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Mission Assurance Framework for Small Satellite Missions

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ABSTRACT

Small satellites organized as a constellation have the potential to offer mission capabilities comparable to traditional large satellites at a significant cost savings. In order to evaluate the viability of using a constellation of small satellites for any given mission, we investigate how system performance and cost relate to mission assurance. In this paper, we compare three satellite mission architectures to a global satellite communications reference mission. The three satellite mission architectures include (1) large constellation of low-cost small satellites (15 kg), (2) medium-sized constellation of medium-sized satellites (800 kg) and (3) small constellation of large satellites (3000 kg). Mission assurance is assessed for each architecture, with performance risk factors including individual satellite life expectancy, operating environment, and other external factors affecting mission performance. We also consider resiliency as it relates to a system's ability to degrade gracefully. This aspect of resiliency is particularly relevant to a system consisting of a large number of small satellites.

I INTRODUCTION

Small satellite technology efforts within academia, industry and government have resulted in a burgeoning market place of low-cost nanosatellite (nanosat) busses, components, and payloads [1]. (We define small satellites as <500 kg, and nanosats as between 1 kg and 15 kg.)

With a growing track record of mission success, the advent of the low-cost nanosat is forcing a new look at mission assurance expectations. The analysis of mission assurance for a nanosat constellation requires the consideration of their low-cost, replace-ability and resiliency when comparing to the mission assurance of large satellites. Ideally, these two architectures must possess similar mission assurance and comparable mission capabilities. This calls for a look at how innovations in modular systems, open architectures, and life-cycle management will impact mission assurance.

Mission assurance is defined as the assurance of mission success. More specifically, a mission is successful if it meets its mission requirements with a predefined high probability of success. Typically, mission assurance consists of four components: Cost, Performance, Schedule, and Techniques. Each of these components has elements which contribute to overall mission assurance. Figure 1 depicts these components as well as some of their contributing elements.

This paper examines system performance and cost interplay with respect to mission assurance. The performance component is defined as the ability of the satellite constellation to successfully perform the mission. This includes factors such as mission lifespan as well as technical capabilities of the satellites. Performance is of importance as it enables the analyzation of mission capabilities. The cost component is defined as the overall monetary cost of the constellation including development, satellite launch, and the continued operation of the satellites throughout the mission lifespan. Cost is of importance as it is a major discriminator in comparing various satellite architectures.

Resiliency is also introduced as an aspect of our mission assurance framework as it is a defining characteristic of a nanosat constellation. Resiliency is defined as, "the ability of a system to circumvent, survive, and recover from failures to ultimately achieve mission objectives" [2]. Resiliency is applicable to a constellation of nanosats as the loss of an individual satellite may not significantly impact the functionality of the overall system. In that regard, our definition of resiliency focuses on system survivability and the ability to degrade gracefully [1, 2].

In this paper, the components of mission assurance are applied to and analyzed using a defined reference mission. We define this reference mission as providing commercial satellite communication capability globally over the next 15 years. Within this reference mission, we compare three satellite constellation architectures: (1) large constellation of low-cost, low-earth orbiting small satellites (referred to as NanoSat Architecture), (2) medium constellation of medium-cost, medium-sized satellites (referred to as MediumSat Architecture), and (3) small constellation of high-cost geosynchronous satellites (referred to as LargeSat Architecture). We construct our mission assurance framework based on key mission parameters to analyze these architectures.

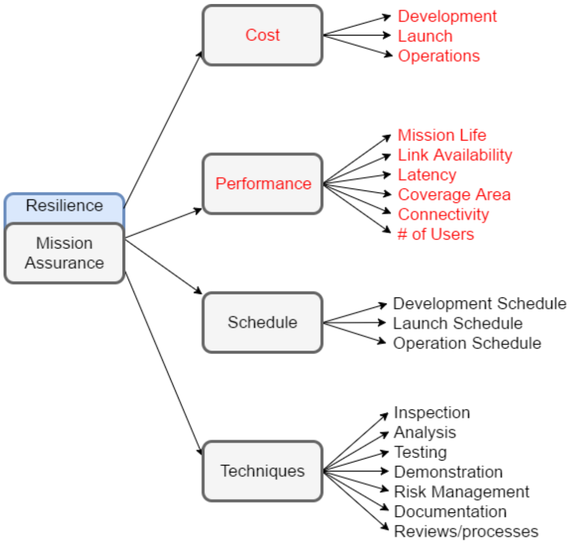

Figure 1: The four defined components of mission assurance as well as elements of each component. Resilience is shown to be an aspect of mission assurance, sharing the same four components. The discussion in this paper focuses on the performance and cost components, shown in red.

This paper is organized as follows: the design reference mission and the key design parameters for the three constellation architectures are given in Section II. A discussion of our mission assurance model as well as its performance and cost is given in Section III while the role of resiliency for satellite mission assurance is discussed in Section IV. The paper concludes with current progress and future work in Section V.

II DESIGN REFERENCE MISSION AND ARCHITECTURES

Our reference mission is defined to remain in line with the interests of government and commercial satellite missions. This mission is to provide users with global connectivity in near real-time for the purposes of data transfer, instant messaging and voice communications. Key performance parameters include coverage area of the entire Earth's surface, bandwidth of 1 Mb/s, latency no larger than 500 ms, and a user base of 748,000, which is the reported number of users on the Iridium satellite phone network during 2015 [3]. Table 1 provides the list of the reference mission requirements.

Table 1: Reference Mission Requirements

Mission Life	15 Years
Link Availability	98%
Latency	500 ms
Coverage Area	100% (Global)
Connectivity	1 Mbps
Total # of Users	748,000

The next step involves detailing three architecture design parameters, including satellite sizes and constellation characteristics representative of currently available or proposed commercial satellite configurations. The first architecture uses nanosats, while the remaining two are constructed using traditional, medium- and large-sized satellites. Constellation parameters are obtained from prior research [4, 5, 6, 7] in conjunction with the use of an orbit analysis software tool, Systems Tool Kit (STK) by Analytical Graphics, Inc. (AGI) [8]. Each constellation was created in STK and the analysis output was collected to determine the derived parameters of the constellations. For example, the Earth coverage of the constellation and maximum data transmission delay (assumed as solely distance travelled with the speed of light between opposite sides of the Earth) were computed using STK to help design mission architecture. Table 2 lists a comparison of the three defined satellite constellation architectures, while Figure 2 provides a visualization of the constellations using STK.

The first architecture design (NanoSat Architecture), intended to demonstrate a potential application of small satellites, provides a globally-connected network using nanosats in Low-Earth Orbit (LEO) constellation at an altitude of 600 km. This constellation was inspired by the commercial satellite company OneWeb, which aims to use small satellites to provide internet connectivity to the entire world [9]. In our analysis, we choose to use nanosats (a subcategory of small satellites) to exemplify the low-cost standardization of small satellites [1]. Due to the low altitude and limited field-of-view of this architecture, a very large constellation is needed to ensure global coverage. However, low launch and development cost of nanosats make this large constellation an affordable option. Therefore, a large number of satellites (338) are selected for this architecture based on STK analysis.

Table 2: Architecture Design Parameters

	Architectures		
	NanoSat (15 kg)	MediumSat (800 kg)	LargeSat (3000 kg)
Heat Flux Exposure	1612.31 W/m^2	1612.31 W/m^2	1371 W/m^2
# Satellites	338	68	5
Inclination Angle	87.9˚	86.4˚	3˚
Orbit Altitude	600 km	780 km	36,000 km
Global Coverage	100%	99.84%	98.17%
# Users/Satellite	2,219	11,030	150,000
Max Packet Delay	81.79 ms	91.13 ms	388.54 ms
Field of View	60˚	75˚	8.7˚
Expected Lifespan	5 years	5 years	10 years

The second architecture (MediumSat Architecture) uses medium-sized (800kg) satellites at a slightly higher altitude (780 km). This constellation is inspired by commercial satellite constellations such as Iridium NEXT, Globalstar, and Orbcomm, which aim to provide worldwide telecommunication for services including satellite phone coverage [3, 11, 12]. The size of the satellites in this constellation exceeds the small satellite definition of 500 kg, yet is differentiated from the largest of satellites used in the third constellation architecture [1,10]. The cost of each individual satellite is definitely higher than the first architecture but it has a smaller number of satellites in the constellation.

The third architecture (LargeSat Architecture) involves the largest satellites residing in Geosynchronous-Orbit (GEO) at an altitude just above 35,000 km. This altitude causes the satellites to orbit the Earth at the same speed as the Earth's rotation, making them appear stationary from the Earth's surface [10]. This constellation is inspired by commercial SATCOM constellations such as Inmarsat, a commercial constellation which provides worldwide telephone and data services using five GEO satellites [13]. Each individual satellite in the LargeSat architecture is considerably larger and more expensive than the two alternative architectures because they require more fuel to get to GEO, larger service areas per satellite and higher radio transmit power to overcome the distance. However, due to the large coverage area per satellite, only five satellites are needed to provide global coverage.

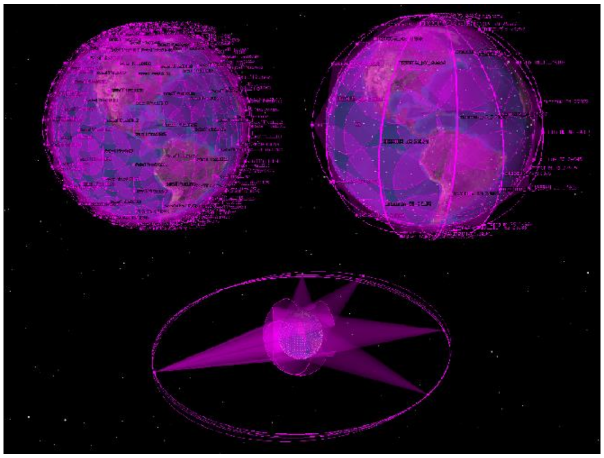

Figure 2: The constellations of each architecture within STK. Top-left is the NanoSat Architecture, top-right is the MediumSat Architecture, and bottom is the LargeSat Architecture. Satellites are depicted as pink dots, their orbits as pink lines, and their fields of view as pink, transparent cones.

III MISSION ASSURANCE MODEL

Quantifying mission assurance and applying its associated metrics are very complex. This is because mission assurance involves identifying a multitude of risks that are not always well defined. For example, the expected lifetime of a satellite cannot be guaranteed due to the occurrence of unexpected factors; instead, expected lifetimes are calculated based on expected equipment durability, reliability records, and prior mission behavior. Our model is represented as a multi-layer network in which categorical nodes are defined and connected by links reflecting conditional dependencies inspired by a Bayesian network [14]. At its highest level, the model accepts mission parameters as input and calculates a risk estimate for each element of mission assurance.

The model allows for the establishment of relationships between mission requirements and derived requirements, which will vary for different mission architectures. These relationships can be visualized as links between the nodes of the model (Figure 3). Mission requirements consist of the key mission assurance parameters identified in Figure 1. In Figure 3, mission requirements are shown on the right portion of the model and are dependent upon the mission architecture's derived requirements.

Derived requirements are not explicitly demanded by the mission requirements yet are necessary to meet them. In Figure 3, the leftmost derived requirements reflect the fundamental architecture design parameters defined in Table 2. These nodes connect to a middle layer of derived requirements, which identify multiple dependencies of additional design parameters.

Note that Figure 3 is an example depiction of a potential configuration of the global communication reference mission; the links between nodes as well as the nodes themselves may differ in practice.

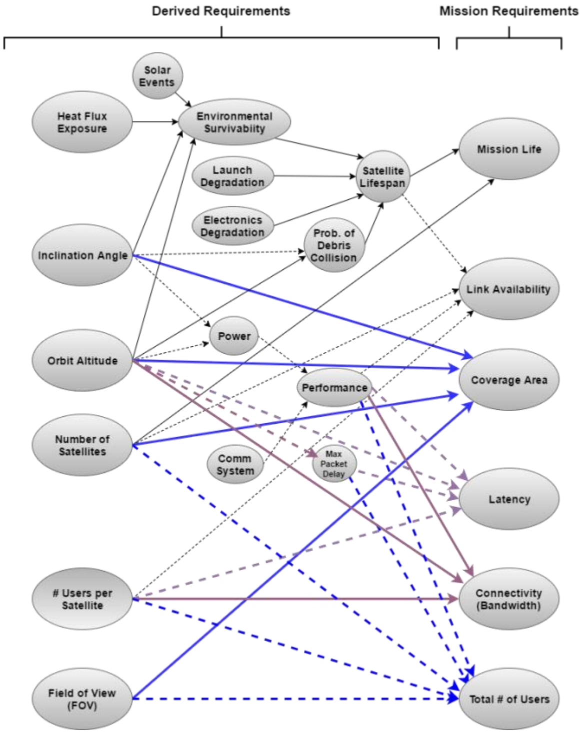

Figure 3: Multi-layer network representation of the mission assurance model. Left and centrally located nodes represent the derived requirements of an architecture while rightmost nodes represent mission requirements.

To facilitate explanation of our mission assurance model due to its complexity, we examine mission life separate from other mission requirements. Mission life and its corresponding derived requirements are shown in Figure 4, consisting of both independent and dependent nodes. In this case the independent nodes, which have no incoming connections, are Heat Flux Exposure, Inclination Angle, Orbit Altitude, Solar Events, Launch Degradation, Electronics Degradation, and number of satellites. For each of the three mission architectures, many of these requirements can be defined based upon the architecture design parameters found in Table 2.

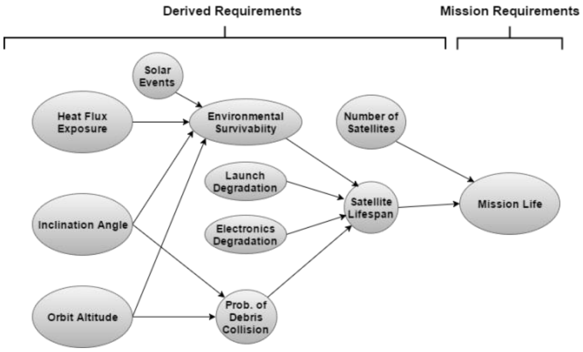

Figure 4: The portion of the Mission Assurance model associated with the Mission Life requirement, showing relationship to the various derived requirements.

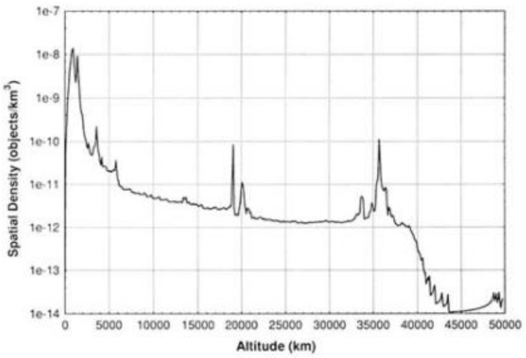

Figure 5: Spatial density of debris objects as a function of altitude. Obtained from data obtained by Kaman Sciences Corporation [16].

The characteristics of the dependent nodes are defined by their various incoming connections. For example, "Environmental Survivability" takes into account a variety of environmental factors which may be detrimental to satellite survivability, including radiation, weather, etc. Also, examine the node titled "Prob. of Debris Collision." This node represents the likelihood that a satellite will be negatively impacted by the presence of space debris, leading to the possibility of collision and consequential damage. The defined characteristics of this node are used as an input into the calculation of the expected "Satellite Lifespan." For example, the "Prob. of Debris Collision" is a function of a spatial density of space debris. An example spatial density is shown in Figure

5, which depicts the spatial density of debris as a function of altitude as observed by NASA [15]. While this data may be somewhat dated, it shows a baseline which can be used as a parametric distribution for this node. In addition, if increased fidelity is desired, further analysis can be conducted using tools such as NASA's ORDEM estimation tool [16].

Our approach to mission assurance was inspired by previously conducted research concerning satellite constellation reliability. In Engelen, et.al. [17], major components of a satellite, such as a satellite's On-Board Computer (OBC), are defined as being probabilistically dependent upon numerous derived requirements including system storage, payload, and propulsion. However, one differing aspect of our model is the simplicity required to analyze the very high-level concept of mission assurance. Engelen, et.al. [17] suggests to model constellation components using Markov Chain analysis whereas for our mission assurance model, we incorporate a more basic interpretation of the probabilistic dependencies. Maintaining simplicity allows the mission assurance framework to remain relevant to mission assurance analysis as numerous and very different derived requirements play a role in the estimation of mission assurance.

Currently we are incorporating cost estimation into our mission assurance model to aid comparison of satellite architectures. Mission assurance costs cannot be avoided, but with methodical application of the right design approach and proper risk assessment at the right time in the acquisition lifecycle, the right level of mission assurance could be achieved for both space systems and ground architectures with minimal reactive costs and risks.

IV RESILIENCY

While each of the three mission architectures are designed to meet the same mission requirements, one aspect in which the architectures differ is resiliency. Resiliency has become an increasingly important concept due to the emergence of low-cost, disaggregated, and responsive nanosat systems. As discussed previously, resiliency is particularly relevant to the constellation with a large number of satellites since a single or partial system failure may not significantly impact the functionality of the overall system.

Resiliency is not present as a node in the Mission Assurance model shown in Figure 3. Instead, resiliency is a companion to mission assurance which should always be considered when analyzing an architecture's ability to meet mission and derived requirements. For example, link availability and coverage area, which are two mission requirements used to describe the performance of a mission, are defined based on orbit parameters during nominal operations (Table 2). When we consider resiliency, the extent to which these mission requirements are fulfilled may change based on the operational condition. The performance component of mission assurance, which includes link availability and coverage area, changes based on satellite availability. The degree of resiliency is characterized by the changes in this system performance.

As an example, consider the effect of the percentage of global coverage area resulting from individual satellite failures as it relates to resiliency. Coverage redundancy due to the overlap in coverage area of nearby satellites strengthens system resiliency in the event of individual satellite failure. During the STK analysis of the three design architectures, it is observed that a larger number of satellites per constellation results in increased coverage area overlap. We attempt to depict this resiliency trend in Figure 6 using hypothetical coverage values following individual satellite failures to compare the three design architectures. A more slowly decreasing slope indicates a constellation's ability to maintain a higher coverage area percentage while the percentage of functioning satellites in the constellation decreases. Also, a large number of satellites in a constellation helps to avoid gaps in coverage area percentage following the failure of an individual satellite.

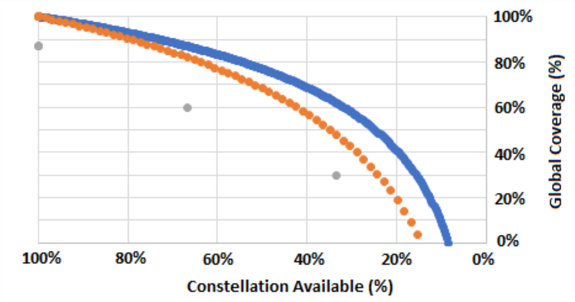

Figure 6: Global coverage percentage, indicating operational utility, for each of the three design architectures as a function of the percentage of the constellation available. The coverage curve corresponding to the NanoSat architecture is shown in blue, SmallSat in orange, and LargeSat in gray.

The interplay between resiliency and the cost component of mission assurance is another differentiating aspect in the selection of design architectures. The standardization of satellite systems as seen in nanosats facilitates reduced non-recurring engineering cost and short production time. These factors allow rapid constellation replenishment, decreasing system down- time and maintaining system resiliency.

VI CONCLUSIONS AND FUTURE WORK

In this paper, we have developed a mission assurance framework for small satellite missions. This development effort is a work in progress as it provides a basis for the analysis of mission assurance of small satellites. We also have introduced the concept of resiliency and its interplay with mission assurance, further differentiating small satellite architectures from that of traditional satellites. As made evident by our analysis, various factors play a role in the consideration of mission assurance. These factors make mission assurance model and analysis challenging and complex. Nevertheless, they must be considered in the establishment of mathematical models for the overall system mission assurance and their continual development. Once model elements have been finalized, the outcome of this effort will be a framework that can be used to compare small satellite design architectures to traditional satellites and select the most viable option.

Future work involves the establishment of mathematical models for each element contributing to the performance and cost components of mission assurance. These models can then be used to conduct simulation analysis of the selected satellite design architectures and determine the viability of using a constellation of small satellites.

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