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Creating Advanced Architectures for Space Systems: Emergent Lessons from New Processes

Hugh L. McManus* and Joyce M. Warmkessel†
Massachusetts Institute of Technology, Cambridge Massachusetts 02140

Techniques are considered for developing clean sheet designs of advanced architectures for space systems. The terrestrial observer swarm A, an ionospheric mapping system using a swarm of small satellites, is used as an example. A process for exploring open-ended trade spaces is briefly described, and its application to the system followed. The utilities and costs of 1380 possible architectures are calculated. The trade space is explored; the two primary missions of the system are found to drive the architecture in opposite directions, suggesting a rethinking of the mission mix. This tension is coupled to the available funding level because larger, more expensive swarms can do both missions. The process is observed to require careful definition of a set of utility metrics to capture user needs, and updating of the design parameter set to be explored, as understanding of the system and its technical challenges emerges. Overall, both the process used and the swarm technology considered are found to be useful for defining and understanding a large set of available architectures.

Nomenclature

d_{ij} = distance between vehicle i and vehicle j, m
e = indicates if the swarm is at latitudes between ± 20, dimensionless
f_B = scoring function for bonus high-latitude utility, dimensionless
f_H = scoring function for high-latitude utility, dimensionless
f_L = scoring function for low-latitude utility, dimensionless
T = integration time, min
U_H = utility metric for high-latitude mission, dimensionless
$U_{H\max}$ = maximum value of utility metric for high-latitude mission, dimensionless
U_L = utility metric for low-latitude mission, dimensionless
$U_{L\max}$ = maximum value of utility metric for low-latitude mission, dimensionless
U_T = total (combined) utility metric, dimensionless
$\boldsymbol{y}$ = vector of distances from center of swarm to vehicles in east–west direction, m
y_i = distance from center of swarm to vehicle i in east–west direction, m
$\boldsymbol{z}$ = vector of distance from center of swarm to vehicles in up–down direction, m
z_i = distance from center of swarm to vehicle i in up–down direction, m
τ_H = total time spent at high latitudes while utility metric is integrated, min
τ_L = total time spent at low latitudes while utility metric is integrated, min

Introduction

THE goal of this work is to develop methods by which advanced architectures for space systems can be efficiently explored and optimum architectures found. New technology, new missions, and/or the need for reduced cost and increased flexibility may enable, or demand, radical new architectures for space systems. However, rationally deciding which to choose out of a vast set of possible architectures is difficult and not supported by current design methods. Typically, an a priori choice of architecture is made and the system designed around it. Such an approach allows optimization in a local, for example, spacecraft, sense, but not necessarily in a global, for example, architecture, sense.

The Space Systems, Policy, and Architecture Research Consortium is working on this problem through a series of design exercises focused on using swarms of space vehicles for ionospheric measurements. These exercises use an advanced design process to define architectures. The lessons learned in the exercises are in turn used to revise and update the process. A series of exercises has been performed. This paper describes the results of the first exercise, dubbed the terrestrial observer swarm A project (A-TOS).

This paper will briefly describe the process used to create the A-TOS architectures and review the architectures themselves. The process used in this exercise has been described in some detail in a previous paper.[1] The process has since evolved, and the current process description is contained in companion papers.[2,3] This paper will give an overview of the process used, but the majority of this paper will concentrate on the A-TOS exercise itself. The emergent lesson from this exercise is that the most valuable result from the advanced process used is not the solution itself, but an understanding of the underlying tradespace. This understanding can be used to refine both the product and the process. As a corollary to this finding, the process itself can be seen as a learning process, during which uncertainties concerning user needs, feasible design spaces, and available technical knowledge are resolved in an orderly, though not linear, fashion.

Background

Typically, clean sheet designs, especially those involving new technologies, are not developed systematically. The intuition and common sense of experienced designers and system engineers is relied on,[4] aided by heuristics and, perhaps, good fortune. Usually, a point design is quickly arrived at and then varied in an attempt to optimize it. Traditional trade studies explore the variation of a small number of design variables as they vary on excursions from a point design. Such methods are vulnerable to finding locally optimal designs and give only a vague picture of the complexity of the space of possible designs. If the potential user is not satisfied with the design arrived at, it is back to the drawing board.

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*Principle Research Engineer, Department of Aeronautics and Astronautics, MIT 41-205, 77 Massachusetts Avenue. Associate Fellow AIAA.

†Senior Lecturer, Department of Aeronautics and Astronautics, MIT 33-409, 77 Massachusetts Avenue. Member AIAA.

Table 1 A-TOS missions

Equatorial survey	Equatorial snapshot	High-latitude survey
One vehicle	All vehicles	All vehicles
Night only	Night only	Day or night
1-s-long, 1-kHz sample	30 s of data at 500 Hz	Single reading every 30 s
Look for chaotic behavior	Data time and position stamped	Want vehicles separated by 20 km vertical, 75 km horizontal
Binary success criteria	Key is difference in readings between vehicles separated by a variety of baselines	Strings of vehicles allow desirable correlation with ground to GPS measurements
Low value, but triggers snapshots	1 m–200 km baselines of interest	Medium value
	High value	

The process used in the A-TOS project focused not on a point design, but on capturing and quantifying the functional needs of the user, and then exploring a large space of possible solutions. The process involved a number of steps that drew on previous research at the Massachusetts Institute of Technology (MIT). A vital first step was found to be the assembling of the needs of the various customers for the proposed system. The evaluation of user needs was informed by work done at MIT's Lean Aerospace Initiative on the dimensions of value and the assessment of total life-cycle value.[5]

The process used to explore the trade space was based on the generalized information network analysis (GINA) method for distributed satellite systems.[6] This method treats satellite systems as information disseminators in a transfer network from source to sink, borrowing powerful insights from information theory to allow meaningful and quantitative trades at the conceptual design level. The Space Systems Laboratory of MIT has been exercising and refining the GINA methodology on a variety of space system applications over the past few years. The techniques have been applied to NASA's Terrestrial Planet Finder mission,[7] the U.S. Air Force's Techsat21, and spacecraft operations studies.

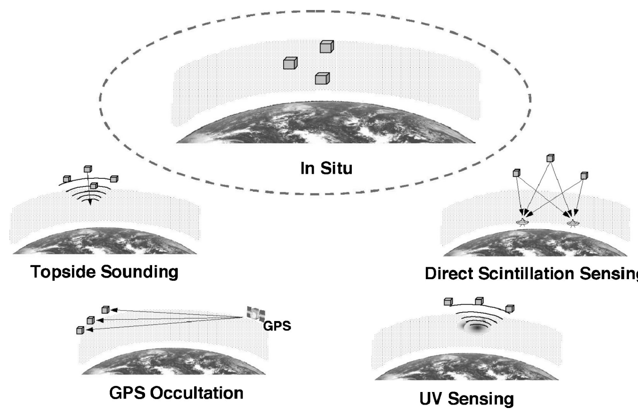

Fig. 1 Techniques for measuring the properties of the ionosphere.

Project Goals

The goal of the project was to develop a set of architectures for a swarm-based space system for ionosphere observations and to capture the process by which the architectures were created, all in a period of five months. The state of the ionosphere is of interest primarily because variations in this state can disrupt communications. The density and composition of charged particles in the ionosphere can vary widely. A wide range of behavior is noted, from stable, calm behavior to chaotic variations in time and space. An analogy to weather in the lower regions in of the atmosphere is apt, and ionospheric behavior makes up a major component of space weather.

There are a variety of different techniques that can be used to determine the state of the ionosphere. Measurements can be made in situ by probes flying through the ionosphere, indirect measurements can be made by various schemes for passing signals through the ionosphere, and the energy released (mostly at UV wavelengths) by ionospheric activity can be observed. Some of these techniques are shown in Fig. 1.

The project was also used as a testbed for the design of satellite swarms. Swarms can be loosely defined as collections of satellites in orbits with the same periods and similar initial conditions, such that they will tend to stay reasonably close to one another for long periods of time without using maneuver fuel. Sensing functions can be distributed amongst satellites in the swarm. A variety of arrangements are possible for vehicles in a swarm; the ones of interest here are Hill's orbits, in which vehicles with slightly elliptical orbits appear to rotate about a central vehicle in a circular orbit with the same period (see Ref. 8). The original work on this effect dates to the1870s[9]; recent work shows that some other approaches, such as using thrust to remain in fixed formations, are not practical.[10]

Process

The process used in this work is under continuing development. The current state of the process is described full in companion papers[2,3] and will not be described here. For this discussion, we will consider the following process steps: narrow (coarsely) tradespace and scope, find customer needs and define utility metrics, define the tradable design parameters (the design vector), develop simulation models that predict utility and cost given the design vector, explore trade space with simulation, and understand trade space as a basis for design selection and/or further architecture study.

The first step was the coarse narrowing of the trade space to be considered. The original thought was that the GINA process could perform this function, but it was found that the magnitude of the unconstrained problem was overwhelming. Instead, interaction with the technical experts interested in the data such as system could collect (the science customer) allowed a reasonable scoping. Figure 1 shows the variety of different technical approaches to ionspheric measurements considered. In situ sensing was selected as reasonable for a first cut at the process because it was expected to present the fewest technical problems.

Another dimension of scoping was how far to follow the information generated. Lean philosophy suggests that the values of the end users (such as communications managers and warfighters) should be considered. However, the lack of maturity of the systems between the raw information generated by the space system and its eventual use made this impractical. Instead, the project was driven by the consumers of the raw data, the science community that would use the data to understand the global behavior of the ionosphere. The project was also constrained by the needs of the funding agency. The project would be used as a swarm technology testbed, and so single-vehicle architectures were not considered, and a 63.4-deg inclination orbit was also specified.

Once the customer was defined, the needs of the customer could be quantified. The customer identified three distinct missions, summarized in Table 1. All involve a simple planar langmuir probe that samples the ionosphere in the immediate vicinity of the vehicle. The first mission is a survey to detect ionospheric instabilities. This mission has a simple, binary success criterion, requiring only a working vehicle in the right position.

The second mission takes measurements of the charge density in unstable regions. The desire is to understand the structure of these instabilities. The key measurement is the difference in charge density

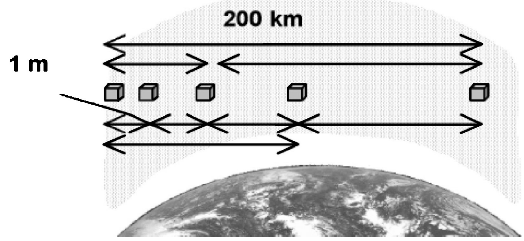

Fig. 2 Equatorial snapshot mission utility.

measured by vehicles separated by a given baseline; the data are valuable to the extent they include the right distribution of baselines. Figure 2 shows a possible distribution of vehicles and the baselines captured. A dimensionless, relative scoring function was devised to capture the usefulness of measurements taken from a given arrangement of vehicles; this function is integrated over several orbits to evaluate the utility metric, the usefulness of a given system for this mission. The utility metric for this mission is calculated from the positions of the vehicles as follows:

$$d_{ij} = \sqrt{(y_i - y_j)^2 + (z_i - z_j)^2} \tag{1}$$

$$U_L = \frac{1}{\tau_L} \int_0^T f_L(d_{ij}) e \, \mathrm{d}t \tag{2}$$

$$\tau_L = \int_0^T e \, \mathrm{d}t \tag{3}$$

$$e \begin{cases} = 1, & \text{if the center of the swarm is at latitudes between } \pm 20 \text{ deg} \\ = 0, & \text{otherwise} \end{cases} \tag{4}$$

The scoring function f_L counts the number of baselines of different sizes included in d_{ij} $(j > i)$. The function is initialized to zero and increases in value by one for each of the ranges (30–100 m, 100–300 m, 300 m–1 km, 1–3 km, 3–10 km, 10–30 km, 30–100 km, and 100–200 km) in which at least one value is found in $d_{ij} (j > i)$. The binary function e assures that only time spent in the equatorial zone where instabilities occur is counted toward the utility. The north–south relative positions are not considered because the Earth's magnetic field tends to make the ionospheric structure relatively uniform in this direction on the scales considered.

The third mission has a similar scoring function. At higher latitudes, the desire is to collect a relatively low-resolution three-dimensional map of the ionosphere. Vehicles spaced roughly 75 km apart in the east–west direction, and 20 km vertically, are desired. Bonus points are awarded for completing strings of measurements that can be correlated with global positioning system (GPS) to ground measurements (Fig. 3):

$$U_H = \frac{1}{\tau_H} \int_0^T [f_H(y, z) + f_B(y, z)](1 - e) \, \mathrm{d}t \tag{5}$$

$$\tau_H = T - \tau_L \tag{6}$$

where f_H is a scoring function that counts how many elements of a 8 by 25 grid of 75-km-wide, 20-km-high squares, in the up–down, east–west plane, centered on the swarm center, are occupied by vehicles. The bonus function f_B adds to the score if groups of three or more occupied grid spaces line up from the top to the bottom of the sampled plane (Fig. 3).

Finally, a total utility was calculated, with the low-latitude mission utility metric counting twice as heavily as the high-latitude mission utility metric:

$$U_T = \tfrac{2}{3}(U_L / U_{L\,\max}) + \tfrac{1}{3}(U_T / U_{T\,\max}) \tag{7}$$

This weighted average is a crude total calculation of total utility and has been superseded by more sophisticated methods in later work.[2]

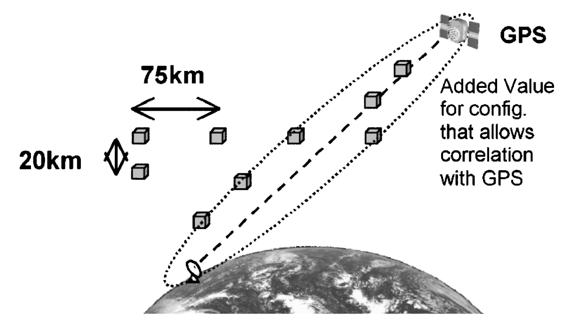

Fig. 3 High-latitude survey mission utility.

The significant design parameters were grouped into three categories: the design vector, the constants vector, and intermediate variables. The design vector is the set of parameters that remained open throughout the study. The constants vector contained important values that are invariable, unlikely to create differentiation between the architectures, or outside the scope of the study; they were fixed at reasonable values. Intermediate variables are captured by dedicated calculations within the simulation. For example, the launch vehicle suite necessary for system deployment is not specified in the design or constants vector, it is calculated using an internal optimizer to meet mass/orbit requirements at the lowest cost.

The design vector evolved in parallel with the definition of the utility metrics. Techniques such as quality function deployment[11] can be used to select design parameters that are most likely to affect the utility metrics. However, in this case the initially nonintuitive nature of the utility metrics, and the lack of intuition and experience (on the project team) on how various design parameters would affect the metrics, made applying these methods problematic. Instead, the design vector evolved over time, settling primarily on parameters controlling the geometry of a swarm. In retrospect, this was the obvious choice because the utility metrics calculated earlier are calculated from the histories of the vehicle positions.

Table 2 shows the evolution of the design vector over time. The first cut list from the middle of month 2 of the project represents an early estimate of the most important design drivers. A scoping exercise utilizing the GINA method narrowed the design vector significantly by the end of month 2. This design vector set allowed initial coding tasks to begin. However, in the middle of month 5, a more detailed awareness of customer needs arose from an understanding of the utility metrics, which, combined with emerging technical issues, led to another reconfiguration of the design vector. Finally, in late month 5, schedule practicalities led to a further culling, where the interesting concept of using a swarm mothership was excluded due to limited available time and lack of necessary resources.

The swarm geometry was eventually limited to a single Hill's swarm. Identical vehicles are arranged around a central vehicle with similar but slightly perturbed orbits, all having the same period. In the frame of reference of the central vehicle, the other vehicles appear to revolve around the central one once per Earth orbit, following elliptical paths. The geometries studied were limited to those with 2–26 vehicles, on 1 or 2 vertical planes (subplanes), arranged in 1–4 elliptical rings (suborbits) per plane. The swarms were 1–200 km across. The central vehicle's orbit was from 200 to 800 km in altitude.

To evaluate the tradespace defined by the preceding parameters, a model was devised that simulated the behavior of a candidate architecture, used the utility metrics to evaluate its usefulness, and used a cost model to assess its lifetime cost. The challenge in developing these models was finding the right level of fidelity, so that the models could accurately distinguish between architectures, but were computationally tractable. The models evolved with the growing understanding of the system; in the end, high-fidelity orbit calculations were needed to assess swarm geometries, but other aspects (such as the modeling of the relatively simple vehicles) were left at a lower level of fidelity.

Table 2 Evolution of design vector

First cut (mid-month 2)	After GINA exercise (late month 2)	After utility characterization and module progress (mid-month 5)	Schedule crunch (late month 5)
Swarm type	Concept type	Swarm perigee	Swarm perigee
Swarm orbit	Swarm altitude	Swarm apogee	Swarm apogee
Number of satellites/swarm	Number of satellites/swarm	Number of satellites/swarm	Number of satellites/swarm
Number of swarms	Number of swarms per plane	Number of subplanes/swarm	Number of subplanes/swarm
Intraswarm orbit	Number of orbital planes	Number of suborbits/subplane	Number of suborbits/subplane
Instrument type	Swarm orientation	Yaw angle of subplanes	Yaw angle of subplanes
Number of instruments/satellite	Swarm geometry	Maximum satellite separation	Maximum satellite separation
Control scheme	Separation within swarm	Mothership (yes/no)	
Ground station	Mothership (yes/no)		
Mission lifetime			
Processing scheme			
Position control scheme			
Latitude of interest			

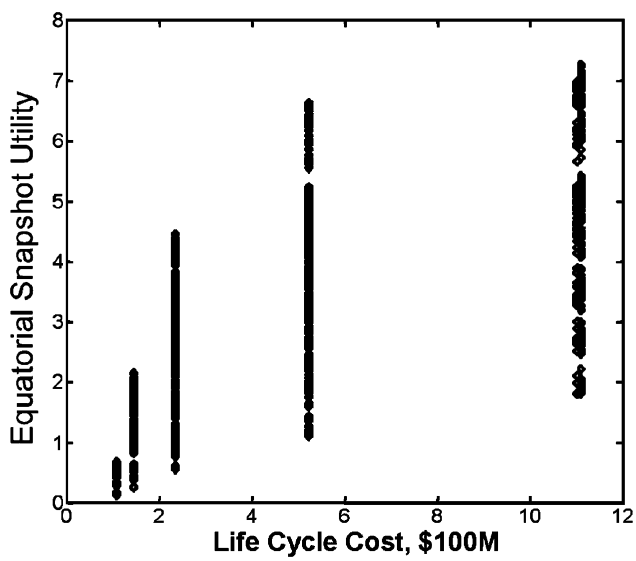

Fig. 4 Equatorial snapshot utility vs cost.

Code modules based on simple models of the spacecraft, its reliability, the orbital environment, launch and replenishment options, and operations were written and implemented in MATLAB®. Orbital calculations were done using Satellite Tool Kit®. The spacecraft models were based on typical conceptual design study practice (e.g., Larson and Wertz[12]). The launch model was modified from an earlier MIT study.[7] The operations model was new; it was based on estimated organizational overhead costs and benchmarked to the Iridium operations concept. These modules were linked to cost and utility modules. The cost module was based on a cost engineering relationships model, itself based on The Aerospace Corporation's small satellite cost model. The utility module evaluated Eqs. (1–7) using a sample period of several orbits.

These modules were integrated into a predictive suite of codes that determined expected performance of many possible architectures as functions of the design parameters. An exhaustive search of the space defined by varying all elements of the design vector between reasonable limits revealed the best architectures for the mission; as important, the search generated information on the nature of the tradespace.

The key sensitivities of the results were determined to assure their validity. The utility metrics were dominated by orbit position calculations, which were carried out at a high level of fidelity for a period of several orbits. It was found that this period was sufficient to give consistent utility values. Over longer periods, estimated drag and disturbance forces were calculated and assumed to be corrected for, which added to system cost but did not change the utility metrics. The cost calculations were based on relatively low-fidelity models. Fortunately, the costs were completely dominated by the number of

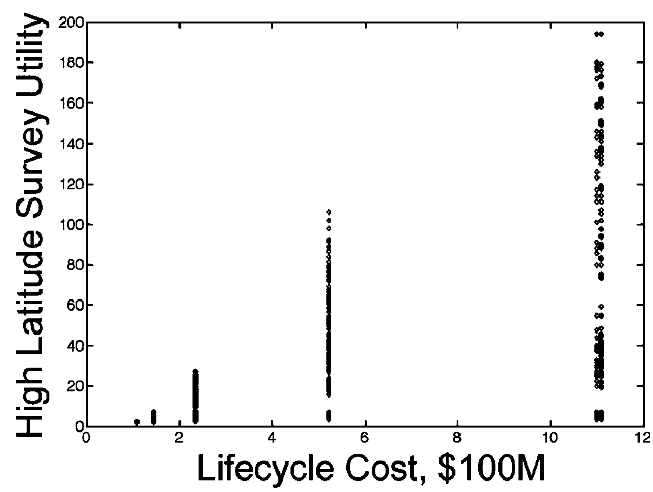

Fig. 5 High-latitude survey utility vs cost.

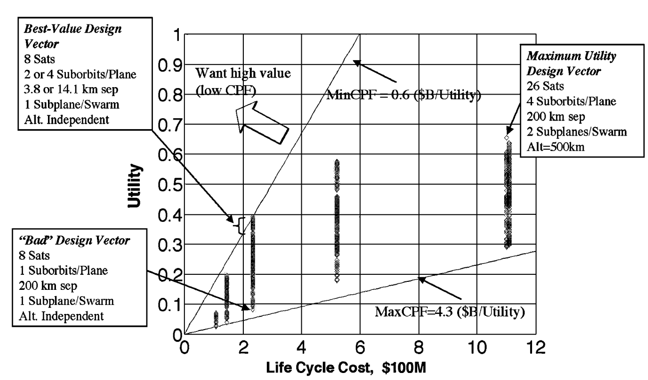

Fig. 6 Combined utility vs life-cycle cost.

vehicles in the swarm, so that although the absolute cost values are estimates, the relative cost rankings between architectures were of high confidence.

Results

A total of 1380 architectures were evaluated, each represented as a single point in Figs. 4–7. Utility metrics are given in dimensionless, comparative figures. The utility metric for the low-latitude survey has a value range from 0 to 8. The utility metric for the high-latitude mission has a value range from 0 to 200. The life-cycle cost is for a five-year mission, including a conservative estimate for operating costs, making it seem quite high for systems of this type. Although the exact percentage varied by system, as a rule of thumb, the vehicle and launch costs are about 40% of the lifetime costs, with the balance due to operations.

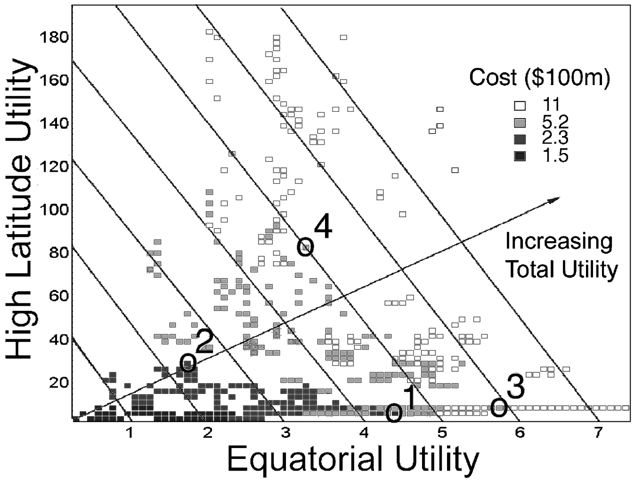

Fig. 7 Visualization of the trade space.

Results for the first mission, equatorial survey, are not shown because they did not provide a meaningful discriminator. The mission was easy to accomplish (only one vehicle needed to be functioning) and so all architectures studied could do it equally well. Figure 4 shows the results for the equatorial snapshot mission. The cost bands correspond to the number of vehicles in the architecture. A clear Pareto front (line of best architectures) is evident, and the curve has a knee: The very high-cost architectures show diminishing returns. The best of the about $250 million architectures appear to provide best value for this mission. These architectures are compact, well-populated swarms that provide most or all of the shorter baselines desired, thus, doing well on the scoring function f_L and, consequently, the utility metric [Eq. (2)].

Figure 5 shows the results for the high latitude survey mission. A Pareto front is clear, but there is no knee in the curve; more satellites results in better performance, with no limit, at least in the range of architectures studied. Large swarms of well-spaced vehicles have the best chance of populating the large grid used by the scoring function f_H and, hence, achieving a high utility for this mission [Eq. (5)].

Figure 6 shows a combination of Figs. 4 and 5, using the total utility from Eq. (7). The results resemble those in Fig. 4, indicating that the equatorial mission utility dominates the total utility. Also shown on Fig. 6 are some expansions of architectures of interest. The best value architectures proved to be relatively small swarms. Several architectures scored very closely; all had eight satellites on a single plane. The utility was independent of the altitude; either two rings of four vehicles or four rings of two provided best value. Note that these architectures achieve high utility metrics by ignoring both the entire high-latitude survey mission and the desire for long baseline measurements in the equatorial region; they have gamed the total utility metric by providing very good information on smaller baselines for the equatorial mission, at reasonable cost. The highest total utility architecture, on the other hand, did both missions well with a massive swarm. Eight rings of vehicles, on two different planes, arranged over an area 200 km across, provided high-quality data for both missions, at large cost. Also shown in Fig. 6 is a worst-value architecture, with a few vehicles scattered on a single 200-km-diam ring. It is a feature of the process that many bad architectures are evaluated. However, the computational and human effort expended in doing so is minimal, and the bad architectures may then be rejected on quantitative grounds rather than by intuition. Conversely, nonintuitive architectures may prove to provide high utility for unexpected reasons, so that evaluating a wide variety of possible architectures is desirable.

Figure 7 is an attempt to visualize the entire trade space. Fortunately, with the irrelevance of the equatorial survey mission, the space of outputs (utilities and cost) is three dimensional, although discontinuous. Figure 7 shows the two utility metrics on the two axes, with shade indicating cost. Isolines of combined utility are also shown. A band of architectures, many of them good value ones, are seen across the bottom of the chart. These are architectures that score poorly on the more difficult high-latitude mission. The best value architecture (point 1) is on this band. Note that, if a user wishes to select an architecture that does perform both missions at the same cost (point 2), combined utility is sharply reduced. This suggests that the original idea of combining these two missions may need to be revisited. Interestingly, if a higher level of funding is available, performance on the equatorial mission can be enhanced somewhat (point 3), but dramatic improvements can be made in a combined mission (point 4). In this case, a combined mission may make sense. Note that if further study of this problem is desired, swarm configurations beyond the simple geometries considered here should be explored. Creative geometries may manage to meet the needs of both missions at reasonable cost. Repeated application of the process could be used to screen large numbers of such new swarm geometry ideas.

Note that in all architectures, the vehicle design (which was roughed out by the code, mostly to calculate a cost) is very similar. Therefore, for this set of missions, vehicle design could probably proceed even if optimization was still being done on the architectures. Conversely, if funding cuts hit part way through a program based on these missions, the architecture would have to be revisited. For example, by the earlier discussion, the inclusion of the high-latitude mission may become impractical, but the vehicle design work would not be wasted.

Conclusions

The A-TOS exercise resulted in apparently viable architectures for an interesting mission and insight into the tradespace from which the architectures came. It also successfully demonstrated a process for rapid architecture design and provided important insight into the process, which assisted in its continuing evolution. Finally, it provided some insight into the potential advantages of swarm architectures.

For the mission considered, the utility was dominated by the geometry of the swarm. It was found that the two proposed missions, the equatorial instability snapshots and the high-latitude surveys, were in conflict. The first favored vehicles in relatively close proximity, whereas the later favored widely spaced vehicles. Only higher cost architectures could satisfy the needs of both missions. The missions required simple spacecraft, whose basic design was almost independent of the architecture selected. The cost of the mission was dominated by operations cost, due mostly to the five-year lifetime selected. The overwhelming cost discriminator between architectures was simply the number of vehicles in them.

The process proved effective but evolved significantly during the exercise. The primary process lesson was that the stages in the process were far from linear. The emergent understanding of the users needs, the technical issues faced, and the practicalities of constructing the simulation models caused the utility metrics and design vector to evolve right up to the end of the process. Indeed, the lessons gleaned from the tradespace would almost certainly cause further evolution of both if the process had been continued through another iteration. User input was necessary for all stages of the process, including the interpretation of the tradespace that resulted. Good technical expertise and (where available) experience was necessary both for the construction of the models, and more important, for the soft choices of utilities to consider, parameters to include in the design vector, and levels of fidelity to reach in the modeling. These lessons have been incorporated into the more formal process used in later studies.[2,3]

Both the process used and the swarm-based architectures considered allowed consideration of large, open tradespaces. There is an evident, and probably necessary, synergy between process and product in this case. The combination holds promise for the rapid evaluation of new architectures for advanced space systems.

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J. Korte
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