

New Scientific Capabilities Enabled by Autonomous Constellations of Smallsats

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ABSTRACT

Several scientific missions exist that require hundreds to thousands of near-simultaneous measurements at widely distributed locations within the earth's magnetosphere. The current paradigm of individually building, designing, launching, and operating satellites is not capable of performing these missions. An autonomous constellation of smallsats and nanosats, developed as an ad hoc network of distributed wireless sensors will enable real-time, distributed, multi-point sensing of relevant phenomena. A low-cost and mass-producible solution to support this new class of space missions has been designed [1] and this paper addresses the significant system issues driven by this revolutionary technology. The constellation uses smallsats in the ~ 100 kg class as communication and computation nodes and multiple ~5 kg nanosats as distributed sensors to continuously measure plasma parameters in the ionosphere as part of a global space weather monitoring system. The constellation is comprised of separate orbital rings that consist of one or two nodes and between ten and fifty nanosats. Each of the nanosats is a distributed sensor and routing device that generates data messages and routs neighboring data to the nodes. The nodes maintain both an instantaneous data map of the entire orbit distribution of sensors and a time history of all measurements.

NOMENCLATURE

Distributed sensor satellite = DSsat = A single ad-hoc sensor node.

Communication & Computation Node satellite = CCsat = A single hub satellite for one orbit ring in the network.

Ad-Hoc Network = A self-configuring network of mobile routers.

Platform Design = A design that can be easily modified for different missions.

INTRODUCTION

Scientific and military missions in space that require near-simultaneous measurements of local or remote phenomenology at widely distributed locations are very difficult and expensive to perform due to the nature of the manner by which satellites and satellite constellations are designed, built, constructed, and operated. Constellations such as the Global Positioning Satellite (GPS) system can provide high fidelity nuclear detection system (NDS) measurements and navigation beacons from very

sophisticated platforms that are individually controlled by a large force of space operators. These satellites are extremely complex and can be built in a multiple sequential, if not mass produced, fabrication environment and there is little question that the cost of the system is well worth the benefits. Each satellite has multiple payloads and performs several on-orbit functions.

There are several other missions where the measurement requirements can be accomplished with very low cost, power, and mass sensors and the value of the measurements is driven by the ability to make measurements with high geographic fidelity over a global area of interest in a short period of time. The historical approach of building, launching and maintaining complex satellites that each must perform multiple missions (to justify the cost of build, launch, and operation) does not lend itself to performing such a mission.

For several years the advances in miniaturization have lead to various small satellites in the few to tens of kilogram class. While these individually have demonstrated some interesting capabilities (on a per kilogram basis) there is not a significant global utility to the sum total of the Cubesats, nanosats, picosats, etc. that have successfully flown. That does not diminish their individual value – particularly educational – but it keeps the tiny satellites in a niche that is interesting to the aficionado but of no great interest to the community at large. If the number of space operators still scales with the number of satellites then the cost of ground operations remains one of the significant cost factors in operating a potential constellation of many satellites.

Many small satellites missions have been proposed which require some form of precision formation flying and attempt to perform "big satellite" missions at lower cost by creating artificial big apertures (SAR, optical, etc.). While there are undoubtedly some future capabilities that will be enabled by evolving technologies the necessary benefit-cost ratio will have to be very large to overcome perceptions of known risk for big satellite solutions and to force a change in the paradigm of mission constructs. These formation flying satellites generally require some form of propulsion, autonomous (and integrated) navigation solutions, precision attitude determination and control system (ADCS) solutions and, ultimately some moderate amount of ground operation with at least the main satellite in the formation. These are great areas of research and development and will undoubtedly lead to useful future constructs.

The situation with these miniature spacecraft is somewhat analogous to the development of the facsimile machine. The first ones developed were very expensive but had minimal value because there were very few other facsimile machines with which to communicate. As facsimile prices dropped dramatically with the advent of mass production and technology advances the value of each individual machine grew markedly because now there were so many more facsimile machines available for communication. While not quite a network the very large number of point-to-point connections enabled still represented enormous changes in the ability to move information from location to location and person to person.

The purpose of this paper is to explore a concept for using miniature satellites, with the most rudimentary capabilities possible, to solve a problem that cannot affordably be solved with conventional methods – and that does not require significant ground-based operations. While this may appear to be the development of a solution in search of a problem the primary objective is a mission motivation of sufficient magnitude to justify pursuing the investigation.

AD-HOC DISTRIBUTED SENSOR NETWORKS

Definitions

Throughout this paper several terms will be referenced in order to describe objects and relate critical concepts. The definitions used here are adapted from common terminology used in the rapidly evolving development of terrestrial sensor networks [2]. An "Ad-hoc Network" is a self-configuring network of mobile routers connected by wireless links. The premise for this constellation construct is that it acts in orbit as the terrestrial equivalent acts on the ground. One of the on-orbit spacecraft types is a "CCsat", which is a communication and computational node in the network. A CCsat will act as a hub satellite for the network; it provides the majority of the computing power and space-to-ground data transmission for the network. A "DSsat" will be considered an ad-hoc sensor node in the network that performs a mission based on the payload. A DSsat "platform" is a distributed sensor satellite that is designed to be mounted with any type of integrated payload.

Each DSsat is responsible for:

- making some number of measurements with its integrated payload;

- compressing or configuring the data into broadcast packets;
- sending self-generated packets at a designed time interval;
- receiving and re-transmitting packets from other DSsats for some number of "retries"; and,
- autonomously operating ADCS, EPS, and basic housekeeping functions.

The DSsats are not expected to communicate with the ground although the nature of the omni-directional antenna patterns is such that some ground stations will probably be able to hear some percentage of the DSsat routing messages.

Architecture

The CCsats are assumed to be deployed for this exercise at a density of one per orbit ring of x number of DSsats. Each CCsat is responsible for:

- receiving all of the data packets from all of the DSsats in the orbit ring;
- manipulating the aggregate data for transmission to the ground when in view of a ground station (or, conceivably, preparing the data for semi-continuous / burst transmission to a "TDRSS" node);
- computing real-time space weather models / maps based on received data;
- communicating at random intervals with globally-dispersed ground users to provide real-time space weather information;
- exchanging "own node" data packets with CCsats in other orbit rings whenever there is a communication solution; and,
- care and feeding of all of the DSsats in its own ring.

Fundamentally each CCsat has a real-time collection of data packets from all of the DSsats within that orbit ring and constantly updates (with arbitrary fidelity the on-board space weather forecast. The existence of the first orbit ring and one ground station establishes initial operating capability (IOC) for this construct. As additional orbit rings are added the sensor coverage increases in spatial and temporal fidelity that is sent to the ground. As additional orbit rings are added there are opportunities for CCsats from different rings to share "ring data" and increase the fidelity of the space weather forecast that is on each CCsat. Data packets diffuse throughout the integrated constellation whenever distributed sensors from one orbit ring are in range of the next orbit ring. In addition nodes from one orbit may exchange data

packets with other orbit nodes at regular intervals. The resulting directed and randomly diffusing message packets quickly build a real-time, time-sensitive, global model of the plasma conditions in the ionosphere.

Significant Attributes

Three significant and unique technical capabilities arise from this architecture. The first is the ability for users on the ground to be immediately updated to the state of the ionosphere whenever a CCsat is in view. The ground user can query the CCsat for a map of critical space weather conditions that may, for example, disrupt satellite communications or disturb GPS satellite signals and position and velocity accuracies.

The second capability is rapid collection and dissemination of dispersed ionospheric data that can continuously update the global space weather models to an unprecedented degree of accuracy and fidelity. The total amount of simultaneous, globally-dispersed data being gathered and downloaded to the space weather community is analogous to the terrestrial reading of thousands of temperatures, barometric pressures, humidities, wind speeds, etc. used to characterize the "state" of the system and enable models to forecast future conditions at high granularity.

The third, and perhaps most important attribute of this constellation, is demonstrating a working ad hoc wireless network and architecture that can be exploited for many sensing missions in space. One of the most critical system drivers for the constellations is the message passing and routing requirements in an energy-constrained environment. The relationships among number of DSsats, CCsats, orbit rings, ground stations, data rate, packet size, routing protocols, and probability of successful transmission need to be explored in depth as they affect the size, cost, and complexity of the constellation. Several approaches to finding optimal solutions to energy-efficient routing protocols have been used to identify technologies and communication architectures that satisfy data measurement requirements while minimizing the energy, power, and mass of distributed sensors, nodes, and geographic distributions in terrestrial wireless ad hoc networks [2].

As demonstrated in Fig 1, the Ad-Hoc Satellite network can become extremely complex but require only simple operations if certain data flow protocols

are followed. The following assumptions at the lowest level would consist of:

- DSsats will never communicate with a ground station, but will communicate with each other and CCsats.
- CCsats will communicate with each other, DSsats, and the ground stations.
- Individual DSsats are addressed when necessary by the ground operators via the CCsat.

Advantages

A distributed sensor ad-hoc network offers many advantages over the traditional constellation designs. This global network of sensors would be able to collect, process, and immediately transmit a thorough report, including global data, of current mission status to the ground-based user. Since it is impossible to predict exactly what future payloads may be needed in space, a satellite “platform” can be designed to fit a diversity of payloads, requiring only small design changes to adapt. The constellation design is a platform design as well due to its ability to be changed easily to satisfy different mission requirements.

SPACE WEATHER FORECASTING

The topic of space weather forecasting was chosen in order to demonstrate the capabilities of distributed sensor ad-hoc networks. Specifically, the objective is to provide sufficient fidelity electron energy and density measurements to update the global weather model in a timely manner and to detect and report, in real-time space weather conditions such as plasma bubbles, turbulence, and discontinuities that can affect such operations as navigation via GPS signals and communication via geosynchronous satellites. In each case the presence of space weather disturbances can cause so much electromagnetic signal disruption that the position and velocity estimates derived from GPS signals are severely degraded and communication links through the ionosphere become unusable.

Problem

Plasma bubbles are created through a daily interaction between the Earth’s atmosphere and the Sun’s radiation. This radiation hits certain particles in the atmosphere, splitting them apart into protons and electrons, and creating plasma [5]. This plasma causes many different atmospheric effects; so far, most of them have not been studied in great detail. However, it is known that plasma bubbles interfere

with satellite communications, making it harder to send and receive data accurately.

While there are a number of satellites that continuously collect plasma parametric data and forward that data to the space weather community, the data is so sparse in spatial and temporal terms that the global picture is based on very under-sampled averaged data and the regions that have high fidelity spatial and temporal measurements are very localized.

Possible Benefits

The long-term use of this distributed sensor architecture could have many potential benefits. The data could be studied over a period of time in order to determine the effects of many different variables on the plasma. So far, the following three different variables have been identified as having a significant effect on the plasma layer: latitude, time of day, and solar cycles. For example, it is already known that time of day affects the plasma layer but it is uncertain as to how much effect there is on the plasma density. As can be seen in Fig 2, there is a large variation in the density and altitude of the plasma between sunlight and nighttime conditions. During nighttime, there is no longer radiation from the sun striking the atmosphere and creating plasma and therefore some of the plasma recombines and the plasma layer thins out, lifting to a higher altitude. At night the lower layer of plasma is higher in the atmosphere than during the day potentially creating a more stable atmosphere with fewer plasma bubbles. Finally, there could be fluctuations due latitude or solar cycles and studying the data over time could reveal many different insights on how these variables can have an effect on the plasma layer. A figure of merit (FOM) for the system should account for these diurnal variations and provide a set of measurements that has a spatial and temporal fidelity on a sub-diurnal variation timescale.

Global Coverage

The first principle advantage of this type of system is the capability of global coverage. The system is designed so that in a single earth day, the system-wide coverage of the earth is near 100 percent. More specifically, in order to measure the percent coverage of the globe, the globe is divided into 100 km by 100 km boxes, called “buckets.” The first version of the architecture takes all of the measurements at a constant altitude of 400 km. The FOM for coverage is therefore the percentage of the spherical surface at 400 km that is sampled at least once in less than twelve (or twenty-four) hours. The "vertical" models

of plasma energy and density distributions can be extrapolated from measurements at one point in altitude. Future constructs will place appropriate value on three dimensional measurements (latitude, longitude, and altitude) of the plasma parameters.

For the purposes of this exercise all geometric points in latitude and longitude have equal value and there is no additional value for sampling a region of space more than once within the time period of interest. This collected data can be accessed as a whole to gain global awareness of the current space weather or network status. In reference to the global data, an analyst would be able to determine a certain behaviors occurring within the atmosphere.

Therefore;

$$FOM = \text{cov}_{\%}; t \leq t_{\text{cycle}}$$

The relevant data can also be accessed by a single user in a near real time situation in order to gain the same important information. For example, interference with a satellite communication link can cause many problems, especially in the military. Specifically, the military relies on the GPS system for many precision guided weapons. If the plasma bubbles interfere with the GPS system, accuracy could be reduced, from one meter to nearly 70 meters. This could mean the difference between hitting a valid military target or hitting a civilian target and causing countless unneeded casualties, or even mission failure. Because of this potential problem, the system is being designed so that as much up-to-date real-time data as possible would be available to users. If either recent information or historical information is available to a commander, they will be able to make potentially critical decisions about the timing of missions. For example, if historical data suggests that around 1400 every day, the accuracy of GPS is at its lowest, the commander would try to avoid planning GPS-reliant missions around this time period.

Information Database

A second advantage of this system is the ability to compile comprehensive amounts of simultaneous, spatially distributed data about the atmosphere in a short amount of time. This database could have both scientific and strategic use. The scientific uses of all this data are nearly endless. In fact, analysis of most of the data would require the development of new computer software in order to even compile and analyze the data. On the most basic level, the database could be used for anomaly resolution. Anomaly resolution could occur using the following

method. First, an observation could be made on the ground where the cause of an anomaly is unknown. If the system is set up correctly, at that specific time a Nanosatellite would record the relevant anomaly data and transmit it to the database. Once compiled, the data could be examined and perhaps the cause of the anomaly could be discovered.

As the system is in operation for extended periods of time; daily, monthly, and yearly data would be stored on a huge database. This data could be examined to establish patterns, hopefully relating to the variables discussed above. These patterns could then be compared to astronomical data and further knowledge could be gained. As further discoveries are made about the causes and effects of space weather, predictions could be made, with increasing accuracy. Just as atmospheric predictions are made largely based on previous data, space weather predictions could be made in the same way.

SATELLITE AND CONSTELLATION DESIGN

The adaptability of the distributed sensor ad-hoc network is resolved on two levels, satellite payloads, and constellation design. A payload using “platform design” only needs to be modified slightly in order to fulfill different missions.

Payload Design - SmartMESA

The basic payload for the space weather mission is a miniature electrostatic analyzer that can measure the density and temperature (energy) of the ambient plasma constituents. "Smart" MESA refers to the fact that the instrument will have on-board signal process, data collection, and instrument control functions and can be programmed to autonomously collect and analyze data. Since SmartMESA is a retarding potential analyzer it can be configured to measure either ions or electrons. For the purposes of this exercise it is assumed that electron energy and density are the measurement objectives.

Platform Design - DSsat

The DSsat is designed to support a single, integrated payload. An integrated payload is a mission-ready experiment that can do all of the collection, compilation, and storage autonomously. The satellite is only required for power, communications, and the Attitude Determination and Control Subsystem (ADCS). By designing with this method, a simple DSsat can be mass produced, only requiring integrated payloads ready for operation. Basically, an assembly line can be created that produces a mass

amount of these satellites ready to be bought and have final modification for specific missions. This will allow the cost to be significantly decreased. By designing these satellites to be simple and cheap, they will be replaced easily. Using components designed for a shorter lifetime will allow cost to be decreased yet again. Once launched, it will not matter much if a single satellite fails. The key to this network design robustness is the ability to only slowly degrade constellation effectiveness as DSsats fail or drop from orbit. The key to the architectural concept utility is the ability to easily replace DSsats and CCsats.

There are several important performance drivers that have a significant effect on the DSsat design: ADCS, EPS, and communication. A payload such as SmartMESA has no need for attitude knowledge or control, just time and orbit location. This is because this application of SmartMESA is measuring electron energies and the velocity of even the ambient electrons is so much greater than the DSsat velocity that attitude knowledge is not required to back out the spacecraft velocity component of the energy measurement. In this DSsat implementation, however the value associated with the maximum number of simultaneous, widely-dispersed measurements from a fixed number of platforms places significant importance on the ability to communicate with nearest neighbors. Simple gravity gradient configurations that enable maximum gain from a cylindrically-symmetric gain pattern may maximize communication in the direction of nearest neighbors without requiring yaw control. Simple permanent magnets can be used to augment mass distributions that provide a stabilizing gravitational gradient torque on the DSsat.

There are some DSsat payloads of interest that will require three-axis knowledge or control and embedding magnetorquers in the structure or miniature MEMS-based yaw and pitch wheels will be cost effective when designed as part of a mass-produced product.

Miniature GPS receivers are now available and the baseline DSsat design incorporates one for time and position information.

The EPS is nominally assumed to be based upon simple body-mounted, high efficiency solar cells with the best possible energy density batteries such as ion polymer technologies. There have been recent advances in tightly-wrapped, deployable thin film arrays that have the promise of providing several 10^3 's of W input to spacecraft of the scale of a DSsat. That is expected to be commercially available within a

relatively short time period and is a target technology for future implementations.

Communication requirements are the most stressing part of the DSsat design. Conventional approaches to communication systems on satellites tend to focus on continuous duty performance. For this constellation we can design a typical (e.g., QPSK or GMSK) modulation scheme that will provide a $1E-5$ BER performance metric at a nominal transmission rate. The required E_b/N_0 of ~ 10 results in DSsat EIRP power levels of 10^+ W to get ranges in the thousands of kilometers. This type of steady state power load is not consistent with existing technologies for this scale.

Reference [12] is a review of several approaches to communication architectures in highly constrained environments. The concept of using multi-routing to get signals from widely distributed sensors to the correct location minimizes the instantaneous range requirements but increases the total number of data packets that must be relayed.

A simple scaling is as follows. Assume that each SmartMESA is sampling plasma parameters at a rate of 100 samples per second. The data is maintained within the payload memory and an average value of electron temperature and density is calculated for a nominal 100 km by 100 km region of the ionosphere at the altitude of the spacecraft. The size of the data packet is of the order of:

Time: 4 bytes
Position: 12 bytes
Electron density: 4 bytes
Electron temperature: 4 bytes
DSsat / Packet ID: 4 bytes

With some protocol overhead, embedded error correction and perhaps bit packing each DSsat will broadcast a minimum of approximately 200 bits per message.

These packets are one-way transmission and the probability of successfully passing the packets on to the next router (DSsat) is a function of the number of broadcasts of the packets, the range to the next DSsat, and possible interference from other DSsats in time or frequency. The DSsats are designed to be generally omni-directional.

Each DSsat must re-broadcast packets received some number of times. If every packet is successfully broadcast then the total number of packets sent by each DSsat scales linearly with number of DSsats in

the orbit ring, the number of retries required, and the number of hops that each DSsat is capable of.

Figures 5 and 6 show the scaling of required transmission rate (in bps) and number of DSsats per orbit ring for single hop and double hop broadcast scenarios. The power required for communication scales as $(\text{range}^2) \cdot \text{bps}$ and it shows that going from 10 to 20 DSsats per orbit ring cuts the power requirement in half and going to 50 reduces the power in half again.

Platform Design – CCsat

The design of the CCsat is a straight forward small satellite design that includes enough data storage for up to twenty-four hours (figure 7). Approximately 50 MB of data storage includes a 100 per cent overhead for 50 DSsats.

Minimal ADCS is required such as a gravity gradient stabilized satellite. The spacecraft avionics could include a separate payload processor that stores and manipulates the incoming data from the DSsats and updates the local copy of the space weather forecast.

When a second orbit ring is added, with another CCsat, there is an occasional opportunity to exchange complete data sets from another ring. Allowing for that possibility merely doubles the total data storage requirements to less than 100 MB.

EPS requirements are also nominal for a small (~ 100 kg class) satellite.

Constellation Design

By definition since the constellation is ad-hoc it will be self configuring. In space the concept of self configuration is a two way street. The satellites, as previously discussed, serve as a platform so most of the configuration should occur in the integration phase before launch, and at the electronic digital level when deployed in space. On the other hand, since the satellites serve as single nodes within a constellation, the design of the constellation itself is critical. The constellation needs to have flexibility, but at what cost? At the lowest level this type of constellation serves the purpose of orbital geometry and communication. By analyzing the constellation in terms of orbits, and communication, it is possible to study the costs, and related tradeoffs.

At the orbital level, the constellation dynamics are extremely complex. Although mobile, they are unlike traditional ad-hoc networks because they have predictable movement-orbits. Optimizing these orbits becomes essential, since at the core for space weather forecasting the nodes orbits must occur

within the medium they are measuring. In order to accomplish the space weather forecasting mission with a single orbit of multiple sensors a minimum of 11 satellites are required to accomplish successful crosslinks with Current-Off-The-Shelf-Technology (COTS) technology. Introducing redundancy in a single orbit would require doubling the number of DSsats in order to half their line of site transmission distance to allow failure of one DSsat in the chain (single-orbit redundancy). However, because the orbit is a circle, it takes two failures to isolate a portion of the network. On the other hand another solution is to introduce additional orbits that would be in close proximity of physical orbital geometry to the original orbit in order to offer crosslink capabilities during moments of approximate required line of site (cross-orbit redundancy). Multiple orbits with varying inclinations offers a redundancy in crosslink communication, but it also adds additional complications in initial delivery and inefficiencies in coverage. The inefficiencies in coverage are introduced due to excessive coverage that occurs at the higher and lower latitudes of the earth (+-75 degrees). At these altitudes the coverage rates are high per period because the total area of interest is exponentially smaller than the area of coverage required at the equator. At the equator the bulge of the earth results in over spacing so that complete coverage of this part of the sphere occurs at a smaller rate. Therefore another tradeoff to consider is the difference between coverage rates in polar vs. near equatorial orbits. With orbits of inclination close (+-30 degrees) to the equator there will be near instantaneous coverage of the bulge of the earth, but total coverage of the earth would not occur. Likewise a completely polar orbit guarantees complete coverage of the earth, but it will always require a longer amount of time. As a final consideration, since the Nanosatellites will never be in direct contact with the ground, positioning must be known for network maintenance and efficiency. In the case of space weather forecasting and as a general nanosatellite platform we propose using a standard GPS integration for space use to allow the constellation positioning to be known at all times.

The orbital level is also elementary because it sets a basis for communication. In general, as in any network, the distributed sensor ad-hoc network will need to resolve issues such as: network saturation, storage, transmission rate, data encryption, data modulation, transmission and transmission verification (handshaking, send it and forget it, relaying). Some specific twists that a three-dimensional space atmosphere introduces to these issues include: hierarchy of network, satellite

constraints in data processing, storage, and transmission, optimized timing vs. optimized data rates, routing schemes, and transmission distances all balanced with COTS. For example at the data relaying and network hierarchy we must consider the trade offs between ratios of DSsats to CCsats, and DSsat to DSsat communication. As more CCsats are added to the network, there is an increase in data reception, computation and data relay to earth. On the other hand, an over abundance of DSsats could result in more data collection, more data transmission, and likelihood of network inefficiencies. In-between the two exists an optimal number which in relation to network geometry will allow for optimal transmission (without congestion), data computation, DSsat coverage of the desired atmosphere, and minimal power consumption in transmission.

Considering the previous tradeoffs, we propose the following solution to the space weather forecasting problem. A constellation of 44 DSsats at an altitude of 400 km and 4 CCsats at an altitude of 700 km divided evenly between two polar orbits. This solution offers the maximum redundancy, minimal transmission power, lowest inefficiency (due to excess coverage), greatest coverage rate and simplicity. The polar orbits offer complete coverage of the earth guaranteed within 24 hours. The total number of 44 satellites accomplishes single-orbit redundancy which is divided between 22 satellites per orbit. Additionally the dual orbits offer a redundancy at the poles because if both the forward and reverse DSsats in a single orbit fail, there will still be a 12 minute point in every period in which there is cross-orbit window of redundancy at the poles. This also translates into a continuous stream of approximately 12 minutes (LOS) contact of cross-orbit communication at the poles available for network transmission optimization. The two polar orbits introduce an inefficiency of .1% of excessive coverage due to multiple orbits, but it is over 23% of inefficiency due to the number satellites. Additionally the LOS calculated for 11 satellites per orbit is 4587.48 km, at this LOS the required power using optimal COTS requires approximately .5 watts of power and ensures the stated previously stated redundancy assuming substantial atmospheric degradation due to extremely LEO.

Figure 8 and figure 9 graphically and pictorially demonstrate the following support for our proposed solution. Figure 3 shows the coverage of the earth (as a percentage) as time increases for several different constellation designs. The first design (Single orbit, 11 total satellites), is an example of the minimal amount of satellites required in a single orbit in order to create a viable line-of-site network. Figure 4

demonstrates the difference between a single and a dual orbit constellation. The sharp bend that exists at the twelve hour is a result of a combination between the inefficiencies of polar orbits, and numerous satellites. In other words, after twelve hours, the Earth has rotated 180 degrees. This means that the buckets occupied at the start of the simulation are being encountered again. A bucket is only counted as filled once so when a satellite occupies it again, that information is ignored. As the number of DSsats in a single orbit increase, to increase the redundancy of the network, the initial slope and the final coverage increase as well. When a double orbit is used, there are three bends in the graph. This occurs because instead of 180 degrees (or a 12 hour rotation) until the satellites encounter areas of space that have already been examined, there is only 90 degrees of rotation, or 6 hours.

CONCLUSION

The first potential flight demonstration will be on FalconSAT-6, a 100 kg student-built microsatellite, and will incorporate multiple nanosats that are released in a controlled manner to demonstrate distributed sensors and communication. This flight is expected to launch in 2011 following a launch of FalconSAT-4 in 2009, which will demonstrate two distributed sensors (PCBSats with the MESA payload) and establish flight heritage for the PCBSat system configuration and components [3].

Our proposed solution was optimized for the problem of space weather forecasting. The space weather forecasting mission is simply one of many different mission types that could benefit from an ad-hoc network. As simple as possible, this example demonstrates the power and versatility of a distributed sensor ad-hoc network. This example also demonstrates the tradeoffs and considerations in planning required to design even the simplest network. Finally this example and discussion of distributed sensor ad-hoc networks provides a viable future alternative option to current satellite mission philosophy.

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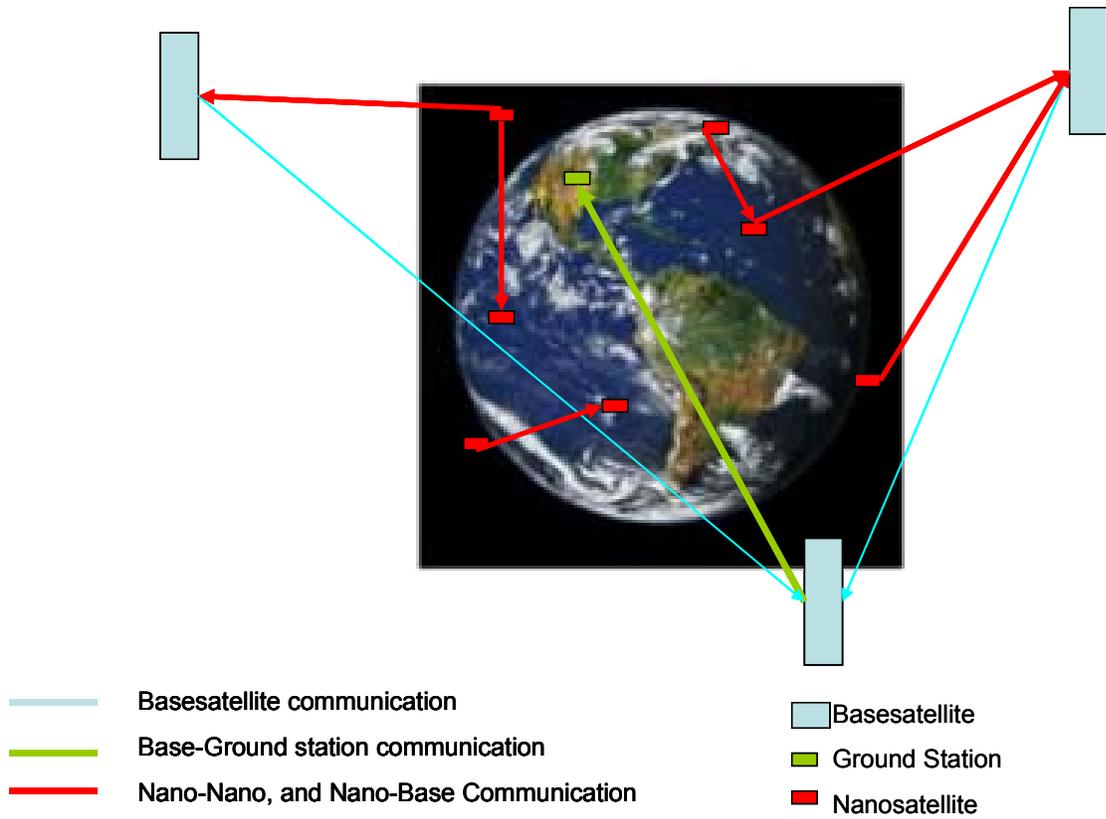


Figure 1: Ad Hoc Constellation Architecture

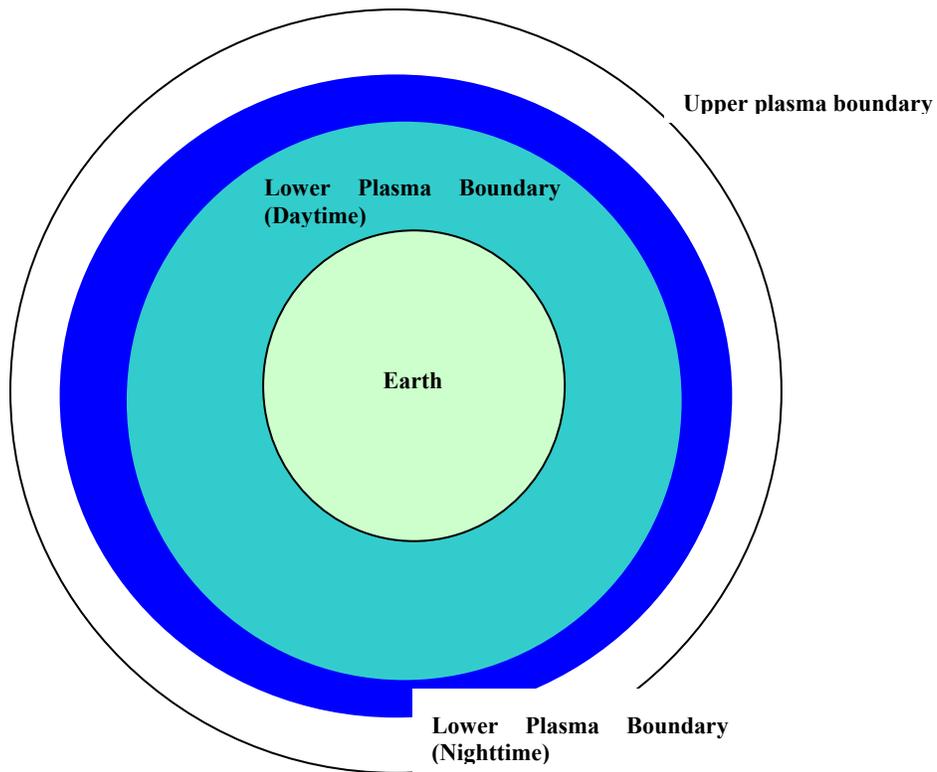


Figure 2: Plasma Diurnal Variations

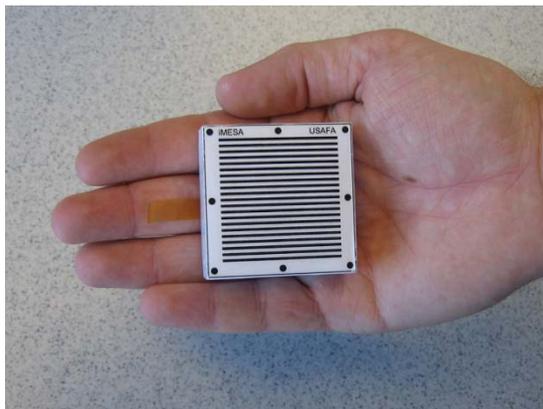


Figure 3: SmartMESA Sensor Head

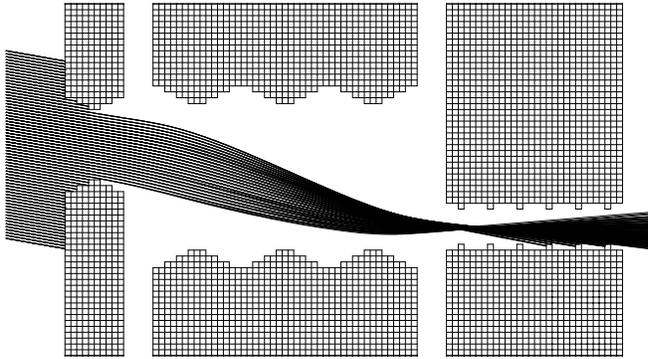


Figure 4: Particle Trajectory in SmartMESA

Figure 5:

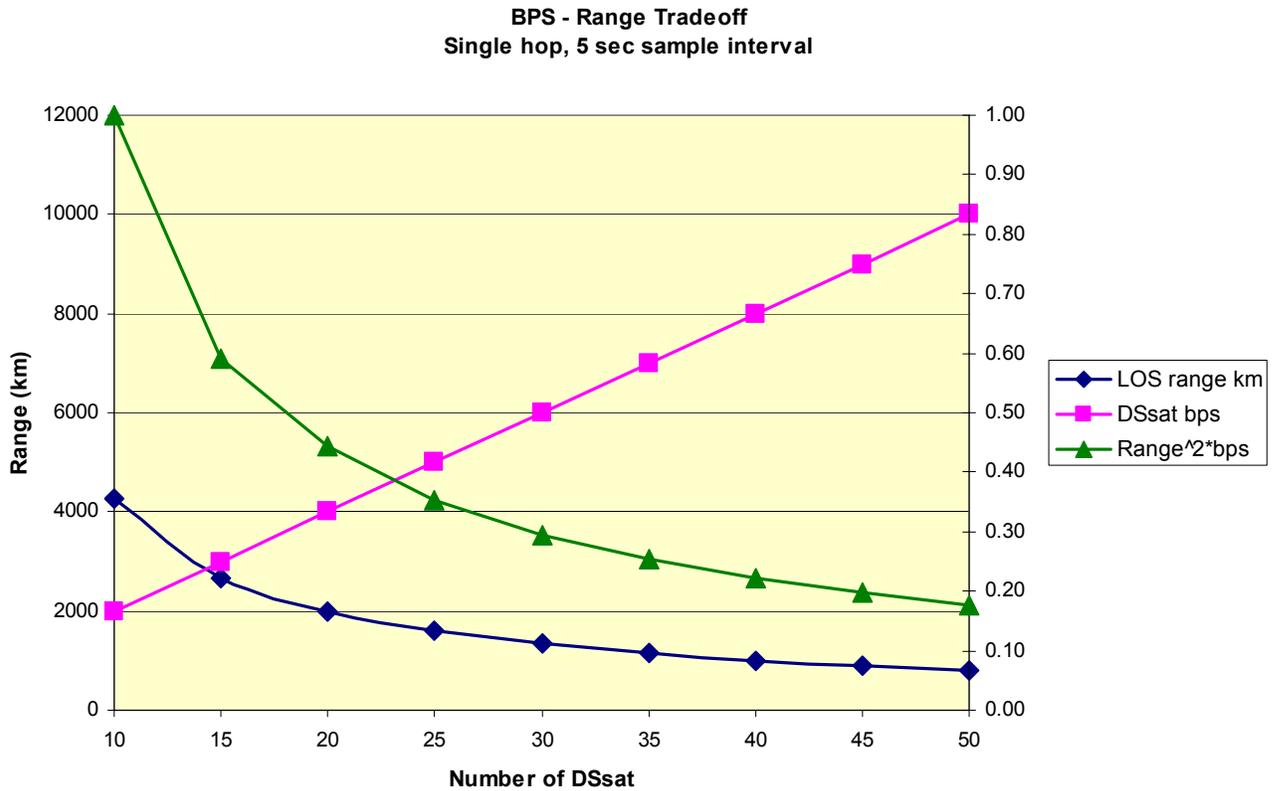


Figure 5: Range – bps Tradeoff, Single Hop

BPS - Range Tradeoff
Two hops, 5 sec sample interval

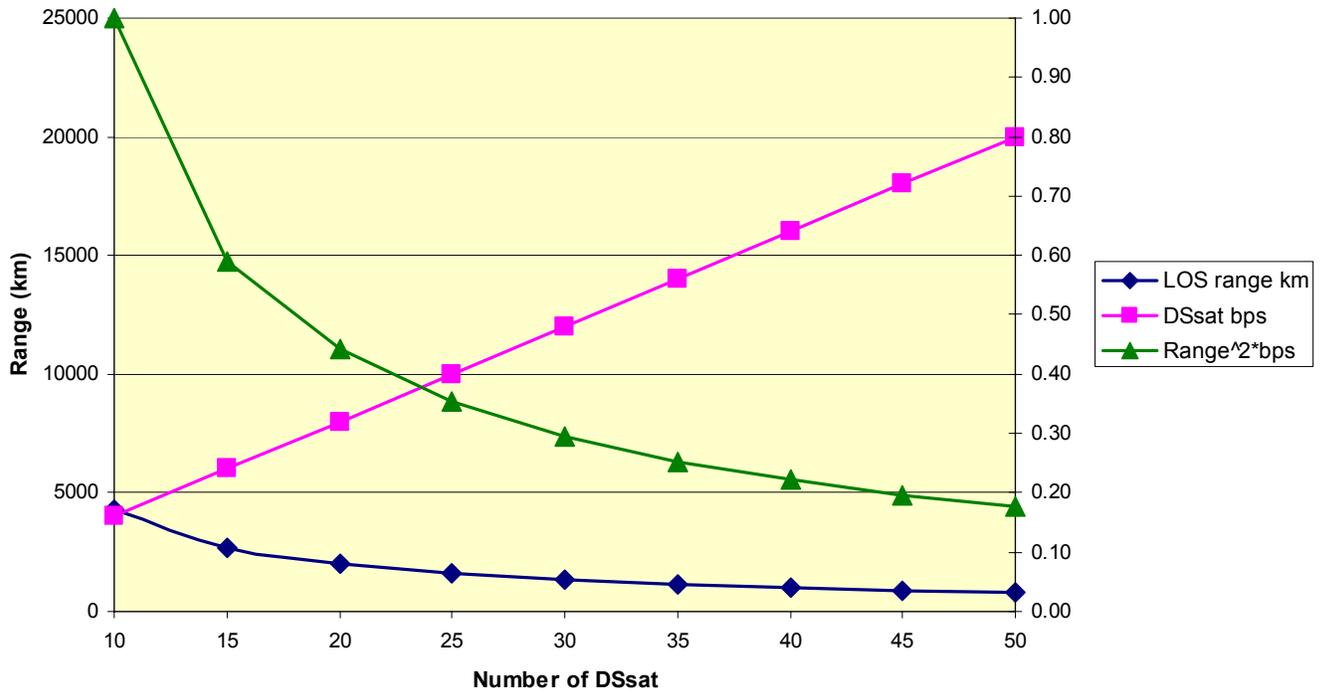


Figure 6: Range – bps Tradeoff, Two Hop

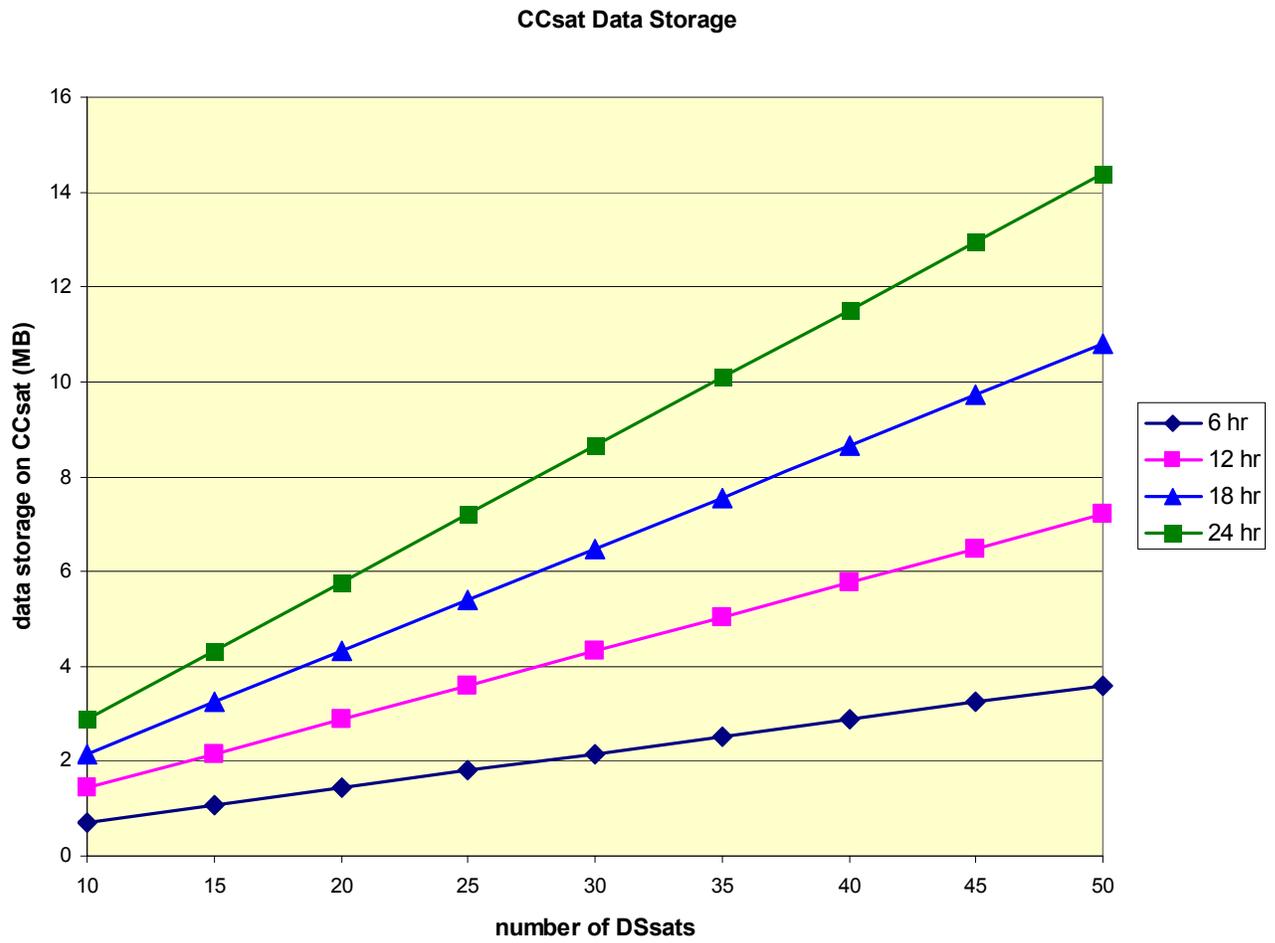


Figure 7: CCsat Data Storage Requirement

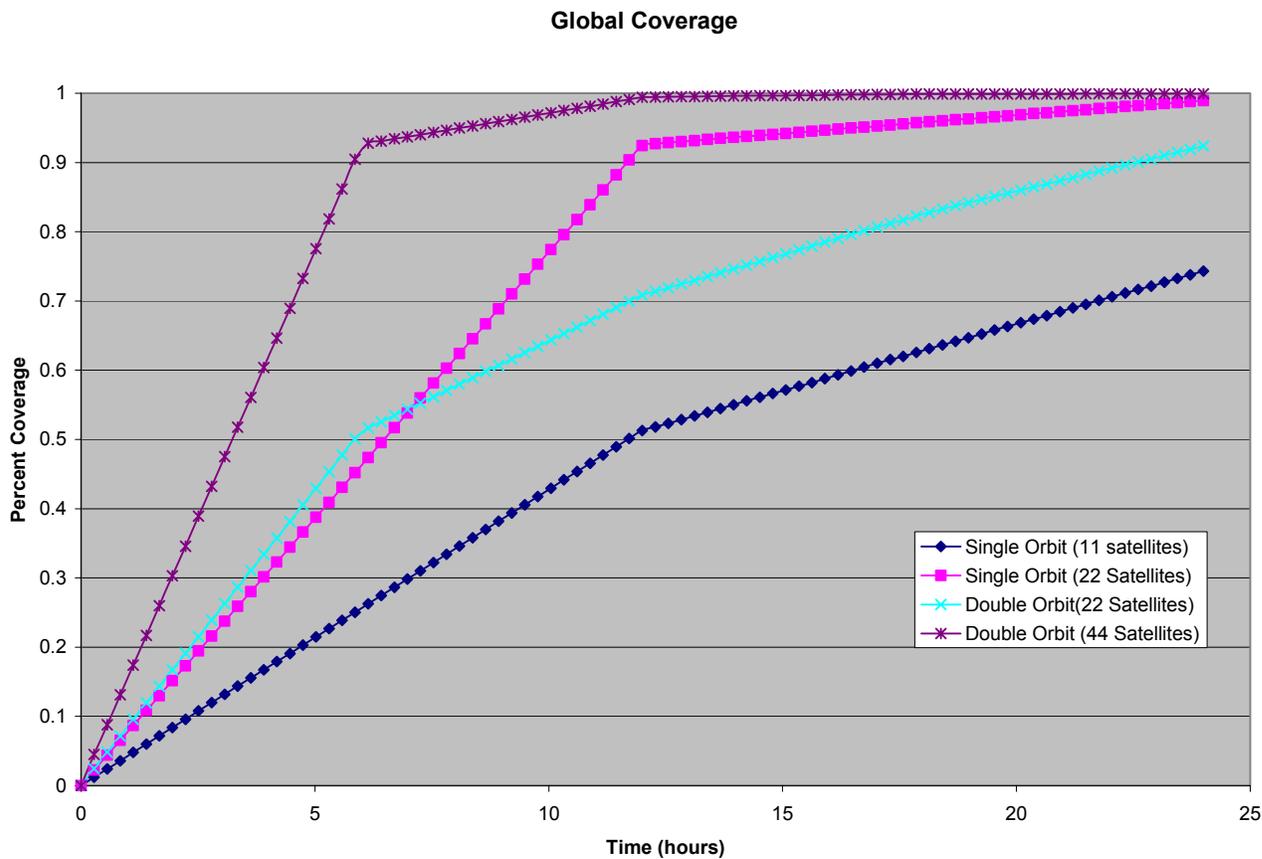


Figure 8: Constellation Coverage Figure of Merit

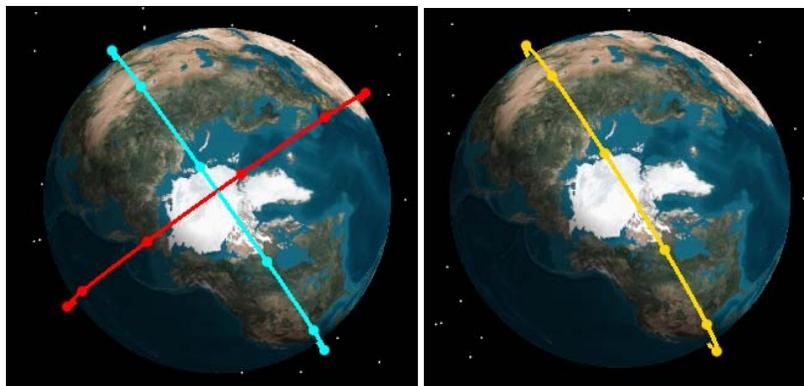


Figure 9. Double orbit, 11 satellites per orbit (left). Single orbit, 11 satellites per orbit (right).