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ATLAS SOLAR POINTING OPERATIONS

C. A. Tyler[1] and C. J. Zimmerman[2]

The ATLAS-series Spacelab missions is comprised of a diverse group of scientific instruments, including instruments studying the sun and how the sun's energy changes across an eleven-year solar cycle. The ATLAS solar instruments are located on one or more pallets in the Orbiter payload bay and use the Orbiter as a pointing platform for their examinations of the sun. One of the ATLAS instruments contained a sun sensor allowing the scientists and engineers on the ground to see the pointing error of the sun with respect to the instrument and correct for the error based upon the information coming from the sun sensor. This paper presents the solar operation activities and flight experience from the ATLAS 1 and ATLAS 2 missions with particular attention given to identifying the sources of pointing discrepancies of the solar instruments and to describe the crew and ground controller procedures that were developed to correct for these discrepancies. The Orbiter pointing behavior from the ATLAS 1 and ATLAS 2 flights presented in this paper can be applied to future flights which use the Orbiter as a pointing platform.

INTRODUCTION

The Atmospheric Laboratory for Applications and Science (ATLAS) series of Spacelab missions, an element of NASA's Mission to Planet Earth, is chartered to study the composition of the middle atmosphere and the possible atmospheric variations due to solar changes across an eleven-year solar cycle. The first and second missions in the ATLAS series successfully flew in March 1992 and April 1993 and mission planning has begun to support the ATLAS 3 launch scheduled for October 1994.

The ATLAS payload complement comprises investigations for both solar sciences and atmospheric sciences. The ATLAS instruments are also co-manifested with other payloads. As a result, the solar operations are scheduled during the orbital day portion of 20 to 30 orbits during the flight. The orbital night portion of each revolution is devoted to other non-solar science operations or to instrument cooling.

OVERVIEW OF ATLAS SOLAR OPERATIONS

In order to better understand the driving force behind global atmospheric changes, the solar science portion of the ATLAS payload intends to measure the total solar irradiance and the solar energy distribution and how these properties vary with time. Two of the ATLAS solar instruments, the Active Cavity Radiometer Irradiance Monitor (ACRIM) and the Measurement of Solar Constant experiment (SOLCON) examine the solar irradiance, also known as the solar constant, and how this value changes with time. The Solar Spectrum Measurement experiment (SOLSPEC) and the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) study the solar energy variations at various wavelengths. Although the ATLAS solar science instruments operate only briefly in the context of an eleven year solar cycle, their ability to be precisely calibrated before and after flight provides an excellent calibration source for satellites operating for extended periods of time. Three of the ATLAS solar instruments have sister instruments on free-flying satellites. During the ATLAS missions, ACRIM and SUSIM took coincident measurements with their counterparts on the Upper Atmospheric Research Satellite (UARS) which was launched in 1991. SOLCON provided comparison data for the Nimbus-7, the Earth Radiation Budget Satellites, as well as the ACRIM instrument on ATLAS and UARS. [1]

[1]Teledyne Brown Engineering, Huntsville, Alabama 35807-7007
[2]EO43, Marshall Space Flight Center, Huntsville, Alabama 35812

Implementation of solar experiment operations on ATLAS missions typically calls for dedicated blocks of time in units of one orbital revolution of approximately 90 minutes. During each revolution, the orbiter experiences a 90 minute "day" where a portion of time is spent in darkness and the rest of the time is in daylight. A minimum of 45 minutes of orbital daylight is required for a standard solar observation which consists of all of the solar instruments operating simultaneously. The amount of day/night time during each revolution is a function of the solar beta angle and may be controlled by selecting a certain launch time of day.

A group of consecutive revolutions dedicated to solar science, referred to as a solar period, is constructed and laid out under several general guidelines. First of all, a majority of the solar instruments desire as many consecutive revolutions as possible in order to observe short term solar variations. One of the instruments, SUSIM, requires at least 4 consecutive revolutions to assure an effective observation session. The desire for consecutive observations is offset however by the need to keep instruments from overheating. Thus an individual solar period is limited to 8 revolutions or less. An additional guideline expressed by the solar science group states that the individual solar periods should be scheduled throughout the mission to provide the greatest possible separation between the first and last observations. This guideline is accomplished by placing the first solar period directly after mandatory 24-hour out-gassing. The last solar period is scheduled such that the final observation occurs just before the required Passive Thermal Conditioning period prior to de-orbit. The remaining solar period(s) is distributed as equally as possible between the first and last solar periods.

A summary of the ATLAS 1 and ATLAS 2 solar periods is shown in Figure 1. ATLAS 1 nominally planned for 20 solar observations occurring in groups of 8,4, and 8 revolutions each. Once the payload had been in orbit for several days, flight controllers at Johnson Space Center granted an extension day to be used by the payload. Solar experiments were allocated a group of 4 revolutions on the extension day of which they were able to use three for a total of 23 solar observations. ATLAS 2 performed 26 solar observations in groups of 8,6,4 and 6 revolutions each and an additional 2 solar observations during an extension day.

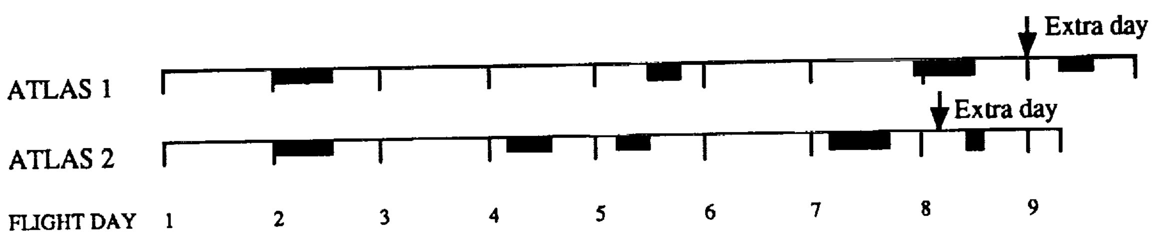


Figure 1. Layout of Solar Observation Periods for ATLAS 1 and ATLAS 2

ATLAS SOLAR OPERATIONS

Once the overall layout of solar periods has been set, details regarding what type of observations are performed can be planned. Solar observations on ATLAS missions are regarded by the payload planning team to fall into two general categories: nominal and special.

Normal Solar Operations

The first category, which is used for the majority of observations, simply points the instrument viewing axes directly at the sun and holds this orientation for the duration of the orbit day. At this point it is assumed that all of the solar instruments are aligned with each other and in turn aligned with the orbiter -Z body axis (directly out the payload bay). The orbiter azimuth co-elevation coordinate system is shown in Figure 2. This system locates the origin along the -Z axis and may be used to conveniently describe solar pointing vectors in the orbiter body system.

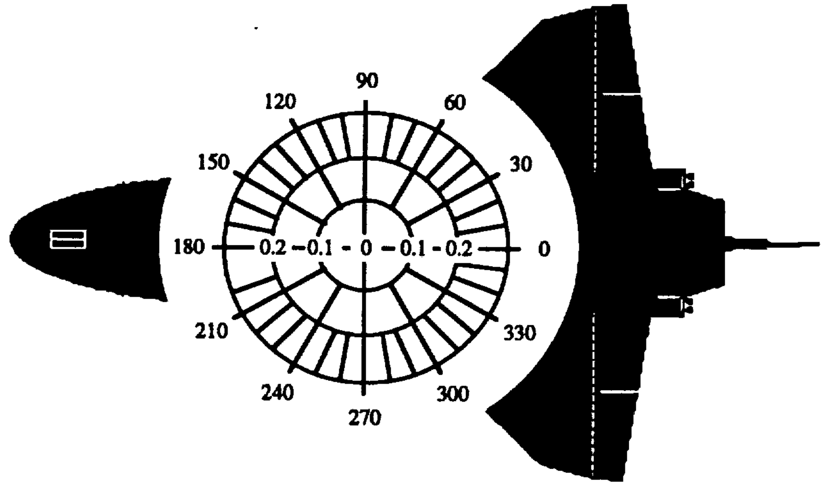


Figure 2. Orbiter Azimuth Co-elevation coordinate system

Although the solar criss-cross was designed specifically for the SOLCON experiment, the other The apparent movement of the sun is taken into account (removed) by using the orbiter Digital Auto Pilot (DAP) sun target logic which allows any orbiter body axis to be pointed toward the sun. Since the DAP depends on information from the Inertial Measurement Unit (IMU) to derive a predicted sun location, an IMU alignment is desired prior to the beginning of each solar period.

Figure 3 shows actual and predicted sun positions during the fourth and fifth observations of the first solar period of ATLAS 1. Note the rectangular shape created from the 0.1°/axis. attitude deadband standard for solar observations. The first plot, solar observation number four, has clearly two separate locations for actual and predicted sun position. The second plot, solar observation number five, shows the actual and predicted sun positions collapsed onto one location after an IMU alignment was performed just prior to the observation. The 0.1°/axis. deadband for solar observations can be decreased as far as 0.033°/axis in special circumstances assuming propellant budget is available. The rate deadband was fixed at 0.01°/sec/axis on ATLAS 1 and 0.02°/sec/axis on ATLAS 2. With one exception, instrument fields of view are large enough to tolerate these minor pointing errors. The SUSIM instrument with an operational field of view of $\pm 0.75°$ requires a fair amount of attention to be given to pointing precision during real time. [2]

Special Observations

Special observations, the second category, are used for any performances which require the orbiter to execute a maneuver during an observation. ATLAS 1 planned for the performance of two special observations nicknamed "criss-cross" designed for the SOLCON experiment and "5-point scan" for the SUSIM experiment. ATLAS 2 planned for these maneuvers as well as a third special observation nicknamed "asterisk". These procedures were developed separately under guidelines specified by individual experiments as a way to verify instrument/detector responses.

The solar criss-cross consists of two single axis maneuvers each designed to sweep the instrument axes through an eight degree arc with sun center located at the midpoint of the arc. Although the solar criss-cross was designed specifically for the SOLCON experiment, the other solar experiments are not excluded from taking data. Solar criss-cross maneuvers were planned for the first observation of the first solar period and the last observation of the last solar period for both ATLAS 1 and ATLAS 2.

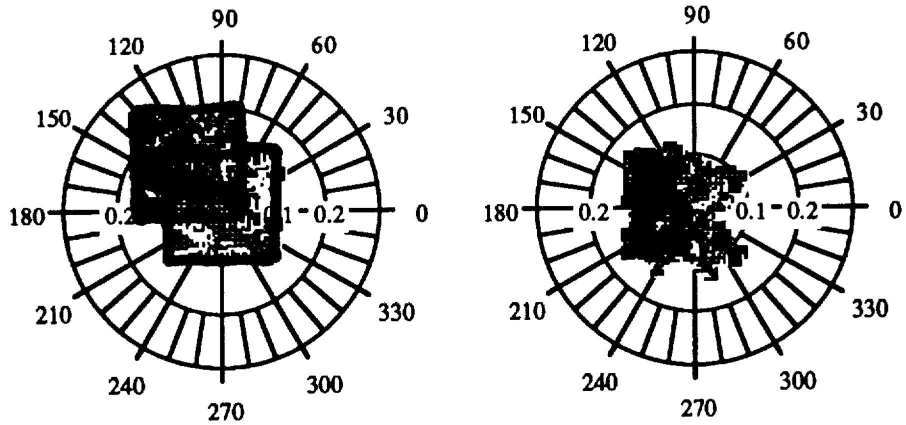


Figure 3. Actual and predicted sun position during solar observations 4 and 5 on ATLAS 1

The SUSIM Alignment Verification or 5-point scan is performed to provide data for assessing degradation of the instrument sensitivity and to map the sensitivity throughout the instrument field-of-view (FOV). The instrument FOV is mapped by observing the sun center in different regions of the FOV by pointing the instrument line-of-sight at different five points on the sun. The SUSIM Alignment Verification is performed twice: once early in the mission during the first solar period and again during the last solar period. The SUSIM instrument pointing for the alignment verification is performed using five different solar inertial attitudes with very small 0.033° attitude deadbands. [3]

Figure 4 shows examples of the solar criss-cross maneuver and the SUSIM 5-point scan generated from ATLAS 1 IMU telemetry data.

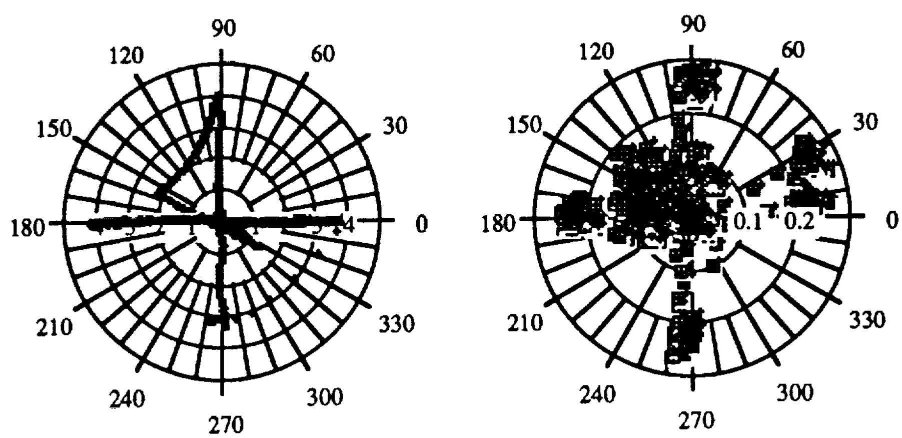


Figure 4. Solar criss-cross maneuver and SUSIM 5 point scan

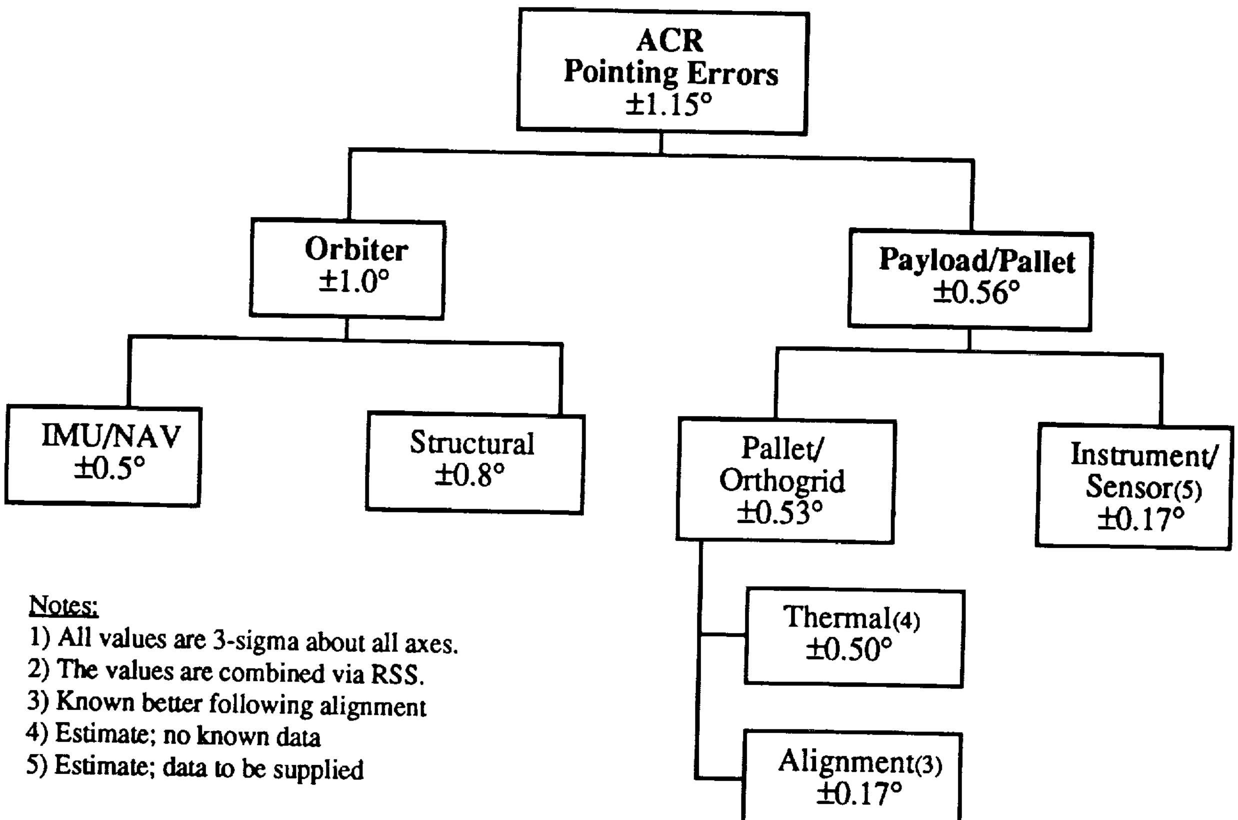
ORIGIN OF POINTING ERROR

Before the ATLAS-1 mission, very little accurate information was available describing the on-orbit pointing environment within the payload bay. Accurate pointing information is essential to the processing of data gathered by the ATLAS instruments. For one ATLAS instrument, the Millimeter Wave Atmospheric Sounder (MAS), a pointing error of 0.1° will cause an uncertainty of 3 kilometers in position for the experiment's examination of the atmosphere at the earth's limb. [4]

This need for accurate pointing information caused the creation of the Pointing and Alignment Workstation (PAWS) which brought together a small team of engineers to gather realtime pointing information from Orbiter and payload sources and to examine the pointing behavior of the Orbiter and the ATLAS instruments. The PAWS engineers were also tasked to determine the magnitudes of the instrument pointing errors resulting from the various contributing sources.

Prior to the ATLAS-1 flight, possible errors sources and their advertised limits were researched. The pointing error sources were identified and grouped as Orbiter-related and instrument-related. The primary Orbiter-related error sources are the IMU uncertainty and Orbiter thermal distortions. The payload-related pointing errors sources are thermal distortions and misalignment of the pallet, instrument calibration errors and mechanical misalignments. [5]

Using the identified pointing error sources and advertised accuracies from Orbiter and ATLAS payload documentation, a pre-mission error tree was constructed to provide the only prediction to the on-orbit pointing environment. The pre-mission predictions of an example ACRIM instrument pointing errors budget are shown in Figure 5.



Notes:
1) All values are 3-sigma about all axes.
2) The values are combined via RSS.
3) Known better following alignment
4) Estimate; no known data
5) Estimate; data to be supplied

Figure 5. Pre-mission Pointing Error Budget Tree [5]

Orbiter-based Pointing Error

The Orbiter uses three Inertial Measurement Units (IMUs) to determine the *believed* orientation of the Orbiter within the capability of the IMUs. The IMUs can be operated in a shared mode whereby the IMU information is selected from the units using the Redundancy Management (RM) logic, or by prime-selecting an IMU. For the ATLAS series, IMU alignments are performed approximately every twelve hours. This frequency is a compromise between the desired increase in pointing accuracy that IMU alignments provide and the time consumed by these alignments which reduce the available on-orbit time for the experiments.

Orbiter pointing errors also result from structural thermal distortions caused by solar heating along the distance between the Orbiter Inertial Measurement Units (IMUs) and the ATLAS pallet. Since, for the most part, this distance lies along the long axis of the Orbiter, the pointing error is most significant in the pitch axis. Prior to the first ATLAS flight, predicting the pointing error due to thermal distortions was difficult due to the changing thermal environment and the uncertainty of the effect on the Orbiter structure. The structural thermal distortions were actually the largest contribution to the pointing error seen by the ATLAS solar instruments.

Payload-based Pointing Error

The payload-related errors can be a result of mechanical misalignments at assembly, calibration errors due to internal instrument misalignments, or due to thermal distortions and misalignment of the pallet where the ATLAS instruments are mounted. [5]

The assembly mechanical misalignment errors are unavoidable due to the inherent inaccuracies of the optical alignment measuring devices and the instrument alignment which is performed in a 1-g environment. [5]

Another problem which increased the difficulty of pointing during the ATLAS missions is the misalignment of the solar instruments' line of sight with respect to each other. Figure 6 illustrates the instrument line of sight with respect to the SUSIM alignment cube on ATLAS 1. For ATLAS 1, the solar instrument pointing problem was even greater since the SUSIM alignment cube was aligned to the -Z axis rather that the center of the SUSIM field of view (SUSIM Science), complicating solar pointing. During assembly and alignment for ATLAS 2, the SUSIM field of view was properly aligned with the -Z axis so that an offset was not required.

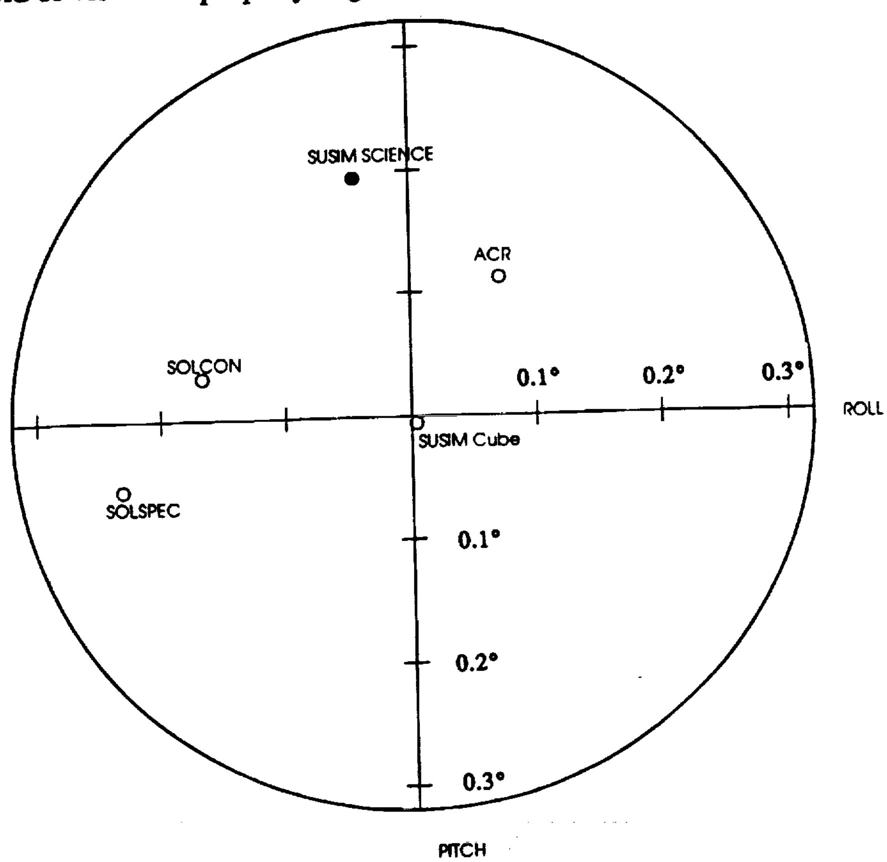


Figure 6. Solar Instrument Relative Alignment

POINTING BEHAVIOR DURING ATLAS SOLAR OPERATIONS

During any given solar observation, pointing errors may accumulate due to instrument misalignment, IMU uncertainty and drift, as well as other sources. If these errors become too great data may be lost or degraded as a result of the sun tracking outside of an instrument field of view. Prior to the flight of ATLAS 1, the payload planning team developed a procedure to allow for the solar experimenters to request pointing corrections in the event of instrument misalignment. One of the ATLAS solar instruments, SUSIM, was equipped with a sensor to determine the relative position of the sun in the instrument field of view. During ATLAS 1, it became clear that the SUSIM sun sensor would be used as the basis for determining pointing accuracy for the solar experiment complement. Fortunately, the majority of solar observations were performed without difficulty. However, at the beginning of the third solar period, SUSIM noted from their data that a pointing correction would be necessary. This initiated a call/response loop between the planning team and SUSIM which proved only marginal effectiveness at fixing the problem and in some cases made it worse. Figure 7 shows a histogram of the SUSIM sun sensor data for the first four observations of the third solar period on ATLAS 1 [5].

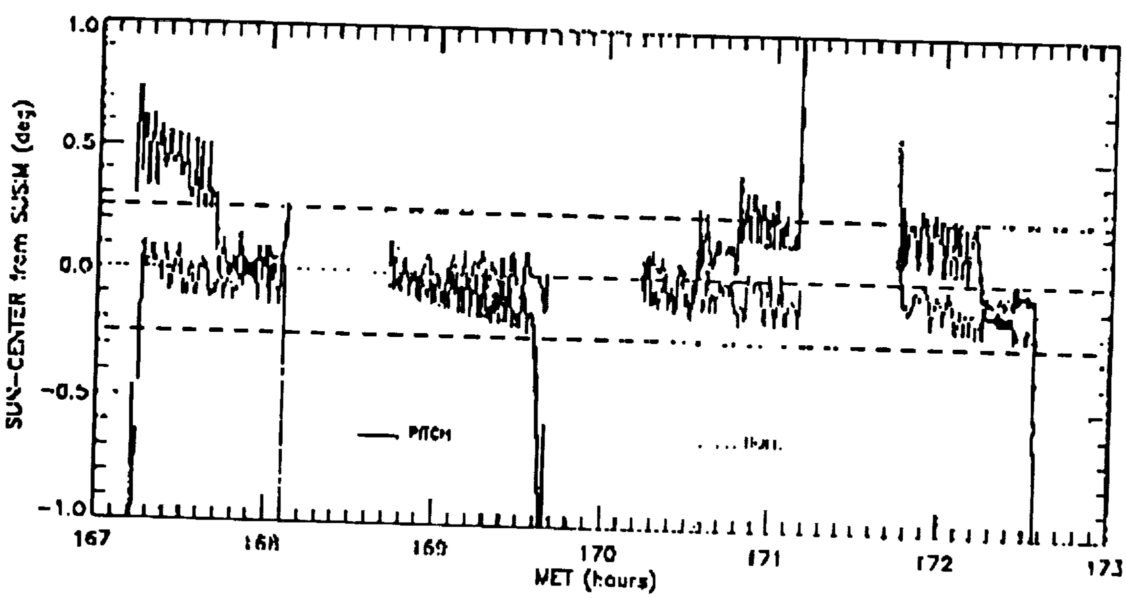


Figure 7. SUSIM Sun Sensor data from ATLAS 1

Clearly, from Figure 7, instrument pointing during the first observation begins with a pitch offset well away from sun center. A pitch correction based on this information was computed by the payload planners and executed by the orbiter crew halfway through the observation.

The first plot of Figure 8 shows IMU telemetry data during this observation. Point A in Figure 8 is sun centered according the IMU. The pitch correction maneuver applied halfway through the solar observation is shown by point B. This correction places sun center approximately 0.25° toward the nose of the orbiter. The same pitch offset applied to the following observation appears at first to have completely corrected the problem; however, returning to Figure 7, the end of the observation has drifted enough in pitch to require a further correction on the following pass.

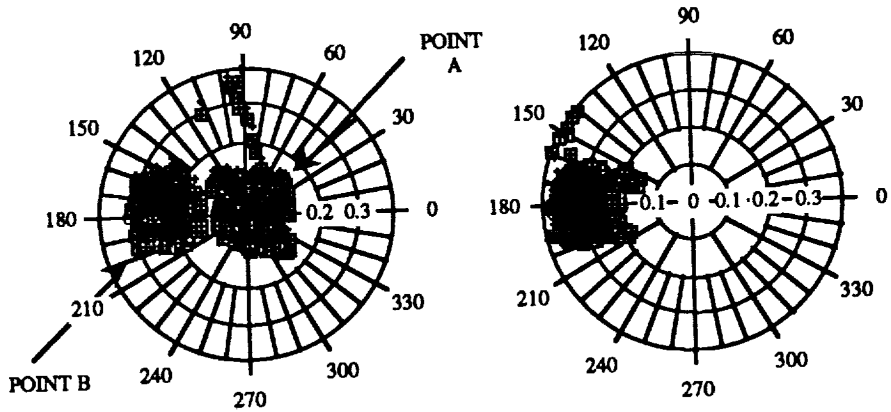


Figure 8. First and second observations of the third solar period.

Pointing behavior during the third solar period was confusing to the planning team mainly due to the fact that all of the data shown here was not available in real time. The large drift rate was at first attributed to orbiter IMU; however, the Guidance, Navigation, and Control (GNC) officer denied that the magnitude of error being suggested by the SUSIM sun sensor could have this cause. The actual cause of the large pitch drift during these observations turns out to be mainly related to thermal bending. Since the solar instruments became misaligned relative to the IMU reference system, the attitude adjustments did not correct the position of the sun in the instrument fields-of-view. Corrections which were performed before the misalignment trends were well-established or understood resulted in incorrect adjustments illustrated by the final observations of Figure 7.

During both ATLAS 1 and ATLAS 2, a sinusoidal variation in instrument pointing was observed by several PIs and by the PAWS engineers. The amplitude and phase of the sinusoidal variations changed when maneuvering from +X/VV to -X/VV. Investigations of the cause of this pointing error has shown that during ATLAS 2 one of the aging KT-70 units performed poorly and when the Redundancy management (RM) logic computed the pointing information, the RM logic caused rapid switching between the three IMU units when one IMU was not "prime-selected". The roll drift between the "good" and "bad" IMUs was 0.12° to 0.20°. The sinusoidal pointing error can be explained, in part, by the on-board computer shifting between one IMU unit's reference system to another unit's system. [6]

New HAINS IMU units are beginning to replace the older KT-70 units. The new units are expected to have an IMU drift rate for small dispersions (1-sigma) of approximately 0.006°/hour. This new capability will provide reduced IMU pointing error. Also, to minimize the IMU drift during the solar operations, an IMU alignment is scheduled immediately before the start of the solar period. Another IMU alignment is scheduled immediately following the last sun observation of the solar period to characterize the IMU drift throughout the period.

An on-orbit crew procedure called SUSIM nulling was developed for ATLAS 2 to center the -Z body axis using the SUSIM sun sensor. Pitch and roll fly-to angles were used to correct the instrument pointing misalignments from the planned solar attitudes since these values would be more meaningful to the Orbiter crew making the corrections. Using this procedure, the misalignment was properly corrected. One problem with the SUSIM nulling procedure was that the process required a crewman to reposition the monitor to allow the pilot to see the SUSIM sun sensor information. The nulling process could not be performed if the crew was busy at other tasks.

In addition to the new SUSIM nulling crew procedure developed for ATLAS-2, the SUSIM 5-point alignment verification crew procedure was added. Previously, the pilot followed a long list of attitudes and maneuvers in the attitude timeline (ATL) to orient the Orbiter -Z body axis at a sequence of five fixed points on the solar disk. The maneuvers were very small, approximately 0.3°, and were extremely difficult to perform manually. Consequently, the ATLAS-2 SUSIM alignment verifications were performed from a detailed list of procedures for the complex operations, and by using the DAP, the pilot performed precise Orbiter pointing.

The solar criss-cross activities are much less complex than the 5-point alignment verification and are directed from the attitude timeline. A special solar crisscross on ATLAS-2 was developed to perform eight scans across the sun in a pattern resembling an asterisk. Since this complex sun scan was developed during the flight, it was not possible to develop a crew procedure and so it was scheduled using the attitude timeline. For future ATLAS missions, a crew procedure will be developed to simplify the complex sun scan activities.

CONCLUSIONS

There was much pressure during the ATLAS 1 on-orbit operations to quickly assess and correct the pointing errors. Immediate action caused two problems: to understand the pointing behavior, time was required to let the trends develop and to examine these trends; the second, is to properly coordinate the necessary changes to the solar operations through a number of different groups located at different NASA centers and ultimately to the crew.

Resulting from lessons learned during ATLAS 1, hardware and procedural changes were made to allow the ATLAS 2 crew to view on-board instrument pointing data and to correct the instrument pointing errors immediately. The crew and flight planners were extensively trained prior to the second ATLAS flight to perform the correction procedures.

The flight of ATLAS 1 for payload planners provided many lessons for understanding the behavior of the Orbiter as a pointing platform. This experience permitted improved solar operations for ATLAS 2 and can be applied to future flights which use the Orbiter as a pointing platform.

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