Distributed Space Mission Design for Earth Observation using Model-based Performance Evaluation

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Abstract

Distributed Space Missions (DSMs) are gaining momentum in their application to earth observation missions owing to their unique ability to increase observation sampling in multiple dimensions. DSM design is a complex problem with many design variables, multiple objectives determining performance and cost and emergent, often unexpected, behaviors. There are very few open-access tools available to explore the tradespace of variables, minimize cost and maximize performance for pre-defined science goals, and therefore select the most optimal design. This paper presents a software tool that can multiple DSM architectures based on pre-defined design variable ranges and size those architectures in terms of pre-defined science and cost metrics. The tool will help a user select Pareto optimal DSM designs based on design of experiments techniques. The tool will be applied to some earth observation examples to demonstrate its applicability in making some key decisions between different performance metrics and cost metrics early in the design lifecycle.

1. Introduction

Distributed Space Missions (DSMs) are gaining momentum in their application to Earth Observation (EO) missions owing to their unique ability to increase observation sampling in spatial, spectral, angular and temporal dimensions simultaneously. Spatial resolution of an image can be increased by using multiple satellites in formation flight to synthesise a long baseline aperture as shown for optical interferometry[1] and synthetic aperture radars. Constellations of evenly spaced satellites on repeat track orbits ensure temporal sampling within a few hours as well as continuous coverage maintenance. Spectral sampling can be improved by fractionating the payload (fractionated spacecraft) such that each physical entity images a different part of the spectrum and has customized optics to do so. Angular sampling or the ability to look at the same point on the ground at different angles (for reflectance studies or navigation) improves by flying many satellites in formation[2]. Radiometric resolution depends on the resolution of the other sampling dimensions for a fixed instrument mass and complexity. Since DSMs allow sampling improvement in any dimension by increasing number of satellites in place of their individual sizes, radiometric resolution can be improved without compromising on other science sampling requirements.

Since traditional single satellites are called monolithic systems, DSMs can be considered homogeneous or heterogeneous combinations of monoliths. They include homogenous and heterogeneous constellations such as the Global Positioning System and A-Train respectively, autonomous formation flying clusters such as PRISMA, fractionated spacecraft such as the recently canceled System F6 Program[3] and cellularized systems such as the DARPA Phoenix Program[4]. Formation flight, as required in clusters, fractionation or cellularization, entails active control of the individual spacecrafts in order to maintain relative distances, orientations and geometry[5]. Fractionated spacecraft have the different spacecraft subsystems distributed over the physical entities and they exchange data, power and telemetry among each other (Figure 1-right). Cellularized systems are formed by assembling on-orbit resources called satlets to make aggregate but distributed systems.
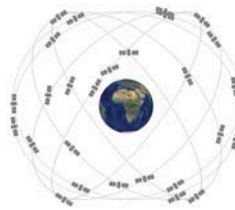
Since DSM architectures are defined by monolithic architecture variables and variables associated with the distributed framework, it leads to a large number of design variables. The number increases further in heterogeneous cases. DSMs are also expected to increase mission flexibility, scalability, evolvability and robustness as well as to minimize costs and risks associated with launch and operations. As a result, DSM design is a complex problem with many design variables, multiple objectives determining performance and cost and emergent, often unexpected, behaviors. There are very few open-access tools available to explore the tradespace of variables, minimize cost and maximize performance for pre-defined science goals, and therefore select the most optimal design.

2. Decisions in Space System Design

Space Systems are one of the most complex engineering systems designed by man and designing them. Designing them is not only technically challenging but also involves making hundreds of decisions early in the design cycle for allocating limited resources across the system and optimizing performance and cost. *EO performance* can be simplistically represented by spatial resolution, spatial range (swath, coverage), spectral resolution (wavelength bandwidth), spectral range (spectrum covered), angular resolution (number of view and solar illumination angles for the same image), angular range (spread of those angles), temporal range (mission lifetime), temporal resolution (repeat or revisit time), radiometric range (number of bits) and radiometric resolution (bits, signal to noise ratio).

2.1. Monolithic Systems - Traditional

Decisions in monolithic systems include but are not restricted to allocations of resources such as mass, power and volume among different subsystems. For example, stable imagery of the Earth requires better pointing control which requires better attitude control systems therefore more mass, power and cost. High resolution images need higher downlink capacities,

which in turn need bigger antennas and bandwidth. Onboard storage and processing capabilities can relieve communication requirements but at the cost of bigger and better processors. Longer lifetimes for satellites save on development and launch costs for follow-on missions and ensure continued science, however need more reliable electronics and radiation hardening either using thicker aluminum or code. More mass and power to orbit translates to development and launch costs. Since better images, as those indicated above, as direct metrics of Earth Observation performance, it needs to be traded against increasing need for resources.

Conflicting trade-offs seen and associated decisions are required not only among subsystems but also choice of an orbit for the satellite. Lower altitude orbits provide more spatial resolution because of smaller pixels but lower temporal resolution because the orbital velocity is slower. Increasing the instrument field of view (FOV) increases global coverage but more than 15 deg FOV causes angular resolution to be too coarse for earth science applications[6]. Larger FOV allows frequent revisits but has no direct affect on repeats, which is a function of altitude and inclination only. Repeat period is the time to visit the same ground spot at exactly the same look angle while revisit is to visit the same at any look angle. Polar orbits allow global coverage and also the possibility of regular solar illumination essential for many earth science applications (called sun synchronicity) however equatorial orbits allow frequent revisits of the tropical regions. Sun synchronous orbits also allow far less launch flexibility than regular orbits. Therefore, orbit inclination choices are also a quantitative decision.

2.2. Distributed Systems - Revolutionary

Distributed systems have all the trades associated with monolithic systems *and* more associated with the network. Extra design variables include but are not restricted to the number of satellites and their individual masses, their orbits and inter-satellite spacing, existence and nature of inter-satellite communication and downlink schedules. These variables directly impact performance and cost.

Performance variables, as defined earlier, can be mutually conflicting across the spatial, spectral, temporal, angular and radiometric dimensions and

within each dimension. For example, most earth observation satellites are put in repeat ground track orbits so that the same point on the Earth is revisited regularly and frequently. Obviously, more frequent revisits imply that the rotation of the Earth and the orbit has to be adjusted in such a way that the satellite comes back to the same spot frequently, and as a result has less time to visit similar spots on other longitudes. Therefore, global spatial coverage or spatial range and temporal resolution are conflicting metrics. Both can be improved by increasing the swath of satellite or the size of any instantaneous ground image. However, for a given number of pixels in an image, increasing its size or swath with increase the size of the pixels and coarsen resolution. Therefore, spatial range and temporal resolution are both conflicting metrics with respect to spatial resolution. Design variables need to be permuted to consider architectures that trade these metrics for an optimal design.
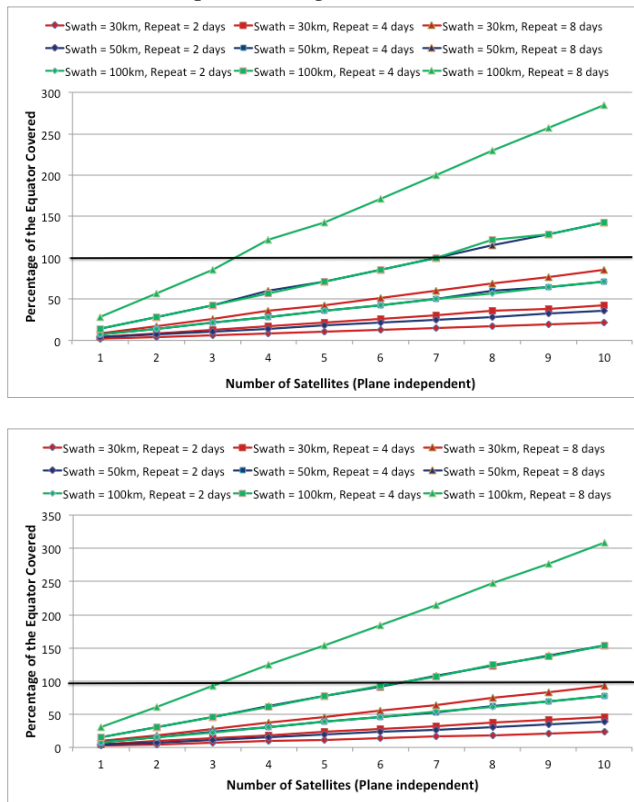

Figure 2: Trade-off between the number of satellites (X-axis), spatial coverage at the Equator (Y-axis), spatial resolution (function of swath, shown in colors), temporal resolution (repeat period shown in marker shapes) and altitude (top: 780km, bottom: 350 km). Thick black line indicates full equatorial coverage.

Figure 2 shows the results of spatial coverage at the equator as a function of the number of satellites in the constellation, temporal resolution (repeat time of 2, 4, 8 days) and spatial range (swath of 30, 50, 100 km) for a Walker constellation deployed at the altitude of the Iridium Comm Constellation or 780 km and the International Space Station (ISS) or 350 km. Only the architectures below the black line achieve full global coverage. For example, for a 50 km swath and 8 day repeat (blue triangles), a minimum of 7 and 6 satellites is needed respectively. If spatial resolution can be compromised to half and swath 100 km is allowed, then the same number of satellites can provide a 4 day repeat (double temporal resolution).

Since the above coverage analysis is performed only at the Equator, the trade-off is linear. Revisit time is independent of the constellation arrangement hence very simple, unlike other temporal metrics. Global coverage analysis over the full latitude-longitude grid is non-linear, not as predictable and is an example of only one conflicting trade-off between the different performance dimensions in Earth Observation. There are many other complex decisions that will be discussed in detail in Section 3 and 5, hence the need for a comprehensive trade tool.

3. Software Tools for SpaceSystem Design

Computational tools for spacecraft and system design have been very important in making early design decisions. Model-based systems engineering is a focus of the INCOSE working groups and the developed tools have been applied to existing missions such as RAX[7] and PHOENIX[4]. Tools for space logistics and interplanetary transportation such SpaceNET, modular and open source, are also available[8]. The CubeSAT standard and associated documentation also provides an excellent resource to develop and integrate anything upto 3U (4 kg) spacecrafts[9].

3.1. Existing Tools in Distributed Space Missions

Existing tools for monolithic spacecraft and other space design can be and have been adapted for distributed space systems. Individual components of space system design can be combined from different softwares. For example, orbit design can be done using NASA

GSFC's GMAT tool or NASA JSC's Copernicus tool. Spacecraft operations can be aided by NASA JPL's APGEN, ASPEN or Maestro tools. Specific interfaces for risk and science return for Saturn and Mars missions are also available. Tools for specific science data analysis such as USGS's ISIS and ESA's Rosetta Science Planning tool can be modified for some mission design. Cost and risk associated with distributed launches, staged deployment and reconfigurable constellations, all of which allow flexible design but also increased costs, have been academically studied at MIT[10], [11].

3.2. *Need for a new Tool for Earth Observation*

While all the above tools are great for specific missions and specific components, there is no off-the-shelf, modular tool for DSM design that can be used at the high-level architecture phase when key decisions are made. With the advent of hundreds of small sats in orbit currently and companies such as PlanetLabs and Skybox launching constellations in dozens, there is need for an integrated and modular tool which will modify MBSE for DSMs and enable easy plug into science metrics such as those for earth observation (extendable to astrophysics or navigation, etc.). Such a tool will allow rapid simulation of hundreds of architectures and their valuation so that the "best" ones can be selected early in the design cycle.

4. Description of a New Software Tool for Distributed System Design

We are currently developing a software tool, developed on the MATLAB engine interfaced with Systems Tool Kit or STK[12], that is based on tightly coupled science and engineering models. The *orbits module* can generate multiple DSM architectures based on pre-defined design variable ranges and size those architectures in terms of pre-defined science and cost metrics. Design variables include but are not restricted to mission lifetime, constellation type, chief orbit of the formation, differential orbital elements in a formation, FOV of instrument, altitude, latitudes or regions of interest, inclination, planes and satellite numbers. Intermediate performance metrics include number of accesses, revisit time, coverage access and angular coverage at every point of the Earth's grid as well as average values. The *payload module* interfaces with the

orbits and control modules and has been described in detail in [13]. Design variables include ground pixel size, look and solar angles, altitude, wavelengths, pixel numbers, spectral elements, wavebands, pointing errors. Final performance metrics, based on science goals, are a function of the intermediate metrics. The tool will help a user select Pareto optimal DSM designs based on design of experiments techniques.

Model-Based Systems Engineering (MBSE) has demonstrated success in small satellite design[7] in trading conflicting design variables and is a useful tool for pre-Phase A DSM design. MBSE may be extended to DSM design since it is a function of a much larger number of variables than its monolithic counterparts as well as has higher costs, and thus imperative to understand the trade-offs and interdependencies among the variables early in the design stage. In the traditional sense, observing system simulation experiments (OSSE) are used to quantify the impact of observations from future observation systems such as satellite instruments or ground-based networks on e.g. weather forecasts, by mimicking the process of data assimilation. In land or atmospheric applications alike, they have been used to validate science return for proposed instruments and therefore tweak their designs better.

Our tradespace sofware tool combines the MBSE approach with the OSSE approach. The tool enumerates dozens of architectures with different combinations of the design variables. Constraints may also be added; For example, altitude-inclination combinations as available for easy commercial launches or spectral elements/detectors as available within specific organizations[13]. The tool has previously been applied to formation flight design for angular reflectance measurements to estimate bi-directional reflectance distribution functions[2],[14], global earth radiation budget estimations[15] and snapshot imager selections for angular acquisition[13]. The tradespace of designs can be analyzed by varying the variables in the MBSE model and assessing its effect on data assimilation and science products using OSSEs. This paper introduces *only* the architecture enumeration and technical metrics (which serve as inputs to the OSSE models) of the tool and discusses their applicability in making design decisions.

Decisions are obviously more refined when the OSSE component and science impact is considered, as shown in separate literature for constellations[15] and formation flight[2].

4.1. Spatial and Temporal Sampling

Spatial coverage and sampling is a product of the orbits module, given inputs from the payload module (for pixel sizes and spectrometer type). Parameters such as the grid size on the earth (default: 5degX5deg in both latitude and longitude) and time sampling (default: 1 minute) can be defined. Using the required characteristics, automatic scripts on MATLAB drive STK to generate multiple architectures on STK by permuting the orbit design variables. Three architectures are pictured in Figure 3's left column. MATLAB-driven STK commands each architecture to generate a full access report as a .cvaa file, many of which are seen in Figure 3's second column. The reports are named in keeping with the design variables for easy post-processing. For example, the first one is a 1 plane, 1 satellite (monolithic) design at a 400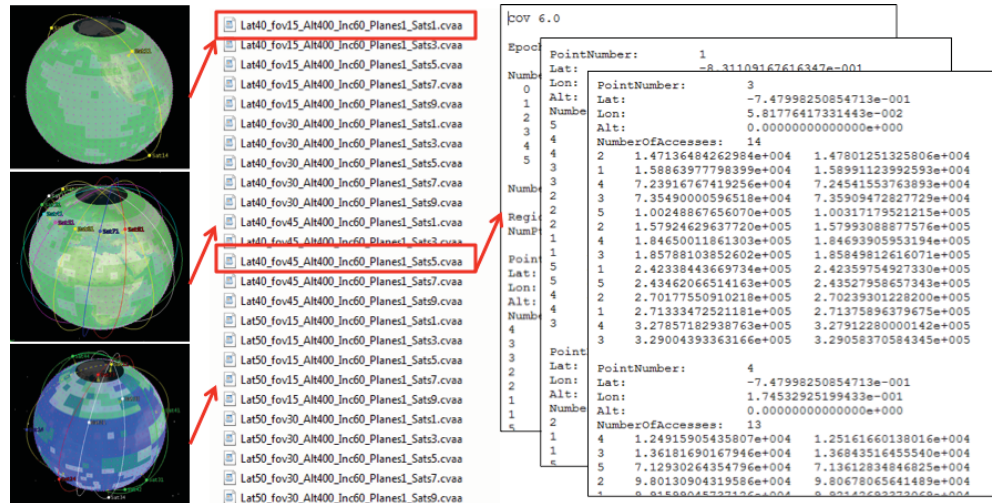 km altitude and 60 deg inclination with a 15 deg instrument field of view with latitudes of interest below 40 deg. Each access report is a detailed text file - Figure 3 third column - containing the time period (from when to when) at which every grid point is accessed by every sensor. The file is post-processed to provide customized temporal metrics such as revisit time, time for first access, number of accesses, time for global coverage, etc. for every grid point and the globe. Science metrics dependent on such temporal metrics can easily be calculated by plugging in another module, modeled after an OSSE. Since the analysis is global and across any length of mission lifetime, the metrics calculated are spatial and temporal.

A separate script is also available for analyzing specific grid points in the same way as above, thus saving the computational resources required for full global analysis. For any target location or ground station, a text access report is automatically generated by MATLAB-commanded STK and automatically repeated for many architecture. Each generates an access report, which can be post-processed to generate customized metrics as described above.

Figure 3: Process Flow for Temporal Metric calculation globally or specific areas or latitudes of interest.

4.2. Angular or Customized Sampling

STK, without the parallel processing license and dozens of available cores, was found to be inefficient for architecture studies using customized metrics. Angular coverage will be discussed as a case study, because it is a new area of interest owing to the need of measuring Earth reflectance at different angles for products such as albedo and total outgoing radiation. For angular sampling metrics, the following angles are required to be calculated at every grid point and time instant for every architecture: measurement zenith angle or MZA for each satellite (angle between the satellite vector at the ground spot and the zenith; <90 deg), solar zenith angle or SZA (angle between the sun vector at the ground spot and the zenith; <90 deg for solar spectrum) and relative azimuth angle or RAZ (angle on the horizontal between the satellite vector projection and sun vector projection at the ground spot;

<360 deg). The number of calculated angles is the product of the number of ground points (1651 by default), number of satellites, number of angles (3 by default), number of architectures and number of time steps (1441 if in minutes, for just one day). The only way to calculate all of them is using a tool called Grid Inspector which loops over the number of points, satellites and angles, and re-calculates access for all loops, therefore taking 5 days to compute only 1 angle for a 64 satellite constellation.

To improve efficiency, our tool restricts the use of STK for customized metric calculations outside of temporal and spatial analysis. First, the High Precision Orbit Propagator (HPOP) using the Jaccia-Roberts Atmospheric Model as upto J4 terms is used to propagate the orbits for all satellites in every

architecture and the resultant states per time step saved as text files. Second, the access reports for all architectures – as seen in Figure 3 - are saved for exact global coverage. Third, the grid point information is saved. These three outputs from STK are then post-processed to calculate the required hundreds of thousands of angles offline. The results are validated against those calculated by STK's Grid Inspector for one satellite propagated over one day. A reasonably good fit is seen for all grid points and all times with less than 5 deg of average error. This error is less than half the angular resolution available by a grid and time resolution of 5 deg and 1 min, for a satellite ground velocity of 7.3 km/s, hence considered negligible. All sampled angles and their dependent metrics, or any other customized metrics dependent on global or temporal coverage, will be calculated in the above way
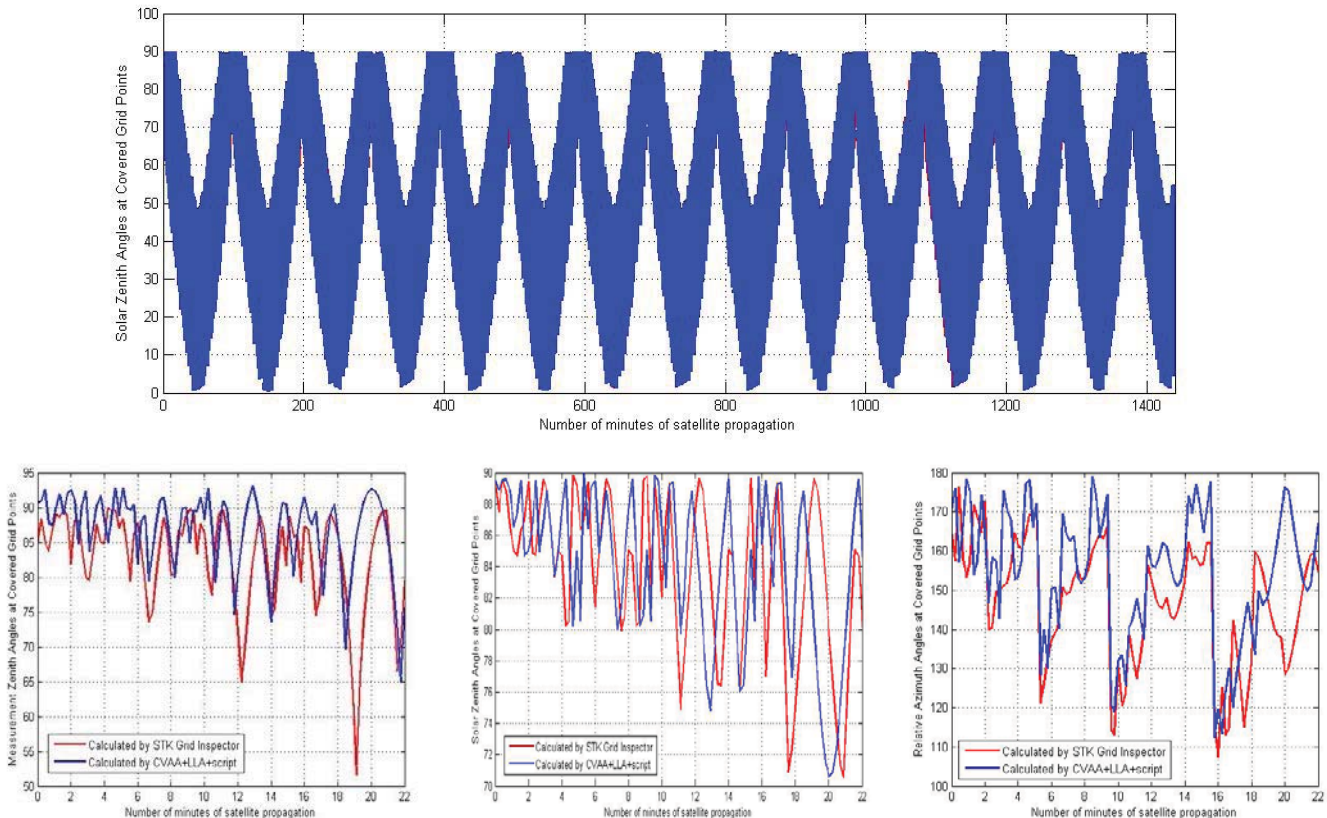

Figure 4: Validation of the solar illumination and view angles calculated by the proposed tool (blue) at every grid point and time instant those calculated by the Systems Tool kit (red). The top panel shows one angle as seen by a single satellite at every minute for a day while the bottom panels show all three angles over a 22 minute period, for better visualization. Average error is <5 deg, negligible compared to the grid resolution of 5 deg and time resolution of 1 min, for a satellite ground velocity of 7.3 km/s.

4.3. Others - Spectral Sampling, Cost, Risk

Performance of any architecture is also determined by the extent of spectral sampling in the image – both spectral range or the amount of spectrum and spectral resolution or the width of each wavelength band. All the performance metrics of every architecture are then compared to the cost and risk of development and operations to make a Pareto optimal decision.

The spectral sampling trades are primarily a function of the payload of the satellite and the type of spectrometer or radiometer being used. The payload model[13] is a MATLAB-based tool that calculates the effect of the design variables on optical system requirements such as detector pixels, focal plane size, focal length, aperture diameter and eventually on system metrics such as signal to noise ratio (SNR), swath and number of wavebands possible. The metrics are conflicting in themselves hence decisions on the design must be made after considering the trade-offs between the metrics. The payload model is inherently dependent on the types of available spectral elements, and has been described in detail in [13]. Examples of some trade-offs will be shown in the next section.

The cost model is discussed in detail in [11]. Its development has been challenging due to the unavailability of enough data on pricing the cost of multiple copies of the same unit as well as operations cost of a complex multi-disciplinary system.
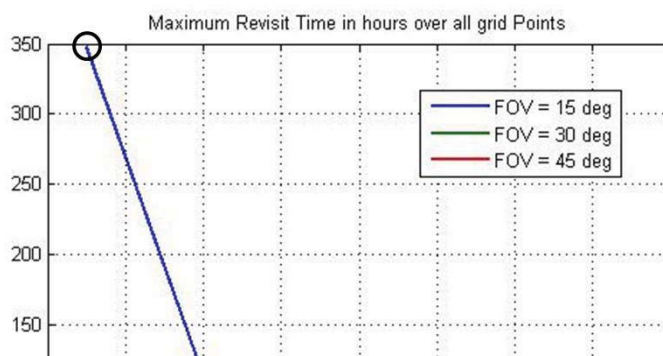
5. Example Applications of the Tool

The described tool for designing distributed space systems is applied to a few candidate examples in earth observation to demonstrate its utility in making decisions after due consideration to multiple conflicting objectives of performance i.e. spatial, spectral, angular and temporal sampling, and cost.

5.1. Temporal vs. Spatial Trade-Off

A simple example of temporal vs. spatial trade-off at the Equator was seen in Figure 2. If revisit time is considered as a metric instead of repeat time, the calculations are more complicated because revisit is a non-linear and non-analytical function of orbits of satellites, their relative arrangement, payload FOV and geographic location of the points on Earth.

A Walker constellation with varying number of satellites (arrangement not considered because it does not affect revisit time as long as uniformly arranged) and FOVs were simulated for a constant altitude of 709 km and inclination of 98.18 deg, in keeping with the orbit of the A-Train and EOS satellites. Only latitudes below 70 deg were considered. Figure 5 shows the maximum revisit time provided by all the architectures.

All other variables baselined, Revisit Time in hours for 16 Satellites
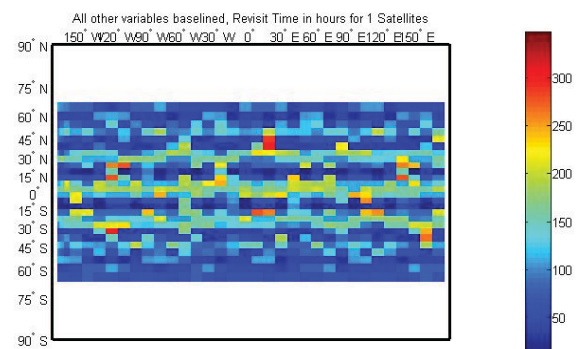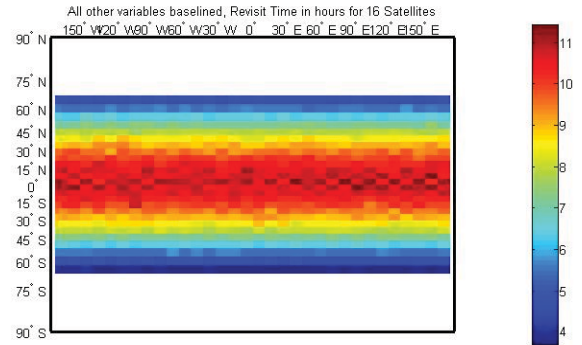
Figure 5: Results from our temporal trade tool using Revisit time as a metric. [Left] Maximum revisit time over all gridpoints as a function of payload FOV and number of satellites in a Walker constellation at 709 km altitude, 98.18 deg inclination. The thick black line indicates at least a 24 hour revisit for any point and the black circles indicate the designs for which global revisit time is shown on the right. [Right] Average revisit time at every grid point, calculated over a 16 day period, for a 1 (top) and 16 (bottom) satellite constellation.

The current monolithic spacecrafts with 15 deg FOV (e.g. Landsat) provide a 350 hour revisit – black circle on Figure 5's left and full global map on Figure 5's right top. The results show that at least 14 such satellites are required for a daily revisit (Figure 5 black line) and 16 satellites for a daily repeat (analytical calculation). By doubling the FOV to 30 deg allows the same revisit in about quarter the satellites (4 satellites). The right panel also shows that revisits are far more frequent at higher latitudes than lower ones for polar constellations. While revisit time does not depend on constellation arrangement, metrics such as time required for full global coverage does. Figure 6 shows the time taken for the last grid point on the globe is accessed by different constellation architectures. The results from our tool show that global coverage is faster if the same number of satellites are arranged in more planes. In fact, lesser number of satellites (e.g. 8 satellites in red vs. 12 satellites in grey) can achieve coverage faster if arranged in more planes. The trade-off however is in terms of cost because launching into 8 planes requires 8 times more fuel or needs 8 times the number of launches than launching into 1 plane. The increased performance and cost saved in developing 4 extra satellites can be compared against the cost of launching into 8 instead of 1 plane for the optimal design decision.
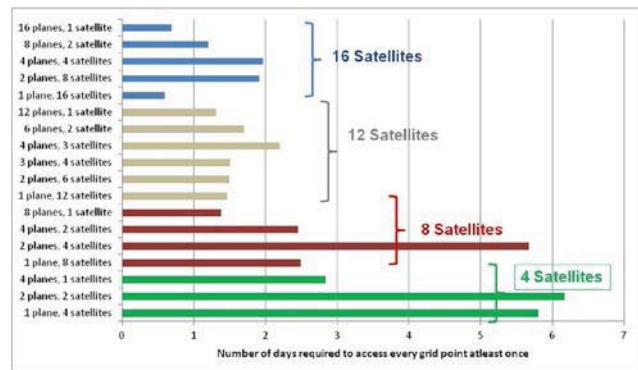

Figure 6: Time required to global coverage for Walker constellations (at 709 km, 98.18 deg) with varying number of satellites and their planar arrangement. Walker Delta constellations, on an average, show lesser time than Walker Star.

The 8 satellite arrangement can be further analyzed by plotting the timeline of global access (until 100% is accessed) - Figure 7. Walker Delta arrangements are seen to be better than Walker Star in time to global access and all curves are compared to the monolithic counterpart in the same orbit. The monolith takes 14 days for full global access as seen earlier and is shown with a black line, called 'Landsat' because it is an existing spacecraft in the same orbit with a 16-day repeat cycle. Figure 7's curves are very useful in deciding which design to choose depending on the integration time available over measurements and the coverage flexibility. For example, if a 2 day integration time is available, then the 8 plane constellation is equivalent to having continuous global coverage and there is no value in adding more satellites. Our tool

can be used to select a design, given a required temporal resolution, spatial coverage and budget.
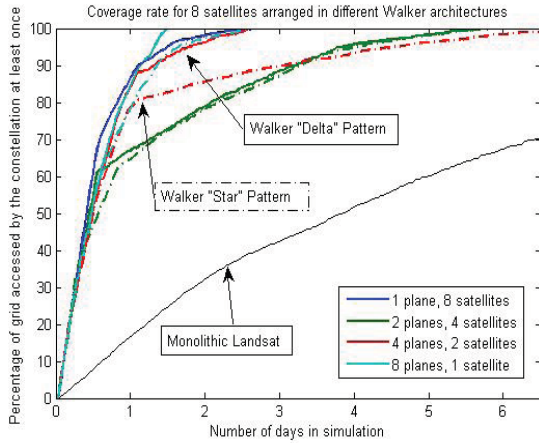

Figure 7: Percentage of the globe covered with respect to time for Walker constellations (at 709 km, 98.18 deg) with 8 satellites arranged in different planes (colors) and in Delta (continuous line) or Star (dotted line) arrangements.

5.2. Angular vs. Spatial Trade-Off

Angular coverage is achieved by looking at the same ground spot at different angles using multiple satellites and at different sun illumination angles. For the same set of optics, increasing look angles causes the ground spot to increase in size and spatial resolution to coarsen trigonometrically[13]. This angular effect and coarse resolution is also the reason that most EO satellites such as Landsat guard against their FOV exceeding 30 deg[6]. Since the diffraction limited aperture diameter of the payload and its associated focal length increases with finer spatial resolution and higher altitudes, a design decision based on informed trade-offs is critical. Larger optics need larger space structures and increase costs. Figure 8 shows the minimum required payload diameter as a function of the above variables. Focal length for a shutter F# of 1.5 has been contoured. Such results from the tool help decide on the design of optics, given a required range of angular range, spatial resolution (GSD) and spacecraft chassis constraints.

Spatial range or swath, as seen in Figure 9, is a function of slant height from the ground pixel to the aperture, number of pixels and the type of spectrometer used. Slant height is affected by altitude and look angle as contoured in Figure 9. Spectrometer dependence is analyzed by comparing two types of

spectrometers: AOTF and WG. AOTFs are tunable filters which take 2D spatial images at every instant and sample the full spectral range in time, as the aperture remains exposed to the ground spot. Thus, all the pixels on the AOTF FPA are available for spatial imaging because the spectral signal is extracted temporally, but the total number of pixels for the AOTF spectrometer is severely restricted to allow for imaging and readout of all spectral bands (86 in Figure 9). A waveguide (WG) spectrometer uses optical waveguides to extract the spectral content of each pixel in the 2D image so the total pixels on the WG FPA are shared between 86 spectral bands and actual spatial pixels, limiting the swath. The trade-off between spatial range, angular range and pixel number is apparent from the results and helps make a design decision. AOTFs provide less than a third of the swath compared to WGs so Figure 9 scales down by a third.
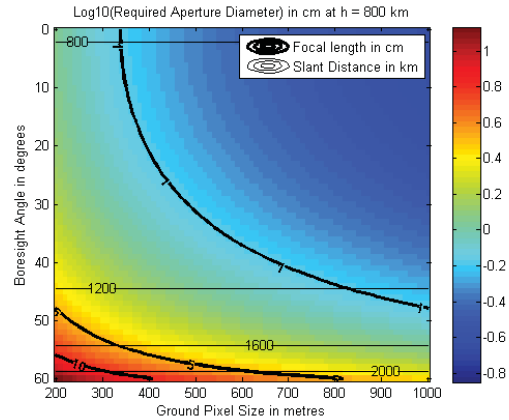

Figure 8: Variation of required aperture diameter (as log10) at altitude = 800 km as a function of look angle to the image and ground resolution. The corresponding required focal length and the slant distances are contoured. Lower altitudes need lower diameters and focal lengths (not shown).
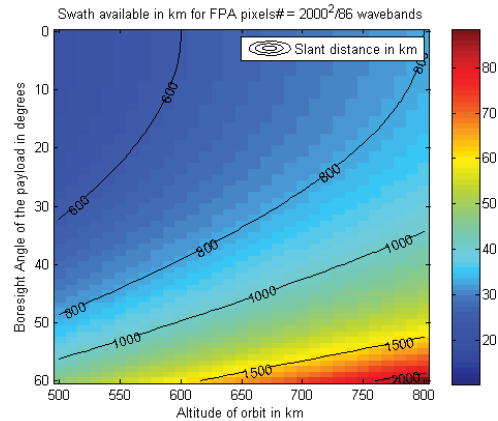
Figure 9: Simulated swath for a WG spectrometer as a function of a given number of FPA pixels – marked on top and arranged differently for each spec, look angles to the image and altitude. More pixels provide more swath and the AOTF spectral extraction mechanism less swath (both dependences not shown for compactness).

6. Conclusion and Future Work

We introduce the complex problem of DSM design decision-making and initial results of a modular tool being developed for the purpose. Future work includes integrating the tool into GSFC's GMAT and make it python-based to remove the closed license dependence on STK and MATLAB. It will then be made freely available to all communities.

5.3. *Spatial vs. Spectral Trade-Off*

As was apparent from the previous discussion, either the imaging and read out time (AOTFs) or the FPA pixels (WGs) need to be shared between the spatial and spectral content of any image, thus leading to conflicting performance metrics and the need to make a decision between them.
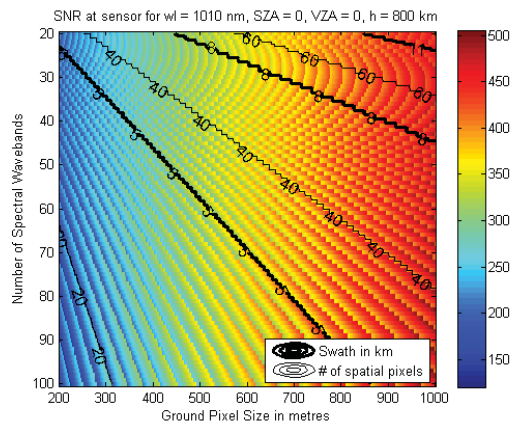

Figure 10: Simulated SNR for AOTFs as a function of spectral wavebands and ground resolution required to be imaged for a nadir looking satellite at 800 km, wavelength of 1010 nm and solar incidence at noon. The contours represent achievable swath (thick black) and effective number of spatial pixels available on the FPA (thin black), calculated dynamically to maximize swath for at least 5% image integration time.

In order to operate within nominal radiometric resolutions, spectral range and spatial range will need to be traded off among each other. Our tool provides more quantitative estimates of the *signal to noise ratio (SNR)* for this purpose as seen in Figure 10[13] (only AOTF shown for compactness). Dependence of SNR on spatial range (swath), resolution (GSD), spectral resolution (wavebands), angular range (SZA,VZA=0 shown only) and altitude is seen. The tool's results can be used to make informed design decisions and behavior of the trade-offs has been explained in [13].

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