# About Me

- College: United States Air Force Academy
- Major: Mathematics
- Hometown: Austin, TX
- Hobbies: Skiing, gliding, soccer
- Interesting Fact: I have been on HGTV

# Architecting with Information Theory

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# Motivation/Scope

- Traditionally, new architectures are developed considering a single intelligence type
  - Performance modeling specific to an ‘INT’ (GEOINT, SIGINT, etc.)
  - New architectures are not assessed within a multi-INT enterprise
- Measuring the value of each ‘INT’ type within an enterprise is difficult
  - No standardized metrics across ‘INTs’
  - Lack of common value metrics leads to stovepiped/traditional designs
- Information Theory provides metrics agnostic to ‘INT’ type
  - Information value of a sensing agent measured in Shannon Bits
  - Shannon Bit can be compared across various sensing agents
  - More bits are better
  - Implemented Harney information equations, a reformulation of Johnson’s criteria which was built on Shannon’s seminal work on information theory (see Works Cited chart for reference)

# Problem Formulation

## Problem Statement

- Design a LEO architecture to maximize the amount of information, in terms of access and resolution, that can be collected against a Somali Pirate Scenario.

## Objectives

- Maximize Probability of Access to each event in the scenario
- Maximize total amount of information bits collected on the scenario
- Minimize number of satellites
- Minimize altitude of satellites
- Maximize number of sensors

## Decision Variables

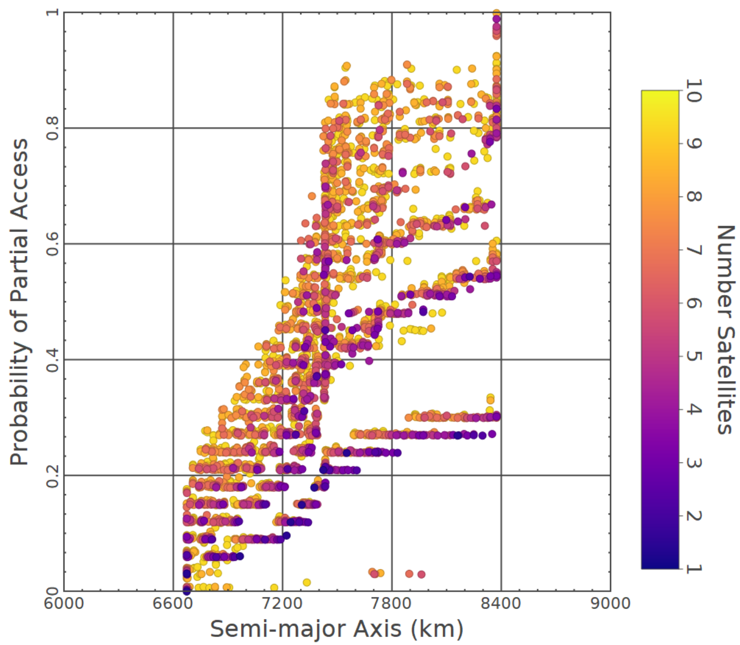
- Number of satellites (1-10)
- Circular LEO orbit parameters (SMA, INC, RAAN, MA)*
- Sensor type for each satellite (informed by list of commercial sensors)

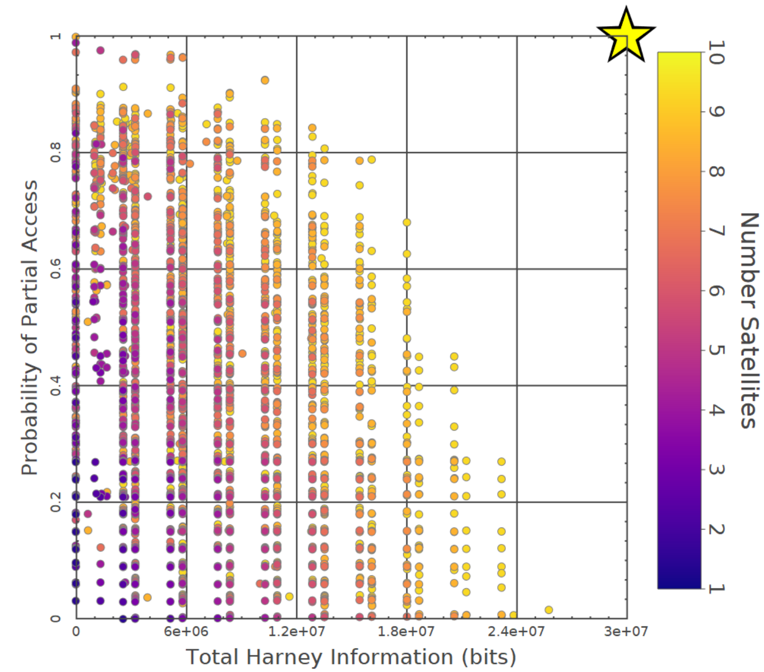
*SMA – Semi-Major Axis; INC – Inclination; RAAN – Right Ascension of Ascending Node; MA – Mean Anomaly

## Parameters/Constraints

- Somali Pirate Scenario
  - Defines number of entities, locations, velocities, and activity state
  - Currently generated as a deterministic scenario
  - In the future (TBD) will randomly generate with repeatable random seed

# Preliminary Results: GRIPS




- Validation of expected trends
  - Access Metrics vs. Constellation Semi-major Axes
  - Access Metrics vs. Number of Satellites
- New Results
  - Information Metric vs. Probability of Access

# Preliminary Results

**DiscoveryDV**

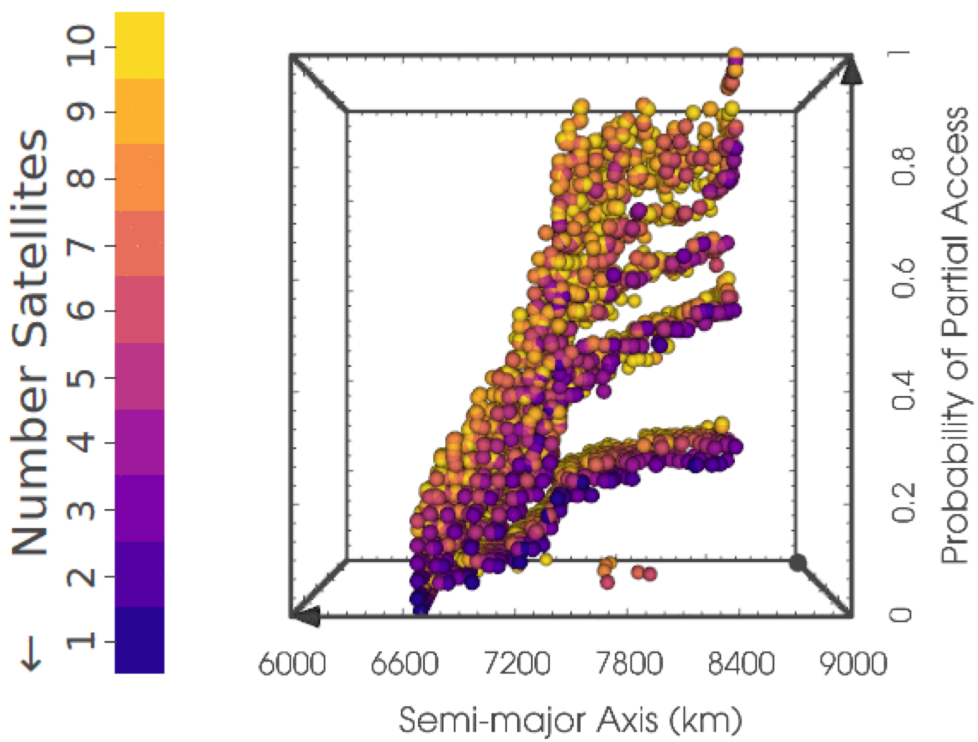
- **Quick insights and understanding of the data through high-dimensional plotting tool**

**Information and Number of Satellites**

- **The third axis and color mapping clarify the tradeoff between these two objectives**

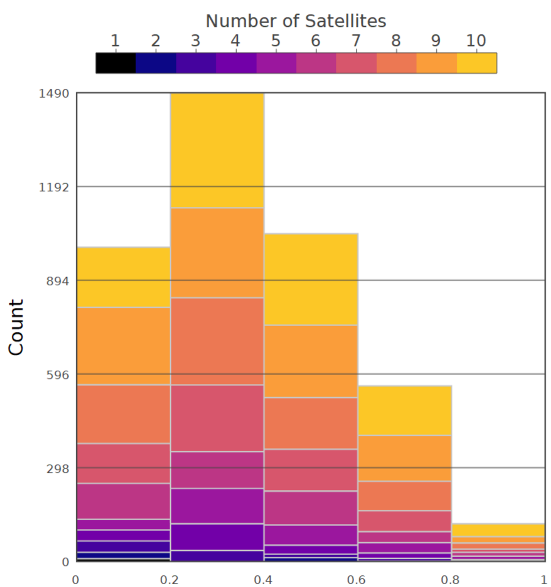
**Information and Access**

- **The cascade of the data along information highlights this trend**

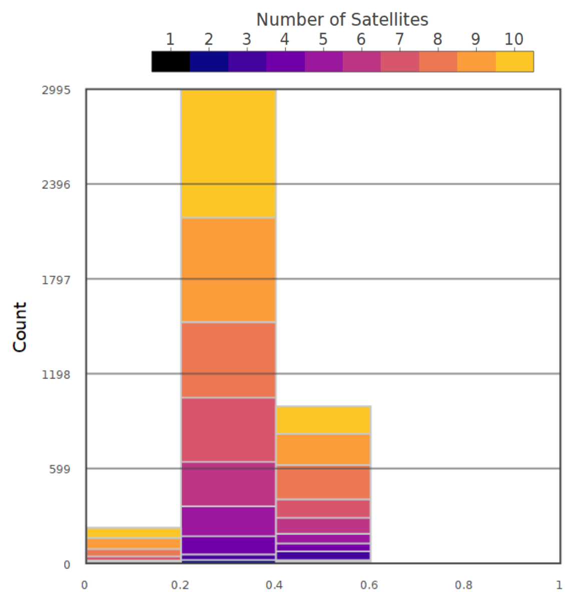


# Preliminary Results: GRIPS

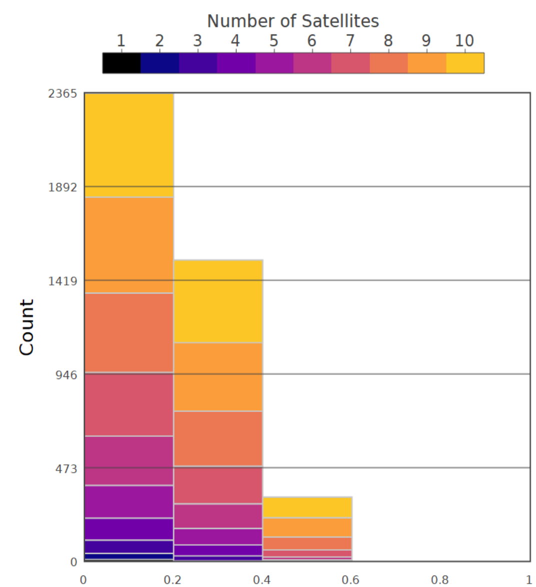
## Information Mapping




Spatial




Spectral




Temporal

This mapping creates a better understanding of the solutions

# Key Takeaways

- The model is performing as expected
  - Objectives (altitude, information, access, and unique sensors) are providing feasible solutions
  - Improved Access Metric Formulation
- There is a tradeoff between Information and Probability of Access
  - Conventional approaches miss solutions
  - Integrated constellations need more than an access metric
- Future models need to better account for the different information types

# Future Steps

- Project
  - Address bias towards spatial data
    - Resulting architecture designs should balance spatial, spectral, and temporal information gain
  - Expand ground truth scenario
    - Different locations
    - Different scenario types
  - Address real life complexities
    - Staleness of information
    - Not all information is equal
    - A refined metric for cost of sensors
- For me
  - Back to Academy
  - Gliding Instructor Pilot
  - Singapore
  - Hopefully Graduate School

# Works Cited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- August, Peter, and Y. Q. Wang. "Resolutions of Remote Sensing." University of Rhode Island, 2009.
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- L. Roux and J. Desachy, "Information fusion for supervised classification in a satellite image," *Proceedings of 1995 IEEE International Conference on Fuzzy Systems.*, Yokohama, Japan, 1995, pp. 1119-1124 vol.3. doi: 10.1109/FUZZY.1995.409823
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# BACKUP

# Ground Truth Scenario

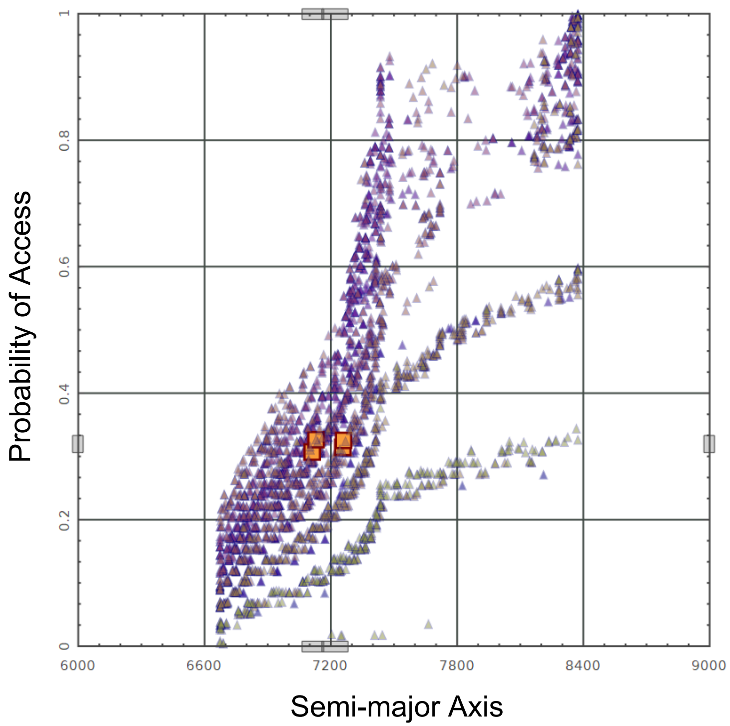
- **Purpose: Create a test ground problem for creating optimal satellite constellation designs**
  - **Test problem simulates piracy of commercial merchant ships off the coast of Somalia, well studied in open literature***
- **Pirate model:**
  - **Merchant ships with a set of observable characteristics (i.e., length, color, AIS) travel along a known path**
  - **Pirate ships with a set of observable characteristics (i.e., length, color) may ambush merchant ships along path**
  - **Scenarios generated with Finite State Machines**
- **Given specific scenario(s), apply GRIPS to design an architecture to maximize information bits and maximize probability of access**
  - **Decision Variables:**
    - **Sensor on each vehicle**
    - **LEO orbit parameters**
  - **Objectives:**
    - **Probability of Access of an Event (max)**
    - **Information Collected (max)**

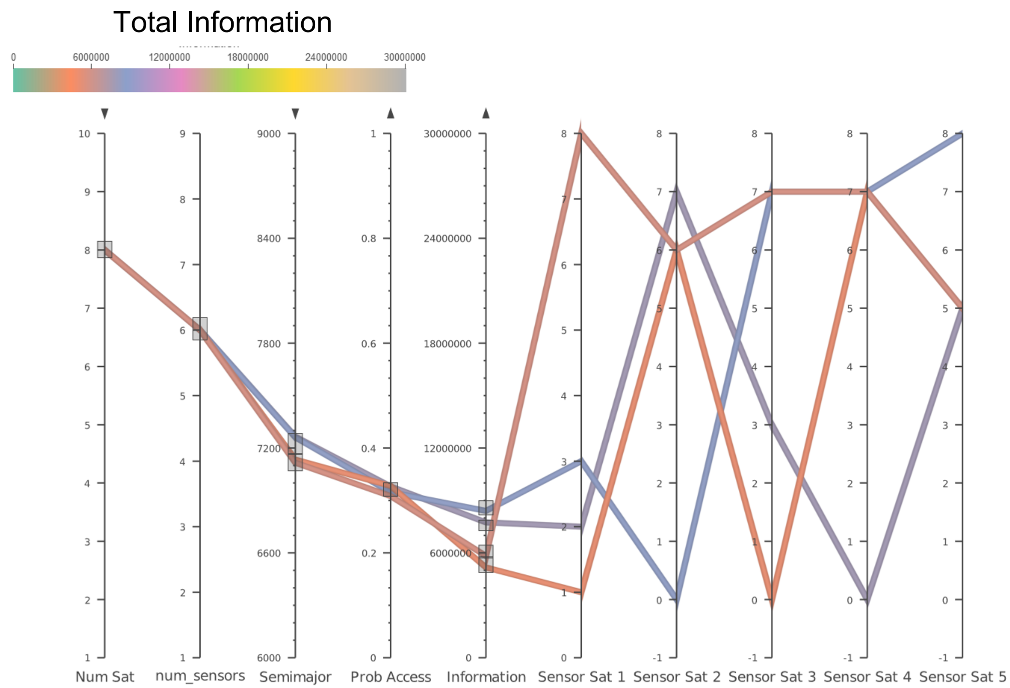
* Jakob, Michal, et. al. *Adversarial modeling and reasoning in the maritime domain year 1 report.* Technical report, ATG, CTU, Prague, 2009.
Jakob, Michal, et. al. *Adversarial modeling and reasoning in the maritime domain year 2 report.* Technical report, ATG, CTU, Prague, 2010.

# Preliminary Results: Sensor Data

| Sensor | Information Content | Column3 | Column4 | Column5 | Column6 | Column7 | SNR | Model |
|---|---|---|---|---|---|---|---|---|
| VNIR - ASTER - Terra | Intensity | angle | | | | | 175 | H_i |
| SWIR - ASTER - Terra | Intensity | angle-angle | | | | | 200 | H_i |
| TIR - ASTER - Terra | Intensity | angle-angle | | | | | (NE delta T) < .3K for bands with design goal of <.2 K | H_i |
| CERES - Terra | Intensity | angle-angle | | | | | >500 | H_i |
| MISR - Terra | Intensity | angle-angl | Color | | | | >900 | H_i+H_h |
| MODIS - Terra | Intensity | angle- angle | | | | | 100-900 | H_i+H_h |
| MOPITT | | | | | | | <1000 | |
| AIRS - AQUA | Intensity | angle | | | | | (ratio at albedo of 0.4) > 100 | H_i |
| AMSU - AQUA | Intensity | angle | | | | | | |
| HSB-AQUA | Intensity | Angle | | | | | | |
| AMSR-E - AQUA | Intensity | Angle-Angle | | | | | | |
| CERES - AQUA | Intensity | Angle | | | | | >500 | |
| HIRDLS - Aura | Intensity | Angle | | | | | | |
| MLS - Aura | Intensity | Anglee | | | | | | |
| OMI - Aura | Intensity | Angle | | | | | | |
| TES - Aura | Intensity | Angle | | | | | 600 | |
| ETM+ Landsat 7 | Intensity | Angle | | | | | 16-39 | |
| SeaWinds - QuikScat | Intensity | Angle | | | | | | |
| ACRIM3 - ACRIMSAT | Intensity | | | | | | | |
| Poseidon-2 - Sage III M3M | Intensity | Angle | Altitude | | | | | |
| JMR - Sage III M3M | | | | | | | | |
| DORIS - Sage III M3M | | | | | | | | |
| TRSR - Sage III M3M | | | | | | | | |
| LRA - Sage III M3M | Intensity | Altimeter | Gravity | | | | | |

# Preliminary Results: Sensor Profiles



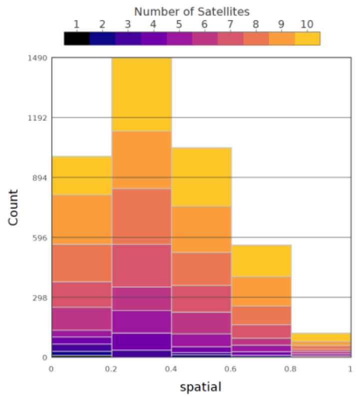



# Preliminary Results: Sensor Data

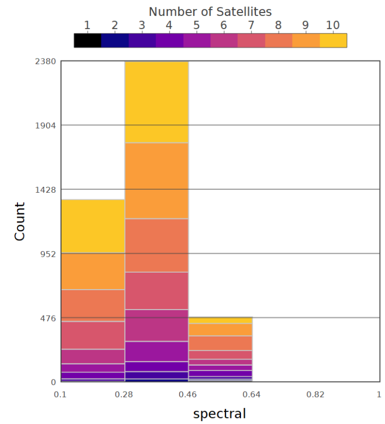
| Mission | Agency | Status | Launch date | EOL date | Applications | Instruments | Orbit details & URL |
|---|---|---|---|---|---|---|---|
| 3D Winds<br><br>Three Dimensional Tropospheric Winds from Space Based Lidar | NASA | Considered | 2030 | 2033 | Phase-3 DS Mission, launch order unknown, 3-year nominal mission. Tropospheric winds for weather forecasting and pollution transport. | HDWL (3D Winds) | Type: Sun-synchronous<br><br>Altitude: 400 km<br><br>Period:<br>Inclination: 97.03 deg<br>Repeat cycle: 12 days<br>LST: 6:00<br>Longitude (if geo):<br>Asc/desc: Ascending<br>Links: mission site |
| ACE<br><br>Aerosol Clouds and Ecosystem Mission | NASA | Considered | 2022 | 2023 | Phase-2 DS Mission, launch order unknown, 3-year nominal mission. Aerosol and cloud profiles for climate and water cycle; ocean colour for open ocean biogeochemistry. | Cloud Radar, Lidar, Multi-band UV/VIS Spectrometer (ACE), Next Gen APS (ACE), OCI | Type: Sun-synchronous<br><br>Altitude: 650 km<br><br>Period:<br>Inclination: 98.2 deg<br>Repeat cycle:<br>LST: 13:00<br>Longitude (if geo):<br>Asc/desc: Ascending<br>Links: mission site |
| ACRIMSAT<br><br>Active Cavity Radiometer Irradiance Monitor | NASA | Mission complete | 20-Dec-99 | 14-Dec-13 | 5-year nominal mission life, currently being decommissioned due to age-related degradation of batteries. Operational mission will end in 2014. | ACRIM III | Type: Sun-synchronous<br><br>Altitude: 600 km<br><br>Period: 98.5 mins<br>Inclination: 97.81 deg<br>Repeat cycle: 1 day<br>LST: 18:00<br>Longitude (if geo):<br>Asc/desc: Descending<br>Links: mission site \| data access |

# Binning Equations

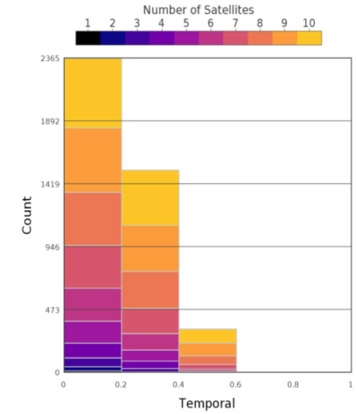
$$\frac{\sum_{Constellation} \frac{BestResolution(Constellation)}{SpatialResolution(satellite_i)}}{(NumSats)}$$



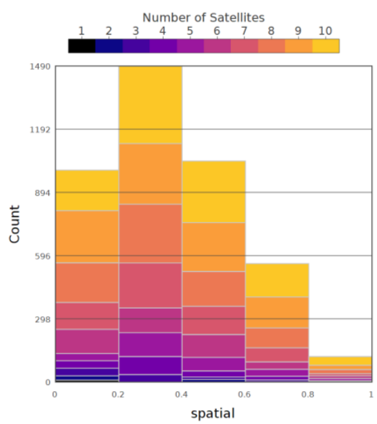

$$\frac{\sum_{Constellation} \frac{Bandwidth(satellite_i)}{LargestBandwidth(Constellation)} + \frac{NumBands(satellite_i)}{MaxNumBands(Constellation)} + \frac{SNR(satellite_i)}{BestSNR(Constellation)}}{3(NumSats)}$$



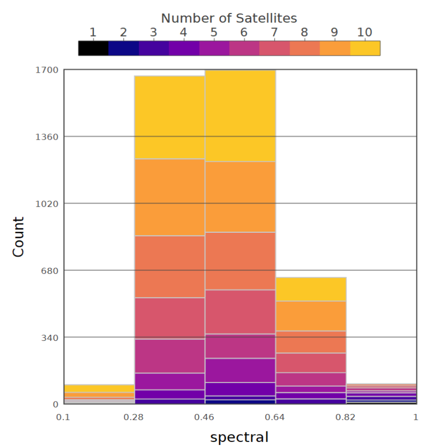

$$\frac{|\sum_{Constellation} \frac{VelocityRes(satellite_i)}{LargestVelocityRes(Constellation)}| + P(PartialAccess)}{2(NumSats)}$$



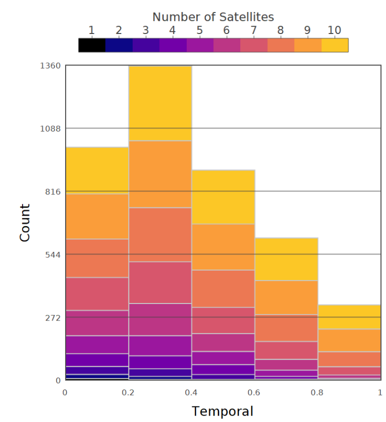

$$\frac{\sum_{Constellation} \frac{BestResolution(Constellation)}{SpatialResolution(satellite_i)}}{(NumSats)}$$




$$\frac{\sum_{Constellation} + \frac{NumBands(satellite_i)}{MaxNumBands(Constellation)} + \frac{SNR(satellite_i)}{BestSNR(Constellation)}}{2*(NumSats)}$$




$$P(PartialAccess)$$



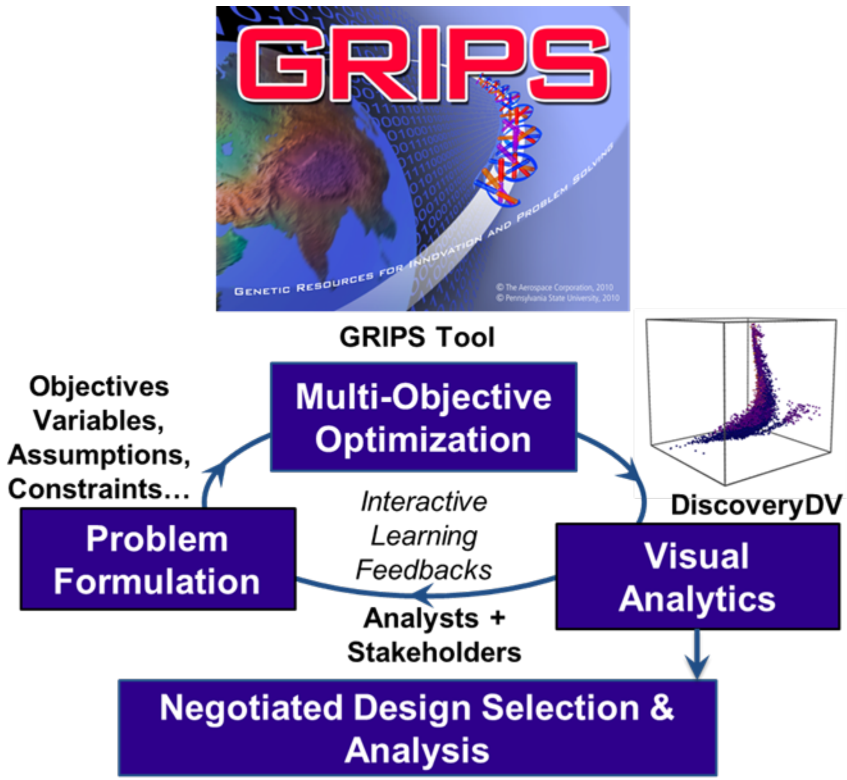
# What is GRIPS?

### The Tool: Searches for Optimal Solutions to a Problem

- Many-objective optimizer
- Parallelized computation
- Ingests a variety of models

### The Process: Searches for Optimal Problem Expressions

- Structured, iterative process
- Acknowledges many stakeholders, many objectives
- Stakeholders learn about their decision space
- Help decision makers arrive at consensus



# Performance Modeling

- Two basic aspects of any intelligence question are:
  - What is the probability of gaining access to a target? – Right place, right time
  - What is the probability of resolving characteristics about a target? – Right sensor, right target
- Probability of Access can be defined by:
  - An event duration
  - Access/gaps to event location
- Probability of Resolving can be defined by information theory:
  - Robert Harney* defined the information collected by a sensor across information types:
    - Intensity, color, range, velocity, RF, etc.
  - For a given sensor, the function defining its information collection is a summation of these types.
- GRIPS (Genetic Resources for Innovation and Problem Solving)
  - An Aerospace Corporation tool
  - Used to design satellite architectures with diverse sensing types to simultaneously optimize probability of access and probability of resolving in terms of information theoretic metrics
  - Estimates the potential information that could be gathered by various numbers of satellites in different orbits, given ground scenarios

*Howerton, Phil. Managing Uncertainty and the Practice of Intelligence, [PowerPoint slides], 2019.
Harney, R.C. (1997). Information-based approach to performance estimation and requirements allocation in multisensory fusion for target recognition. *Optical Engineering 36*.