Streamlining the Design Tradespace for Earth Imaging Constellations

Sreeja Nag[1,2], Steven P. Hughes[1] and Jacqueline J. Le Moigne[1]

[1]NASA Goddard Space Flight Center

[2]Bay Area Environmental Research Institute

Tradespace Design Context

Distributed Spacecraft Missions

Tradespace exploration is required early in the design cycle

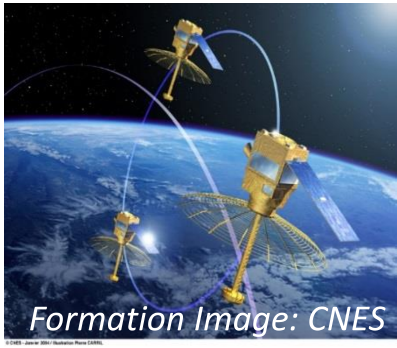
Performance: Improve sampling in spatial (synthetic apertures), temporal (constellations), spectral (fractionated S/C), angular (formations) dimensions

Cost: Need more inter-operability planning, autonomy, scheduling commands + data, ground station networks

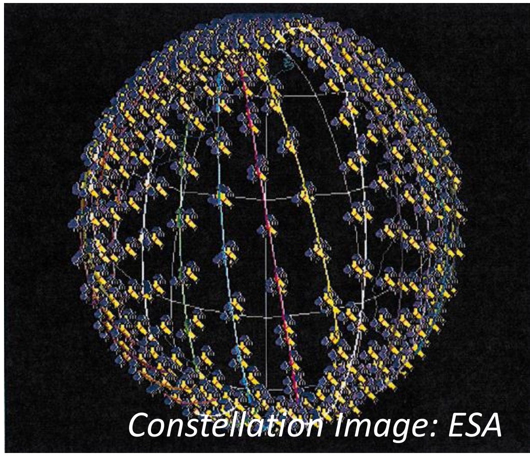
Ilities in Operations: Flexibility, Reconfigurability, Scalability, etc.

Better Design: Many conflicting variables and objectives thus better methods needed in Phase A+ - coupled models, machine learning, planning/scheduling methods, etc.

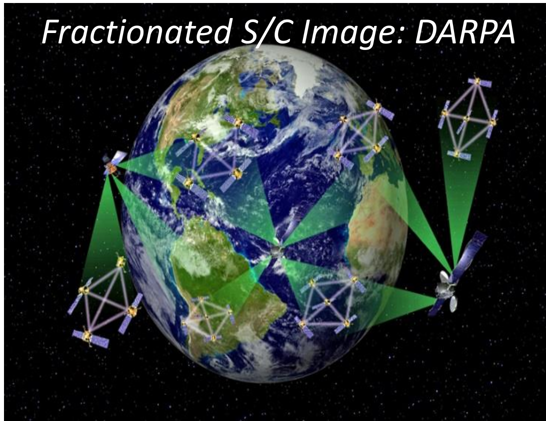
NASA GSFC is building a software tool called Tradespace Analysis Tool for Constellations (TAT-C), to address some of the above questions.



Formation Image: CNES

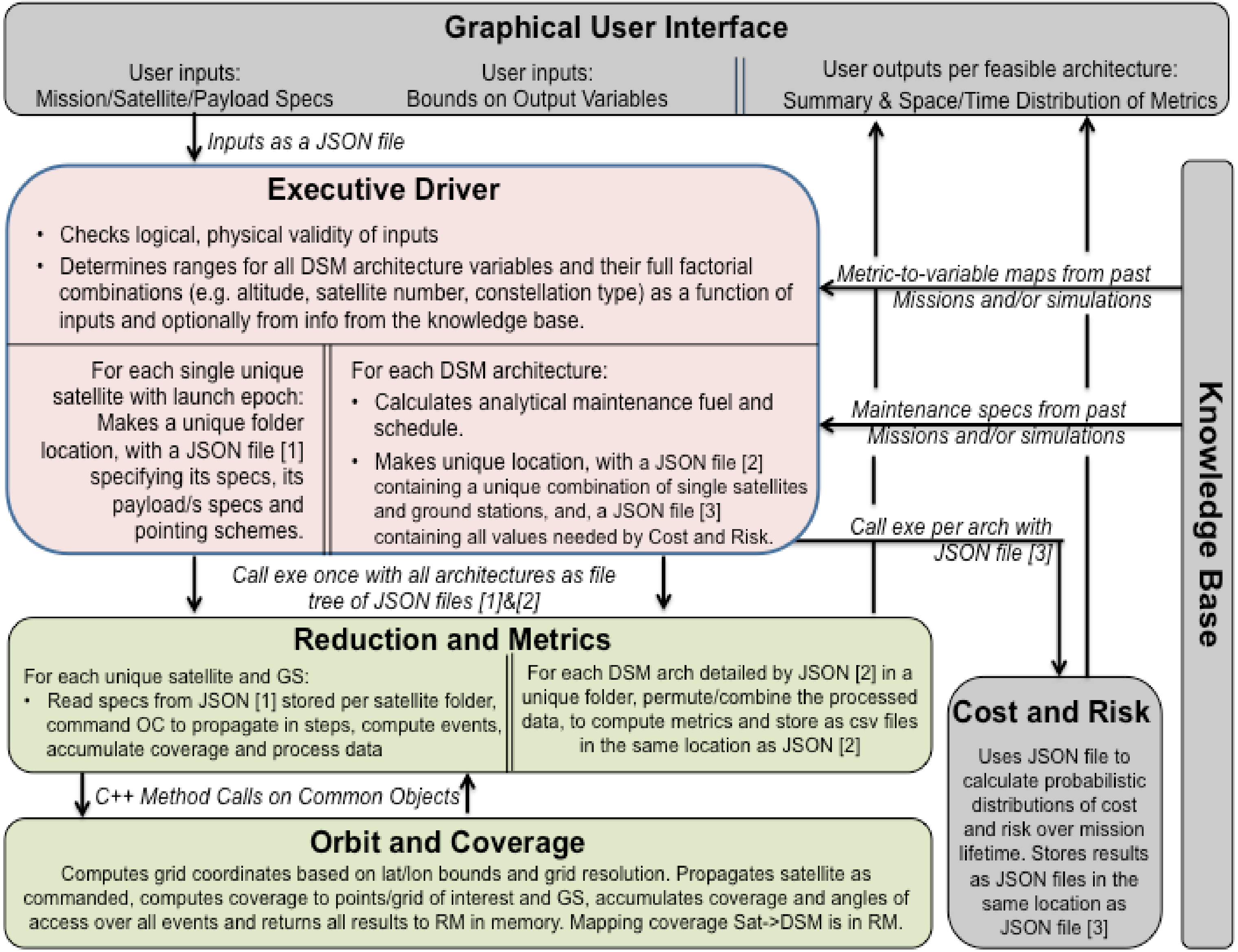


Constellation Image: ESA



Fractionated S/C Image: DARPA

Tradespace Search Iterator



- Pink: Python
- Green: C++
- Grey: Not covered in this paper

Inputs to the Exec Driver:

- Yellow: Imaging
- Green: Pairs of sats
- Blue: Occultation

Green highlighted rows correspond to variables needed only for pairs missions, including occultations with satellite pair option.
Blue higlighted rows correspond to variables needed only for occultation missions. Yellow highlighted rows correspond to variables needed only for imaging missions.

Mission Concept		
Attribute	**Characteristics**	**Description**
Mission Owner	Select	Select from 'Academic', 'Military', 'Commercial', or 'Government'.
Start Epoch	UTC time	Date when the satellites will initialize. Default is current time.
Mission Duration	exact	Total time the mission is expected to last, starting from the first launch. Default is 30 days.
Performance Period	min,max	Ranges of times within mission duration, when outputs will be calculated. Default is the first 30 days.
Area of Interest	exact locations	Lat/Lon/Alt list or Lat/Lon bounds. Global is default.
Ground Stn options	Select and/or file	If the user has existing satellites to complement. Row=GS num, columns=GS lat, lon, alt, band. Default is NEN.
Launch preferences	Select and/or file	If the user has existing satellites to complement. Row=LV num, columns=LV specs. Default is all.
Propagation fidelity	low, med, high	Three levels of propagators to be selected against (time and description provided). Default is low.
Output options	Select	Which of the output veriables is the user interested in. Default is all but angles.
Output bounds	min, max	Min and Max for any of the variables in the Outputs sheet. Default is in the output sheet.

Orbit Specifications		
Attribute	**Characteristics**	**Description**
Existing Sat options	Select and/or file	User has a sat/constellation in mind. Default is none.
Number of new Sats	min, max	Number of new sats allowed in the DSM in addition to existing. One and ten is default respectively.
Altitude Range of Interest	Select or min, max	Ranges of altitudes the user is interested in, LEO (300-1000 km) is default.
Inclination Range of Interest	min, max	Ranges of inclinations the user is interested in, 50-90 deg is default.
Special Orbits only	Select	Select between only SSO with LT option, frozen, critically inclined, ISS
Number of satellite types	exact	Enter 1 if const. is homogeneous or number, if heterogeneous. ***If hetero., all satellite specs per instance.***

Satellite Specifications		
Attribute	**Characteristics**	**Description**
Satellite Mass	Approximate	Default is 2200 kg.
Satellite Volume	Approximate	Default is 1550 W.
Satellite Power	Approximate	Default is 26.4773 m^3.
Maximum Slew Angle	min, max	Maximum coning angle in the along and cross track for a scanning satellite. Default is 0.
Scan Rate	min, max	Scan rate of the satellite, between the maximum angles. Default is 0.
Number of payloads/sat	Exact	For multi-instrument sats. Default is one. ***If more than one, all payload specs tperinstance.***
Comm band	exact bands	For downlinking data to ground stations. Default is Ka-band.

Payload Specifications		
Attribute	**Characteristics**	**Description**
Occulation or Imaging or Pairs	Select	Determines payload's measurement conops. Imaging is default.
Payload Mass	Approximate	Default is 420 kg. Payload mass will be checked within reasonableness of sat mass.
Payload Volume	Approximate	Default is 590 W. Payload volume will be checked within reasonableness of sat volume.
Payload Power	Approximate	Default is 4 m^3. Payload power will be checked within reasonableness of sat power.
Payload TRL	exact	Where is the payload at in the development cycle?
Radiometric resolution	min	Number of bits per pixel. 12 bits is default.
Occultation or Pairs coupling	Exact or file	Mark observer or occulter/pair, for every occulting or pairs mission.
Nadir swath or FOV	min, max OR exact	Conical or rectangular dimensions of the full spot size. Default is 15 deg in Along and Cross track.
Nadir GSD or iFOV	min, max OR exact	Conical or rectangular dimensions of a single pixel. Default is 30 m in Along and Cross track.
Object/s of interest	Select and/or file	Select between celestial body or 'satellite' if an occultation mission. Fill row 33 if latter. Default is Sun.
Occultation Altitude	max, min	Tangent altitudes between which occultation measurements will be made. Default is 10-50 km.
Measurement time	min, max	Sum of exposure and integration time per image or measurement. Default is half-pixel travel time.
Solar conditions	Select	Determines if the sat is sunlit or eclipsed or agnostic when measuring. Default is agnostic.
Sun Glint preference	Select	Select if sun glint (<5 deg relative Azimuth) to be included, avoided or no preference. Default is no preference.
Spectral or other Channels	Exact wavelengths	Central wavelength for multi-spectral imaging. 300:100:1000 nm is default.
Spectral resolution	exact binwidths	Band or bin width of each central wavelength in the spectral range. 50 nm is default.

Outputs from the RM Module

- Yellow: Imaging
- Green: Pairs of sats
- Blue: Occultation

All the listed outputs except * will be available per architecture, per ground spot, per unit time. The characteristics indicate bounds that the user can set as inputs.
Output tabs will include panels for attributes vs. cost, spatial bins and time series.

Spatial Metrics

Attribute	Characteristics	Description
Effective Spatial Resolution	min, max, average	Ground pixel size.
Effective Swath	min, max, average	Cross and along track extent of one full image.
Percentage Image overlap	min, max, average	% of every image that overlaps with another. 100% for complete 2-fold and 0% for none.
Covered positions (w/ FOV)	lat, lon	Spatial positions where imaging measurements are made per sat per arch within I/P "Area of Interest".
Percentage POI covered	min,max	Percentage of the required points of interest within the area of interest covered within mission performance period.
Spacecraft Ephemeris	lat, lon, alt	Ephemeris over time for all constituent spacecraft in a DSM.
Occultation positions	lat, lon	Spatial positions where occultation measurements are made per sat per arch within I/P "Area of Interest".
Inter-Sat Range and Rate	min, max, average	Distances and Rate (AT,CT,R,euclid) between each satellite in the virtual group (stereo)
Possible positions (w/ FOR)	lat, lon	Spatial positions where imaging measurements CAN BE made per sat per arch within I/P "Area of Interest".

Temporal Metrics

Attribute	Characteristics	Description
Occultation time*	min, max, average	If an occult mission, time which each occultation lasts for
% period time in Sun*	min, max, average	Fraction of the orbit that the sat spends in the Sun (vs. eclipsed)
Time to Coverage*	min, max, average	Time to cover the "Area of Interest" entirely once
Access Time*	min, max, average	Time that any ground spot has access to a satellite (within FOR)
Latency to downlink*	min, max, average	Time between observation and downlink to the next ground station
Repeat Time*	min, max, average	Time between repeats (within 1 deg of view angle) of every point in the "Area of Interest". Calc. for virtual and real sats for Stereo/Comm missions
Revisit Time*	min, max, average	Time between revisits of every point in the "Area of Interest"

Angular Metrics

Attribute	Characteristics	Description
View Zenith Angle	min, max	Between the payload-target vector and zenith, if imaging mission. Default is none for all angles.
View Azimith Angle	min, max	Between the payload-target vector projection on target normal plane and true north projection on the same plane, , if imaging mission
Solar Zenith Angle	min, max	Between the sun-target vector and zenith for day measurements, if imaging mission
Solar Azimuth Angle	min, max	Between the sun-target vector projection on target normal plane and true north projection on the same plane, if imaging mission
Lunar phase	min, max, average	For night measurements.

Radiometric Metrics

Attribute	Characteristics	Description
Signal to Noise Ratio	min, average	Expected signal and noise (SNR) of each architecture's satellites with respect to a selected one.

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Blue higlighted rows correspond to variables needed only for occultation missions. Yellow highlighted rows correspond to variables needed only for imaging missions.

Executive Driver, Data Reduction and Metric Computation

Example of a JSON file capturing ED inputs:


```
{
 "MissionConcepts": {
        "StartEpoch"            : 1455213665
        "MissionDuration"    : "0:2592000"  ,
        "PerformancePeriod"    : "0:2592000"  ,
        "AreaOfInterest"       : "Landsat_landImages.txt"
        "ObjectsOfInterest"    : ""                     ,
        "GroundStationOptions": "DSN"           ,
        "LaunchPreferences"    : "Primary",
        "MissionDirector"         : "Government"
        },
 "SatelliteOrbits": {
        "ExistingSatelliteOptions"    : "",
        "NumberOfNewSatellites"       : "1:8"
        "AltitudeRangesOfInterest"    : "710:710"
        "InclinationRangesOfInterest": "98.2:98.2"      ,
        "SpecialOrbits"               : ""
        "PropagationFidelity"         : 0
        },
 "ObservatorySpecifications": "ObservatorySpecifications.txt",
 "InstrumentSpecifications" : "InstrumentSpecifications.txt" ,
 "OutputBounds": {
        "TimeToCoverage"    : "",
        "AccessTime"        : ""            ,
        "RevisitTime"       : ""   ,
        "CrossOverlap"      : ""            ,
        "AlongOverlap"      : ""            ,
        "SignalNoiseRatio"  : ""            ,
        "LunarPhase"        : ""            ,
        "ObsZenith"         : ""      ,
        "ObsAzimuth"        : ""            ,
        "SunZenith"         : ""      ,
        "DownlinkLatency"  : ""      ,
        "SunAzimuth"        : ""            ,
        "SpatialResolution": ""       ,
        "CrossSwath"        : ""     ,
        "AlongSwath"        : ""     ,
        "ObsLatitude"       : ""            ,
        "ObsLongitude"      : ""            ,
        "ObsAltitude"       : ""            ,
        "ObjZenith"         : ""            ,
        "ObjAzimuth"        : ""            ,
        "ObjRange"          : ""
        }
}
```

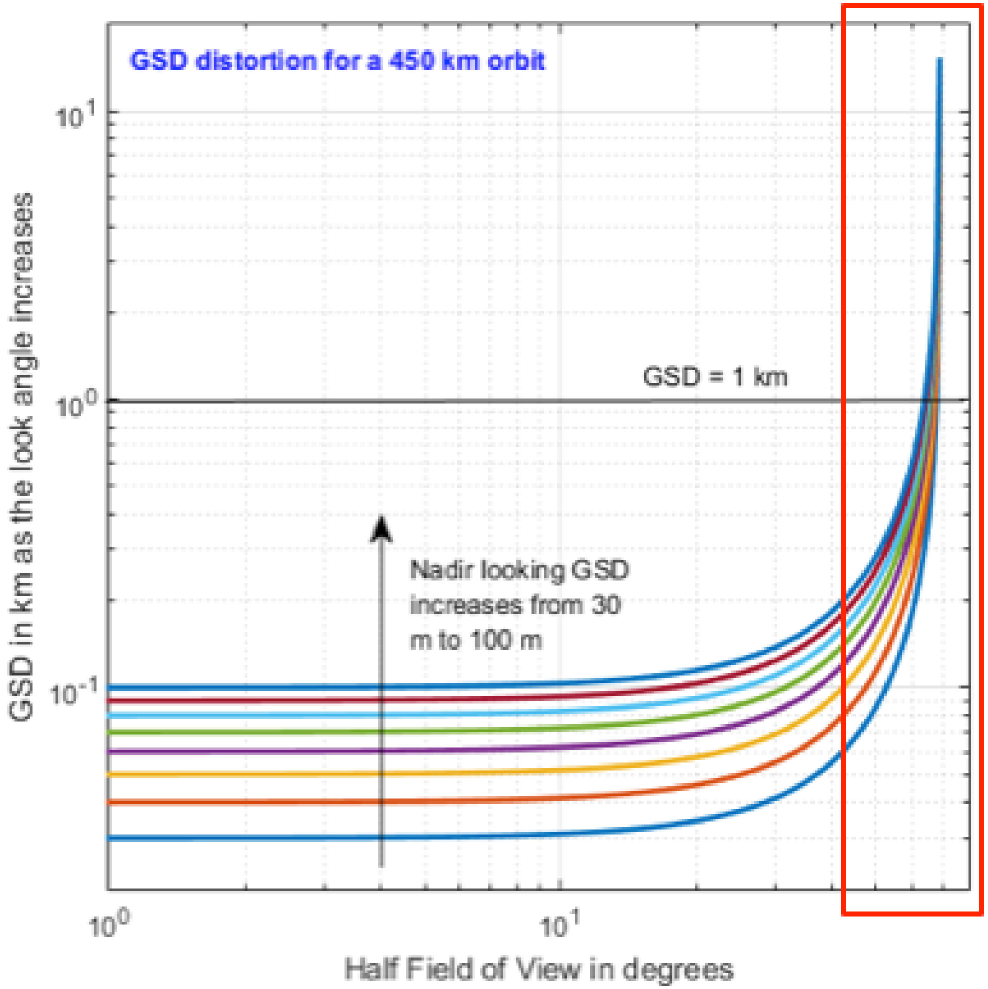

Example of a file tree capturing ED outputs:

```
User Directory
├───TradespaceSearchRequest.json
├───InstrumentSpecifications.txt
├───ObservatorySpecifications.txt
├───Landsat_landImages.txt
├───Mono
│   ├───Orb0000_GS00_Pnt000_Pay00
│   │   ├───ReductionMetrics.json
│   │   ├───ephemeris.txt
│   │   └───angles.txt
│   ├───Orb0001_GS00_Pnt000_Pay00
│   ├───Orb0002_GS00_Pnt000_Pay00
│   ├───Orb0003_GS00_Pnt000_Pay00
│   └───....
└───DSMs
    ├───Subspace00000
    │   ├───Manifest.json
    │   ├───CostRisk.json
    │   ├───gbl.csv
    │   ├───lcl.csv
    │   └───CostOutput.json
    ├───Subspace00001
    ├───Subspace00002
    └───.....
```

Preliminary Sizing for Streamlining

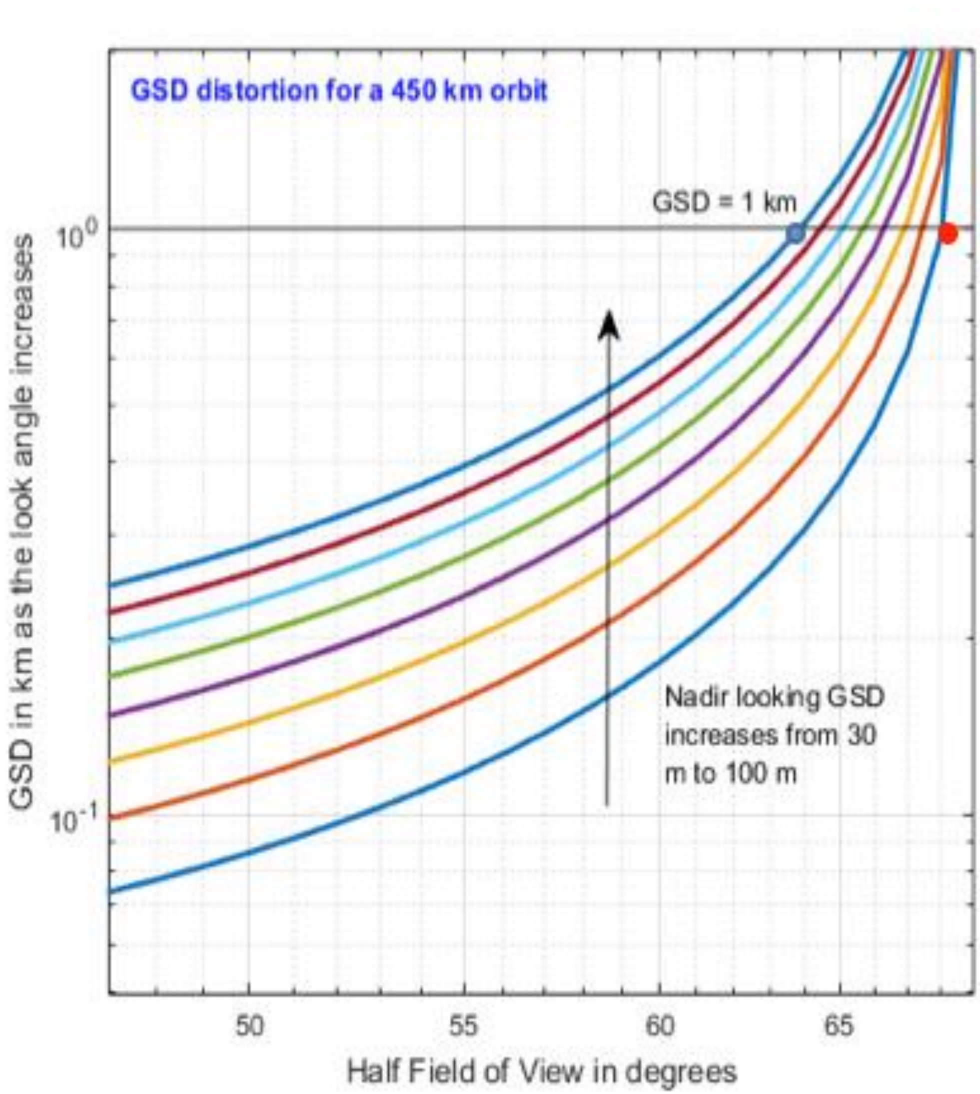
Spatial Metric Dependence on Constellation Design Variables:

Given altitude, maximum spatial resolution or ground sample distance (GSD) is limited by maximum FOV. Even w/ awide angle FOV, only those pixels in the retrieved image that satisfy max GSD will be useful. Thus, the effective FOV is limited by the GSD limits.



Preliminary Sizing for Streamlining

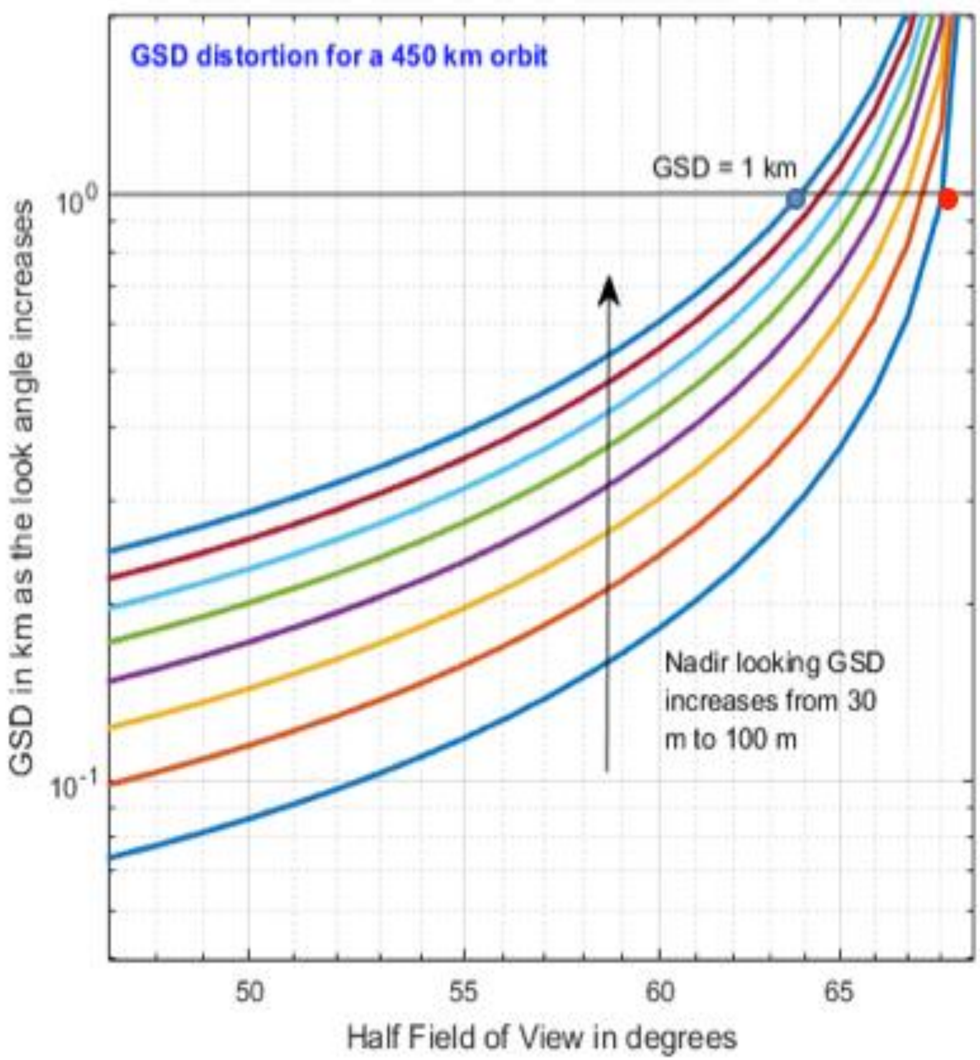
Spatial Metric Dependence on Constellation Design Variables:



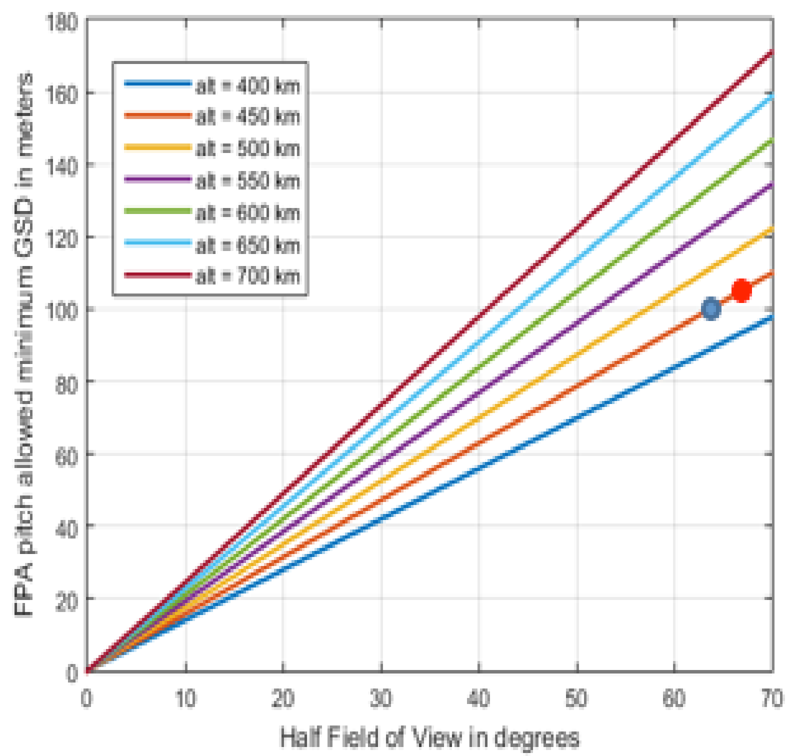
The lower the GSD is at nadir, lower it will be at off-nadir….

Preliminary Sizing for Streamlining

Spatial Metric Dependence on Constellation Design Variables:



The lower the GSD is at nadir, lower it will be at off-nadir....



… however, the entire FOV will be more limited due to the physical extent of pixel-delimited imaging.

Preliminary Sizing for Streamlining

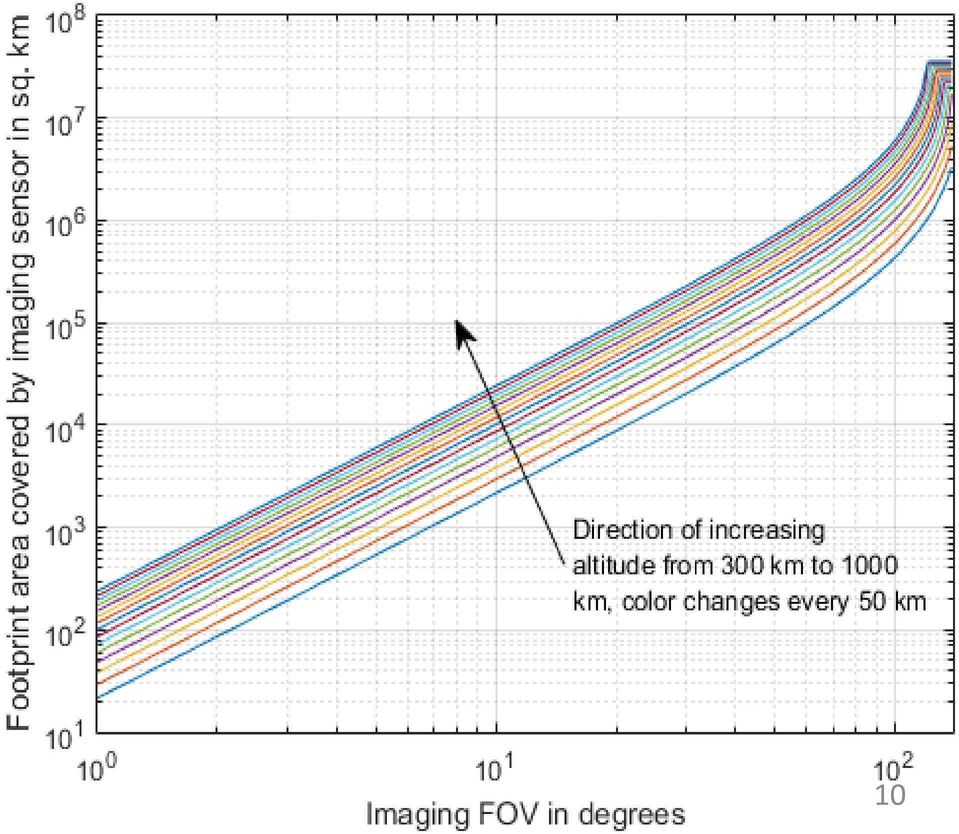
Temporal Metric Dependence on Constellation Design Variables:

The maximum and minimum number of satellites can be, very approximately, computed from the swath or an orbital sensor, its altitude and the required revisit time. If the user has specified the range of satellite number desired, those values will override these computations, if they lie outside the computed bounds.

Dependencies can be calculated at run time OR the common ones could be stored and used for streamlining when user variables fall within those values.

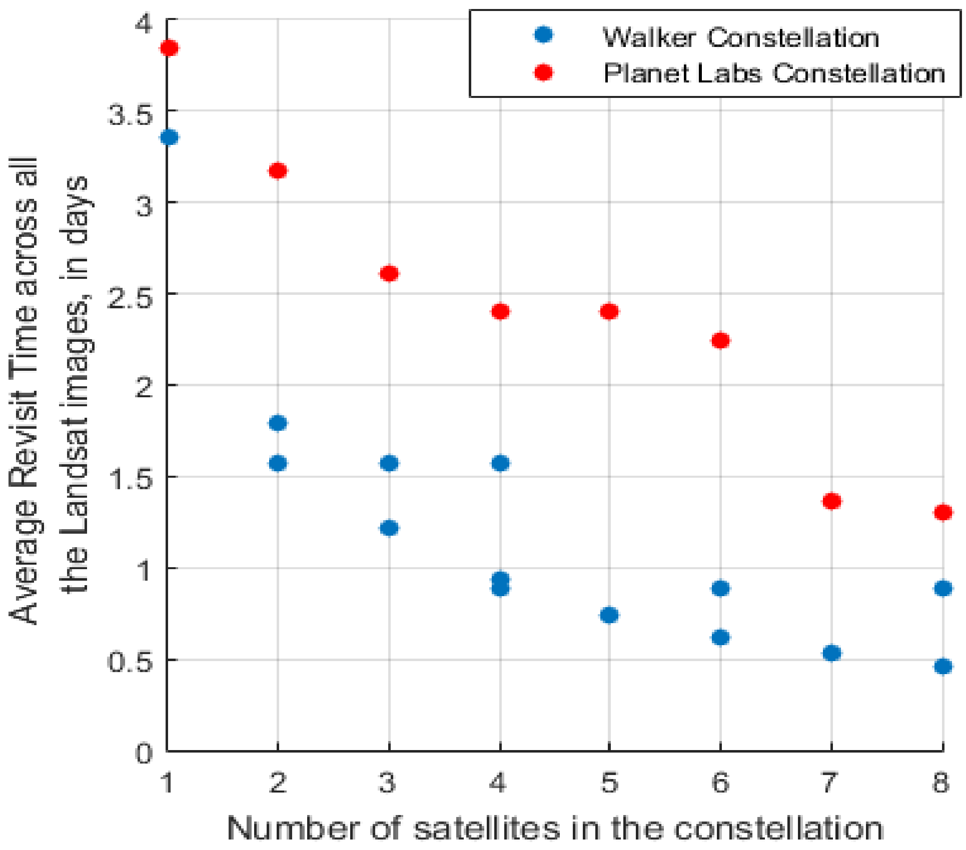
Maintenance Predictions:

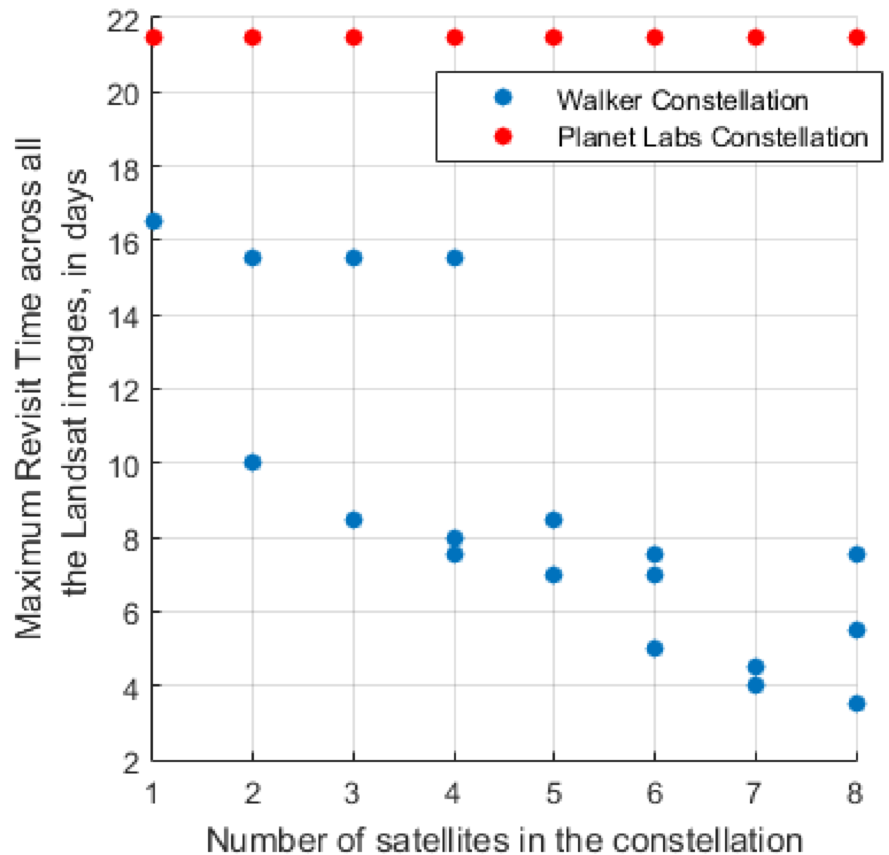
- Drag
- J2 caused mean anomaly drift
- RAAN drift relative to orbits is currently minimal due to homogeneous constellations
- No on-off switch for maint yet



Case Studies - Landsat

Landsat w/ 1-8 sats => 20 uniform Walker constellations and 8 Ad-Hoc constellations
Area of Interest: USGS Landsat grid of 17000 land/coastal images.
ED along with RM and OC took **<15 hours** of run-time on a Mac OS X version 10.10.5 with a 2.5 GHz processor and 16 GB of 1600 MHz memory.

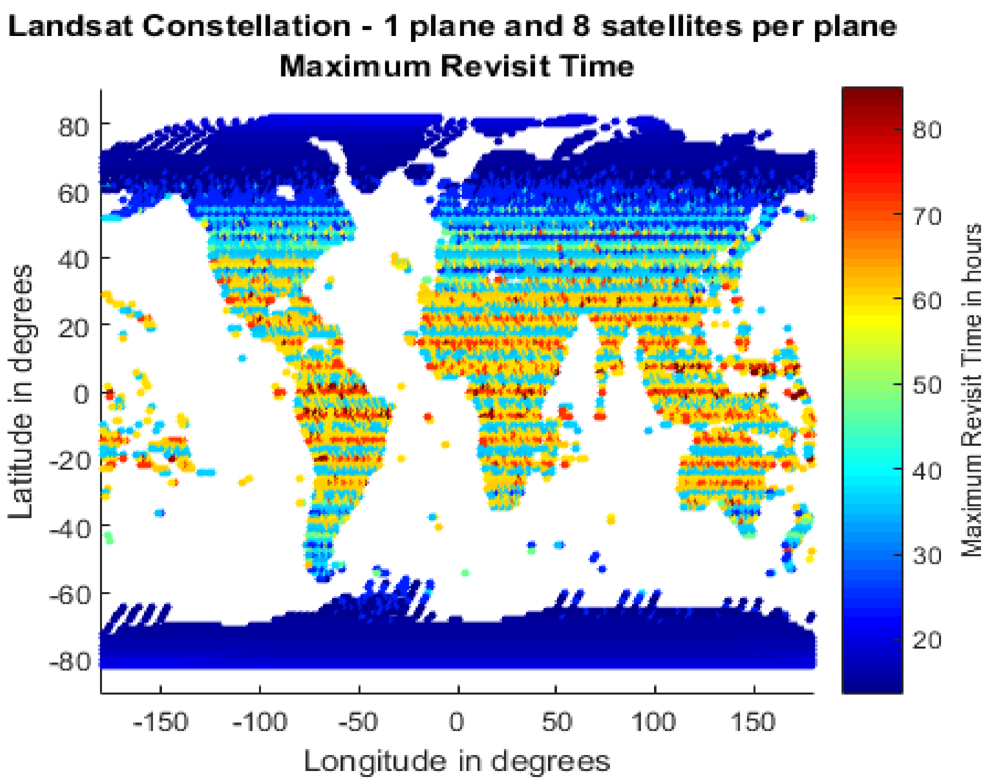


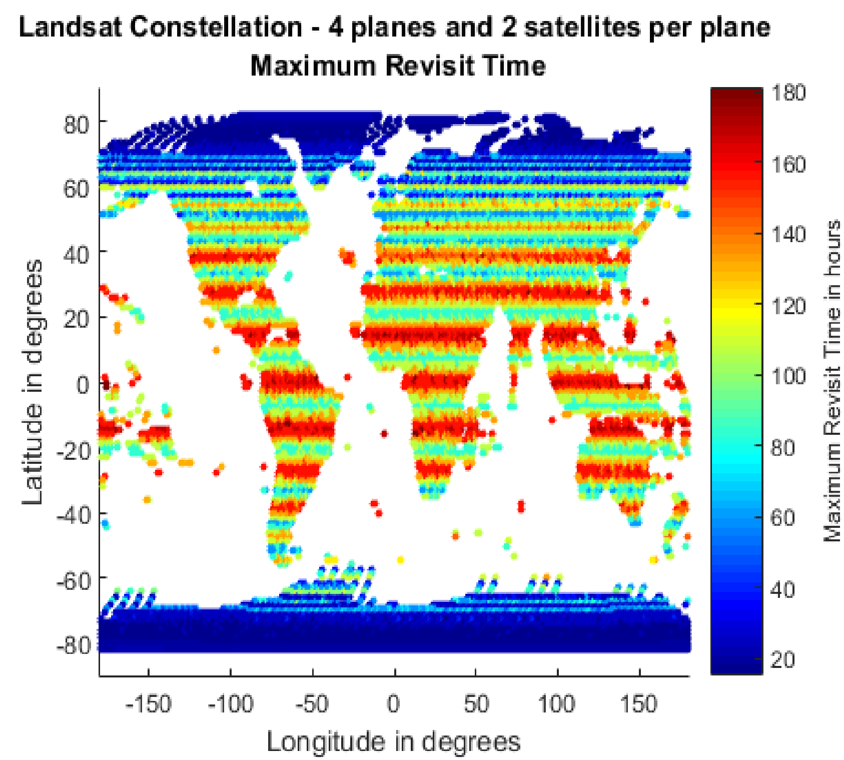


Case Studies - Landsat

Trades between any pairs or triplets or quadruplets of metrics possible.

Every constellation architecture can be evaluated spatially (and temporally as a time series) using data published by the RM module in gbl.csv and lcl.csv



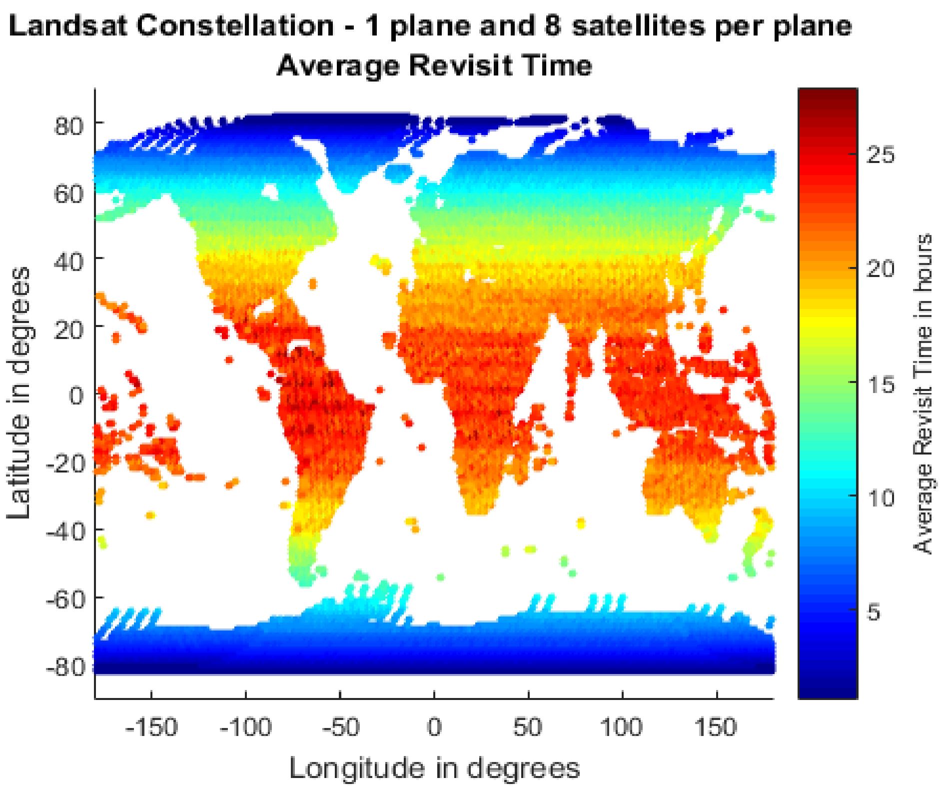


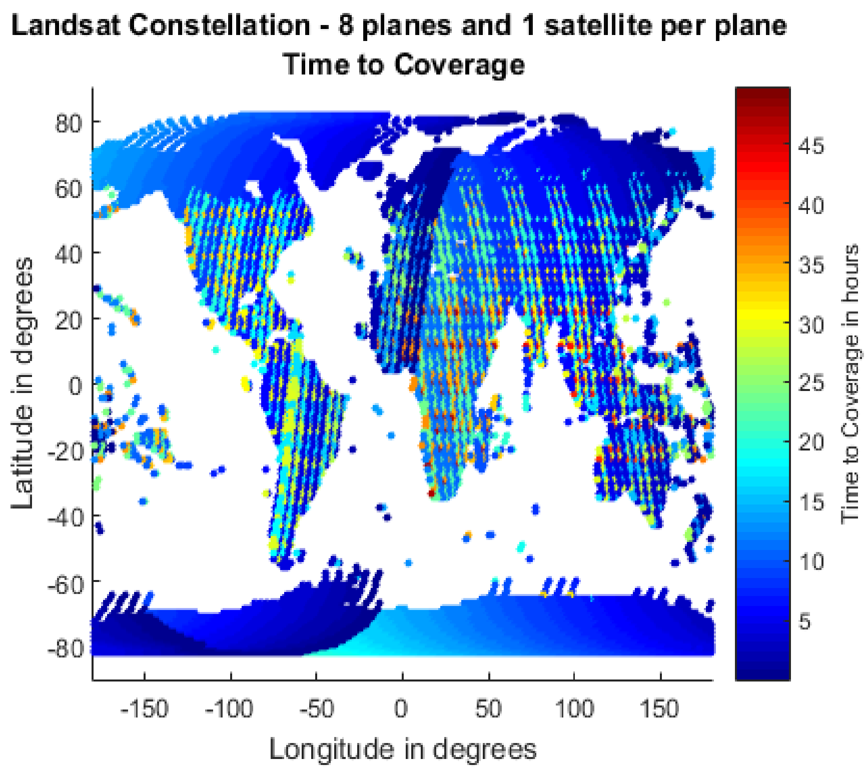
**Figures made with MATLAB for demo purposes. TAT-C's figures will be made with Python

Case Studies - Landsat

Trades between any pairs or triplets or quadruplets of metrics possible.

Examples of a few other spatially varying metrics:

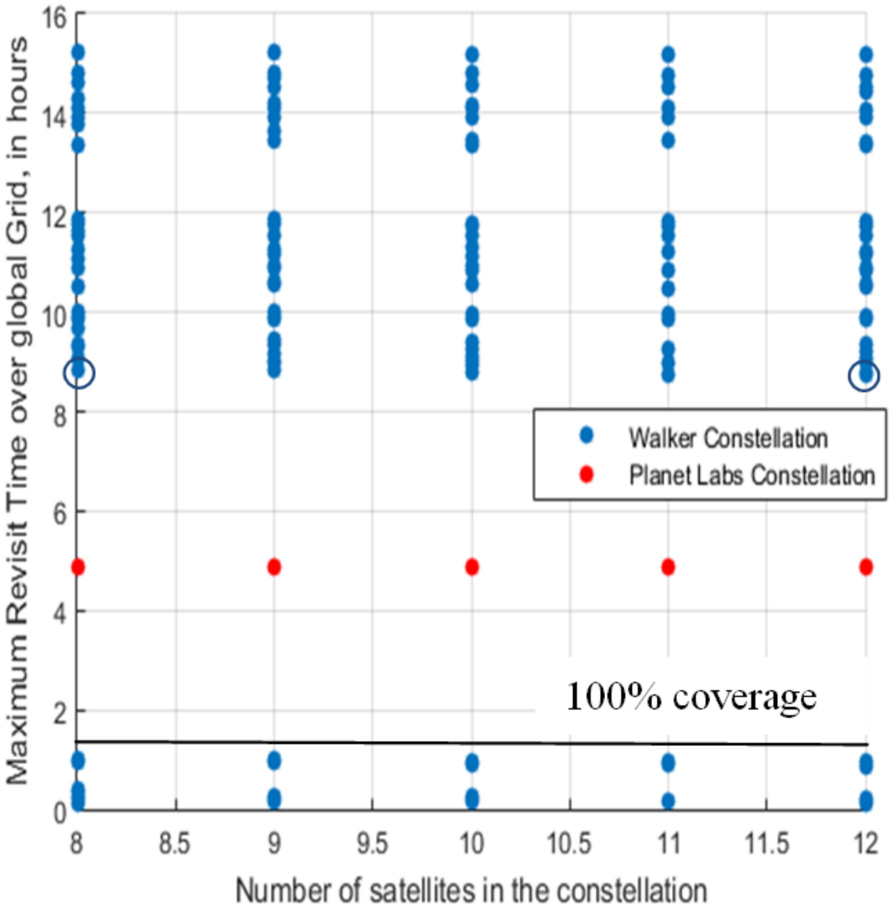


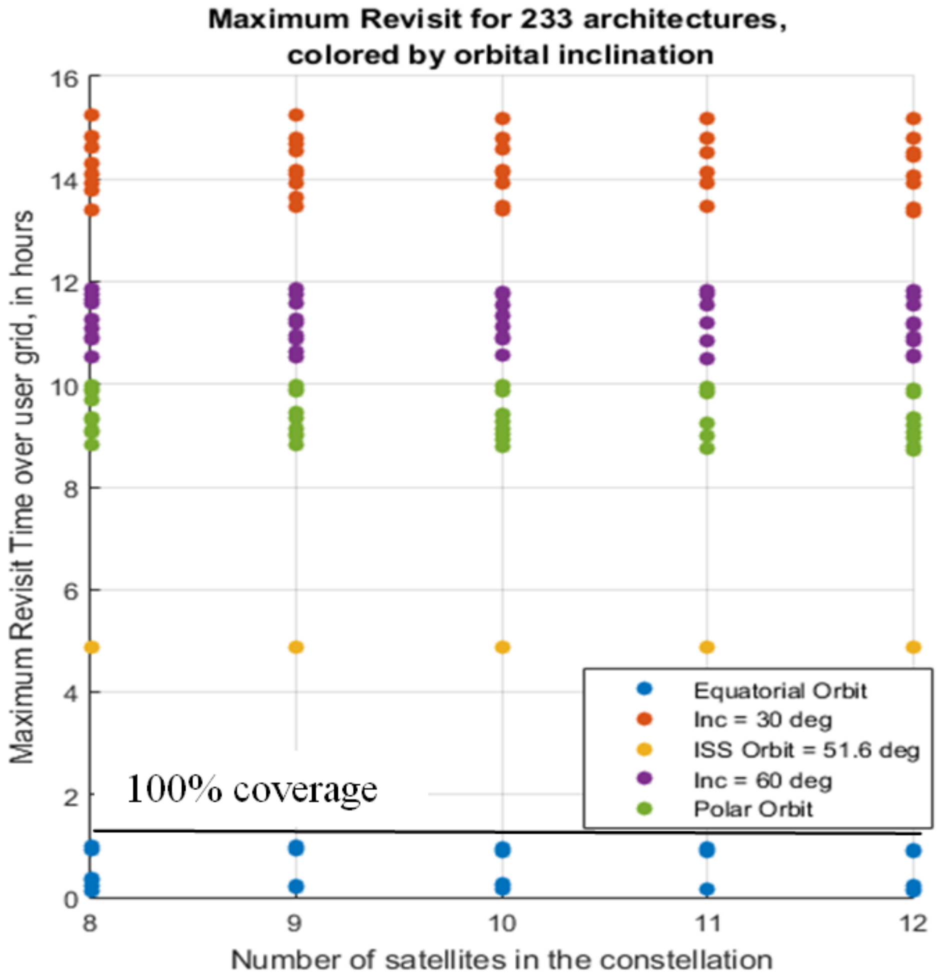


**Figures made with MATLAB for demo purposes. TAT-C's figures will be made with Python

Case Studies – Wide Angle Radiometer

130 deg FOV sensor w/ 8-12 sats in 500-700 km orbit looking within 40 deg parallels => 228 uniform Walker constellations and 5 Ad-Hoc constellations (1353 unique orbits). Run time = **40 minutes**.



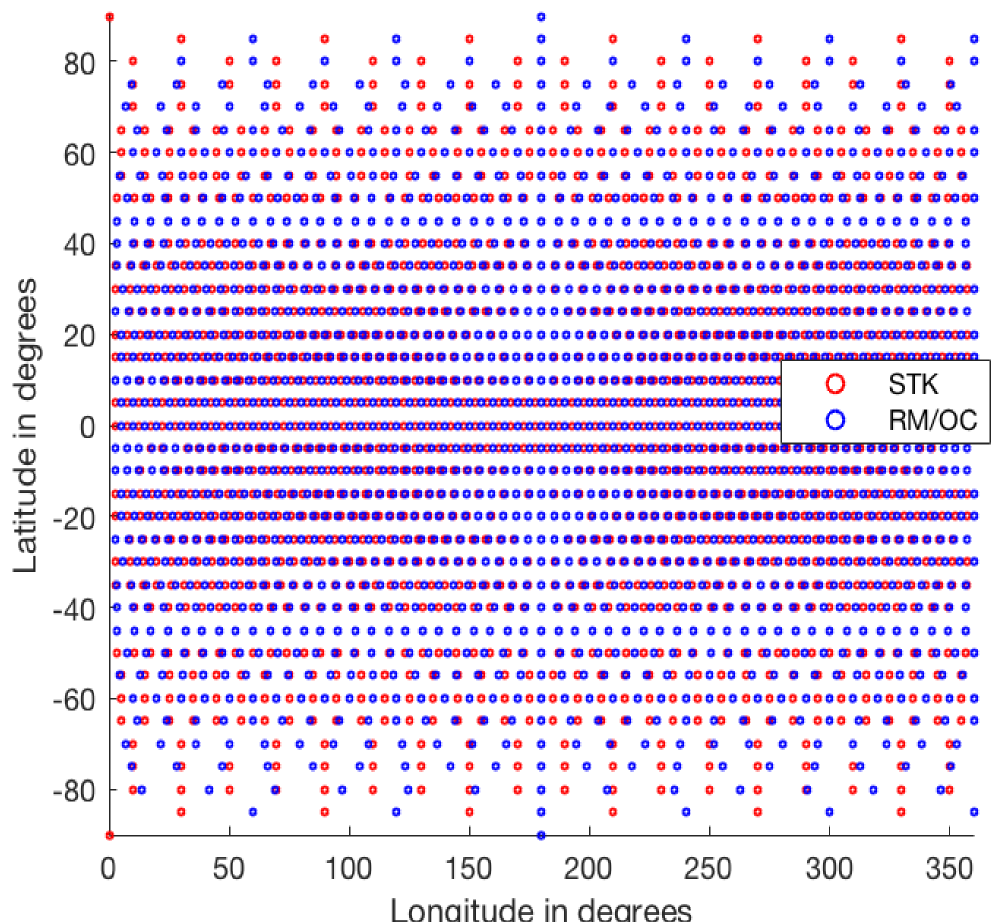


Initial Results Validation

Validation of Grid Points

The Area of Interest is discretized into grid points (user provided or OC generated)

The algorithm to place near-equally spaced points was termed the "Helical" algorithm by Schiff and Mailhe [7] as the points look much like what is obtained by peeling an orange in one piece.



Grid size of 10°, 5° and 1° for a full Earth grid = > RM/OC generated 412, 1650 and 41252 points respectively.
In comparison, STK generated 410, 1652 and 43424 points respectively.
ED thereby demonstrated less than 1% of grid spacing error globally.

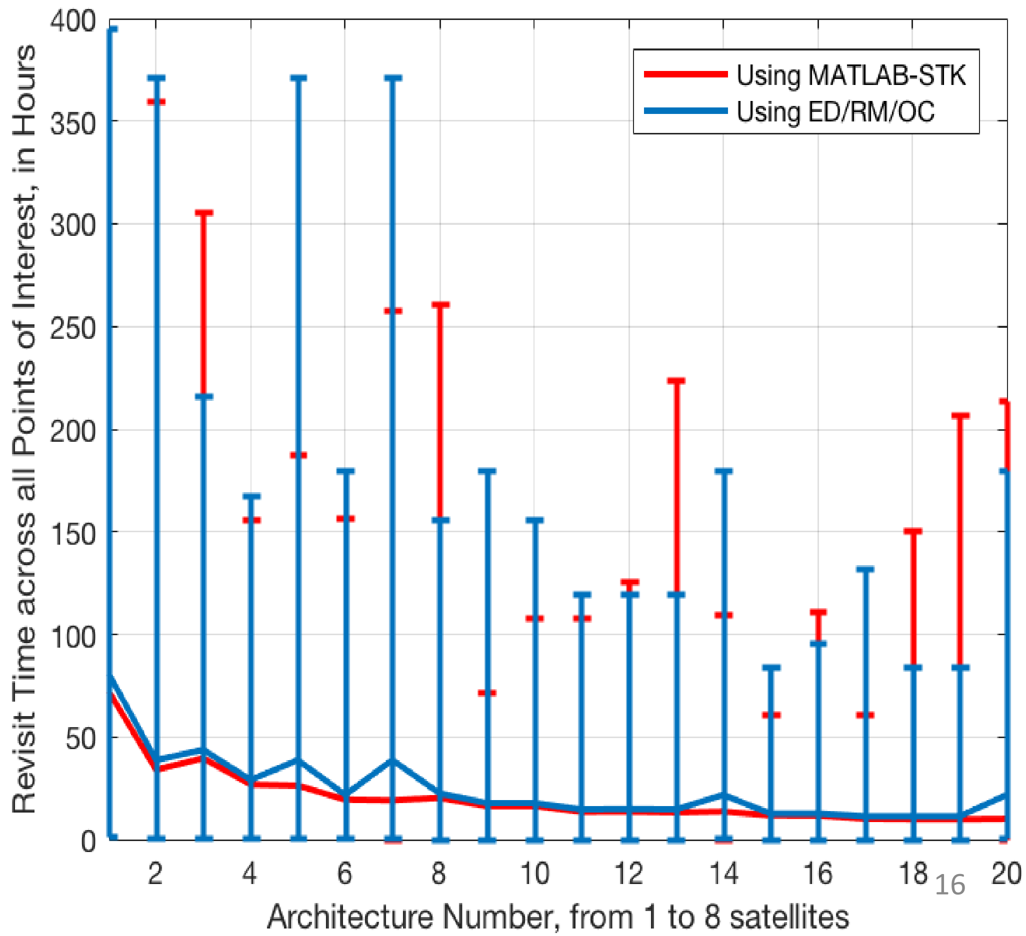
Initial Results Validation

Validation of Temporal Metrics – Landsat Use Case

STK+Matlab generated results vs. ED+RM+OC generated results. STK because of its high standing in the orbital mechanics community, utilization in several mission designs and decades of commercial success

Relative shape of the curves, especially in the average revisit time, is similar. Difference could be because of lower fidelity models in OC. **<15 hrs vs. 10+ days i.e. 16 times speed.**

SECONDARY CHECK: maximum revisit times for WFOV radiometer = 10.4883 hours by STK vs. 8.83 hours and 8.73 hours by ED, RM, OC. BUT for the single satellite revisit numbers matched up exactly. **1-5 sats => 10 mins**



Summary / Future Work

- Software tools for the pre-phase A design of constellations for Earth Science are essential to understand trade-offs at the concept stage
- TAT-C will facilitate DSM Pre-Phase A investigations and by allowing the users to optimize DSM designs with respect to a-priori science goals [Full tool in a future publication]
- Executive Driver (ED), Orbit and Coverage (OC), Data Reduction and Metric Computation (RM) modules read user inputs and output constraints, generate architectures of constellations, propagate them and evaluate metrics
- Use Cases – Landsat, Wide Angle Radiometer. Results validated against AGI STK
- Future work: Heterogeneous constellations and precession type constellations; Scaling tables within the ED where partial outputs can be processed to inform further tradespace; Concept of operations for non-imaging missions (e.g. occultation).

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Other AIAA presentation: Date/Time/Venue

Thank you!

Questions?

Sreeja.Nag@nasa.gov