Streamlining the Design Tradespace for Earth Imaging Constellations

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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.
Tradespace Search Iterator

Graphical User Interface

- User inputs:
  - Mission/Satellite/Payload Specs
  - Bounds on Output Variables
- User outputs per feasible architecture:
  - Summary & Space/Time Distribution of Metrics

Inputs as a JSON file

Executive Driver

- Checks logical, physical validity of inputs
- Determines ranges for all DSM architecture variables and their full factorial combinations (e.g. altitude, satellite number, constellation type) as a function of inputs and optionally from info from the knowledge base.

For each unique satellite with launch epoch:
- Makes a unique folder location, with a JSON file [1] specifying its specs, its payload/s specs and pointing schemes.

For each DSM architecture:
- Calculates analytical maintenance fuel and schedule.

Call exe once with all architectures as file tree of JSON files [1]&[2]

Reduction and Metrics

- For each unique satellite and GS:
  - Read specs from JSON [1] stored per satellite folder, command OC to propagate in steps, compute events, accumulate coverage and process data
- For each DSM arch detailed by JSON [2] in a unique folder, permute/combine the processed data, to compute metrics and store as csv files in the same location as JSON [2]

C++ Method Calls on Common Objects

Orbit and Coverage

- Computes grid coordinates based on lat/lon bounds and grid resolution. Propagates satellite as commanded, computes coverage to points/grid of interest and GS, accumulates coverage and angles of access over all events and returns all results to RM in memory. Mapping coverage Sat->DSM is in RM.

Cost and Risk

- Uses JSON file to calculate probabilistic distributions of cost and risk over mission lifetime. Stores results as JSON files in the same location as JSON file [3]

Knowledge Base

- Metric-to-variable maps from past Missions and/or simulations
- Maintenance specs from past Missions and/or simulations

- Call exe per arch with JSON file [3]

Pink: Python
Green: C++
Grey: Not covered in this paper
**Inputs to the Exec Driver:**

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

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### Mission Concept

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

### Orbit Specifications

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

### Satellite Specifications

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Mass</td>
<td>Approximate</td>
<td>Default is 2200 kg.</td>
</tr>
<tr>
<td>Satellite Volume</td>
<td>Approximate</td>
<td>Default is 1550 W.</td>
</tr>
<tr>
<td>Satellite Power</td>
<td>Approximate</td>
<td>Default is 26.4773 m³.</td>
</tr>
<tr>
<td>Maximum Slew Angle</td>
<td>min, max</td>
<td>Maximum coning angle in the along and cross track for a scanning satellite. Default is 0.</td>
</tr>
<tr>
<td>Scan Rate</td>
<td>min, max</td>
<td>Scan rate of the satellite, between the maximum angles. Default is 0.</td>
</tr>
<tr>
<td>Number of payloads/sat</td>
<td>Exact</td>
<td>For multi-instrument sats. Default is one. If more than one, all payload specs per instance.</td>
</tr>
<tr>
<td>Comm band</td>
<td>exact bands</td>
<td>For downlinking data to ground stations. Default is Ka-band.</td>
</tr>
</tbody>
</table>

### Payload Specifications

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occultation or Imaging or Pairs</td>
<td>Select</td>
<td>Determines payload’s measurement concepts. Imaging is default.</td>
</tr>
<tr>
<td>Payload Mass</td>
<td>Approximate</td>
<td>Default is 420 kg. Payload mass will be checked within reasonableness of sat mass.</td>
</tr>
<tr>
<td>Payload Volume</td>
<td>Approximate</td>
<td>Default is 590 W. Payload volume will be checked within reasonableness of sat volume.</td>
</tr>
<tr>
<td>Payload Power</td>
<td>Approximate</td>
<td>Default is 4 m³. Payload power will be checked within reasonableness of sat power.</td>
</tr>
<tr>
<td>Payload TRL</td>
<td>exact</td>
<td>Where is the payload at in the development cycle?</td>
</tr>
<tr>
<td>Radiometric resolution</td>
<td>min</td>
<td>Number of bits per pixel. 12 bits is default.</td>
</tr>
<tr>
<td>Occultation or Pairs coupling</td>
<td>Exact or file</td>
<td>Mark observer or occulter/pair, for every occulting or pairs mission.</td>
</tr>
<tr>
<td>Nadir swath or FOV</td>
<td>min, max OR exact</td>
<td>Conical or rectangular dimensions of the full spot size. Default is 15 deg in Along and Cross track.</td>
</tr>
<tr>
<td>Nadir GSD or iFOV</td>
<td>min, max OR exact</td>
<td>Conical or rectangular dimensions of a single pixel. Default is 30 m in Along and Cross track.</td>
</tr>
<tr>
<td>Object of interest</td>
<td>Select and/or file</td>
<td>Select between celestial body or ‘satellite’ if an occultation mission. Fill row 33 if latter. Default is Sun.</td>
</tr>
<tr>
<td>Occultation Altitude</td>
<td>max, min</td>
<td>Tangent altitudes between which occultation measurements will be made. Default is 10-50 km.</td>
</tr>
<tr>
<td>Measurement time</td>
<td>min, max</td>
<td>Sum of exposure and integration time per image or measurement. Default is half-travel time.</td>
</tr>
<tr>
<td>Solar conditions</td>
<td>Select</td>
<td>Determines if the sat is sunlit or eclipsed or agnostic when measuring. Default is agnostic.</td>
</tr>
<tr>
<td>Sun Glint preference</td>
<td>Select</td>
<td>Select if sun glint (&lt;5 deg relative and size) to be included, avoided or no preference. Default is no preference.</td>
</tr>
<tr>
<td>Spectral or other Channels</td>
<td>Exact wavelengths</td>
<td>Central wavelength for multi-spectral imaging. 300:100:1000 nm is default.</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>exact binwidths</td>
<td>Band or bin width of each central wavelength in the spectral range. 50 nm is default.</td>
</tr>
</tbody>
</table>
## Outputs from the RM Module

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

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

### Temporal Metrics

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

### Angular Metrics

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

### Radiometric Metrics

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal to Noise Ratio</td>
<td>min, max, average</td>
<td>Expected signal and noise (SNR) of each architecture's satellites with respect to a selected one.</td>
</tr>
</tbody>
</table>

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

```json
{
    "MissionConcepts": {
        "StartEpoch": 1455213665,
        "MissionDuration": "0:2592000",
        "PerformancePeriod": "0:2592000",
        "AreaOfInterest": "Landsat_landImages.txt",
        "ObjectsOfInterest": ""
    },
    "SatelliteOrbits": {
        "ExistingSatelliteOptions": "",
        "NumberOfNewSatellites": "1:8",
        "AltitudeRangeOfInterest": "710:710",
        "InclinationRangeOfInterest": "98.2:98.2",
        "SpecialOrbits": ""
    },
    "ObservatorySpecifications": "ObservatorySpecifications.txt",
    "InstrumentSpecifications": "InstrumentSpecifications.txt",
    "OutputBounds": {
        "TimeToCoverage": "",
        "AccessTime": "",
        "RevisitTime": "",
        "CrossOverlap": "",
        "AlongOverlap": "",
        "SignalNoiseRatio": "",
        "LunarPhase": "",
        "ObsZenith": "",
        "ObsAzimuth": "",
        "SunZenith": "",
        "DownlinkLatency": "",
        "SunAzimuth": "",
        "SpatialResolution": "",
        "CrossSwath": "",
        "AlongSwath": "",
        "Ob1Latitude": "",
        "Ob1Longitude": "",
        "Ob1Altitude": "",
        "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
│   │           └── Orb0000 GS00 Pnt000 Pay00
│   │               └── Orb0001 GS00 Pnt000 Pay00
│   │                   └── Orb0002 GS00 Pnt000 Pay00
│   │                       └── Orb0003 GS00 Pnt000 Pay00
│   │                           ...
│   └── DSMs
│       ├── Subspace0000
│       │   └── Manifest.json
│       │       └── CostRisk.json
│       │           └── gbl.csv
│       │               └── lcl.csv
│       │                   └── CostOutput.json
│       └── Subspace0000
│           └── Subspace0001
|               └── Subspace0002
|                   ...
```
Spatial Metric Dependence on Constellation Design Variables:

Given altitude, maximum spatial resolution or ground sample distance (GSD) is limited by maximum FOV. Even with a wide 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....
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.
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
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**
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**.
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?

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