Development of the Large Aperture Reflector/Boom Assembly for the SMAP Spacecraft

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ABSTRACT

The Jet Propulsion Laboratory's (JPL) Soil Moisture Active/Passive (SMAP) mission is to measure and monitor global soil moisture dynamics and freeze/thaw states. The rotating Reflector and Boom Assembly (RBA) on SMAP presents significant design and development challenges. The payload configuration utilizes a common Radiometer and Radar feedhorn and a 6-meter deployable mesh reflector all spinning at 14.6 rpm. The evolution of the RBA system solution, development of the mass properties management approach and RBA dynamics are discussed.

1. MISSION OVERVIEW

SMAP is a single spacecraft Earth Observation mission designed to collect measurements of the planet's surface soil moisture and freeze/thaw states. The SMAP satellite is schedule for launch on a Delta II from Vandenberg Air Force Base in California the fall of 2014. The mission life is planned for a little over 3 years; 3 months post-launch in-orbit checkout, a 12 months system Calibration and Validation phase and 24 months Routine Observation phase. NASA's Jet Propulsion Laboratory (JPL) is leading the spacecraft development and is responsible for on-orbit operation and mission data processing. A diagram of the SMAP Spacecraft is shown in Fig. 1, courtesy of JPL.

The primary SMAP mission objective is to collect detailed ecosystem measurements related to the "process that links water, energy and carbon cycles and to enhance the predictive skill of weather and climate models". The resulting data will likely improve weather forecasting; providing early warning for major climatic events such as flood and drought cycles; advance agricultural and forestry management; assess and project the impacts of climate change.

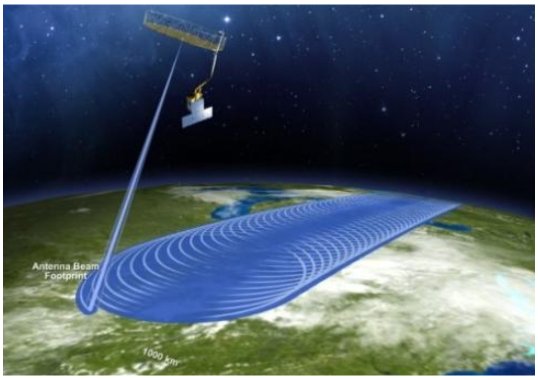

Figure 1. SMAP Spacecraft

The spacecraft instrumentation suite consists of an L-band synthetic aperture radar and an L-band radiometer. The use of the L-band frequency will allow the observation of the soil moisture through moderate level of vegetation cover. As noted earlier the radar and radiometer share a common feedhorn and a 6-meter large aperture deployable mesh reflector. The feedhorn, reflector and boom assembly rotate at 14.6 rpm to allow 1,000 km scanning width on the earth's surface. When the radar and radiometer data are jointly processed; soil moisture results will have spatial resolution data of 10 km and freeze/thaw state data with a spatial resolution of 3 km. The satellite will be placed in a sun-synchronous orbit; allowing for continuous data update, scanning the whole planet every 3 days.

2. RBA DEVELOPMENT

The RBA requirements are unprecedented in scope for a large deployable reflector: not only must the deployable reflector and boom be exceptionally light and stable to minimize deflection during high speed rotation; it must also have extremely accurate and predictable mass properties when spinning, since it is not practical to measure or test the system's rotational dynamics on the ground. At SMAP program inception the launch vehicle was undefined and spacecraft requirements had to consider the possible use of the Minotaur rocket; resulting in a RBA stowed envelope that was extremely compact to support the mission goal of lofting to orbit on this small Launch Vehicle.

Northrop Grumman's Astro Aerospace was selected to provide the RBA SMAP mission utilizing its AstroMesh reflector technology. AstroMesh is a patented perimeter truss deployable mesh reflector design with significant flight heritage. The AstroMesh® family of deployable mesh reflectors has evolved over more than 15 years of continuous development to become the most advanced and reliable reflector technology available. AstroMesh is the only unfurlable mesh reflector with 100% on-orbit deployment success; no incidents, no anomalies and no failures, flight history is shown in Fig. 2.

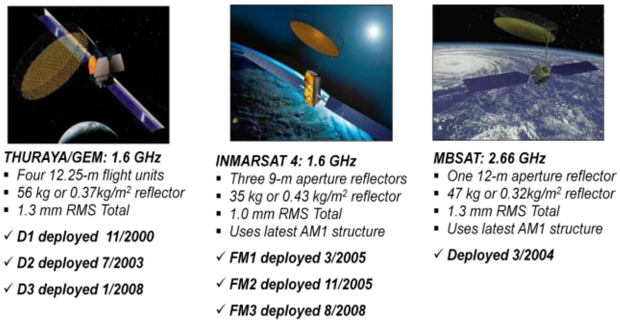

Figure 2. AstroMesh Flight History

Astro Aerospace's solution to SMAP's challenging requirements is to utilize its latest AstroMesh reflector configuration, optimized for the 3 to 8-meter aperture class, known as AM-Lite (AstroMesh-Lite). The reflector along with its flight heritage derived boom, deployment hinge and spacecraft interface technology are applied to meet or exceed the design requirements.

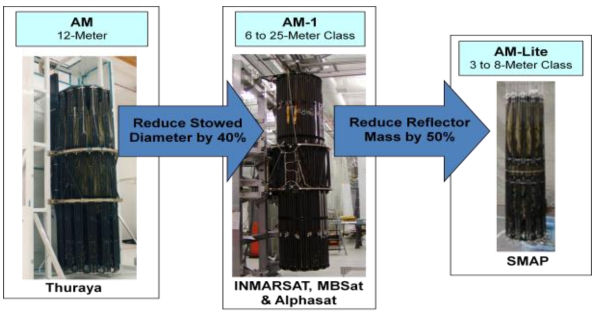

Figure 3. AstroMesh Reflector Family Evolution

The AM-Lite reflector configuration was evolved from the larger AstroMesh frame size, but optimized for mass and stowed volume to meet the 3 to 8-meter reflector class market, Fig. 3. As an example the SMAP 6-meter reflector with elliptical deployed truss dimensions of 6.63x6.15 m, has a mass of only 13 kg and stows into a compact 1.83x0.36 m envelope.

All AstroMesh reflectors, including AM-Lite, have the same robust deployment kinematics and deployed perimeter truss configuration. When deployed the reflector forms an exceptionally mass efficient pseudo-geodesic structure that is extremely stiff, stable and accurate. As part of our AM-Lite development the Engineering Qualification Model (EQM) was configured for high-frequency applications (Beyond Ka-Band) and completed a full range of qualification level performance and environmental testing [1] equivalent to Technology Readiness Level 6 (TRL 6), Fig. 4.

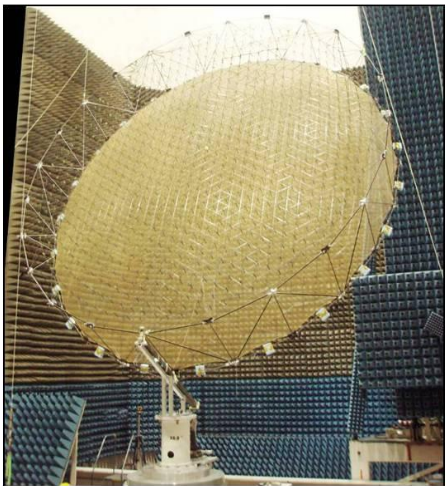

Figure 4. AM-Lite EQM 50GHz Performance Test at NASA GRC

SMAP will be first application of the AM-Lite configuration and JPL's first deployable mesh reflector system since the use as the high gain antenna on the Galileo mission which failed to deploy. Astro has supported the development of the mission since its genesis as the Hydros mission back in 2004 and the large rotating reflector has always been the critical element of the payload and so the reliability of the AstroMesh reflector gave JPL the confidence to go forward.

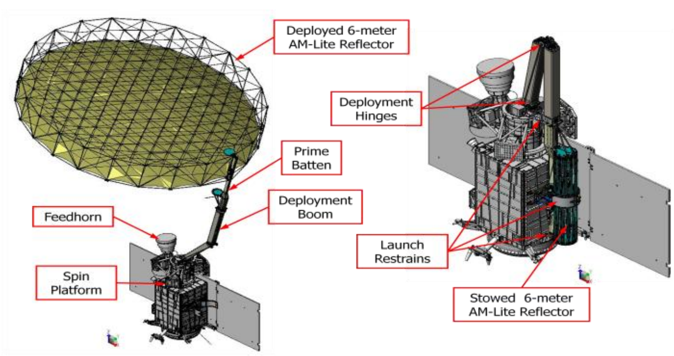

Figure 5. RBA Assembly on SMAP Spacecraft

The SMAP RBA assembly, shown in Fig. 5, draws extensively on past flight heritage. The Launch Restraint system is similar to the configuration used on the Thuraya reflector. The deployment boom hinges are based on the MBSat heritage design. Although the actual deployed and stowed configurations are unique to the SMAP application the deployment sequence is based on the AstroMesh heritage process: 1) Pyro release of launch restraint, 2) Hinged boom deployment, 3) Pyro reflector release/bloom and 4) Motorized reflector deployment. RBA deployment sequence is shown in Fig. 6.

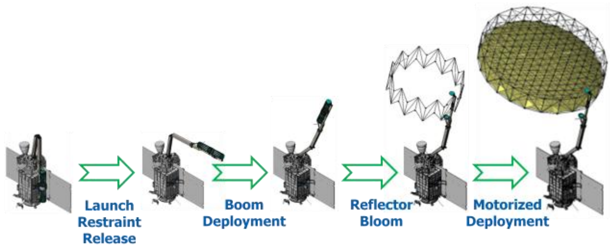

Figure 6. RBA Deployment Sequence

The RBA activity successfully completed its Critical Design Review (CDR) in December 2011 and fabrication of the flight hardware is well on its way. The SMAP program completed the Project Level CDR in July 2012 and the satellite now has a committed launch date on a Delta II from Vandenberg in October of 2014.

3. RBA ANALYSIS

A typical deployable structure for space application is analyzed for three distinctive configurations and corresponding environments: Stowed, during deployment, and deployed. In the following sections these configurations will be discussed with the emphasis on the dynamics analysis and related topics.

3.1 Stowed Structural Analysis

Natural Frequency Requirements

The stowed RBA shall have a minimum resonant frequency of 50 Hz in the axial direction and 35 Hz in the lateral.

Natural Frequency Analysis

The FEMAP/NX Nastran is used for the RBA stowed analysis. The computed modes meet requirements. The first mode is 38.54 Hz and mainly involves the deployment boom as shown below in Fig. 7.

Launch Load Requirements

1. The preliminary design load for the RBA structure is the RSS of 30G in each axis applied to the RBA mass while integrated with the SMAP spacecraft. The design loads will be verified with launch vehicle coupled load analysis (CLA) in October 2012.

2. The stowed RBA is also designed to random vibration environment.

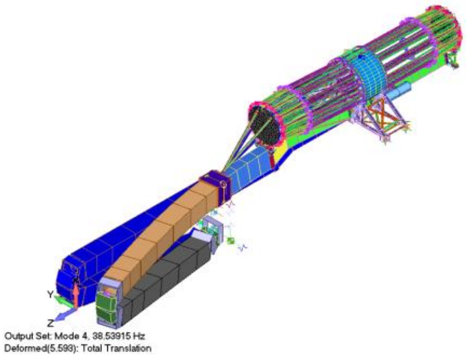

Figure 7. First Stowed Mode

Launch Load Analysis

The integrated RBA stowed FEM and spacecraft (SC) is shown in Fig. 8.

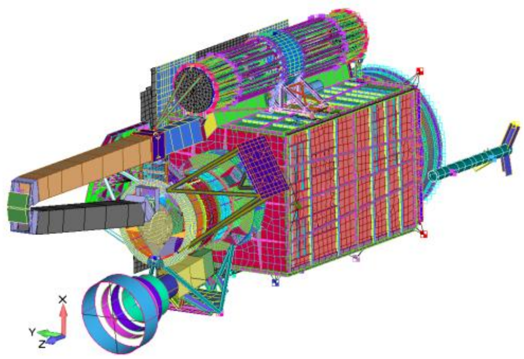

Figure 8. Stowed FEM

The modal damping used for the random vibration analysis is 5%. A typical stowed AstroMesh has high modal damping [~8%] due to the stowed webs and mesh within the truss members. Also the participation of the individual truss member local excitation in the primary modes increases the effective damping [2].

3.2 Deployment Analyses

Deployment Analysis Requirements

The only explicit requirement for the RBA deployment is the deployment time to be less than *30 minutes* from the start of powered deployment for boom deployment and a similar requirement for reflector deployment. Currently it is planned to disable/ minimize the attitude control during RBA deployment. Also the partial deployed RBA during the boom deployment should behave as a structure with minimum free play. The ADAMS software is used for the deployment analysis of the RBA attached to free-flying SC.

Boom Deployment Analysis

The boom deployment using ADAMS is shown in Fig. 9. During this simulation the SC attitude control was disabled which caused SC to rotate about 26 degrees. During this operation the RBA behaves as a structure with varying natural frequency. The natural frequency of the RBA for several intermediate configurations of the boom deployment is shown in Fig. 10.
The spacecraft rotation about three axes during this phase is shown in Fig. 11.

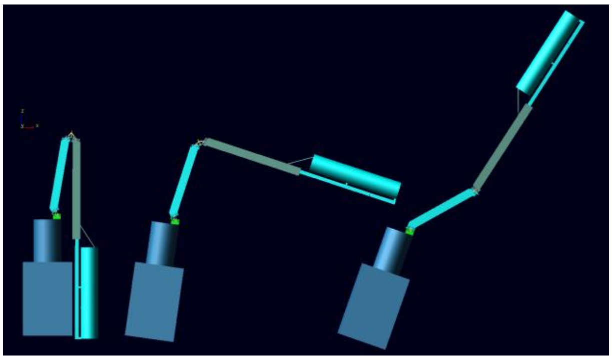

Figure 9. Boom Deployment

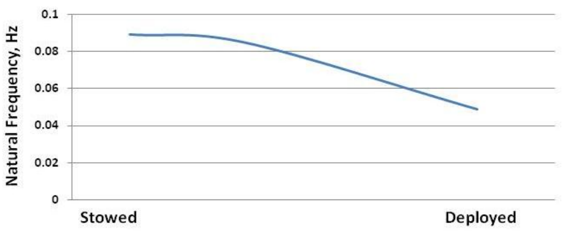

Figure 10. Natural Frequency - Boom Deployment

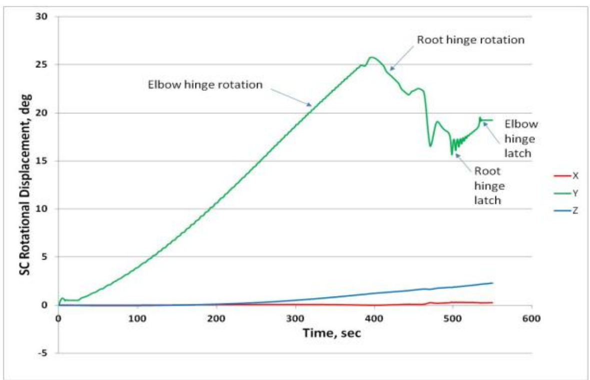

Figure 11. SC Rotations During Boom Deployment

Reflector Deployment Analysis

The reflector deployment is comprised of two events: The first, where the reflector secondary release is actuated, causes the stowed reflector to bloom to about 3 m in diameter. After the reflector becomes stationary the deployment motor is then commanded on until the reflector is fully deployed and latched. The reflector deployment ADAMS simulation is shown in Fig. 12.
During this simulation the SC attitude control was disabled and the SC rotates about 2.6 degree. The SC rotation during the initial bloom is shown in Fig. 13.

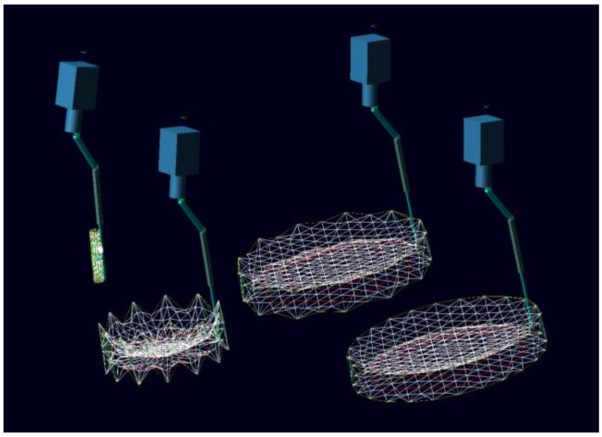

Figure 12. Reflector Deployment

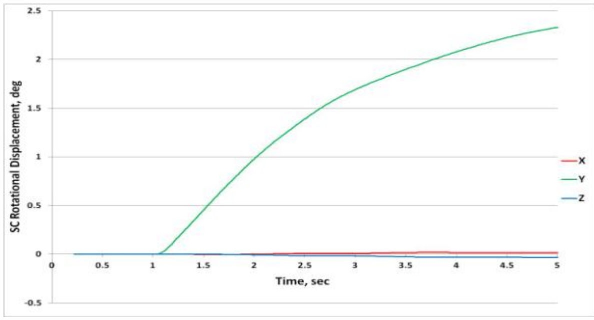

Figure 13. SC Rotations - Reflector Deployment

3.3 Analyses of the Deployed Configuration

The top level requirements for the deployed configuration are the deployed natural frequency, surface accuracy, and mass properties for the specified on-orbit environments:

Deployed Frequency Requirements

The SMAP Observatory has both an Attitude Control Subsystem and a Spin Subsystem that both contain controllers. Additionally, there is a clear disturbance source at the spin rate frequency and the first harmonic. Because of the controllers' bandwidth and the disturbance sources, frequency separation is key for maintaining reliable and predictable Observatory performance [3].

The RBA is the hardware element in the system that sets the first mode of the Observatory. As such, the first mode of the RBA in a configuration where it is attached to a spacecraft in a free-free state was required to be greater than 1.45 Hz, giving a decade separation between the Observatory first mode and bandwidth of the spin controller.

Additionally, based on system analysis the RBA is required to have a minimum of 0.2 Hz frequency separation between its first two modes. This is required to have the discrete modes of the RBA sufficiently separated in frequency such that they do not interact. Two low frequency modes close to each other in frequency may generate a much stronger pole frequency than the spin controller is designed for and hence break the margins of the spin controller.

Deployed Frequency Analysis

The deployed frequency characteristic of SMAP is unique since the first fixed base mode is essentially motion about the spin axis. To create an effective set of deployed frequency requirements, the RBA is attached to a simplified mass representation of the spacecraft in a free-flying spacecraft configuration. The RBA is attached to the spun instrument (SPA) portion of the SMAP observatory represented by a rigid body. The SPA is rigidly attached to the bus with the spin axis free to rotate. The mass properties of the SPA and of the bus each include a single lumped mass with representative inertia properties. In the resulting free-free deployed frequency analysis there are seven rigid body modes. The first 3 structural modes are: 1.8, 2.3, and 3.3 Hz as presented in Fig.'s. 14-16. Note that the first mode is the Pitch Mode and the typical Yaw Mode is no longer the fundamental mode. Furthermore the simplified model of the spacecraft has been validated by attaching the RBA FEM to a detailed FEM of the spacecraft as shown in the figures and the resulting frequencies correlate well. Finally, the minimum frequency requirement and the frequency separation requirement between the first two modes have been met.

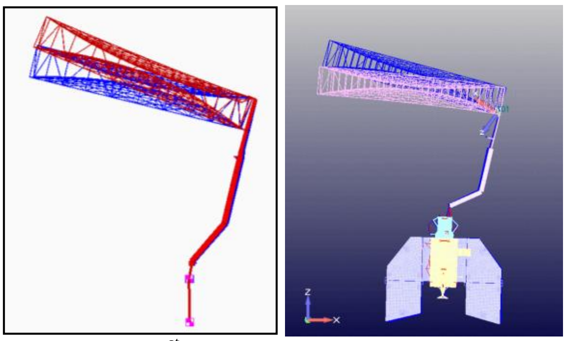

Figure 14. 1st Free-Free Structural Mode, 1.8 Hz

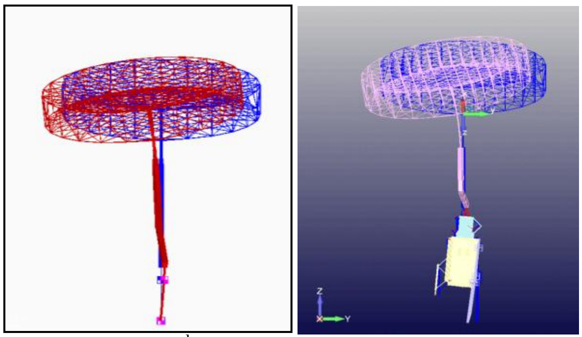

Figure 15. 2nd Free-Free Structural Mode, 2.3 Hz

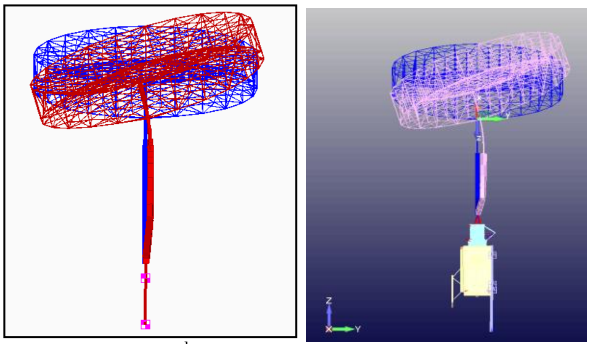

Figure 16. 3rd Free-Free Structural Mode, 3.3 Hz

Effect of Spin on Natural Frequency

It should be noted that the spun RBA will have higher frequencies compared to an un-spun RBA [3]. However due to limitations of finite element software, the frequency requirements are based on a stationary or de-spun RBA configuration. Earlier in the project this effect was investigated using ADAMS software. Astro Aerospace utilizes ADAMS software to determine the state of the reflector during its deployment. The natural frequency computation was done indirectly inside ADAMS. The reflector in its fully deployed configuration, attached to a rigid stationary spacecraft, (fixed base boundary condition) was given an external disturbance and from its steady state responses the natural frequency was determined. This process was done for both de-spun and at 14.6 rpm spun configurations. The results are presented in Tab. 1.

Table 1 – Comparison of Spun and Un-spun Natural Frequency

Configuration	Frequency
Un-Spun	1.5 Hz, Pitch Mode
Spinning at 14.6 rpm	1.63 Hz, Pitch Mode

Surface Accuracy Requirements

On orbit the RBA is subjected to thermal and to dynamic loading. The surface accuracy requirements are specified separately for constant and time varying errors. The constant error pointing requirement is ±100 millidegrees, while the time varying error is ±12 millidegrees. The time varying error is a combination of both diurnal and seasonal variations. The total surface error requirement is 2 mm, RMS of the half path length error (RMS hpl).

The largest contributor to the constant pointing error is the centripetal acceleration of the nominal 14.6 rpm spin. The location on the RBA furthest from the spin axis sees 1.1g acceleration due to the spin. The complete surface accuracy analysis results are presented in [3]. The surface accuracy and pointing error due to spin are discussed below:

Surface Accuracy Analysis

The deployed RBA surface accuracy and pointing is analyzed using a finite element model. The analysis includes a Monte Carlo simulation to analyze the effects of manufacturing tolerances [4], on-orbit dynamics, and thermo-elastic effects on the surface accuracy of the reflector.

For the SMAP program the mechanical pointing errors are multiplied by beam deviation factors (BDFs), which account for the difference between the mechanical pointing and the electrical pointing. The mechanical pointing error is the difference in position of the best fit paraboloid (BFP) and the design paraboloid. Pointing errors in this paper include BDFs of 1.83 (roll axis) and 1.65 (pitch axis).

To correct the spin induced constant pointing error the RBA is built such that it will deflect into the design position at the nominal 14.6 rpm spin rate. The change in pointing, from the as-built RBA to the nominal spin, is 350 millidegrees. The deflection at the reflector tip, furthest from the boom, is 2 cm. The built in correction accounts for the bending of the boom and for the flexibility at the boom/reflector interface. The pointing error due to spin is corrected within the accuracy of the analysis and of the measurements. The analysis uncertainty and measurement uncertainties are budgeted in the constant pointing error. The residual surface error after the correction is made for the spin is 0.32 mm (RMS hpl). The maximum bow in the truss after correction is 1.7 mm.

The reflector tension ties are designed to achieve an optimum tension field in the reflector webs while maintaining a minimum required tension in the webs to prevent web distortion and to react on orbit loading. For a typical AstroMesh reflector the optimization is done without regard to external loading. For the SMAP reflector the optimization is done to include the loading due to the nominal spin. This allows for an optimum tension field at the nominal spin rate.

Mass Properties Requirements

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. 17 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.

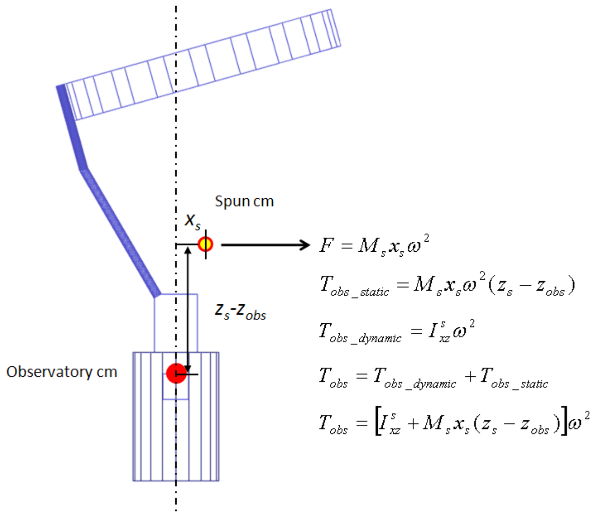

Figure 17. Observatory Balancing

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:

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

$$m_{RBA} x_{RBA} \leq C_1 \quad (2)$$

where m_{RBA} is the mass of the RBA, $\boldsymbol{x}_{RBA}$ and $\boldsymbol{z}_{RBA}$ are the x and z center of mass locations of the RBA, and $\boldsymbol{z}_0$, 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 Properties Management Approach

One of the most challenging aspects of the SMAP satellite design is the management of the RBA mass properties including the deployed moment of inertia (MOI) and product of inertia (POI). Ground testing and characterization of the RBA was evaluated but was considered impractical. It was determined that a program of detailed analysis and modelling (detailed to the screw, nut, washer and glueline level) in conjunction with a rigorous hardware mass properties measurement process at the piece parts and subassembly level could effectively characterize the system mass properties within the requirements dictated by the spacecraft dynamics.

Mass Properties Analysis

Throughout the design process of the RBA, the Effective Product of Inertia and CMx constraints must be tracked to determine if the RBA will meet the requirements. A finite element model is created in FEMAP to find the mass properties of the RBA so that the constraints given in equations (1) and (2) can be calculated. When there is a design change, the mass properties model can be re-run to determine if the design change has a significant effect on the Effective Product of Inertia.

There are several uncertainties that contribute to the mass properties uncertainty of the RBA. These include part mass, center of mass, position, moment of inertia, and product of inertia. A sensitivity study was performed to determine the major contributors to the mass properties uncertainty and it was found that part mass uncertainty was the most significant source of overall RBA mass properties uncertainty. The part mass uncertainty is large due to the design maturity of the RBA. These large uncertainties are high in the beginning of the RBA design process and reduce as the design matures and is finalized.

Since there is a large variation in part mass during the RBA design process, a Monte Carlo simulation is set up to create random RBA mass configurations. For each configuration, the mass properties of the overall RBA system are found and the Effective Product of Inertia and CMx are calculated. The results are then analyzed to determine the number of cases that meet both requirements.

A FEMAP finite element model is used for the Monte Carlo simulation. Component mass values and the uncertainties are taken from a top level mass report which is a combination of measured mass values and CAD mass values. Random mass inputs are created in an Excel spreadsheet that uses a uniform distribution between the minimum and maximum expected mass of the parts.

A program is written with the FEMAP Application Programming Interface to input the random mass values from Excel to the FEMAP model, run mass properties within FEMAP, then export the mass properties back to Excel. The Monte Carlo simulation runs 5,000 random mass cases. Plots summarizing the Monte Carlo results for Effective Product of Inertia and CMx are shown in Fig.'s. 18-19. The plots show a histogram of the calculated Effective Product of Inertia and CMx for every case along with the limits of the constraints ε and C_1.

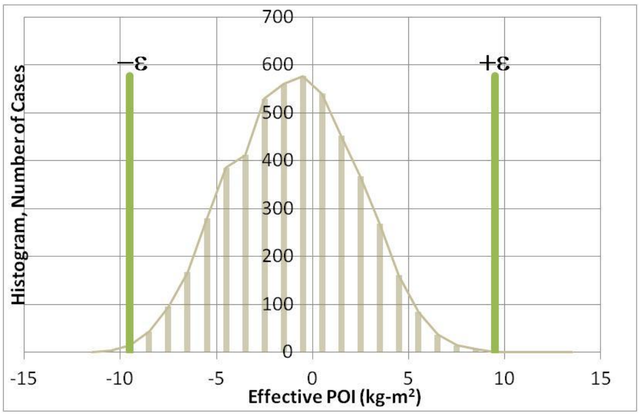

Figure 18. Monte Carlo Results for Effective POI

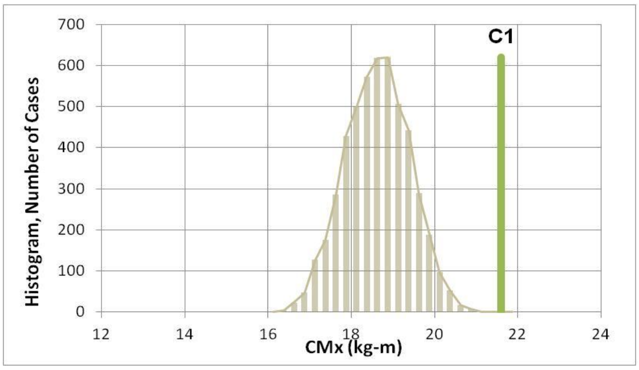

Figure 19. Monte Carlo Results for Effective CMx

Using the results from the Monte Carlo simulation, instant feedback can be obtained to determine if the current RBA design meets the Effective POI and CMx requirements. Presented in Fig. 20 is the flow chart to describe the process of updating and capturing the information required for mass properties through the life of the SMAP RBA from design to final assembly and test.

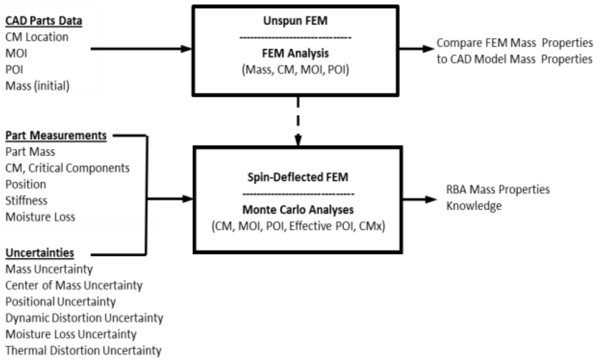

Figure 20. Flowchart for Mass Properties Analysis

4. CONCLUSION

The SMAP instrument presents several design and analysis challenges due to the RBA rotation relative to the de-spun spacecraft at 14.6 rpm. Astro Aerospace AM-Lite excellent features including deployed surface accuracy, high stiffness, low mass, and compact stowed envelop, along with Astro’s 100% on-orbit deployment success has led to its selection for use on the NASA SMAP program for JPL. The characterization of 6-meter rotating RBA necessitates a thorough and novel approach to mass properties and dynamic analysis. This process will result in acceptable RBA rotational dynamics without on-orbit adjustment. With CDR complete, hardware fabrication is now well underway leading to a SMAP spacecraft launch scheduled for the fall of 2014.

5. ACKNOWLEDGEMENTS

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