong></td>
<td>10</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>8</td>
<td>2</td>
<td>10</td>
<td>4</td>
<td>7.75</td>
</tr>
</tbody>
</table>
We have a few challenges!
Space Environment Effects and Impacts

We apply time and effort to operate through the space environment impacts. They are a background noise that could conceal real threats.
## Anomaly Attribution

Halloween 2003 Storms Retrospective Analysis*

### Cyber Attack?
- **RHESSI** – spontaneous reset of CPU (3x)
- **GOES 8** – unrecoverable shutdown of X-ray sensor
- **Landsat** – all instruments turned off or safed
- **Cluster** – some of four spacecraft CPU’s reset
- **Mars Odyssey** – MARIE instrument has temperature “red alarm” and is powered off; never recovered

### Jammer Attack?
- **MER 1, MER 2** – Entered sun idle mode after excessive star tracker events
- **Kodama** – safe mode triggered by increased noise on Earth sensor, recovered 10 days later

### Directed Energy Attack?
- **GOES-12** – magnetic torquers disabled
- **CHPs** – spacecraft tumbled, later recovered
- **Inmarsat** – two spacecraft had speed increases on momentum wheels requiring firing of thrusters
- **POLAR** – despun platform went out of lock 3x; auto recovery after each event
- **FedSat** – stabilized platform started wobbling

### Coater System Attack?
- **Midori** – power dropped, entered safe mode; telemetry lost; total loss
- **GOES** – Electron sensors saturated
- **GALEX** – two UV experiments turned off due to high voltage caused by excessive charge
- **Chandra** – build-up of grease on an optical filter in front of one cameras

*From: Susan Andrews, “Distributed Threat Warning Study”, MIT/LL Conference
Confirmation Bias

• Tendency to search for, interpret, favor, and recall information in a way that confirms one's preexisting beliefs or hypotheses, while giving disproportionately less consideration to alternative possibilities

• Many of those who’ve contributed to the present-day problems are the only ones who have access to provide solutions
What Happens When We Don’t Share Information?  
Partial Knowledge Can Lead to Wrong Decisions

You MUST Measure It to Know It; you MUST Predict It to Understand It!
Forces acting on a Spacecraft

- Antenna thrust (AT)
- Thermal forcing (TRR)
- Solar radiation pressure (SRP)
- Planetary gravity
- General relativistic effects
- Earth gravity
- Solar gravity
- Lunar gravity
- Tidal effects
- PRP (planetary radiation pressure)
- and atmospheric drag
Understanding a Population
“Tag and Track”

• Identify individuals of a certain species in the population
• Tag those individuals
• Formulate initial hypotheses
• Track the behavior of those individuals over time, space, and frequency and their interactions with their environment to include individuals of other species
• Test hypotheses
• Identify correlations
• Infer or determine causal relationships
Detecting Vs Tracking

Synoptic search produces >10k observations on 1000’s of targets nightly
Unique Space Object Identification

Raw Observations

Hypotheses Generation

Unscented Transform

Compute Residuals (O-C) and Innovations Covariance (P) for Multiple Hypotheses

Hypotheses Pruning

Compute Mahalanobis Distance for Multiple Hypotheses

\[ k^2 = (O - C)^T P_{innov}^{-1} (O - C) \]
Data Engineering, Modeling, Science, and Analytics

Images from Oracle

<table>
<thead>
<tr>
<th>Problem Classification</th>
<th>Sample Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomaly Detection</td>
<td>Given demographic data about a set of customers, identify customer purchasing behavior that is significantly different from the norm</td>
</tr>
<tr>
<td>Association Rules</td>
<td>Find the items that tend to be purchased together and specify their relationship – market basket analysis</td>
</tr>
<tr>
<td>Clustering</td>
<td>Segment demographic data into clusters and rank the probability that an individual will belong to a given cluster</td>
</tr>
<tr>
<td>Feature Extraction</td>
<td>Given demographic data about a set of customers, group the attributes into general characteristics of the customers</td>
</tr>
</tbody>
</table>
From Data to Discovery: Patterns in the Graph

- Discovering "Latent Knowledge"
- Our framework facilitates multi-source information curation and analytics to identify correlations
  - One must ask the right question (make the correct query)
- Find which correlations have causal relationships
- Link these data (e.g. Vietoris-Rips Complex, Voronoi Clustering)
Example of Hot Science and Cool Result from Our ASTRIA Research!
Biometrically-Inspired Space Object Recognition (BISOR)

**Enrollment**

**Verification**

**Identification**
**Satellite spin measurement**

High rate photometric detectors allow for an accurate spin measurement of the passive, sunlit satellites.

- **Spinning TOPEX/Poseidon light curve**
- **Phase Dispersion Minimization**

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**Graphical Representation:**

- **Photon Flux ($10^6$ counts/s) vs. Time (s):**
  - Graph a) shows a representative light curve with peaks at regular intervals.
  - Graph b) and c) depict similar patterns but shifted in time.

- **Spin Angle:**
  - Range: $0^\circ$ to $360^\circ$

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**Additional Information:**

- **Spin Period:** 11.4 s (3 rotations)

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**Contextual Note:**

- Spinning satellites, such as TOPEX/Poseidon, produce light curves that can be analyzed to determine their spin rates and other characteristics.

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**Technical Details:**

- **Photometric Detectors:** Essential for precise measurement of light intensity variations.

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**Conclusion:**

Accurate spin measurements are crucial for understanding satellite dynamics and improving mission planning.
Satellite spin measurement

High rate light curve analysis

TOPEX/Poseidon light curve
- Phase folded pass, 57 rotations (11 minutes)
- mix of specular and diffuse reflections from different sides / surface elements of the spinning body
Specular and diffuse reflections form geometrical patterns.

**BRDF Lambertian model**

- **S**: sun
- **T**: telescope
- **P**: phase vector = $S + T$
- **$p$**: phase angle
- **$i$**: inclination angle ($< 0.25^\circ$)

The intensity of diffuse reflection depends on the angles between Sun, Telescope and the Normal vectors.

**Satellite spin measurement**

**Phase folded light curve**

**Spin angle** ($0^\circ - 360^\circ$)

**Time of pass (11 minutes)**

**Brightness**
Space Object Centered Celestial Sphere and Mollweide Projection
Hyper-temporal photometry

HTP generates detailed reflectivity maps by projecting satellite brightness measurements onto a phase vector expressed in the body fixed coordinate system.

Time dependent pattern (depends on the view angle)

Time independent pattern (fixed with the satellite body)

\[ P_{\text{Body}} = S P_{\text{Inertial}} \]

\( P \): phase vector
\( S \): transformation m.

The specular reflection occurs when the phase vector and surface normal coincide, thus the location of the specular reflections in the Body frame is fixed (assuming rigid body).

Kucharski et al., Photon pressure force on space debris TOPEX/Poseidon measured by Satellite Laser Ranging, AGU Earth and Space Science, 2017
High-definition photometry

1) Reflectivity map, log intensity scale

2) Polar, N

2015-July-9

2015-July-10
Unsolved Challenges

- Ontology-based Knowledge Graphs are still in their infancy with TBD outcomes
- How do we represent all types of uncertainty?
- How do we represent random and uncertain variables?
- How about multi-level security and info-protection?
- How do we handle conflicting evidence?
- Must have a simple process to map new data instances ASTRIAGraph
- Natural Language queries would be ideal
- Which ontologies make sense? Must have an associated dictionary/thesaurus, and provenance
- How do we develop “biometrics” for resident space object identification?
  - Enrollment, Verification, and Identification process?
  - Class dependent?
  - N-factor recognition process: begin with RSO kinematic features
- Can we develop a classification/taxonomy for resident space objects?
What is UT Austin Uniquely Suited to Contribute?

• Bring scientific inquiry, rigor, and resources to the pressing questions at hand
  - Academics are at liberty to question the current state-of-practice in context of, and in contrast to, the state-of-the-possible

• Develop NEW solutions: from state-of-the-possible to a refreshed state-of-practice
  - The highest-impact science is primarily grounded in exceptionally conventional combinations of prior work yet simultaneously features an intrusion of unusual combinations

• Provide Track II Diplomacy
  - Universities can pursue purely scientific collaborations with nation states in a way that develops confidence via transparency

• Deliver a modern, resilient workforce
  - By crafting new degrees and integrated curricula, universities have the potential to produce well-rounded individuals who have been exposed to the many facets of SSA.
Towards Establishing a Transdisciplinary Educational Program!

- Astronautics (astrodynamics, GN&C, satellite design, space environment, space propulsion)
- Space Law and Policy
- Space Environmental Science and Sustainability
- Astronomy

What about a “Hogwarts” for Space?

- Advanced degrees
- Certifications
- Apprenticeships
- Visiting scholars program

By crafting new degrees and integrated curricula, universities have the potential to produce well-rounded individuals who have been exposed to the many facets of SSA.
Who Cares?
Who Cares?
Who Cares?
Who Cares?
Who Cares?
Who Cares?
Who Cares?
Who Cares?
Who Cares?
Who Cares?
It’s Not Enough!!!
“The problem with the world is that the stupid are cocksure and the intelligent are full of doubt”

*Bertrand Russell*

Questions?

https://sites.utexas.edu/moriba