VAN ALLEN PROBES ON-ORBIT VERIFICATION OF SPACECRAFT DYNAMICS

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Abstract: *The Van Allen Probes were launched into Earth orbit on August 30, 2012 for a nominal two-year mission to study the Earth's radiation belts and their interaction with the Sun as part of NASA's Living With a Star Geospace Program. The two nearly identical spacecraft are spin-stabilized at approximately 5.5 rpm, flying in highly elliptic orbits to pass within and immediately exterior to the Van Allen Radiation Belts. An instrument used for electric field measurement dominates the dynamics of the probes.*

A set of three earlier papers described and analyzed the dynamics of the Van Allen Probes. Just prior to launch, certain configurations on the spacecraft had to be changed. This paper updates the predictions based on the the as-flown configuration. While there are no major changes, there are subtle changes that are worth examining.

The Van Allen Probes have been operational for over a year and a half. During this time, both spacecraft have been subjected to many maneuvers and have flown through many perigees and eclipses. The spacecraft carry a set of sun sensors and a magnetometer. The sun sensors provide a sun pulse (and thus a spin period) and a sun aspect angle when not in eclipse. The magnetometer provides a measurement of the earth's magnetic field. This paper examines the available telemetry data from these sensors to validate the dynamics predictions.

Keywords: *Spinning spacecraft, flexible booms, dynamics modeling, on-orbit performance*

1. Introduction

The Van Allen Probes[1] are a pair of identical spacecraft in NASA's "Living With a Star" program[1]. The mission's main objective is the scientific exploration of the geospace—the region of space that stretches from the Earth's upper atmosphere to the outermost reaches of the Earth's magnetic field. The instruments on the spacecraft investigate populations of relativistic electrons and ions in the radiation belts—their formation and their response to Solar emissions. The mission targets the fundamental processes that energize, transport, and cause the loss of the time-varying charged-particle populations in the Earth's inner magnetosphere (the area in and around the Earth's radiation belts) that are hazardous to spacecraft and astronauts. The Van Allen Probes were launched in August 2012. Since their commencement of science operations in late October 2012, they have return vast amounts of information about the radiation belts. One of the important scientific contributions that the probes have made is the discovery of a third radiation belt in the Van Allen belt region of the atmosphere. Figure 1, from the Van Allen Probes project website[1], shows an artist's rendering of the Van Allen Probes with the science instruments marked.

[1] These were called Radiation Belt Storm Probes (RBSP) while being built

One of the main instruments on board the spacecraft, the Electric Field and Waves (EFW) instrument[2], has a large impact on the dynamics of the spacecraft. EFW consists of three orthogonal boom pairs designed to measure the local 3D electric field around the spacecraft. An axial boom pair (12 m dipole length, tip-to-tip) is co-aligned with the spin axis. The two other boom pairs are spin-plane booms (SPB), long wire booms extending radially outward in the spin plane. Each SPB is made up of a long thin wire, a pre-amplifier, a thinner outer wire, and an electric sensor at the tip. Each pair of the SPBs forms a dipole 100m in length (tip-to-tip). The booms, while providing only 0.25% of the total mass of the spacecraft, account for about 80% of the (rigid) spin inertia. The Van Allen Probes nominally spin at 5.5 rpm and the centrifugal force of spacecraft spin rate keeps the wire booms deployed. However, these booms have very low bending stiffness and so, are free to oscillate about their attachment point[2]. This pendular motion heavily influences the dynamics of the spacecraft.

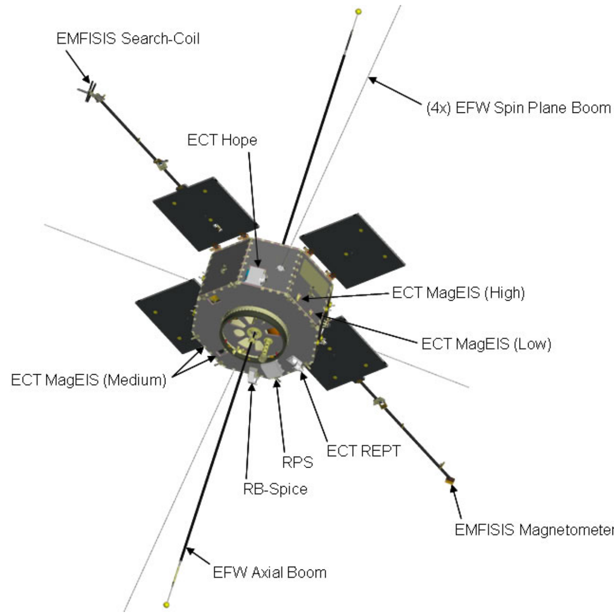

Figure 1. Van Allen Probes Spacecraft with Science Instruments Marked

In addition, the spacecraft also has two 3-meter booms in the spin plane housing magnetometers for magnetic field measurement; these are attached to one pair of deployed solar panels. The axial and magnetometer booms and the solar panels also complicate the dynamics of the system.

2. Spacecraft Description

Copious information on the Van Allen Probes has been collected in a compendium published by Springer [3]. This section describes sensors, actuators, spacecraft configuration and as-flown parameters most relevant to this discussion.

2.1. Sensors

The main attitude sensors on the Van Allen Probes is a pair of sun sensors from Adcole, Inc., mounted on opposite sides of the spacecraft hub. Each sensor independently provides a sun pulse and a sun-aspect angle, once per revolution. The sun pulse provides the spin rate of the hub through the difference between successive sun pulses from the same sun sensor. However, the sun-aspect angle has a low resolution of about 0.125° and is thus not particularly useful in discerning the dynamics of the spacecraft. Note that the sun sensor do not provide any data during an eclipse.

[2]Note that the actual attachment point is not at the surface of the spacecraft, but is recessed ∼18 cm into the core.

The spacecraft also carry the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS), a science instrument which measure the electric and magnetic field around the earth. The EMFISIS fluxgate magnetometer provides 64-Hz magnetic field data. As the spacecraft is rotating, the x- and y-components are also rotating. By fitting a sine curve to the magnetic field measurement along one axis (piece-wise), the spin rate of the spacecraft can be putatively estimated. As will be shown below, the estimates are not reliable near perigee as the earth's magnetic field changes rapidly as the spacecraft fly through perigee. Near apogee, the magnetic field is weak and the estimates are noisy. In essence, the magnetic field data is not usable directly for this purpose. The magnetic field data is publicly available at NASA Goddard Space Flight Center's Coordinated Data Analysis Web [4].

2.2. Actuators

The Van Allen Probes carry a set of eight 0.9N thrusters. Different thruster set selections provide pure force (for ΔV), pure torque along the spin axis (for spin adjust), and a pure torque along the transverse axes (for precession of the spin axis). The spacecraft does not have a closed-loop control system. Selected thrusters can be fired by ground command. A special mode allows thrusters to be fired after a fixed delay following a sun pulse facilitating a rhumb-line precession.

The probes carry two fluid-filled ring nutation dampers along the hub transverse axes (X and Y) to damp out hub transverse body angular rates. These were designed and built in-house at the Johns Hopkins Applied Physics Lab. Fluid-filled dampers rely on the rotational oscillations of the hub. An important consequence of this is that they are only effective on modes that exhibit hub rotational oscillation; they are not effective on hub translational oscillations, or in modes that only involve the wire booms. Thrusters and nutation dampers are discussed in detail in reference [3].

In addition, inherent damping in the wire booms emanates from dry friction and hysteretic behavior in the wire[5]. In a linear analysis, the damping is modeled as viscous damping. Since the basic behavior is hysteretic in nature, the equivalent viscous damping is a function of the mode frequency. These effects are discussed by Shankar, et al[6]; this is also explored further in a set of three papers [7, 8, 9]. Viscous damping is represented in the boom equations using the equivalent viscous damping coefficient, c_{eqv}. It is observed that the wire boom damping is only effective at large boom angles. They are much less effective below 5°.

Finally, propellent sloshing in the tanks provide some damping. The Van Allen Probes carry three propellent tanks distributed evenly around the spin axis. However, the damping provided is very small and is ignored.

2.3. Van Allen Probes Spacecraft Configuration

The hub of the Van Allen Probes spacecraft consists of a core, two solar panels along the $\pm$Y-axes, two magnetometer booms (which are attached to and extend beyond the solar panels). The Y-axis the minimum moment of inertia; the spin moment of inertia is the major axis. The spin-plane booms are mounted in the plane containing the spacecraft center of mass and are rotated 55° from the spacecraft (and hub principal) axes. Figure 2 shows the spacecraft configuration in flight.

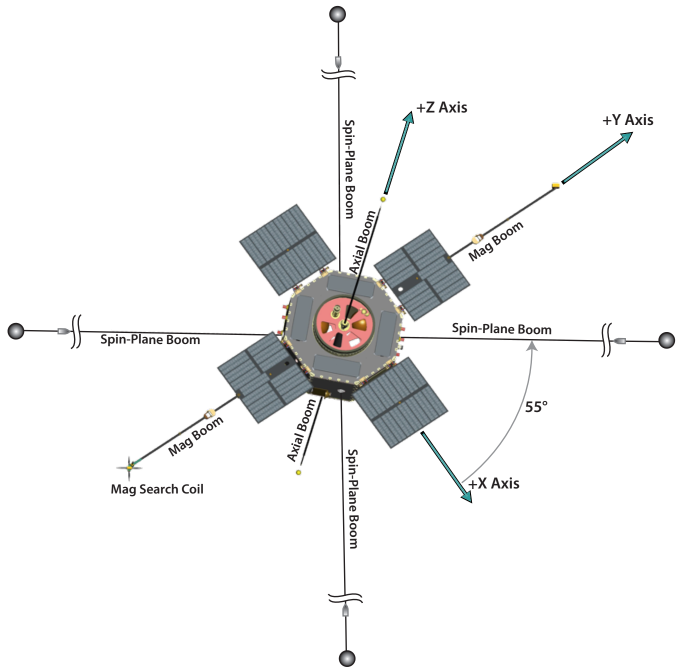

Figure 2. Van Allen Probes Axes

2.4. As-Flown Parameters for Deployed Spacecraft

As originally designed, the Van Allen Probes' two pairs of wire booms were of different dipole length: one dipole at eighty meters and the other at a hundred meters. Just prior to launch, the EFW instrument manufacturer discovered that at 5 rpm and a boom at forty meters, there was a possibility that the centrifugal force on the sensor at the end of boom was inadequate and the outer wire could unfurl. To avoid this, it was decided to extend both dipoles to a hundred meters each, and increase the spin rate of the spacecraft to 5.5 rpm. A quick study revealed that this resulted in no major changes to the dynamics (stability, etc.). This paper updates the predictions based on the new lengths and on the as-flown mass properties of the spacecraft and wires. While there are no major changes, there are subtle changes that are worth examining. Table 1 shows the relevant parameters for the Van Allen Probes as flown.

3. Van Allen Probes Orbit

The Van Allen Probes are in a highly-elliptical orbit around the earth, completing each orbit in about nine hours. The orbit is at about 10° inclination. The two spacecraft have slightly different orbits: Probe-A is enclosed within the orbit of Probe-B. Probe-A has a perigee of about 605 km and an apogee of about 30,550 km; Probe-B has a perigee of about 624 km and an apogee of about 30,681 km. The different orbits allow for simultaneous science measurement over differing spacecraft separations several times over the course of the mission. The orbits are designed so that Probe-A laps the other every 75 days. The orbit is not nominally maintained and is allowed to precess. Due to the nature of this orbit, the Van Allen Probes are in eclipse some months in the year. As the orbit is precessing, eclipses can occur at any point in the orbit: perigee to apogee.

Table 1. Van Allen Probes As-Flown Parameters

Parameter	Symbol	As-Flown Value†	Units	Comments
Hub Parameters				
Hub inertia	J_{xx}	479.5	$kg \cdot m^2$	Nominal values
	J_{yy}	314.2		
	J_{zz}	561.2		
Hub body rates	ω_x	0	rad/s	Simple 5.5 rpm spin about Z-axis
	ω_y	0		
	ω_z	0.576		
Hub mass	m_h	600.8	kg	Nominal hub mass
Nominal (Deployed) Boom Parameters				
Attachment radius	b	0.779	m	Attachment point recessed 18 cm from outer panel
Attachment height from c.m.	z_0	0.00	m	
Boom pair 1 length	L_1	41.67	m	All booms same length as launched
Boom pair 1 tip mass	m_1	0.235	kg	
Boom pair 2 length	L_2	41.67	m	
Boom pair 2 tip mass	m_2	0.235	kg	
Nutation damper equivalent wheel parameters				
Inertia	J_d	0.179	$kg\ m^2$	Nominal design
Damping	c_d	0.107	N m s/rad	
Inherent wire boom damper parameter				
Wire damping	c_b	0.64	N m s/rad	Nominal value

† Note, these values are for Probe-A, since all the cases examined were from Probe-A.

4. Spacecraft Dynamics and Mode Shapes

As noted earlier, the two pairs of wire booms dominate the spacecraft dynamics. Each boom has two degrees of freedom as it is free to oscillate about the attachment point. Along with the six degrees of freedom for the hub and three for the dampers, the system has seventeen degrees of freedom.

References [7, 8, 9] discuss the spacecraft dynamics and the resulting mode shapes in detail. Reference [7] develops, from first principles, the nonlinear equations describing the motion of the spinning spacecraft with long tethered booms. The nonlinear equations are intractable for simplified analysis and to get a qualitative understanding of the dynamics, the nonlinear equations were linearized. The linearized equations naturally separate the dynamics into two regimes—out-of-plane dynamics ([8]) and spin-plane dynamics ([9]). The former includes re-orientation maneuvers and the latter boom deployment, spin up/down, and ΔV maneuvers.

The spacecraft dynamics can be described with the concept of mode shapes. This is a carry over from a linearized model of the dynamics. Each mode shape is described by activation of certain degrees of freedom while other degrees do not participate. The relative degree of participation for each degree of freedom is fixed in each mode. As an example, consider the "spin-ripple" mode, also known as the "clothes-washer" mode, one of the dominant spin-plane modes. In this mode, the central hub's spin rate oscillates, while the wire booms lag behind exactly out of phase. This is the only spin-plane mode with active rotation from the hub. The other modes only invoke the wire booms and possibly translation of the hub. Since the only spin measurement is of the hub, this is the only spin-plane mode that is observable from telemetry.

In the out-of-plane dynamics, three modes involve motion of the hub: "mutual precession," "boom nutation," and "hub nutation." These modes should be evident in the sun sensor aspect angle measurement. Since the resolution of the angle measurement is large (0.125°), they are usually not observable, with the exception of precession maneuvers. Of these modes, the mutual-precession mode, where the hub and the wire booms (their tips acting as a plane) precess mutually around each other. This mode is lightly damped and seems to be easily invoked.

Figures 3 (from [9]) and 4 (from [8]) show pictorially the spin-plane and out-of-plane modes, respectively.

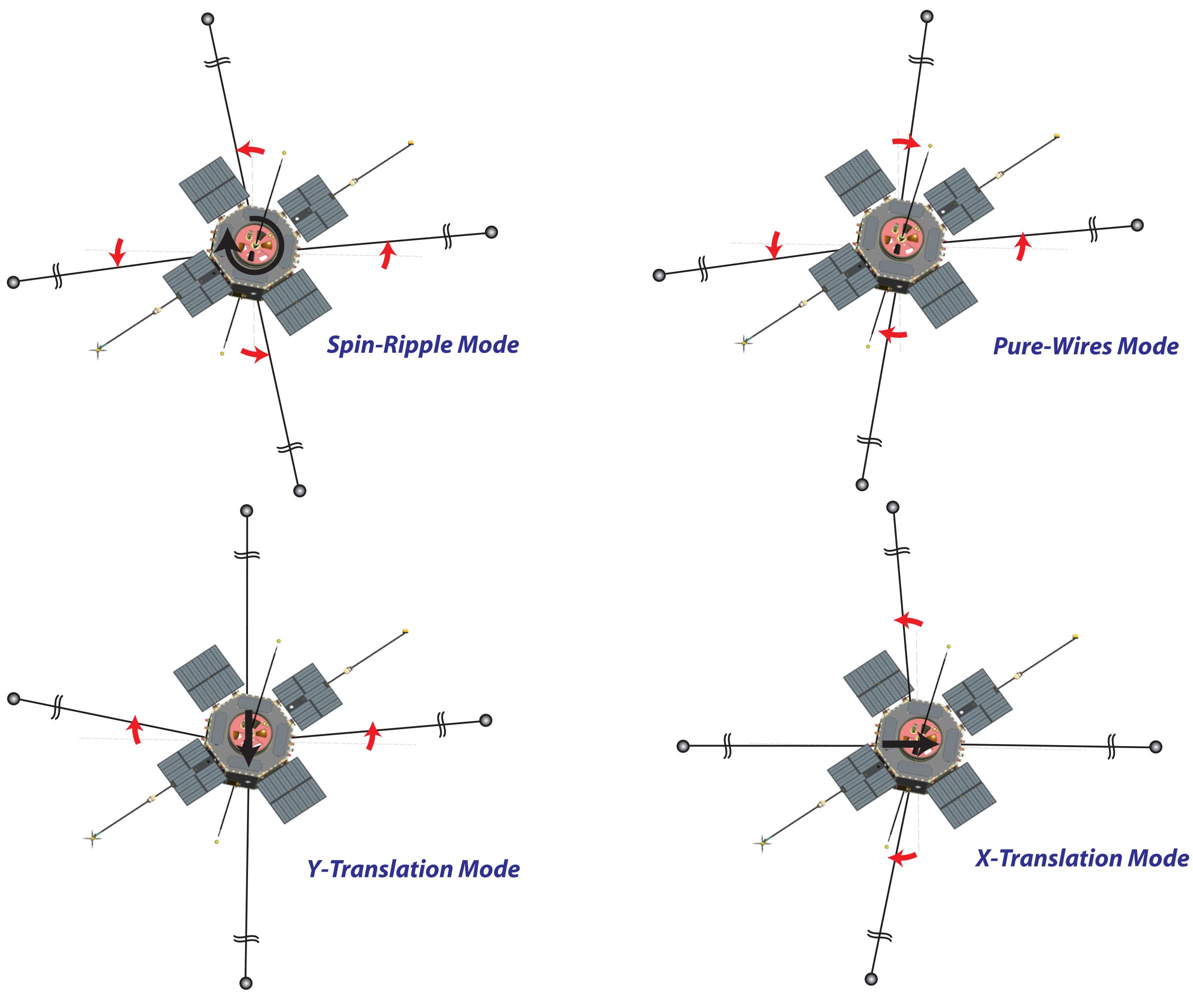

Figure 3. Spin-Plane Modes (from [9])

However, the distinction between spin-plane modes and out-of-plane modes stems from a linearized analysis and in a nonlinear setting, out-of-plane modes "bleed" to spin-plane modes. Also, the sun

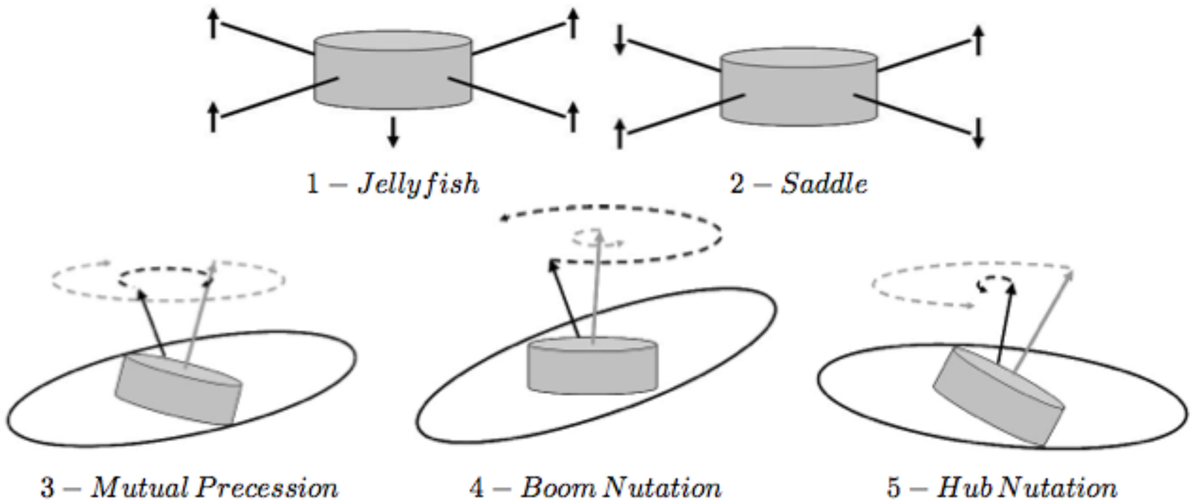

Figure 4. Out-of-Plane Modes (from [8])

sensor is mounted on the hub and is measuring spin rates by clocking sun pulses with the sun about 20° above or below the spin plane. The consequence of this is that the sun sensor spin measurement can catch rotations of the out-of-plane body rates. Hence we see the mutual-precession mode in the spin period. This is also evident in flight data, as will be seen below. The hub-nutation mode also shows up in the spin period measurement; this mode is well damped.

Note that the modes frequency is proportional to the spacecraft spin rate. References [9] and [8] discuss the spin-plane and out-of-plane modes in more detail.

5. Flight Performance Cases

To validate the linear and nonlinear models used to predict the dynamics of the Van Allen Probes, this paper examines several maneuvers on Probe-A and compares the dynamics to those predicted by the models. One example each of several types of maneuvers are considered. Table 2 lists these cases.

5.1. Wire Boom Deployment

Reference [10] describes activities during the commissioning and early operations of the Van Allen Probes. One of the major activities during the commissioning of the spacecraft were the wire-boom deployments. These booms were deployed over a period of nine days. The process involved adjusting the spin rate to account for the spin-down caused by the increasing spacecraft spin inertia as the booms deployed, deploying each pair of booms 5m at a time. As a representative of the dynamics during deployment, one case was examined: the deployment from 40m boom length to 45m. At the start of the maneuver on Probe-A, both pairs of booms had been deployed to 40m. Then, one pair was slowly deployed to 45m. The booms deploy as the wire is released from a rotating spool. The spool turns at a constant rate, so the actual linear deployment rate is not constant. In this case, the deployment rate was about 0.0065 m/s. Table 3 shows the spacecraft parameters relevant to this

Table 2. Cases Examined

Case	Probe	Date	Time	Comments
Wire Boom Deployment	A	2012:267	20:52:00	Final stage of initial wire boom deployment
Spin Down	A	2013:136	14:30:00	One instance on Probe-A that needed a spin down
Eclipse	A	2014:028	05:40:00	Spacecraft dynamics during eclipse
Perigee Pass	A	2013:028	21:54:29	Spacecraft dynamics during a perigee pass (but not in eclipse)
Delta-V Maneuver	A	2013:235	15:40:00	One instance of a probe doing a collision-avoidance maneuver
Precession	A	2012:355	16:00:06	One instance of a spin-axis precession

case.

Table 3. Deployment Details

Parameter	Symbol	Value	Units	Comments
First boom pair length	L_1	40.0	m	Values at deployment initiation
First boom pair tip mass	m_1	0.209	kg	
Second boom pair length	L_2	40.0	m	
Second boom pair tip mass	m_2	0.209	kg	
First boom pair deployment rate	$\dot{L}_i$	~ 0.00635	m/sec	Deployed in pairs
Second boom pair deployment rate	$\dot{L}_i$	0	m/sec	

Figure 5 shows the dynamics of the spacecraft during deployment. The top-left figure shows the spin period obtained from sun sensor data. The light and green line shows the prediction from a linear model from [9]. The linear analysis accurately predicts the behavior of the spin period during deployment. The bottom-left figure shows the oscillation in the spin period by removing the linear trend from the previous figure. Again, it clearly shows that the linear model predicted the deployment dynamics very well.

The pictures on the right show the residual oscillations after the deployment was complete (i.e., both pairs of booms completely deployed). A fast-Fourier transform of the spin period shows two close frequencies (resulting in the beat phenomenon) that damp out in about four hours. A numerical fit to the data confirms the dynamics.

The equations in [9] predict a single "spin-ripple" mode at this frequency. The estimated damping with both the passive and wire damping is about 0.7 hours. The actual data shows a double mode around this frequency with the damping as the same order of magnitude as predicted. It is not clear why the theory predicts a single frequency while the data shows a close double frequency.

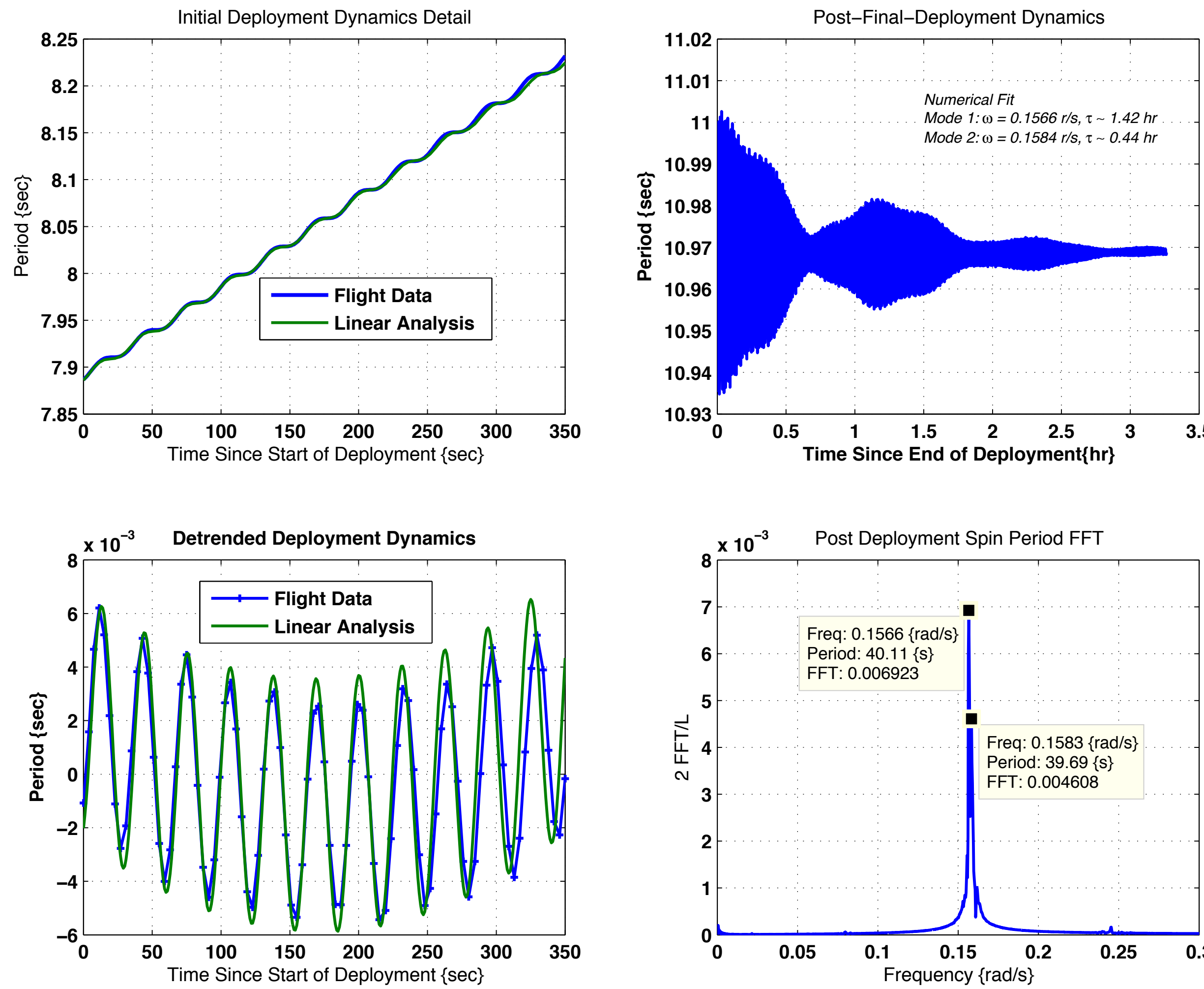

Figure 5. Dynamics During Wire-Boom Deployment

5.2. Spin-Down Maneuver

During normal operations, the Van Allen Probes rarely need a spin-adjust maneuver. However, Probe-A requires a spin-down maneuver about once a year to keep the spin rate within the required 5.5 ± 0.25 rpm. This is due some slight misalignment in the thruster set that increases the spin rate slightly during precession maneuvers. Probe-B does not exhibit this behavior, as the thrusters seem to be better aligned.

This affords an excellent opportunity to examine the dynamics during spin-up/down. Figure 6 shows the dynamics during the spin-down maneuver. The top-left figure shows the entire process, with the actual thrusting period highlighted. The figure on the top-right side shows the maneuver in detail compared with predictions. It is seen that the linear model predicts the dynamics during spin-down very well. The figure in the bottom-left corner shows the spin period oscillations (i.e., the oscillations with the linear trend removed) of the spacecraft during deployment. A fast-Fourier transform of the de-trended data shows three dominant modes, and this is confirmed by the curve fit. The spin-ripple mode is seen here as well and at about the expected frequency and damping.

One of the modes, at about 0.022 rad/sec, is the "mutual-precession" mode described in [8]. This is a very-lightly damped mode that persists over several hours. Note that as can be seen in the top-left figure, this was present before the maneuver started, and is not strictly caused by the spin-down maneuver. The second mode appears to be the "hub-nutation" mode. As discussed earlier, these out-of-plane modes "bleed" into the spin period measurement and are thus observable.

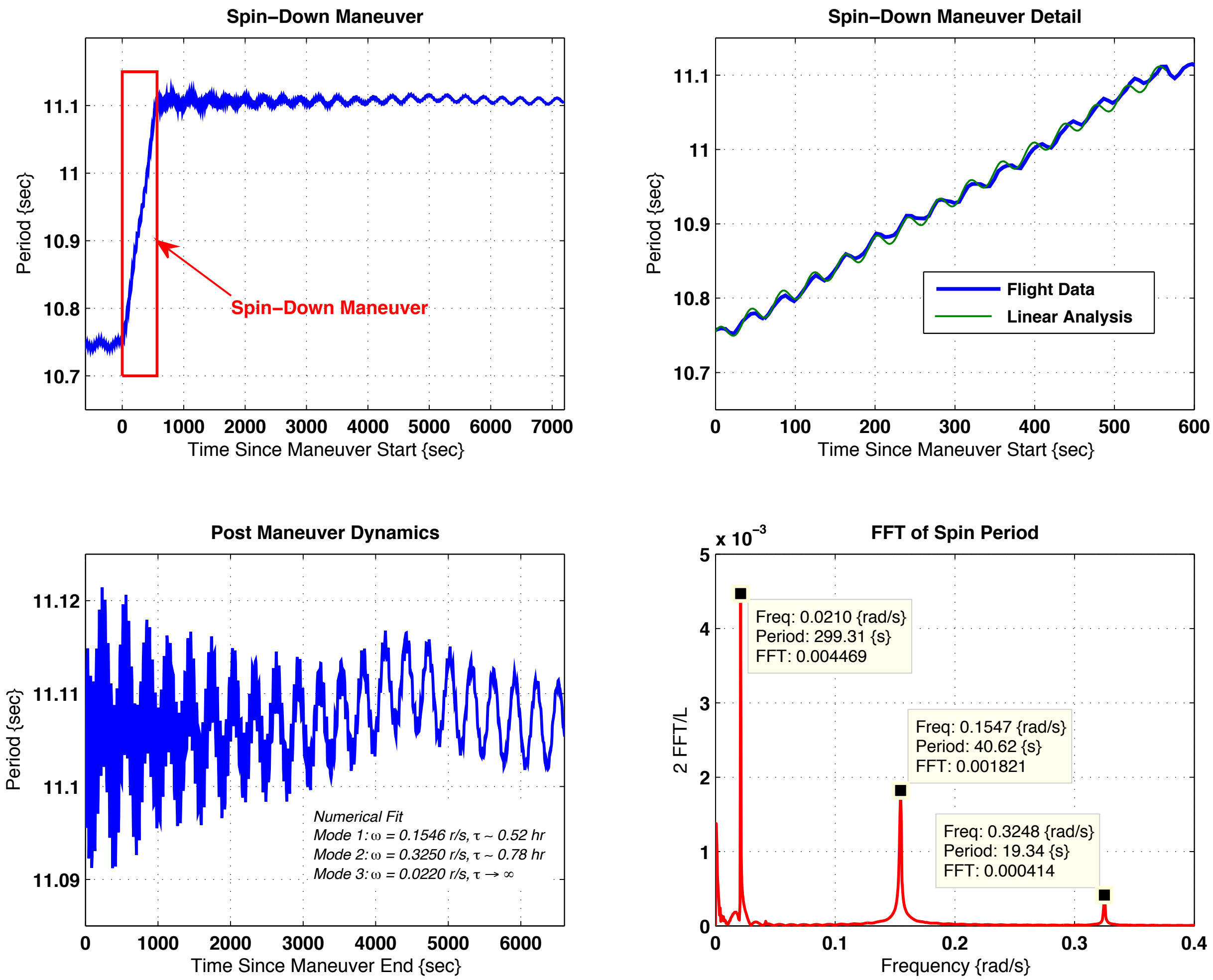

Figure 6. Spin-Down Maneuver

5.3. Spacecraft Behavior During a Perigee Pass

During a perigee pass, Earth's albedo heats the wire booms which cause them to expand. Before launch, the coefficient of expansion of the wire booms was thought to be very small. However, as the spacecraft goes through perigee, when the geometry relative to the sun is right, the booms heat up and expand, the total spacecraft inertia increases, and cause a noticeable change in the spin period.

Figure 7 show the dynamics of the Van Allen Probes during a perigee pass. Note that since the sun sensors do not provide any data during an eclipse, for the purposes of this paper, a non-eclipse perigee pass was chosen.

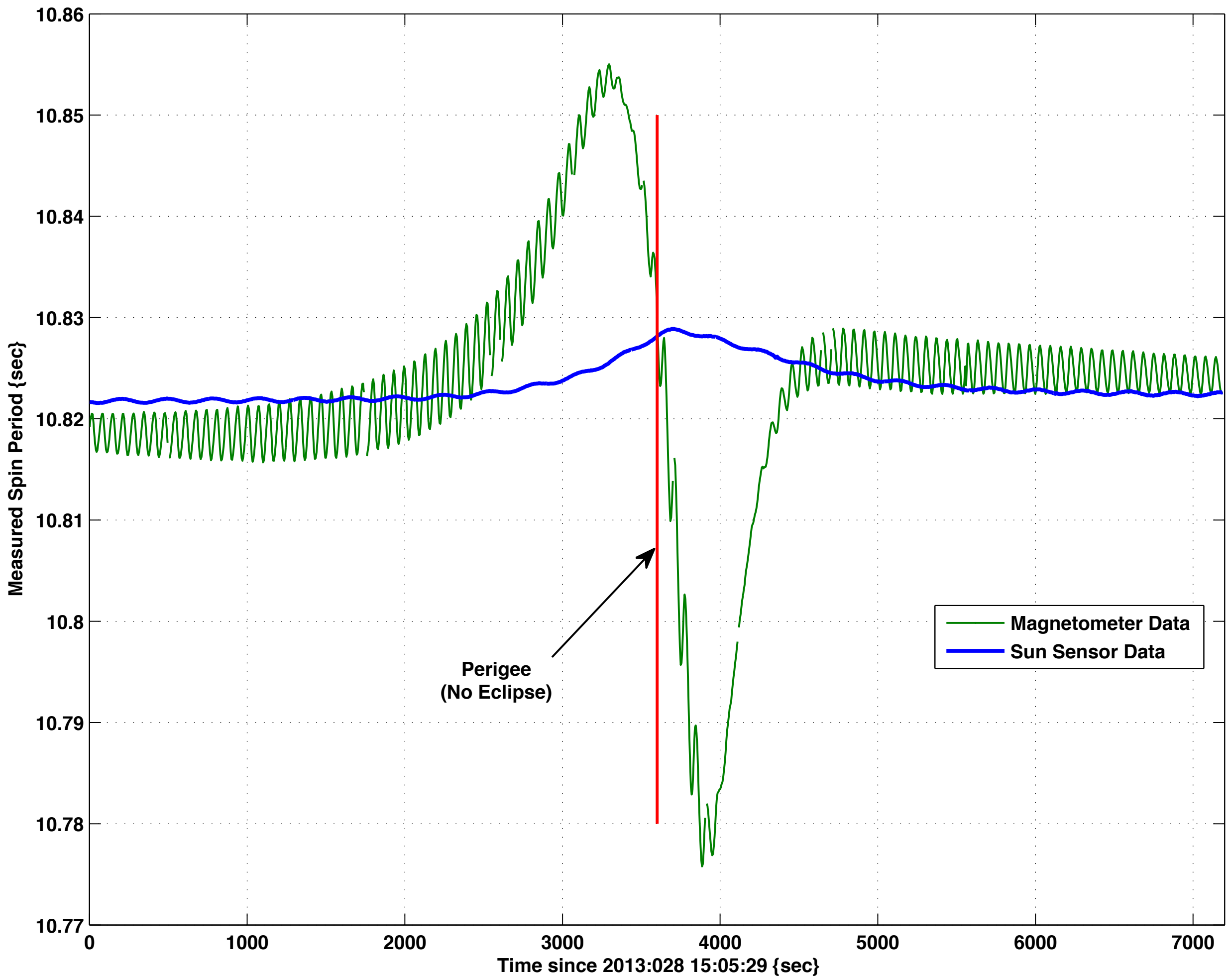

Figure 7. Spacecraft Dynamics During a Perigee Pass

The Earth's albedo in this pass changes the spacecraft spin period by less than 0.01 sec. However, the sun sensor pulse function is sensitive enough to pick this up. The figure also shows the spin rate derived from the fluxgate magnetometer in the EMFISIS instrument. Two things are evident: the magnetic field derived spin rate is not accurate near perigee, and the magnetometer derived spin rate has a high frequency content (around 60-second period) that is not present in the dynamics of the spacecraft. The sun sensor data also shows the obiquitous low-damped mutual-precession mode.

5.4. Spacecraft Behavior During an Eclipse

When the spacecraft goes through an eclipse an opposite phenomenon to the albedo-warm up takes place. During eclipse, the spacecraft cools down and causes the wire booms to shrink. This amount of shrinkage was not expected before flight since it was generally thought that the coefficient of thermal expansion of the wire booms was very small.

Figure 8 shows the spin rate change of the Van Allen Probes during an eclipse. Of course, during the eclipse, the sun sensor does not put out data. The fluxgate magnetometer derived spin rate is superposed on the sun-sensor derived data. However, the magnetometer data cannot be used to determine the actual spin period during eclipse, as was seen in the perigee case. The magnetometer data shows the spin period increasing just before eclipse (as though the spacecraft was being heated by albedo); however the "gold-standard" sun sensor data shows that this is not the case. This again confirms that the magnetometer data can not be directly used to discern spin rate changes.

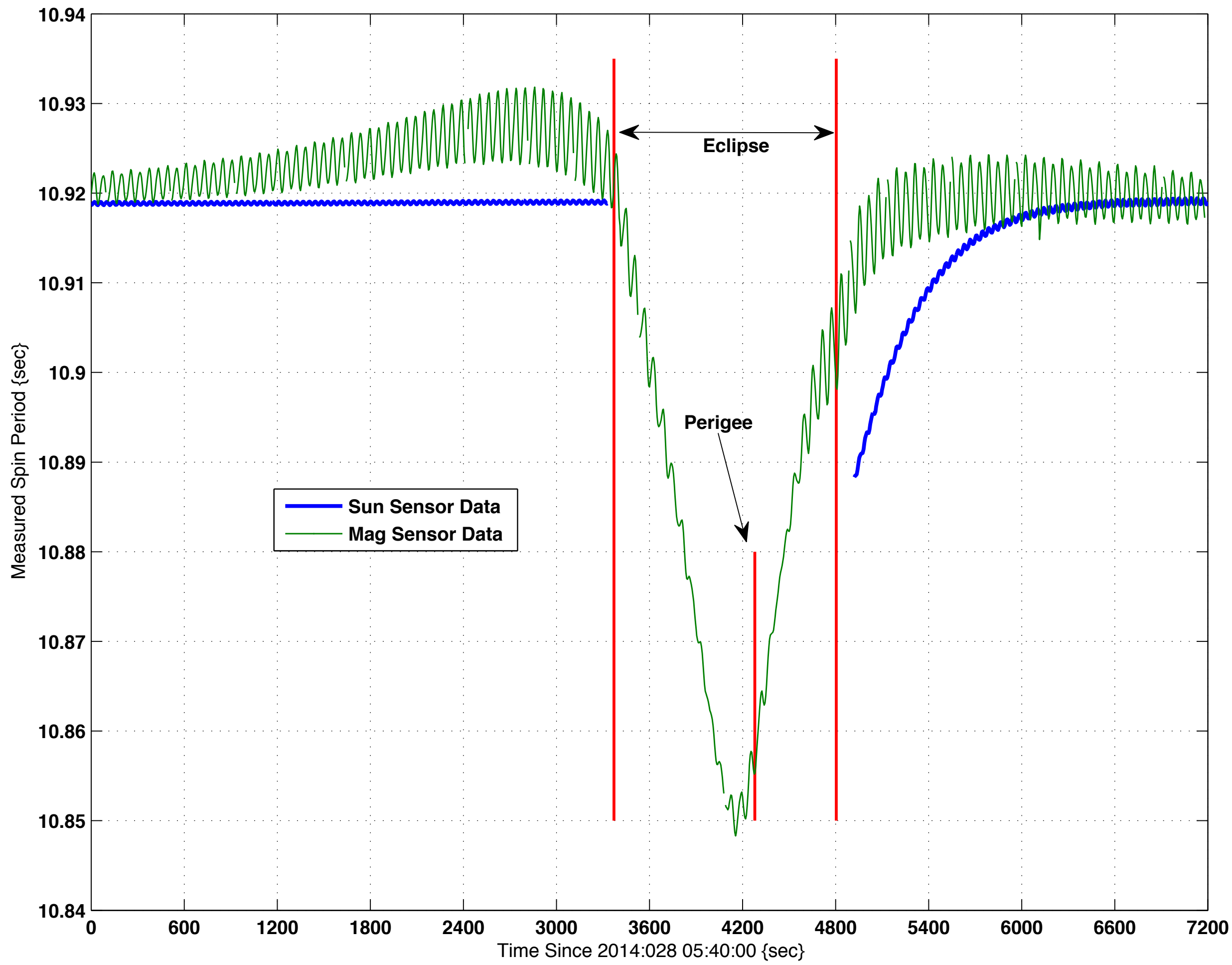

Figure 8. Spacecraft Dynamics During an Eclipse

5.5. Delta-V Maneuver

In nominal operation, the Van Allen Probes do not use a Δ-V maneuver as there is no requirement to adjust the orbit. The only exceptions are the de-orbiting maneuvers at the end of the mission, and an occasional collision-avoidance maneuver to evade asteroids or space debris. Probe-A performed one such maneuver to avoid debris from a Long March 4 launch vehicle.[3]

[3] 26200 CZ-4 debris from a Long March 4 launch vehicle dating back to 04 Oct 1999. The predicted closest approach distance was $\sim$406 m.

Figure 9 show the dynamics of the Van Allen Probes during a short Δ-V maneuver. Just as the theory predicts ([9]), the sun sensor does not register the maneuver. Only the hub rectilinear motion and the boom motion are evoked. Neither is overtly or indirectly observable.

Curiously, the magnetometer data shows considerable animation during and after the maneuver. It is perhaps due to the oscillation of the magnetometer boom excited by the force due to the thruster.

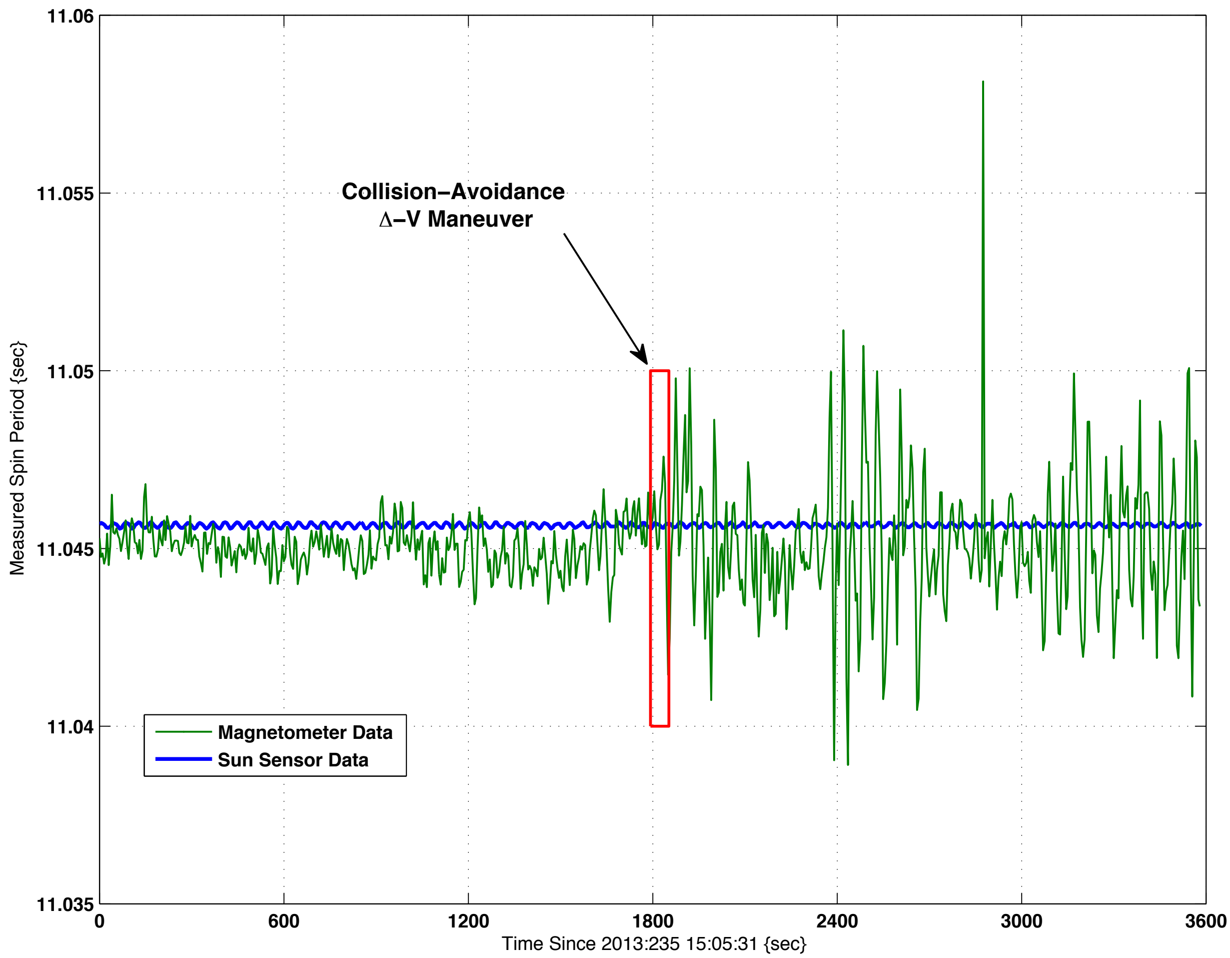

Figure 9. Spacecraft Dynamics During a Collision-Avoidance Maneuver

5.6. Precession Maneuver

The Van Allen Probes have a requirement to keep the spin axis between 17° and 27° of the sun. As the Earth revolves around the sun at about a degree per day, the probes have to precess the spin axis about every three weeks or so. Twice a year, each spacecraft does a north-to-south precession to keep the top deck of the spacecraft pointed at the sun. The spacecraft executes a rhumb-line precession by firing a thruster torquer pulse after a fixed delay after a sun pulse.

Figure 10 shows the dynamics of the Van Allen Probes during and after a typical precession maneuver. The top-left figure shows the sun-sensor measured spin period during the maneuver. Two of the out-of-plane modes described in [8] are in evidence: the mutual-precession mode (around

0.0215 rad/sec) and the precession mode (0.33 rad/sec). The former, as discussed earlier, is very lightly damped, and the latter has a damping time constant of about 0.6 hr. These are as predicted by the models of [8]. The lower-left figure shows the sun angle during the maneuver. As can be seen, the resolution of the sun angle is very coarse for the purpose of this paper. The right-hand side shows the dynamics after maneuver is complete. Again, the same two modes are in evidence. The fast-Fourier transform shows the two frequencies. The curve-fit confirms these modes both during precession and after the maneuver.

One of the modes at about 0.0215 rad/sec is the "mutual-precession" mode, as discussed earlier and as described in [8]. This is a very-lightly damped mode that persists over several hours. The second mode appears is the "hub-nutation" mode. Again, as discussed earlier, these out-of-plane modes "bleed" into the spin period measurement and are thus visible.

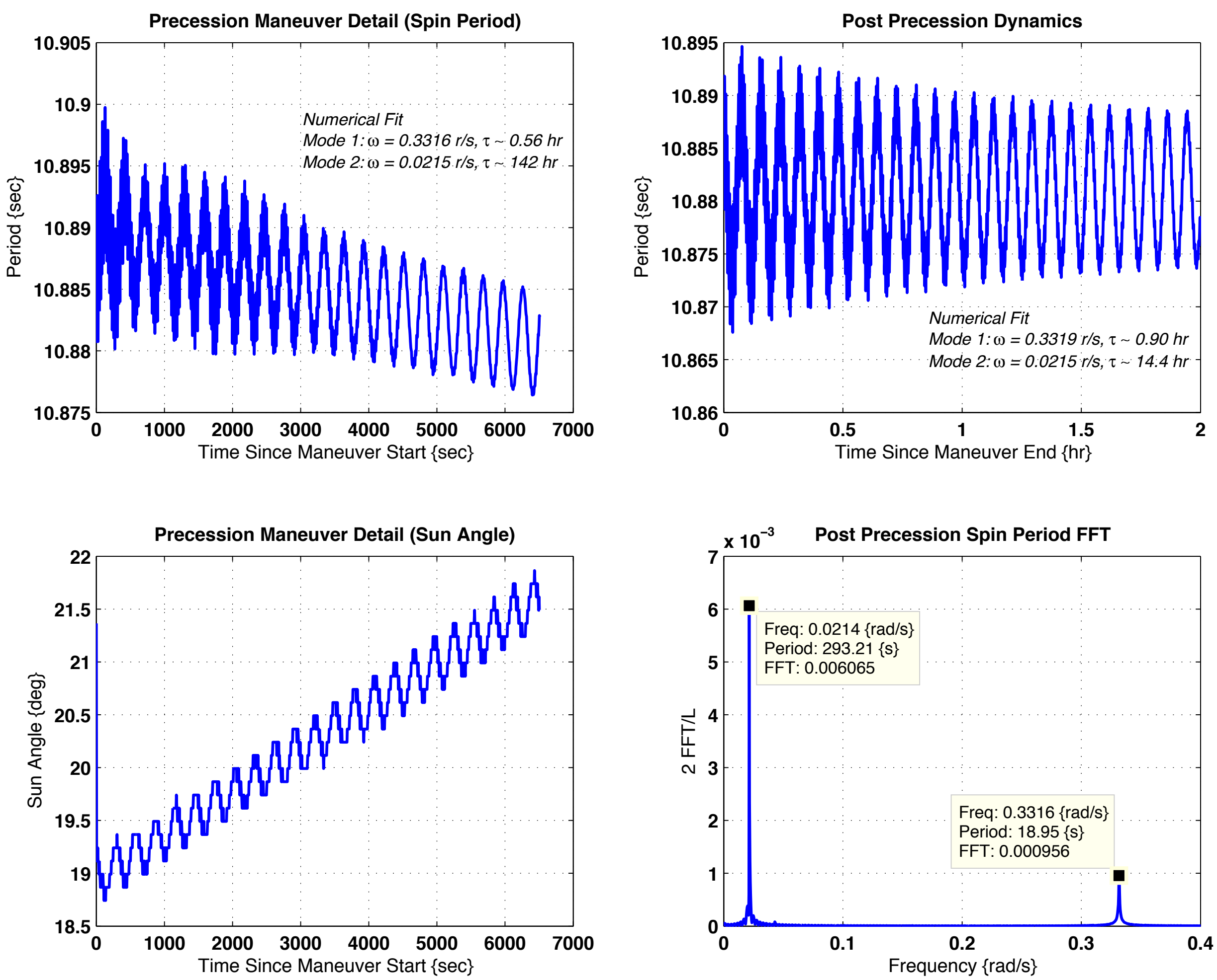

Figure 10. Spacecraft Dynamics During and After a Precession Maneuver

6. Conclusions

The Van Allen Probes spacecraft dynamics is heavily impacted by the EFW booms. The linearized equations of motion for the deployed system predicted the motion correctly. The linearized equations predicted most of the dynamics during boom deployment, spin-down, and precession. Not much could be verified of the Δ-V maneuver, other than the fact that the spin rate did not change, exactly as predicted. During perigee and eclipses, the spacecraft exhibits all signs of warming up and cooling down, respectively. However, during an eclipse, it is not known the extent to which the booms cool down and the spacecraft speeds up.

Acknowledgments

This work was sponsored by NASA under contract NAS5-01072/12.

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