The University of Texas at Austin
Environmental Science Institute

Hot Science - Cool Talk # 121

Sustainability of Outer Space

Dr. Moriba Jah
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The University of Texas at Austin
Aerospace Engineering and Engineering Mechanics
Cockrell School of Engineering

Sustainability of Outer Space

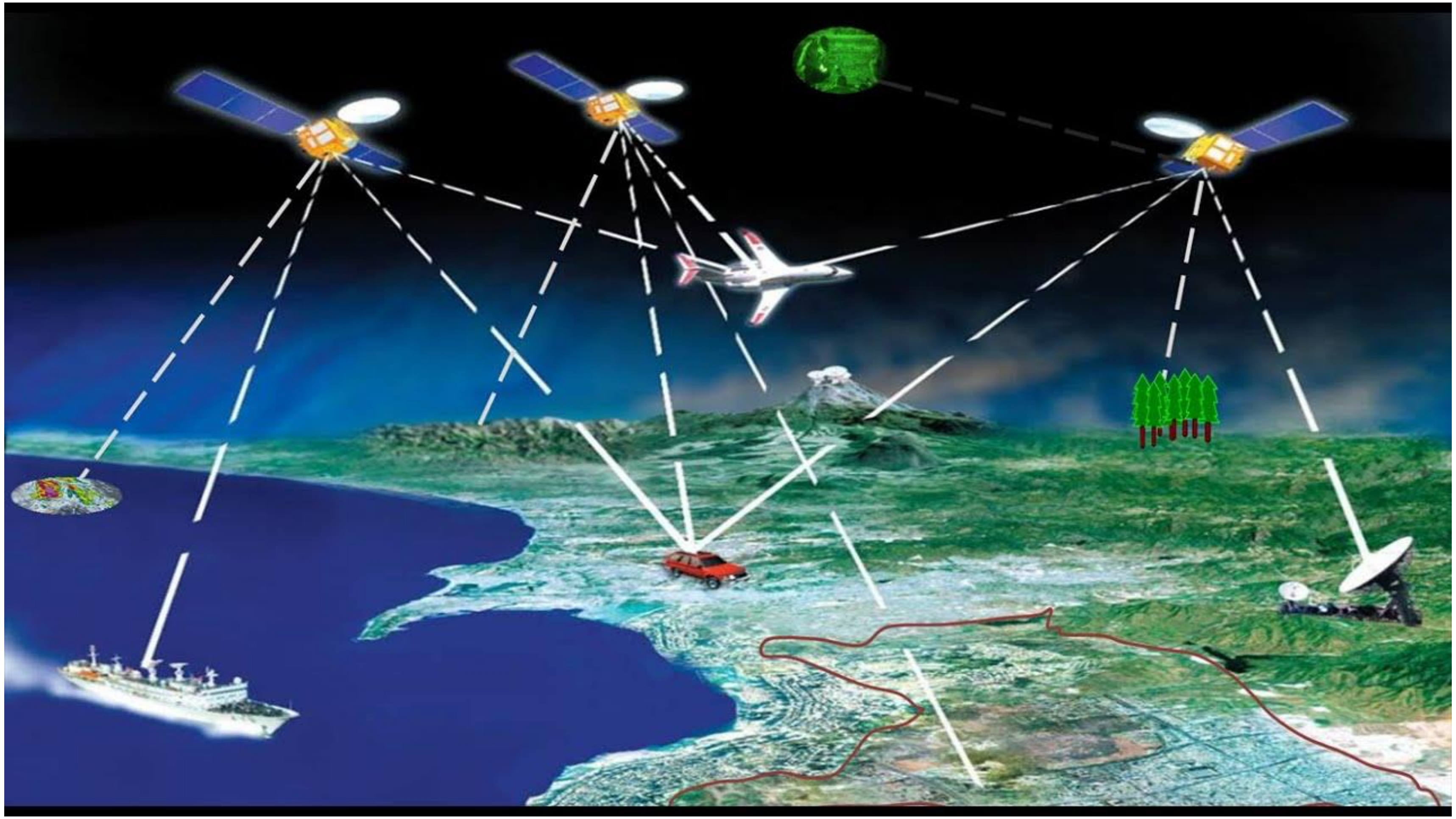
Avoiding a Tragedy of the Commons

Moriba Kemessia Jah, Ph.D.
Associate Professor
Aerospace Engineering and Engineering Mechanics Department
The University of Texas at Austin

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?



Satellites: So What?

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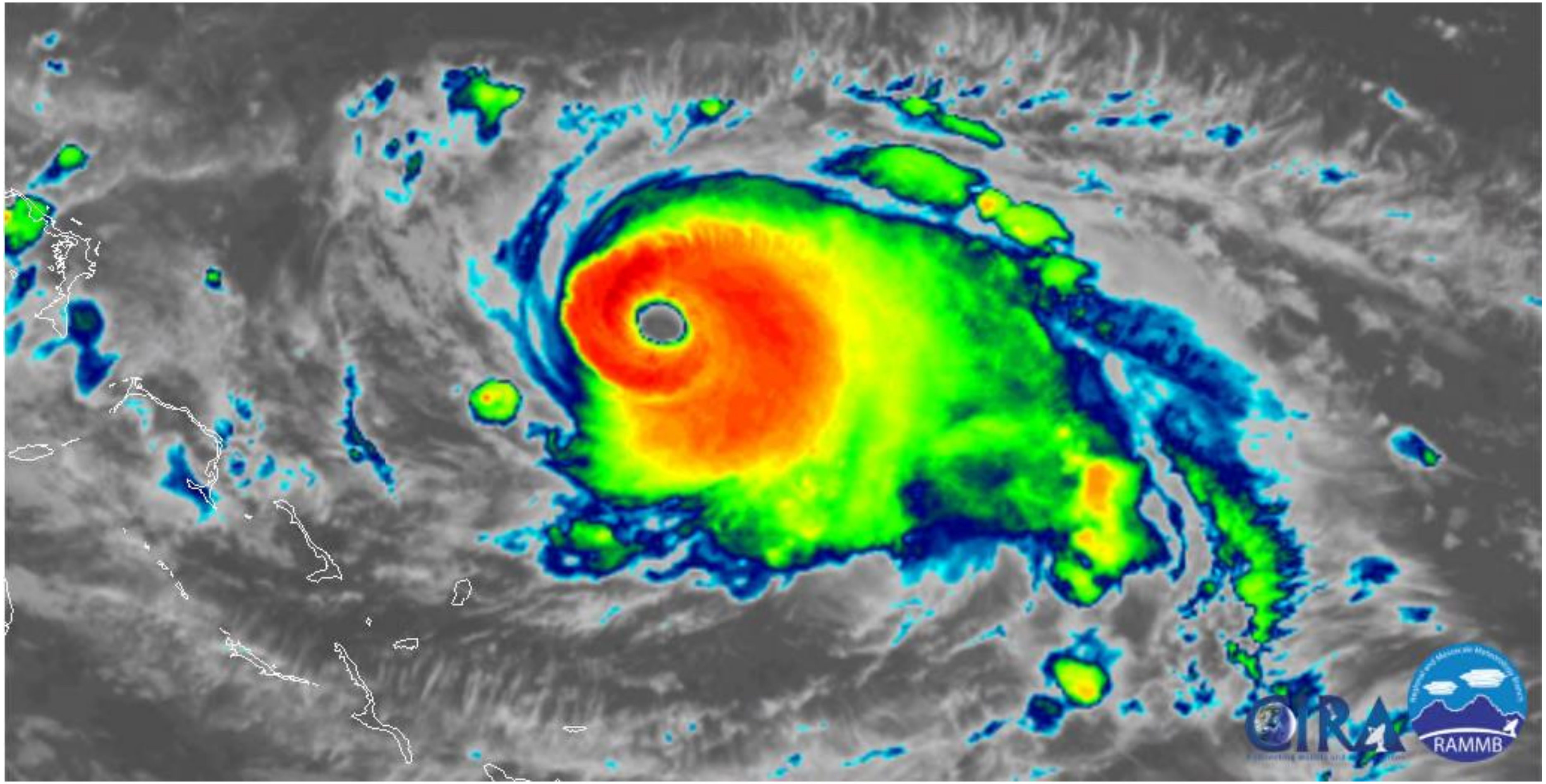

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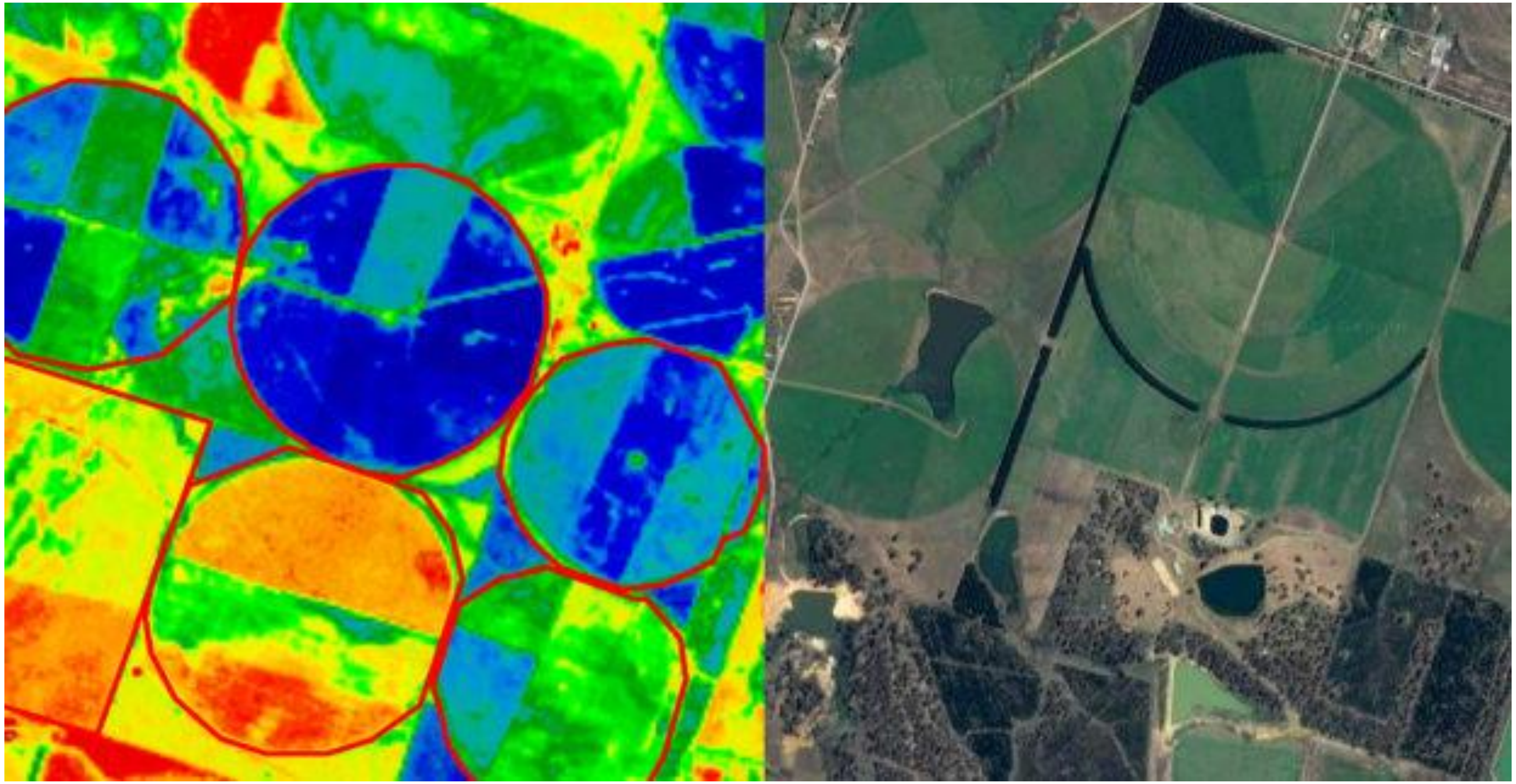

Satellites: So What?

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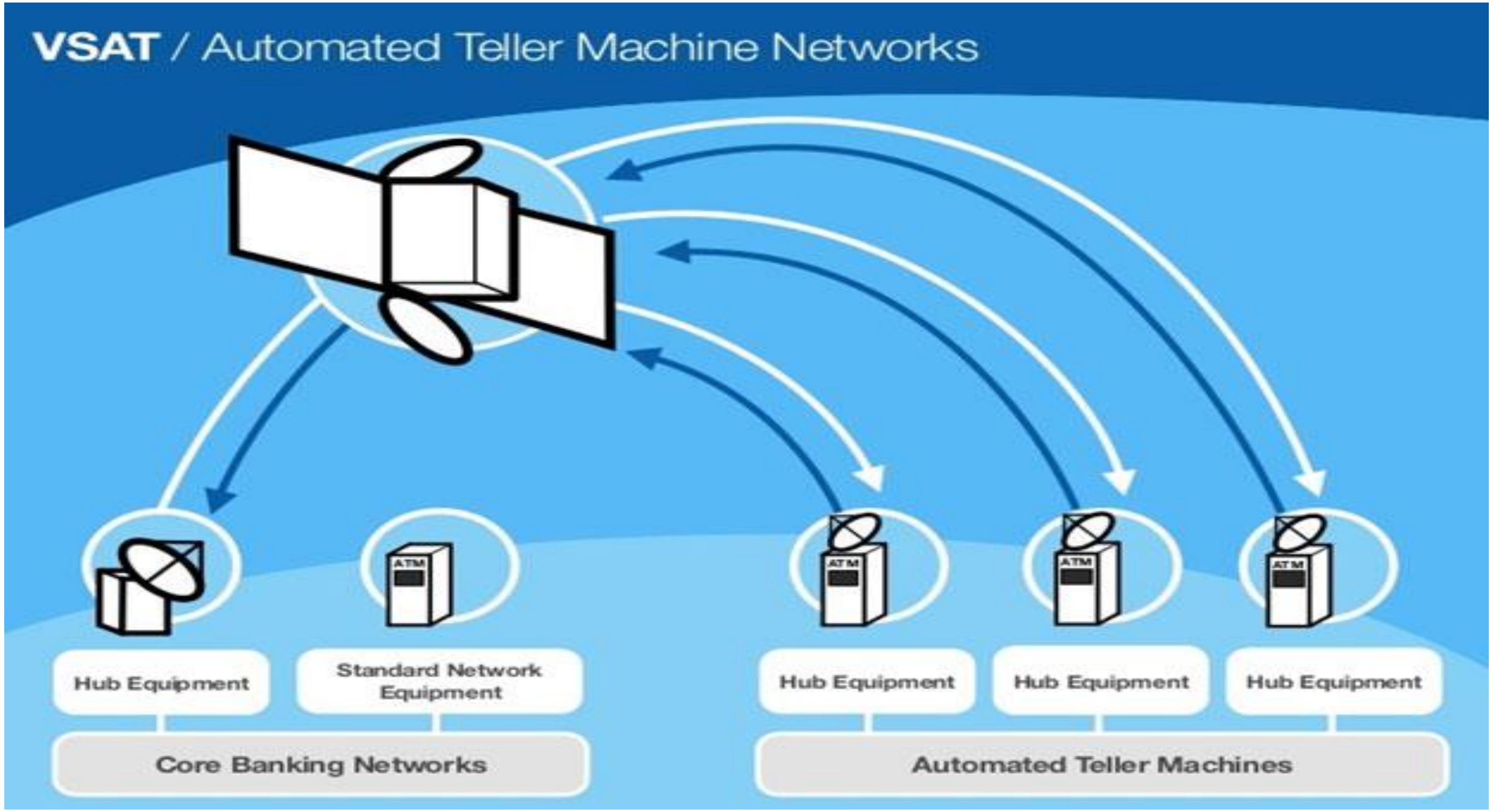
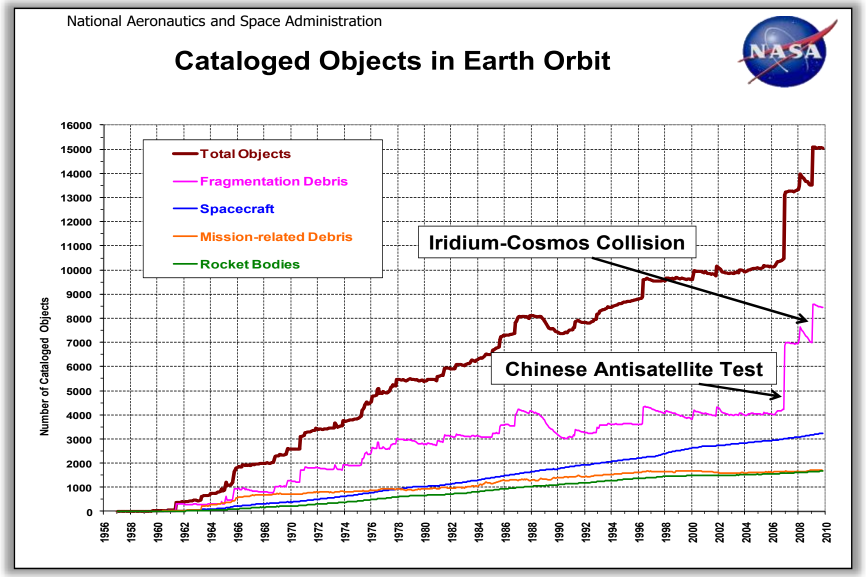
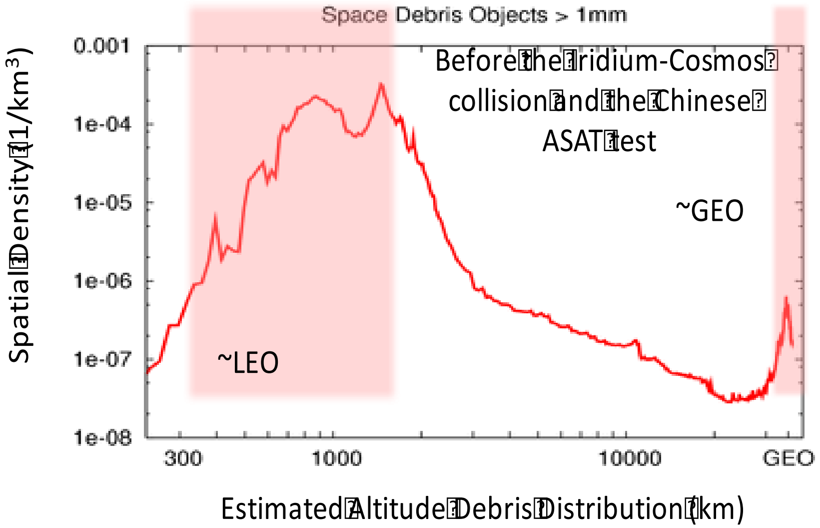


What if Satellites Disappeared?

Assumed Space Object Population





~1200 "Live" objects

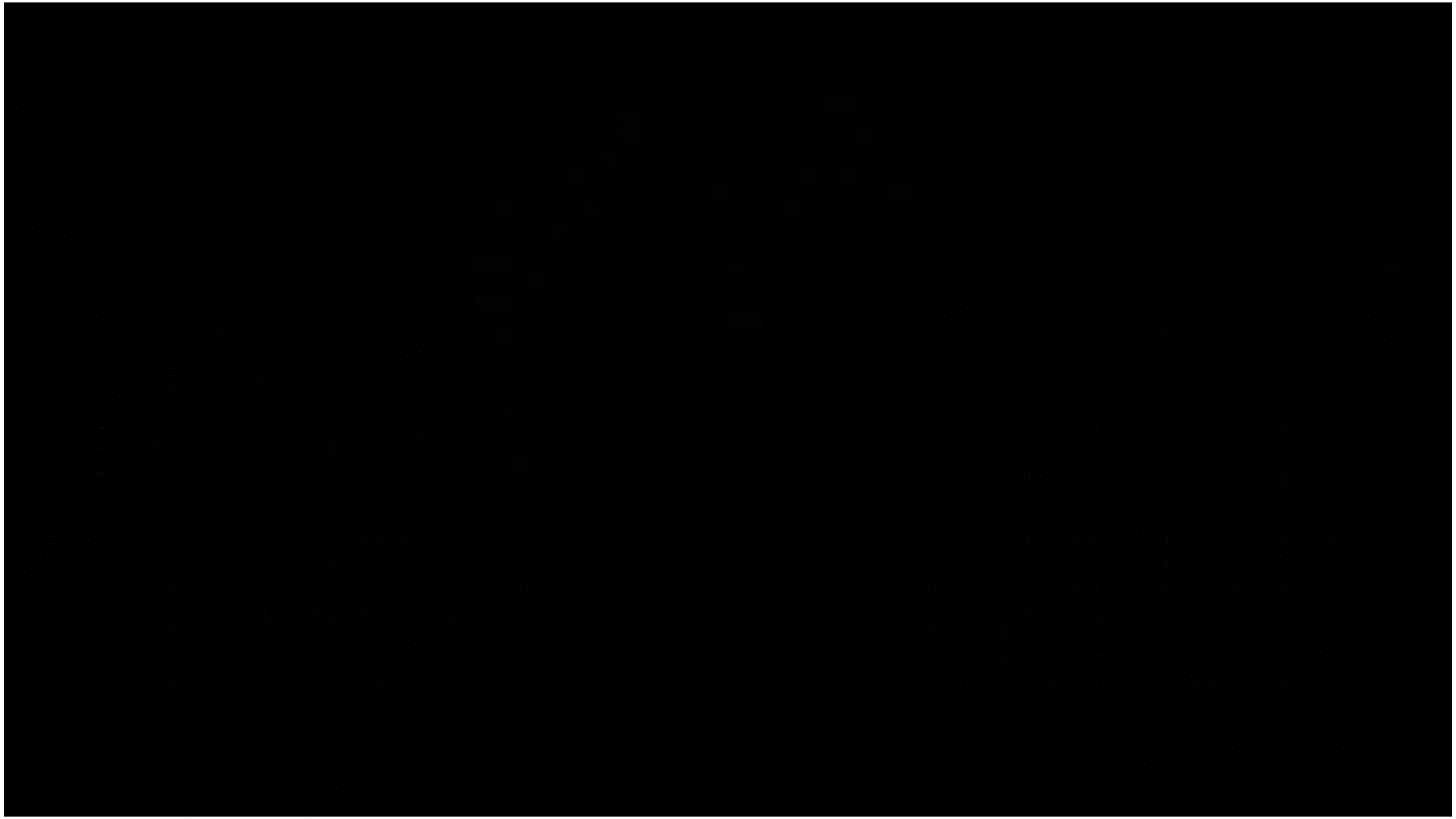
~20,000 objects > 10cm

~3-600,000 objects > 1cm

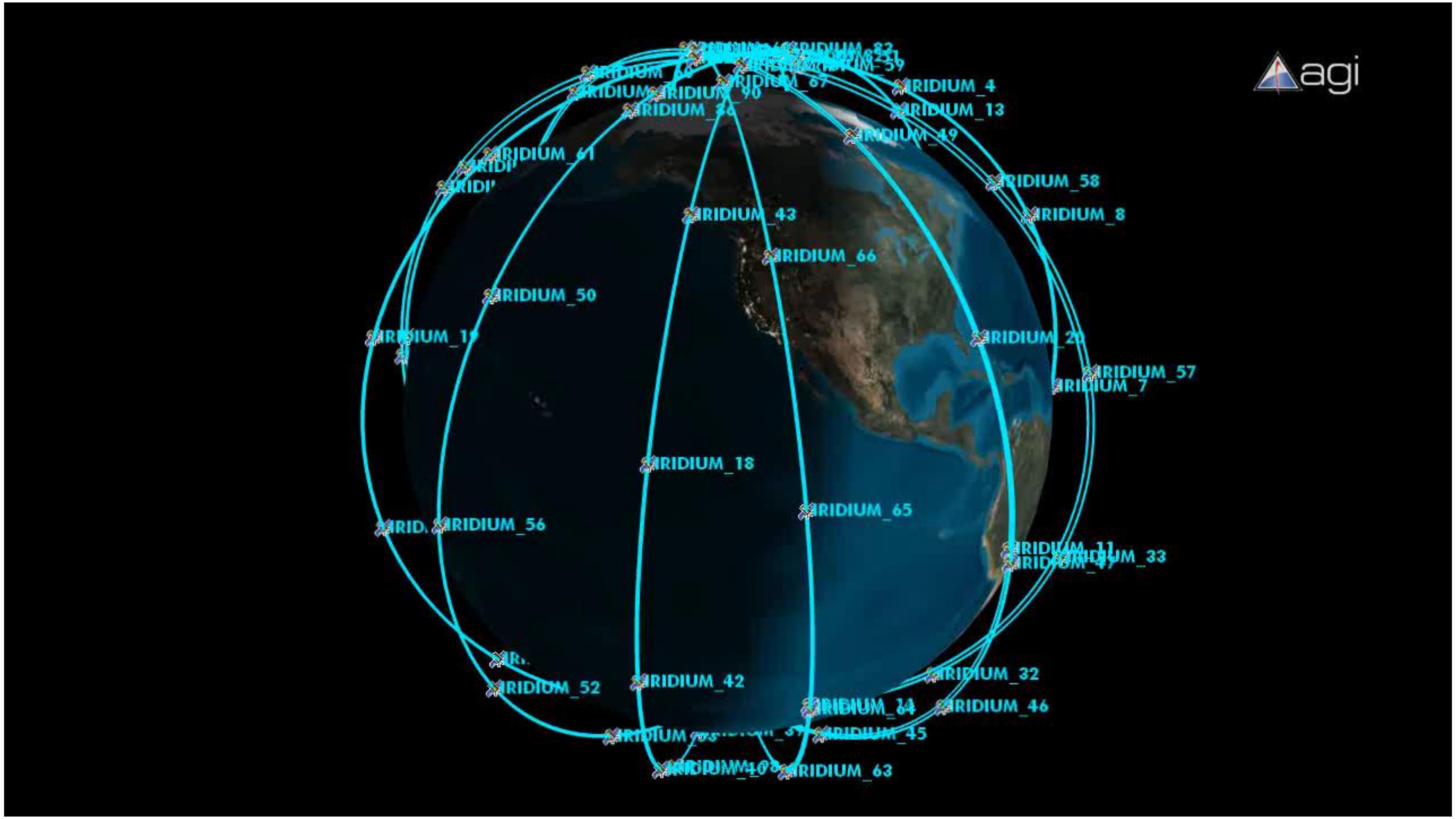
Space participants are proliferating – 43 countries today

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

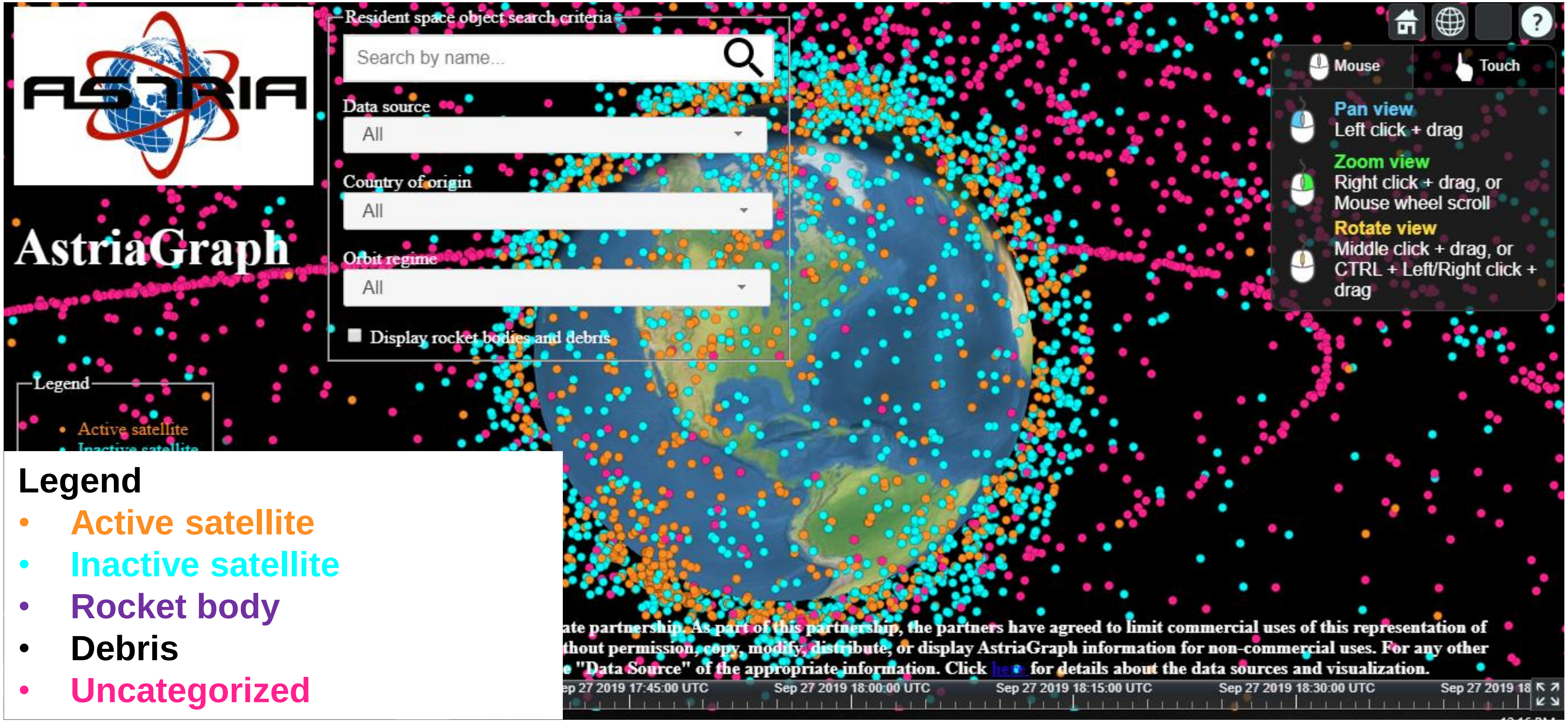
Space Object Population Growth Over Time



Example: Iridium vs Cosmos Collision



Currently Tracked Resident Space Object Population



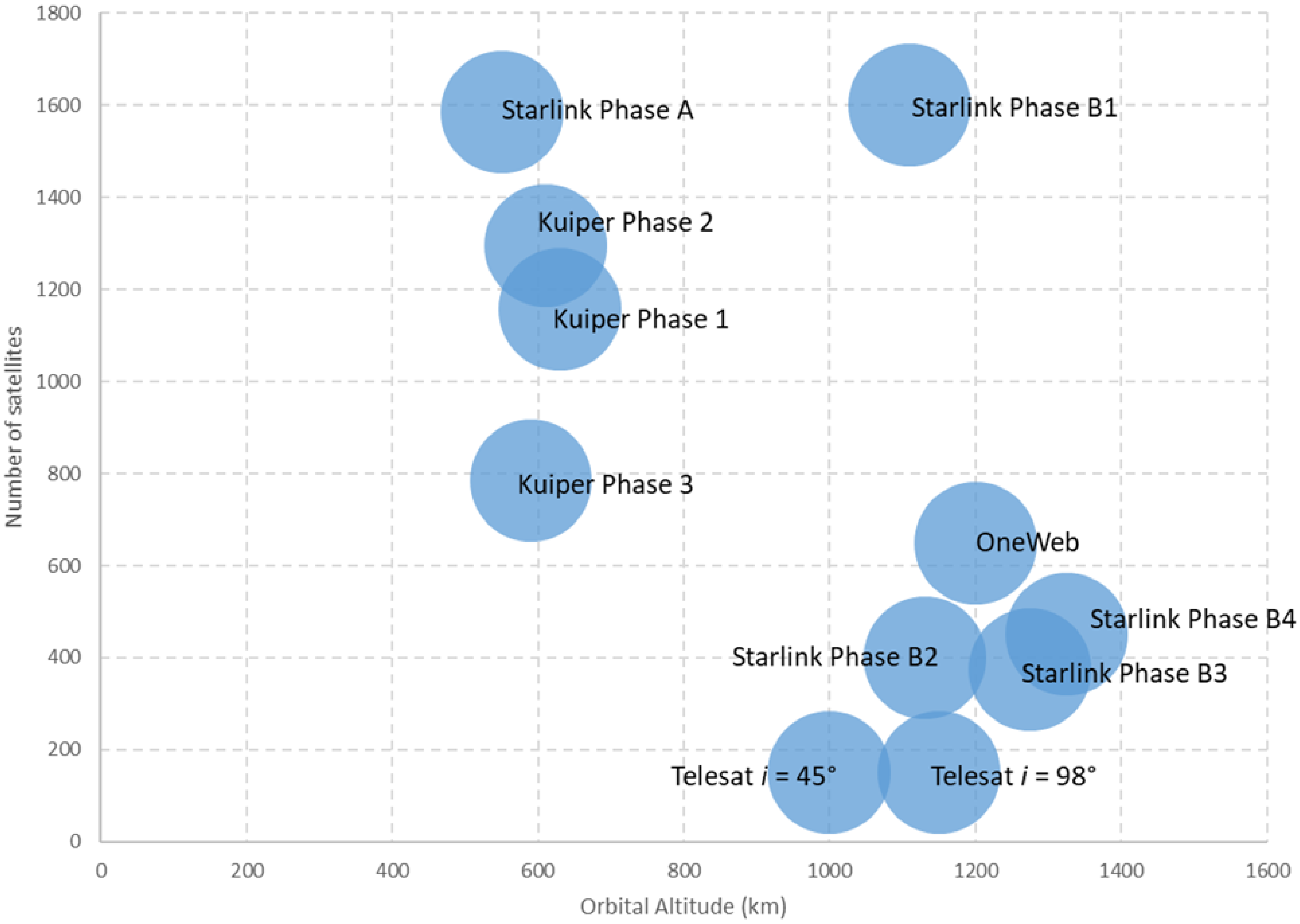
Legend
- Active satellite
- Inactive satellite
- Rocket body
- Debris
- Uncategorized

Planned US Sources to the Space Object Population

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

Courtesy Prof. Marek Ziebart, UCL

Planned US Sources to the Space Object Population



Courtesy Prof. Marek Ziebart, UCL

What’s The Problem?

The Space Frontier: Wild West!

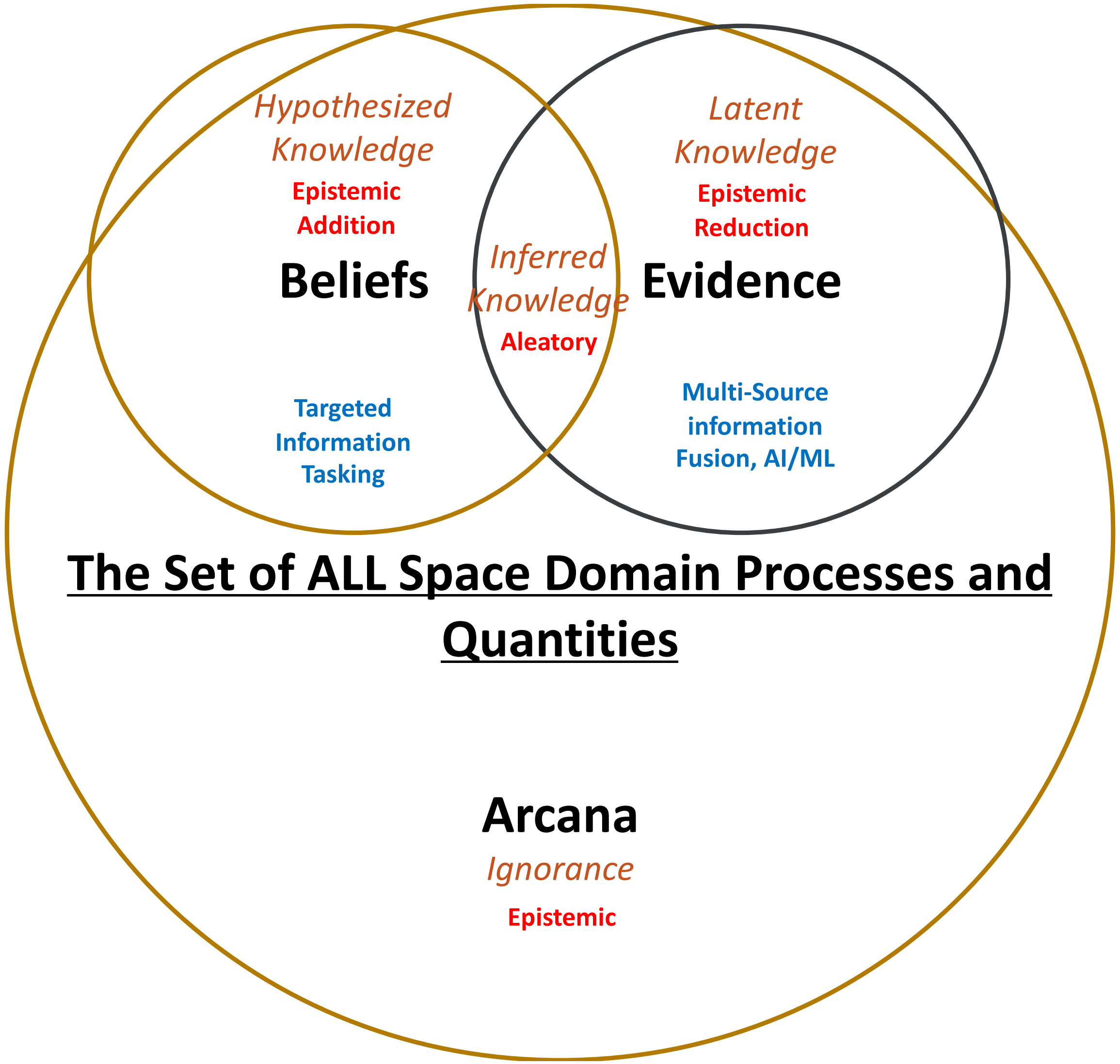
- Little-to-no Rules, no real-estate deeds: What should be regulated? “Lawlessness of the West”
- Potential to make lots and lots of money near term: “Gold Rush” Bonanza!
- Easier and cheaper access to space seen as the biggest barrier: “Transcontinental Railroad”
- “New Space” not following the paradigm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

There are no Space Traffic rules!

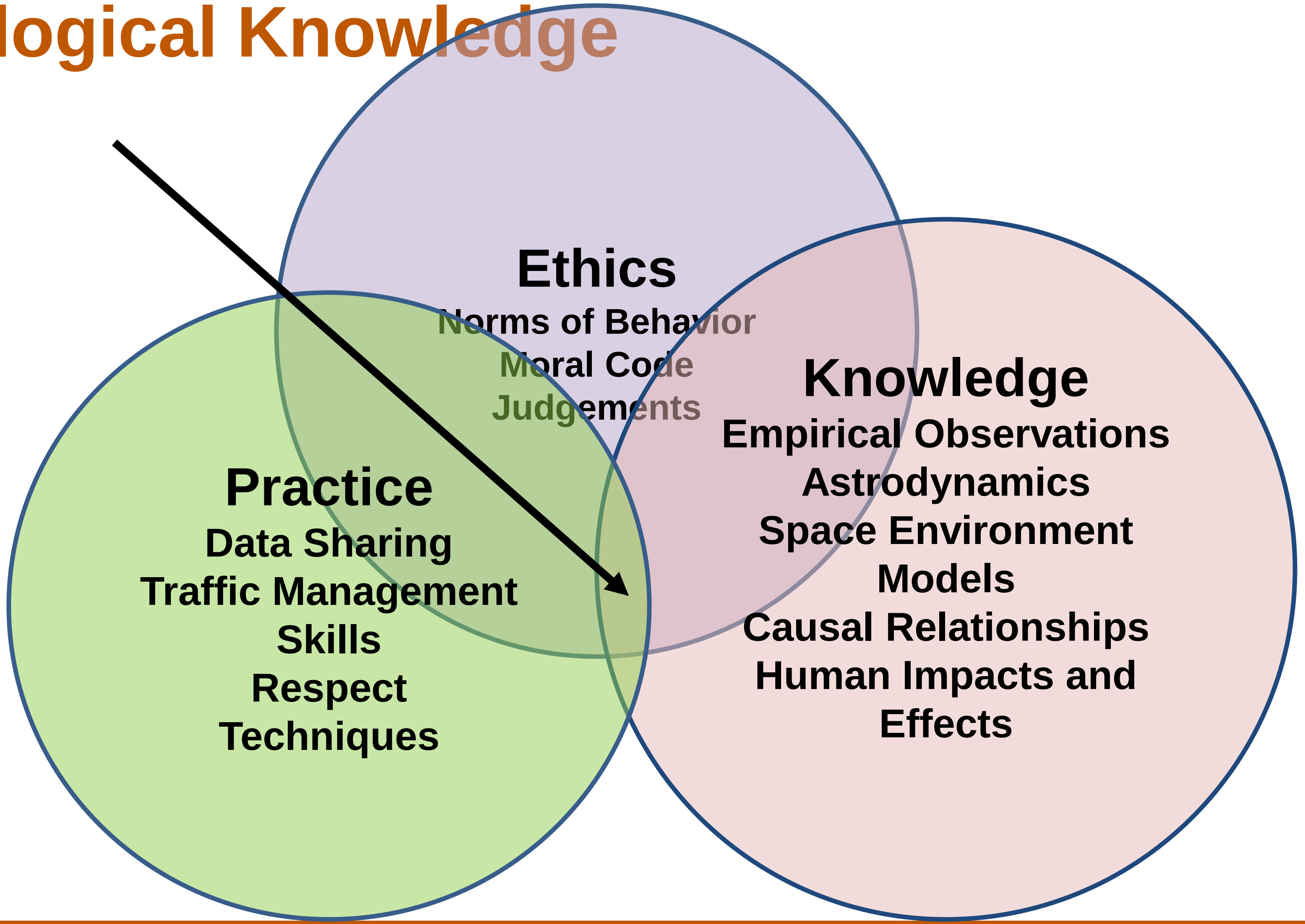
Traditional Ecological Knowledge (for Space)

- 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.

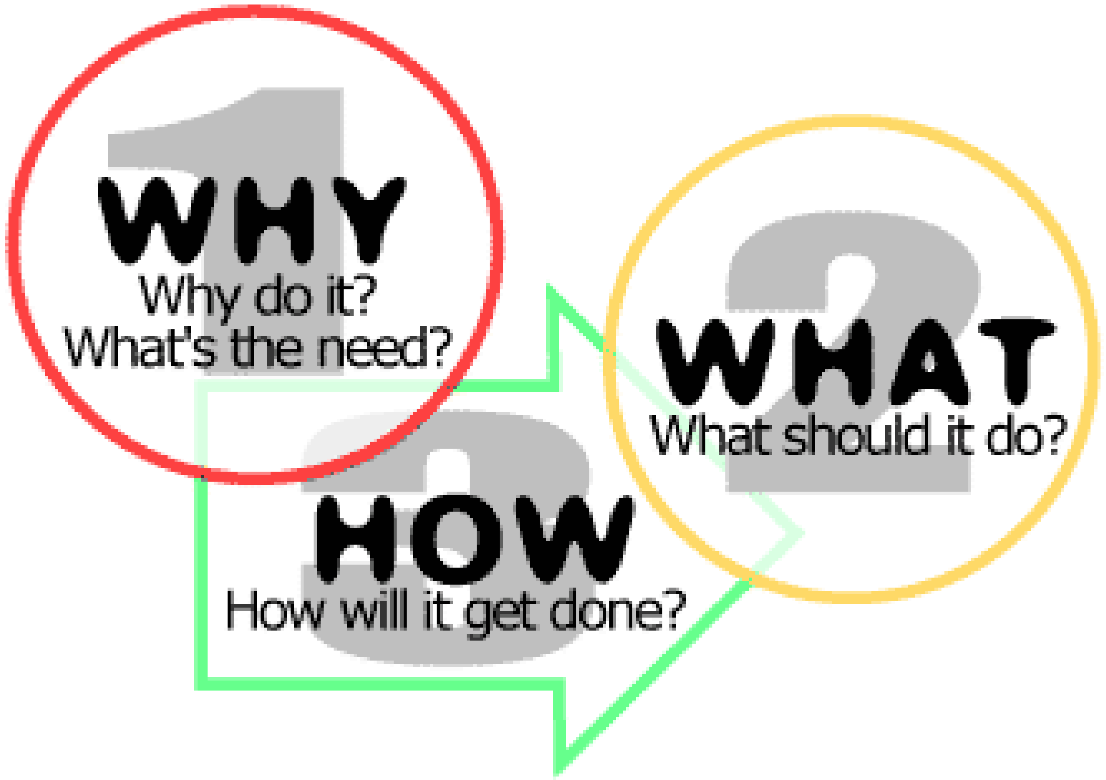
Space Events and Processes Venn Diagram



raditional Ecological Knowledge



Space Situational Awareness and Space Traffic Management



SSA: The "Why"

Space Hazard "A Harsh Environment"	Space Hazards "The Safety of Flight"	Space Threats "The Adversary"
The space environment is hostile and hazardous • Electronics upset • Materials age • Radio waves degrade The space environment affects the dynamic behavior of objects	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!	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 environment needs to be understood and managed	Traffic management of space congestion needs to assure safe operations, security, and sustainability	The threat must be detected, understood, and addressed

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

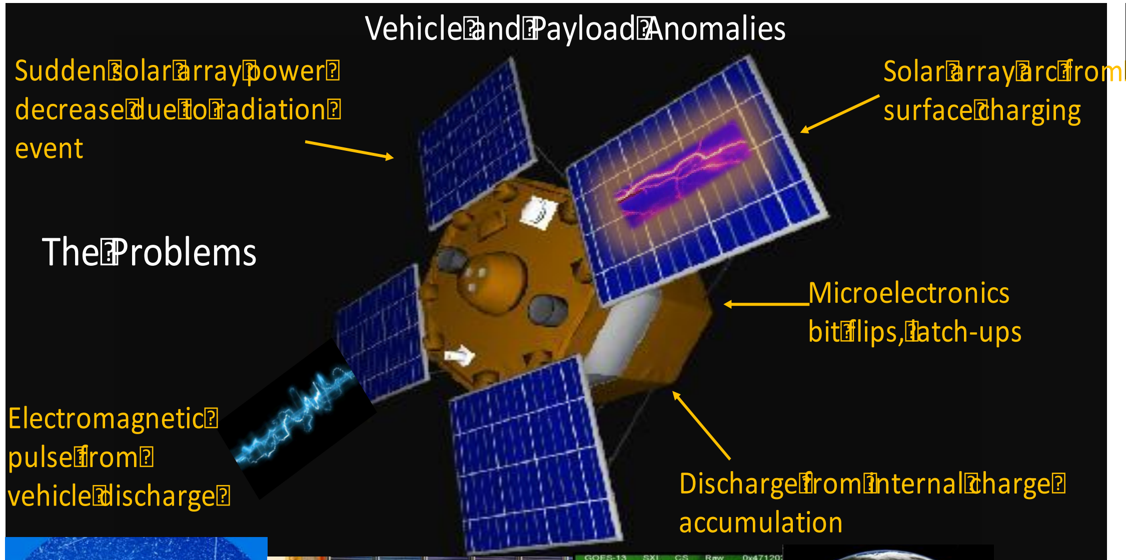
Space Traffic Footprint

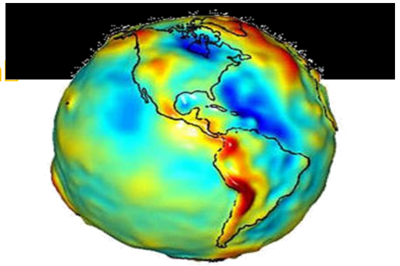
- Is a calculation risk based on Weighted Variables which parameterizes the possibility of loss, disruption, or degradation of space activities, services, or capabilities of other resident space objects given the existence and behavior of any given RSO. Example:

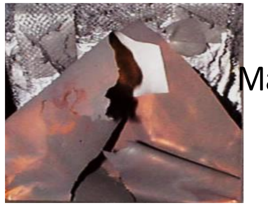
	Maneuverability	Trackability	Robust Design	Design for Demise	Neighborhood Population	Size	Event Coordination	Natural Removal Regime	STF
ISS	2	1	1	1	3	10	2	3	2.875
Flock 1C 10	9	5	2	7	8	2	2	4	4.875
WorldView1	4	3	2	4	8	4	2	4	3.875
Fengyun 1C Deb	10	8	10	10	8	2	10	4	7.75

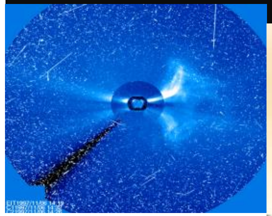
We have a few challenges!

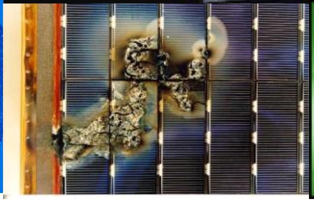
Space Environment Effects and Impacts

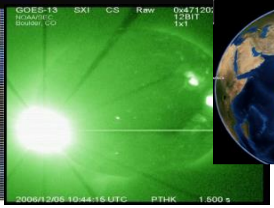


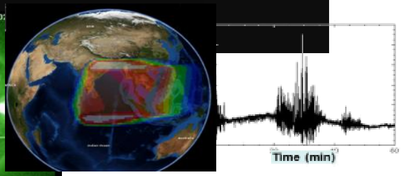



Material Aging & Damage


Sensor Noise


Arcing Damage


Solar RFI



Signal Scintillation

The Space Environment Imposes
- Design constraints
- Performance limitations
- Knowledge uncertainties

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?	JAMMER 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	**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?	**COATER SYSTEM 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	**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

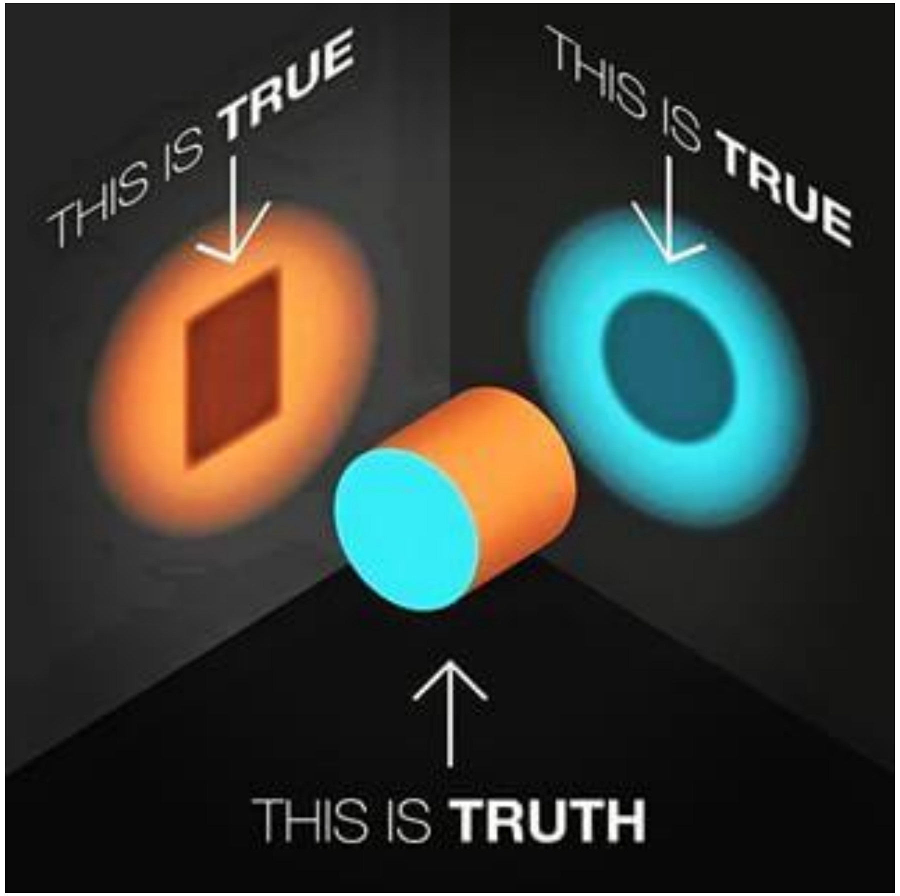
*From: Susan Andrews, "Distributed Threat Warning Study", MIT/LL Conference

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

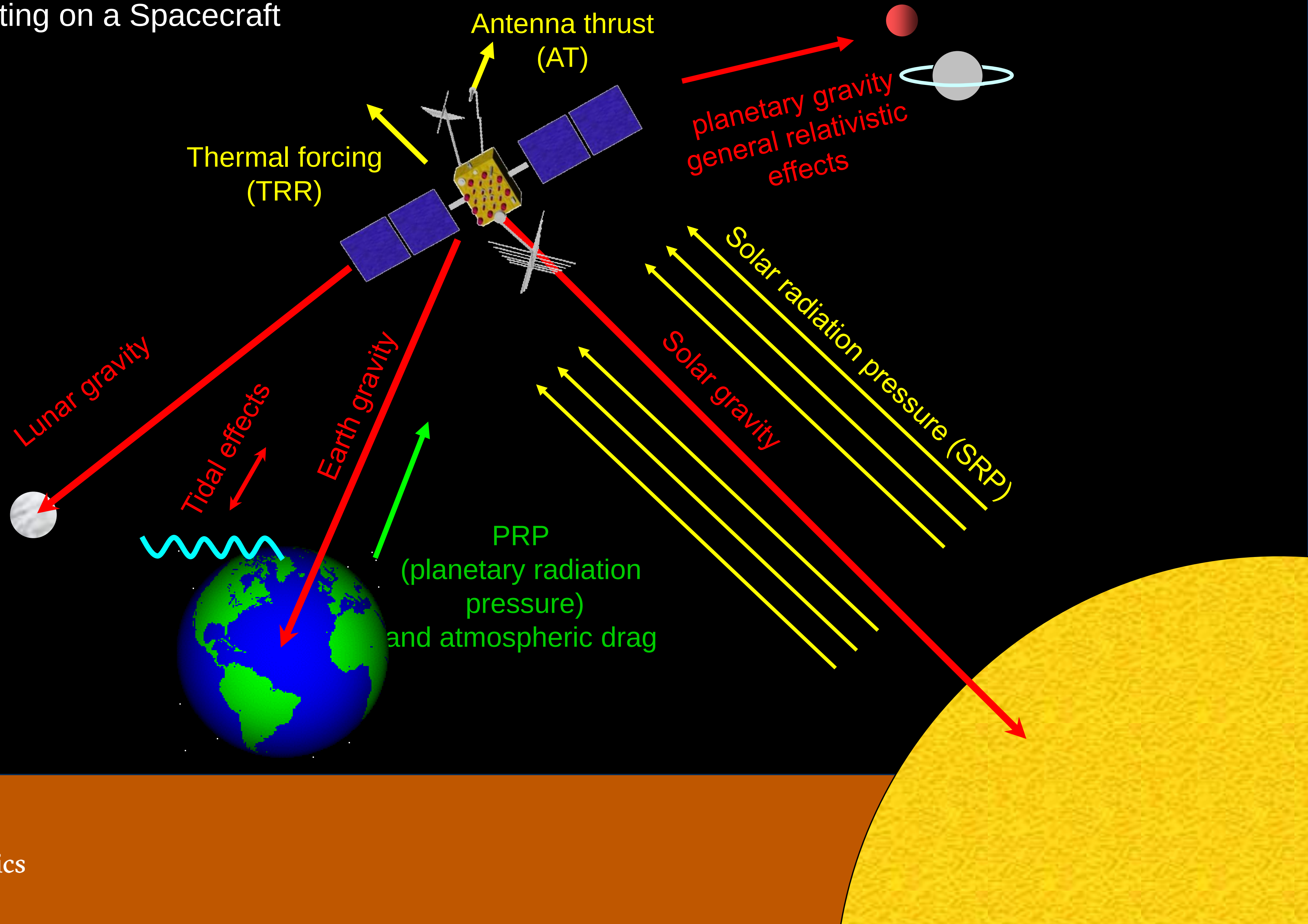
- Many of those who've contributed to the present-day problems are the only ones who have access to provide solutions

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!

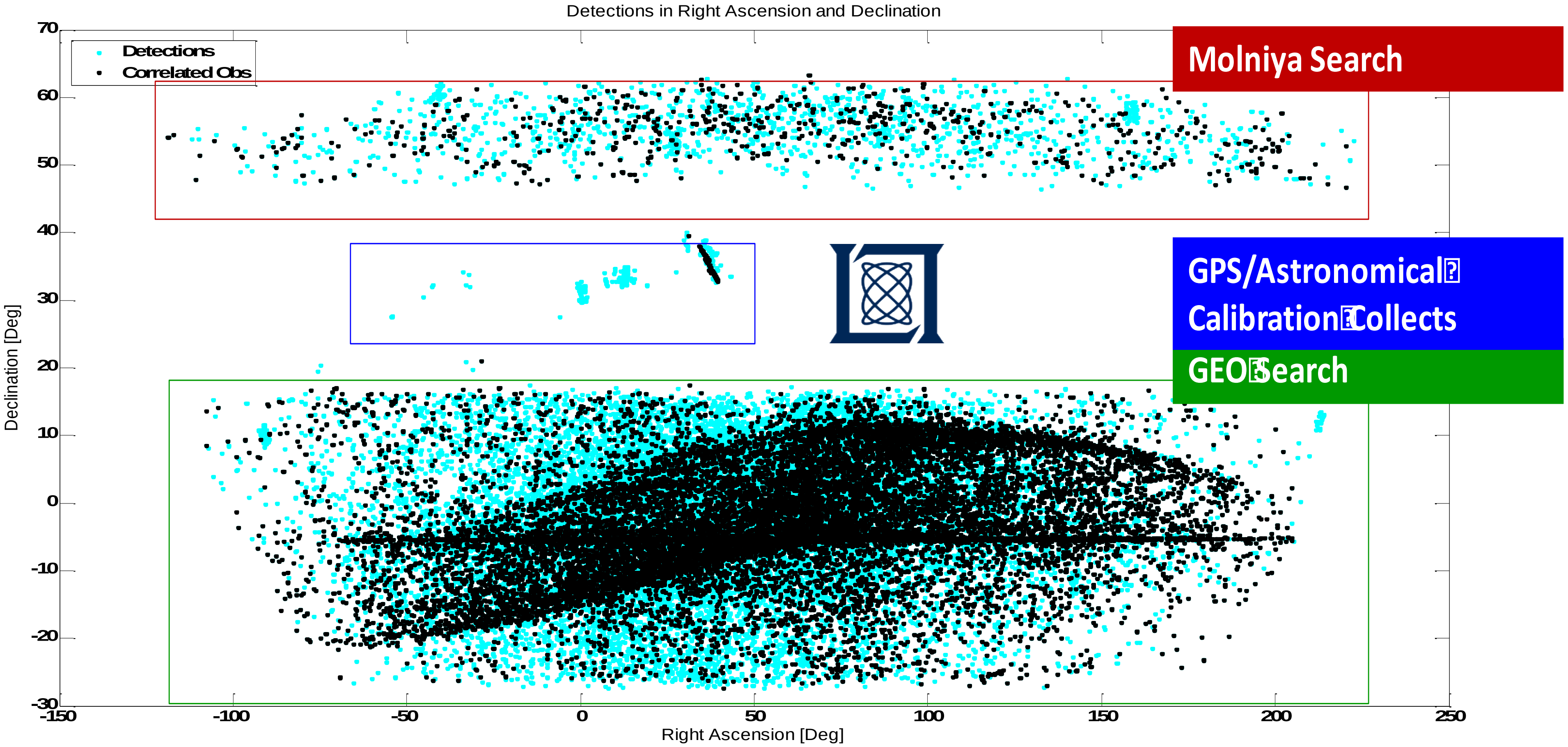
Forces acting on a Spacecraft



Understanding a Population
"Tag and Track"

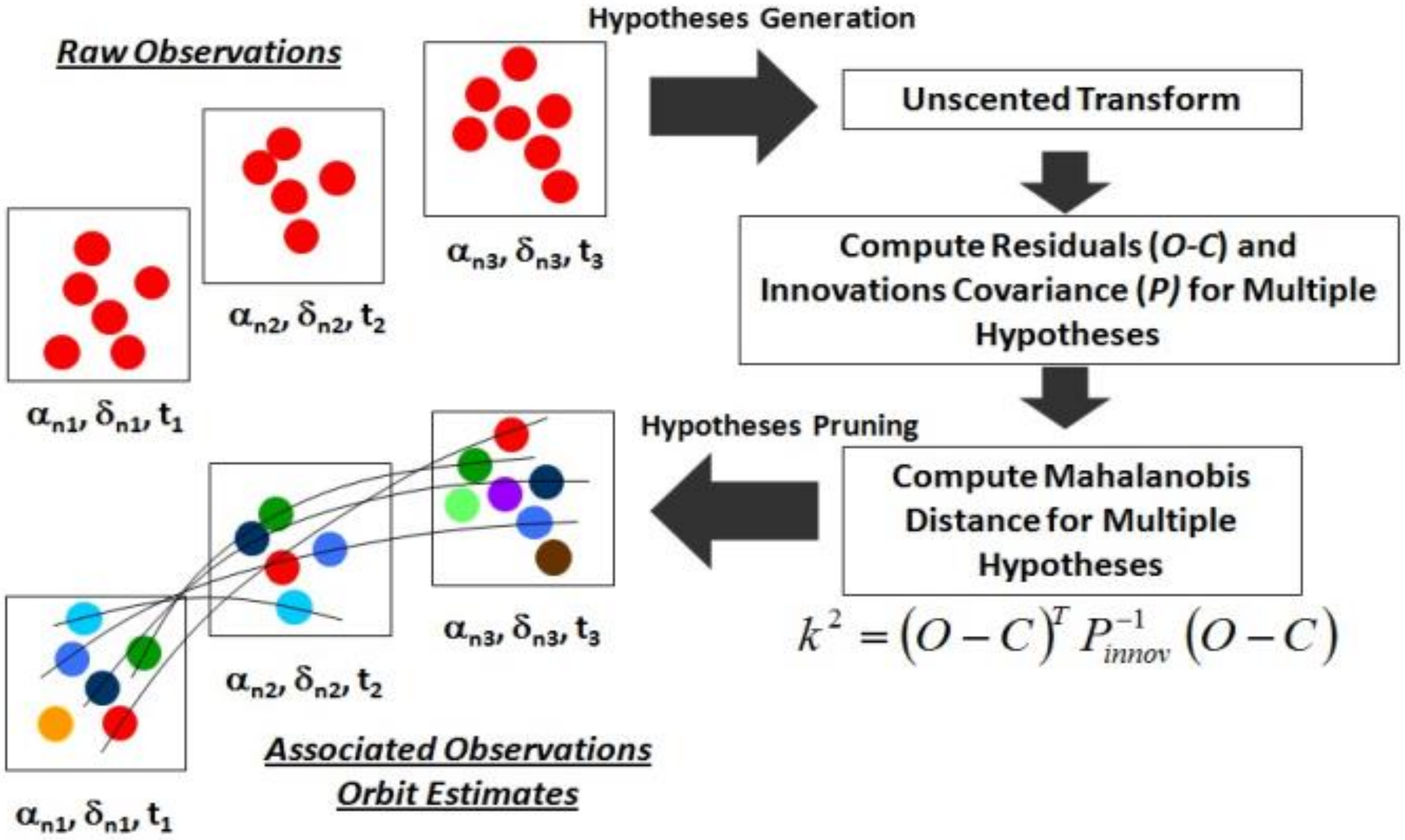
- Identify individuals of a certain species in the population
- Tag those individuals
- Formulate initial hypotheses
- Track the behavior of those individuals over time, space, and frequency and their interactions with their environment to include individuals of other species
- Test hypotheses
- Identify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

Detecting Vs Tracking



Synoptic search produces > 10k observations on 1000's of targets nightly

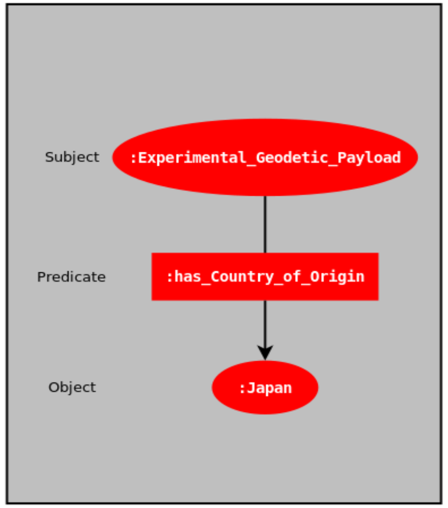
Unique Space Object Identification

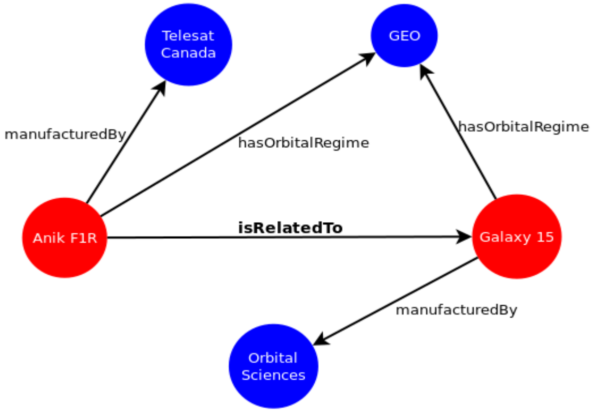


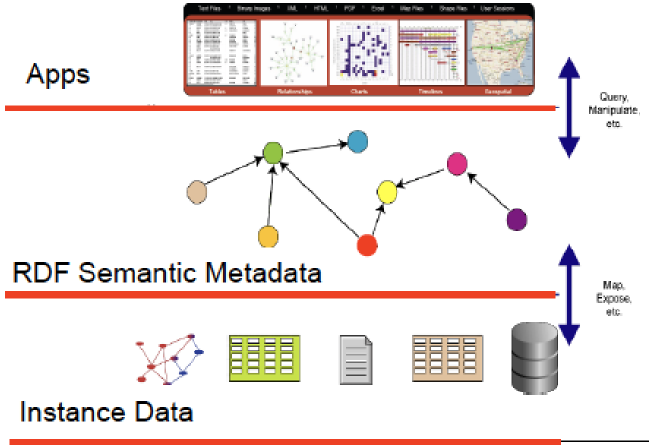
Ontologies

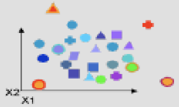
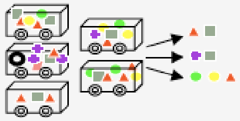
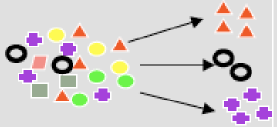
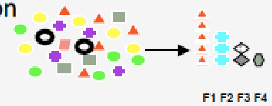

RDF Knowledge Graph
Orbital Systems Ontology
Physical Charchteristics
Material Properties
Specularities
Diffusivities
Reflectivities
Emissivities
Transmisivities
Absorptivities
Age (Gerontology)
Temperature
Size
Shape
Mass
Inertia Tensor
Kinematic
Translational
Velocity
Position
Rotational
Body Rates
Orientation
Functional Characteristics
Communicatons
GNC
Power
Payloads
Attitude Control System
Operational Characteristics
Mission/Purpose
Momentum Management CONOPS
Orbit Trimming/Stationkeeping
Safemode
Operational Modes
Owenership
Behavioral Database
Country-Specific Cultural Context
Observed Patterns
Geopolitical Climate
Space Environment Ontology
Gravitational
Point Mass
Tides
Asymmetries (Gravity Field)
Relativistic
3rd Body
Radiative
Earth Radiation
Solar Plasma
Earth Albedo
Solar Flux
Solar Wind
Geomagnetic
Magnetic Field
Charged Particle Environment
Particulates
Neutral Density
Micrometeoroid
Sensor Systems Ontology
Types
Inertial
Magnetic
Electro-Optical
Radio Frequency
Measureables
Angles
Angle Rates
RF Phase
Range
Range Rate
Resolved Imagery
Vibration
Polarization
Spectra
Flux
ElectroMagnetic Field Strength
Intensity
Instance Data
IADC Debris Guidelines
Space Treaties
Space Laws/Policies
Solar Activity?
UCS Satellite Database
WAAS Ephemerides
NOAA Weather Radar
NOAA Charged Particle Environment
Operator Specific
SpaceX
Planet Labs
Applied Defense Solutions
LeoLabs
Zodiac
Seradata
RF: Radar
RF: TDOA/FDOA
RSO Database
Electro-Optical: Angles
Orbital System Models
Ephemerides
Twitter Feeds

Data Engineering, Modeling, Science, and Analytics





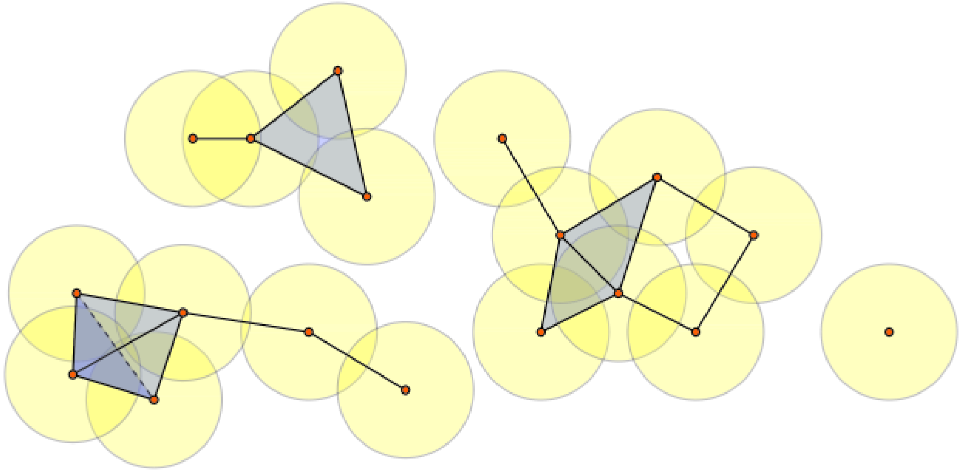


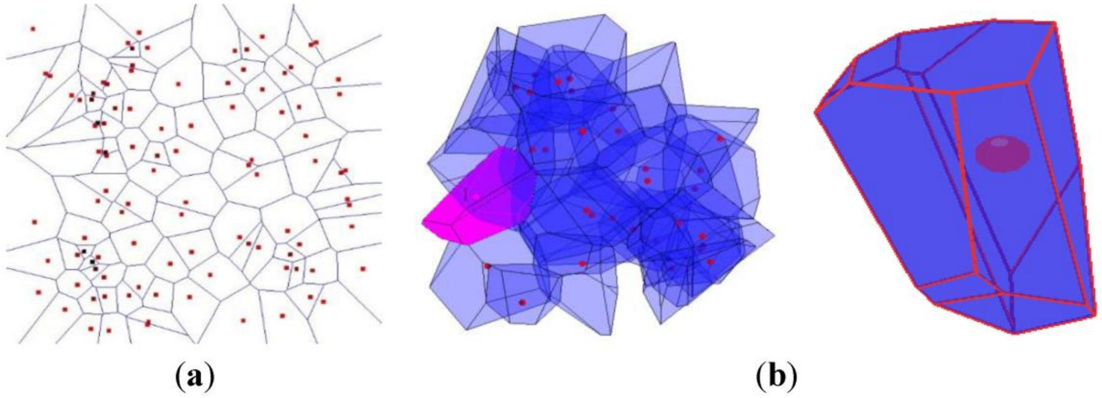
Problem Classification	Sample Problem
Anomaly Detection 	Given demographic data about a set of customers, identify customer purchasing behavior that is significantly different from the norm
Association Rules 	Find the items that tend to be purchased together and specify their relationship – market basket analysis
Clustering 	Segment demographic data into clusters and rank the probability that an individual will belong to a given cluster
Feature Extraction 	Given demographic data about a set of customers, group the attributes into general characteristics of the customers

Images from Oracle

From Data to Discovery: Patterns in the Graph

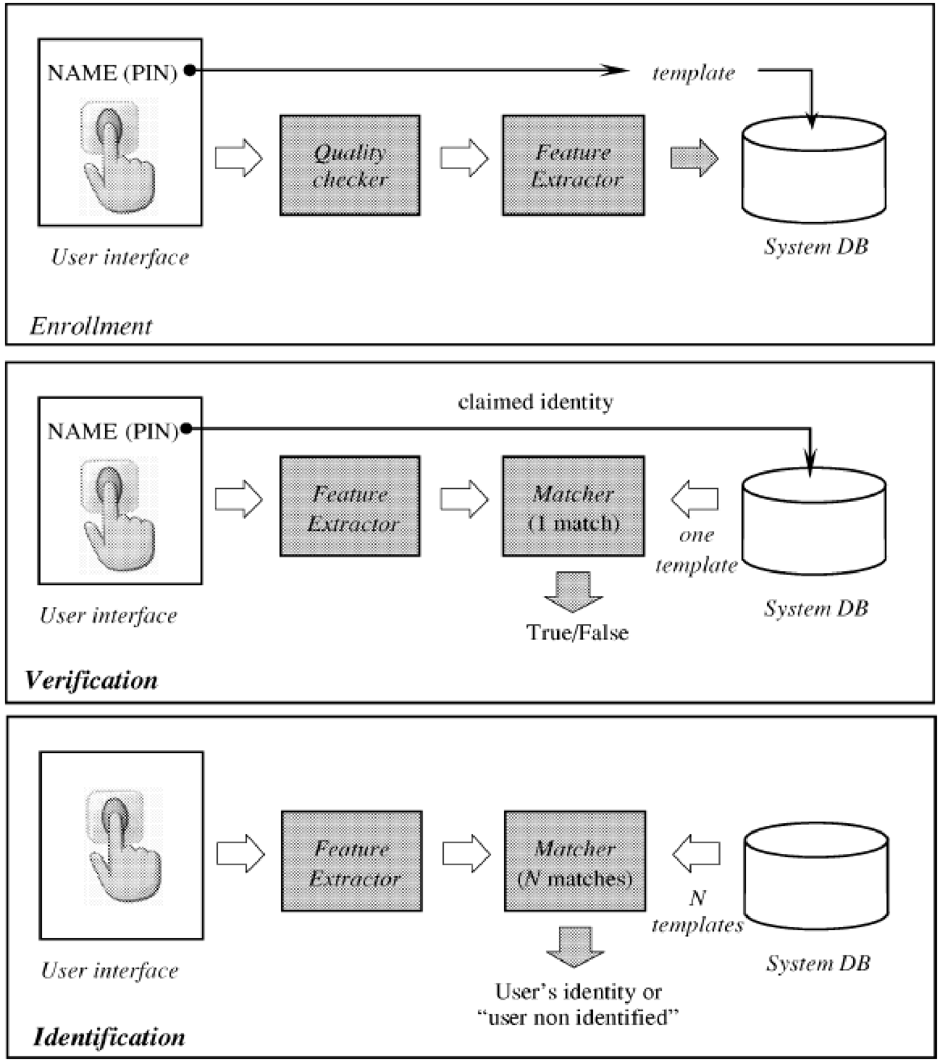
- Discovering ”Latent Knowledge”
- Our framework facilitates multi-source information curation and analytics to identify correlations
  - One must ask the right question (make the correct query)
- Find which correlations have causal relationships
- Link these data (e.g. Vietoris-Rips Complex, Voronoi Clustering)





Example of Hot Science and Cool Result from Our ASTRIA Research!

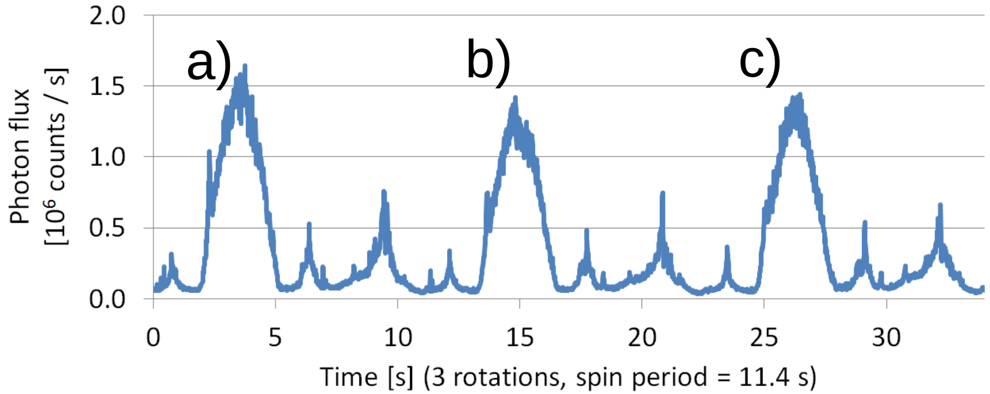
Biometrically-Inspired Space Object Recognition (BISOR)



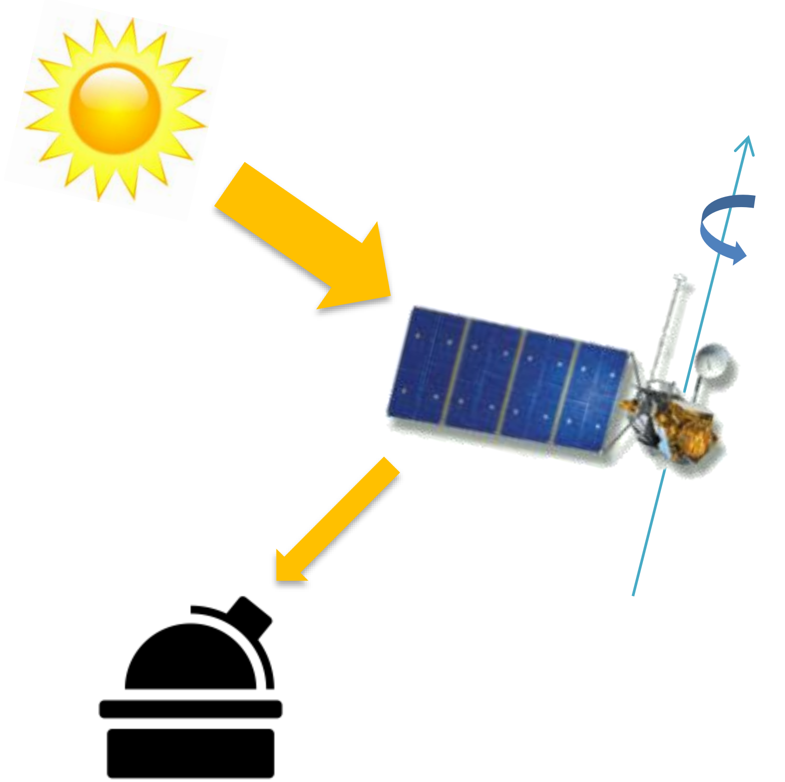
An Introduction to Biometric Recognition
Anil K. Jain, *Fellow, IEEE*, Arun Ross, *Member, IEEE*, and Salil Prabhakar, *Member, IEEE*

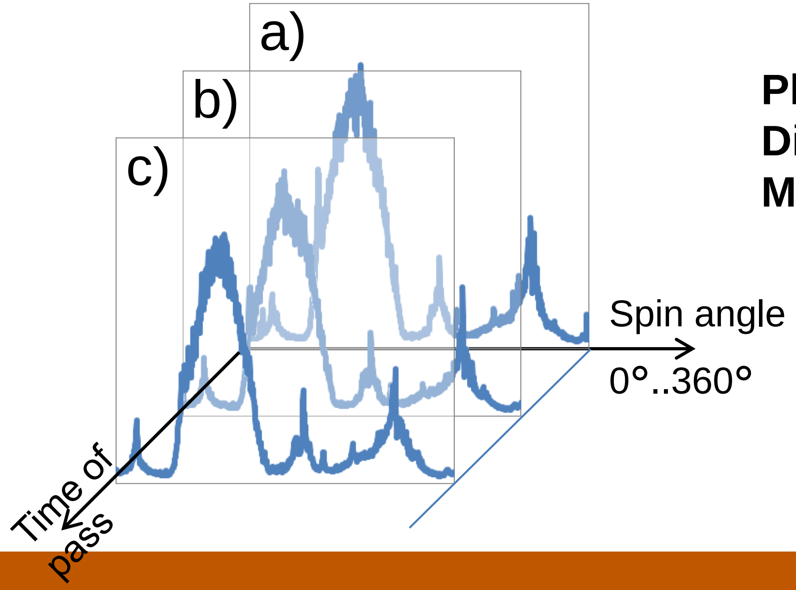
Satellite spin measurement

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



Spinning TOPEX/Poseidon light curve





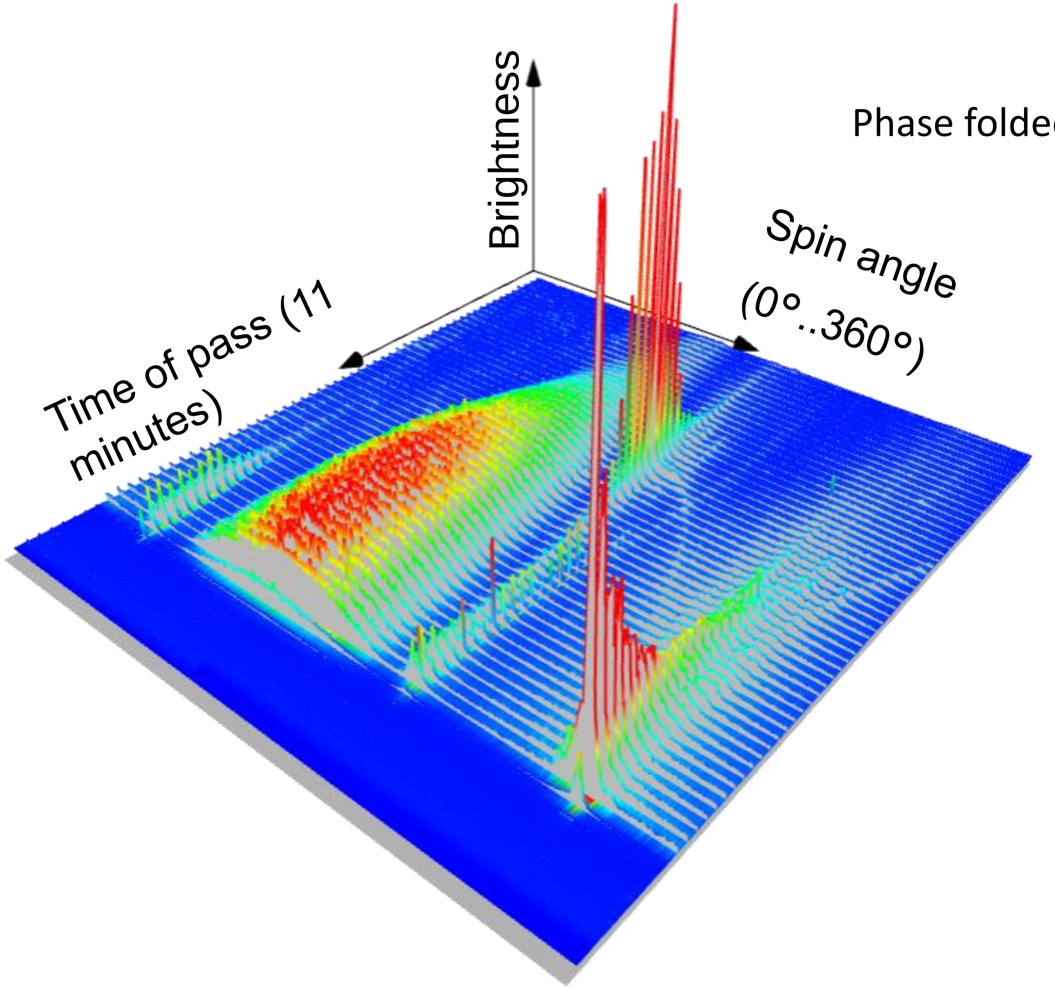
Phase
Dispersion
Minimization

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

TOPEX/Poseidon. Author: D. Ducros

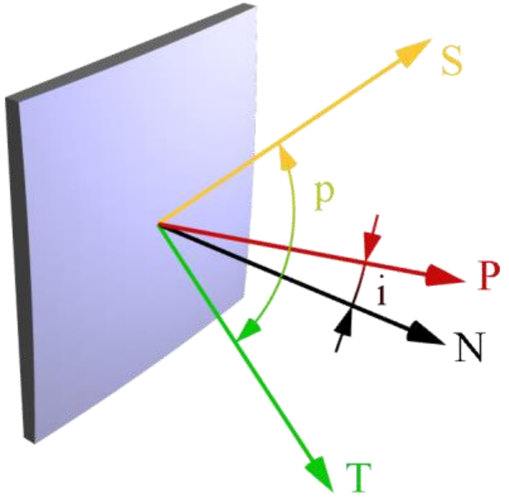


Phase folded light curve

Satellite spin measurement

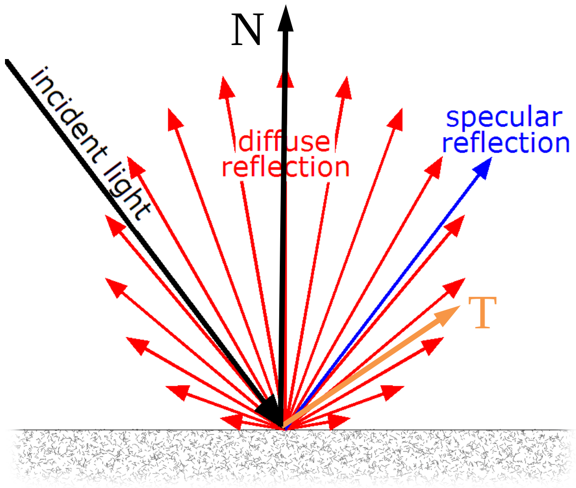
Specular and diffuse reflections form geometrical patterns

Specular reflection



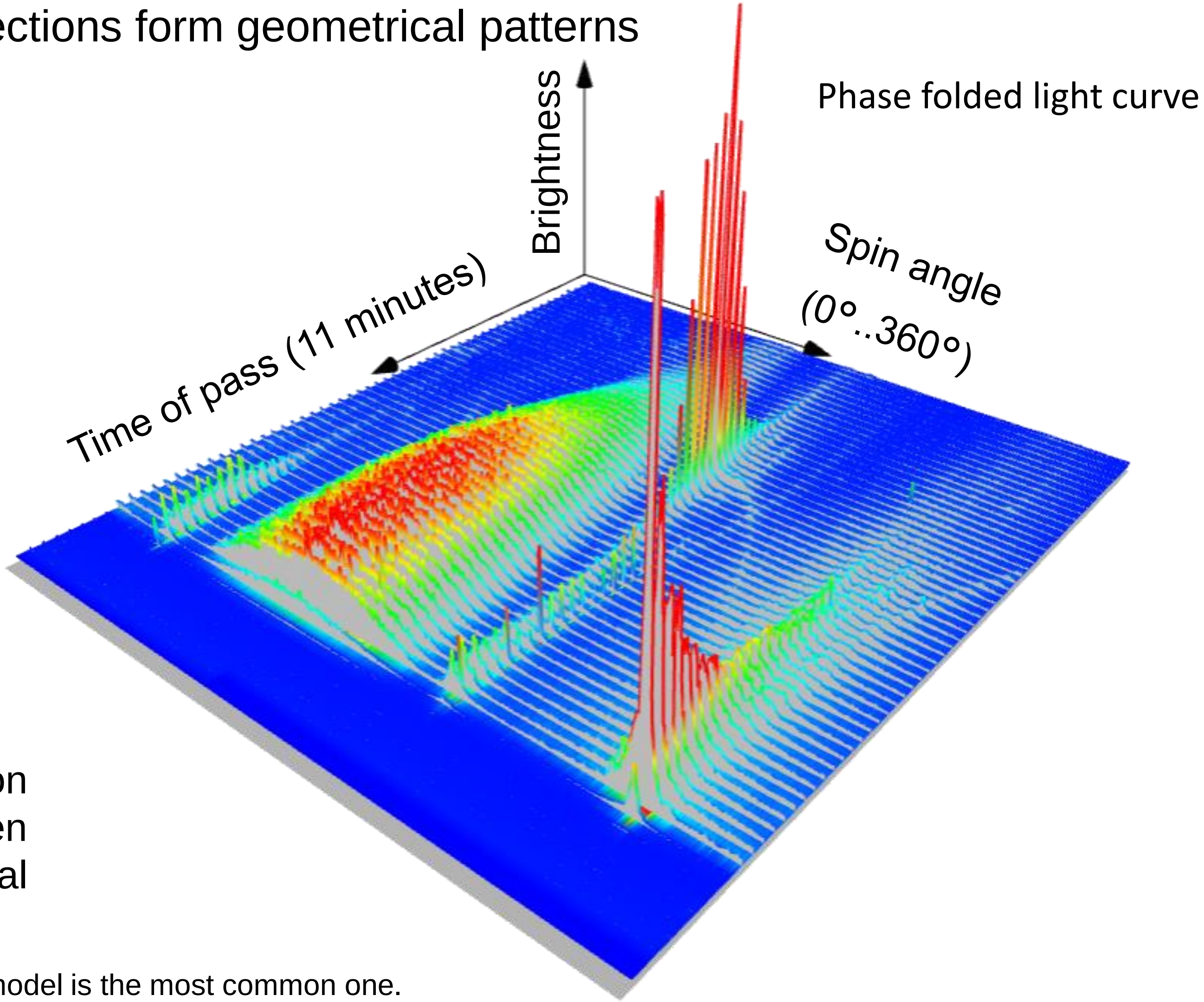
S: sun
T: telescope
P: phase vector = S + T
p: phase angle
i: inclination angle (<0.25°)

Diffuse reflection



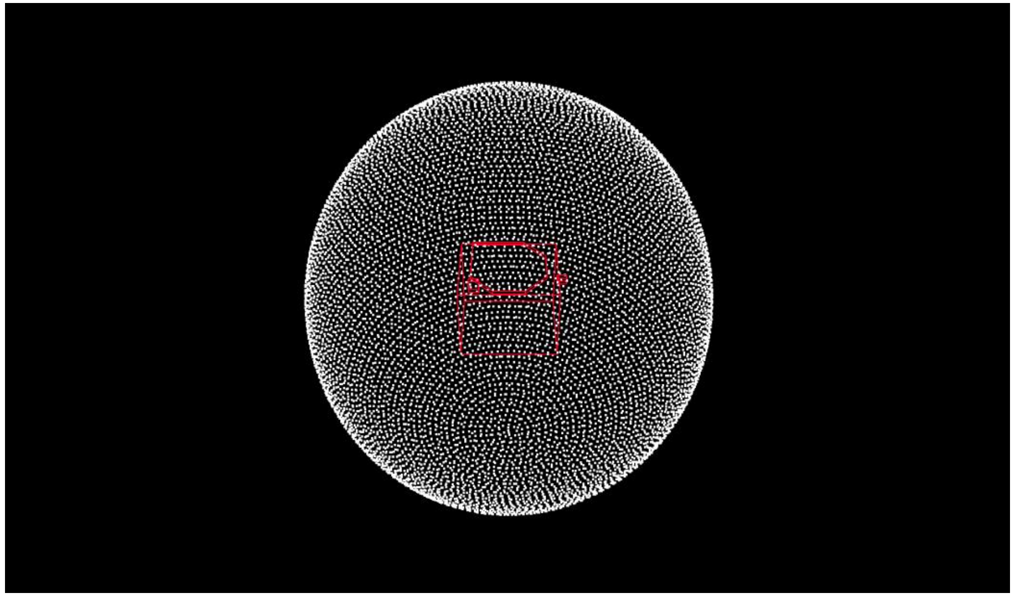
BRDF Lambertian model

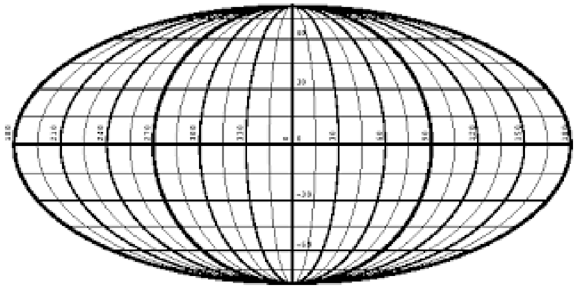
The intensity of diffuse reflection depends on the angles between Sun, Telescope and the Normal vectors.



BRDF: bidirectional reflectance distribution function; Lambertian model is the most common one.

Space Object Centered Celestial Sphere and Mollweide Projection

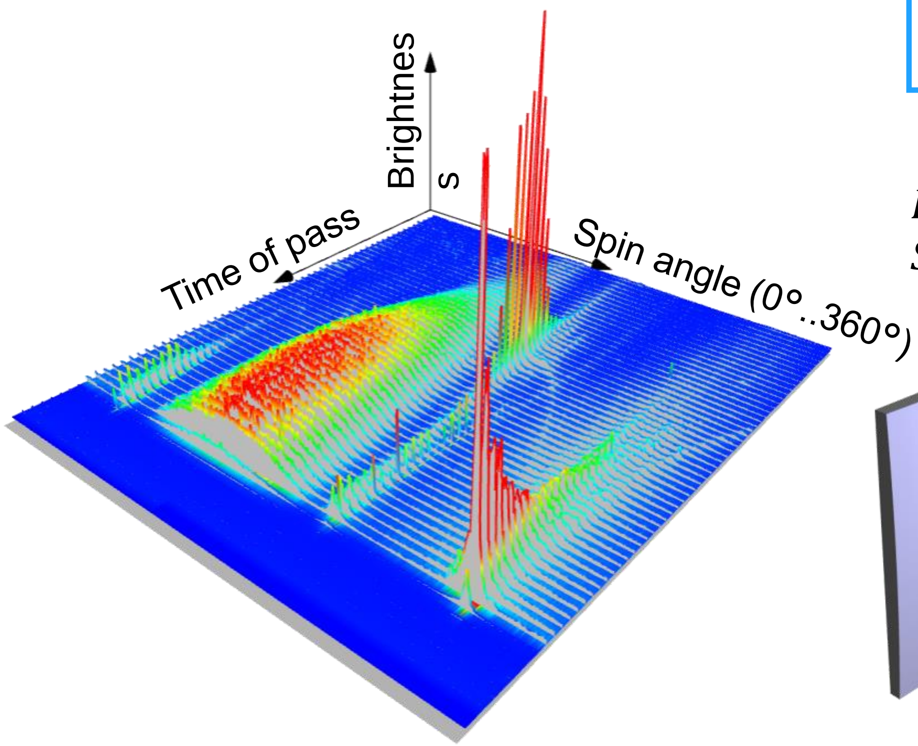




Hyper-temporal photometry

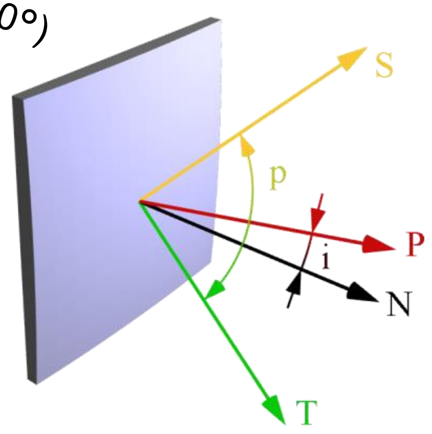
HTP generates detailed reflectivity maps by projecting satellite brightness measurements onto a phase vector expressed in the body fixed coordinate system.

Time dependent pattern
(depends on the view angle)

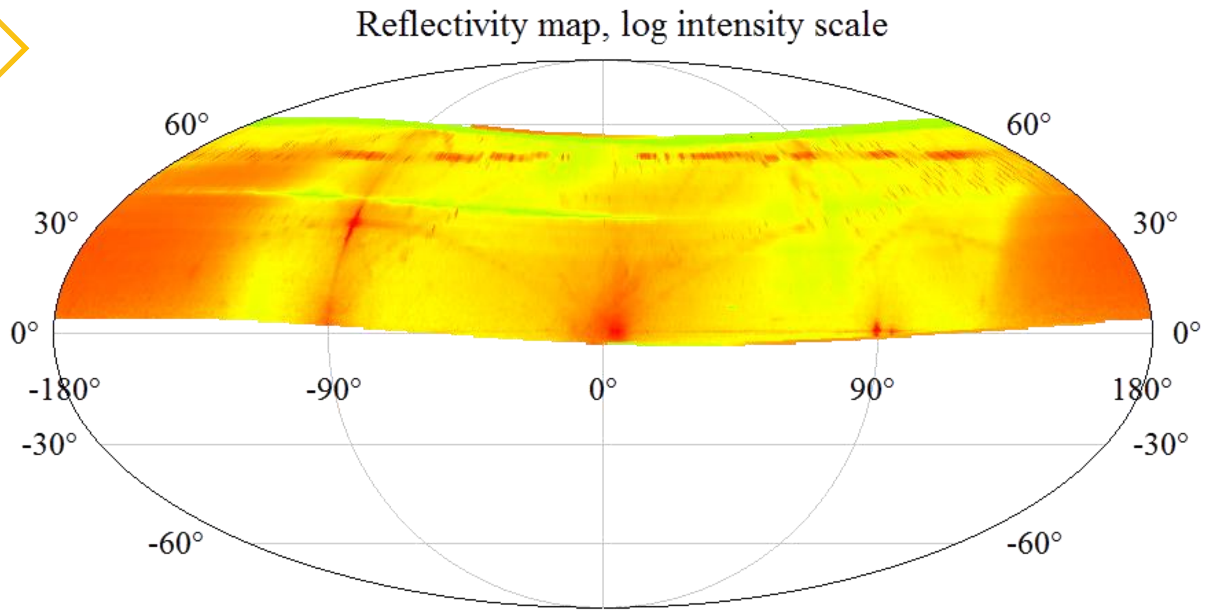


$$\boldsymbol{P}_{Body} = \boldsymbol{S}\,\boldsymbol{P}_{Inertial}$$

P: phase vector
S: transformation m.



Time independent pattern
(fixed with the satellite body)

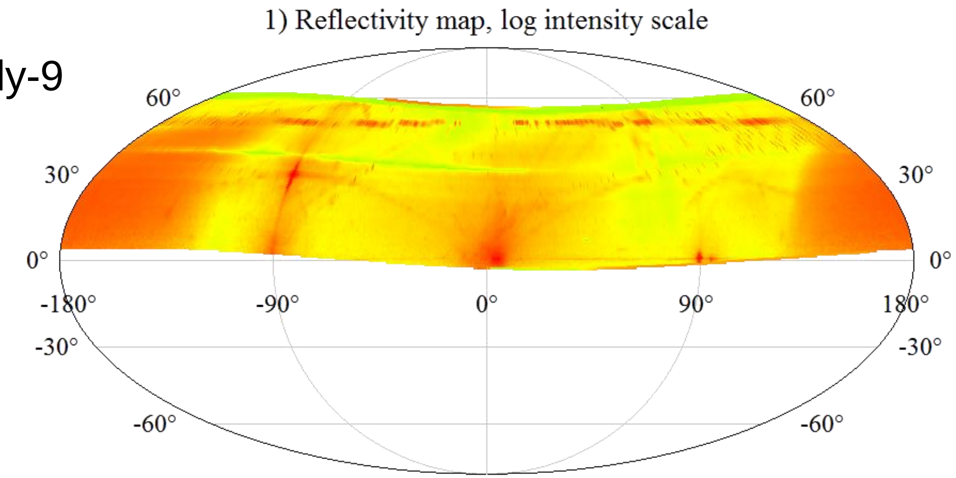


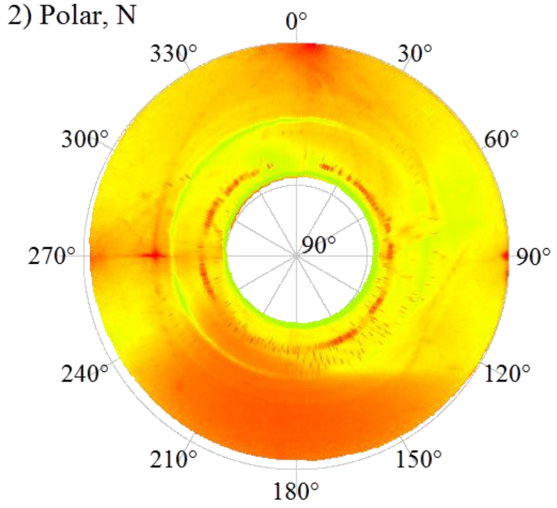
The specular reflection occurs when the phase vector and surface normal coincide, thus the location of the specular reflections in the Body frame is fixed (assuming rigid body).

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

2015-July-9





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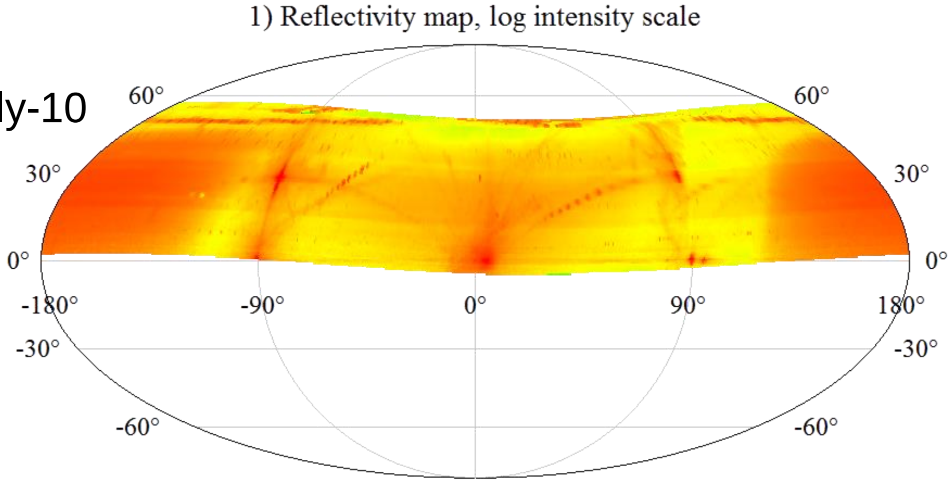

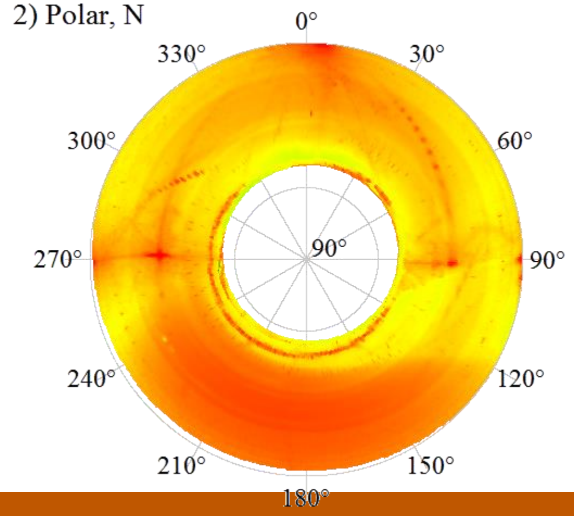

Unsolved Challenges

- 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.

UT Austin: Hogwarts for Space!

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?

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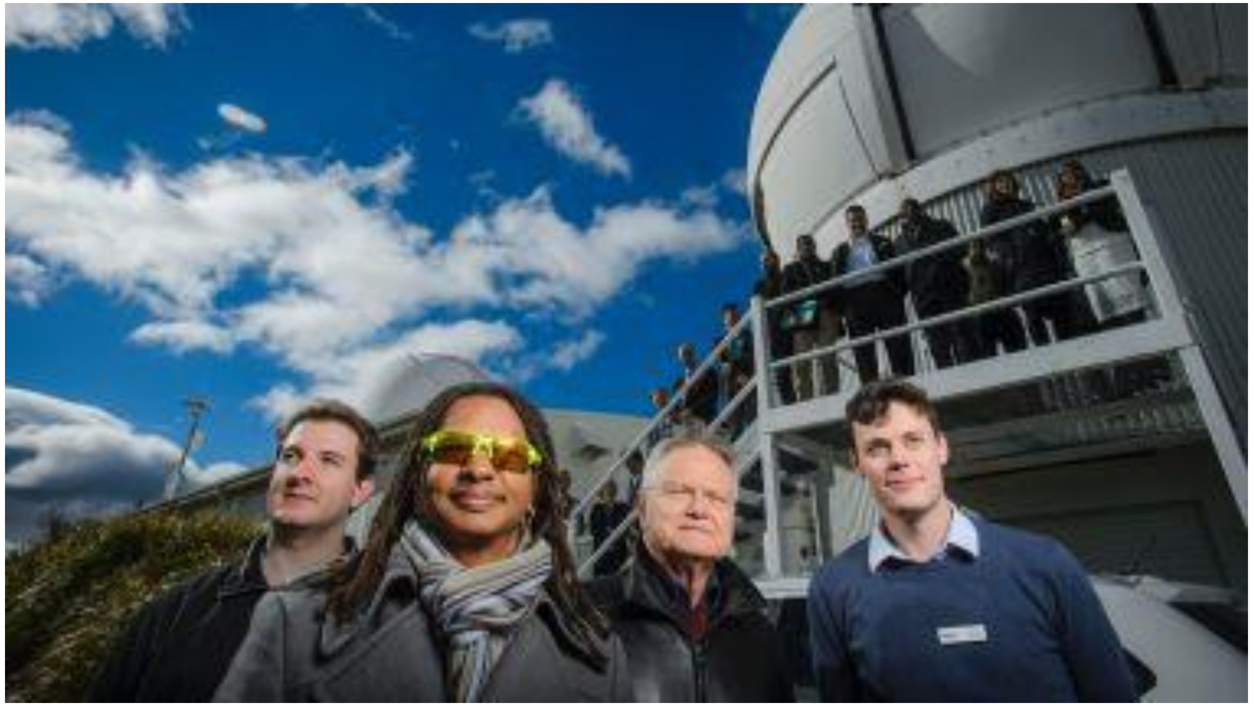

Who Cares?

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

The University of Texas at Austin
Aerospace Engineering and Engineering Mechanics
Cockrell School of Engineering