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I. Introduction/Summary

A burn was executed on 10/11/00 (day 285) to alter the inclination of the Landsat 7 orbit. To accomplish this, the spacecraft was slewed around its yaw axis 90.75° in order to orient the thrust vector (from its maneuver jets) perpendicular to the velocity vector. Inclination prior to the burn was approximately 98.175°. <u>The predicted change in inclination was to be 0.045 degrees.</u> A total of 42448 cumulative pulses on jets 1-4 were commanded (approximately 19 min 32 sec). Due to off-pulsing of these jets during the burn to control pitch and yaw, the pulses were distributed among the four jets 11184, 11722, 10040, and 9502 respectively. In addition, pulses were commanded on jets 6 and 8 (a total of 78 pulses each). Jets 5, 6, 7, and 8 were used to control the roll axis during the burn. After the burn was completed, the spacecraft was returned to a nominal yaw orientation (via a -90.75° slew). <u>The actual inclination change was 0.0467°.</u> Orbit inclination and Mean Local Node Crossing times from the beginning of normal operations to just after the Delta-i burn are shown in **Figure 1**. The ETM+ cooler door was moved to its “outgas” position to protect the radiative cooler from contaminates and as a mitigation against pointing the cooler at the sun in the event of a loss of attitude control. Closing the door to this position caused several specific elements in the ETM+ to heat past their operational ranges. A 27 hour ETM+ cooldown, with special calibration imaging, followed the slew-burn-slew sequence.

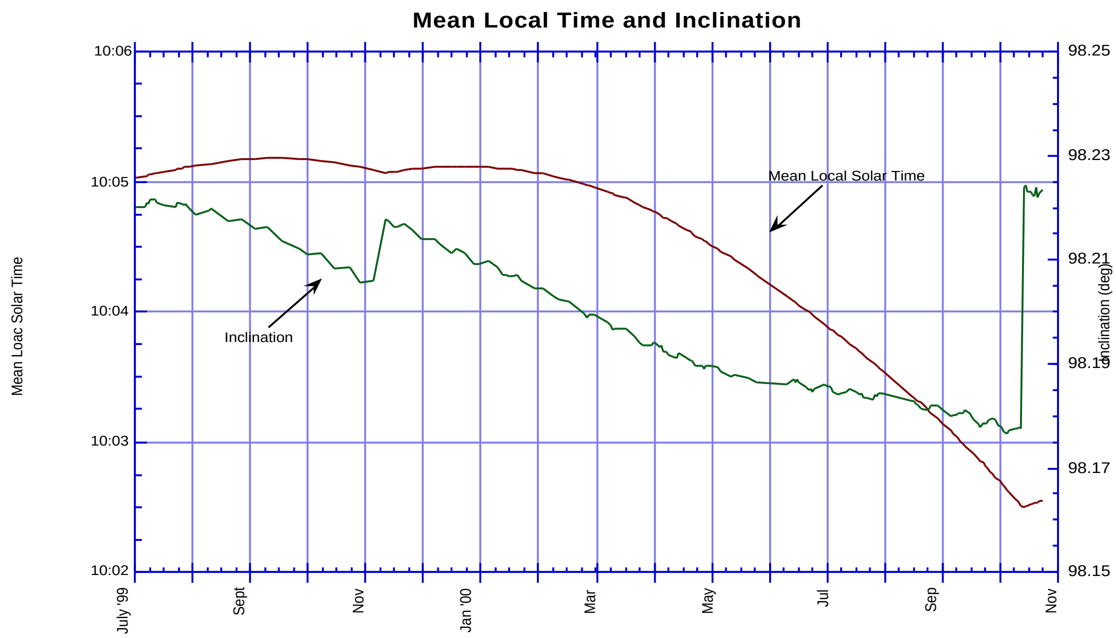


Figure 1 - Mean Local Time Crossing and Inclination

II. Preparation work

Several planning meetings were held and members from NASA, USGS, FOT, Flight Dynamics, LMMS sustaining engineering, and SBRS were involved. Operational plans, timelines (for product delivery and the maneuver itself), and decisions about prepping the spacecraft for the maneuver were all discussed.
Four new items were discussed prior to this delta-i.

1. The LPSO requested that ETM+ imaging be conducted during the cooldown period in an effort to calibrate data at various component temperatures. To accomplish this, a large effort was necessary in the Mission Planning area to ensure that only those images requested were taken (i.e. shut down the Long Term plan), and that these images were downlinked in contacts separate from "science" images still stored on the SSR.

2. The alignment of ACS components. In July 2000 a new alignment matrix was uplinked for the CSA. Alignment numbers for the CSA were measured prior to launch. In an effort to provide similar numbers for the gyros, a series of offset (±10°) slews were conducted in August, 2000. However, failing to reach a clear set of alignment numbers that could be agreed upon by all involved, the uplink of new values was postponed. The initial intent was to update the alignment matrices of the CSA and IMU prior to the delta-i maneuver in order to facilitate a quicker convergence of the precision attitude filter. However, it was decided by the group that the possible gain in uplinking new IMU alignment values was outweighed by the risk of using a set of numbers not agreed to by all parties.

3. The abort limit during maneuver mode was widened for the Pitch and Roll axes. During the 1999 Delta-i, the Roll axis reached an error of –2.6° with all systems performing nominally. It was felt that more margin was desired between "nominal" performance and the abort limit. A new limit of ±5.5° was agreed upon and uplinked prior to the 2000 Delta-i. Plans are to leave the limit at ±5.5° for all future burns.

4. The temporary IMU bias calculated by FSW is placed into housekeeping data as well as PCD. It is conceivable that this value, if large enough, could cause an overflow condition in the routine that places it into PCD. This overflow would halt the SCP. It was unknown how large the IMU tempbias might grow upon beginning the Precision control mode convergence after returning to our normal orientation. It was decided that the scale factor applied to the value would be altered prior to the delta-i sequence to ensure it did not grow too large for FSW to handle. The MOC was temporarily altered to convert the value using the scale factor. After Precision control had been re-established, the scale factor in FSW and the MOC were returned to normal.

In addition, simulations were conducted on LSIM in an effort to characterize what sort of behavior might be seen during the slew/burn/slew sequence. On-orbit experience with the PRADS filter combined with LSIM data and results from a star transit prediction tool were used to draft a clear timeline for regaining precsion attitude control.

Several of the configuration and set-up issues resolved prior to the 1999 Delta-i were followed again:

1. The Delta-i maneuver should take place while the ground track error is a few kilometers "West" of nominal center (i.e. we have a negative WRS error). The burn was certain to add a large eastward drift rate to the error, and in fact, a delta-V maneuver was planned for two days after the Delta-i to take care of the increased drift. The eastward drift is created intentionally using the yaw angle larger than 90° to avoid imparting a westward drift. A westward drift could send the s/c outside of its ±5km WRS requirement with no recourse but to wait for atmospheric drag to lower the orbit in order to reverse the drift. The only other way to reverse westward drift is to perform a retrograde delta-V which involves a 180° yaw slew.

2. Since jets 1-4 were to be used for the burn and we normally only exercise jets 1 and 3 in our delta-V burns, we switched to thruster configuration 7 for the last three delta-V burns prior to the Delta-i burn to gather data on the performance of jets 2 and 4.

3. In previous 4 jet burns, a negative yaw transient had been seen during the burn and was consistent in most burns. In addition, the burn angle was to be biased in order to ensure an *eastward* drift of WRS error after the Delta-i. Adding to these two factors the estimated jet misalignment, and it was decided to increase the nominal 90° yaw slew to 90.75°.

4. It was decided that the Delta-i was to be performed during a descending path. An ascending path was considered because it meant stopping the solar array during a shadow, minimizing power balance effects. This plan was rejected by the group due to solar array cooling concerns. With the array stopped in the 0° position (as it should be during all 4 jet burns), it remains edge on to the Earth, making it to cool faster and deeper than it would if the array were rotating. Using past data, it was determined that the array at the 0° position during an entire shadow period would cool it well into its yellow limit range. Over time Large temperature transients like this could alter the properties of the glue used to bond the solar cells to the substrate. To avoid abnormal temperature transients it was decided to execute the burn during a descending path, in daylight.

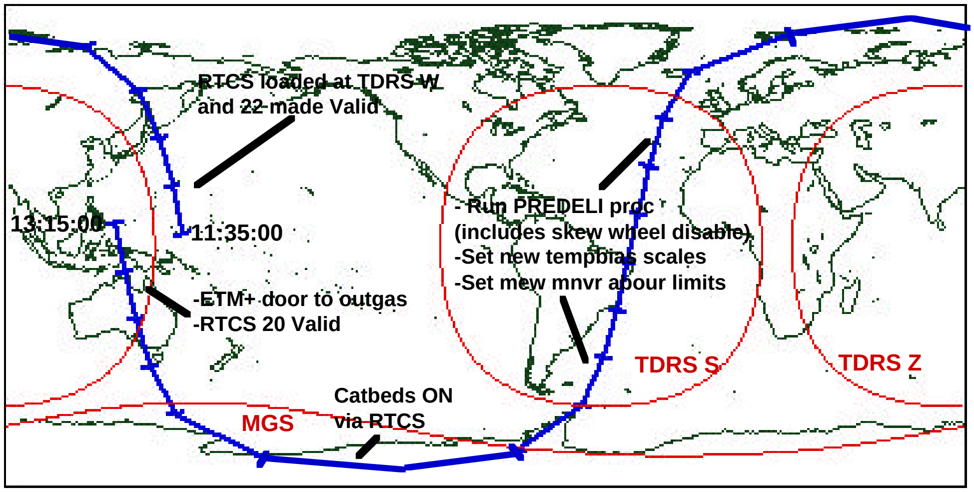
5. The ETM+ cooler door was closed one stop to the Outgas position. This was to protect the cooler door against contamination. A recommendation was made during the post-launch orbit raising maneuvers that burns not executed at a nominal yaw angle should be done with the ETM+ cooler door in the Outgas position. In addition to contamination issues, this ensures the immediate protection of the ETM+ radiative cooler against sun impingement in the event of loss of attitude control. The timeline executed for the 2000 Delta-i allowed the cooler door to remain in the Outgas position for a shorter amount of time than in 1999. This limited heating effects on the Cold Focal Plane (CFPA).

The final effort in preparing for the Delta-i was training. A Delta-i training package was generated for the FOT to give background information on Delta-i maneuvers and our implementation. In addition to this package, dry runs of the entire sequence were executed using the simulator (LSIM) for any personnel that would be present for the actual burn sequence.

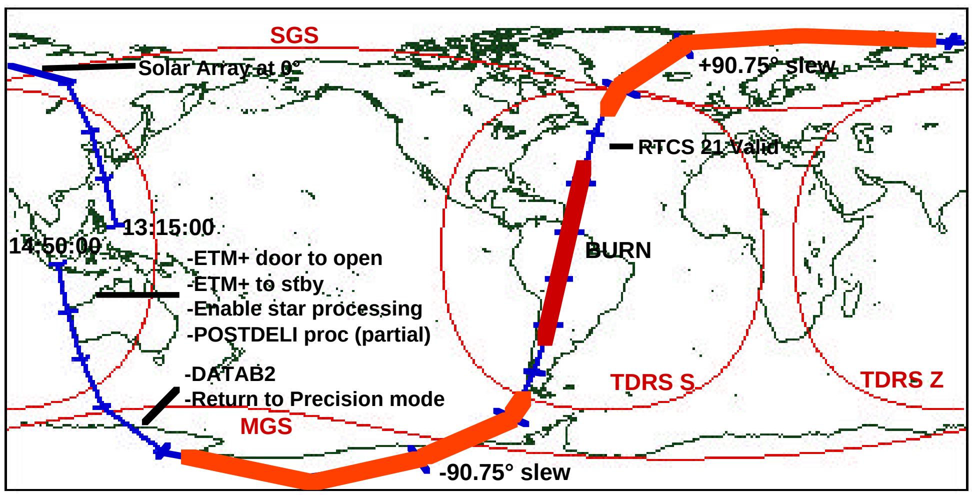
III. Sequence summary, map, and timeline

Below is a high level sequence of planned events over three orbits.

Orbit 7935



Orbit 7936



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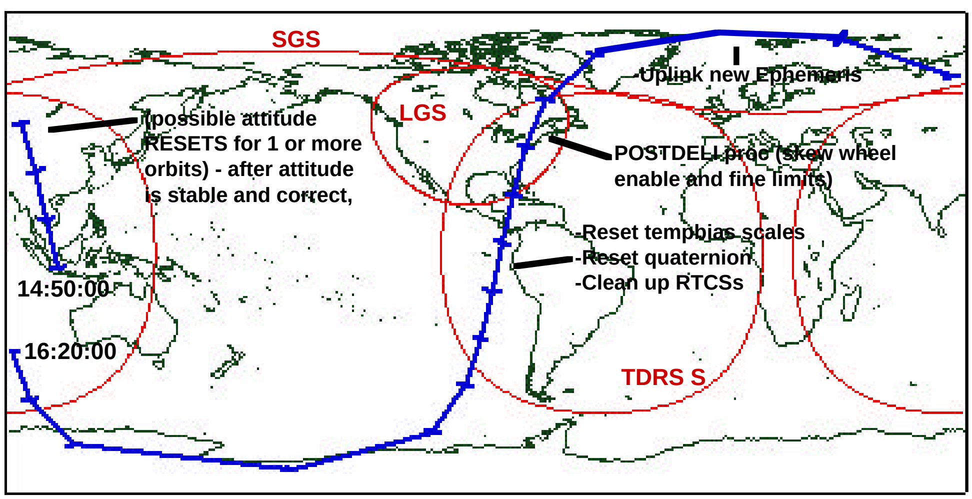

Delta-i #2 Report (October 2000)

Following is a timeline of events as executed. Appendix A contains a more detailed events listing. **All times in this report are GMT.**

Delta-i sequence summary (as performed)

285-12:12:04.9	Skew wheel = DISABLED
285-12:33:00.0	Skew wheel reaches 0 RPM
285-12:14:07.4	TEMPBIAS scale changed to x'0020'
285-12:16:32.6	Abort limits changed to +/- 5° on SCP 1
285-12:18:40.4	Abort limits changed to +/- 5° on SCP 2
285-12:52:42.2	Prime/Redundant Catbeds ON
285-13:05:54.5	ETM+ cooler door at OUTGAS
285-13:16:33.8	Solar Array to Open Loop, Slew Fwd
285-13:23:45.8	Solar Array to Cmd Position, 0 deg
285-13:30:22.0	Solar Array slows to FAST
285-13:31:23.0	Solar Array at Index position
285-13:35:04.3	entered DATAB_1 state
285-13:35:38.2	entered SLEW state
285-13:48:00.0	Yaw slew Ends
285-13:52:44.3	Burn Starts; RTCS 21 = ACTIVE
285-14:12:16.9	Burn Ends; ACS mode = Precision
285-14:17:40.0	Yaw slew starts
285-14:29:30.0	Yaw slew ends
285-14:30:04.6	Entered DATAB_2 state
285-14:30:50.3	entered PRECISION state
285-14:31:11.2	Enable Star processing
285-14:31:50.9	Solar array in Ephemeris mode
285-14:42:52.0	ETM+ cooler door in Open position
285-14:44:46.0	Full Reset of PRADS filter
285-14:48:26.6	ETM+ in STBY mode
285-14:49:08.0	CFPA htr DISABLED
285-14:49:26.3	Blackbody htr DISABLED
285-14:49:48.9	Baffle htr DISABLED
285-14:52:44.4	Prime/Redundant Catbed htrs OFF
285-15:14:14.5	Post-burn Ephemeris uplink complete
285-15:19:06.9	Skew wheel = ENABLED
285-15:20:13.3	ACS limits = FINE
285-15:25:17.5	PRADS filter converged
285-15:28:18.1	Reset TEMPBIAS scale values
285-15:43:29.6	entered DATAB 1
285-15:46:20.0	Reset Slew Quaternion
285-15:46:51.8	entered DATAB 2 state
286-01:24:02.5	Blackbody htr ENABLED
286-01:24:37.9	Blackbody T3 selected
286-09:42:19.7	Baffle htr ENABLED
286-17:47:29.1	CFPA htr ENABLED

IV. Spacecraft performance

Overall, the spacecraft performed as expected during the entire sequence. Below is a breakdown of different areas of spacecraft performance.

ACS Performance

Skew Wheel Spindown/Spinup

During long thruster firings, as a precaution to abnormal jet firing, an additional safety margin in system momentum unloading capacity is sought which will keep the total spacecraft momentum from building up beyond the saturation limits of the Reaction Wheel Assembly (RWA). This additional safety margin is achieved by "spinning down" the skew wheel prior to the Delta-i's long thruster firing sequence. The spin down consists of disabling the spacecraft's skew reaction wheel bias within Flight Software (FSW) which has the affect of driving all the wheels toward 0 RPM.

While the FSW was operating in the PRECISION ACS submode, the skew wheel was spun down toward 0 RPM starting from its nominally biased value of 1922 RPM. The operation started at 2000/285-12:12:04 and ended at 2000/285-12:32:28. The total spin down time was 20 minutes 24 seconds, which was slightly outside the 20 minute TDS contact that had been scheduled. Upon removal of the skew speed bias ALL wheels headed toward 0 RPM. In 1999 the skew spin down started from a lower RPM setting (1272 RPM) and completed in approximately 13 minutes. However, the rate of spin down in 1999 and 2000 were unchanged, at approximately 100 RPM/minute. **Figure 2** shows a nominal speed profile of ALL 4 wheels during and several minutes after the skew spin down.

<u>Note: In general, the ACS section uses the subscripts (0), (1), and (2) to represent the Roll, Pitch and Yaw axis, respectively, in the spacecraft navigation frame; the subscript (4) is used for the skew "axis".</u>

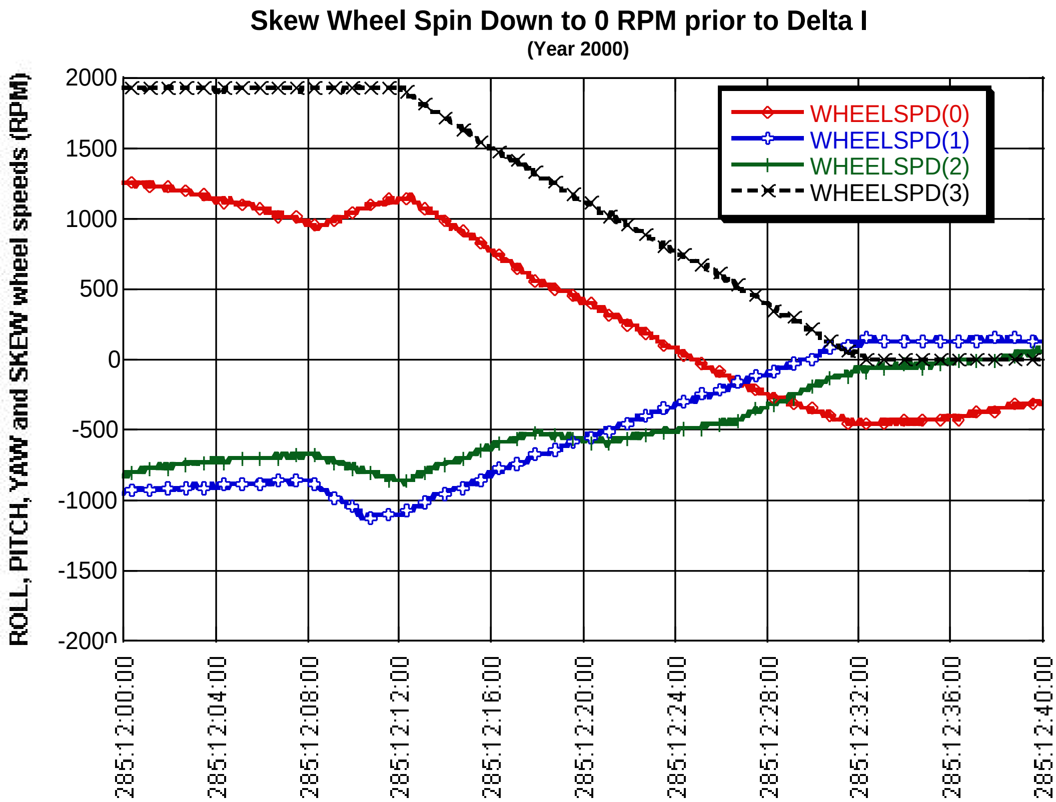

Figure 2 – Skew Wheel Spin down to 0 RPM prior to "Slew-Burn-Slew"

Upon completion of the Delta-i sequence, the Skew wheel bias was reapplied. Starting from 0 RPM, the skew wheel achieved its nominal bias 2 minutes 10 seconds after command execution and a steady state had been reached within 10 minutes 38 seconds. At this time, all wheel speeds were safely driven away from 0 RPM and as had been the case prior to the Delta-i, nominal friction levels were reestablished. **Figure 3** shows wheel speeds during skew wheel spin up during 1999 and 2000.

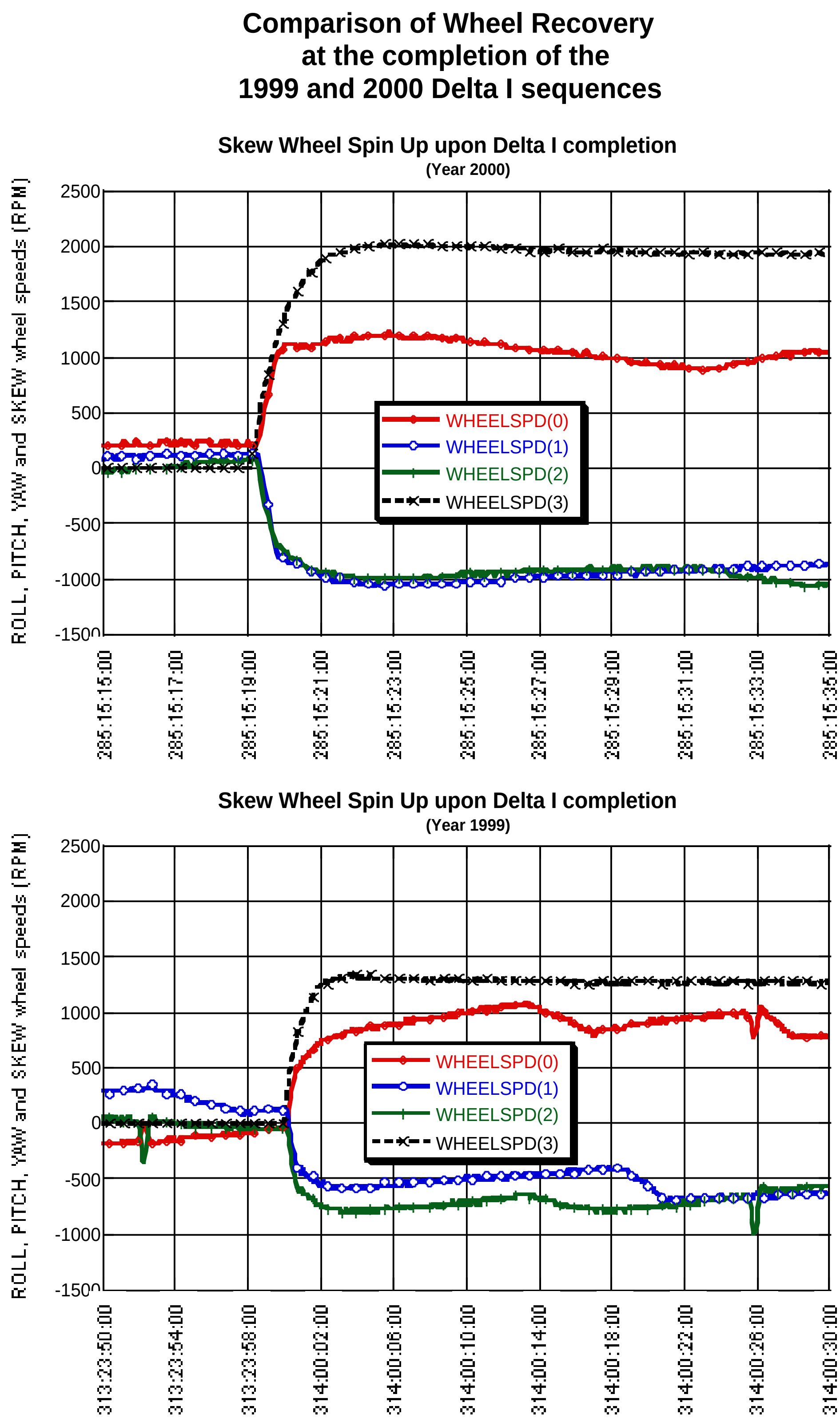

Figure 3 – Skew Wheel Spin up after "Slew-Burn-Slew"

During the spin down, the spacecraft attitude and rate signals remained in a nearly unperturbed state. **Figures 4** and **5** depict very steady state attitude and rate errors within the PRECISION control law, with the exception of the transients observed at spin down start and stop. As expected, the Yaw axis had the most stable attitude response during spin down, as it is the axis with the greatest inertia. Meanwhile, Pitch and Roll attitude response signatures were slightly more pronounced at the spin down start and stop points. Roll having the least inertia and Pitch carrying orbit rate were most perturbed during these times; of these, pitch yielded the greatest error though it never exceeded ±0.013 degrees. On all axes, attitude perturbations were settled within 2 minutes of the response start. Rate error response was less eventful and **Figure 5** shows tight control during spin down. Though Roll rate seems to be the least behaved of all, its control is still approximately within ±0.003 degrees per second and well within specification. The other two axes demonstrate less rate error but their signatures seem “noisier”. This is explained by Flight Software (FSW) clamping very small numbers to 0 in telemetry, in order to avoid a computer underflow condition during on board telemetry compression.

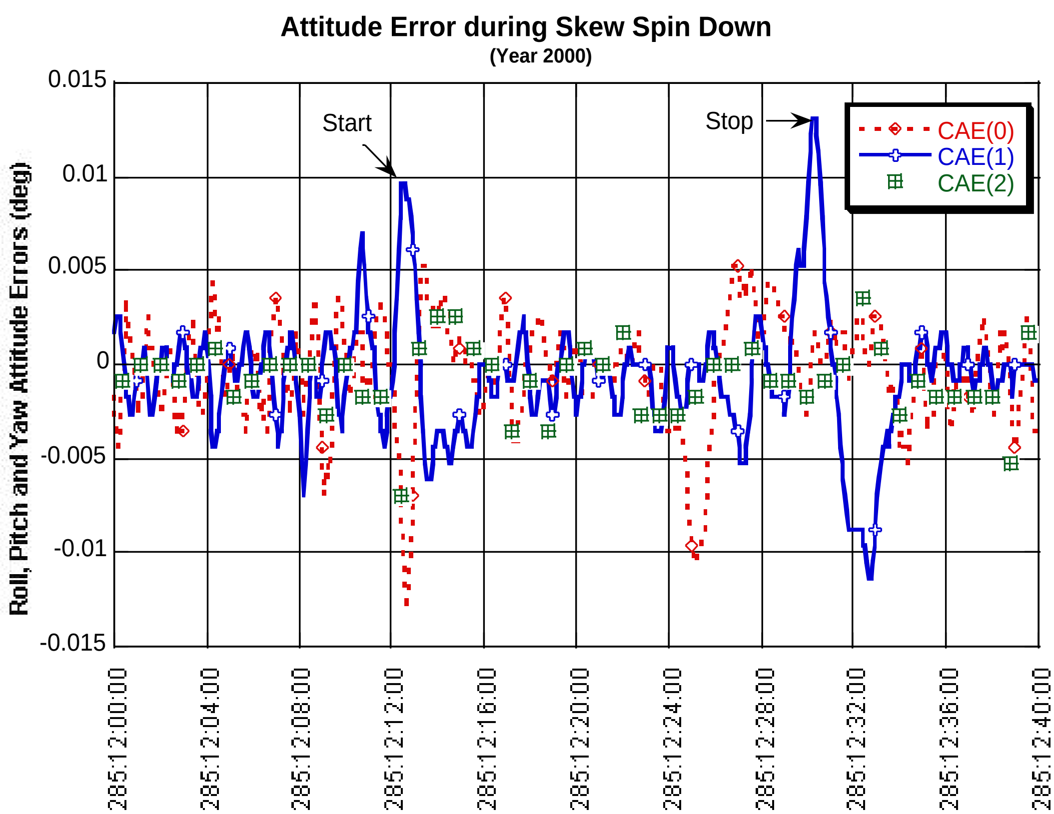

Figure 4 – Attitude Error during Skew Spin down

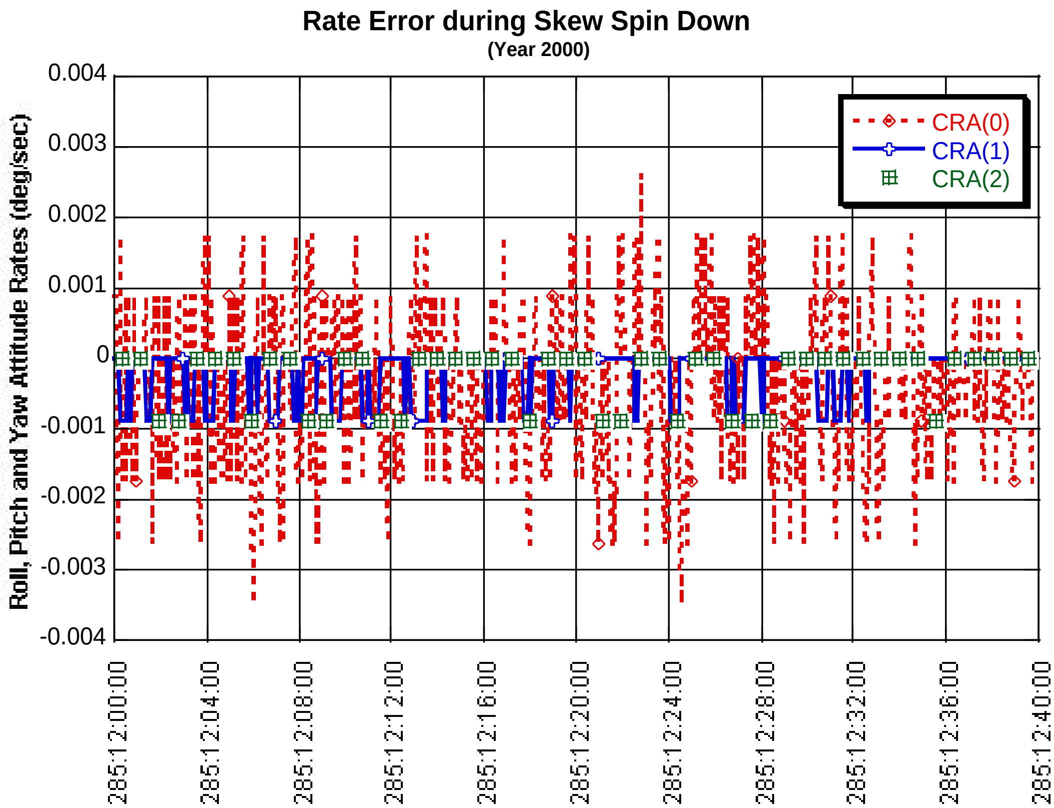

Figure 5 – Rate Error during Skew Spin down

The operation of spinning the skew wheel down is accomplished by disabling the torque commands sent by the FSW to the skew wheel. **Figure 6** shows the effect of commanding zero torque on the skew wheel. Upon skew spin down, the effect on the remaining wheels amounts to very fine adjustments to the wheel torque commands for Roll, Pitch and Yaw. As the saturated torque command is equivalent to ±256 counts, in all instances the wheels were very gently commanded to their new settings at a fraction (±20 counts) of the maximum torque capacity. After the spin down completes, the Roll torque is inverted and the Pitch and Yaw torques are hovering about null. This profile is also highlighted by the wheel speeds in **Figure 2** and further supported by **Figure 7**, which represents the current wheel friction as computed by FSW. **Figures 8** and **9** show wheel friction during skew wheel spin up.

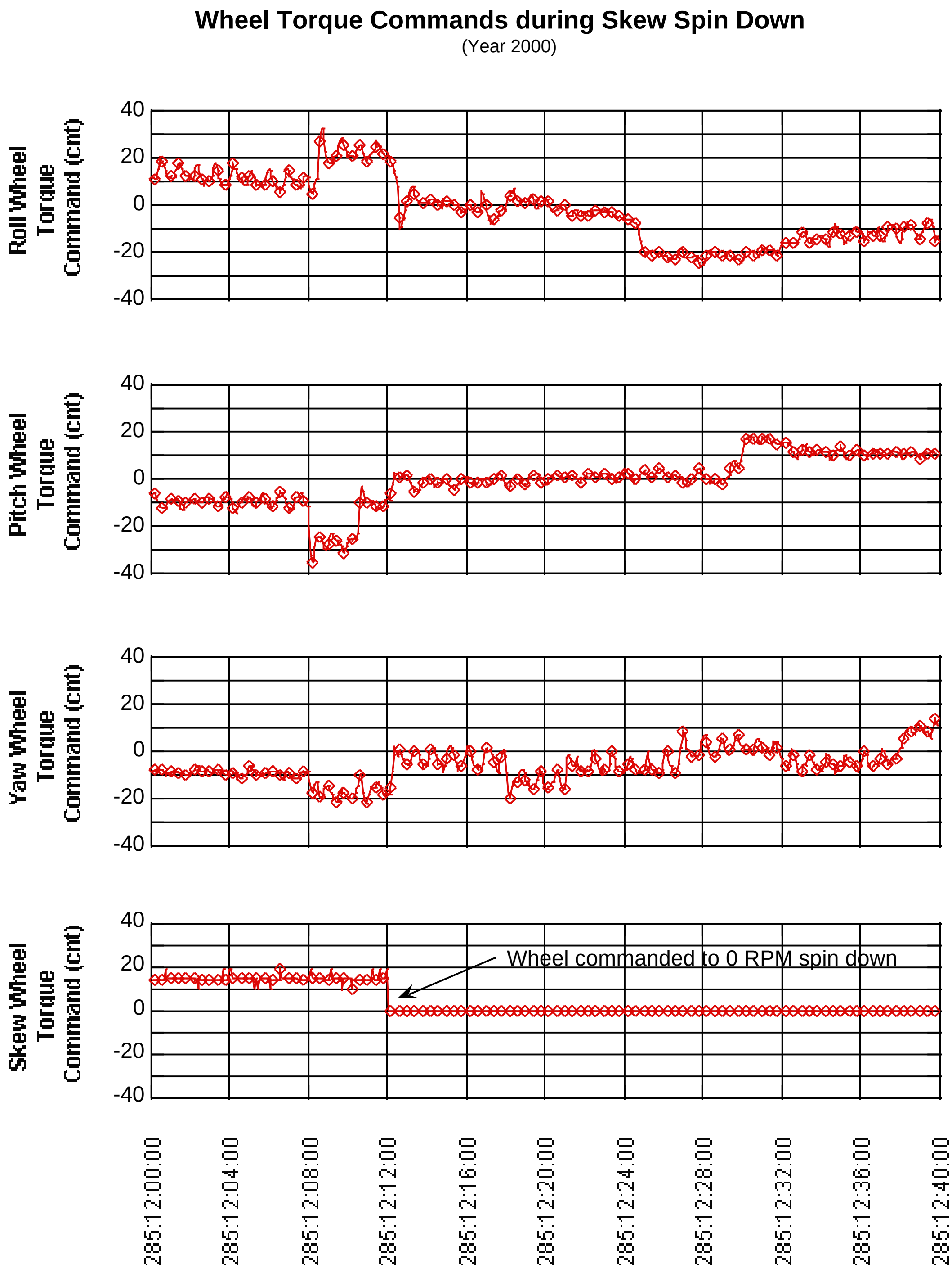

Figure 6 – Wheel Torque Commands during Skew Spin down

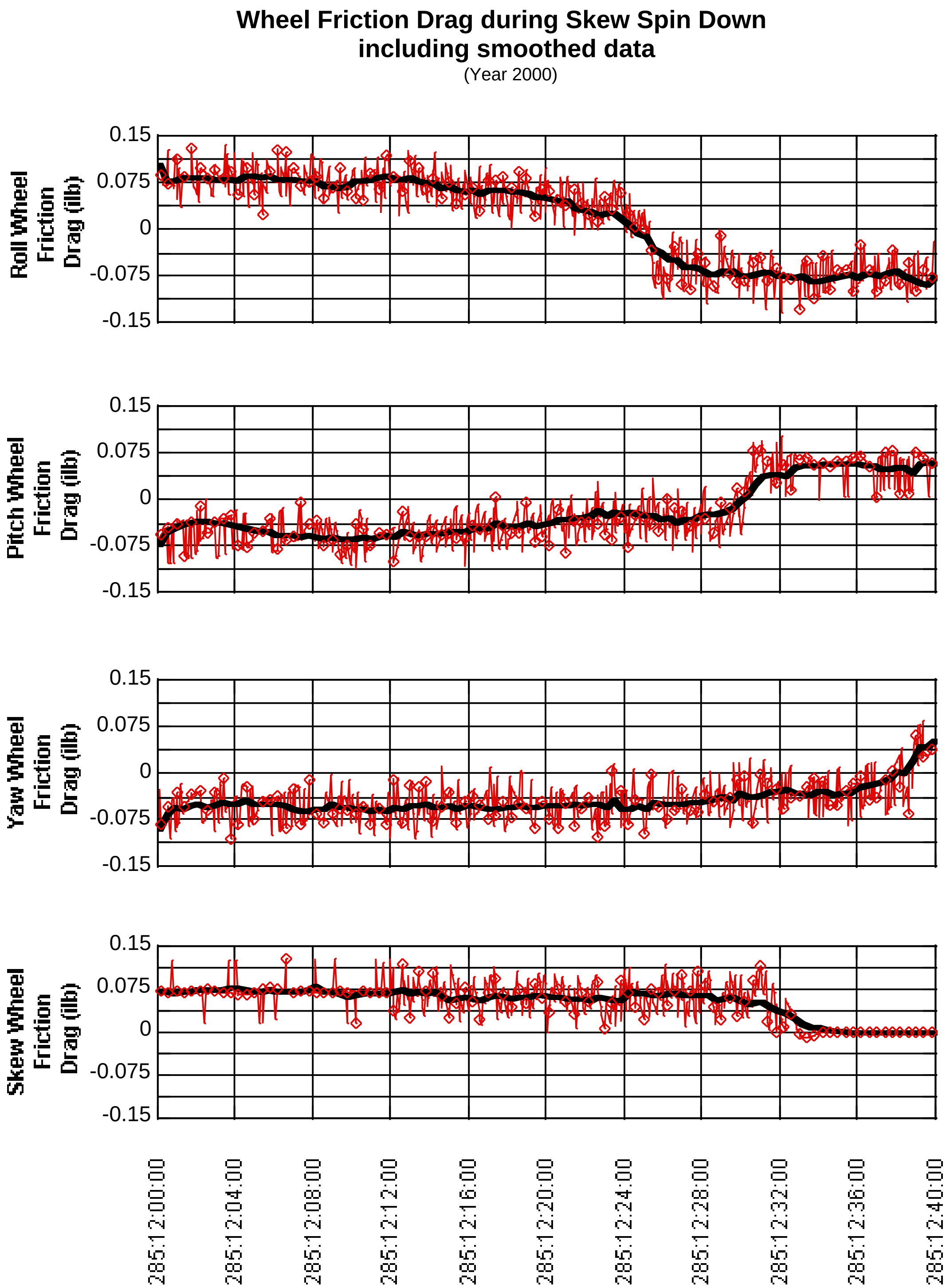

Figure 7 – Wheel Drag during Skew Spin down

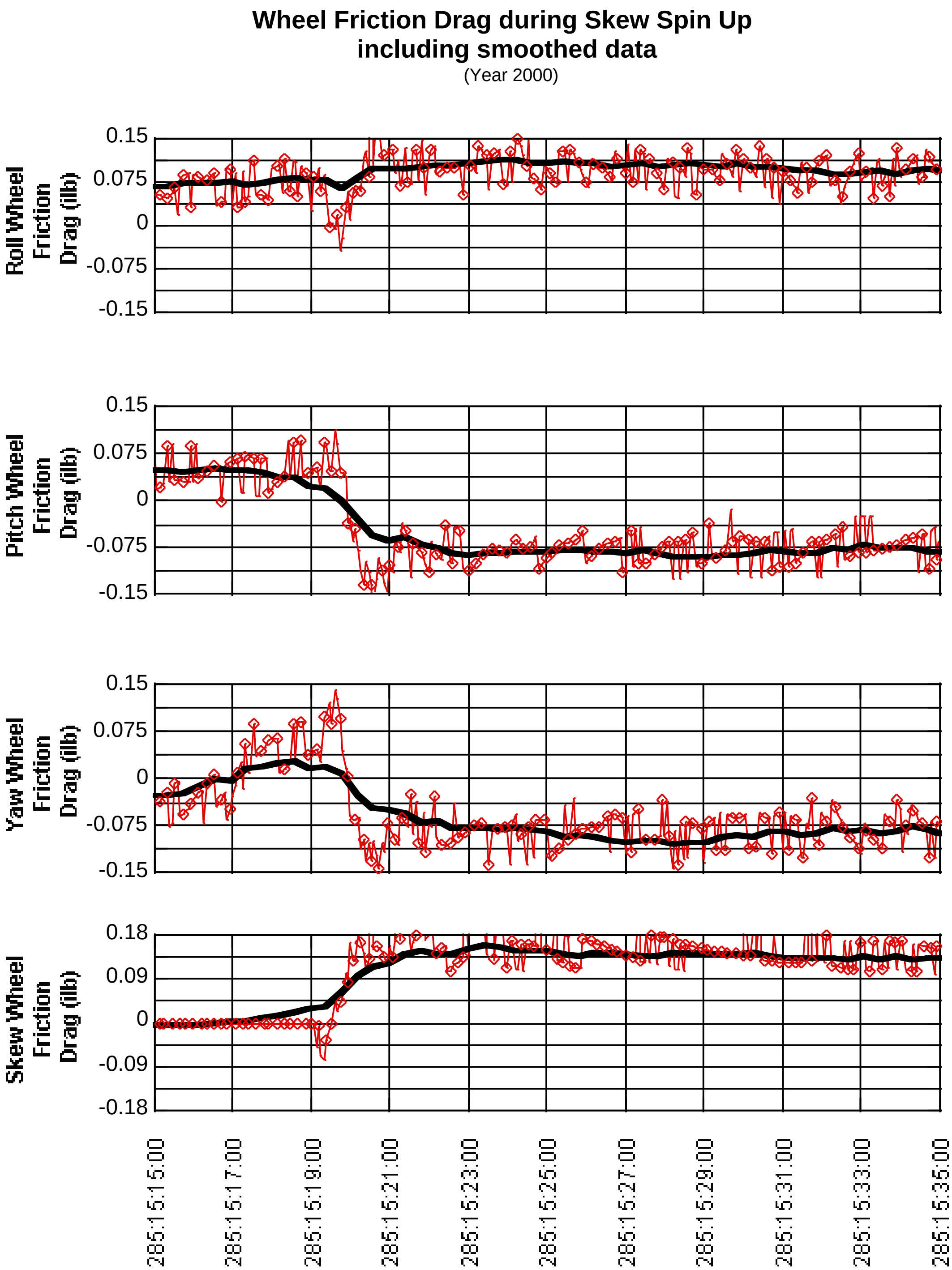

Figure 8 – Wheel Drag during Skew Spin up (Year 2000)

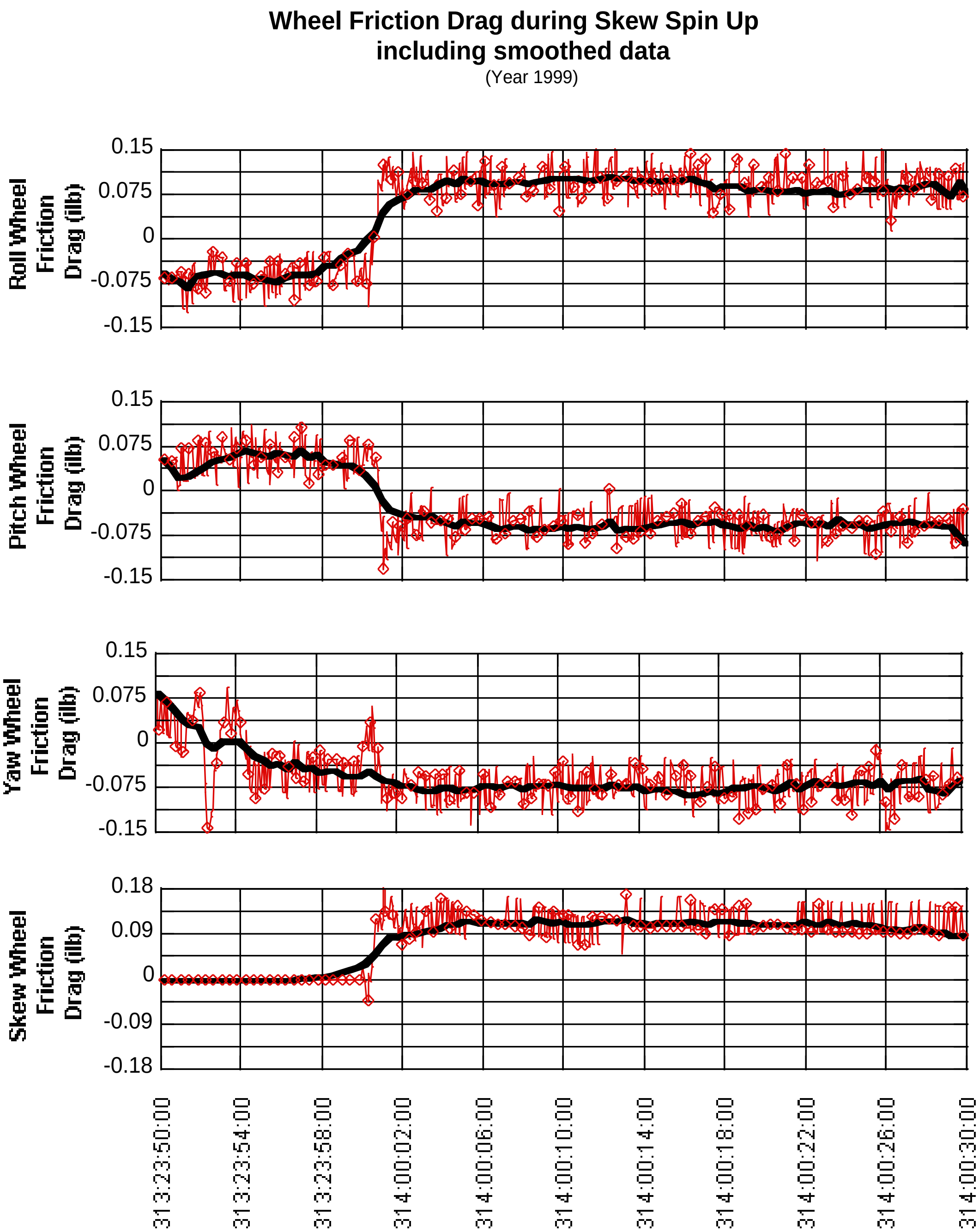

Figure 9 – Wheel Drag during Skew Spin up (Year 1999)

Transfer of wheel momentum during the skew spin down was smooth and **Figure 10** verifies the pickup of the wheel momentum in the spacecraft body momentum. The Roll axis shows the largest change in system momentum; a change of 20 in-lbs was noticed on this axis that corresponds to 1/12th the capacity of the reaction wheel (total 240 in-lbs). Both the Pitch and Yaw axis absorbed only 1/24th of the capacity of their reaction wheels and together, all wheels were kept well within their on-orbit intended operating range (±3000 RPMs).

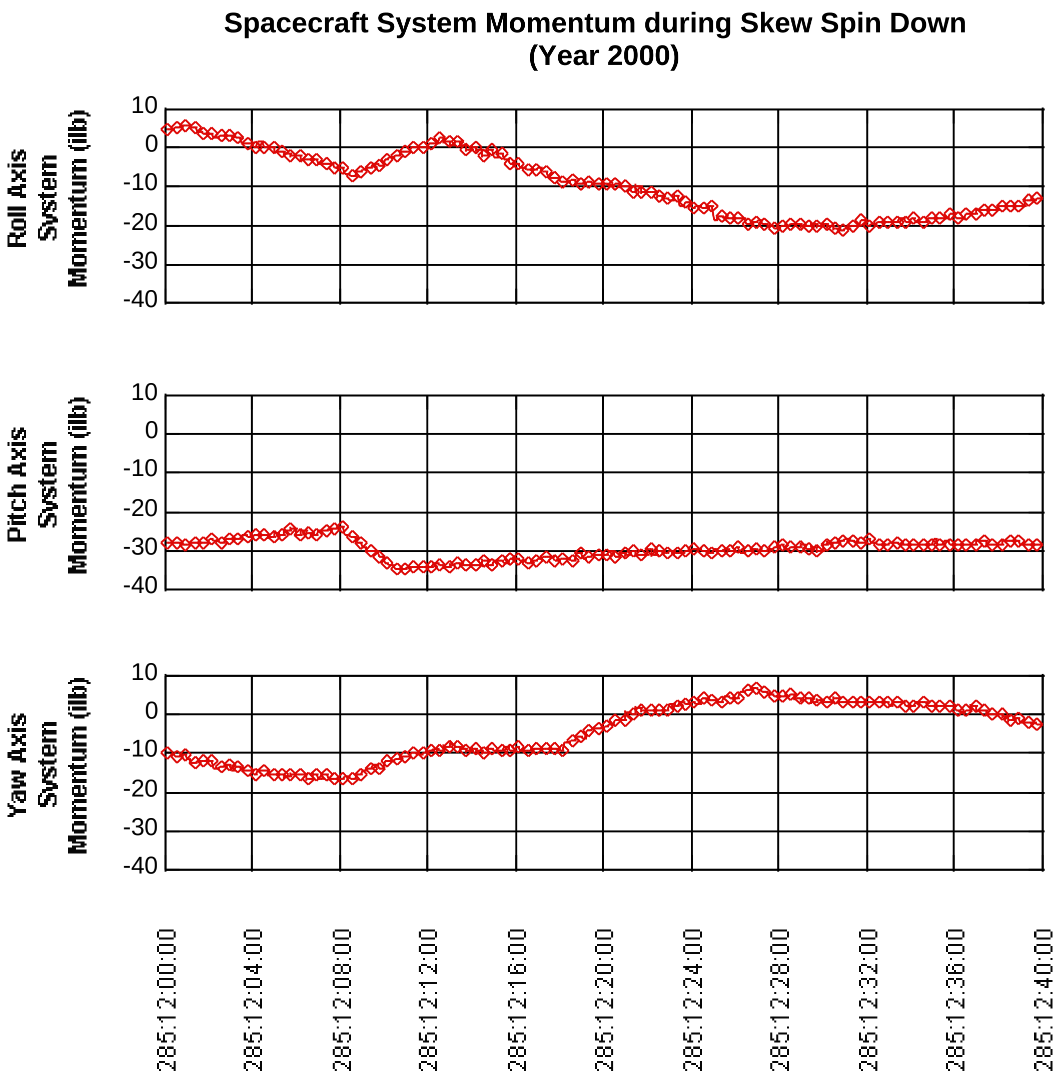

Figure 10 – Spacecraft System Momentum during Skew Spin down

Yaw Slews

The year 2000 Delta-i operation consisted of slewing out about the spacecraft yaw axis by +90.75 degrees, burning the Orbit Adjust jets for 19.5 minutes and slewing back by -90.75 degrees. This sequence of slew-burn-slew spanned 55 minutes which consisted of the following activities: a 13 minute 19 second slew to +90.75 degrees, followed by 3 minutes 47 seconds of settling, a 19 minute 32 second burn, followed by 5 minutes 24 seconds of settling, and a 13 minute 18 second –90.75 degree slew before retuning to near nominal attitude. **Figure 11** summarizes the various transitions of the ACS control mode during the Delta-i sequence. All ACS transitions were commanded via stored or ground commands, except for the transition from Maneuver to Precision which was done autonomously via FSW.

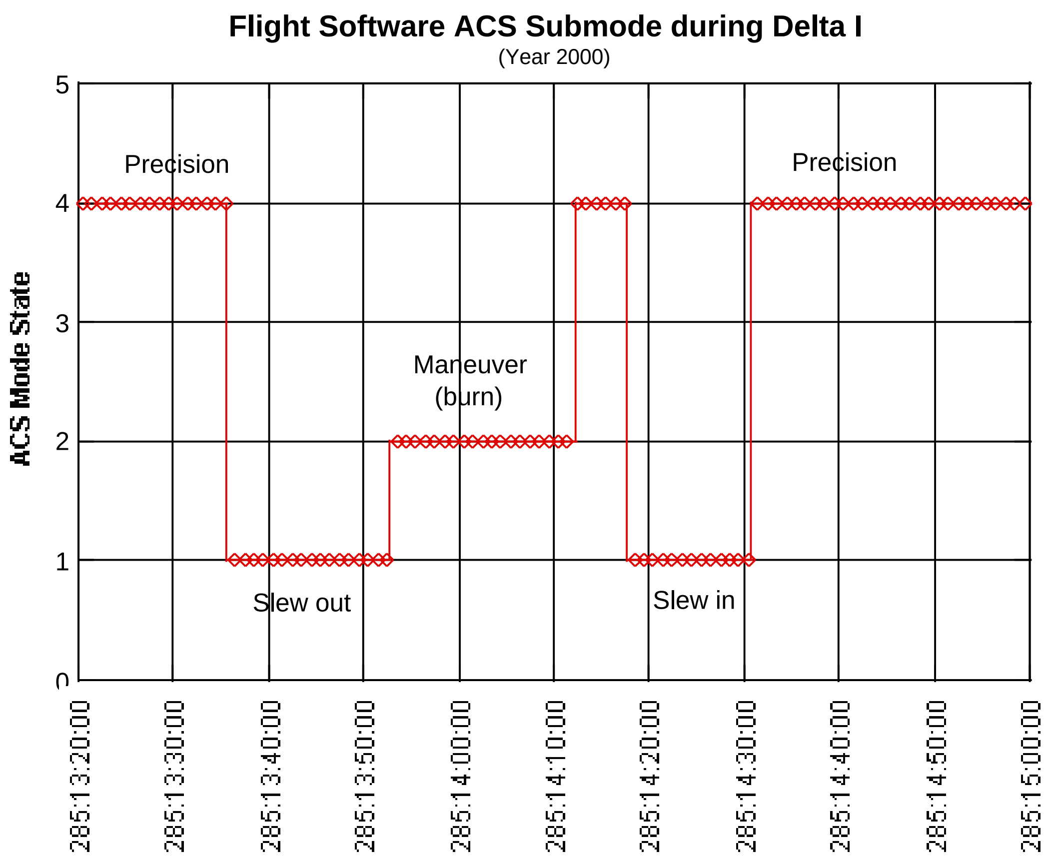

Figure 11 – ACS Submode during Delta-i

Figure 12 depicts the slew out activity in terms of controller Attitude and Rate errors, and the Earth Sensor Assembly (ESA) derived Yaw error. While in the SLEW control mode, the spacecraft was rotated about the Yaw axis by introducing a yaw attitude error into the FSW, with a maximum commanded slew rate of 0.125 deg/sec over an input period of 12 minutes 6 seconds (sequence: RTCS YAW_SLEW). The SLEW control law worked correctly to diminish the induced error, whose maximum yaw attitude error peaked at -5.25[1] degrees within 90 seconds of the command. At this time, a peak yaw rate error of -0.125 degrees/sec was registered. FSW correctly clamped the attitude error at -5.25 degrees and thereafter the residual error was used continually to drive the spacecraft out to its final destination.

The yaw error drifted below -4 degrees after the slew commanding was completed at 285/13:47:40, at which time the controller used the remaining yaw attitude error to "coast" to the intended target of +90.75 degrees. When the slew commands terminated, the yaw error once again increased rapidly consequently peaking the yaw rate error at +0.125 degrees/sec. After 1 minute and 13 seconds of coasting and driving beyond the null yaw error, a peak yaw attitude error of 1 degree was recorded. Subsequently another 3 minutes and 47 seconds elapsed, before all control errors and rates were finally settled out. During the period of minimal yaw attitude error increase, the yaw rate error was minimized to near zero.

Upon completion of the initial 90 degree Yaw slew, the roll rate was placed on the spacecraft Pitch axis and the orbit pitch rate was transferred onto the spacecraft Roll axis. **Figure 14** depicts the same activity for the case of the slew back from +90.75 degrees toward nominal attitude. In both slew instances, all Attitude and Rate error parameters were within specification.

([1]The FSW reports a negative in the attitude error upon slew out, as the actual attitude reference state lags behind the desired attitude reference state, which is being propagated forward.)

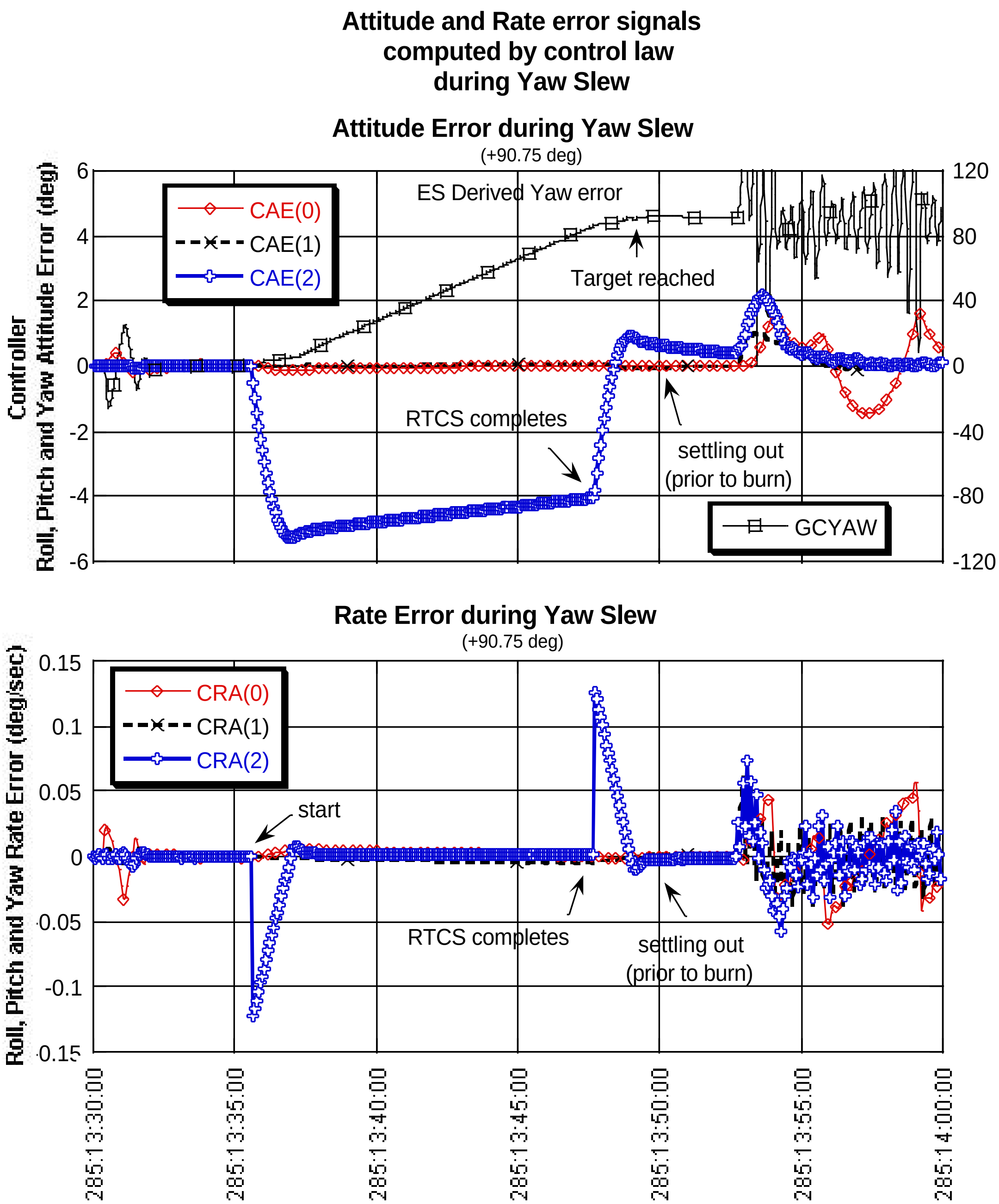

Figure 12 – Attitude and Rate Errors during Yaw out

Figure 13 shows nominal wheel speeds and torque commands during the slew out to +90.75 degrees. The yaw wheel speed reached 2800 RPM within 90 seconds of the start of the slew and settled down to 2500 RPM prior to slew completion. The yaw wheel torque commands were peaked out at +256[2] counts upon start of slew and at -256 counts upon the end of slew. Each of these peaks were sustained for approximately 90 seconds during which time the wheels were being spun rapidly in either the forward or reverse direction.

As a comparison to wheel torque during a slew, other high torque events are shown in **Figures 13** and **15**, such as solar array start and stop, and thermal snap, which generate similar torque magnitudes but are sustained over a much shorter time span. More importantly, these figures show that at the start of the jet firings, the spacecraft wheel speeds had sufficient margin to execute thruster firings and stay within the wheel operating range of ±3000 RPM during the burn. The pitch wheel was at +137 RPM; the yaw at -254 RPM; the skew at 0 RPM; and roll at +725 RPM.

Figure 15 depicts nominal torque and wheel speed profiles for the slew back from +90.75 degrees. Pitch and Roll speeds can be seen "crossing over" on the return to nominal attitude, as the orbit rate is once again placed on the pitch axis and the spacecraft roll axis is positioned along the velocity vector. In all instances, Wheel Speeds and Torque Commands were as expected.

([2]For all wheels, the positive torque polarity denotes an increase in wheel speed while the negative polarity denotes a decrease in wheel speed.)