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Determination of SAMPEX Attitude in Ground Processing

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Abstract

The Master Data Files (MDFs) for the SAMPEX spacecraft, in which form the science teams received the spacecraft's data, included information on its changing attitude. However, this attitude set was not complete even under nominal operating circumstances (i.e., without telemetry data gaps), and it was necessary to calculate the attitude of the spacecraft on the ground to enable further analysis of sensor data. In addition, the nominal determination and reporting of attitude (onboard and in the MDFs) was designed for a spacecraft rotation rate of approximately one revolution per orbit (ca. 90 min), and a different procedure was necessary to calculate attitude for the large portion of the mission during which the spacecraft was spinning at approximately 1 rpm instead. These corrected attitude values, along with quality flags, are available in the online SAMPEX Data Center, and the purpose of this report is to document how they were calculated, including circumstances that limit their accuracy in some cases.

Acknowledgments

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1. SAMPEX Pointing Strategies Throughout the Mission

The SAMPEX (Solar, Anomalous, and Magnetospheric Particle Explorer) satellite was launched on July 3, 1992 into a 520-km x 670-km low Earth orbit (LEO) at 82° inclination (Baker et al., 1993). The spacecraft was three-axis stabilized, with two fixed coplanar solar panel "wings"; the orientation of the satellite was always chosen to keep this plane normal to the direction of the sun (hereinafter the sunline), even when the spacecraft was in eclipse. The satellite had a magnetometer and sun sensor for attitude determination, and magnetic torque rods and a momentum wheel for attitude control. The four energetic-particle sensors aboard the spacecraft had co-aligned boresights, which were aimed at right angles to the solar panel normal, as diagrammed in Figure 1.

During the planning phase of the mission, starting with the proposal in 1988, the attitude program was planned to be a simple Orbit Rate Rotation (ORR), with the spacecraft turning once about the solar panel normal direction during the course of each ~90-min orbit so that the sensors are aimed upward when the spacecraft passes above one polar region and then, after half a rotation of the spacecraft (in an inertial frame) and half an orbit, aimed upward above the other polar region, as shown in Figure 2 for two orbit orientations relative to the sunline. However, when the LDEF (Long-Duration Exposure Facility) was recovered in 1990, and its samples analyzed, it was discovered that orbital debris and micrometeoroid fluxes in LEO were 50 to 100 times larger than had been assumed in the SAMPEX proposal (Frakes et al., 1992). The Heavy-Ion Large Telescope (HILT) sensor on the spacecraft had a flow-through isobutane proportional counter, with the gas volume sealed at the aperture by foils that would be susceptible to puncture damage from this hazard. Thus an additional constraint was programmed into the spacecraft's Attitude Control Subsystem (ACS) before launch, requiring that the

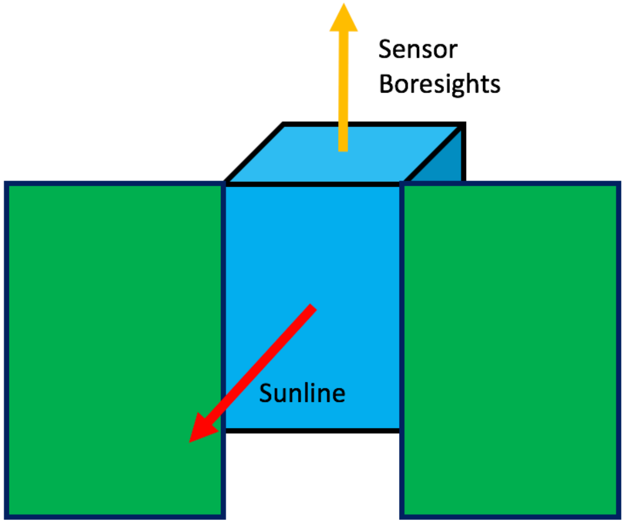

Figure 1. Sketch of SAMPEX spacecraft, showing relative orientations of sensor look directions and solar panel normal.

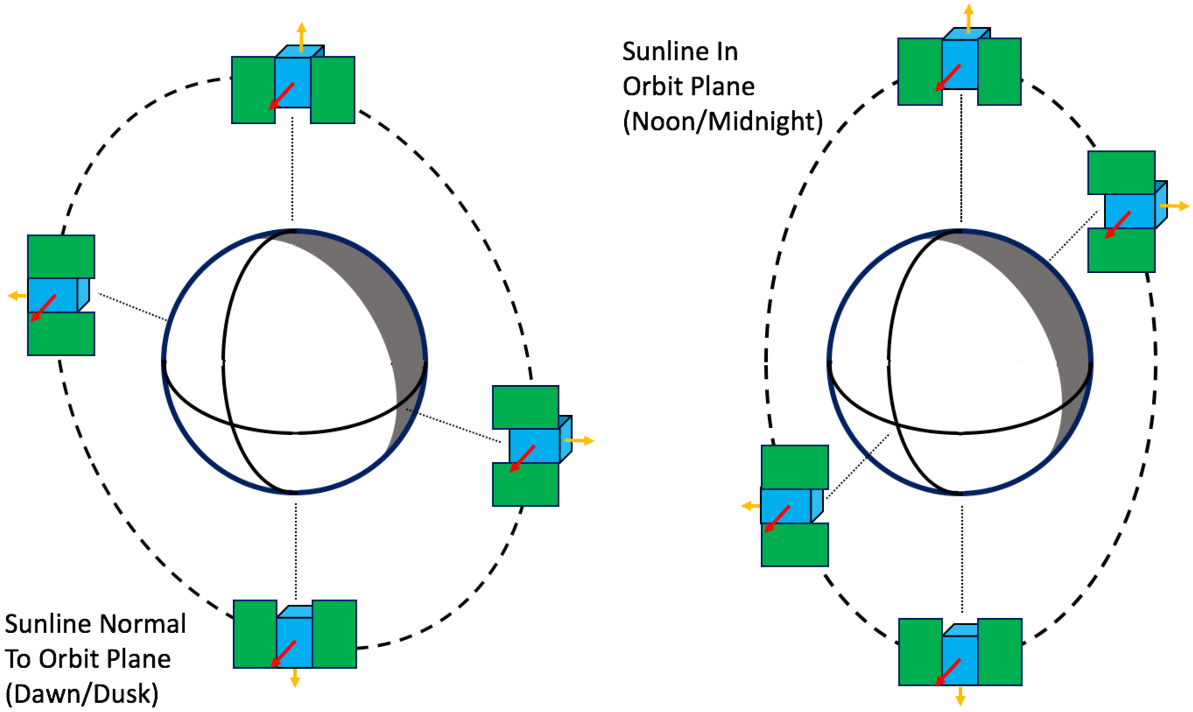

Figure 2. Schematic (not to scale) of spacecraft orientation in simple ORR mode for dawn/dusk and noon/midnight orbits, after Figure 4 of Baker et al. (1993).

boresight vector of the sensors (normal to the vulnerable foil aperture) always be pointed at least 90° away from the ram direction, the direction parallel to the spacecraft's velocity vector, from which the debris hazard would be greatest.

Then, after launch, a strong temporal modulation of the number of inner-zone particles counted by the sensors was observed, with about a three-month periodicity. The spacecraft's orbit precessed relative to the sun-Earth direction about every six months, so that while the orbit was in a dusk-dawn plane at launch, in a month and a half it had moved to a noon-midnight plane, followed by dusk-dawn again but with the opposite sense of revolution about the sunline after three months, then into a noon-midnight plane again (with revolution opposite the first) before returning to the original dusk-dawn orbital configuration after six months. The interaction of the rotating spacecraft's orientation with the direction of the magnetic field in the South Atlantic Anomaly (SAA, where spacecraft in LEO encounter the inner zone) meant that the amount of time that the sensors' boresight direction was aimed nearly perpendicular to the field vector, in which direction geomagnetically trapped particle fluxes are highest, was modulated with a period of half the precession period.

To maximize the number of particles counted and to ensure continuous coverage of the changing low-altitude energetic-particle environment, a Modified Orbit Rate Rotation (MORR) attitude program was implemented in 1994 that increased the time spent pointing at or near the field-normal direction in the SAA (Markley et al., 1995). Specifically, when the spacecraft was at low latitudes where the geomagnetic field magnitude fell below 0.3 Gauss, the orientation was chosen so that the sensors' boresight direction pointed as nearly perpendicular as possible to the local field direction, while when the field magnitude was greater than this value at higher latitudes, the boresight direction was pointed as nearly as possible along the local magnetic field direction, parallel or antiparallel depending on the hemisphere (south or north) so that the look direction was generally upward. In both cases, the magnetic field pointing constraint was subordinate to the requirements that the solar panels be face-on to the sun and that the boresight direction be at least 90° from the ram direction. By 1996 the isobutane supply for HILT had been exhausted so that a micrometeoroid pinhole in the aperture foils would no longer reduce sensor capability, so the requirement for ram avoidance was dropped late in the year.

Thus, there were three main attitude control schemes in the early part of the mission: ORR, MORR with ram constraint, and MORR without ram constraint. These were all variations on a basic scheme of one rotation per ~90-min orbit, so while the changing constraints along each orbit resulted in occasional complex turns and reversals, the speed of rotation was always fairly modest. In 1996, however, with the three-year prime mission completed and the HILT isobutane exhausted, it was decided that it would be desirable to take the risk of setting the satellite spinning about the sunline at approximately 1 rpm, so as to sample a wider range of pitch angles throughout each traversal of the radiation belts. This spin mode was implemented during parts of 1996 through 2000, including about a year and a half covering the period of minimum solar activity between cycles 22 and 23, as tabulated in a summary report available from the SAMPEX Data Center at http://www.srl.caltech.edu/sampex/DataCenter/docs/SAMPEX_pointing_history2.pdf and further spelled out in Appendix A.

After the period covered in that report (through the end of the nominal mission on June 30, 2004), the spacecraft's momentum wheel failed in late 2007, leaving only the torque rods available for attitude control. It was determined that the best control of attitude in the absence of the momentum wheel would be achieved by putting the spacecraft back into spin mode and leaving it there, rather than in some variation of ORR, so this was done, and the spacecraft stayed in spin mode (with a few interruptions due to safeholds) until it re-entered the atmosphere in 2012.

The basic cadence of attitude and ephemeris information in the SAMPEX telemetry is 6 seconds. For the purposes of the calculation of attitude documented here, the distinctions between ORR, MORR, and with or without ram avoidance are not material; they resulted in dramatically different measurement coverage of geomagnetically trapped particles, but they did not produce motions that are substantially different on a timescale of 6 seconds. Thus, a common algorithm will be described below for after-the-fact determination of attitude on the ground in all of these non-spinning modes, and distinctions between them will not be considered further. When the spacecraft was spinning at about 1 rpm, however, a 6-second sample time covered an attitude change of about 36°, so a different algorithm for attitude determination in spin mode had to be developed and will be described separately below.

2. Method of On-Board Attitude Determination

Figure 3 shows the method by which the SAMPEX ACS determined the orientation of the satellite in space so that it could be adjusted as necessary to achieve the pointing goals described in Section 1. The spacecraft carried a sun sensor and a magnetometer, so that the vector directions of the sun and the local magnetic field relative to the body of the spacecraft could be measured (the sunline was kept close to the solar panel normal, but was not expected to be perfectly orthogonal at all times). The ACS had an orbit propagator that it used to calculate the position in space of the spacecraft; this calculation was re-initialized regularly with information uplinked from the ground. Updates included a time-stamped state vector of position and velocity determined from tracking of the satellite, and atmospheric drag parameters to calculate the varying rates of orbital decay as solar activity rose and fell and as the spacecraft's orbit dropped in altitude over time. The ACS also had a magnetic field model based on the IGRF-1990 model updated to epoch of date. Thus, the ACS could calculate the position of the spacecraft at any point in its orbit, and could calculate the magnitude and direction of the Earth's magnetic field at that location; it could also calculate the direction of the sun in inertial coordinates (e.g., GEI) from the time of year.

Given both measured and modeled directions for two vectors, a coordinate transformation matrix can be calculated to align the modeled and measured directions as closely as possible. Since the accuracy of the modeled sun direction was known as well as is the Earth's orbit, whereas the modeled magnetic

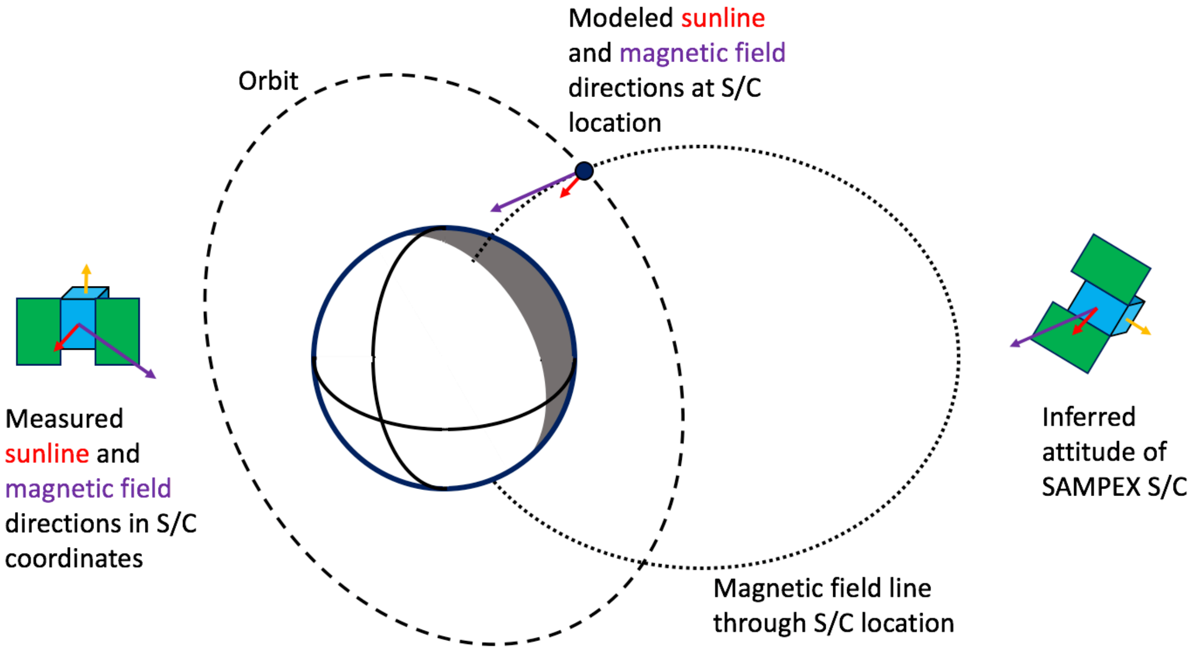

Figure 3. Schematic (not to scale) of method of attitude determination used onboard by ACS.

field and the position of the spacecraft were much less firmly pinned down, the ACS would first align the measured and modeled sunlines. This determined the spacecraft's attitude subject to an arbitrary rotation about the sunline; the value of that rotation was determined by aligning the measured and modeled magnetic fields as closely as possible, which meant aligning their projections into the planes normal to their respective (measured or modeled) sunline. This procedure provided a unique solution to the spacecraft's attitude, unless the sunline and magnetic field direction happened to be parallel or anti-parallel; how the ACS dealt with such a degeneracy is discussed below.

3. Information Relevant to Spacecraft Attitude in the MDFs

The science teams received SAMPEX data in Master Data Files (MDFs), whose contents are documented in a report available from the SAMPEX Data Center at http://www.srl.caltech.edu/sampex/DataCenter/docs/MDF_description_V1.6.pdf. The files were originally created using the Tennis data format standard, which distributes the data among "sets" with a two-letter designation and further subdivides these into "games" of associated variables, and within these into "points" containing scalars or arrays of specific character or numerical data. Reference will be made herein to the AS, MF, PS, and RS sets, which contain respectively the attitude values determined by the spacecraft's onboard ACS, the raw measurements from the onboard magnetometer, a broad range of ephemeris and attitude variables calculated from orbit propagators and field models on the ground combined with the information in the AS sets, and the countrates from the four sensors in the payload.

The PS sets contain information on a 6-second cadence about the spatial location (geographic and GEI inertial coordinates) of the spacecraft and about the local magnetic field at that location determined from the same model as was used by the ACS. They also contain information about the model field line on which the spacecraft lay at the moment, such as loss cone angles, the locations of the field line's footpoints and equator crossing, and the conjugate point for particles mirroring at the spacecraft. The AS sets contain the ACS-determined attitude of the spacecraft on a variable cadence (nominally a new one was issued when spacecraft attitude in an inertial frame changed by one degree), stored as quaternions (Wertz, 1978). The MDF generation software combined attitude from the most recent quaternion with the spacecraft's location and the model field at that location to calculate the pitch angle of particles traveling down the sensors' boresight direction, the angle between the boresight direction and the local zenith, and the azimuth of the projection of the boresight direction into the plane normal to the zenith. The pitch, zenith, and azimuth angles were recorded in the PS set, along with a direction cosine array calculated from the most recent quaternion. (If there were any PS sets with time stamps before the first quaternion of the day, then that first quaternion was used to calculate these attitude variables for those PS sets instead of the last one from the previous day. This would result in invalid attitude information in the PS sets, which we corrected on the ground by introducing the last quaternion from the previous day and using the algorithms described below as we would for any gap in the sequence of quaternions.)

The above algorithm produced attitude information on the 6-second cadence of the PS sets. The RS sets contain single-detector and coincidence rates accumulated for six seconds, and the PS sets are nominally synchronized to them. There are always exactly 14,400 PS sets per day with ephemeris and attitude information, with the first one having a time stamp of between 0 and 5 seconds of the day and the rest being exactly 6 seconds apart; the phasing was chosen so that a PS set time stamp would synchronize with the time stamp of the first RS set of the day (there may be fewer than 14,400 of them in a day, so the first one may have any value less than 86,400 as its time stamp). However, because the PS set time stamps were a mathematical independent variable for a calculation whereas the RS set time stamps were read off a spacecraft clock, there was often a drift of 1 second or occasionally more in the latter by the end of the day.

The counts in the rates of an RS set were accumulated over six seconds starting at the time stamp of the set; between that and the clock drift, the particle events counted in a particular set may have occurred up to six seconds or even more after the time stamp of the nearest PS set. The spacecraft's location didn't change much on a 6-second timescale, and when it was not spinning, neither did the attitude, so using that information from the PS set with the time stamp nearest to each RS set was good enough to organize the data. However, when the spacecraft was spinning at about 1 rpm, it would slew about 36° in six seconds, which is larger than the fields of view of many of the sensors' channels. Thus, when spin mode was first implemented, another algorithm was created to obtain attitude values more suitable to the contents of the RS sets. First, the two quaternions on either side of the midpoint of the RS set accumulation interval (time stamp plus 3 seconds) were identified, and they were interpolated to that midpoint to determine the attitude at that time. Second, the magnetic field at the spacecraft at that time was calculated using the same IGRF model as in the ACS, and third, the attitude and field vector were used to recalculate the pitch, zenith, and azimuth angles. These angles were stored as new variables (points of a new game) in the RS set after spin mode was first implemented.

Thus, the PS sets nominally contain all the attitude information needed to perform scientific analyses of the data outside of spin mode, and the RS sets contain attitude information better suited for use in spin mode. (Actually, for the SAMPEX Data Center, we did not copy this attitude information directly from the RS sets, but rather redid the calculation described above after some checks to delete bad quaternions, which were easily recognized by an isolated jump in the sunline direction to well off the spacecraft Y axis, and to straighten out occasional jitter in the RS set time stamps—that is, not the gradual clock drift, but separations of the time stamps by, e.g., 6, 6, 5, 7, 6, 6, seconds, etc., so that one RS set's time stamp had to be adjusted by one second to restore the continuous 6-second cadence.) In addition, for the corrections described below, we needed to use the raw attitude information from the AS sets as a starting point, and we also needed the magnetometer measurements stored in the MF sets.

4. Coast Mode

As noted in Section 2, the ACS algorithm for determining spacecraft attitude did not give a well-defined solution if the sunline and magnetic field direction were aligned. In order to avoid spinning the spacecraft abruptly because of small errors in the magnetic field measurement or model, the ACS ceased to update attitude information if the angle between the model sunline and magnetic field vector was less than 5° (or greater than 175°) while the spacecraft was in sunlight. If it was in eclipse so that the sun sensor was not measuring the sunline, the calculation ceased if this angle dropped below 40° (or rose past 140°).

The spacecraft is said to have been in coast mode when this occurred. The spacecraft's attitude did not freeze in coast mode –maneuvers under way when coast mode was entered continued to be carried out, including spinning if in that state –but the ACS stopped putting updated attitude quaternions in the telemetry, so that AS sets disappeared from the MDF. However, since attitude angles (pitch, zenith, and azimuth) and the direction cosine matrix in the PS set were calculated using position and magnetic field from models but attitude from these ACS quaternions, the attitude in the PS sets did appear to freeze in inertial (GEI) coordinates during coast mode, then abruptly jumped to a new value when coast mode ended and AS sets started appearing again. Coast mode and the accompanying invalid attitude information in the PS sets could occupy a significant fraction of the day, especially when the orbit was in a noon-midnight orientation, so it became clear early in the mission that corrected attitude would be needed.

5. Correcting Non-Spinning Attitude Data During Coast Mode or Other Gaps

Since invalid results from a calculation of attitude after the fact on the ground would have no impact on spacecraft operations, we decided to perform during coast mode the same calculation done outside of coast mode by the ACS and diagrammed in Figure 3. The PS sets contained the modeled magnetic field on a steady cadence, and the calculated sunline vector could be obtained from the time, while the MF sets contained the measured magnetic field vector on a five-second cadence or less regardless of coast mode, so all we needed in order to replicate the ACS calculation was the measured sunline in spacecraft coordinates. This data is not available directly from the MDFs; however, it is a simple matter to use the quaternion in the last AS set before commencement of coast mode to rotate the calculated sunline into the spacecraft frame, thereby recovering the measured value that the ACS must have used to calculate the quaternion. This meant that, unlike the modeled values and the measured field, the measured sunline was often up to tens of minutes out of date; however, since all attitude programs actively kept it close to the spacecraft Y axis (solar-panel normal) outside of coast mode, it changed very little even during coast mode periods, and we found that jumps in the sunline direction as measured in the spacecraft frame between the last AS set before coast mode and the first one after were usually small.

The attitude data in the SAMPEX Data Center includes a quality flag to tell the user the source of the attitude information for any given 6-second interval. In non-spinning mode, the flag is 0 for valid attitude data straight from the PS set (outside data gaps or coast mode), and 1 for corrected coast-mode attitude data derived via the procedure above. These values indicate data that is generally safe to use; there are also flag values indicating data of more dubious quality. If the MF set used for the correction calculation for a given PS set was no more than 5 seconds old but the AS set was over 1800 seconds old, this indicated missing data rather than (or in addition to) coast mode, and the flag was set to 2. If the magnetic field data was over 5 seconds old, there was a gap in the MF sets, so attitude was interpolated between the values in the nearest PS sets on either side that had flags of 0, 1, or 2, and the flag was set to 3; if the calculated angle between the sunline and the magnetic field was less than 10° we decided not to trust the result but again interpolated between the nearest instances with flags of 0, 1, or 2, and the flag was set to 4.

6. Correcting Spin-Mode Attitude Data During Coast Mode or Other Gaps

As was the case outside coast mode, a different calculation was needed to fill in coast mode attitude information when the spacecraft was spinning at about 1 rpm, but the calculation turned out to be simpler than for non-spinning periods because we could rely on angular momentum to sustain the spin. Outside of spin mode, the ACS nominally put a new quaternion in the telemetry stream whenever the spacecraft's attitude in an inertial frame changed by 1°; that was infeasible when it changed by 6°/s, so in spin mode, the AS sets nominally came out once every six seconds (sometimes a bit less). A gap between quaternions of more than six seconds indicated coast mode or a data gap.

In non-spinning periods, the attitude in the PS sets of the MDFs was simply invalid during coast mode. However, the MDF generator did provide corrected attitude data in the RS sets during coast mode: the spacecraft was assumed to be rotating at a constant rate of 0.1053 radians per second about its Y axis (the solar panel normal) from the last available quaternion to the midpoint of the RS set accumulation period (time stamp plus three seconds). As mentioned in Section 3, for the SAMPEX Data Center, the spin-mode attitude outside of coast mode was generated by replicating the calculation described there after scrubbing the AS sets for bad quaternions and correcting jitter in the RS set times. Similarly, we redid the coast-mode calculation for the Data Center, with two small modifications: first, instead of rotating about the spacecraft Y axis, we determined the axis of the rotation between the last quaternion before the gap and the first one after (which, of course, was always close to the Y axis). Second, instead of rotating from the last quaternion before the gap by assuming the fixed rotation rate of 0.1053 radians per second, we used that value to determine how many complete rotations of the spacecraft would have occurred during the gap, and then tuned the rotation rate for the correction so that the time between the two quaternions bracketing the gap, multiplied by the tuned rate, matched the angle between those two quaternions.

As with non-spinning mode, there are quality flags for attitude data in spin mode. Data calculated using the procedure described in Section 3 for periods not in coast mode have a flag of 100, and data calculated using the coast mode procedure described above have a flag of 101. Both of these should be safe to use; we also had flags for more doubtful data. If the rotation axis determined from the quaternions bracketing a gap was more than 2.5° off of the spacecraft's Y axis, a flag of 102 was given to all attitude data during that gap, and if the two quaternions were separated by more than 1100 seconds (indicating a telemetry gap rather than coast mode) a flag of 103 was assigned.

7. Summary of Data Quality Flags

Finally, 10 was added to the value of the flags for times during which the spacecraft was spinning up or spinning down, rather than at the full spin rate or in non-spinning mode. These times are tabulated in Appendix A. Also, either spinning or non-spinning algorithms were used on whole days' data, so the non-spinning part of a day calculated using spinning algorithms, or vice versa, would also have 10 added to the flags during that partial day. Flag values and validity are summarized in Table 1. Values marked "No" in the "Trust?" column are not necessarily invalid, but their inputs were not as expected by the correction algorithms (i.e., recent AS and MF updates, spin axis near solar panel normal), so they should be checked for unexpected behavior before use.

Table 1. Summary of Attitude Data Quality Flags in the Data Center. 10 was added to any value for parts of (mostly) spin-mode days that were not at full spin speed, or parts of (mostly) non-spinning days during which spacecraft was spinning up or down or at full speed.

Flag Value	Meaning	Trust?
0	Non-spinning, direct from PS set	Yes
1	Non-spinning, calculated using recent sunline/magnetometer data	Yes
2	Non-spinning, calculated with recent magnetometer data but sunline data > 1800 sec old	No
3	Non-spinning, interpolated between adjacent values with flag < 3 because magnetometer data > 5 sec old	No
4	Non-spinning, interpolated between flag < 3 values because angle between sunline and magnetic field direction is less than 10°	No
100	Spinning, calculated as in RS set with quaternions <= 6 sec apart	Yes
101	Spinning, calculated as in RS set with quaternions > 6 sec apart	Yes
102	Spinning, as in 101 but with rotation axis > 2.5° off of spacecraft Y axis	No
103	Spinning, as in 101 or 102 but with quaternions > 1100 sec apart	No

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Appendix A—Times When Spacecraft Was Spinning Up or Down

Table A1 lists times when the spacecraft spun up or down. Per Section 7, non-spinning attitude data for times between the first and fourth columns will have 10 added to their quality flags, as will spin-mode attitude data before the times in the second column or after the times in the third column. Spin-mode attitude calculations were only performed for day 129 of 1996 and later, not for the brief tests in early 1996, so no definite time period at full spin rate was logged during these early periods. Times are given as year/day/seconds; "(SH)" indicates time uncertain because of a spacecraft safehold.

The last line is indeterminate because the reaction wheel failed on 2007/229, leaving the spacecraft in a non-spinning but poorly defined attitude control mode. We do not have MDFs for days 2007/236–269 except for 2007/250 and 2007/252-253, but during this period, the decision was made to spin the spacecraft up to 1 rpm so that the spacecraft's angular momentum would provide stability no longer available from the reaction wheel, and leave it in that state for the rest of the spacecraft's lifetime. Because this period was well after funding for mission data analysis ended (June 2004), so that attitude correction calculations were run essentially automatically and unmonitored, we do not have a detailed breakdown of exit from and resumption of spin mode during safeholds occurring on 2007/348, 2008/191, 2009/087, 2011/275, 2012/101, and 2012/263, and 10 was not added to attitude quality flags to denote invalid data. Recovery from these (resumption of spin mode, reconfiguration of all sensors) was completed by days 2007/362, 2008/204, 2009/112, 2011/342, 2012/115, and 2012/276, respectively; all sensor and attitude data should be viewed with caution until after these dates.

Table A1: Summary of Times of Entry and Exit of Spin Mode

Spin-up start	Full spin reached	Spin-down start	Spin-down complete
1996/032/54545			1996/032/72611
1996/044/49441			1996/047/67211
1996/065/55440			1996/068/66850
1996/129/48783	1996/129/51070	1996/232/18365	1996/232/???? (SH)
1996/239/32343	1996/239/34569	1997/310/80417	1997/310/82810
1997/321/48364	1997/321/52331	1997/352/47285	1997/352/60731
1998/014/45901	1998/014/48734	1998/111/54482	1998/111/56588
1998/118/58205	1998/118/60672	1998/127/50711	1998/127/53110
1999/351/68282	1999/351/72190	1999/359/73248	1999/359/???? (SH)
1999/362/83105	1999/362/85819	2000/033/63182	2000/033/68468
2007/269/????	2007/269/????	2012/313/????	Re-entry

Appendix B—Attitude and Ephemeris Just Before Re-Entry

The orbit propagator built in to the SAMPEX ACS was designed for a three-year mission, during which the orbit would remain close to its initial ~600 km altitude. As the satellite's mission went on through nearly two complete solar activity cycles, however, the altitude eventually dropped to the point that it was encountering much more drag than the orbit propagator was designed to correct for. This caused systematic errors in the spacecraft ephemeris just before the end of the mission, and since the attitude calculation required information on the spacecraft's position in order to calculate the magnetic field vector at that position, there were also systematic errors in the attitude calculations in the ACS, in the MDFs, and in the (now incorrectly) corrected values in the SAMPEX Data Center.

Because drag predominantly changes the satellite's orbit in-track rather than across-track, we have considered the possibility that we might be able to make a simple correction via a time offset along the orbit, and use that to redo the ephemeris as well as the attitude calculation on the ground. One diagnostic we considered to determine the correction was the comparison between the magnitude of the field measured by the onboard magnetometer vs. the value from the ephemeris in the PS sets.

Figure B1 shows this comparison for the first day of the mission, which saw the spacecraft in the original orbit-rate rotation mode. There are some differences of magnitude at the peaks and valleys, but overall the agreement is good enough that a horizontal (temporal) offset should be clearly visible.

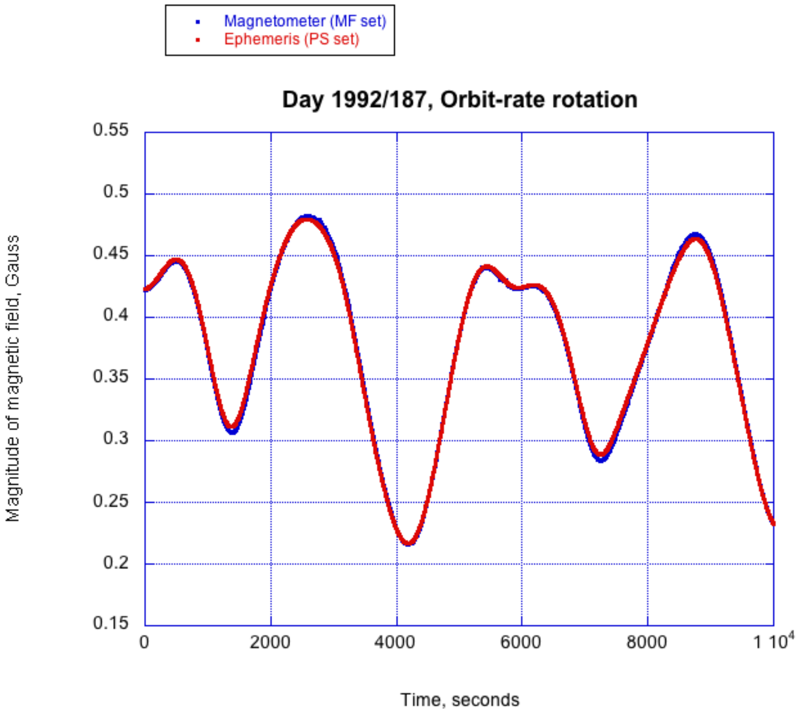

Figure B1. Measured and modeled magnetic field magnitudes for first day of mission.

A complication not mentioned heretofore is that the magnetometer also measured the field imposed by the torque rods when they were active. The ACS had access to the instantaneous electrical current in each of the three torque rods, and corrected the magnetometer values via a known linear combination of these to get a clean measurement of the external field for purposes of the calculation diagrammed in Figure 3, but that information is not available to us in the MDFs. We saw no evidence of glitches due to torque rod contamination in our non-spinning coast mode corrections, presumably because currents were comparatively small then; however, since the spacecraft was not balanced for spinning around the Y axis, the torque rods had to work harder to keep the spin axis from precessing during spin mode, and in Figure B2 we see noticeable deviations in the measured field. (Fortunately, as described in Section 6, we didn't need to use MF set data to correct attitude during spin mode.) Again, however, the correlation is good enough that a temporal offset should be detectable.

Figure B3 shows the comparison from the last day for which we have an MDF, and though there is a lot of magnetometer noise due to the torque rods, a temporal offset is clearly visible. We tried to fit a variable offset, changing linearly from the start of the day to the end of the day, to the data, but the magnetometer data were too noisy to enable this. Thus, we simply calculated the RMS difference

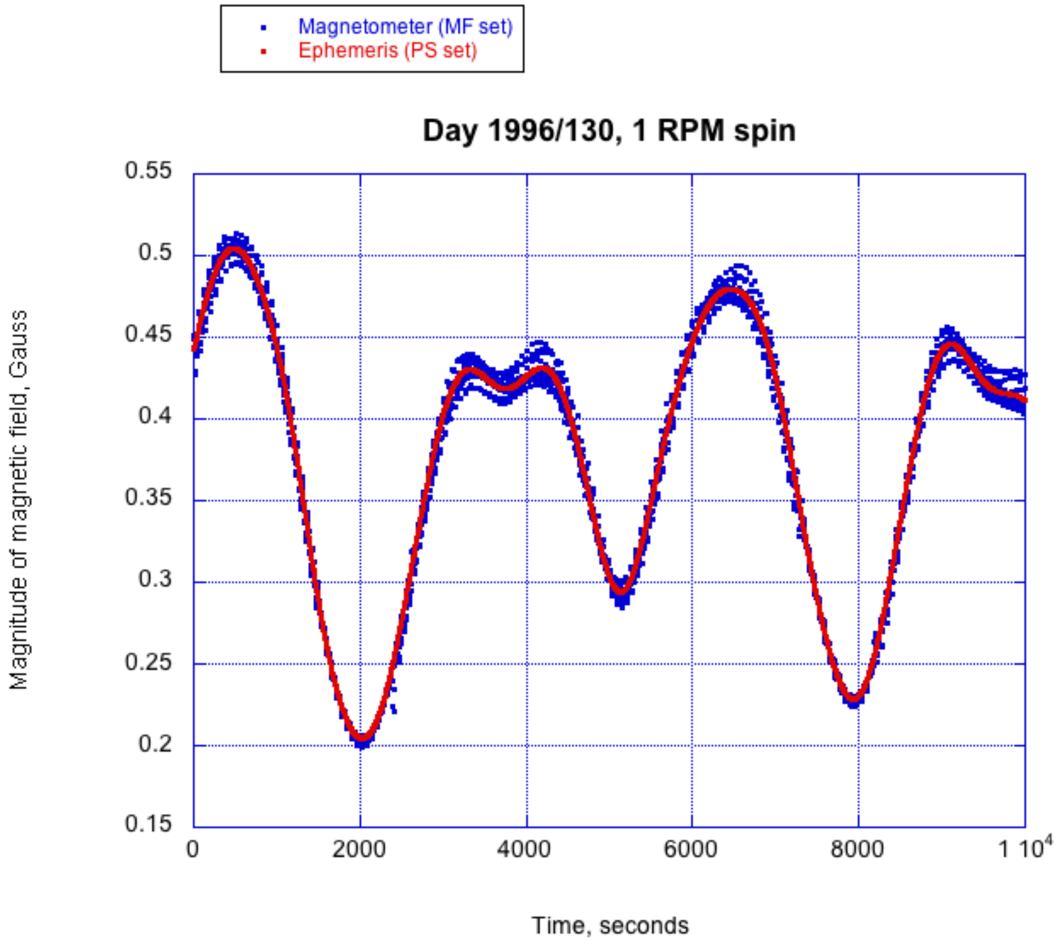

Figure B2. Comparison of measured and modeled field magnitudes for a day in spin mode.

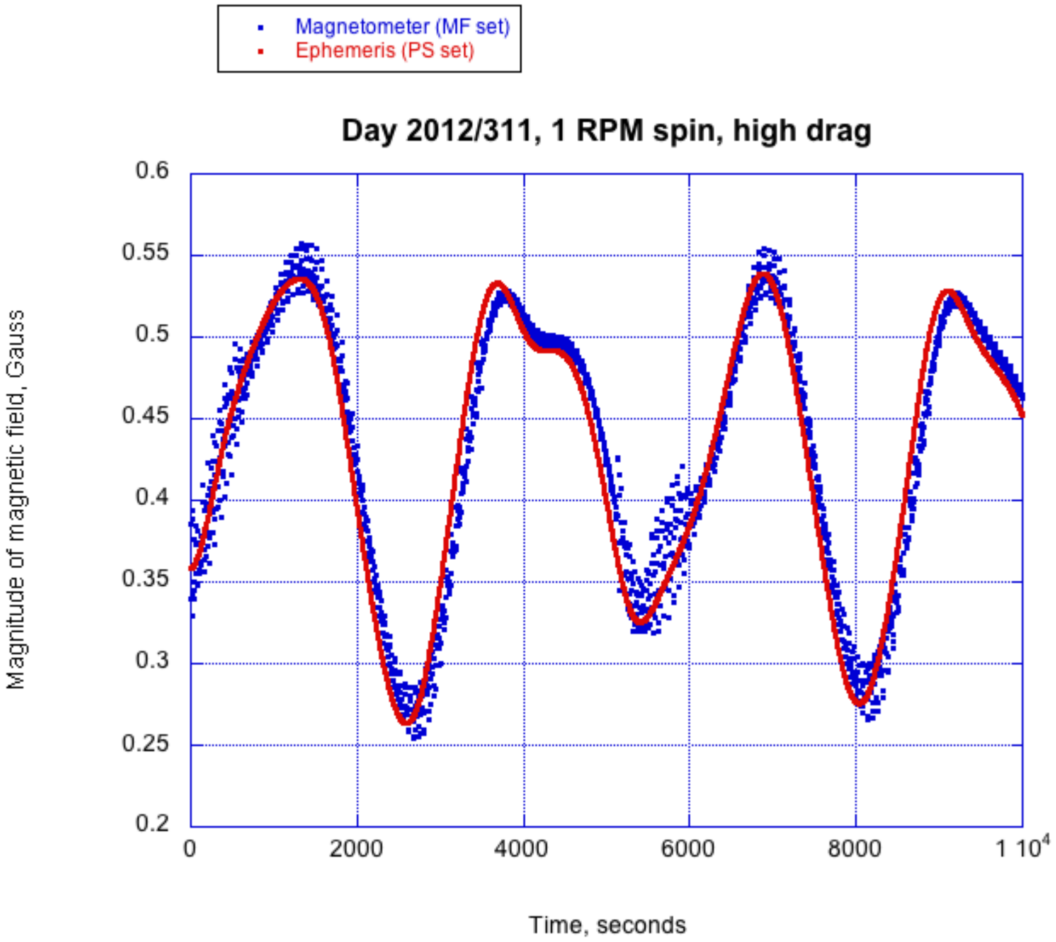

Figure B3. Comparison of measured and modeled field magnitudes on last day of mission.

between the two magnitudes at matching times as a function of the offset, and chose the value of the offset to minimize that difference.

Figure B4 shows the result of this minimization, for the final year of the mission. The X axis is the decimal year, and the offset starts rising dramatically around day 250–270. Unfortunately, this was right after the launch of the Van Allen Probes on August 30 (day 243), so this correction will need to be done more carefully, probably by hand for each of the few days of overlap, in order to enable proper comparisons of observations between the two missions during this brief period.

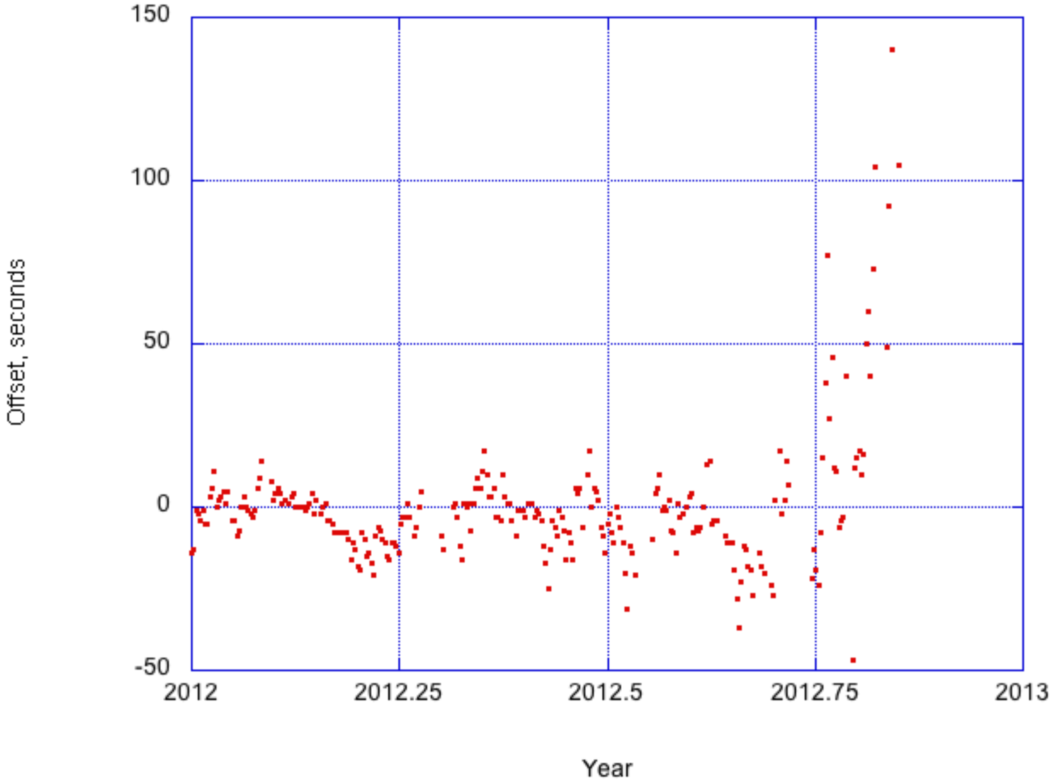

Figure B4. Temporal offset that gave the best RMS fit between measured and modeled field magnitudes throughout 2012.

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