Constellation Operations and Instrument Analysis for Earth Science Missions using TAT-C

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Constellation Architecture Questions

- With smaller satellites, newer launches, commercial providers.... what does a constellation look like?
- When and where to add new sensors?
- Which instruments can be placed on which platforms?
- Where are synergies with existing platforms?
- Lack of existing information systems tools to study NOS *architecture trades* during conceptual design phase:

Tool	License	Simulation	Automation	Trades?
Systems Tool Kit (STK)	Commercial	Full mission operations	STK connect commands (w/integration module)	Slow
FreeFlyer	Commercial	Full mission operations	Runtime API (w/license tier)	No
General Mission Analysis Tool (GMAT)	Open (Apache 2.0)	Orbital dynamics	GMAT script	No
Orekit	Open (Apache 2.0)	Low-level library	Java/Python API	No

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TAT-C Vision and Unique Capabilities

The **Trade-space Analysis Tool for Constellations** using Machine Learning (TAT-C ML) will provide a framework to facilitate **Pre-Phase A** investigations of Distributed Spacecraft Missions (DSM) and optimize DSM designs to **a priori science goals**.

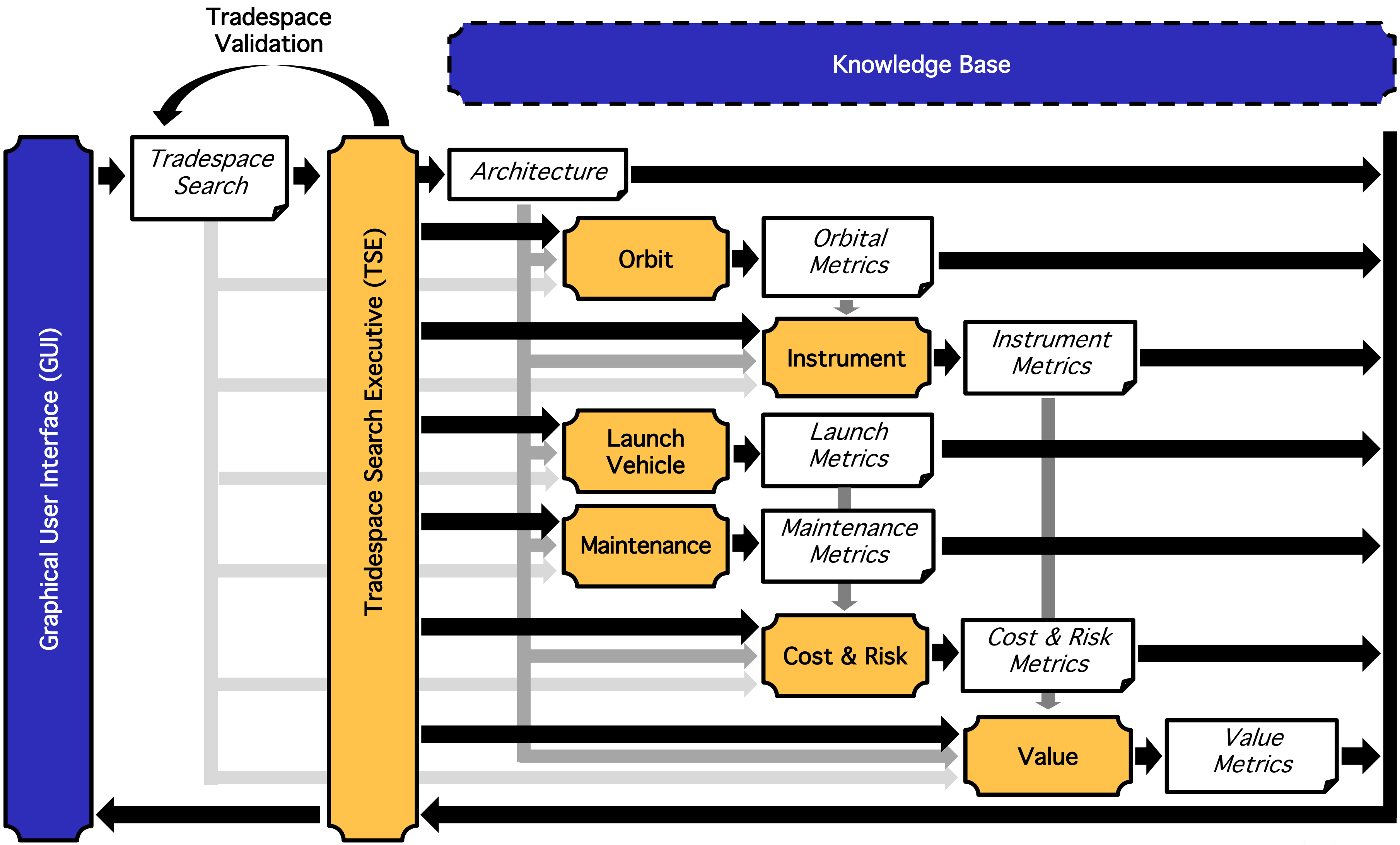
1. Science-first: leave architecture as a variable
2. Modular software components extensible by user community
3. Efficient pre-Phase A analysis made scalable with intelligent/learning technologies
4. Can be utilized with operations optimizers, planners and different concept of operations

Combinatorial Architecture Tradespace

- Architecture variables:
  - Number of satellites [1, 2, 4, 6, 8, 12]
  - Constellation geometry Walker Delta with [1, 2, 3, 4] planes
  - Orbital plane specifications
    - Altitude [400, 500, 600, 700] km
    - Inclination [30, 50] °
  - Satellite bus specifications [A, B, C]
  - Instrument specifications [A, B, C, D]
  - Ground network [A, B, C, D]
- Resulting architectural tradespace has around $6 \times 4^{4 \times 2} \times 3 \times 4 \times 4 = 18$ million alternatives
- Knowledge-driven algorithms to search design space

L. Portelli, M. Sabatini P. T. Grogan, "Ontology Development for Knowledge-driven Distributed Space Mission Systems Engineering", AIAA Science and Technology Forum and Exposition, CA, 2019

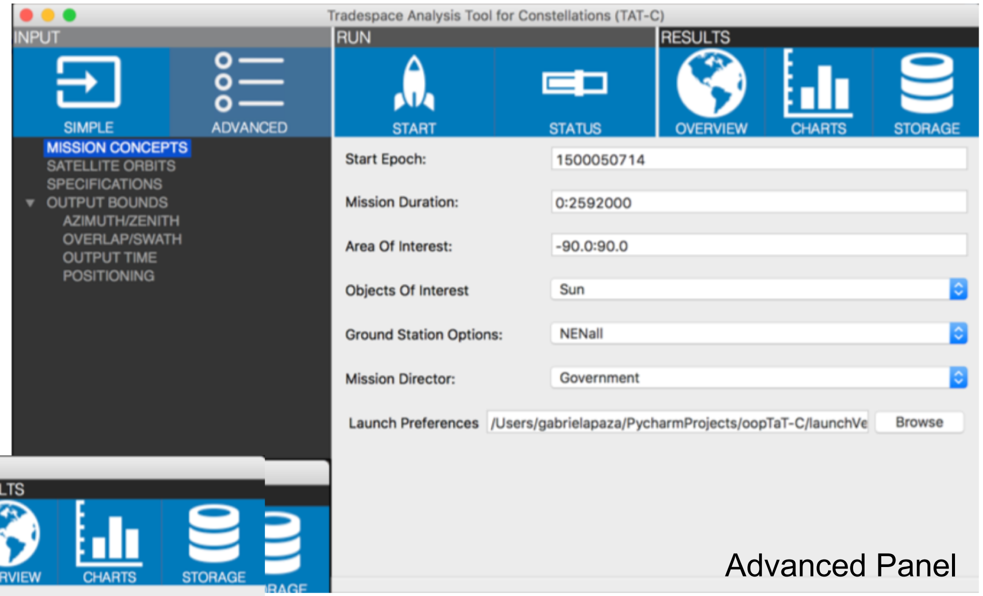
TAT-C Functions and Modules



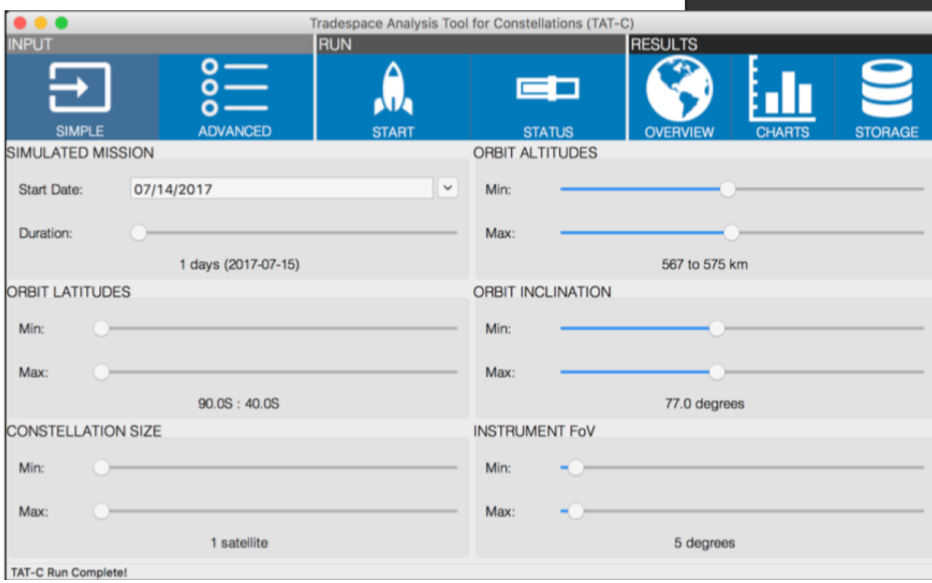
TAT-C GUI: Input Section

Both interfaces generate a JSON file that defines the constraints of the trade space

- Simple Panel – simplifies process of creating JSON file
- Advanced Panel – allows the user to edit every part of the JSON file



Advanced Panel



Simple Panel

J. Le Moigne, P. Dabney, O. de Weck, V. Foreman, P. Grogan, M. Holland, S. Hughes, S. Nag, "Tradespace Analysis Tool for Designing Constellations (TAT-C)", IEEE International Geoscience and Remote Sensing Symposium, Texas USA, July 2017

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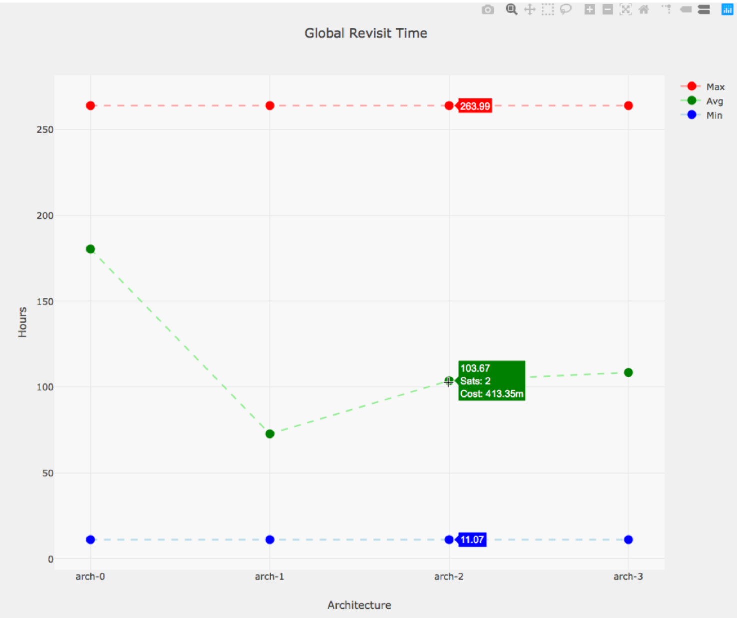
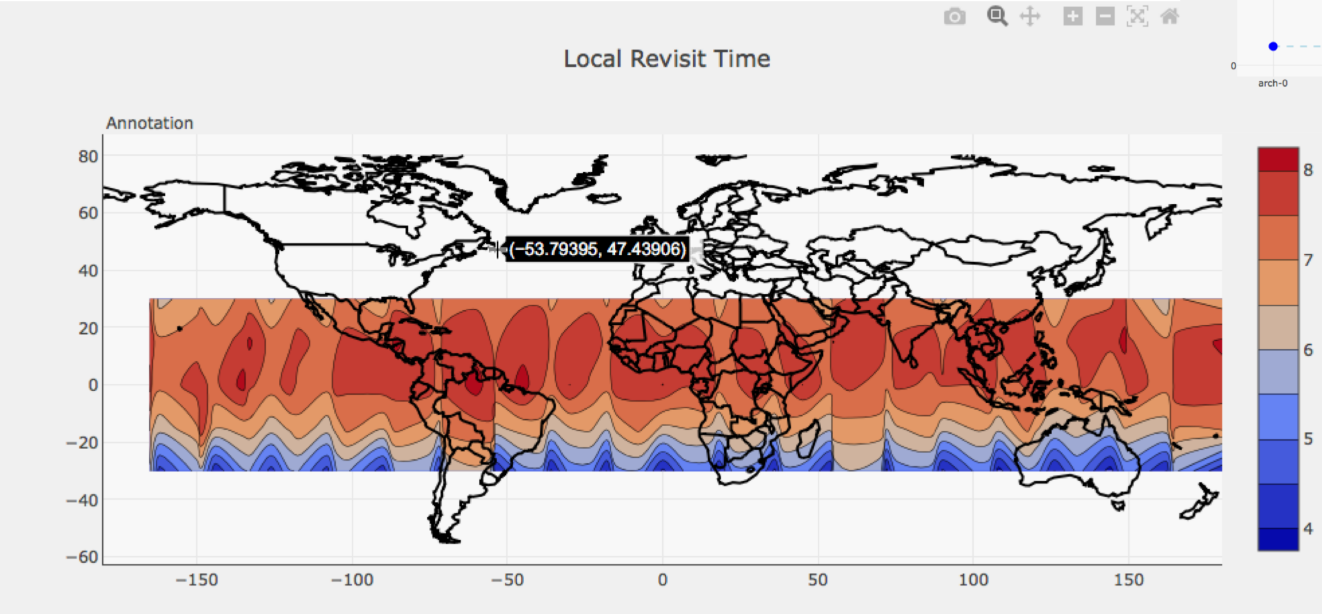
TAT-C GUI: Output Section

Comparing Global Metrics: Revisit Time
- Shows avg/min/max revisit time for each architecture
- Annotations show number of satellites per architecture and costing data





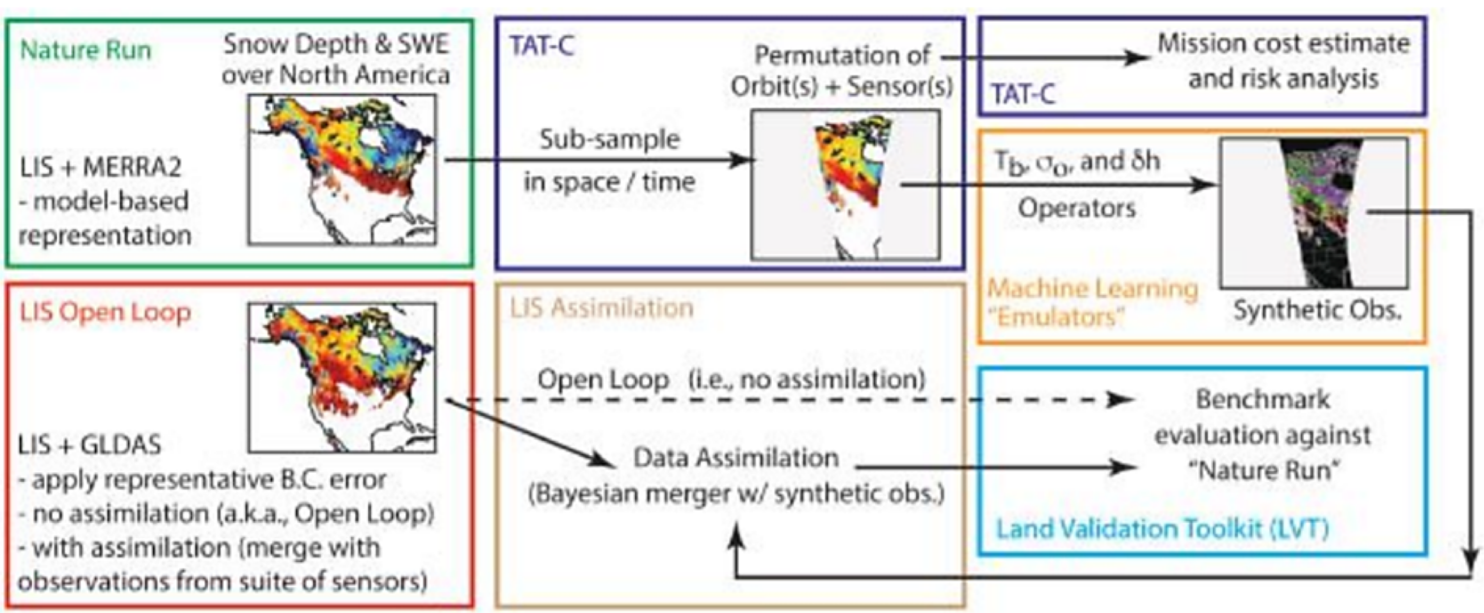
Exploring Global Metric Variation: Revisit Time
- Heatmap over Area of Interest
  - Red: high average revisit time
  - Blue: low average revisit time
- Annotations show lat/lon bounds of cursor

Application Case : Sustainable Land Imaging (SLI)

- Existing government programs
  - U.S. Landsat (7 and 8)
  - E.U. Sentinel-2 (A and B)
- New commercial systems
  - Planet Flock (100+, 4 kg): 1 (x28), 1b (x28), 1c (x11), 2e (x20), 2p (x12), 2k (x48), 3m (x4), 3p’ (x4), 3s (x3), 3k (x12), 4a (x20)
  - Planet RapidEye (5 x 150 kg)
- Plausible SLI Scenarios:
  1. Monolithic: Landsat 10 is a single satellite
  2. Distributed: Landsat 10 is a distributed spacecraft mission with multiple satellites
  3. Hybrid: Landsat 10 provides government cross-calibration for numerous commercial platforms

Other Application Cases
B. Forman – LIS AIST OSSE

- TAT-C is key enabler of Bart Forman AIST16
- Provides orbital dynamics into Forman LIS OSSE machine learning model
- Also provides cost and risk analysis to prioritize spacecraft and instrument trade-offs



Constellation Types

Delta Homogeneous Walker
- Decisions = [h,inc,#sats,#pl,f]
- Fixed altitude and inclination
- Evenly spread RAAN and mean anomalies

Delta Heterogeneous Walker
- Decisions = [h,inc,#sats,#pl,f]
- Allows for a mix of h, inc
- FF: Enumerate all possible planes in homogeneous Walker and take all possible combinations of planes
- GA: Enforce evenly spread RAAN and mean anomalies

Precessing Type
- Decisions = [#sats, rocket]
- Multiple relight rockets drop off h-i combis
- Current implementation: Take #relights, ΔV from available rockets and use to compute h-i spread for satellite batches within #sats

Train
- Decisions = [h,$\overline{\mathrm{LTAN}}$,#sats,ΔLTAN]
- Fixed altitude and $\overline{\mathrm{LTAN}}$
- RAAN and mean anomalies calculated to obtain desired ΔLTAN

Ad-hoc
- Decisions = [#sats]
- Current implementation: Take #sats random satellites from Planet Labs constellation

S. Nag, S.P. Hughes, J.J. Le Moigne, "Navigating the Deployment and Downlink Tradespace for Earth Imaging Constellations", International Astronautical Congress, Adelaide, Australia, September 2017

Tradespace Search Strategies

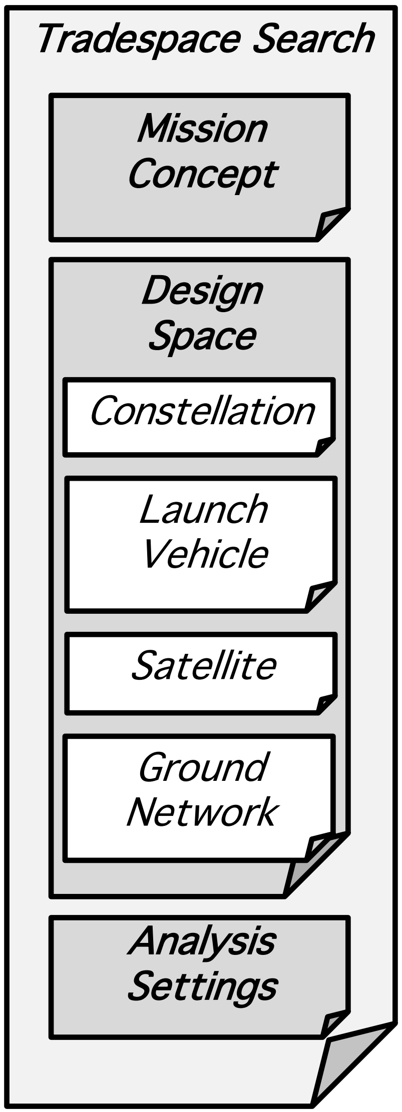
Enumerating → Search strategy

- Full-factorial enumeration
  - Simple but rigid formulation
  - Exhaustive but expensive computationally
- Evolutionary algorithm
  - Flexible formulation and still relatively simple
  - Anytime algorithm but may need many function evaluations
- Knowledge-driven optimization
  - More complex
  - Uses knowledge (existing and new) to find better architectures faster

S. Nag, S.P. Hughes, J.J. Le Moigne, "Streamlining the Design Tradespace for Earth Imaging Constellations", AIAA Space Conference, CA 2016

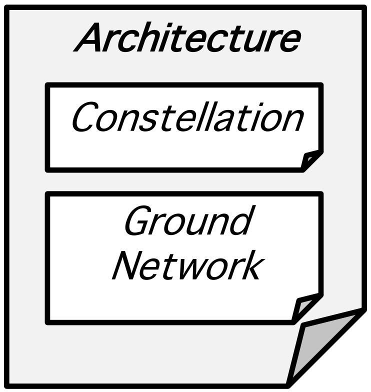
N. Hitomi and D. Selva, "Constellation optimization using an evolutionary algorithm with a variable-length chromosome", IEEE Aerospace Conference, Big Sky, MT 2018

Application Case: Applying TAT-C to SLI



- Mission Concept:
  - Government-directed
  - 90-day reference simulation period
  - Global imaging mission
- Design Space:
  - Existing Landsat 8/9 satellites (with OLI)
  - Existing Sentinel-2 A/B satellites (with MSI)
  - New constellation with 1-10 satellites:
    - Sun-synchronous with 1-2 orbital planes
    - 400-800 km altitude
  - Standard launch vehicle database
  - Satellite bus evolved from Landsat 9 (with OLI)
  - Standard Landsat international ground network
- Analysis Settings: standard outputs

Application Case: Applying TAT-C to SLI

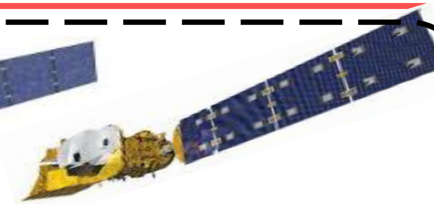


- New constellation with 1 satellite:
  - Satellite bus evolved from Landsat 9 (with OLI)
  - Sun-synchronous with 1 orbital plane
  - 600 km altitude
- Standard Landsat international ground network

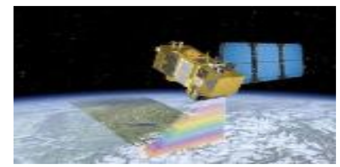
Orbital Analysis

Evaluation of an architecture by propagating the orbit and calculating its coverage over entire mission duration,
e.g. suitable monolithic-Landsat-10 spacecraft working alongside NASA, ESA spacecrafts for EO SLI.

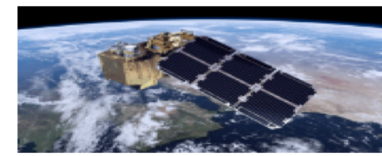
Landsat-8
credit: NASA



Landsat-9 (planned 2020)
credit: NASA



Sentinel-2A
credit: ESA



Sentinel-2B
credit: ESA

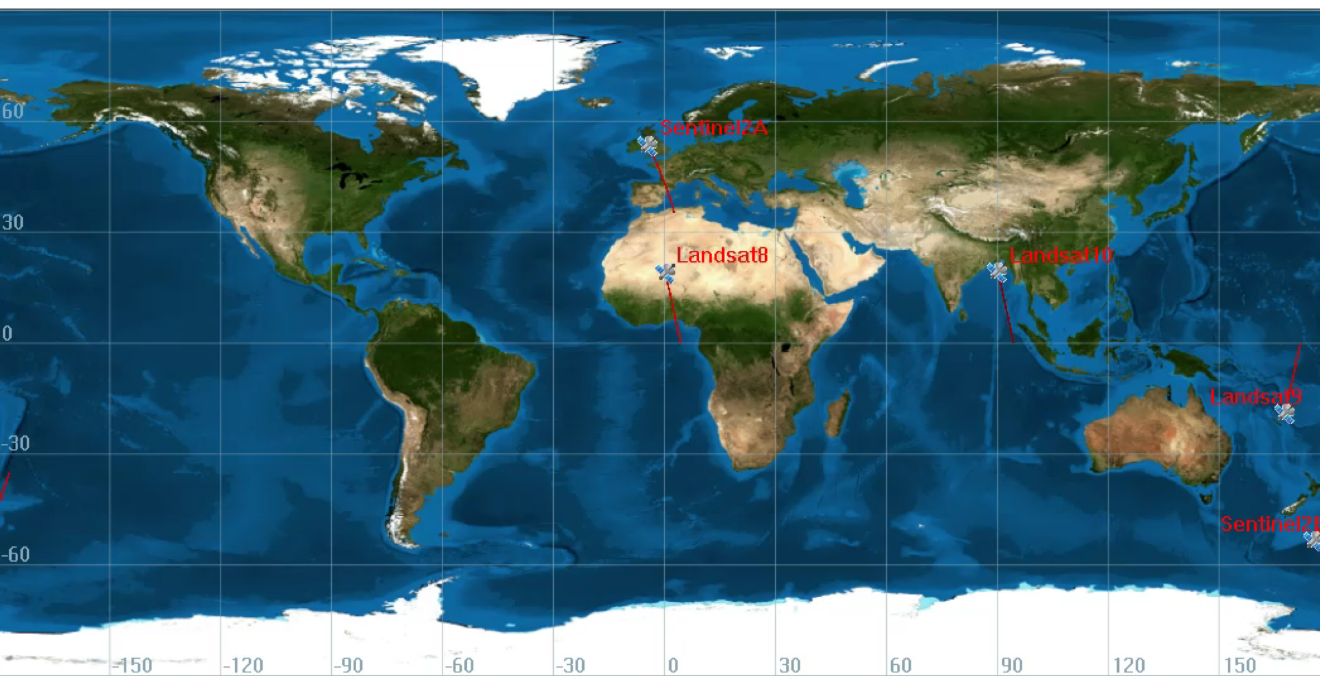
Existing satellites

?

Landsat-10

Satellite under study

Visualization of an architecture, simulated in the NASA General Mission Analysis Toolkit (GMAT):



Orbital Analysis

- Numerical simulation in C++
- **Orbit propagation:**
  - Computationally light, utilizing the point-mass model of Earth with consideration of J2-perturbations.
  - Option to include effect of atmospheric drag.
- **Coverage (*dependent on Instrument*):**
  - Generation of a set of grid-points within regions of interest
  - Calculation of access times of the grid-points
  - Supported FOV geometries:
    - Cone
    - Rectangular
    - Custom shaped

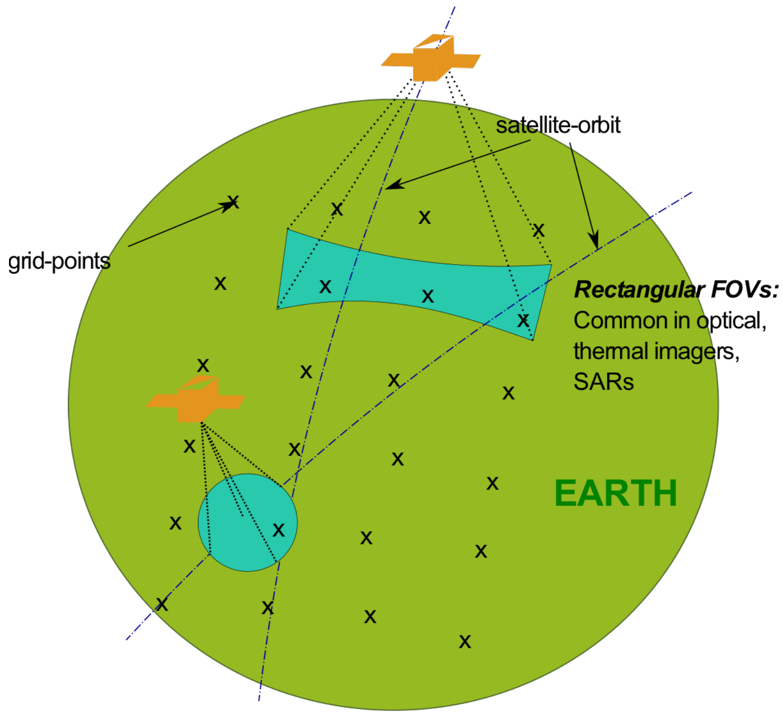


Illustration of satellite orbit and coverage

Orbital Analysis

INPUTS:


```
  "orbit": {
            "@type": "Orbit",
            "orbitType":
"KEPLERIAN",
            "semimajorAxis":
6978.14,
            "inclination": 97.787,
            "eccentricity": 0.0,
            "periapsisArgument":
0.0,
"rightAscensionAscendingNode": 0.0,
            "trueAnomaly": 0.0
          }
{
 "Orientation":
                        {
"eulerAngle1": 0.0, "eulerAngle2":
0.0, "eulerAngle3": 0.0,
"eulerSeq1": 1, "eulerSeq2": 2,
"eulerSeq3": 3
   },
 "fieldOfView":
   {
   "geometry": "CONICAL",
   "coneAnglesVector": [7.5, 7.5,
7.5, 7.5],
   "clockAnglesVector": [0.0092
179.9908  180.0092   -0.0092],
   "AlongTrackFov":0.0024,
   "CrossTrackFov": 15.0
   }
}
```

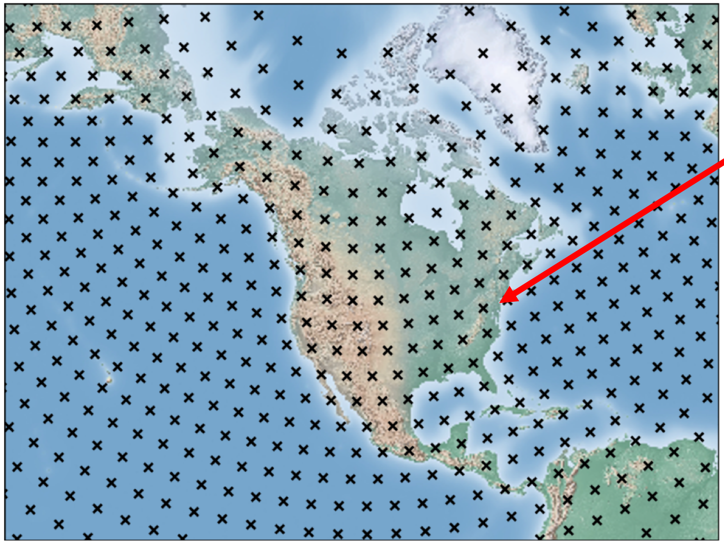

Initial orbit specs from TLEs

Landsat-8
credit: NASA

Instrument FOV specifications

Inputs are orbit specifications of satellite and sensor FOV, orientation specifications.

OUTPUTS:



Outputs are access-events captured during the entire mission at each grid-point.

```
(38.9 N, 77.0 W)

ACCESS EVENT #1

Satellite: Landsat-8
OLI

Access From [JDUT1]:
2457954.41

Access Duration [s]:
14e-3

Satellite position
[km]:-
1016.74,240.63,7001.42

Satellite velocity
[km/s]:
-0.11,7.49,-0.27


ACCESS EVENT #2
Landsat-9 OLI …

ACCESS EVENT #3
Sentinel-1B MSI …

ACCESS EVENT #1324
Landsat-8 OLI …
```

Instrument Analysis

- Quantifies the **relative** instrument performance of the architecture using quality of the data-products gathered
- Implemented as a lightweight **Python package** called 'InstruPy'.
- Three types of instruments supported
- Real world space instruments are complex and unique. Modeling of sophisticated systems with "equivalent" parameters of preselected basic-simple model. Tradeoff of **computational efficiency vs fidelity**

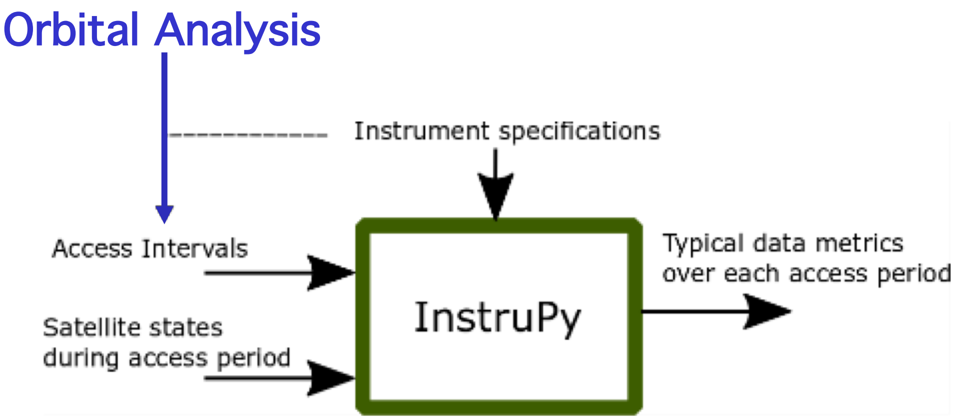
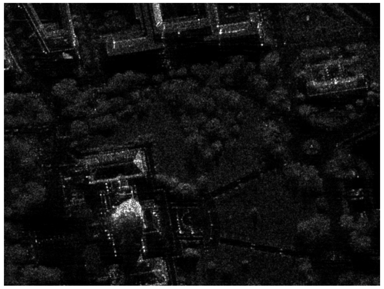


Figure: The high-level function of the InstruPy package is shown in the figure.



SAR image of Capitol at DC (σ_{NEZ0}<-30 dB)
credit: Sandia Labs

Simulated SAR image of Capitol at DC (σ_{NEZ0}=-15 dB)
credit: Sandia Labs

Example of how image metrics relate to quality of image

Instrument Analysis

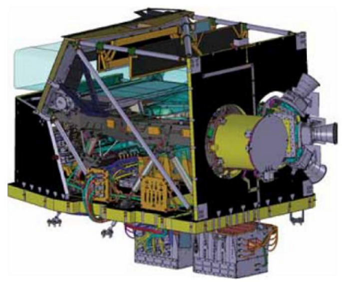
INPUTS


```
{
"@type": "Passive Optical
Scanner",
"name": "Sentinel-2A MSI Band2",
"mass": 290,
"volume": 1,
"power": 266,
"dataRate": 450,
"snrThreshold": 154,
"orientation": {
"convention": "SIDE_LOOK",
"sideLookAngle": 0
},
"fieldOfView": {"sensorGeometry":
"RECTANGULAR",
"alongTrackFieldOfView": 0.00072,
"crossTrackFieldOfView": 20.6},
"opticsSysEff": 0.75,
"apertureDia": 150e-3,
"Fnum": 4,
"focalLength": 600e-3,
"scanTechnique": "PUSHBROOM",
"numberOfDetectorsRowsAlongTrack"
: 1,
"numberOfDetectorsColsCrossTrack"
: 28763,
"detectorWidth": 7.5e-6,
"operatingWavelength": 492.4e-9,
"bandwidth": 66e-9,
"quantumEff": 0.85,
"targetBlackBodyTemp": 290,
"bitsPerPixel": 12,
"numOfReadOutE": 40}
```


General specs

Telescope specs

Focal Plane Array specs

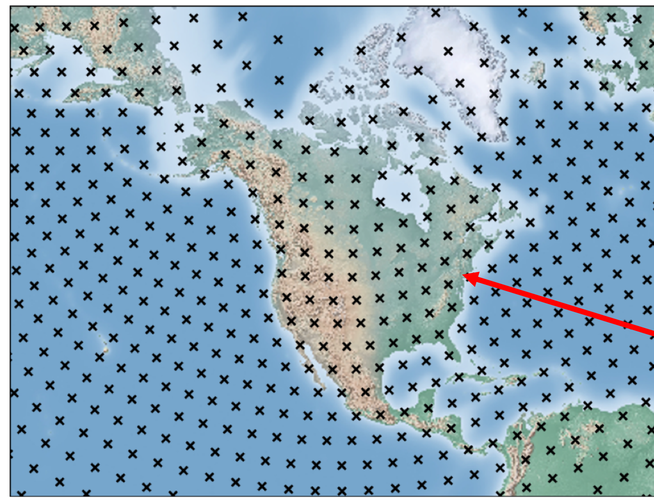


Sentinel-2 MultiSpectral Imager (MSI)
credit: ESA

```
(38.9 N, 77.0 W)
ACCESS EVENT #1
Satellite: Landsat-8
OLI
Access From [JDUT1]:
2457954.41
```

Inputs are the instrument specifications and access-events computed during Orbit Analysis

OUTPUTS



Outputs are metrics of observations made at the respective grid-point.

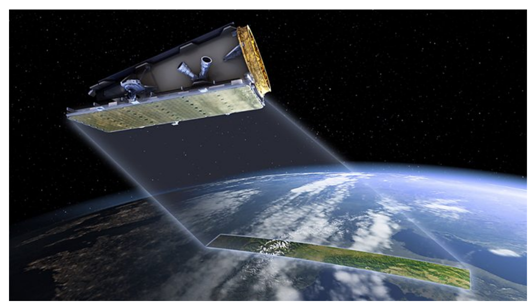
```
(38.9 N, 77.0 W)
ACCESS EVENT #1
Landsat-8 OLI
SNR: 889.73
Dynamic Range: 39601
Along-track Pixel
resolution [m]:
29.85
Cross-track Pixel
resolution [m]:
NEDT: NA
Coverage: YES
ACCESS EVENT #2
Landsat-9 OLI …
ACCESS EVENT #2
Sentinel-1B MSI …
```

S. Nag, V. Ravindra, J.J. LeMoigne "Instrument Modeling Concepts for Tradespace Analysis of Satellite Constellations", IEEE Sensors Conference, Delhi 2018

Instrument Analysis

Three types of instruments supported:

1. **Passive-Optical Sensor:** Modeling of passive imagers working at visible/ thermal/ UV electromagnetic spectrum
    1. **Pushboom**; *Examples:* TIRS and OLI on Landsat 8, MSI onboard Sentinel 2A, 2B
    2. **Whiskbroom**; *Examples:* ETM+ onboard Landsat 7, MODIS onboard Terra, Aqua
    3. **Matrix**; *Examples:* PlanetScope PS2 onboard DOVE
2. ***Synthetic Aperture Radar:*** Modeling of active radars working at microwave electromagnetic spectrum. Only Stripmap type. *Examples:* SeaSat, PALSAR onboard JAXA's ALOS, DLR's TERRASAR-X, CSA's RADARSAT
3. **Basic Sensor**
   To represent sensors whose sophisticated engineering models are not supported in InstruPy
   Examples: GLAS (LIDAR) onboard ICESAT, CATS onboard ISS.
   Very basic metrics (range of observation, elevation angle) used for more sophisticated data metrics e.g. SNR, NETD

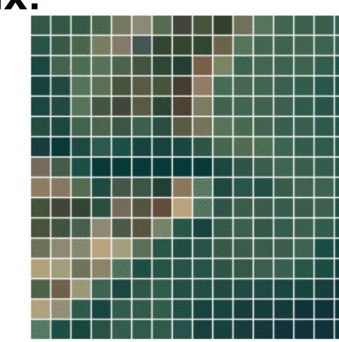


NOVA**SAR**
stripmap concept
credit: SSTL

Pushbroom:

Whiskbroom:

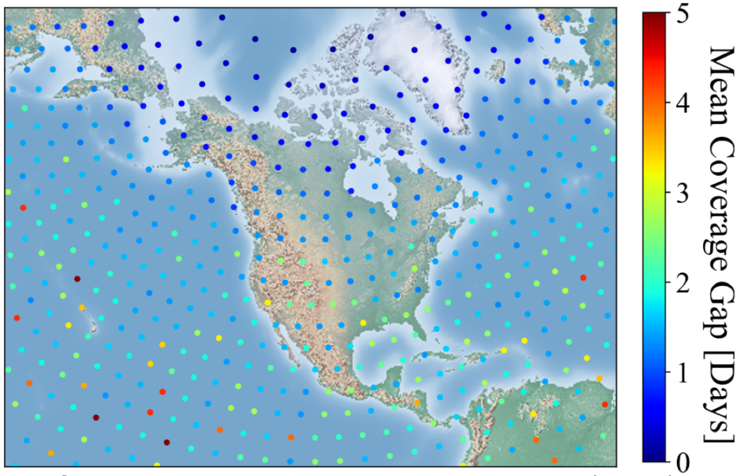
Matrix:



Application Case: Applying TAT-C to SLI

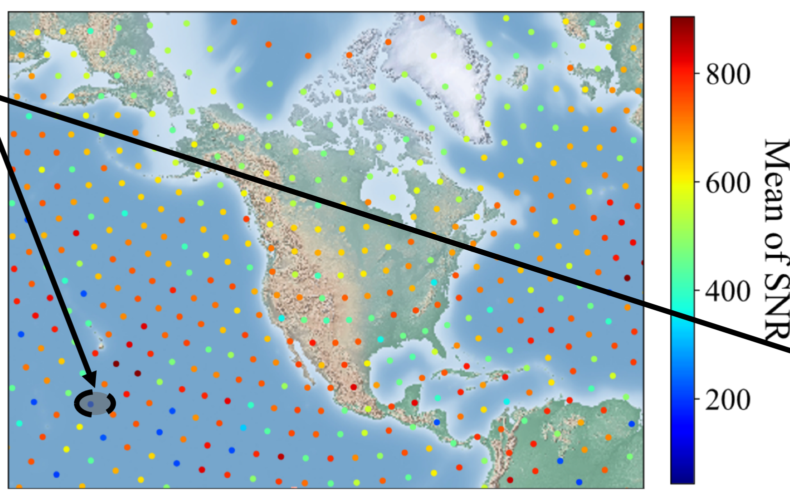
- **One architecture** with Landsat-8, 9, Sentinel 2A, 2B and ***new-satellite* Landsat-10** was analyzed by the Orbit and Instrument modules.

- Examples of performance metrics evaluated by these modules are shown … among the many available metrics which quantify the performance of the architecture used by the Optimizer to compare against other architectures.

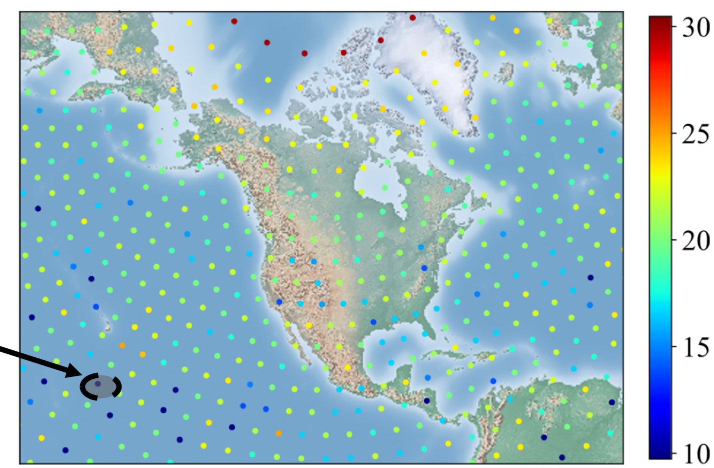


Since all satellites in Polar orbits, low (good) revisit time at Poles.

Bad SNR, Fine Resolution, probably imaged by the Sentinel MSI, not the Landsat OLI



Mean of Ground Pixel Cross-Track Resolution [m]



Application Case: Augmenting TAT-C for SLI

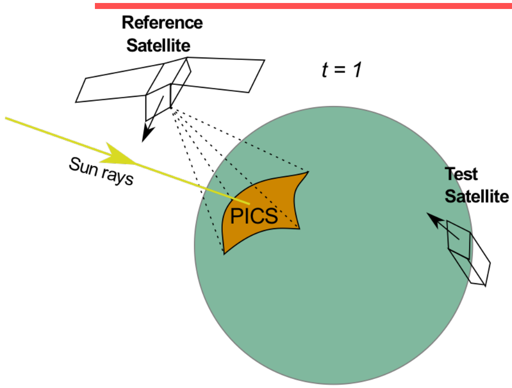


Image by reference satelltie at t =1, at some solar, observation zenith angles

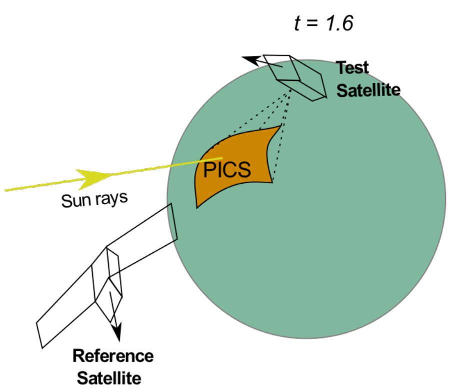
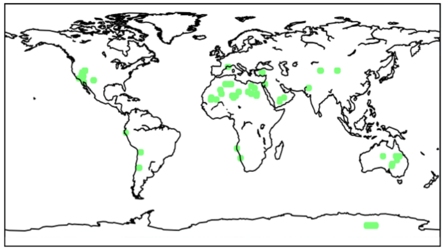


Image by test satelltie at t =1.6, at potentiall different solar, observation zenith angles

- Example ***test satellites*** - Cubesat with CCD matrix imager (2 deg x 55 deg Field Of Regard) and capability to maneuver.
- Current ***reference satellites*** – Landsat 8, 9 with pushbroom OLI, Sentinel 2A, 2B with pushbroom MSI, Sentinel 3A, 3B with pushbroom+12.6 deg off-nadir OLCI
- An optimal calibration opportunity ~ **minimizes the differences in target site viewing geometries.**



Worldwide Pseudo Invariant Calibration Sites (PICS) - *Chander, G., et al (2013), Overview of intercalibration of satellite instruments. IEEE Transactions on Geoscience and Remote Sensing, 51(3), 1056-1080.*

User defined criteria

PICS

Orbit, Coverage, Instrument

Reference Satellite Access data

Test Satellite Access data

Calibration Opportunity Calculator

Calibration Opportunity, related viewing data

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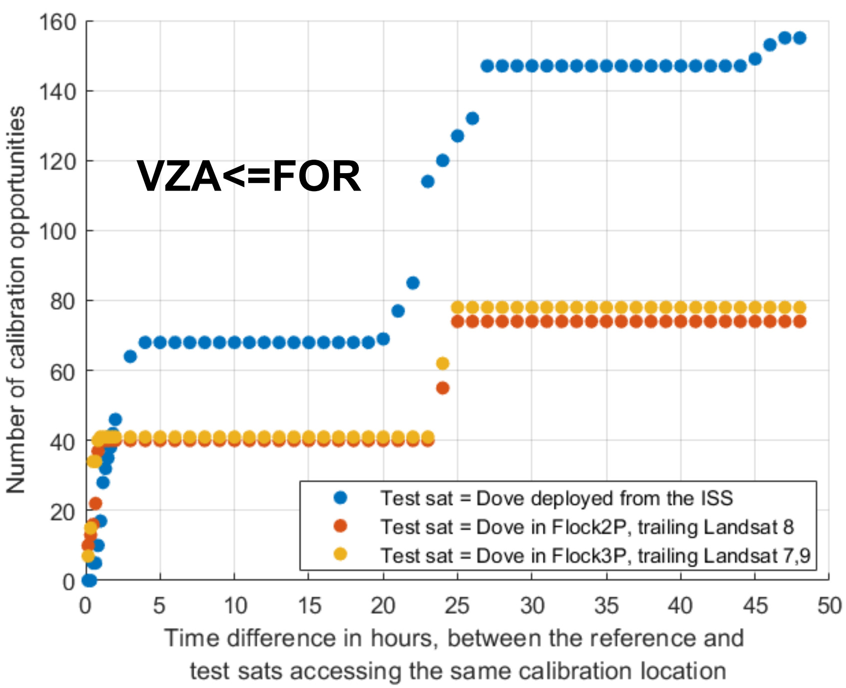
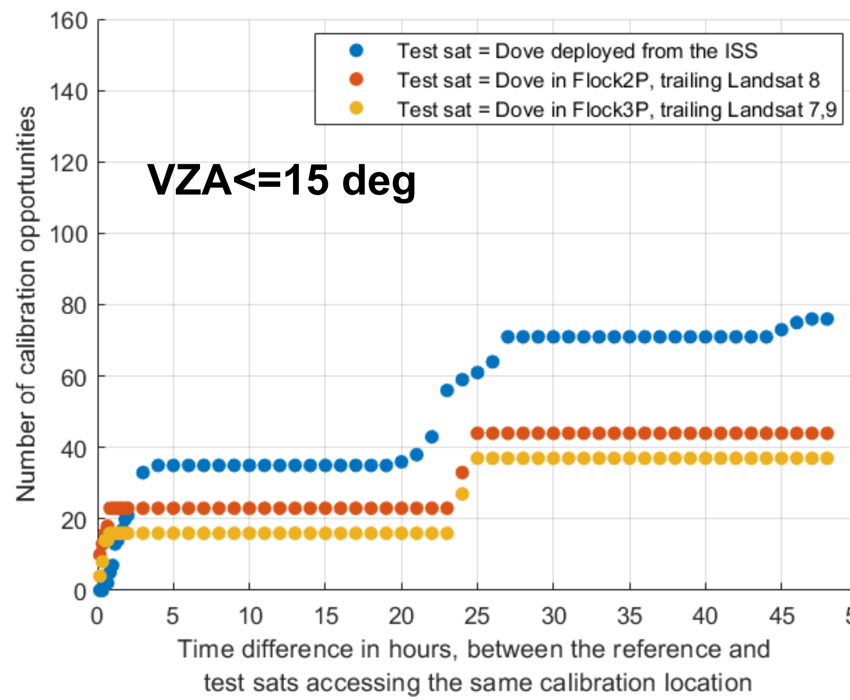
Application Case: Augmenting TAT-C for SLI

User Customized criteria for allowed opportunity:

- Max time difference ⇔ radiometric stability
- Max view zenith difference, solar zenith difference
- Mim image size, reference satellites allowed
- Can be different per calibration location





How to design the optimum constellation architecture for Transfer Radiometers? Likely non-SSO and global coverage of invariant sites.

=> Augmented TAT-C

Key Takeaways and Next Steps

- Executing the NOS demands new methods and tools for conceptual design:
  - Synthesize multiple observation platforms
  - Use science-relevant metrics to inform architecture decisions
  - Search a combinatorically-large design tradespace
  - Flexible/modular interfaces for application-specific models
- TAT-C supports NOS by aiding rapid architecture analysis for future missions
  - Pareto optimal architecture for complex value modeling
  - Inputs for higher fidelity operations modeling; e.g. planning for adaptable sensors, calibration opportunitiies
- Ongoing work on hosted platform for TAT-C analysis on AIST Managed Cloud Environment (AMCE)

Acknowledgements

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  "Generalizing Distributed Missions Design Using the Trade-Space Analysis Tool for Constellations (TAT-C) and Machine Learning (ML)"

- Thanks to other team members:
  - Jacqueline Le Moigne (TAT-C PI 2015-2018)
  - Steve Hughes, Mike Stark, Wendy Shoan (GSFC, GMAT)
  - Vinay Ravindra (BAERI)
  - Joseph Gurganus, Christian Billie, Gabriel Apaza (GSFC)
  - Pau Garcia Buzzi and Prachi Dutta (TAMU)
  - Matt Sabatini (Stevens Institute of Tech)
  - Eric Magliarditi (MIT)

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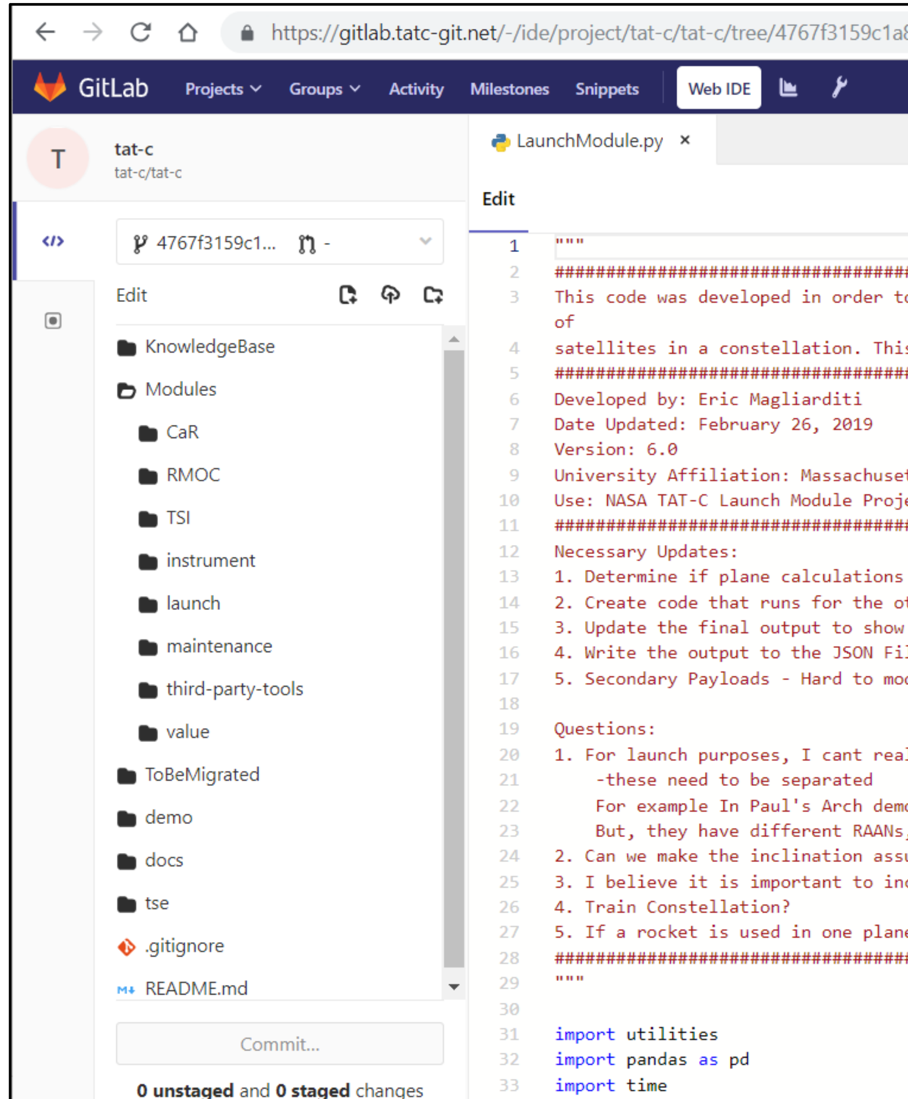
Backup Slides

Source Code Availability

Goal is to have TAT-C tool and source code publicly available as open source, building a community around its use and evolution

- Source code managed through AIST Managed Cloud Environment (AMCE)
- Release of software requires following NASA's Software Release Authority (SRA)
- Paperwork is the draft stage of submission with NASA Tech Transfer Office/ Strategic Partnership Office



Agenda

- Constellation Design to aid New Observing Strategies
- TAT-C Vision and Unique Capabilities
- Application Case: Sustainable Land Imaging (SLI)
- Overview of Core Functions and Modules:
  - Knowledge Base Schemas
  - Visualizations/User Interface
  - Orbital and Instrument Analysis
  - Launch Analysis
- Tradespace Search Capabilities

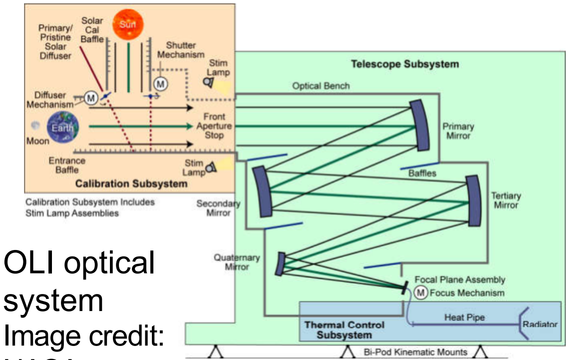
Instrument Analysis: Framework

Assumptions:

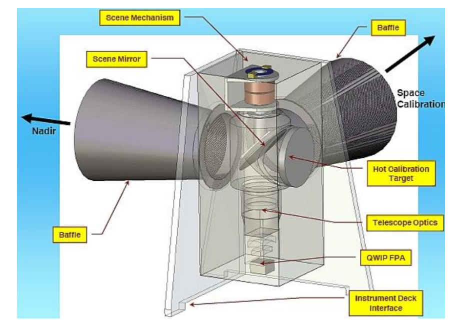
- Real world space instruments are **complicated** and **unique**.
- Modeling of sophisticated systems with “equivalent” parameters of preselected basic-simple model.
- Tradeoff of **simplicity** vs fidelity

Limitations currently undergoing work:

- Simplified physical models. **Example:** atmospheric losses, surface reflectivity not considered while evaluating radiance.
- Only one “feature” of instrument considered in analysis. **Example:** The Landsat-8 OLI can image at 9 bands, but only 1 band can be considered at a time.



OLI optical system
Image credit: NASA

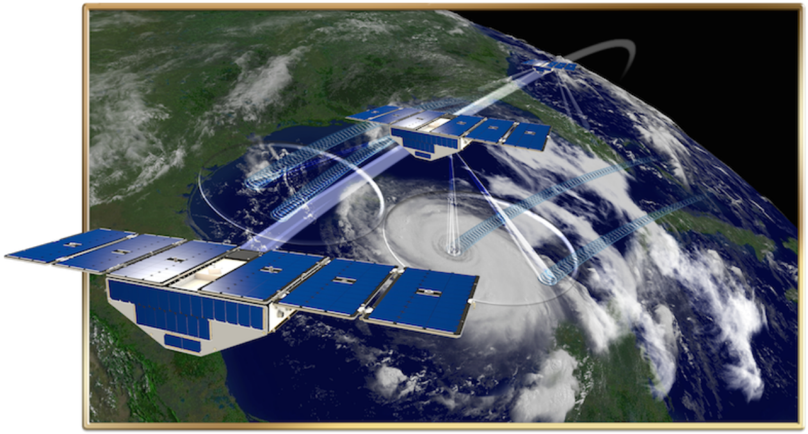


TIRS optical system
Image credit: NASA

Example: Optics assembly in Landsat-8 OLI is ***reflective*** with 3 mirrors, while the TIRS is ***refractive***. Impractical to start building custom models of all “possible” optics. Instead we simplify analysis by allowing the user to input an ***equivalent telescope focal-length, aperture diameter, F#.***

ESTO's New Observing Strategy (NOS)

- Flexible constellation of multiple observations:
  - Space, airborne, in-situ
  - Spatially and temporally correlated observations
- Autonomous control and data collection:
  - Scalable and selective
  - Automatic targeting
- Challenges:
  - Technical: security, autonomy, calibration, processing, complexity
  - Social: new concepts, culture change, complexity

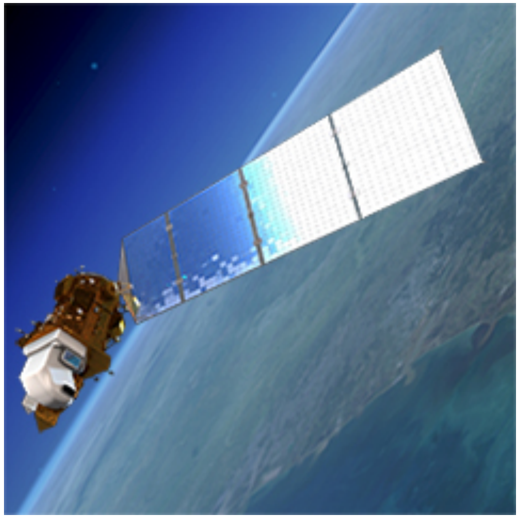


CYGNSS (NASA/Univ. Michigan)

Case Study: Sustainable Land Imaging (SLI)

- Landsat Program (NASA/USGS):
  - 47-year continuous record of moderate-resolution (~30 m) global land imagery
  - Solar reflective and thermal infrared
  - Spacecraft in mid-morning sun-synchronous orbit, 16-day repeat cycle

- Sustainable Land Imaging Program:
  - 2019 SLI Architecture Study to consider beyond Landsat 9 (2026 and beyond)
  - Maintain consistency for calibration, coverage, spectral/spatial characteristics, data quality, and availability

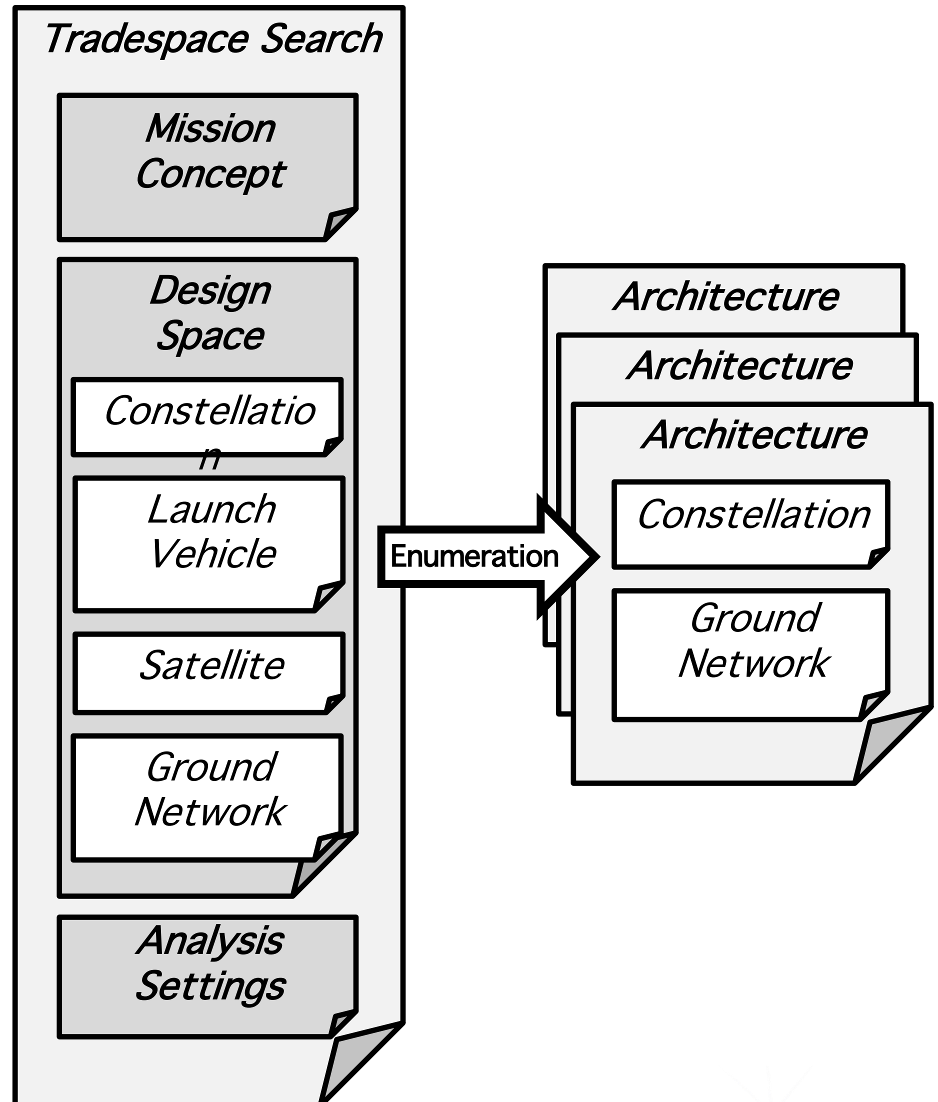


ESTO Earth Science Technology Office

Knowledge Base Schemas

- Standard serialized object templates for module interoperability
  - Human- and machine-readable documents
  - Linked to (more formal) semantic definitions
- Key-value dictionaries in JavaScript Object Notation (JSON):

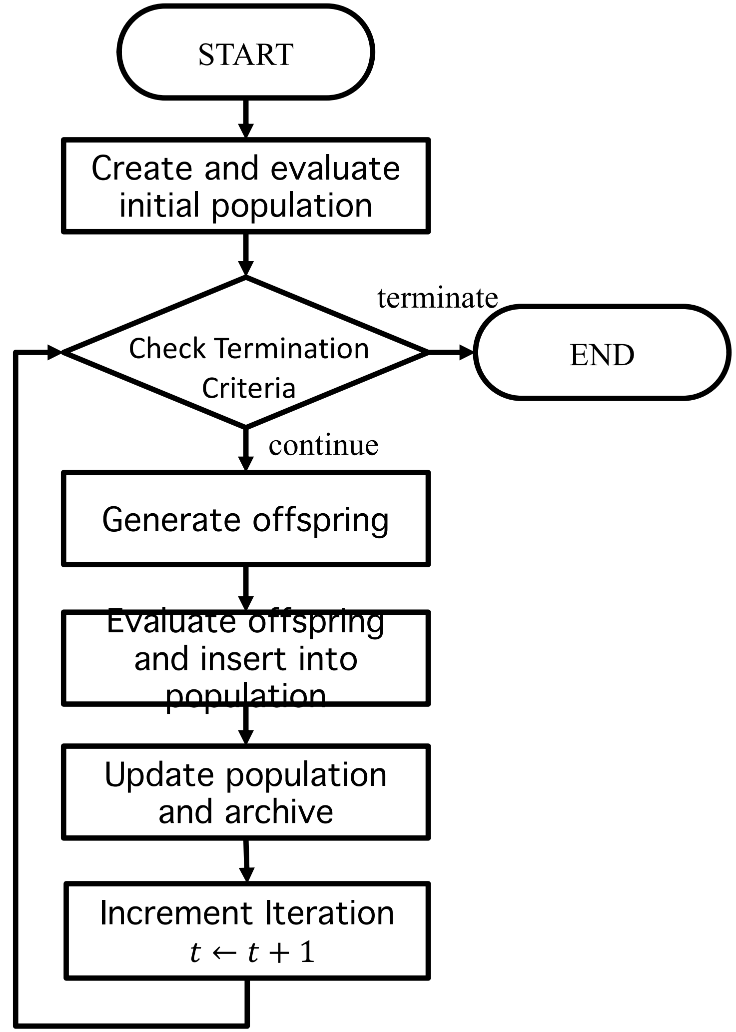
```
{
"@type": "GroundStation",
"name": "Gilmore Creek",
"latitude": 64.9764,
"longitude": -147.5208,
"elevation": 306.418
}
```



Earth Science Technology Office

ε-MOEA: Evolutionary algorithm

- **Idea:** Evolutionary algorithms mimic natural evolution
- Specifically, use ε-MOEA
  - Multi-objective
  - Steady-state algorithm
  - Maintains an archive of best solutions found so far
- **Challenge:** Develop crossover and mutation operators for complex constellation types (e.g., heterogeneous)
- **Pros:** Simple, flexible
- **Cons:** May need many function evaluations to converge



Baseline evolutionary algorithm

FF enumeration – example results (TROPICS)

Key params: 7-day simulation, 57x20 deg FOV, coverage grid over tropical regions, 3U CubeSat

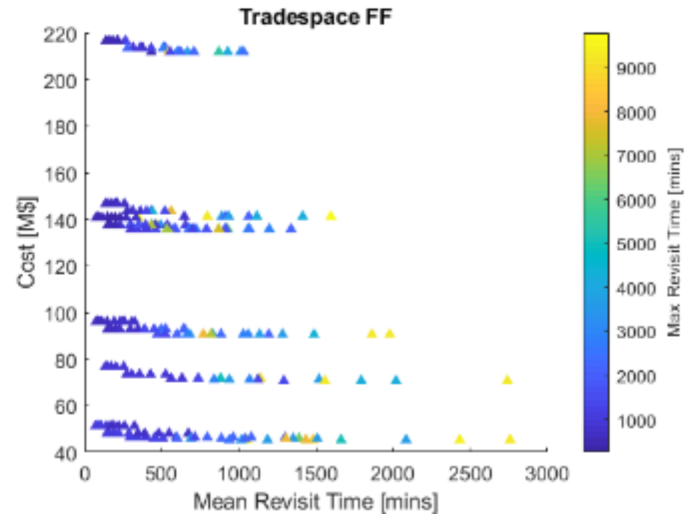
Design space

Decision	Options
# satellites	[1,2,3,6,12]
# planes	[1,2,3]
Altitude	[400,500,600,700, 800]
Inclination	[30,51.6,90]

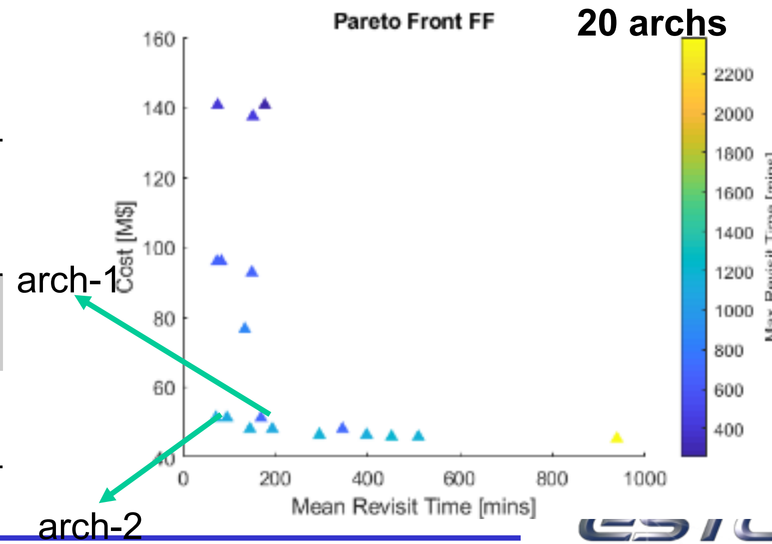
Some good architectures

#id	#sats	#planes	h	inc	Cost [M$]	Mean revisit [h]	Max revisit [h]
Arch-1	12	1	800	90	51	2.8	11.7
Arch-2	12	1	800	30	51	1.2	18.4

300 archs



20 archs



Earth Science Technology Office

ε-MOEA – example results (TROPICS)

Key params: 7-day simulation, 57x20 deg FOV, coverage grid over tropical regions, 3U CubeSat, 3 objectives (cost, avg revisit, max revisit)

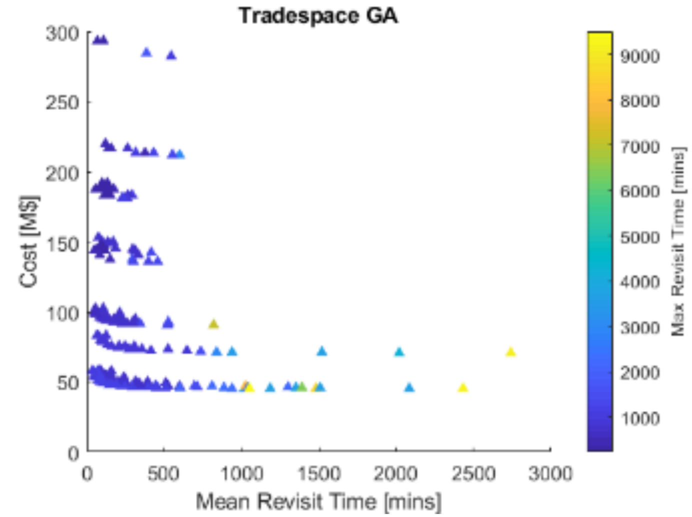
Design space

Decision	Options
# satellites	[1,2,3,4,6,8,10,12,16,18,24]
# planes	[1,2,3,4]
Altitude	[400,500,600,700,800]
Inclination	[30,51.6,90]

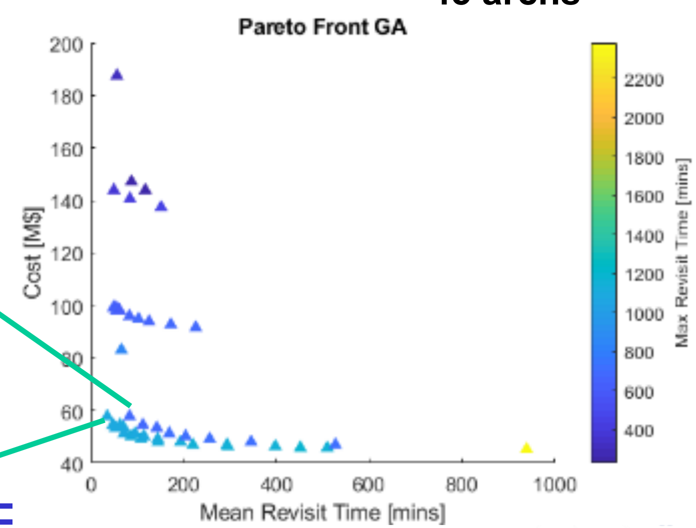
Some good architectures

#id	#sats	#planes	h	inc	Cost [M$]	Mean revisit [h]	Max revisit [h]
Arch-1	24	1	800	90	58	1.4	11.6
Arch-2	24	1	800	30	58	0.6	18.3

500 archs



45 archs



arch-1

arch-2

Knowledge-Driven Optimization with Adaptive Operator Selection

- **Idea:** Maintain a pool of operators (e.g. different types of crossover or ops. based on expert knowledge) and use ML to learn which one(s) work best for the problem at hand
- **Challenge 1 - Credit assignment:** Measure performance of each operator over time
  - $c_{i,t}$ = credit received by o_i at iteration t
  - Example: $c_{i,t} \propto f(\vec{x}^p) - f(\vec{x}^{o_{i,t}})$
- **Challenge 2 - Operator selection:** Assign solutions to operators proportionally to their quality ($q_{i,t}$ = quality of operator o_i at iteration t). For example:

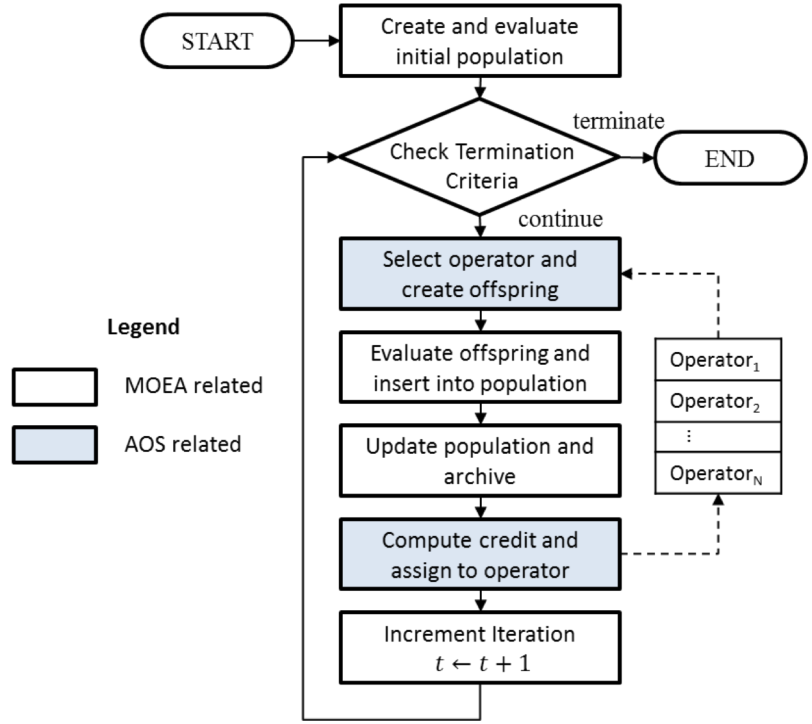
$$q_{i,t+1} = (1-\alpha) \cdot q_{i,t} + \alpha \cdot c_{i,t}$$

$$p_{i,t+1} = p_{min} + (1 - |O| \cdot p_{min}) \cdot \frac{q_{i,t+1}}{\sum_{j=1}^{|O|} q_{j,t+1}}$$

$\alpha \in [0,1]$ = adaptation rate

p_{min} = minimum selection probability

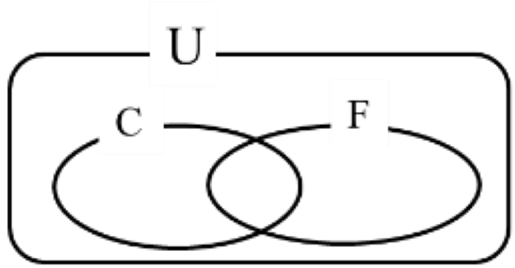
Pros: Minimizes NFE to achieve search performance



Cons: More complex

KDO\AOS: On-line discovery of new operators

- **Idea:** New operators can be discovered online using feature extraction
- **Approach:**
  - Define set of base features
  - Use **association rule mining** to search space of conjunctions of features for target region C (top 25% architectures)
  - Use **mRMR** to select top few (e.g., 4) features
  - Automatically transform top features into operators
  - Add operators to pool
  - Repeat every few iterations



U: All possible designs
C: Designs within target region
F: Designs with the feature

$$supp(F) \equiv \frac{|F|}{|U|}$$

$$conf(F \Rightarrow C) = \frac{supp(F \cap C)}{supp(F)}$$ (consistency, specificity)

$$conf(\mathrm{C} \Rightarrow \mathrm{F}) = \frac{supp(F \cap C)}{supp(\mathrm{C})}$$ (coverage, generality)

mRMR: $\Phi_i = \Phi_{i-1} \cup \left(\max_{F_i \in \Phi \backslash \Phi_{i-1}} \left[\underbrace{I(F_i, C)}_{\text{relevancy}} - \underbrace{\frac{1}{i-1} \sum_{F_j \in \Phi_{i-1}} I(F_i, F_j)}_{\text{redundancy}} \right] \right)$

Launch Module

- Primary Function: Determines the “optimal” launch manifest for a given constellation
- Optimal: Lowest launch cost to the customer
- Assumptions:
  - A different launch vehicle must be used for each orbital plane
  - Customer pays the entirety of the launch cost
- Database Construction:
  - Launch vehicle information was gathered through vehicle user guides and the FAA Annual Compendium of Commercial Space Transportation: 2018

Launch Module Formulation

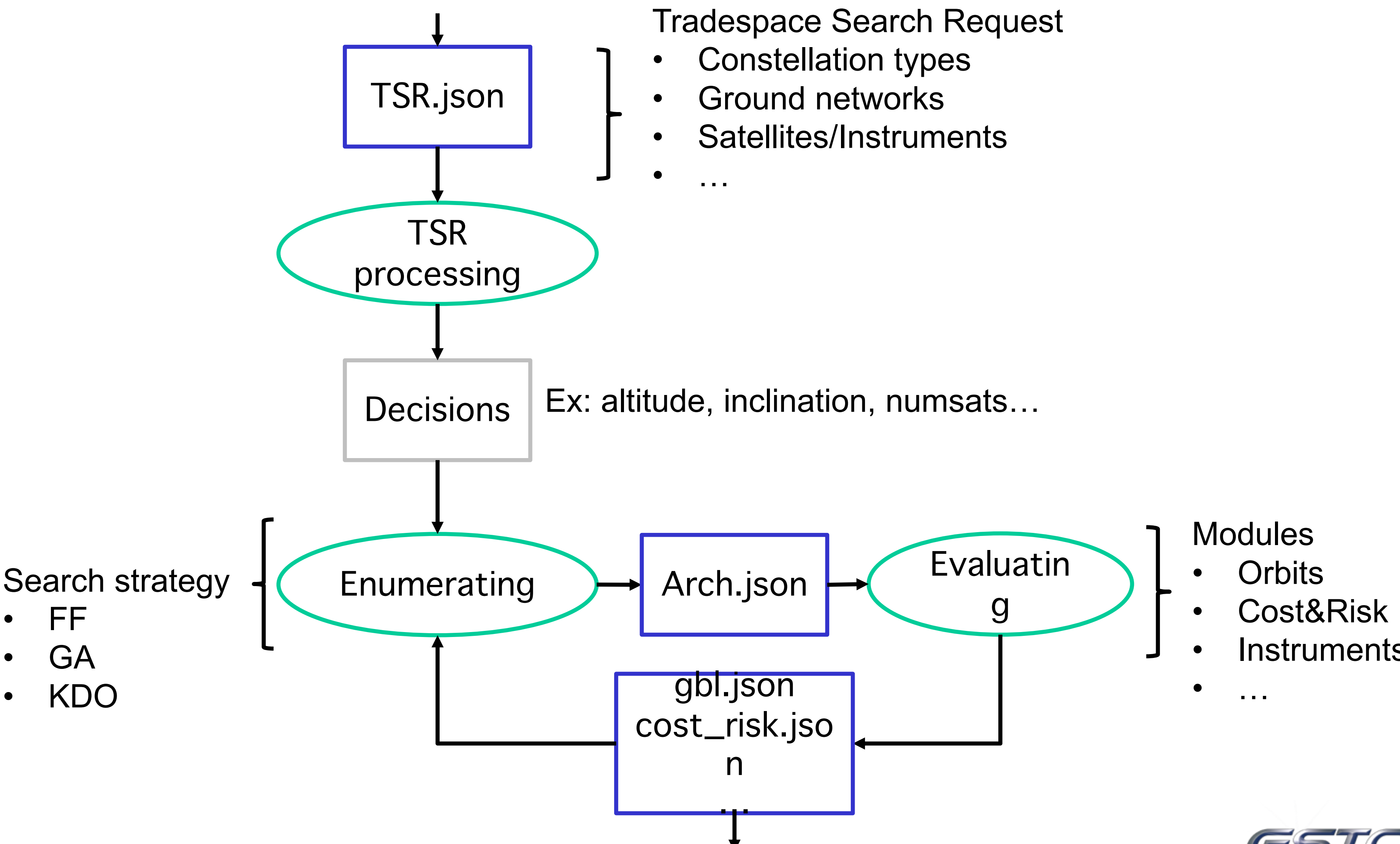
- An Integer Program is used to assign satellites within a plane to a launch vehicle
- Constraints:
  - Each satellite can only be placed on a single launch vehicle
  - Payload mass cannot exceed payload capacity of the launch vehicle
  - Payload volume cannot exceed volume capacity of a launch vehicle (assuming a cylindrical fairing)

Launch Module SLI Example

- SLI-2 Architecture 74
- Constellation Type:
  - Delta Homogenous
- # of Satellites: 10
- # of Planes: 2

	Plane 1	Plane 2
LV Used	Atlas V 551	Atlas V 551
Satellites on LV	0,1,2,3,4	5,6,7,8,9
LV Cost	$165 M	$165 M
	Total Cost	$330 M

Tradespace Search Executive (TSE)



Tradespace Search Request (TSR)

- Json file containing all user-provided information to define
  - The mission concept
  - **The design space**
  - Some settings for the different analyses
- The TSE processes the TSR.json and **formalizes** the design space
  - through a set of decisions and options, constraints, objectives to optimize (when applicable).
- The TSR may not contain all the information required to uniquely define a design space
  - So the TSE must fill out missing information with reasonable values and **resolve any ambiguities**


```
    "@type": "Constellation"
},
{
    "constellationType": "DELTA_HOMOGENEOUS",
    "numberSatellites": [
        2,
        4,
        6,
        8,
        10
    ],
    "numberPlanes": [
        1,
        2
    ],
    "orbit": {
        "orbitType": "SUN_SYNCHRONOUS",
        "altitude": [
            400,
            500,
            600,
            700,
            800
        ],
        "eccentricity": 0.0,
        "@type": "Orbit"
    },
    "satellites": [
        {
```

Full Factorial Enumeration

- **Idea:** Given a set of allowed options for each decision, enumerate the Cartesian product of the sets of allowed options
  - Nested for loops
  - Can be visualized as a tree
- **Challenge:** Different types of constellations require slightly different enumeration approaches
- **Pros:** Simple and complete, allows full sensitivity analysis
- **Limitations:** It may be computationally too expensive to enumerate all architectures.

```
Foreach x in decision 1
   Foreach y in decision 2
      Foreach z in decision 3
         …
            Arch(n++)=create_arch(x,y,z,…)
```

Example: for Homogeneous Walker, decisions are [h,inc,#sats,#pl,f], ground network, satellite/payload type