IGARSS 2021 - 2021 IEEE International Geoscience and Remote Sensing Symposium | 978-1-6654-0369-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/IGARSS47720.2021.9553234

HETEROGENEOUS CONSTELLATION DESIGN FOR A SMART SOIL MOISTURE RADAR MISSION

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ABSTRACT

This article explores the tradespace for a constellation of heterogeneous smart satellites intended to measure soil moisture using a combination of L and P band radars, radiometers, and reflectometers. Orbit inclination, repeat cycle, number of satellites, and number of planes were treated as input variables to create a set of architectures for evaluation. Attempting to optimize multiple output variables (cost, average revisit time, maximum revisit time, and percent coverage) results in a complex tradespace with suitable options at various cost caps. Therefore, several cost ranges are examined to find the best constellation for a given cost cap. It was found that a relatively simple constellation of three satellites in one plane offers acceptable performance at a low cost. This preliminary submission shows results for a homogeneous constellation, while the final paper will include satellites with various instrument configurations.

Index Terms— Constellation design, tradespace exploration, soil moisture.

1. INTRODUCTION

Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions (D-SHIELD) [1] is a NASA project to develop a software tool to simulate constellations with science-driven task planning. The tool requires a constellation to simulate, for which we are performing this tradespace exploration. Tradespace exploration is a useful method for examining potential options, or architectures, in early mission design efforts [2]. As a case study for the tool, we are examining the design of a constellation of heterogeneous satellites to provide global, daily high-resolution (1km) measurements of soil moisture. The primary instruments under consideration are L and P band radars, radiometers, and reflectometers. It is difficult to assign a value to a given constellation design, especially in a computationally inexpensive manner. This issue is compounded by the fact that this is a mission focused on developing a capability rather than being driven directly by scientific stakeholders. The final version of this paper will contain a more comprehensive review of scientific value, in particular the science score provided by the Value Assessment of System Architectures Using Rules (VASSAR) tool [3]. Since a single measure of scientific value is not available at the current stage of the paper, multiple objectives are considered for this abstract. Section 2 explains the approach to constructing and evaluating the tradespace. Section 3 shows the results of the tradespace exploration. Section 4 provides a conclusion and discusses future work.

2. APPROACH

To explore the mission design tradespace, a full factorial enumeration of the architecture space is done. The architecture space is defined by a set of design variables, allowed ranges, and constraints. Each "architecture" is instantiated by assigning an allowed value to each of the design variables. Once enumerated, the architectures are evaluated using the Orekit astrodynamics library [4] for coverage performance metrics and the USCM8 cost model [5] for the lifecycle cost estimate. The rest of this section provides the details of the architectures and figures of merit considered in the analysis.

2.1. Architecture Enumeration

In the current state of this paper, we restricted the analysis to homogeneous Walker Delta configurations. A specific "architecture" is defined by the orbit (altitude, inclination), the number of planes of satellites, and the number of satellites per plane. The number of planes ranged from 1 to 4, and the number of satellites per plane also ranged from 1 to 4. However, the maximum number of satellites was capped at 6 due to cost considerations, which significantly limited the number of possible combinations. Each satellite has the same payload - an L-band/P-band radar sharing a common dish. As in many Earth observation missions, especially with narrower swaths, a repeat ground track is desirable. Repeat cycles up to 10 days were considered. Since the radars are designed for a 500 km altitude, orbits between 495 and 505 km were

Mass	77 kg
Power consumption	1000 W
Duty cycle	10%
Data rate	40.4 Mbps

Table 1. Radar parameters used as inputs for the tradespace exploration.

searched for repeat ground tracks. Inclinations between 0 and 90 degrees were considered. While retrograde orbits experience different precession than prograde orbits, the difference in coverage between inclinations was of greater interest for this work.

For reference, the instrument parameters for the L- and P-band radars are shown in Table 1.

For the final paper, the radiometers and reflectometers will be included in the architecture space, and we will expand the architecture space to include truly heterogeneous architectures where different satellites have different payloads. Heterogeneous constellation design has been explored previously in [6]. We will also add sun-synchronous orbits.

2.2. Architecture Evaluation

For this work, four objectives were examined: percent coverage in 24 hours, average revisit time, maximum revisit time, and cost. Percent coverage in 24 hours is used as a measure of distinguishing between the coverage performance of architectures that cover only part of the globe with better revisit time (e.g., low inclination or low repeat cycle) vs architectures with truly global coverage but worse revisit time. Average and maximum revisit time, accordingly, are only calculated based on points visible to the relevant architecture, not on the entirety of the coverage grid. Cost as an objective shapes the tradespace by prohibiting large constellations.

To evaluate the coverage metrics, the orbital dynamics library Orekit [ref] was used. The propagation only included the J2 perturbation, as the simulation time of 30 days meant that changes in the orbital elements due to higher order perturbations would have little effect on the coverage calculation. The simulation time of 30 days is short enough that drag will not significantly affect coverage calculations, but long enough to evaluate satellites with repeat cycles up to 10 days. To calculate coverage, a grid of points was distributed over the Earth's land area, spaced by two degrees in both latitude and longitude. Only latitudes between -75 and 75 degrees were considered. The field of regard of the instruments was represented by a 15 degree half-angle imager pointed 45 degrees away from the local vertical, and mirrored across the orbital plane to create two possible viewing areas on either side of the satellite. This is meant to simulate the ability to point the change the look angle of the radars to observe the regions of highest scientific value.

To calculate cost, the VASSAR tool was used. VASSAR sizes the spacecraft bus based on the orbit and instrument, and then computes the cost of the satellite bus based on cost estimation relationships (CERs) from [5]. The NASA Instrument Cost Model was used to determine the cost of the instruments. The bus cost and instrument cost are used to compute the lifecycle cost, which is the cost figure used in the following results section.

3. RESULTS

The results of the architecture evaluation are shown in Figures 1-4.

Examining Figure 1, we see that when considering only average revisit time and cost, constellations with one plane of multiple satellites dominate those with multiple planes. This is due to launch costs, as multiple planes require multiple launches.

Figure 2 contains some interesting patterns. As expected, increasing the number of satellites per plane provides only marginal improvement for maximum revisit time compared to increasing the number of planes. Of course, single-plane constellations are relatively more affordable. Also obvious in Figure 2 is the influence of the number of planes on cost - a 3-plane constellation with a single satellite per plane costs slightly more than \$800M, while a single-plane constellation with 3 satellites costs only $\sim$\$530M. This is due to the common assumption that a single launch vehicle cannot put in orbit satellites at different orbital planes.

Figure 3 offers critical information on the role of inclination. As expected, higher-inclination architectures achieve better values of percent coverage. If we treat 100% coverage as a requirement, we see that 1 and 2-satellite architectures become infeasible. From Figures 1-3, we know that a constellation with 3 or 4 satellites is necessary, and that a high inclination is also a necessity.

Figure 4 allows us to complete our current analysis of the tradespace. The plot has been color-coded by lifecycle cost. We have included costs up to \$916M, that of SMAP, but have grayed out architectures above \$600M, the "medium-cost" price point in the Decadal Survey [7]. If we restrict ourselves to this "medium-cost" price point, the remaining feasible architectures are only those with 1 plane of 3 satellites. The best architecture with 1 plane of 3 satellites is one with a 504 km altitude, an 84 degree inclination, and a repeat cycle of 9 days. This architecture provides us with satisfactory performance: $<$12 hr maximum revisit, $<$5 hr average revisit, 100% coverage, and a cost around $\sim$\$535M. As is clear from the preceding discussion, arriving at this architecture is simply a reasonable compromise between all considered metrics. There are many more designs on the Pareto front that are valid for a given specific scientific application.

4. CONCLUSION

After conducting a tradespace analysis of satellite constellations, a promising soil moisture mission concept has been identified consisting of 3 satellites in a single plane. This concept is tentatively selected as the baseline concept for the D-SHIELD project. This is only the first step in the tradespace analysis for D-SHIELD, however. This analysis will be expanded to include radiometers and reflectometers onboard these radar satellites, and additional smaller satellites with only radiometers or reflectometers. In order to more clearly capture the value of the heterogeneous architectures, a more sophisticated measure of scientific value will be used in the final version of this paper. This measure of scientific value will depend on the multiple objectives used in this preliminary analysis, but must necessarily be more complex to consider the value of the radiometers and reflectometers beyond providing additional coverage.

5. REFERENCES

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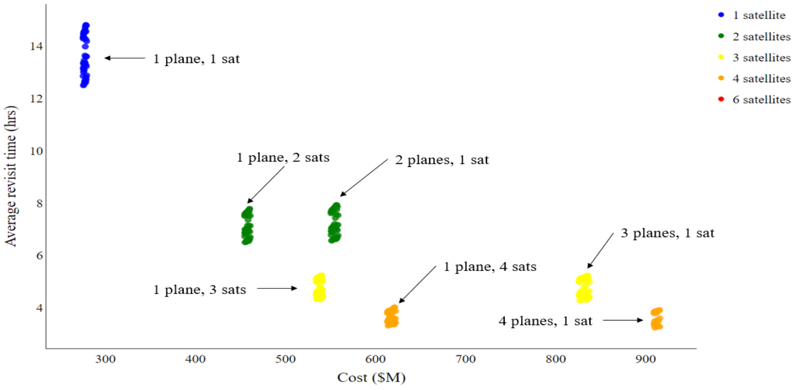

Fig. 1. A plot of average revisit time vs. cost.

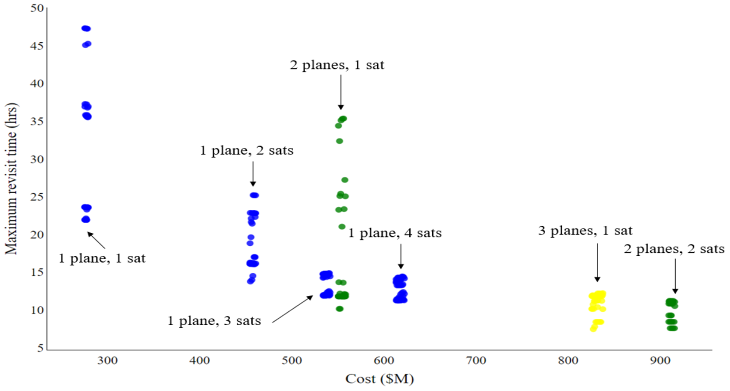

Fig. 2. A plot of maximum revisit time vs. cost.

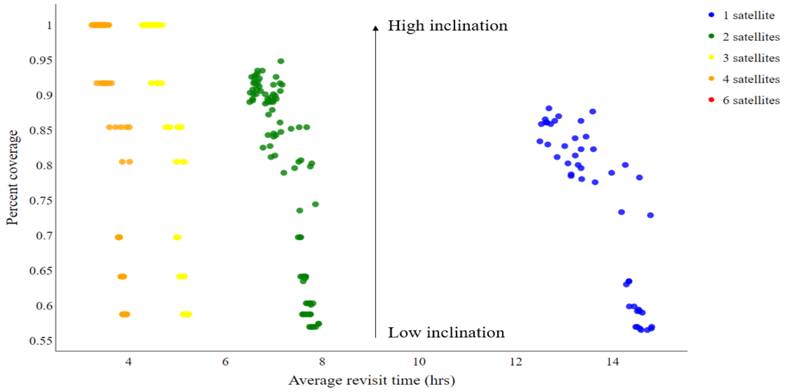

Fig. 3. A plot of percent coverage vs. average revisit time.

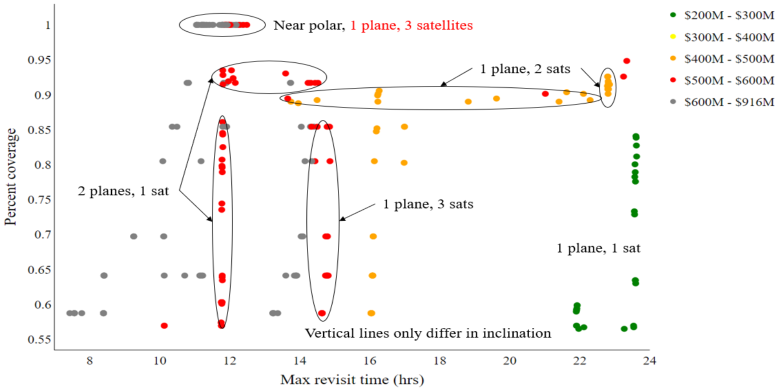

Fig. 4. A plot of percent coverage vs. maximum revisit time.