SMAP Instrument Mechanical System Engineering

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Abstract - The Soil Moisture Active Passive (SMAP) mission, scheduled for launch by the end of 2014, is being developed to measure the soil moisture and soil freeze/thaw state on a global scale over a three-year period. The accuracy, resolution, and global coverage of SMAP measurements are invaluable across many science and applications disciplines including hydrology, climate, carbon cycle, and the meteorological, environment, and ecology applications communities. The SMAP observatory is composed of a despun bus and a spinning instrument platform that includes both a deployable 6 meter aperture low structural frequency Astromesh reflector and a spin control system. The instrument section has engendered challenging mechanical system issues associated with the antenna deployment, flexible antenna pointing in the context of a multitude of disturbances, spun section mass properties, spin control system development, and overall integration with the flight system on both mechanical and control system levels. Moreover, the multitude of organizations involved, including two major vendors providing the spin subsystem and reflector boom assembly plus the flight system mechanical and guidance, navigation, and control teams, has led to several unique system engineering challenges. Capturing the key physics associated with the function of the flight system has been challenging due to the many different domains that are applicable. Key interfaces and operational concepts have led to complex negotiations because of the large number of organizations that integrate with the instrument mechanical system. Additionally, the verification and validation concerns associated with the mechanical system have had required far-reaching involvement from both the flight system and other subsystems. The SMAP instrument mechanical systems engineering issues and their solutions are described in this paper.

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1. INTRODUCTION

In January 2007, the U.S. National Research Council (NRC) released the first decadal survey of Earth science, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond [1]. The Soil Moisture Active/Passive (SMAP) Mission was recommended to be implemented as one of the first in this series of missions. SMAP was formally approved for implementation on May 23, 2012 and is currently being developed for a late 2014 launch. The science objectives of SMAP are to provide frequent, global measurements of surface soil moisture and surface freeze/thaw state. These measurements will be used to enhance the understanding of water, energy, and carbon cycles, as well as improve weather and climate prediction.

To measure both soil moisture and freeze/thaw state at the required resolution, a combined active/passive L-Band microwave instrument is employed [2]. The key instrument requirements were determined by the SMAP Science Working Group to be: 1) Dual-polarization L-Band radiometer measurements at 40 km resolution, 2) Linear HH, VV and HV/VH L-Band radar measurements at 3 km resolution or better, and 3) A wide swath to ensure global three-day refresh time for these measurements (1000 km swath at the selected equatorial orbital altitude of 685 km).

Previous publications have provided high-level descriptions of the SMAP instrument [3]. To accomplish the challenging set of requirements, a 6-meter, conically scanning reflector antenna architecture was selected for the instrument design. The deployable mesh antenna is shared by both the radiometer and radar instruments by using a single L-Band feed. (Fig. 1.)

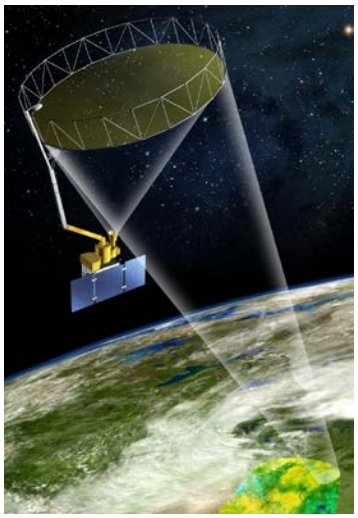

Figure 1 - SMAP in orbit, showing the Astromesh antenna, antenna spot beam, and wide swath.

2. INSTRUMENT SYSTEM ENGINEERING

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3. POINTING

The SMAP Observatory has pointing requirements on the electrical beam boresight for nadir bias, nadir stability, nadir knowledge, azimuth zero crossing, azimuth knowledge, and azimuth rate. The flight system architecture has spun and despun sections. The spun section contains the large, deployable, flexible Astromesh reflector. The despun section of the spacecraft containing reaction wheels which compensate for the spun momentum of the spinning section and provide attitude control capability. Meeting the Observatory pointing requirements with this architecture has required careful consideration of the physics involved, resulting in a decomposition of those effects into a pointing error budget (PEB) that feeds into development of requirements throughout the system and helps definite relevant verification and verification activities. A critical issue is that it is not possible to verify the end-to-end pointing performance, such that development and maintenance of a valid pointing error budget is the only mechanism to verify that the top level pointing requirements are met.

The first branching point for the PEB is from the Observatory level to the Instrument level and Spacecraft level. This paper describes the Instrument Mechanical System Engineering so the spacecraft elements in the PEB will be left to other authors.

The Instrument Pointing Error Budget is broken down into seven major categories described by sixteen minor categories shown in Table 1. These major categories were chosen based on an effort to linearly separate effects that contribute to pointing errors.

Instrument Errors	
Static	Geometry, Deployment, Spinning Lds
	RPM Dependency (13 to 14.6 rpm)
	Elect. To Mech Boresight Bias
	SC command Cal error
Thermal	Thermal Distortion
Spacecraft Wobble	SIA EPOI
	Despun Inertia Ratio
	Despun CM offset
ACS	SC Control system errors: -Sensor -Control (includes nav errors) -Actuator -Disturbances -SC/BAPTA Loop Interaction
Spinning Antenna	BAPTA Torque Disturbance (> 1 Hz)
	SAW
	Spin Subsystem Estimation Sesnor Err
RWA	RWA
Miscellaneous	RF scattering
	RF Horn Effects - thermal
	Timing (reconstruction)

Table 1: Pointing Error Budget

The five elements of the Instrument Mechanical Subsystem are: Instrument Structure, Instrument Devices, Spin Subsystem, Instrument Antenna, and Instrument Thermal. The PEB was used to generate 47 requirements on the elements of Instrument Mechanical System. These requirements guided the mechanical subsystem architecture and element design. The PEB was used during development to trade requirement values in different mechanical subsystem elements against each other as challenges were exposed. As the design went through Preliminary Design Reviews and Critical Design Reviews, refined estimates of worst-case performance against the relevant requirements fed into the worst-case performance represented by the PEB.

The CDR level worst-case pointing performance estimate identified a relatively small set of PEB line items at the Instrument pointing level and at the Observatory pointing level at a significant level. At the Instrument level the following five mechanical line items contribute 10% or above to the total PEB estimate:

1. Thermal distortion
2. Spin Subsystem torque error
3. Mechanical alignments
4. Spin rate range from 13.0 to 14.6 rpm
5. Spin subsystem estimation/sensor error

At the Observatory level, three mechanical line items contribute 10% or more to the total PEB estimate:

1. Spun section mass properties

2. Thermal distortion
3. Mechanical alignments

A relatively small set of the sixteen categories of pointing error contributes the major share of the pointing error. The Instrument requirement verification and validation activities can then be focused on the smaller set of requirements that pertain to these PEB line items. Importantly, as a result of this work, the system architecture is shown to be robust with pointing errors relatively insensitive to the vast majority of hardware on the Observatory.

4. Mass Properties

The SMAP Observatory is composed of a spun instrument section and a de-spun bus. Reaction wheels inside the bus compensate for the momentum so that the system is flown in a zero momentum state. However, in order to maintain a nadir-pointing attitude and minimize wobble around that state, the spun section mass properties must be such that the spin results in a net torque at the Observatory center of mass that is minimal. Constraining the spun static center of mass offset and the product of inertia as shown in Fig. 2 will accomplish this [3]. The term in brackets is called the Spun Section Effective Product of Inertia and setting it to zero allows a family of mass properties that result in zero torque about the Observatory center of mass.

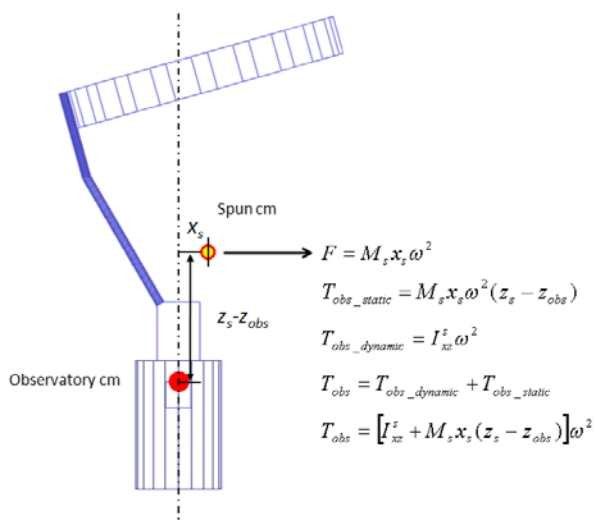

Figure 2. Observatory Balancing

The deployed Reflector Boom Assembly contributes significantly to the effective product of inertia due to its large size and skewed mass distribution. Flowing down the requirement on the Spun Section Effective Product of Inertia to constraints on the mass properties of the RBA is important. The Spun Section is essentially comprised of three elements: the core structure with spin motor and feed assembly, the RBA, and a set of instrument electronics boxes. In configuring the Spun Section, the instrument electronics boxes are able to be placed nearly anywhere on the radial +X axis, from the spin axis out to the maximum location where the boxes do not interfere with the payload fairing when in the launch configuration. With the flexibility of the instrument electronics boxes position plus the constraints, the Spun Section Effective Product of Inertia requirement can be flowed to two requirements controlling the mass properties of the RBA. These are the RBA Effective Product of Inertia and CMx constraint:

$$\left| I_{xz}^{RBA} + m_{RBA} x_{RBA} \left(z_{RBA} - z_0 \right) - C_0 \right| \le \varepsilon \qquad (1)$$

$$m_{RBA} x_{RBA} \le C_1 \qquad (2)$$

where m_{RBA} is the mass of the RBA, x_{RBA} and z_{RBA} are the x and z center of mass locations of the RBA, and z_0, C_0, C_1, and ε are constants. In these two constraints, the parameters C_0, C_1, and ε are determined by the mass properties and uncertainties associated with all the non-RBA spun hardware. Using these two requirements, RBA design could proceed with high confidence that a balanced Spun Section will result.

Mass Property Knowledge

In order to balance the spun section to a near zero Effective Product of Inertia, the RBA has the capability to mount balance mass at the valley nodes around the reflector rim. Because of the size of the RBA, small amounts of balance mass are capable large scale tuning of the spun section effective product of inertia. However, knowledge of the spun section mass properties is required in order to determined necessary balance mass quantities and locations.

The deployed RBA contributes significantly to the spun section product of inertia and center of mass. However, the deployed RBA mass properties are never measured in its deployed, as-spun state for the obvious reason that such a spin test would be nearly impossible to construct given the scale of the RBA, its flexibility, and the necessity to provide a vacuum and gravity offload during such a spin test.

As a result, from a mass property knowledge standpoint the spun section is broken into two components: the RBA and the Spun Platform Assembly (SPA). The SPA is all the spun hardware that is not the RBA. The SPA can be spin balanced, resulting in precise knowledge of its center of mass position and product of inertias.

The SMAP Observatory has an allowable Spun Section Effective Product of Inertia determined by the wobble that the Observatory systems can tolerate. This is largely determined by allowable pointing error due to this effect and the allowable motion of the Observatory that the GNC sensors can tolerate. Given the allowable maximum Spun Section Effective Product of Inertia and the tolerances to which the SPA mass properties will be

known as a result of the SPA spin balance, requirements on the mass property knowledge of the deployed, as-spun RBA can be derived.

The RBA mass property knowledge requirements require knowledge of 0.1 kg on the RBA mass, 10 mm on the RBA center of mass position, and 1.0 kg-m^2 on the RBA Product of Inertias. Given these requirements, a mass property knowledge plan for the RBA has been developed which has the following four elements: 1) mass property measurements at the component and sub-assembly level, 2) selected mass property measurements at the boom and reflector level, 3) photogrammetry of the reflector and boom components to determine the positions of all the component hardware, and 4) analysis to determine the deployed RBA mass properties and errors on those mass properties. The process is refined such that the error determination falls within the mass property knowledge requirements.

5. SPIN SUBSYSTEM

The Spin Subsystem, a collection of hardware and software including the Bearing and Power Transfer Assembly (BAPTA) and the Integrated Control Electronics (ICE), provides spin control of the SMAP instrument. The Spin Subsystem hardware is shown in Fig. 3, below.

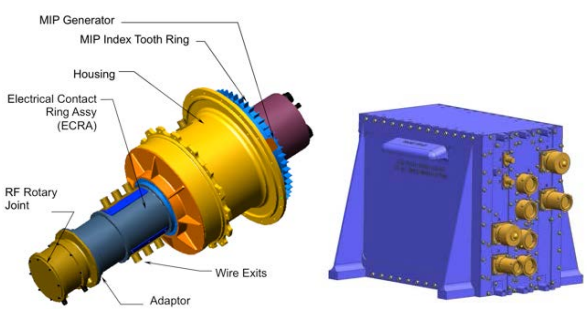

Figure 3 – Spin Subsystem Hardware - BAPTA (left) and ICE (right).

Spin Subsystem Hardware Overview

The BAPTA is the moving mechanical assembly providing a rotating interface and actuator to spin the Spun Instrument Assembly (SIA) mounted atop the 3-axis attitude-controlled spacecraft bus. The rotating mechanism consists of a Be housing and shaft with interference fits to a pair of 5" diameter angular contact bearings, each with 32 silicon nitride balls and 440 CRES races. A single piece CRES retainer with nitrile acrylic foam pockets serves as a reservoir for Pennzane oil, ensuring long life. A dual diaphragm flexure provides the required preload for quiet running once the Observatory is transitioned into the operational configuration. An RF Rotary Joint Assembly (RJA) provides RF transmission through capacitive coupling across the rotating interface, supported by 2 additional soft pre-loaded bearing pairs. An electrical contact ring assembly (ECRA) is used to transfer power and data signals across spinning interface. The ECRA consists of 64 identical 2 amp slip rings assemblies with MoS_2-Ag composite brushes spring-loaded on coin silver rings, supported by an aluminum shaft and housing. The BAPTA actuator includes a direct drive 2-phase, 24-electric pole-pair, slotless, brushless DC motor with a minimum torque constant of 4.88 N-m/A. Sinusoidal commutation of the motor is provided by a single speed, 24-electric pole-pair, half-transformation ratio variable reluctance resolver carefully aligned to the motor on titanium housings. A steel exciter disk on the stator with 48 primary slots and 1 master slot rotates below a pair of variable reluctance magnetic impulse generators (MIPG) to produce electrical pulses, quasi-sine analog waveforms called Index Pulses (IPs), detected by the control electronics and used by firmware to close loop on spin rate.

The Integrated Control Electronics (ICE) is a single string avionics box that performs the rate control of the SIA. The BAPTA-generated index pulses are detected and time-tagged by ICE to produce a timing signal used by the firmware to compute a raw spin rate based on the fixed spacing of the slots in the exciter disk. A comparator circuit detects the analog IP waveforms, generating a digital pulse train with logic corresponding to the arm/detect threshold and the zero-voltage crossing of the Index Pulse (IPs). An FPGA latches the falling logic of the digital pulse to a microsecond resolution and generates digital telemetry called the Time of Arrival (TOA), used by the firmware to compute the raw rate. The ICE contains firmware burned in PROM, loaded into RAM each time the ICE is initialized, and sequenced by a microprocessor. The firmware is sequenced each time the 32.768 msec Real Time Interrupt (RTI) is received by the microprocessor, resulting in a ~30.5 Hz control rate. The interrupt is generated by the same FPGA that produces the TOA of the IPs. A 2nd order low-pass filter is used to compute a rate estimate from the raw rate and generate the control error signal. The commanded torque is computed from the rate error signal by a PI controller with four cascaded bi-quadratic filters to shape the control loop. ICE also contains a motor/resolver drive that effectively acts as a linear torque/current controller for the BAPTA motor. The linear motor controller has an effective full-scale output of 1 A, fed by a torque command with 12-bit quantization computed by the firmware. ICE drives a 2.67 kHz square wave into the BAPTA resolver primary winding, with a 10 V zero-to-peak full-scale output proportional to the commanded torque. ICE detects the resolver sine and cosine secondaries and demodulates the signals by removing the 2.67 kHz excitation frequency, leaving the sinusoidal envelope frequency. The demodulated envelope signals then directly drive the sine and cosine motor amplifiers. ICE feeds back sensed sine and cosine motor current to

close the inner torque control loop.

Spin Control Physics and System Decomposition

Spin control of the SIA is coupled into the spacecraft attitude control system (ACS) performance and the SMAP Observatory dynamics. The spin controller is required to reject sufficient disturbances to meet system pointing-derived requirements while not interacting with the ACS and the low frequency Observatory structural modes. As a result, the low frequency spin control design is dominated by providing sufficient gain for controlling the bearing noise, motor ripple, rate sensor cogging torque, and sensor noise while maintaining bandwidth separation with the ACS. The high frequency spin control is driven by the need to roll the spin controller off to effectively gain stabilize the uncertain structural dynamics.

The performance of the spin controller is coupled to the performance of the ACS and affects pointing through the Observatory dynamics. The spin controller presents a torque disturbance to the ACS by transmitting its torque (control torques and disturbances from the mechanism) across the joint, degrading control authority with the RWA bandwidth (~0.03 Hz). The spin controller also produces high frequency torque disturbances that could excite structural modes (> 1 Hz) if there is sufficient broadband energy or energy at distinct frequencies where modes appear. The ACS performs momentum management using the rate estimate provided by ICE as engineering telemetry, compensating for aerodynamic torques and other low energy or slowly varying disturbances. The rate estimate is also combined with the IP TOA engineering telemetry for science pointing reconstruction. Finally, the total rate control error combines with the spun-side mass properties to erode margin against the Instrument momentum limit because SIA spun momentum at science rates is near the RWA momentum compensation limit.

The gain and phase margins of the spin control loop are also coupled into the ACS properties and Observatory dynamics. The 3-axis RWA attitude control system and system operational modes modify the response of the spin control plant (joint torque to joint rate) at low frequency. Observatory mass properties drive the rigid body stability margins, in particular the spun and despun moment of inertia about the rotation axis. Finally, Observatory low frequency structural modes with high amplification factors couple into the rotation axis and drive stability margins at frequencies above 1 Hz.

Spin Control Requirements Development

The BAPTA and ICE are delivered to the SMAP program by Boeing Space Systems as part of a contract let long before the SMAP system definition and architecture matured. Models were required to facilitate requirements development, and trade studies early in the program and ultimately required for system verification and validation. Low fidelity linear models were developed to capture the frequency response of the controller, actuator, and rate sensor for both discrete time and continuous analysis. These models were used extensively to develop the subsystem plant specification and stability margin requirements, and perform control architecture trades. A high fidelity control model applicable to the non-linear, time domain system performance analysis was also developed. The subsystem-developed modeling utilized a contract-specified simplified plant model for stability and performance requirement verification, subsystem control architecture trade studies, and performance tuning. The contractor-developed control models were delivered for integration into the system non-linear simulation utilizing high fidelity plants for integrated, multi-loop controls analysis and system verification.

As a contracted element with a long lead development, a specification was developed with the intention to decouple the subsystem design and verification from the system design. A 3-sigma torque disturbance allocation was negotiated with the ACS to specify the low frequency spin control performance. The spin control allocation was derived from a margined system RWA torque budget developed to meet the spacecraft ACS pointing performance requirements. A rate knowledge requirement consistent with the momentum management budget was specified and included a low pass filter to provide relief at high frequency. The filter accounts for the low control rate and roll off of the momentum manager. Torque disturbance amplitude and CRMS limits were also negotiated, consistent with worst-case assumptions used in the pointing budget, to specify the high frequency spin control performance. Finally, an azimuth knowledge requirement consistent with the worst-case pointing budget was developed to support science reconstruction.
The spin control design process required a relevant model of the Observatory plant to proceed, so a simplified, single axis, parametric linear transfer function was specified for subsystem design and verification. The simplified plant allowed the subsystem robustness to be tested in a parametric sense over a range of specified uncertainty. Early studies showed the controller was robust to wide ranges of the specified plant parameters. As a result, ideally no specification updates were necessary as the architecture of the flight system evolved, mass properties analyses cycles proceeded, and refinements to the structural design were completed. The specified plant models are shown in Fig. 4, below.

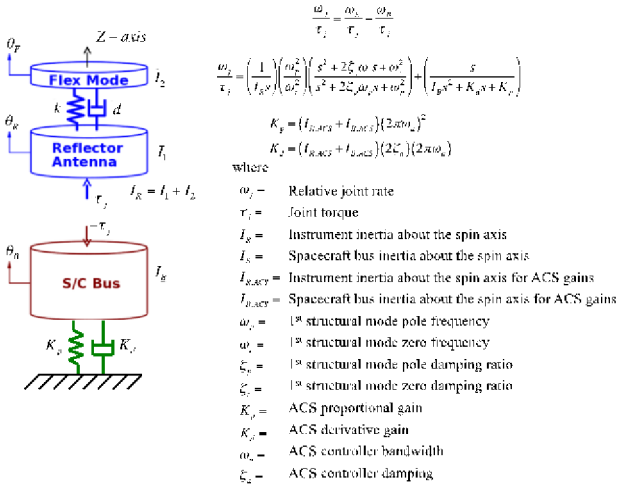

Figure 4 – Spin Control Design Plant Model

The uncontrolled and saturated RWA system modes were accommodated with a free-base configuration while the controlled ACS modes were accommodated with a fixed-case model with a spring/damper system tuned to the RWA controller frequency response. The mass properties and ACS gains were parameterized with specified ranges of spun and despun moments of inertia to cover design uncertainty plus margin. A single structural mode was coded into the transfer function and parameterized over a range of pole frequencies that margined against the lowest and highest frequency of the expected structural modes. System plant parameter studies that varied inertia, stiffness, and damping properties generated a range of plants shown to be bounded by the simplified model. The transfer function also parameterized the pole/zero frequency ratio as a linear function of pole frequency to maintain the worst-case gain above the highest predicted amplitude. As a result, the contract specification provided a simple plant model for subsystem design and verification that mitigated the risk of a spin control performance or stability non-compliance when tested with high fidelity, non-linear plants in system analysis.

An operational concept for spinning the instrument up to the science spin rate was developed in concert with early trade studies to allow the subsystem firmware development to proceed. Key functions and performance requirements were allocated to subsystem operational states consistent with the spin-up architecture: Initial spin up to a transition dwell spin rate, the dwell at the transition rate, spin rate adjustment up to the science rate, and the science state. The operational concept is shown in Figure 5, below.

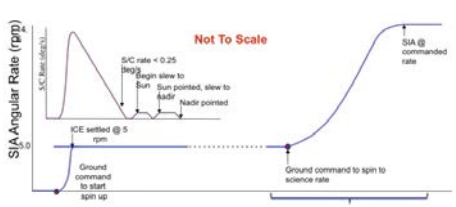

Figure 5 – Spin Up Operational Concept.

The function of initial spin-up to a transition dwell rate was particularly allocated to the subsystem because the MIPG do not have output below ~4 rpm, requiring an open loop behavior to spin the BAPTA up to a rate sufficient for the rate control loop to close. A benefit was the de-coupling of the transients of the initial spin-up of the spin controller from the ACS behavior. The spin controller was simply required to stabilize at the transition dwell rate of 5 rpm within 2 minute of the command, giving the contractor near complete freedom in the design of the open- to closed-loop behavior of the spin controller. The ACS was simultaneously required to recover attitude after presented with a disturbance that bounded the subsystem initial spin up. Once the architecture was agreed upon, telemetry flag requirements were also specified. One flag was required to notify the ACS when the rate knowledge was valid so that momentum management could begin. Another flag for use as an entrance criterion for an ACS system mode transition was specified to notify the flight software when the initial spin up was complete. For the rest of the spin up from the transition dwell spin rate to the science rate the ACS was required to maintain attitude, so a rate command step consistent with the spin-up RWA control authority budget was specified. To further limit decouple the subsystem software and electronics design from the system design, limited local fault protection at the subsystem level was insisted upon, consistent with the SMAP single string architecture. Finally, to mitigate key risks and provide flexibility and design robustness, key parameter reprogrammability was specified. The specified reprogrammability allows the control parameters (gains, thresholds, filter coefficients, etc.) to be modified but not the architecture of the controller.

Spin Control Verification and Validation

The verification program at the contractor was also designed to decouple the system while simultaneously ensuring the validity of the models delivered for system analysis and the conservatism of the subsystem verification. The subsystem performance requirements were verified with the high fidelity model delivered by the contractor to SMAP for system analysis. The high fidelity model simulated the physical hardware parameters at worst-case values. Where possible, the worst-case modeled values were decomposed into not to exceed requirements in the hardware specifications. As a result, verification of hardware parameters (for the most part in test) served as validation of the conservatism of the high fidelity model. This approach also decoupled the hardware functional and performance verification in environments from the subsystem and system-level integrated control performance verification. Because no integrated testing of the control electronics and mechanism was completed before hardware delivery, in-depth review by subject matter experts of the high fidelity

modeling was performed to ensure the synthesis of the physics was correct. The subsystem stability requirements were verified with the low fidelity model utilizing the specification simplified plant model. The low fidelity model was also validated by destabilizing the high fidelity model at gain and phase levels predicted to be marginal in the linear analysis – limit cycles appeared just above the levels predicted by the low fidelity model. The subsystem firmware was verified in hardware in the loop testing utilizing the high fidelity model run in a real time dynamic simulation coupled to a brassboard ICE burned with the flight PROM code. Finally, results from hardware in the loop testing were compared to purely analytic results from the high fidelity model to validate the abstraction of the controller/software in the high fidelity model.

6. OPERATIONAL CONCEPTS

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7. CHALLENGES AND LESSONS LEARNED FROM A COMPLEX CONTRACTUAL RELATIONSHIP

Early in the SMAP Project the Instrument Mechanical Team elected to procure the actuators and drive electronics needed to deploy the mesh antenna and drive on-orbit balancing mechanisms from one common source. This decision was made in part to reduce the likelihood of interface issues between the motors and the motor drive electronics that has been experienced on past projects. The rationale being that procuring both elements from one source accustomed to developing and testing both would eliminate late breaking drive interface issues associated with separate entities developing electro-mechanical hardware. The vendor selected was also providing the BAPTA and its associated drive electronics so there was a perceived efficiency associated with obtaining all the Instrument drive related components from one source.

As the project evolved the on-orbit balancing mechanism and its associated actuators were descoped reducing the overall quantity of motors needed to complete the mission with just the BAPTA and Mesh Antenna, RBA (Reflector Boom Assembly) Deploy Actuators remaining.

The final contractual arrangement developed had JPL procuring the RBA Actuator and associated drive electronics from one vendor and delivering them to the mesh antenna vendor for integration into their reflector and boom development mechanisms. After the RBA was built and tested it would be delivered to JPL for integration with the rest of the vehicle. Although this arrangement was certainly unique the antenna vendor did have some past experience with having the spacecraft provider procure and deliver deploy actuators and associated drive electronics on past flight projects.

One of the key system engineering challenges associated with the RBA Deploy Actuators was the development of clear requirements to allow both the actuator vendor and the antenna vendor to successfully design their hardware without the need for constant interaction. This proved to be a difficult task as certain aspects of the designs turned out to be highly coupled and not easily compartmentalized.

In specific areas such as the actuator and deploy spooler thermal design, attempts to specify clear requirements and boundary conditions were of limited success. Subtle dependencies not appreciated early in the design proved to be difficult to capture effectively in requirements and were a source of confusion during the development. For example the performance of the stepper motor was temperature dependent as motor winding resistance changes when heated. Characterizing the performance of the motor over temperature required a detailed thermal model of not only the actuator but also a representation of the surrounding environment to capture radiation heat transfer from the motor housing to other system elements. The resulting analysis involved a significant amount of active participation from the actuator vendor, the antenna vendor and system thermal analysts. Solutions to all issues encountered where eventually developed but not without a significant effort to hammer out workable strategies with all parties involved.

Another problem area encountered during the development of the RBA Deploy Actuators was focused on interface misalignments. The RBA Actuator output spline interfaces directly into a female spline in the Boom and Reflector Spoolers. While each side of the interface had some compliance it was discovered fairly late in the development that it was not always sufficient to prevent damage or impaired drive performance in certain cases. This potential issue was discussed early in the development of the device but the various parties involved all made different assumptions regarding the capability of the other side of the interface and the potential misalignment during launch and operation. These varying assumptions along with vague and underspecified interface requirements contributed to the issues uncovered later in the project about potential interface incompatibility. Hardware modifications were developed to provide the required interface misalignment capability and solve the issue but not without a significant impact on the unit delivery schedule.

The following lessons learned can be gleaned from the specific examples mentioned above and from the rest of the Actuator development.

a) *Plan appropriately*: When complicated contractual relationships between multiple

delivering organizations are put in place careful, specific planning must be employed to minimize issues later in the program. While the team did employ technical interchanges between all parties and regular reviews during the development more regular, informal exchanges between all the players would have been beneficial. Employing quarterly or more frequent regular exchanges would have reduced the likelihood that assumptions stray from a consistent baseline.

b) *Be Specific*: While certain aspects of the design may not seem to warrant specific requirements it is prudent to capture as much as possible in written requirements and documentation. In many instances writing down a specific requirement and having it reviewed uncovers hidden aspects of the design not obvious to all parties before it was documented. The requirements themselves should be as specific and unambiguous as possible because individual interpretation of vague requirements will cause problems.

c) *Notes & Written Communication*: During the actuator development many of the technical interchanges were very valuable and generated fruitful dialog. We found taking the extra effort to capture a written summary of the discussions covered during and decisions made during the meetings helped immensely a few weeks or months later when topics needed to be revisited. Although this does tax the note-taker the benefit far outweighs the time required to generate the summary. When this was not done the team frequently had limited specific memory of topics covered and specific decisions made in the meeting. Rigorous action item tracking also helps forward progress in the design and prevents important items from getting lost and not addressed properly.

While somewhat general it is hoped that these lessons learned and recommendations can help make future hardware developments less problematic.

8. Instrument Deployment Activity System Design

The deployment of the six meter mesh antenna is comprised of two main events, the release and deployment of the multi-segment hinged boom assembly and the release and deployment of the perimeter truss antenna itself. These distinct events are separated by several days to review deployment data and perform other minor activities. Planning and development of these deployment activities was performed by elements of the Instrument Mechanical Team, the Antenna Vendor and the Flight System with inputs and support from a multitude of other project elements. These project elements included Guidance & Control, System Thermal, Telecom, Fault Protection, Operations, and Flight Software personnel. The combined efforts of all these organizations enabled the development of activity plan for the deployments. This section provides a brief description of the overall design strategy for the deployment and highlights certain key aspects of the plan development.

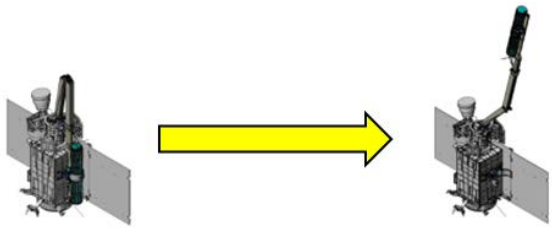

Figure 6 - SMAP Boom Deployment

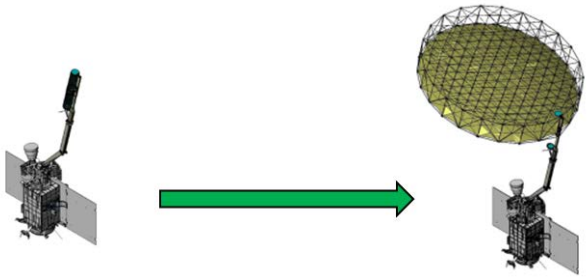

Figure 7 - SMAP Reflector Deployment

The overarching design intent for the deployments is to provide the most favorable environment for the antenna hardware while maintaining adequate vehicle power, thermal, and communication margins throughout the activities. Early concern about unintended interaction between the partially deployed reflector with the vehicle's attitude control system (ACS) led the team to adopt an approach where the vehicle is in an ACS-idle state during the deployment. This approach prevents reaction wheel induced torques from being applied to the Reflector or Boom Assemblies during the deployments. While this is beneficial from a loading standpoint it does complicate other aspects of the system design as the vehicle is free to drift due to external torques while in the idle state. This drift complicates communications link margin, system thermal design and battery state of charge as the vehicle can potentially drift into attitudes where the solar arrays are not facing the sun and unfavorable communications antenna orientations are encountered. These concerns were addressed by working with members of the GNC, Thermal, and Telecom teams to confirm that vehicle health is maintained throughout both deployments. The teams used bounding drift analysis produced by the GNC team to produce design cases for the drift corner cases. Evaluation of those design cases provided positive verification that the vehicle health would be maintained through the boom and reflector deployment activities.

Uncertain commandibility due to vehicle drift during boom and reflector deployments led the team to select a deploy methodology that is largely autonomous. Adopting this approach allows a timely completion of the deployments and minimizes the time the vehicle is in the ACS-idle state with a partially deployed boom or reflector. A dedicated flight software behavior executes the deployments based on telemetry that allows direct or indirect monitoring of spooler deploy cable tension. Rotation sensors on the cable spoolers provide additional information on the progress of the development. Onboard decision making is based on a voting scheme tied to redundant tension sensor states, cumulative spooler rotation and commanded motor steps. The voting scheme adopted was developed to provide a robust method of determining deploy completion while preventing premature deploy aborts. The strategy employed is also tolerant of many combinations of sensor failures. In the event a hardware or software anomaly is encountered that endanger the vehicle and the onboard behavior does not take the proper action a halt deploy ground command can be issued through the majority of the activity to stop the activity.

While the current SMAP hardware design will provide sufficient telemetry to successfully deploy both the reflector and boom careful consideration should be given in the early hardware deployment phase of future missions as to what telemetry would provide the most direct indication of deployment health and progress. System architects would do well to give careful thought to the implications of limited or overly simplified sensor packages as there are far reaching system impacts associated with potentially ambiguous deploy progress indications. The more direct the telemetry is the less complicated some aspects of Fault Protection and Deploy Behavior design become. It is far better to be data rich than data poor in the face of a deploy anomaly.

The Instrument Deployment Scenario development has been a challenging and fascinating exercise in systems architecture and design. It is hoped that the section provides some insight into that process.

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