Leveraging the Emerging CubeSat Reference Model for Space Situational Awareness

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ABSTRACT

Space Situational Awareness (SSA) is a needed strategic and security capability, whose importance directly correlates with the increases in utilization of near/low earth orbit, however the resources available for such are sharply limited. This has focused research on ways and means to improve the efficiency and effectiveness of proposed SSA infrastructure. SSA infrastructure broadly includes distributed and networked sensing, ranging and end effector systems, deployed over land, sea, in the atmosphere and in space. CubeSats, or standardized nano-satellite platforms, offer strong potential for meeting many of the requirements for SSA infrastructure and further CubeSats offer potentially significant reductions in cost, development time and failure risk over alternative infrastructure elements. For example, CubeSats may be rapidly and inexpensively deployed in controlled 'swarms', creating a space based sensor network offering higher capability, flexibility, and robustness than other architectures.

Realizing this potential requires substantial systems analysis to determine the right configuration of individual CubeSats, other SSA infrastructure, and the networks that will actually enable an SSA system to accomplish its missions. However, such work has traditionally required very large budgets and very long time lines. The present work discusses an initiative to reduce by orders of magnitude the budgets & timelines required for SSA systems analysis which is grounded in Model-Based Systems Engineering (MBSE). In particular, this work examines leveraging a CubeSat Reference Model (CRM) within an SSA analysis framework. The CRM was developed by the International Council on Systems Engineering's (INCOSE) Space Systems Working Group and has been recently submitted to the Object Management Group (OMG) standardization process. The SSA systems analysis framework, developed in the Architecture Driven Systems lab at the University of Arizona, enables evaluation of a range of SSA architectures including human machine interactions in conjunction with automation across a range of generated scenarios as well as creation and evaluation of proposed SSA figures of merit. The work discusses suitability of the CRM for SSA systems analysis including validating existing features and suggesting refinements. It concludes by exploring the potential for a future SSA Reference Model.

1. INTRODUCTION

SSA may be defined as the ability to observe, track and predict natural and man-made objects in outer space environments. Natural objects include meteoroids and near earth asteroids. Man-made objects include spacecraft, atmospheric re-entry vehicles and debris. Figure 1 shows an SSA system in its terms of potential building blocks. An SSA system broadly consists of a network of sensors and other assets distributed over space, air, land and sea. These sensors are used collect useful information about objects of interest which include meteors showers, micrometeoroids, satellites launched into space, and debris due to man-made objects in space. An example of a non-sensor asset is a command center or node in the network. Generically, a SSA command center receives sensor data, processes it and controls all SSA assets. Other non-sensor assets might include "effectors" that is subsystems that provide capabilities to change the state of space objects. Neither of these other assets are the focus of this paper; which instead focuses on sensors, especially space based sensors and in particular CubeSats.

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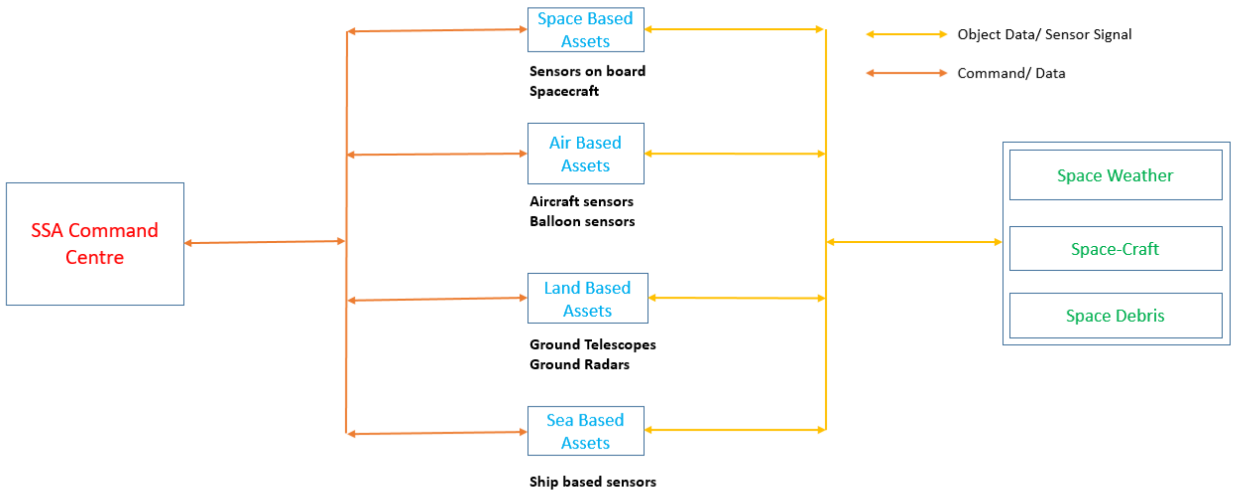

Figure 1: Potential building blocks of an SSA system

The need for SSA systems is rapidly increasing. Reference [1] observed that rapid advances in the use of low earth space by several nations have led to it becoming competitive, contested, and congested. Reference [2] points out that the domain of space in now accessible to over 70 space-faring nations, and well as many more organizations which now include universities, businesses and startups. Reference [3] argues that SSA is critical to any country that seriously grounds its economic well-being and military strength on space based capabilities. Awareness of events and capabilities in near earth space is therefore, necessary from a security and strategic point of view.

Figure 2 gives us an understanding of the scale and complexity of utilizing space based assets for SSA. Since our awareness efforts are directed towards space, an obvious approach is to consider primarily space based assets for improving awareness. While land, sea, and air-based sensors can provide useful information, only space based sensors offer the full range of capability in the domain of interest for SSA. However, networks of space assets or sensors distributed in space on-board commercial satellites are not growing fast enough to meet the growing SSA demand. This is largely due to high costs, long development times and risks involved with launch failures of conventional satellites. This has led to a scarcity of observational coverage via space based assets. This has motivated the investigation into alternatives to conventional satellites and the simultaneous emergence of CubeSats has naturally created interest in leveraging this technology as an alternative to standard satellite technology.

CubeSats are a class of small standardized spacecraft, are also termed as nanosatellites or microsatellites. CubeSats have shown promise as potentially reliable and low cost means of conducting space research. This is due to a defined and standardized spacecraft envelope which also allows commercial off the shelf (COTS) components and instruments to be assembled quickly and at much lower costs [4], [5]. Additionally, they can be deployed in 'swarms' of hundreds per launch greatly reducing the consequences of failure of any individual system.

Our present work explores this notion of a CubeSat-based SSA system by utilizing a Model-based Systems Engineering (MBSE) approach as illustrated in Figure 3. The work prototypes an SSA system via MBSE then attempts to leverage existing work regarding a CubeSat Reference Model to produce a system simulation. The work develops a proposed measure of effectiveness (MOE) for evaluating system effectiveness which the simulation proposes for each SSA architecture. Finally, the work examines a simple set of SSA CubeSat architectures based on this MOE and suggests next steps toward capabilities for evaluating various SSA architectures.

2. RELATED WORK

Previous work has developed significant insights into the architecture and logical relationships of possible SSA systems as well as the scale of the problem. First, the SSA problem is very large and growing more complex. The United States of America maintains the most complete catalog of near earth space objects and runs the largest network of sensors through the Space Surveillance Network (SSN) system [6]. That catalog items more than 17,000 items as present with substantial plans for deploying additional large scale satellite networks in constant play.

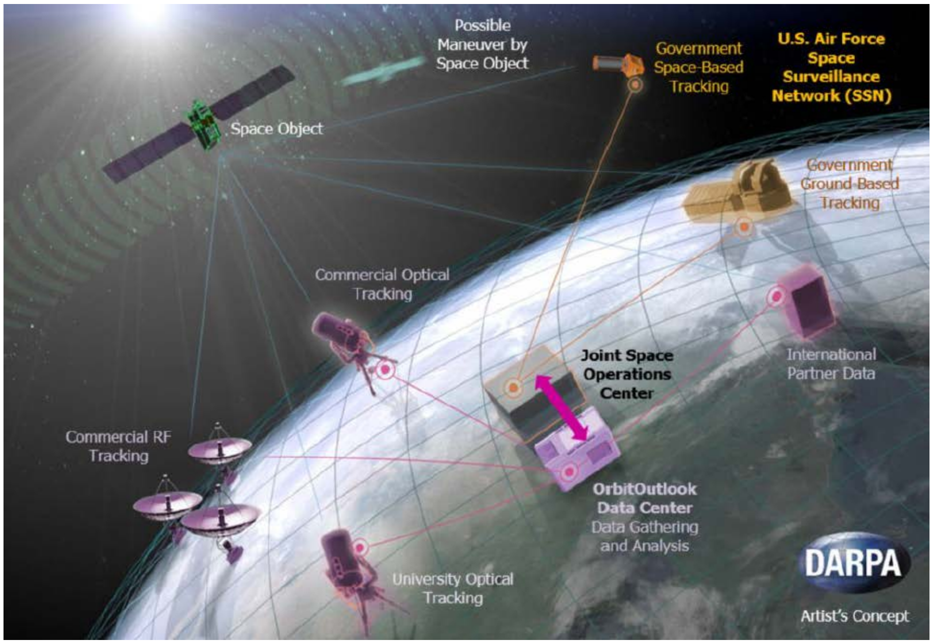

Figure 2: An artist's rendition of an SSA system **[7]**

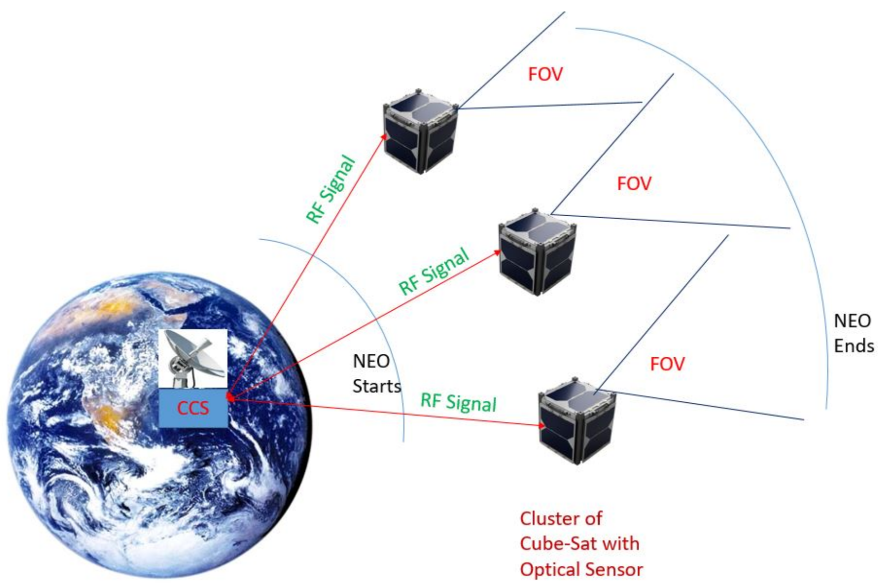

Figure 3: Building blocks of an SSA system based on CubeSats

Various researchers have proposed ways of organizing the SSA problem for action. For example, Reference [8] developed an architecture for Europe's SSA program. The ESA led SSA program is divided into three segments: Space Weather (SWE), NEOs, Space Surveillance and Tracking (SST). Reference [8] created an ontology for each segment, and each ontology can be used alone or incorporated into larger ESA SSA ontology. Furthermore researchers have built on such organizational efforts by suggesting specific SSA architectures. Of particular interest to the present work, Reference [9] proposed an architecture for SSA which will create a network consisting of homogenous sensors. The paper suggested to use a network of phased-array radars on the basis of operational availability and reliability.

Reference [10] proposed a novel approach for design and optimization of a disaggregated and scalable satellite constellation for SSA. None of these approaches however has developed a model to characterize the extent of SSA for a given CubeSat network. This finding motivated the present work.

As is the case for any reasonably complex system, CubeSat design processes require a high degree of concurrency in development over several disciplines of engineering which suggests a productive situation for the application of systems engineering. Each of these disciplines employ specific methods and tools in constrained environments to design the CubeSat's associated subsystem. This causes a need to conduct several design trades over several subsystems to meet requirements within the design space. Implementation of many of these methods cannot proceed in a defined sequence being iterative, and sometimes recursive in nature [11]. This highlights the need for a highly efficient framework that facilitates the development of efficient design methodologies which is a motivation for adopting a MBSE approach.

Systems design in CubeSat missions to date has been carried out using paper based requirements and conventional 'waterfall' approaches. The inadequacy of such methods is reflected in the fact that close to about 50% of present of CubeSat missions fail due to design related issues [12]. As CubeSats missions grow in complexity, there is a need for a more intuitive and robust system engineering methodology that enables the capture of every useful detail in a framework that is interoperable, easy to interface with and one that is able to comprehensively define a 'design space' for the problem (Stephen, 2010), which further suggests that a MBSE approach will be effective.

The International Council on Systems Engineering (INCOSE) INCOSE MBSE initiative's Space System Working Group (SSWG), in their reports [4]; [13], detail the primary needs unfulfilled by a document based approach to CubeSat design as:

1) The ability to improve communication, characterization and specification of the system.
2) The ability to achieve enough commonality to be re-usable.
3) The ability to define a cohesive information flow model.

In their analysis [13], the SSWG found that placing creating and placing system models at a central and governing position in the specification, design, integration, validation and operation of a system greatly enhanced communication as they facilitated the implementation of a model driven information flow model. Reference [14] highlight some of the key differences between a model-based approaches to conventional system engineering approaches. Figure 4 shows an example of a model driven information flow model facilitated by model-based engineering (more general that MBSE). As can be observed, it supports concurrency of recursive and iterative processes required in the design of CubeSats.

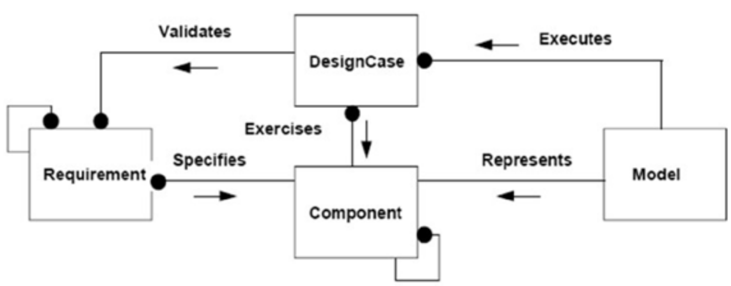

Figure 4: Information flow-model driven system design [14]; Stephen, 2010)

The SSWG further observed [13] that in order to develop a proven set of modelling tools that is testable, the model would need to achieve enough commonality to be re-usable. This finding motivated the SSWG's development of a CubeSat Reference Model (CRM) which is presently being validated by several potential users and which this work attempts to leverage.

3. METHODOLOGY

To begin designing and effective SSA system using a network of CubeSats, several fundamental questions need to be answered. The most critical among these include finding a basis of comparison for the efficacy of competing SSA alternatives, or in classic systems engineering terms MOEs (i.e., measures of effectiveness). As is the case for any reasonably complex system, there will eventually be a family of measures of effectiveness which will certainly include:

1) Development Cost
2) Development Schedule
3) Operational Cost
4) Deployment Schedule (capability to need)

As well as a sub-family of MOEs directly addressing the operational effectiveness of the system. The family of MOEs provides a basis for deciding between plausible system architectures which will inevitably be suggested as system design begins and progresses.

While existing work has explored specific needs, organization, and even capabilities of possible SSA senor assets, there has been very little focused on fundamental MOEs for SSA. Therefore, the present work describes a specific operational effectiveness MOE to estimate the degree of SSA obtained by any specified SSA architecture. The MOE proposed supposes that a SSA system is more effective as the volume of space it can address increases. One way to measure this is to define a mesh of abstract nodes fixed to the Earth's frame of reference as shown in Figure 5 as a proposed measure of effectiveness for SSA systems. In this initial simple formulation, the MOE defines a set of points fixed in Earth's frame of reference, and estimates the degree of SSA due to a given SSA sensor architecture as the fraction of points that the specific architecture can "see", i.e. address with its sensors.

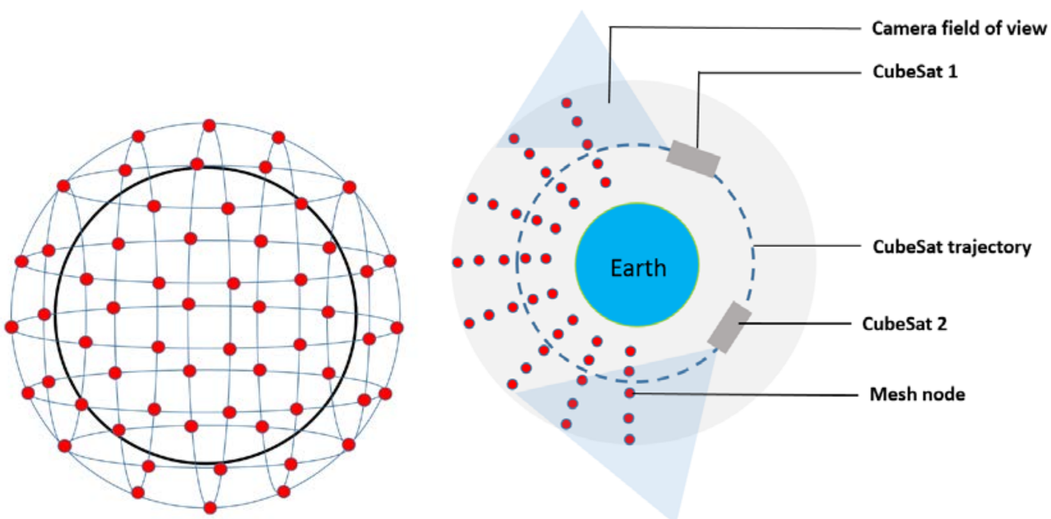

Figure 5: Distribution of fixed spatial nodes in region of interest

The present work's methodology precedes to prototype SSA systems via model-based techniques and evaluate this MOE as basis for comparison. Specifically, the work develops a fundamental definition of a SSA system in SysML and then simulates that definition in a corresponding MATLAB implementation. Grounded in the context of the foregoing discussion regarding CubeSats, this work restricts the SSA system architectures explored to purely CubeSats, and further restricts the CubeSet's consider to consist of one optical camera per CubeSat and 2-D circular orbit of constant radius around Earth. Figure 6 shows the important parameters of interest. The modelled parameters are CubeSat position angle θ, line of sight angle φ, the CubeSat's orbit radius r and the camera's field of view (FOV). For a given network of CubeSats, at a given instant in time, the mesh points covered in a 2D space are uniquely determined by θ, φ, r and its camera's FOV. The network was modelled as consisting of 'i' CubeSats modelled as functions $C_i(\theta,\varphi,t,r)$ of CubeSat parameters and time.

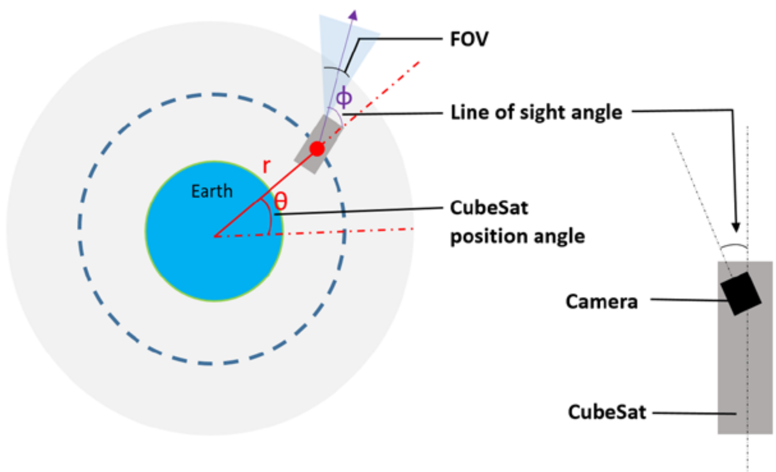

Figure 6: CubeSat parameters modelled in proposed SSA system

Furthering the defintion of the proposed MOE, the present work terms it as a SSA relevance function $R[n,C_i(t)]$ which is a function of each CubeSat in the network at a given instant of time and the node number n in the mesh . For a given network with each CubeSat defined, the angle its camera makes with each mesh point is calculated and $R[C_i(t)]$ is assigned a value of 1 at that mesh point if it lies within the CubeSat camera's FOV and a value of 0 if it lies outside the CubeSat's FOV. The values of SSA relevance functions calculated at each mesh point are summed over each CubeSat over time to given a quantitative estimate of the degree of observability of that mesh point for that given CubeSat network over time T.

$$F(n) = \sum_{i}^{N} \sum_{o}^{T} R[n, C_i(t)] \tag{1}$$

As shown in Equation (1) the relevance summed given the total relevance *F(n)* as a function of node *n* in the mesh. Larger the value of *F(n)*, greater is the observability of that point for the CubeSat network over time and hence it is most relevant from an SSA point of view. *F(n)* is calculated over varying CubeSat numbers per network to simulate the system's behavior.

A CubeSat's development time and complexity can be potentially reduced further by the use of reference models such as the SSWG's. The CubeSat's design is conventionally defined in terms of key parameters of interest. These are broadly defined as (a) mission which defines the entire design space or domain of interest (b) mission objective which sets criteria for success of the mission and helps prioritize functional aspects of the spacecraft (c) environment which specifies the interaction of the CubeSat subsystems with external entities (d) flight system describes the system interactions during flight phase of the CubeSat and (e) ground system describes system components and interactions on earth. In order to model a CubeSat design, these parameters need to be mapped to an object oriented framework [15], [16]. Table 1 describes CubeSat concept mapping to object oriented modelling concepts.

Table 1: Cubesat concept mapping [15]

Cubesat concept	Object Oriented Modeling concept
Mission	Domain
Mission Objective	Use Case
Environment	Environment
Flight System, Ground System	System of Interest, Physical System, Logical System
Subsystem	Logical System

The SSWG's CRM breaks down a CubeSat's design into a mission element, a space element, a stakeholder element and a set of mission objectives. The use of SysML allows for integration of analytical modelling packages such as STK and MATLAB [15], [13]. The CRM further breaks down the CubeSat's design elements to incorporate analytical modelling tool interfaces which should have facilitated leveraging the CRM.

The final point of note about the present work's methodology is that the implementations were constructed in and facilitated by the SSA systems analysis framework developed in the Architecture Driven Systems lab at the University of Arizona. This lab enables evaluation of a range of SSA architectures including human machine interactions in conjunction with automation across a range of generated scenarios as well as creation and evaluation of proposed SSA MOEs. The purpose of the lab is to enable rapid definition, operation, and analysis of architectures dramatically reducing the time and effort to settle upon a system architecture. The lab definition mode available all of the development tools used including No Magic's Cameo System Modeler (CSM), Analytics' Systems Toolkit (STK), and MATLAB in particular. The lab's definition mode provides for creation of system architectures and scenarios. The lab's operational model enables automated processing of scenarios we well as human-in-the-loop exercises including prototype human computer interfaces, and simulation of the system of interest as well as related (perhaps oppositional) systems. The lab's analysis mode enables various analyses of the data collected during the operational mode. The lab achieved initial operating capability at the end of 2017 and this is the first published study based in it.

4. RESULTS AND DISCUSSIONS

In practice however, the methodology discussed ran into immediate challenges in leveraging the SSWG's CRM. Any model is constructed a specific level of abstraction, where highly abstract models are less detailed and less abstract (more concrete) models are highly detailed. The SSWG's CRM is pitched a much lower level of abstraction than the present work supported, and therefore to fully leverage the CRM for SSA, would need a much better understanding of the requirements from a CubeSat network based SSA mission than exist at present. The SSA system models would need to be developed to a higher fidelity to an extent that CubeSat subsystem specific parameters are modelled into it.

The present work did made a first attempt in reducing the available CRM to try and integrate it with our proposed system for CubeSat network based SSA. The reduction approach adopted broke down the CRM into functional sub-models to integrate with our developed SSA model. Figure 7 shows the resulting simplification. Utilizing this reference model to incorporate the proposed CubeSat network SSA system remains a work in progress.

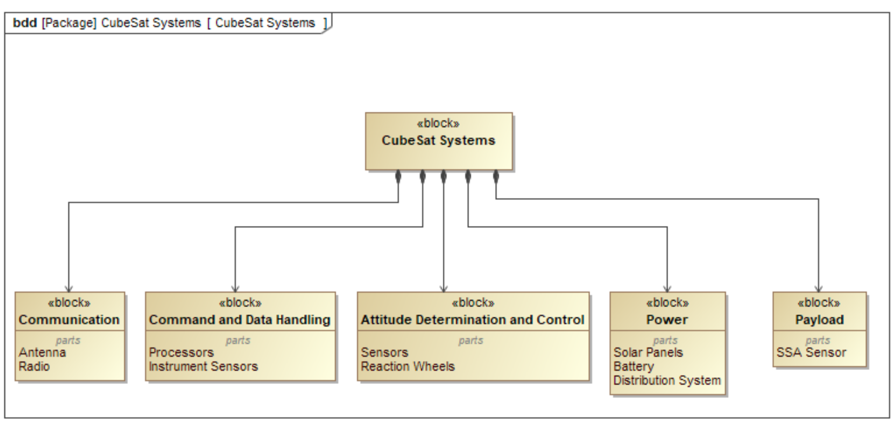

Figure 7: Simplified CubeSat reference model

An additional challenge in applying the methodology were interoperability issues encountered between SysML tools and other engineering analysis such as STK and MATLAB. NoMagic's CSM was used as the SysML tool in this work. Although CSM is capable of running dynamic simulations using behavior diagrams running complex mathematical functions, it is a very inefficient process leading to the use of an external tool. Seamless integration with large MATLAB codes was not achieved to the extent of making the process more efficient than using such an engineering software directly. Moreover, CSM does not support all data types as input. CSM does not interoperate directly with Systems Tool Kit (STK) which is a widely used space mission analysis tool. STK can be run from CSM via MATLAB only. These issues need to be solved in order to apply MBSE more efficiently for any given system and will drive further development of the Architecture Driven Systems lab.

Figure 8 shows the present work's prototype structure of the SSA system for a given network of CubeSats in a SysML Block Definition Diagram. As can be observed major parameters have been segregated into those specific to the mesh that is fixed with respect to the Earth's frame, specific to the CubeSats in the network and specific to the camera on board each CubeSat in the network. The modelled parameters have been discussed in detail in the methodology section. An additional parameter modelled here is the number of CubeSats. As will be describes in further sections, a key objective of this exercise was to understand the effect of number of CubeSats in a given network with respect to the networks SSA ability measured as a function of space and time. While this figure captures the structure of the system, its behavior is captured using the activity diagram as shown in Figure 9.

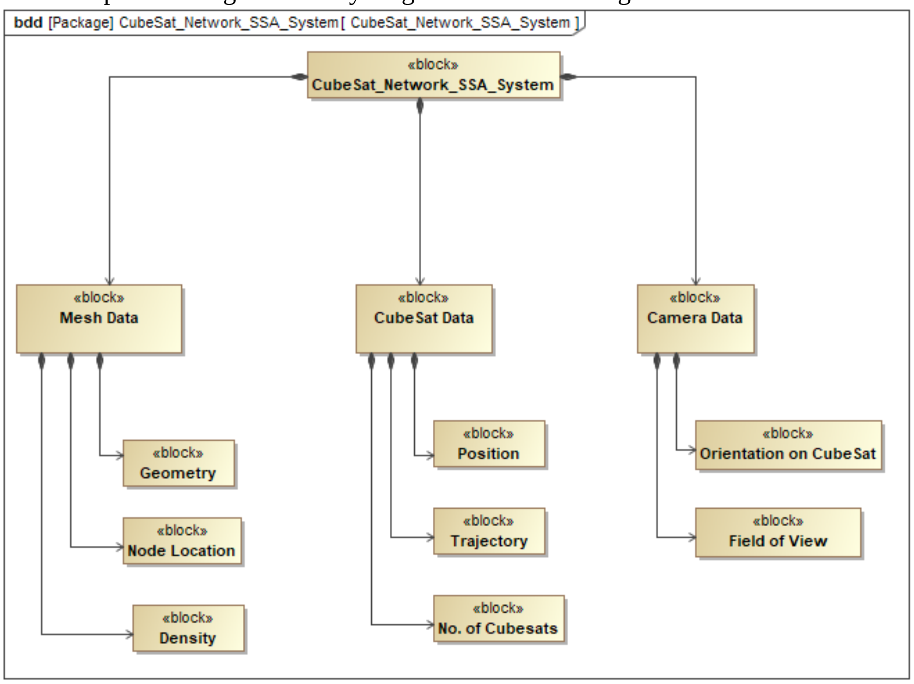

Figure 8: Block definition diagram of SSA system

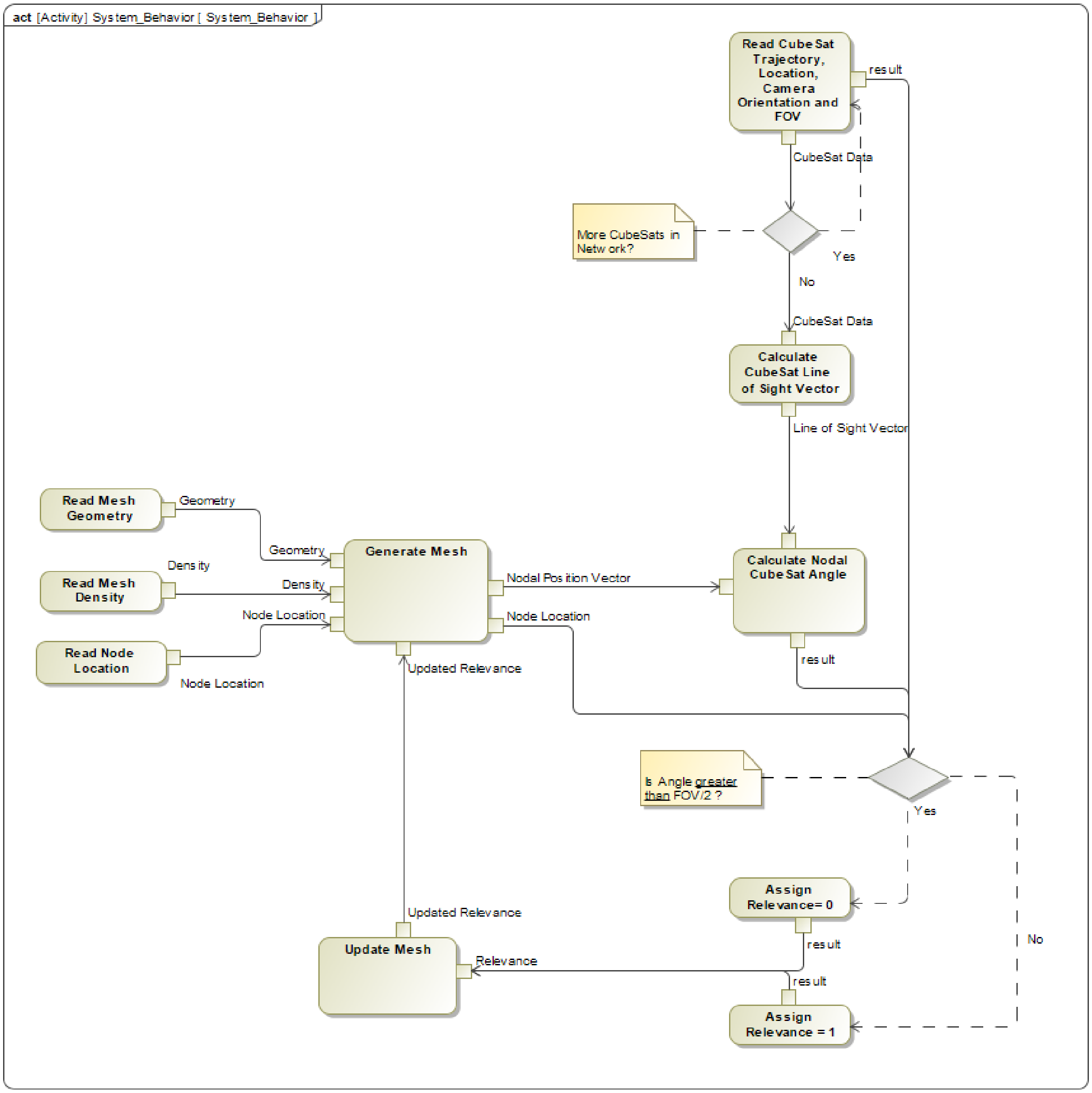

Figure 9: Activity diagram of proposed SSA system

The MATLAB code developed is used to compute and plot SSA relevance function discussed in the methodology as is a direct measure of SSA effectiveness achieved. Figure 10 shows plots for the system's behavior simulated over cases with 10, 20, 100 and 500 CubeSat networks. In each of these test cases, the CubeSats were evenly space and relative positions fixed. In a real SSA system, even spacing would likely be an unrealized objective and surely the system would have to provide for some maneuvering by the CubeSats. For the purpose of this initial analysis as discussed in the methodology, camera and mesh parameters were kept identical. The only varying parameter was the number of CubeSats. The analysis time period was kept constant at 60 days or 2 months and a time step of 1 day was used for computation. The summed relevance values computed over each mesh point are depicted by a color coding. SSA relevance with a value of zero is shown in red and depicts points in the mesh that cannot be observed by the network for the given analysis time. Points depicted in orange have a higher relevance and higher observability for the network over the given analysis period with green being those which are the most observable almost continuously during the specified analysis time period. It can be seen that the red region decreases with increasing CubeSats in the network. With close to 500 CubeSats in the network, virtually all points get covered.

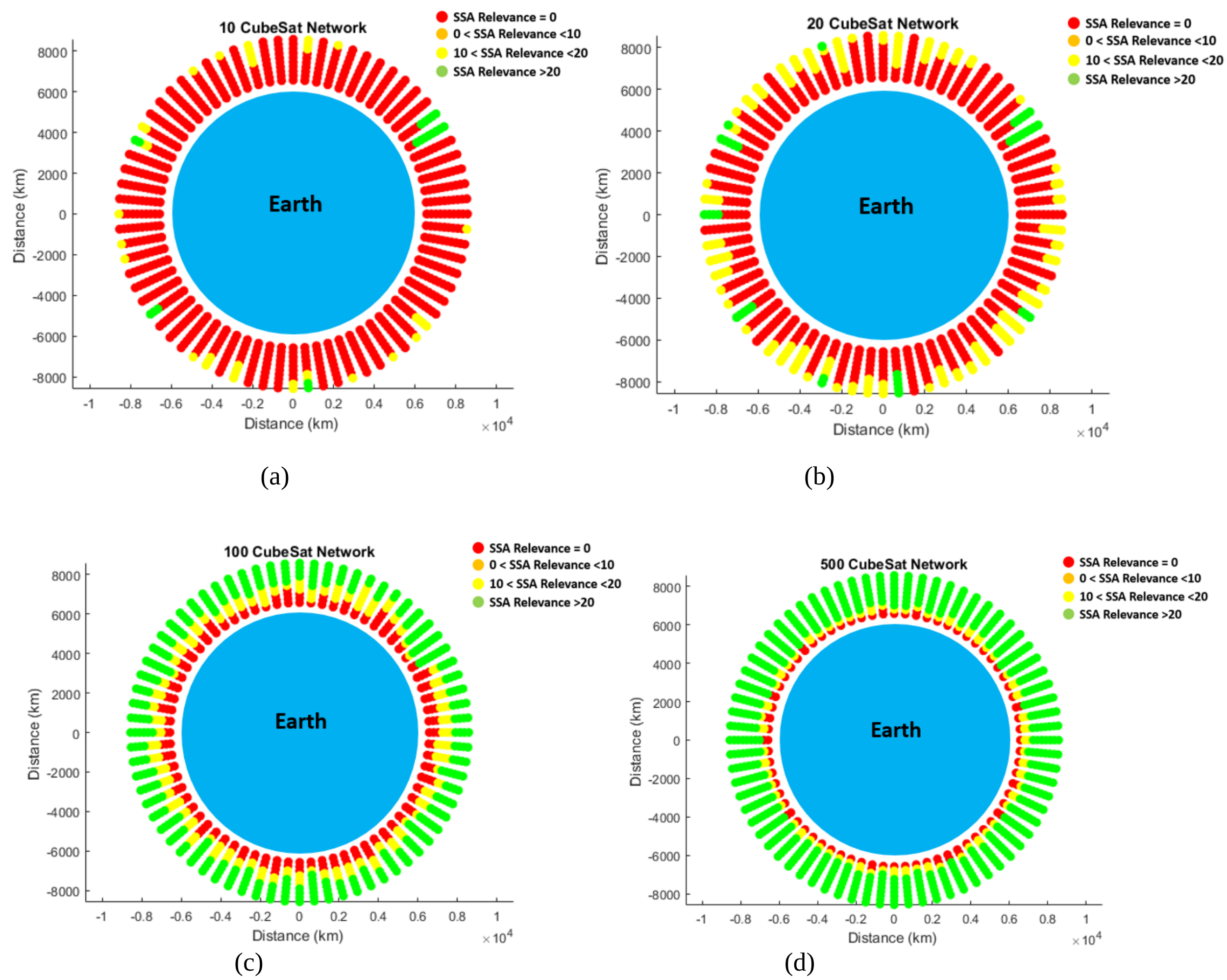

Figure 10: MATLAB plots of the SSA Relevance Measure of Effectiveness over 4 test cases: (a) 10 CubeSat network (b) 20 CubeSat network (c) 100 CubeSat network (d) 500 CubeSat network

5. CONCLUSIONS AND FURTHER WORK

The present work demonstrates a basic suitability for a MBSE approach for defining, evaluating, and comparing SSA system architectures using a network of CubeSats. It defines a new performance oriented MOE and evaluates it by simulating a set of test case systems architectures The results provide a fairly reasonable prima facie credibility for the methodology defined herein noting the real challenges of developing models of compatible abstraction, and that this initial work examines only one dimension of possible architectural variability (the number of CubeSats available). The proposed cumulative relevance MOE shows agreement with expected behavior in response to varying CubeSat numbers. The model in its present state is simplified yet incorporates key aspects of the system. Conducting simulations of the revealed the necessity to include details such as realistic time steps and orbit periods. In its present form, the model gives us a framework to conduct fundamental studies on the effect of mesh, CubeSat and sensor properties and how they interplay to yield effective SSA over a given period of time.

The next step of this research work is to complete a method for reducing the complexity of the SSWG's CRM to fit with a model-based SSA system definition appropriate at this stage of system design. Further, the research should procedure to develop a reference model for SSA systems, with defined approaches for varying the level of abstraction i.e., the type of sensor assets, the detail available, etc. The research should both consider adding needed sophistication to the initial formulation of the MOE herein, such as time varying relevance, and additional performance oriented MOEs. A detailed study is required to understand the sensitivities of mesh, CubeSat and sensor parameters on SSA effectiveness to build a robust model. This would lead to an understanding of optimization methods that can be applied to dynamically modulate a CubeSat based SSA sensor network. Substantial work is needed to improve interoperability between the tools used, as a key enabler for rapid system development and evaluation grounded in MBSE. Additional steps could include comparison of heterogeneous (not solely CubeSat) SSA architectures which might prove more resilient than homogenous architectures motivating still further expansion of the MOEs to be considered for such systems.

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Annotation List

SSA	Space situational awareness
LEO	Low earth orbit
NEO	Near earth object

MBSE	Model-based systems engineering
CRM	CubeSat Reference Model
FOV	Field of View
θ	CubeSat location angle
φ	CubeSat line of sight angle
R	Relevance function
C	CubeSat object
F	Summation function for relevance average
SSWG	Space Systems Working Group
CSM	Cameo Systems Modeler
STK	Systems Tool Kit
n	Number of CubeSats in network
K	Proportionality constant
T	Integration time period