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Satellite Capabilities Mapping – Utilizing Small Satellites

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ABSTRACT

The cost and schedule advantages small satellites have over larger legacy systems have been studied for years, but there has been very little experimentation performed to determine whether small satellites can actually deliver any of the capabilities of a larger spacecraft. To date, a desired operational capability has not been fully realized by a scalable satellite design. Advances in sensor technology have led to significant reductions in size, weight, and power (SWaP) presenting an opportunity to exploit the evolution of space operations by using small satellites to perform specific missions. This paper describes a methodology developed to map a specific set of defined large space vehicle capabilities to a constellation of small satellites. The process includes an analysis of user needs, capability gaps, and examines the utility of advanced sensors. This leads to determining: number of satellites; orbit geometry; sensor configurations; and the satellite bus.

Space weather has been identified as an excellent mission to exploit the potential of small satellites[4]. Advances in micro-electronics have produced sensors with reduced SWaP, making them a viable test subject. Therefore, mapping capabilities to a small satellite, or constellation of small satellites, could provide solutions and affordable options to the adverse challenges facing space operations. The methodology developed here maps the National Polar-Orbiting Environmental Satellite System (NPOESS) Space Environmental Sensor Suite (SESS) to a constellation of small satellites intended to perform this operational mission.

INTRODUCTION

The space industry faces significant challenges in the years to come partly due to soaring costs and delayed schedules. These challenges are illustrated by the recent White House decision to disband the NPOESS joint program office[1]. NPOESS was intended to reduce costs and duplication of effort by merging the Defense Meteorological Satellite Program (DMSP) and Polar Operational Environmental Satellite (POES). Unfortunately, cost over-runs combined with technical and management challenges led to a significant increase in the final cost of a system design with reduced capability. The reduced capability and the delay caused by program termination presents a highly probable space weather (SWx) monitoring gap that is looming on the horizon.

The entire space industry must adapt to more austere economic conditions and develop more efficient practices to reduce costs. Product lines that continually evolve their core technologies are strongest. They create a natural expectation that they will continue to produce greater capabilities at lower price over time. The argument that space operations are more complex and difficult subject which demands more resources than other industries is a hard sell when consumers can easily obtain the functionality (capability) found in today's smart phones. While a smart phone and a satellite are significantly different, it is the evolution of technology demonstrated by smart phones that consumers and taxpayers have grown to expect. The space industry will, by default, be held to those same expectations.

Small satellites (smallsats) have become more attractive due to their size and `weight but still have limitations, primarily related to payload capacity. Even with their limitations, smallsats have sparked interest at universities, commercial companies, and government organizations because of their ability to perform low cost on-orbit experiments and demonstrations. They present a limited solution in some areas of interest to the space community but certainly not all. Space Weather is one area identified as a strong potential beneficiary of smallsats[4].

This paper discusses the method of mapping the capabilities of large satellite systems to one or more small satellites as an opportunity to exploit advanced sensor technologies. Examination of the requirements and deliverables of the large system are used to define a capabilities scope that guides the process and a set of metrics by which the performance will be evaluated. Eliminating the engineering time required to design a new smaller bus or modify an existing one generates additional cost savings and shortens the schedule.

Space weather sensors have advanced their capabilities while reducing their SWaP. There are several SWx sensors ranging from low to high technology readiness levels (TRLs) that are compatible with the CubeSat bus. The capabilities mapping process will be demonstrated by mapping the functions of one of the five SESS instruments to a small SWx sensor compatible with CubeSats. The gap resulting from NPOESS requires a rapid solution and not another four to six year satellite procurement program. Even if de-manifested instruments were installed on one of the remaining DMSP spacecraft, the schedule and cost would delay the integration. In addition, it is not easy to add equipment to a satellite without an active manufacturing line.

IMPACT OF SPACE WEATHER

The Space Environmental Sensing Suite (SESS) was de-manifested from NPOESS in 2006. The SESS was intended to provide 12 environmental data records (EDRs). The loss of the SESS forces the DoD to rely on existing platforms with aging technology for needed SWx. Advanced SWx sensors exist, but there are few initiatives attempting to provide a solution to the looming capability gap[2].

Solar activity produces phenomena that have negative effects on global satellite communications, GPS availability and accuracy, spacecraft operations, and both air and missile defense. Monitoring, understanding, and forecasting solar activity are paramount to all space systems, commercial and government. The removal of the space environmental monitoring capabilities of NPOESS results in consequences that will reduce, and in some cases eliminate, the ability to defend space assets against space weather or to take precautionary action to avoid operational disruption. DMSP provides the data that allows the operators to understand and forecast the changing ionosphere but is expected to reach its end of life in 2017[2]. If no alternative is developed then U.S. space environment sensing capabilities could fall to pre-1980 levels when DMSP goes offline. The 12 EDRs no longer delivered due to the loss of the SESS are listed in Table 1. The far right column shows each capability's status once DMSP reaches its end of life[2].

Table 1: Lost EDRs[2]

No.	EDR	Status
1	Electron Density Profile	No capability
2	Energetic Ions	Degraded
3	Ionospheric Scintillation	No capability
4	Auroral Energy Particles	Degraded
5	Neutral Density Profile	No capability
6	Auroral Energy Deposition	Degraded
7	Medium Energy Charged Particles	Degraded
8	Electric Field	No capability
9	Auroral Imagery	No capability
10	Geomagnetic Field	No capability
11	Auroral Boundary	Meets Req.
12	In-situ Plasma Temperatures	No capability
13	In-situ Plasma Fluctuations	No capability

The loss of these capabilities increases the vulnerability of space assets and all operations relying on data from those assets. Considering the historical performance of satellite programs and the remaining six or more years of DMSP service, this gap is an urgent need.

CUBESATS

The CubeSat bus is a standardized satellite bus that has been utilized mostly for educational purposes. CubeSats have gained acceptance in the space community through successful demonstrations and experimentation; however, an operational success would significantly advance the utility and cause of the CubeSat.

The CubeSat bus measures 10 cm on each side with an initial weight of 1 kg. The payload can be expanded by combining additional units, e.g. a 2U CubeSat measures 10 x 10 x 20 cm and a 3U measures 10 x 10 x 30 cm. The standardized bus saves time by providing a commercial off the shelf product and constrains the design and development to the payload. This allows the CubeSat to be utilized as a quick response to needs or gaps as long as a suitable payload exists. These advantages make the CubeSat a viable platform that can be used to design an operational constellation to fill the gap resulting from the lost NPOESS SESS

CAPABILITIES MAPPING

Capabilities are normally contained within an instrument, sensor, or the like. An instrument determines the value of a quantity under observation and will do so with one or more capable sensors. For example a smart phone has the capability of powering down as a result of no user activity for a specified period of time. Therefore, it is the function performed by an instrument or sensor that will be the target of the capabilities mapping process. In order to understand each individual capability, all sensors contained within an instrument must be identified, separated, and individually analyzed. For each sensor, its requirements, capabilities, and output are needed to begin the capabilities mapping process.

Capabilities Scope

The process of mapping capabilities from one system to another is initiated by first defining the scope of the capabilities to be mapped. It is advantageous to treat the capabilities mapping process like a project and establish a "capabilities scope". The capabilities scope identifies all of the capabilities required to deliver the expected output and establishes a boundary around those to be mapped. As the capabilities are identified, defined, and mapped, it is also beneficial to employ the practices of project management that target and avoid scope creep, or in this process, capabilities creep. Allowing additional capabilities that are not part of the original defined list puts the cost and schedule at risk thus impacting a rapid response to an urgent need. The CubeSat's limited payload capacity provides assistance for controlling the desire to add capabilities. Designed for specific missions, the physical limitations of the CubeSat bus will keep stakeholders and developers mindful of the boundary defined by the capabilities scope. The capabilities scope should be referenced throughout the mapping process to avoid any creep.

Requirements, Capability, and Output

The requirements are defined by a need that relates the action to be performed by a sensor, instrument, or entire system to the expected output. The original system is tested and evaluated against these requirements and determined to be satisfactory or not. The original requirements will play an important role in the capabilities mapping process. The requirements behind the original capability must be met by the new low SWaP sensor(s). The same is true for the output or results expected by the stakeholders. A low SWaP sensor offers significant and several advantages but if it does not provide what a user expects (output), based on the requirements, then all the benefits are lost. Therefore, the original requirements and expected output shall be used as metrics by which the new system(s) will be evaluated. Only when the stakeholders get what they funded and required will a satisfactory system be delivered. Figure 1 shows a flow chart illustrating the capabilities mapping process thus far with black lines and arrows taking the process to a lower, more detailed level.

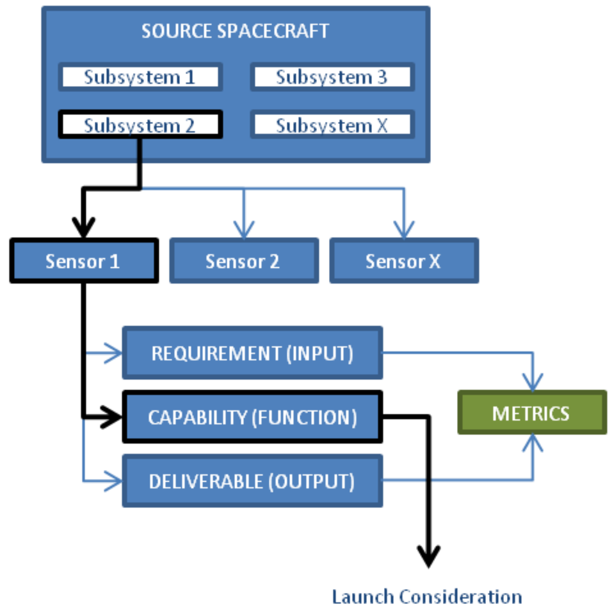

Figure 1. Capabilities Mapping Process (Start)

Launch

The orbital characteristics should be considered and reviewed because some SWx sensors require specific orbital characteristics, e.g. a high inclination orbit is required to measure the phenomena at certain geospatial locations. If the satellite is not put into the required orbit, then the expected output will not be achieved. Thus, if specific orbital characteristics are required then a specific launch will also be required. Figure 2 illustrates the launch considerations in the capabilities mapping flowchart. Indicated by a decision block, questions one asks if the capability requires specific orbital characteristics to accomplish its function. Next, question two determines if the capabilities mapping process should stop as a result of specific orbital characteristics.

CubeSats typically share rides with other spacecraft so the requirement of specific orbital characteristics may have an impact on delivering the capability rapidly. However, nearly all launches have extra space so the recommendation here is to continue with the capabilities mapping process and wait for an available ride on a launch with matching orbital characteristics. Or, take a launch that is close to the desired orbit because even a degraded capability provides a benefit over nothing at all.

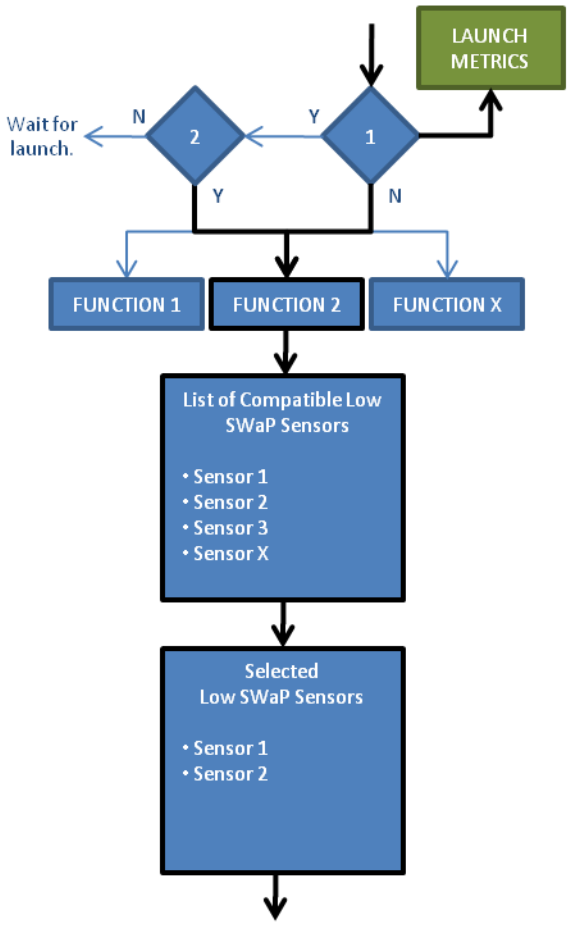

Figure 2. Launch Considerations and Functional Decomposition

Capabilities Mapping

Each capability identified in the capabilities scope must be analyzed and understood in detail. Within each capability, there are functions that perform specific tasks that are specified by the requirements. Performing a functional decomposition, Figure 2, will divide each capability into its most basic functions. A basic function stands alone and performs one task and no more. Each basic function is mapped to a low SWaP sensor capable of either performing the same function or capable of providing the expected output using an alternative method. Returning to the smart phone as an example, the capability to automatically power down the unit is the result of (functional decomposition) the function that monitors user activity and the second function that maintains the length of idle time. The capability is performed using both functions that perform individual tasks.

While aligning the function to a low SWaP sensor, a minimum level of performance must be defined if the new sensor is unable to perform at the same level as the original sensor. One method of doing this is to define the acceptable performance loss as a percentage. For example, if the function to power down the smart phone could be set by the user in one minute increments and sensor had a 10% tolerance of ± 6 seconds, then would a 20% tolerance of ±12 seconds be an acceptable performance level? The definition of what is and is not acceptable will, most likely, vary among sensors. Once the selected low SWaP sensors have been accepted and approved to deliver an acceptable level of performance, they will be integrated.

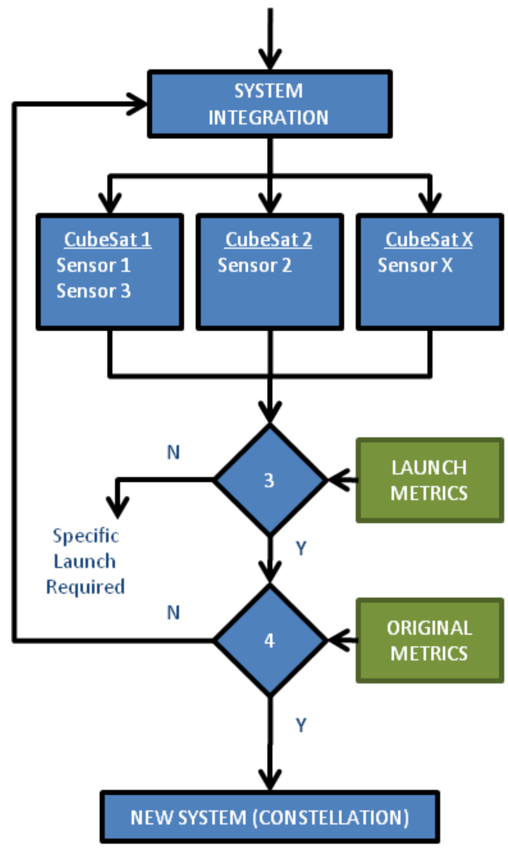

Figure 3. System Integration

Sensor Integration

Sensor integration is not unique to capabilities mapping. Figure 3 shows the system integration section of the capabilities mapping process flowchart. The integration process determines which and how many sensors will be required to perform the mission. Those sensors will be integrated into a constellation of CubeSats. The exact number of CubeSats will depend on two factors. As shown in Figure 3, the number of sensors integrated into a single CubeSat varies depending on the SWaP of each sensor. In addition, the desired coverage will determine the quantity of CubeSats required in the final constellation. The final constellation must be evaluated against the selected launch (i.e. decision block 3 in Figure 3) and original metrics (i.e. decision block 4) defined earlier in the process. The sensor integration process discussed above differs only slightly from that used to integrate larger payloads.

The process of mapping capabilities allows the rapid determination of an alternate capability that could fill a potential, or known, capability gap. For low SWaP sensors that are immature and only offer a degraded performance, it still provides a capability which is better than none at all. While the immature and limited capability sensor is on orbit, the opportunity exists to continue researching, developing, testing, and evaluating the sensor. As the sensor matures, the CubeSat will reach the end of its life which will allow a better performing sensor to simply be plugged into another CubeSat and launched.

APPLICATION

The de-manifested SESS was intended to collect and provide data for selected space environmental parameters. Once relayed to the ground stations, the data would have been ingested into a modeling system that analyzes the data and produces an EDR. The loss of the SESS will leave the United States with either lost or severely degraded capabilities as shown earlier in Table 1. The SESS contains five instruments which are listed in Table 2. Of these five instruments, the capabilities mapping process will analyze the Thermal Particle Sensor (TPS) and map its capabilities to a set of low SWaP sensors capable of monitoring the required space weather phenomena. The TPS is a set of plasma collectors used to measure and characterize the densities, temperature, and drifts of the thermal ionospheric plasma at satellite altitude[5]. It is the primary provider of data for three EDRs as shown in Table 3. The requirements for the NPOESS space environment monitoring mission were revalidated in 2006 by the Joint Requirements Oversight Council (JROC) and have not changed[2]. These requirements and the EDRs (deliverable) will define the metrics by which the solution will be verified and validated. This allows the capabilities scope for the TPS to be defined.

Table 2: NPOESS SESS[5]

No	SESS Sensor	Measurement
1	Thermal Particle Sensor (TPS)	Measures the density, temperature, and drifts of the thermal ionospheric plasma at satellite altitude
2	Low Energy Particle Sensor (LEPS)	Measures auroral and supra-thermal particles precipitating into the upper atmosphere at mid-to-high magnetic latitudes. Also, differential-energy and –angle fluxes of electron and protons within and outside local magnetic loss cone.
3	Medium Energy Particle Sensor (MEPS)	Measures differential-energy fluxes of electrons and protons at 0 degrees and 90 degrees relative to the local vertical.
4	High Energy Particle Sensor (HEPS)	Measures the precipitating flux of high energy ions into the atmosphere
5	Airglow & Aurora Ultraviolet Remote-sensing Observations for Real-time Applications (AURORA)	Measures Far UltraViolet (UV) emissions from atmospheric constituents.

Table 3: EDRs generated from TPS data[5].

No	EDR	Operational Function / Impact
1	In-situ Plasma Fluctuations	The data collected is used to infer the presence of ionospheric scintillation at altitudes below the satellite which can disrupt communications and GPS navigation
2	In-situ Plasma Temperature	The data collected measures the temperature of electrons and ions. While the impact is minor, the data would have been used for future upgrades to a physics-based assimilative model.
3	Electric Field	High latitude measurements that monitor the motion of scintillation-producing, ionospheric density structures within the polar cap and auroral zones.

TPS Capabilities Scope

The scope of the TPS capabilities mapping process will focus on the sensor's ability to measure and characterize the density, temperature, and drift of ionospheric plasma at the satellite altitude. These capabilities will be functionally decomposed to their most basic function and then aligned to a low SWaP sensor. No other capabilities will be included in this process of capabilities mapping. However, if a sensor selected to measure and characterize the phenomena specified also has the ability to detect other phenomena, then those capabilities will be referred to as secondary and considered for use as long as they do not interfere with the primary capabilities. The TPS contains four sensors: plasma driftmeter, Faraday cup / retarding potential analyzer, and Langmuir probe.

TPS Requirements, Capability, and Output

The TPS satisfies the Electric Field, In-situ Plasma Temperatures, and In-situ Plasma Fluctuations EDRs[5]. Since the TPS satisfies these EDRs, the low SWaP sensor(s) must do the same or be evaluated to determine if the level of performance has utility. Likewise, the data analyzed and modeled by the software to generate these EDRs, will be the expected output. Thus, the metrics by which the selected sensors, and ultimately the constellation, will be evaluated are these EDRs. Figure 4 shows the mapping process starting from the identification and separation of the TPS sensors to the launch considerations.

TPS Launch Requirements

The TPS, as stated earlier, measures and characterizes the thermal ionospheric plasma at satellite altitude. While the phenomena are measured at the satellite altitude, the original NPOESS constellation requirements have specific orbital characteristics. The dawn/dusk transition and noon/midnight fluctuations of the ionosphere are of primary interest and therefore require the satellites to be flown in sun-synchronous orbit (altitude of 833±17 km; inclination of 98.7±0.05 degrees) to measure at the same latitude, at the same local mean solar time each day within ±10 minutes[6]. These parameters clearly show that a launch with specific orbital characteristics will be required if the mission of the original SESS is to be accomplished. The final constellation of CubeSats could be flown for different orbital characteristics but the "coverage" may not be as originally required. This presents the importance of knowing what is good enough. To illustrate, the best results will be obtained by the characteristics specified but if they change or are very costly to achieve (i.e. dedicated launch vs. shared ride), then at some point the "degraded" capability becomes no longer beneficial.

The decision to launch the constellation with orbital characteristics other than those specified will be a decision that the stakeholders must make and accept. One method to assist the decision is to establish a threshold and objective defined as a percentage of the original. Specific mission orbital characteristics should not ground an acceptable performing CubeSat but will require careful analysis of procuring a dedicated launch against any degradation resulting from different characteristics. These two factors must be considered and decided upon by stakeholders. If the sensor or constellation performs at a level acceptable by stakeholders (e.g. no less than 60% below current performance) for an available launch then the constellation should fly. If a launch is not available, then stakeholders must decide if the level of performance justifies the cost of procuring a dedicated launch vehicle. If performance of the CubeSat constellation is high (e.g. 90% of the original performance) then the decision is easy. The decisions regarding the launch are important at this point in the process to gain a commitment from stakeholders to proceed. Otherwise, the mapping process is performed at the risk of no launch which will waste time.

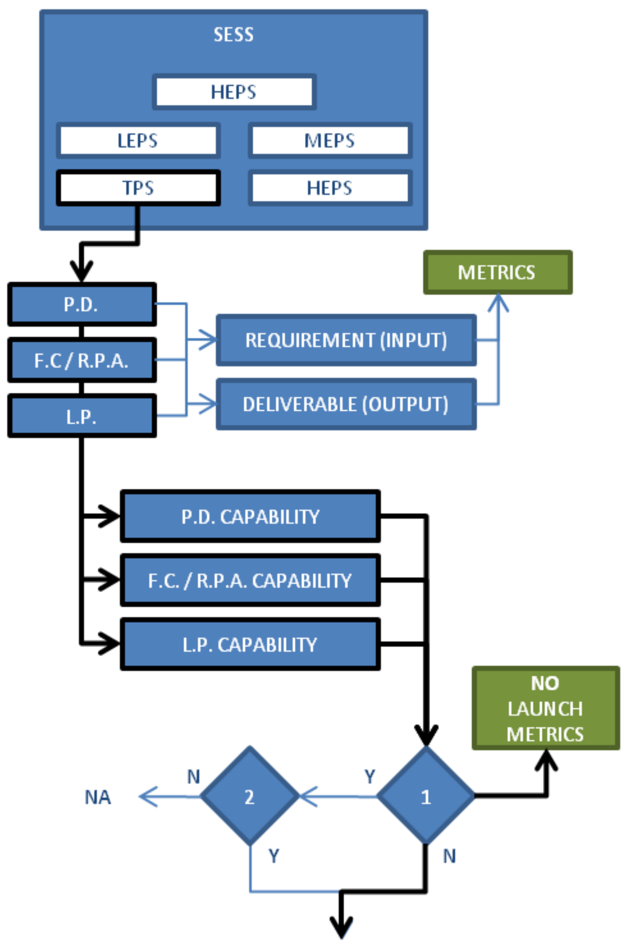

Figure 4. TPS Sensor Identification thru Launch Considerations

TPS Capabilities Mapping

The process of mapping the TPS capabilities begins by performing a functional decomposition to separate the instrument's functions. Figure 5 shows the decomposition of the four TPS instruments: Plasma Driftmeter, Retarding Potential Analyzer, Spherical Langmuir Probe, and Faraday Cup. The basic functions identified in Figure 5, guide the process of aligning these basic functions to low SWaP sensors that are compatible with the CubeSat. The basic functions required of the low SWaP sensors include: horizontal/vertical cross-track motion of the local ionosphere; measurement of ion temperature, density, and masses; measurement of electron temperature and density; measurement of total ion density. Once the basic functions are aligned to a low SWaP sensor, the original instrument becomes irrelevant, unless the original instrument has low SWaP properties that would allow it to be integrated into the CubeSat bus.

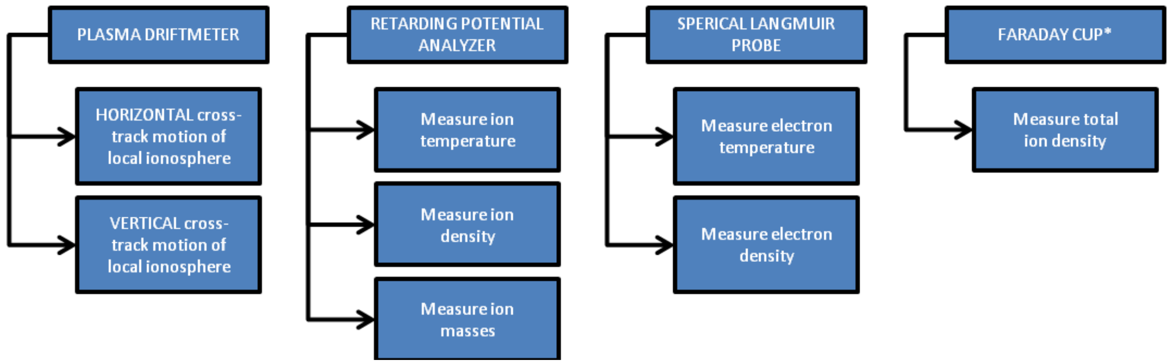

Figure 5. TPS Instrument Functional Decomposition

The four sensors listed in Table 4 are compatible with the CubeSat bus and are capable of performing the basic functions of the TPS instruments. Some of those sensors have been involved with on-orbit experimentation via a CubeSat or other platform. Comparison of each sensor's function leads to the alignment shown in Figure 6 and shows low SWaP sensors can perform nearly all of the functions of the TPS instruments. Although there is a slight degradation of the low SWaP sensor's performance when compared to the equivalent TPS instrument, it is small enough to be considered negligible. However, stakeholders must decide if the CubeSat solution should be abandoned due the degraded performance. Since the degradation is minimal, the process will continue and integrate these sensors on to a CubeSat.

Sensor Integration

The four sensors can be integrated onto as few as four CubeSats as shown in Figure 7, although additional CubeSats would increase the coverage. The final approval and success of the constellation will come when the data received by the modeling software is used to produce an EDR. Flying the constellation with an operational DMSP constellation would allow a side-by-side comparison of the two systems. A successful operational mission will provide support for mapping the other four SESS sensors onto a constellation of CubeSats.

Table 4: Low SWaP Sensor and Function

Low SWaP Sensor	Function
Winds-Ion-Neutrals Composition Suite & Miniature Electrostatic Analyzer (WINCS+)	Measure drift (vertical/horizontal cross-track and horizontal in-track), ion density/temperature
Integrated Miniaturized Electrostatic Analyzer (iMESA)	Measure plasma density and temperature
GPS Occultation	Remote observation of ionospheric total electron content and vertical electron density
UV Photometer	Measure airglow and derive electron density distribution

CONCLUSION

As shown, the SWx mission can utilize small satellites, even as small as nanosats, as an alternative to large satellites. However, low SWaP technology must exist for capabilities to be mapped. In some cases such as imagery, the required sensor or hardware may have physical limitations preventing a low SWaP solution from being developed. However, the capabilities mapping process shows that it is a realistic process. While the term capabilities is used as a target, it cannot guide the process alone. In addition, the process requires the needs, requirements, deliverable (e.g. EDRs), and all functions that complete the capability. The capabilities mapping process separates itself from other practices such as analysis of alternatives (AoA) or trade studies by capitalizing on existing and confirmed information. The process removes the item (e.g. legacy sensor) that is no longer available (e.g. removed for cost purposes) and utilizes what has been established and confirmed by stakeholders, i.e. requirements. The requirements, specified capability,

Attention should be given to the technologies currently under development by private corporations, universities, and laboratories. Satellite sensor technologies continue to increase in performance while their size, weight, and power are reduced. The

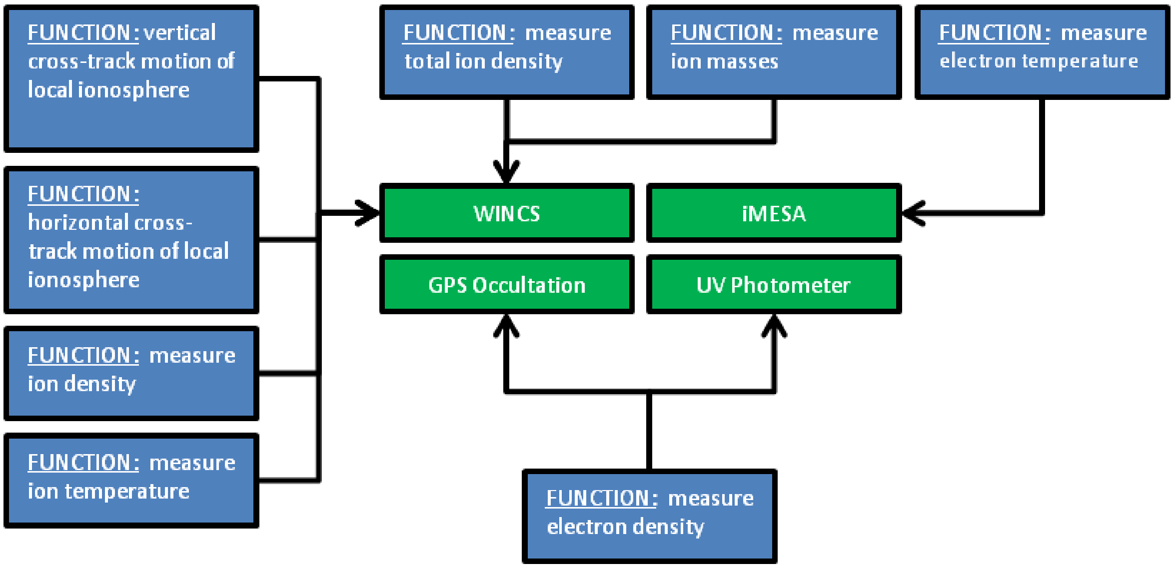

Figure 6. TPS Function to Low SWaP Sensor Alignment

and expected deliverable enable an efficient process that develops a low cost solution. The standardized bus of the CubeSat is equally important due to cost and schedule savings.

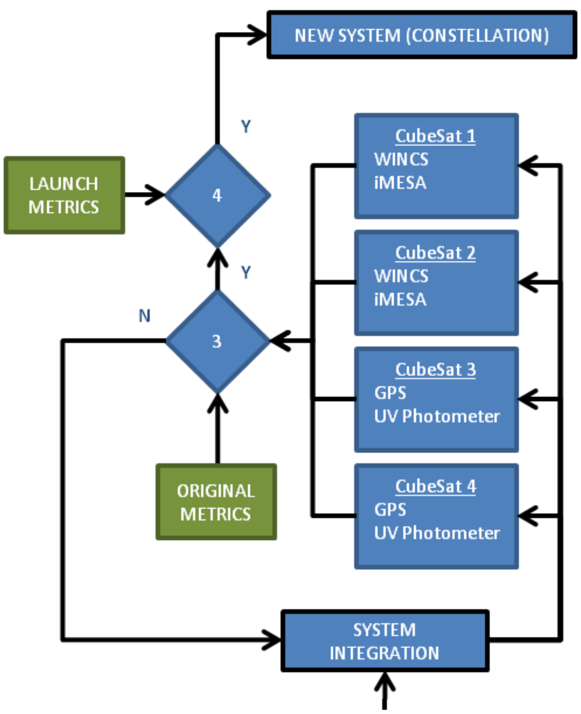

Figure 7. Sensor Integration

operational success of a space weather monitoring CubeSat constellation encourages additional efforts to advance both sensor technologies and the CubeSat bus.

In conclusion, a solution to a specific capability gap has been proposed that would cost a fraction of the original system. While the low cost solution brings a shorter on-orbit life, the need for frequent replacements provides opportunities to deliver improved capabilities at lower costs. This is because the continuous manufacturing line would more easily incorporate technology advances and provide greater quantity buys as an incentive for development. Thus, every two to five years you're replacing a generation with a new more advanced system. Most importantly, the cost remains lower than in the past. The recent disbanding of NPOESS creates an opportunity to exploit small satellites and sensors as well as rethinking the way space systems are procured.

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