SPACE TECHNOLOGY 5 POST-LAUNCH GROUND ATTITUDE ESTIMATION EXPERIENCE

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Abstract

The Space Technology (ST)-5 satellites were launched March 22, 2006 on a Pegasus XL launch vehicle into a Sun-synchronous orbit. The three micro-satellites which constituted the ST-5 mission were kept in a formation which allowed three successive measurements taken of the Earth's magnetic field in order to study short term fluctuations of the field. The attitude of each satellite was computed on the ground using data from the science grade magnetometer as well as the miniature spinning Sun sensor (MSSS) which was the primary attitude sensor. Attitude and orbit maneuvers were performed using a single axial cold gas thruster. This paper describes the ground attitude estimation process and performance as well as anomaly resolutions.

Introduction

Space Technology (ST)-5 was launched on March 22, 2006 at 9:03:52 am EST using a Pegasus XL launch vehicle from the Vandenberg Air Force Base launch site. ST-5 consisted of three 25 kg and 53 cm diameter spinning micro-satellites named 155, 094, and 224. Each satellite was in a 301 x 4570 km Sun-synchronous orbit with a 105.6 degree inclination. The satellites were flown in a formation within this orbital plane. The science mission was to study the Earth's inner magnetosphere and its interaction with the solar wind. The mission officially ended June 30, 2006 after completing a 90 day science collection period. In addition to the science mission, the spacecraft tested several engineering technologies including a Cold Gas Micro Thruster (CGMT), Miniature magnetometer, Miniature spinning Sun sensor (MSSS), and a passive nutation damper. The sensor complement for each spacecraft consisted of the miniature magnetometer and the MSSS. The actuator complement consisted of a single axial CGMT which was used for attitude and orbit maneuvers and the nutation damper. Upon deployment of the magnetometer boom, the spin rates for 155, 094, and 224 respectively were -115, -164, and -111 degrees/second about the +z-axis. The spacecraft attitude estimation was performed on the ground with a requirement of 1 degree (3-σ). The remainder of this paper will address the ground attitude determination system, attitude determination performance, anomalies, and conclusions.

Ground Attitude Determination System

The ST-5 ground attitude estimation was accomplished using the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) Multi-Mission Spin-Axis Stabilized Spacecraft (MSASS) system. This system is MATLAB® based and was hosted on a Windows PC using a 3.2 GHz Xeon processor. A second PC was available as a backup, though it was shared with a mission analysis machine and unavailable most of the time.

The high level architecture of MSASS is shown in Figure 1. This system has been used by various missions including POLAR, WIND, and IMAGE. ST-5 was the first mission which utilized the new Extended Kalman Filter (EKF) called spinKF[1] and the first mission which performed attitude estimation using only a Sun sensor and magnetometer. The new EKF, spinKF, estimates a set of Markley variables[2]. The Markley variable filter is based on the spacecraft (SC) angular momentum which slowly varies. These slowly varying parameters enable the equations of motion to be integrated more accurately which could improve filter performance.

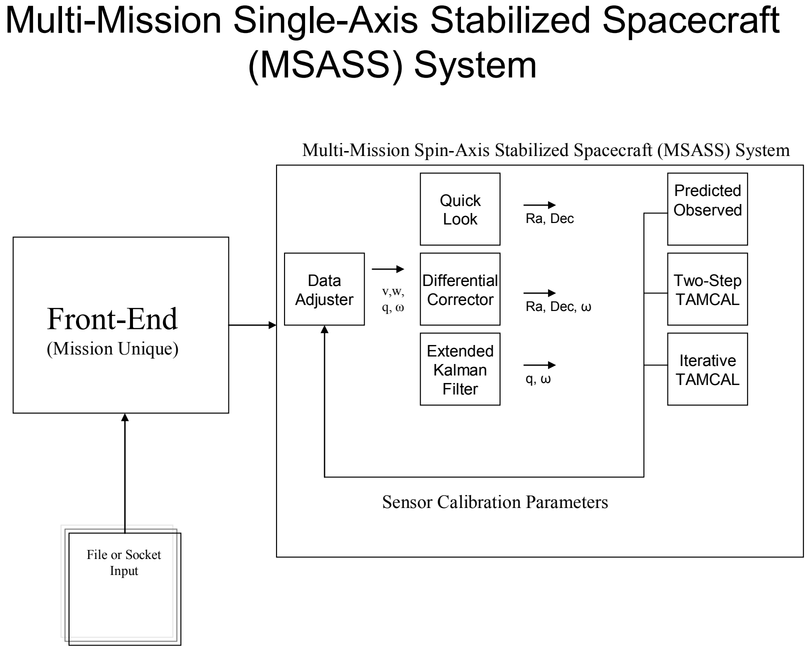

Figure 1: Multi-Mission Spin Axis Stabilized Spacecraft (MSASS) System Architecture

The general flow for attitude estimation consisted of the following steps:

1. Obtain ASCII sequential print telemetry files
2. Load the telemetry into the standard MSASS array format
3. Update estimates of the minimum and maximum spin periods from raw MSSS time-tags
4. Execute Data Adjuster (DA)
    a. MSSS sensor angles compensated for biases and array of Sun vectors in body coordinates generated
    b. MSSS time-tags converted to spin periods and validated
    c. Reference Spacecraft to Sun vectors in Geocentric Inertial (GCI) J2000 computed and associated with body Sun vectors
    d. Magnetometer telemetry is compensated for scale factors, biases, and alignments and transformed to body coordinates

    e. Magnetometer reference data in GCI J2000 computed using the 2005 International Geomagnetic Reference Field (IGRF) model and associated with the body magnetometer vectors
    f. MSSS data were interpolated to magnetometer times and the associated angles between the two observed vectors as well as the angles between the two reference vectors in GCI J2000 were computed
    g. Angle comparison outliers were flagged
    h. The magnitudes of the observed magnetic field and the reference magnetic fields were compared and outliers were flagged
5. Execute the spinKF
    a. Set up start and end times
    b. Compute attitudes and rates
    c. Quality Assure measurement residuals and insure EKF did not diverge
    d. Record attitude and rate estimate

MSASS is designed to be executed either interactively via Graphical User Interface (GUI)s or autonomously via a script. ST-5 attitude support consisted of the following: near-real time attitude estimation post-pass utilizing the GUI option, offline playback processing utilizing automation scripts, sensor calibration, and anomaly resolution.

The near-real time support was performed at least once per day and consisted of attitude and rate estimation for all three spacecraft. After maneuvers, attitude estimation was performed after every pass until the nutation had damped. Figure 2 is a representative example of a spacecraft attitude profile after an orbit maneuver. The time constant for the damper was approximately 60 minutes[4]. In this case, SC 155 performed an attitude maneuver on DOY 096. The efficiency of each attitude maneuver was computed by comparing the attitude solutions immediately after the maneuver with the desired attitude. For orbit maneuvers, the pre-burn attitude was compared to the post-burn attitude.

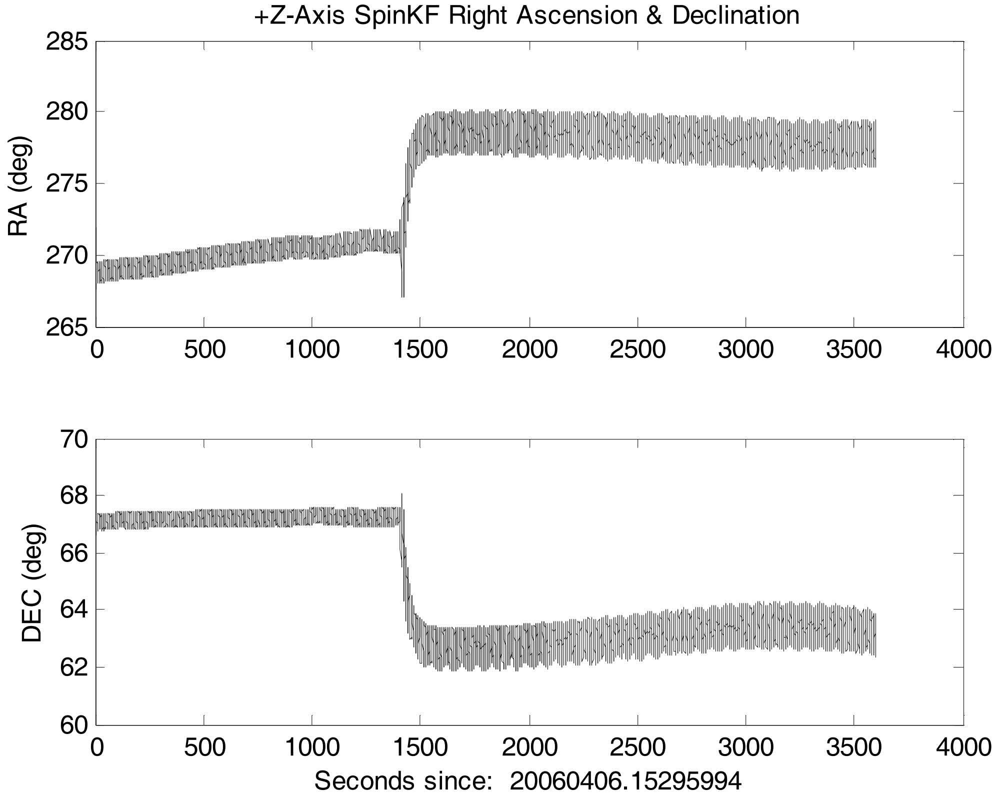

Figure 2: SC 155 Attitude Maneuver Right Ascension and Declination of +Z-Axis

As will be mentioned in more detail later on in the narrative, the playback processing was a particularly troublesome problem. The original plan for processing the playback data consisted of utilizing junior engineers interactively running MSASS. The post-launch anomaly resolution that will be detailed later did not allow for that option. By the time the playback processing was initiated, an automated approach was chosen. The outline of this approach is as follows:

1. PERL script collected the playback sequential print telemetry files every two hours
2. PERL script collected the real-time sequential print telemetry files every two hours (30 minutes after playback PERL script)
3. PERL script collected the Flight Dynamics Facility (FDF) ephemeris files at 1400 local
4. Windows Scheduler starts SC 094 attitude processing at 1830 local
5. Windows Scheduler starts SC 155 attitude processing at 2030 local
6. Windows Scheduler starts SC 224 attitude processing at 2230 local
7. PERL script sends email status message at 0045 local
8. PERL script transmits science files at 0200 local

The schedule was designed to allow problems to be fixed during the day shift of the following day. The attitude estimation automation script was written in MATLAB®. Functionally the following processes were performed:

1. Collect and load in the latest playback telemetry; stop if there is a problem.
2. Output MSSS Sun pulse time file for scientists.
3. Collect the ephemeris file covering the playback data; stop if there is a problem.
4. Execute the DA
5. Perform dot product and magnetometer magnitude checks on the data; stop if there is a problem
6. Find all perigee transit times.
7. Execute the spinKF on 30 minutes of data centered on each perigee times; stop if there is a problem
8. Output Attitude History File (AHF)

Sensor calibration was required to meet the ST-5 attitude knowledge requirement of 1 degree (3-σ). Both MSASS and the Multi-Mission Three-Axis Stabilized Spacecraft (MTASS) system were utilized for sensor calibration. MSASS was utilized for the coarse sensor calibration which consisted of estimating magnetometer time bias which was equivalent to estimating a misalignment between the MSSS and magnetometer in the spin plane. In addition, an attitude independent magnetometer calibration utility utilizing the TWOSTEP[3] algorithm was utilized. The MSASS post-processed MSSS and magnetometer data were then passed to MTASS, which utilized an iterative Three-Axis Magnetometer Calibration (TAMCAL). The Iterative TAMCAL utilized the following steps:

1. Attitude Independent Magnetometer Calibration
2. Adjust the magnetometer data for the attitude independent calibration parameters
3. Execute spinKF using the MSSS and magnetometer data
4. Using the spinKF AHF, execute the Attitude Dependent Alignment Utility.
5. Adjust magnetometer data for estimated relative alignment
6. If the relative alignment has not converged, then return to step 3 using the updated magnetometer relative alignment data from step 5.

Anomaly resolution was the last major function of the attitude ground system. Primarily this functionality was performed using inherent MSASS functionality. However due to the flexibility of MSASS and of using MATLAB®, additional functions and scripts could be quickly configured, as needed, to study the raw and processed telemetry data as well as a variety of intermediate variables. As will be shown in the anomaly section, this capability was heavily utilized.

Ground Attitude Determination System Performance

Due to a variety of anomalies, the attitude estimation for three spacecraft was performed by one person full-time. Anomaly support and daily MSSS Sun crossing time generation was added to the normal attitude estimation support. In the interest of not falling behind processing 24 hour datasets for three spacecraft, the automation scheme was developed in lieu of the manual processing scheme planned pre-launch. In addition a coarse magnetometer sensor calibration was performed which met the science attitude knowledge requirement. Two operations processes were followed. First, get critical data to the Project scientists. Second, work on automating the process in order to have the time to improve the accuracy of attitude estimates.

First, the following steps were required to provide critical spacecraft data to the project and utilized the real-time data:

1. Perform coarse sensor calibration using magnetometer time-tag offset and attitude independent magnetometer calibration. Monitor stability of calibration using dot product checks of MSSS and magnetometer observed and reference vectors as well as magnitude comparison of magnetometer data.
2. Perform attitude and rate estimation for all spacecraft using real-time data nominally once per day. These data were disseminated to Project.
3. Generate and deliver MSSS Sun crossing time file for scientists using playback data.
4. Monitor spacecraft attitude profile and sensor performance.
5. Work on ground attitude automation.

As mentioned before, the automation process was necessary to process the 24 hour playback files in a timely manner. The procedure for automation was as follows:

1. Set up PERL scripts and scheduling for definitive ephemeris and telemetry files that ensured those files were available for evening attitude estimation processing. These files were sometimes not delivered properly and a QA procedure was scripted to catch problems.
2. Set up a MATLAB® automation script that executed MSASS and performed QA after each segment. Stop processing if any QA check was violated.
3. Set up a PERL script to email the automation script diary for each spacecraft.
4. Set up a PERL script to transfer the automation AHF and MSSS Sun crossing times to the science directory.
5. Fine-tune and troubleshoot 1-4 as necessary.

The automation process by itself worked quite well. However, the workload did not sufficiently decrease to fine tune the attitude accuracy as desired due to telemetry file anomalies which will be discussed in the next section.

With the operations procedures discussed, the remainder of this section will discuss the sensor calibration results for each spacecraft and estimates on overall attitude knowledge accuracy. The easiest calibration method consisted of the attitude independent magnetometer calibration utility and the estimation of a magnetometer time-tag offset. The time-tag offset was another mechanism for estimating the relative alignment shift between the MSSS and magnetometer in the spin plane. These methods were utilized using one hour of data for each spacecraft. Another one hour dataset was used for verification purposes. The solved pre- and post-calibration attitude estimation results for SC 094, 155, and 224 are in Tables 1-3 respectively. One measure of the ground attitude estimation accuracy is to convert the 1-σ standard deviations to 3-σ values. Based upon the post-calibration dot-product standard deviation results, the approximate ground attitude knowledge accuracy (3-σ) for SC 095, 155, and 224 relative to the MSSS is 0.460, 0.510, and 0.220 degrees respectively.

Table 1: SC 094 Calibration Results

	Dot Product Mean (deg)	Dot Product Standard Deviation (Deg)	Mag Residuals Mean (mG)	Mag Residuals Standard Deviation (mG)	spinKF MSSS Residuals Mean (deg)	spinKF MSSS Residuals Standard Deviation (deg)	spinKF Mag Resdiuals Mean (deg)	spinKF Mag Residuals Standard Deviation (deg)
Before Calibration	0.046	0.390	-2.92	1.02	0.319	0.390	0.052	0.395
After Calibration	-0.029	0.153	0.03	0.16	0.140	0.178	0.051	0.389

Table 2: SC 155 Calibration Results

	Dot Product Mean (deg)	Dot Product Standard Deviation (Deg)	Mag Residuals Mean (mG)	Mag Residuals Standard Deviation (mG)	spinKF MSSS Residuals Mean (deg)	spinKF MSSS Residuals Standard Deviation (deg)	spinKF Mag Resdiuals Mean (deg)	spinKF Mag Residuals Standard Deviation (deg)
Before Calibration	-0.146	0.814	-2.591	2.259	0.5021	2.300	0.164	0.381
After Calibration	0.003	0.172	-0.004	0.137	0.1641	2.259	0.034	0.241

Table 3: SC 224 Calibration Results

	Dot Product Mean (deg)	Dot Product Standard Deviation (Deg)	Mag Residuals Mean (mG)	Mag Residuals Standard Deviation (mG)	spinKF MSSS Residuals Mean (deg)	spinKF MSSS Residuals Standard Deviation (deg)	spinKF Mag Resdiuals Mean (deg)	spinKF Mag Residuals Standard Deviation (deg)
Before Calibration	0.207	1.451	-1.415	0.830	1.004	1.262	0.033	1.120
After Calibration	-0.007	0.072	0.032	0.130	0.010	0.836	0.011	1.044

Anomalies

The post-launch team was presented with a series of spacecraft anomalies, as is the case with many spacecraft. In the case of ST-5, the anomalies were fairly challenging. The five major anomalies that affected the attitude ground processing are listed below and then described.

1. Orbit Determination (OD) Problems
2. Sensor Time-tag Problems
3. MSSS double Sun pulse
4. Spacecraft Spin Down
5. Playback Sequential Print Problems

The OD problems resulted from problems processing the X-band tracking data. The end result was slowly degraded ephemeris accuracy, degraded real-time passes due to imprecise acquisition data, and loss of playback data. The magnetometer reference field requires a precise ephemeris. Until the tracking data problem was fixed, the ground attitude estimation accuracy was degraded.

The sensor time-tag problem was due to a design flaw with the ground Telemetry and Command (T & C) System and indirectly due to the OD problem. The spacecraft clocks had to be adjusted as soon after separation from the Pegasus as possible. Due to OD problems and the associated acquisition generation errors, the Flight Operations Team (FOT) initially had problems getting clock commands to the spacecraft. The magnetometer reference model is sensitive to time-tag errors as well as ephemeris errors. The result of the time-tag error was the loss of attitude estimation accuracy. The original plan consisted of using a ground-attached time instead of the spacecraft time. However, the T & C system design did not allow the ground-attached times to be output to the telemetry sequential print files. The work-around was to get the start time of the real-time pass, compare this time to the magnetometer time-tag, and calculate a time bias. The FOT was able to set the spacecraft clocks within the first day.

The first real-time pass of any spacecraft is a particularly tense time. For ST-5, the MSSS Sun pulse time data had an unexpected pattern as seen in Figure 3. Instead of outputting one Sun pulse per spin, the MSSS was outputting two Sun pulses (one long and one short) per spin period. The combination of the two pulses was equal to the actual spin period. The actual spin period was verified using the magnetometer data. It was assumed that one of these pulses was the correct pulse. The manufacturer was able to recreate the problem with an engineering MSSS model and the short pulse was determined to be the correct pulse. With these data, the attitude ground system was modified to discard long pulse MSSS data. The problem was due to a signal threshold that was set too low as well as an electronic hysteresis which resulted in more than one Sun pulse per spin period. The low signal threshold allowed stray light to activate the MSSS Sun pulse output. For ST-5, Earth albedo over the Antarctic exceeded the MSSS Sun pulse threshold. There were cases during a given day when the stray light was too weak to set off the MSSS. If you look at Figure 3 again, the correct spin period is seen as a few points between 2 and 2.5 seconds. MSASS had to be modified to look for the short pulse as well as a nominal spin period. The second MSASS modification to MSASS was the creation of an MSSS time-tag file that the scientist would use instead of the MSSS telemetry. This file was critical for science data processing and significant effort was made to calculate the time-tags as precisely as possible with minimal data drop-outs.

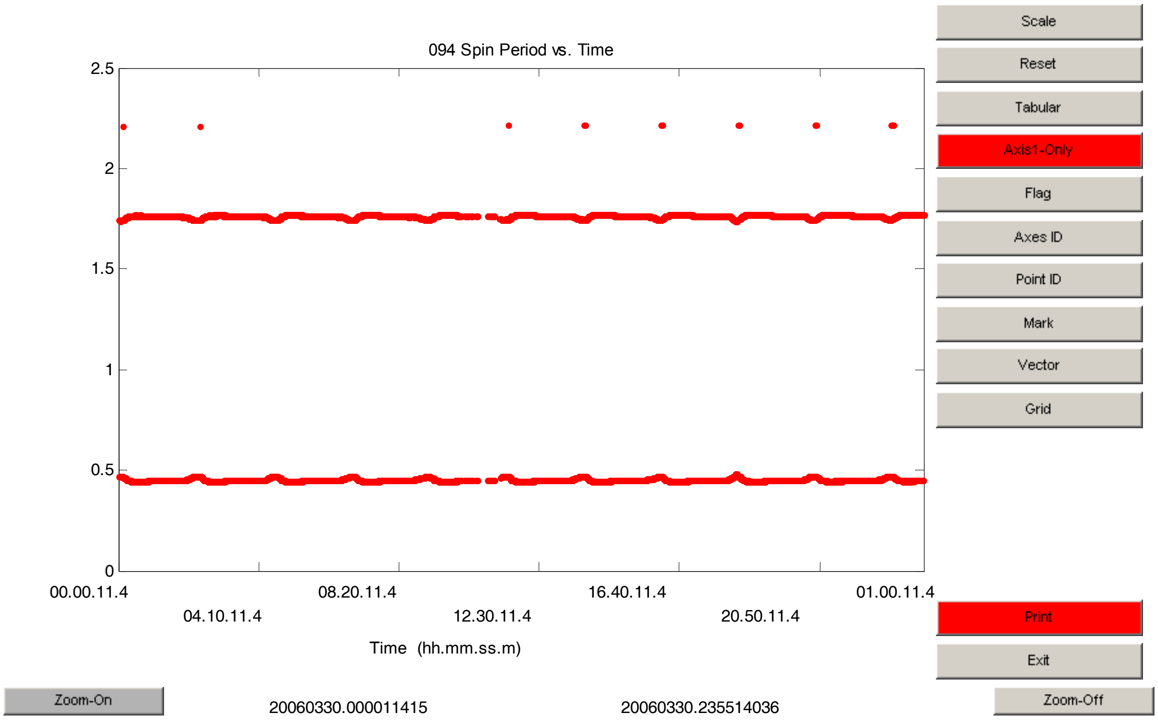

Figure 3: Pre-Processed MSSS Derived Spin Periods in Seconds versus time tag.

The fourth major anomaly was the unexpected spin-down of each spacecraft. A representative 24 hour spin period is shown in Figure 4. Analysis by Guidance, Navigation, and Control (GNC) engineers and consultations with the Project scientist indicated the effect was probably due to the spacecraft's residual magnetic moment and leakage currents interacting with the Earth's magnetic field[4]. The ultimate effect on the spacecraft was minimal due to the short planned mission life. If the mission had been granted an extension, the spin-down would have been a concern depending on the length of the extension. The primary concern with the spin-down was the attitude stability of the spacecraft. From an attitude ground system perspective, the decreasing spin period was a minor nuisance. Namelist parameters existed to determine a reasonable short pulse interval as well as a reasonable spin period range. The spin-down required those parameters to be adjusted periodically throughout the mission life.

The fifth major anomaly was related to the output playback telemetry sequential print files. As mentioned before, the initial playback files were heavily fragmented due to ground station acquisition problems. However after this problem was fixed, the playback sequential print files were still heavily fragmented. The scientists were getting the same files and having the same problem. The FOT was quizzed about the problem and produced a plausible explanation, but no way to fix the problem. The telemetry fragmentation required the MSASS automation scripts to search for suitable contiguous time-spans of MSSS and magnetometer data, which at times was a challenge due to the limited contact times available. Over time, an error was found in the T & C system which was corrected and the sequential prints were re-generated. By that time, the MSASS priority was to compute AHFs for the current data and to re-process all the old MSSS data in order to compute the correct Sun pulse times for the Project scientists.

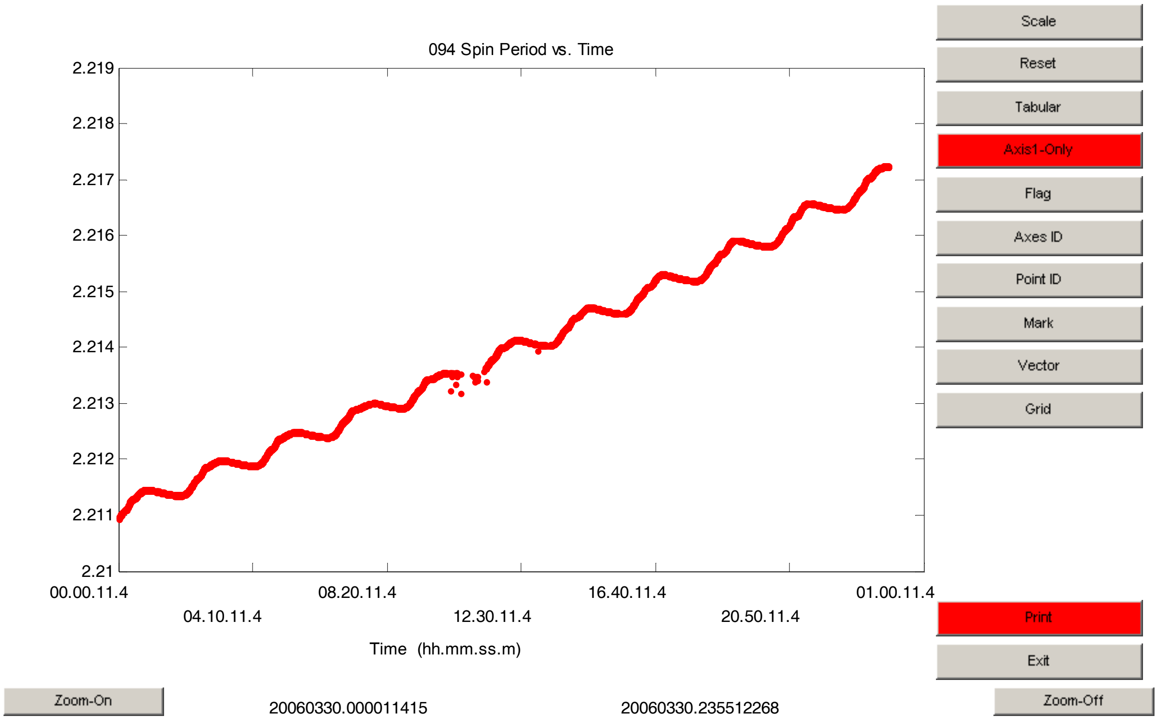

Figure 4: Processed MSSS Spin Periods versus Time define units on Y-axis

Conclusions

ST-5 was the first mission this author supported which involved more than one spacecraft. Shortly before the first real-time contact, the lead flight dynamics analyst requested that the lead attitude analyst would perform the attitude processing for the first two spacecraft and he would take care of the third. This request introduced the lead attitude analyst to the complexity of low cost formation flying. The ST-5 ground attitude determination system as well as the attitude estimation and sensor calibration procedures were outlined as along with the resultant performance. Of the two attitude determination systems, MSASS was the least mature in magnetometer processing. Past spinning spacecraft missions utilized more sophisticated sensors. ST-5 support demonstrated that MSASS was more than capable of supporting missions using a magnetometer as a primary attitude sensor. This capability was further demonstrated on the THEMIS mission which was launched in February 2007.

The primary anomalies affecting the ground attitude estimation were described. In particular:

1. Orbit Determination (OD) Problems
2. Sensor Time-tag Problems
3. MSSS double Sun pulse
4. Spacecraft Spin Down
5. Playback Sequential Print Problems

Each anomaly either was solved or had a work-around developed. Fortunately for ST-5, each probe had the same anomalies. These anomalies had one further effect on the ground attitude estimation. Before launch, the lead flight dynamics analyst and the lead attitude analyst were to share the processing duties with some assistance from junior engineers. After launch, the orbit related anomalies kept the lead flight dynamics analyst busy. In the end, one attitude analyst performed all attitude estimation, sensor calibration, and science product generation for three spacecraft.

The lessons learned on ST-5 include the following:

1. Plan for post-launch anomalies
2. Perform realistic simulations before launch for all mission phases (first ground station contact, playback processing, etc).
3. Attitude determination system and the operators needs to be flexible

Acronyms

ACS	Attitude Control System
AHF	Attitude History File
CGMT	Cold Gas Micro Thruster
DA	Data Adjuster
DEC	Declination
EKF	Extended Kalman Filter
FOT	Flight Operations Team
GCI	Geocentric Inertial
GNC	Guidance, Navigation, and Control
GSFC	Goddard Space Flight Center
GUI	Graphical User Interface
IGRF	International Geopotential Reference Field
MATLAB	Matrix Laboratory
MSASS	Multi-Mission Spin-Axis Stabilized Spacecraft System
MSSS	Miniature Spinning Sun Sensor
MTASS	Multi-Mission Three-Axis Stabilized Spacecraft System
NASA	National Aeronautics and Space Administration
OD	Orbit Determination

QA	Quality Assurance
RA	Right Ascension
SC	Spacecraft
spinKF	Spinner Kalman Filter
ST-5	Space Technology 5
TAM	Three-Axis Magnetometer
TAMCAL	Three-axis Magnetometer Calibration
T&C	Telemetry and Command
THEMIS	Time History of Events and Macroscale Interactions during Substorms

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