Interoffice Correspondence
TRW Space & Electronics Group

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Chandra X-Ray Observatory Sun Exclusion Limits and Operating Procedure	16 March 1999 AXAF.99.333.002	P. Quast
To	**cc**	**Location/Phone**
A. Lavoie (MSFC) B. Graham (MSFC)	Distribution	R9/2294 x38033

References

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[21] IOC AXAF.99.333.003, "IRU Monitor Analysis", P. Quast, release pending

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1. Introduction

The physical limits of the sun position in the observatory coordinate system can be categorized into two principle groups:

- Survival limits necessary to prevent damage to the observatory.
- Performance limits necessary to ensure proper operation of the observatory for science.

Each of these physical limits has a period of time associated with it establishing the maximum duration allowed for the sun position to be beyond it. For some constraints, the sun is prohibited from being beyond it for any period of time. For other constraints, illumination beyond the limits is allowed for a specified period of time, after which the sun must be within the constraints for another specified period of time required for thermal recovery.

The purpose of this discussion is to first clarify the survival limits necessary to protect the observatory. Based on these survival limits, the thresholds for the Pointing Control and Aspect Determination (PCAD) monitors and modifications to operating procedures necessary to enforce these limits will be established. Finally, based on the PCAD monitor limits selected, the Off-Line System (OFLS) maneuvering constraints will be defined. This IOC will not address sun exclusion limits as they relate to performance.

2. Coordinate Systems

For sun exclusion, the coordinate system used most frequently to establish the orientation of a vector in the observatory coordinate system is the sun pitch-roll system as defined in Reference 1. In addition, as viewed from the point in the Chandra orbit closest to the sun, the angle subtended from the sun center to its limb is approximately 0.27^{o}. Care must be exercised to take this into account when specifying the exclusion limits of the sun and when setting the monitor and maneuver limits. Typically, sun position is specified to the center of the sun. However, certain specifications will use other conventions. For example, sun limb avoidance angle will be used to refer to the angle from the observatory line of sight (LOS) to the nearest sun limb. In the discussion presented here, overt distinctions will be made as necessary to distinguish between specification of the sun center and specification of limits applied to any other part of the sun.

When specifying observatory attitudes or vector directions (e.g. sun pitch-roll coordinates), care must be taken to distinguish which coordinate system is being used. The two principle structural units which comprise the observatory are referred to broadly as the telescope and the spacecraft. For purposes of the discussion herein, the telescope will be considered to be comprised of the Optical Bench Assembly (OBA), High Resolution Mirror Assembly (HRMA), Aspect Camera Assembly (ACA) and Integrated Science Instrument Module (ISIM). As discussed in Reference 2, these components are configured such that the HRMA optical axis, the +X axis of the OBA and the LOS of the ACA are aligned within arcseconds of each other and can be considered to be perfectly aligned with each other for sun exclusion purposes. Indeed, after Aspect Camera (ACA) activation and spacecraft fine attitude determination and calibration, it is the telescope/ACA coordinate systems which define attitude reference for the observatory. The spacecraft is comprised of all other components of the observatory which are not part of the telescope. The primary structure of the spacecraft is the central cylinder which is connected to the OBA by 6 struts.

During design and integration, the nominal coordinate system used as a reference is referred to as the observatory coordinate system with respect to which the telescope and spacecraft coordinates are nominally aligned. However, as discussed in Reference 3, considering worst case tolerances where as-built dimensions are unknown, the HRMA optical axis may be misaligned with the spacecraft coordinate system on the order of tenths of a degree. All of the viewing requirements as well as the sun exclusion limitations which involve components of the telescope are relative to the telescope coordinate system.

3. Physical Constraints

There are several physical limits of the sun position for the observatory:

3.1. Science Instruments

Entry of any sunlight into the HRMA field of view (FOV) while the sun shade door is open and a science instrument is at the HRMA focal point will result in immediate damage of the associated instrument. Damage may also occur in this configuration even if the translation table position is such that there are no science instruments at the HRMA focal point due to material destruction by intense heating and resulting contamination. The HRMA FOV encompasses a region 0.5^{o} from the HRMA optical axis. Thus, in order to prevent any sunlight from entering the HRMA FOV directly, pitch angles of the sun center must to be restricted at all times while the sun shade door is open to be greater than approximately 0.77^{o}. Reference 4 further restricts the position of the sun limb to never be closer than 15^{o} to the HRMA LOS for any period of time.

3.2. HRMA

References 4 and 5 identify constraints due to thermal limitations for the HRMA. As discussed in the Reference 6 telecon, the HRMA has an outside diameter of approximately 52.0", but the sun exclusion region for the HRMA is a circle 49.5" in diameter which is coplanar with the HRMA precolumnator face and concentric with the HRMA optical axis. The circle which defines the HRMA sun exclusion region just circumscribes the HRMA aperture. Direct solar illumination of the HRMA sun exclusion region for sun limb angles greater than 15^o is restricted to be less than 12 minutes in duration with an accompanying period of time required after illumination for thermal recovery. However, K. Havey stated in the Reference 6 telecon that although Kodak had concluded by analysis that indefinite illumination of the HRMA outside of this sun exclusion region was acceptable, added margin for HRMA survival would be gained by restricting illumination of the HRMA altogether.

References 7 and 8 provide detailed definition of a boundary, in terms of sun pitch-roll coordinates relative to the nominal observatory coordinate system, inside of which a ray of sunlight will directly illuminate the HRMA sun exclusion region or the Stray Light Shade (SLS) of the Aspect Camera Assembly while the sun shade door is open. In addition, a more detailed assessment in the regions near pitch angles equal to 45^o and near where illumination of the SLS would occur, assuming worst case positions for the hardware involved (HRMA alignment, sunshade door), was performed by D. Lindenman (TRW) and is presented in Table 1.

Table 1: Detailed Roll Constraint for HRMA Sun Exclusion

Pitch (degrees)	Roll (degrees)	Constrained By
45.2	+/- 4.1	HRMA
45.4	+/- 5.7	HRMA
45.6	+/- 7.2	HRMA
45.8	+/- 8.2	HRMA
46.0	+/- 9.1	HRMA
83.0	+ 21.0	SLS
83.2	+ 21.6	SLS
83.6	+ 24.5	SLS
84.0	+ 25.1	HRMA
85.5	+ 26.9	HRMA
86.0	+ 27.2	HRMA

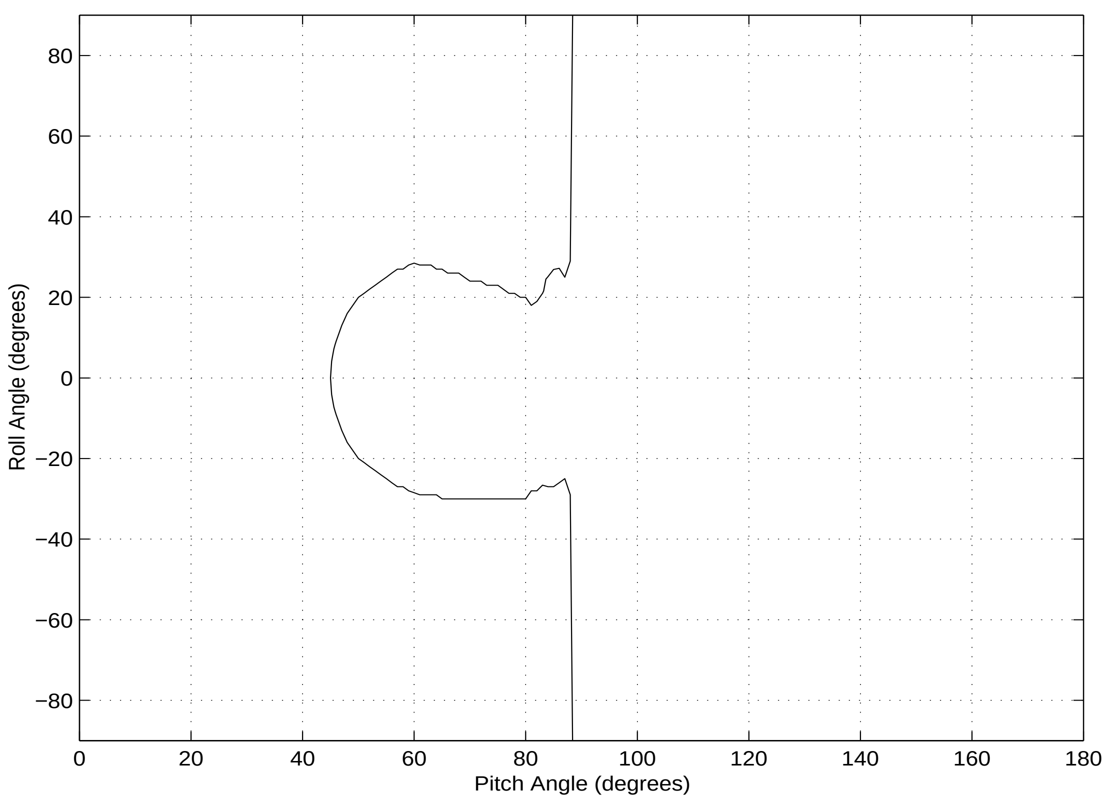
However, the sun pitch-roll angles identified in References 7 and 8 and Table 1 were with respect to a nominal observatory coordinate system. Reference 4 requires that the capacity exist to perform observations with the sun limb at 45^{o} from the observatory LOS, which will, in general, be different from the nominal +X axis of the observatory. Reference 3 provides a detailed assessment of the minimum angle between the HRMA optical axis and the sun limb for zero off-nominal roll which will ensure that the HRMA sun exclusion region is not illuminated assuming worst case observatory component alignments and orientations. The Reference 3 results are summarized in Table 2. The References 7 and 8 constraints as well as those presented in Table 1 are depicted in

Table 2: Summary of HRMA Sun Exclusion Angles

Exclusion Region	HRMA LOS to Sun Limb (degrees)	Sun Pitch Angle (degrees)
HRMA Sun Exclusion Region (49.5" diameter)	45.27	45.54
Entire HRMA (52.0" diameter)	45.67	45.94

Figure 1. Rays of sunlight with zero off-nominal roll and with pitch angles greater than those

Figure 1. HRMA/SLS Sun Exclusion Limits



presented in Table 2 or with sun pitch-roll combinations to the right of the boundary depicted in Figure 1 will not impinge the HRMA/HRMA sun exclusion region or the SLS while the sun shade door is open. Thus, based on the Reference 3 results, the 45 degree sun limb avoidance angle requirement for viewing capability defined in Reference 4 cannot be assured to be met safely by the observatory.

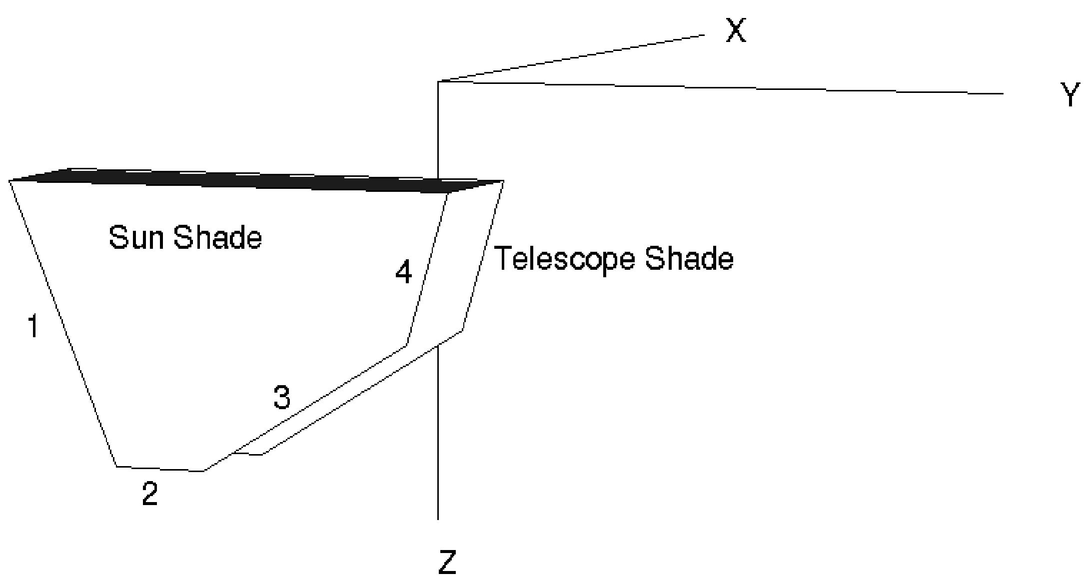
3.3. ACIS

The AXAF CCD Imaging Spectrometer (ACIS) uses a radiator located on the +Z side of the observatory to maintain thermal control of ACIS focal plane temperatures. The radiator has shades adjacent to it to reduce direct or indirect thermal visibility of it by the sun or the observatory. As depicted in Figure 2, the ACIS radiator shades consist of a shade in the +X direction, referred to as the Telescope Shade. A second shade, nearly identical in dimension to the Telescope Shade, parallel to it and translated toward the -X direction by approximately 18 inches, is referred to as the Sun Shade. Illumination of either inner surface of the ACIS radiator shades is problematic for 2 reasons:

- Illumination of the inner surfaces of the shades will result in higher ACIS focal plane temperatures with the possibility of accompanying decrease in ACIS performance.
- Illumination of the inner surfaces of the shades for an extended period of time will result in the destruction of those surfaces and possibly the loss of ACIS capability.

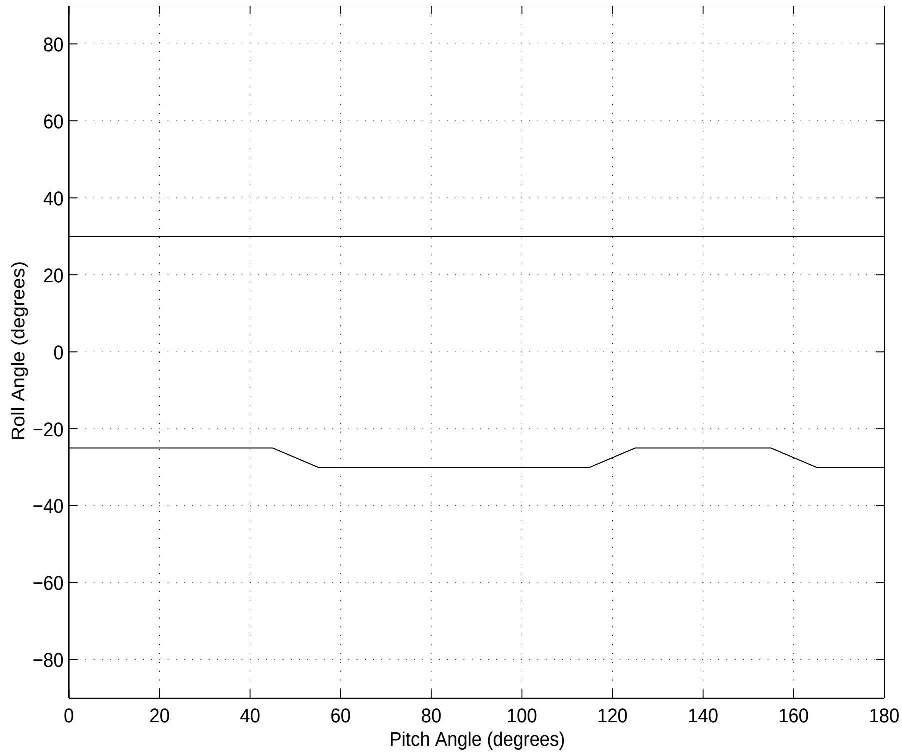
Based on the Reference 9 and 10 conversations, illumination of the inner surfaces of the shades must

Figure 2. ACIS Radiator Shades



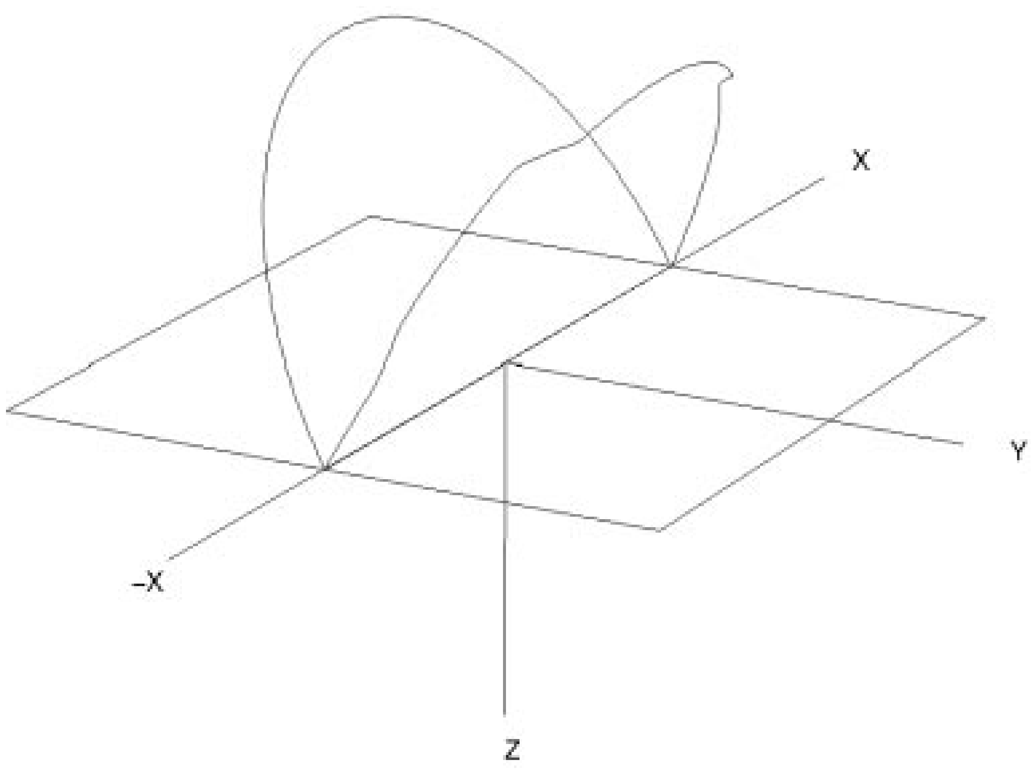
be restricted to less than 30 minutes in duration with an accompanying period of time required after illumination for thermal recovery of the shades and ACIS performance. Illumination times beyond this will result in destruction of those surfaces. As shown in Figure 2, there are 4 pairs of parallel edges of the shades which define four planes. These 4 planes, taken together, form a boundary such that if any part of the sun is beyond this boundary toward the +Z direction, sunlight will impinge

Figure 3. ACIS Sun Exclusion Limits



the inner surface of the shades. For nominal dimensions and configuration of the shades, the planes defined by the pairs of edges numbered 1 and 4 in Figure 2 form the limiting constraint to off-

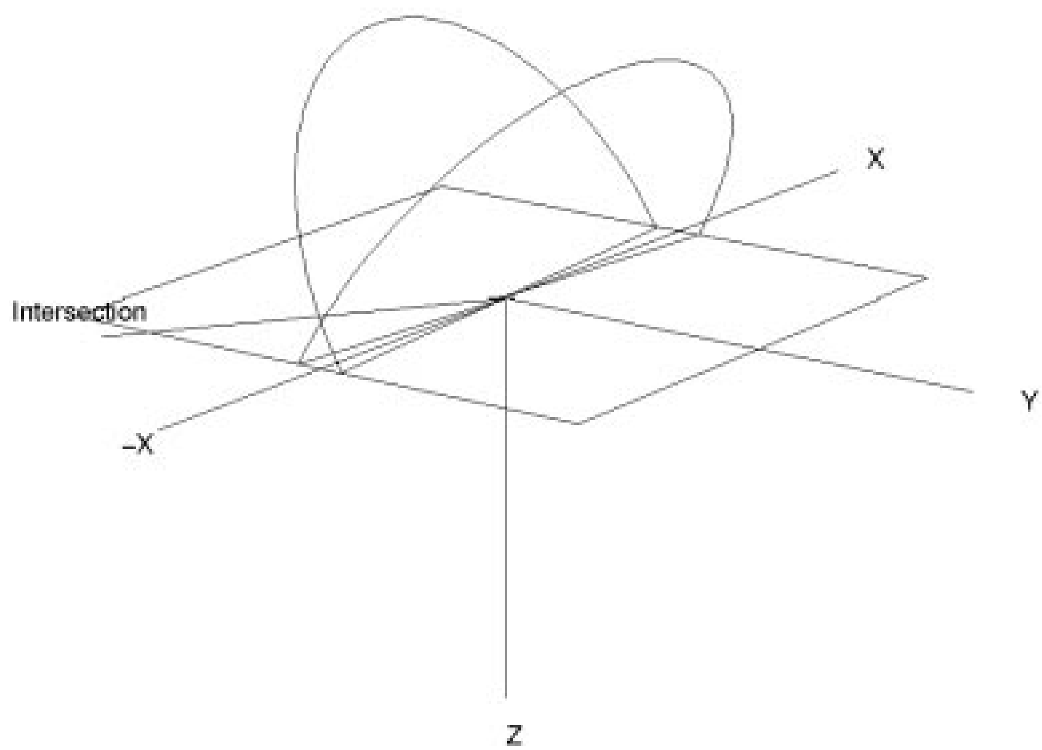
Figure 4. ACIS Sun Exclusion Limits in Observatory



nominal roll sun positions. These planes are oriented relative to the XZ plane by rotations of +/- 30^o about the X axis. The depiction of this constraint, as detailed in Reference 5, is presented in sun pitch-roll coordinates in Figure 3. Note that Reference 4 presents constraints only for sun pitch angles greater than 45^o. For completeness, the limits in Figure 3 have been extrapolated for pitch angles between 0^o and 45^o. The sun pitch-roll constraints for the ACIS radiator shades which are shown in Figure 3 in sun pitch-roll coordinates are also illustrated qualitatively in the observatory coordinate system in Figure 4.

The Reference 4 requirements establish that the observatory be able to observe targets with a sun pitch angle of 180^o (the center of the sun on the -X axis). If a nominal configuration of the ACIS radiator shades is assumed, a sun pitch angle of 180^o (center position located directly on the -X axis of the observatory) will result in a small width of illumination along the outer part of the inner surface of the Telescope Shade (on the order of 0.1 inches) due to the finite arc subtended by the sun. Further, in the Reference 9 conversation, N. Tice (Lockheed Martin) and M. Kilpatrick (Ball) stated that the actual ACIS radiator shade as-build configuration and orientation relative to the observatory coordinate system or their associated worst case tolerances are not certain. Thus, a larger area of the inner surface of the Telescope Shade could be illuminated for a sun pitch angle of 180^o. For example, if the Sun Shade were to be just slightly smaller than the Telescope Shade, then, as depicted qualitatively in Figure 5, the two planes formed by edges 1 and 4 would intersect along a line at a pitch angle less than 180^o. If no portion of the ACIS radiator shades were allowed to be illuminated by any part of the sun for an extended period of time, then assuming a worst case non-nominal configuration of the ACIS radiator shades and accounting for the angle subtended by the sun, limits would need to be applied to restrict the maximum allowable sun pitch angle below 180^o.

Figure 5. Anomalous ACIS Sun Exclusion Limits in Observatory coordinate



However, assuming:

- Probable worst case dimensions for the ACIS radiator shades.
- Probable worst case orientation of the ACIS radiator shades relative to the observatory coordinate system.
- A conservative assessment of the thermal tolerance of the inner surface of the shades to a small area of solar illumination near the edge of the shades.
- The 1/8-1/4 inch of multi layer insulation (MLI) which presently extends beyond the edge of the sun shade and which will expand when illuminated by sunlight.

participants in the References 9, 11 and 12 discussions concurred that for sun exclusion purposes:

1. Nominal dimensions and configuration of the ACIS radiator shades could be assumed.
2. Sunlight could safely and indefinitely illuminate the ACIS radiator shades up to an angle of 1^{o} beyond the planes defined by the parallel edges of nominally configured ACIS radiator shades.

Under these assumptions, the sun pitch angle with respect to the ACIS radiator shades is no longer limited by the planes defined by the pairs of edges numbered 1 and 4 in Figure 2. The limit is instead defined by the plane defined by the pair of edges numbered 2 in Figure 2. In this case, the sun limb is constrained by a plane rotated $+1^{o}$ beyond the XY plane. Thus, a sun pitch angle of 180^{o} can safely be attained.

3.4. ISIM

Reference 5 identifies estimates derived from analysis of off-nominal roll limitations which will maintain Science Instrument temperatures below vendor specified operating limits. These estimated limitations vary depending on which instruments are powered on and also vary over the lifetime of the mission. For the beginning of life (BOL), off-nominal roll is restricted to be no greater than $+/-30^{o}$ (slightly more restrictive when the HRC is in view and 6 ACIS CCDs are operating). As the mission progresses over the first several years of on orbit operation, the analysis derived limits become more restrictive. However, based on discussions with S. Texter (TRW) and J. Vogrin (TRW), the underlying assumption for operation of the Science Instruments with respect to off-nominal roll capability is that the true thermal behavior during operation of these instruments over the life of the observatory is uncertain and will be assessed on an ongoing basis. Since the limits for nominal operation of the ISIM at BOL are not certain and are less restrictive than the off-nominal roll constraints for the ACIS radiator shade, they are assumed to be satisfied at BOL by the ACIS radiator shade constraints.

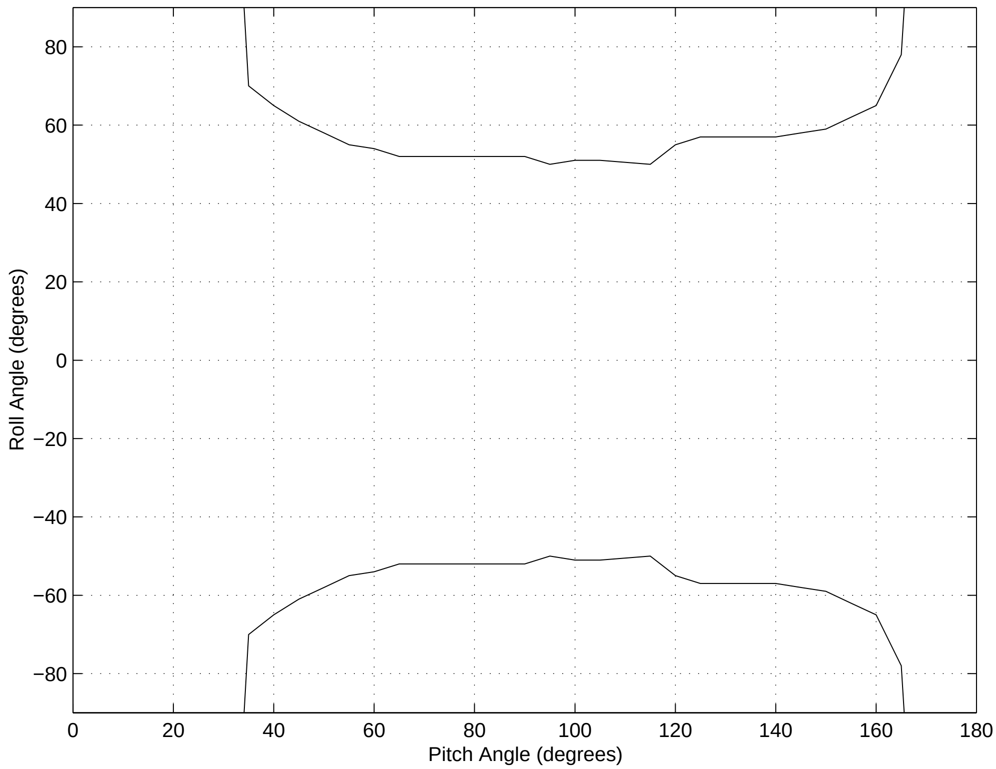
3.5. Electrical Power Subsystem

There are two primary sun exclusion concerns regarding the Electrical Power Subsystem (EPS):

3.5.1. Solar Array Shadowing

In order to prevent damage to the solar arrays due to development of reverse currents in the arrays, Reference 13 item EPS-C-006, “Solar Array Shadows”, provides limitations regarding shadowing of the solar arrays and constraints on the minimum shadow edge rate allowable when shadowed. Figure 6 illustrates the sun pitch-roll configuration for which the solar arrays will be shadowed by

Figure 6. Solar Array Shadowing Sun Exclusion Limits

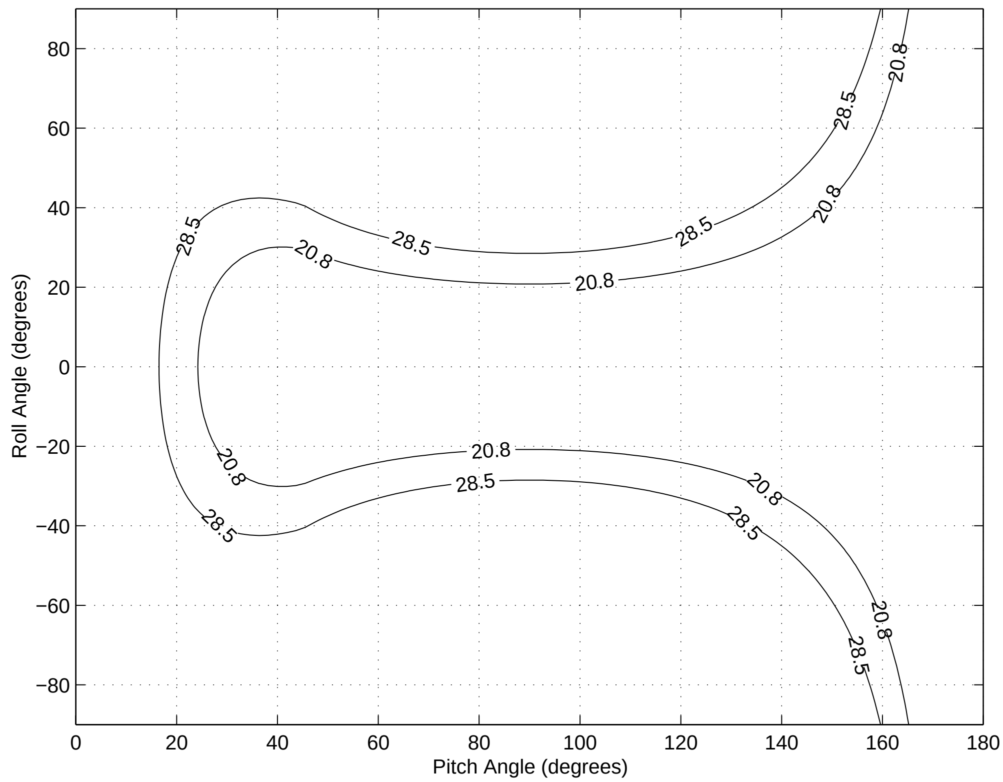


the body of the observatory (off-nominal roll angles between the two boundaries depicted will not result in shadowing).

3.5.2. Solar Array Offpointing

If the normal of the solar arrays is off pointed from the sun, the reduced array temperature will lead to higher array open circuit voltages which may damage the EPS or other electrical equipment depending on the load conditions at the time. Reference 13 item EPS-C-008, “Solar Array Off-Pointing Limits During Transfer Orbit” provides the constraint that the solar array normal may not be more than 20.8^{o} away from the sun during the summer and no more than 28.5^{o} away from the sun during the winter. Figure 7 depicts the sun pitch-roll configurations which will result in solar array off-pointing by 20.8^{o} and 28.5^{o}. Sun pitch-roll combinations to the right and between the constraints depicted in Figure 7 will result in off-pointing by less than these amounts.

Figure 7. Solar Array Off Pointing Sun Exclusion Limits



4. PCAD Monitor Protection

The PCAD subsystem uses several monitors to enforce the Section 3 sun exclusion constraints. The Reference 14 development of the monitor scheme uses 2 monitors for this purpose:

4.1. Commanded Attitude Monitor

The Commanded Attitude Monitor ensures that the current target attitude or the next commanded target attitude, as specified by the commandable variable Q_Targ_Cmd, will not place the sun in an unacceptable location in the observatory coordinate system. The implementation of the monitor requires 2 things:

- An accurate ephemeris to determine the current sun position in inertial space.
- Given an ephemeris derived sun vector, an algorithm for checking whether that sun position transformed into the target frame is acceptable.

An onboard sun ephemeris model is used along with the onboard ephemeris time to predict sun position. The ephemeris model is derived from Reference 16 which claims an accuracy of 0.01^o. Using quaternion algebra, the monitor then performs a transformation of the ECI sun vector to the target frame defined by Q_TARG_CMD. If the monitor trips due to an improper attitude being commanded, then the following action is taken:

1. The target quaternion is set equal to the estimated quaternion.

2. If the PCAD mode is Normal Maneuver Mode or Powered Flight Mode, the PCAD mode is commanded to Normal Point Mode or RCS Maneuver Mode Respectively.

3. SCS 28 is called which:

    1. Terminates all mission SCS's.

    2. Disables itself (SCS 28).

Thus, the effect of tripping the Commanded Attitude Monitor is to have the observatory attempt to hold its attitude at the time of the monitor trip (on gyros or on bright stars).

4.2. Sun Position Monitor

The Sun Position Monitor checks the measured position of the sun against acceptable sun attitudes in the observatory coordinate system. The implementation of the monitor therefore requires 2 things:

- Accurate measurement of the sun position in the observatory coordinate system.
- Given a measurement derived sun vector, an algorithm for checking whether that sun attitude in the observatory coordinate system is acceptable.

For the Sun Position Monitor, the monitor calculates a position of the sun in the observatory coordinate system using data from one of two sensors:

- If the sun is in the Fine Sun Sensor (FSS) field of view (FOV), the monitor uses the sun vector derived from FSS measurements. As described in Reference 17, the worst case accuracy of the FSS is approximately 0.05º.
- If the sun is outside of the FSS FOV, the monitor uses the sun vector derived from Coarse Sun Sensor (CSS) measurements. As discussed in Appendix A, there are several sources of error that affect the determination of sun vector using CSS data. These sources of error include:

    1. In-plane, out-of-plane and torsional solar array deflection.

    2. Discrepancies between the solar array resolver determination of solar array rotation and the true attitude of the outer edge of the array relative to the observatory coordinate system.

    3. Differences in the gain between CSS units (as-built unit to unit differences, temperature dependency).

    4. Differences of the gain of all CSSs together from the nominally assumed value (unit

degradation over time, thermal differences, changes in earth-sun distance).

As presented in Appendix A, considering all possible combinations of error sources in sun vector determination, the estimated maximum error in CSS sun vector determination is approximately 5^o when the sun is near the solar array normal and up to approximately 20^o when the sun is 60^o off of the solar array normal.

4.3. Monitor Specification of Sun Boundaries

As discussed in Sections 4.1 and 4.2, the Commanded Attitude Monitor and Sun Position Monitor require an algorithm for determining the acceptability of a particular attitude of a sun vector in the observatory coordinate system. In the Reference 15 flight software implementation of these monitors, both monitors use the same algorithm and share the same associated constants to describe regions in the observatory coordinate system which are acceptable locations for the sun. The implementation is as follows:

- Two ellipses are defined in the XY plane of the observatory, the interiors of which define the acceptable locations for the projection of a unit sun vector in the XY plane. The ellipses are centered about the pitch=90^o, roll=0^o vector orientation and are symmetric for a given pitch angle with respect to roll angle.
- The ranges of sun pitch angles over which either of these 2 ellipses apply is specified (in terms of the X component of a unit sun vector).
- A limit of the maximum value allowed for the projection of a unit sun vector onto the Z axis is specified. This limit equates to restricting the proximity of a unit sun vector to the XY plane.

For a unit sun vector with components X,Y and Z, these monitor constraints can be summarized as requiring that the following two conditions be met:

$$Z \le \text{KP.Plus\_Z\_Lim} \qquad (1)$$

and

$$\frac{X^2}{(\text{KP.X\_Ellipse(i)})^2} + \frac{Y^2}{(\text{KP.Y\_Ellipse(i)})^2} \le 1 \qquad (2)$$

for KP.Sun_Vec_X_Thresh(2) < X < KP.Sun_Vec_X_Thresh(1)

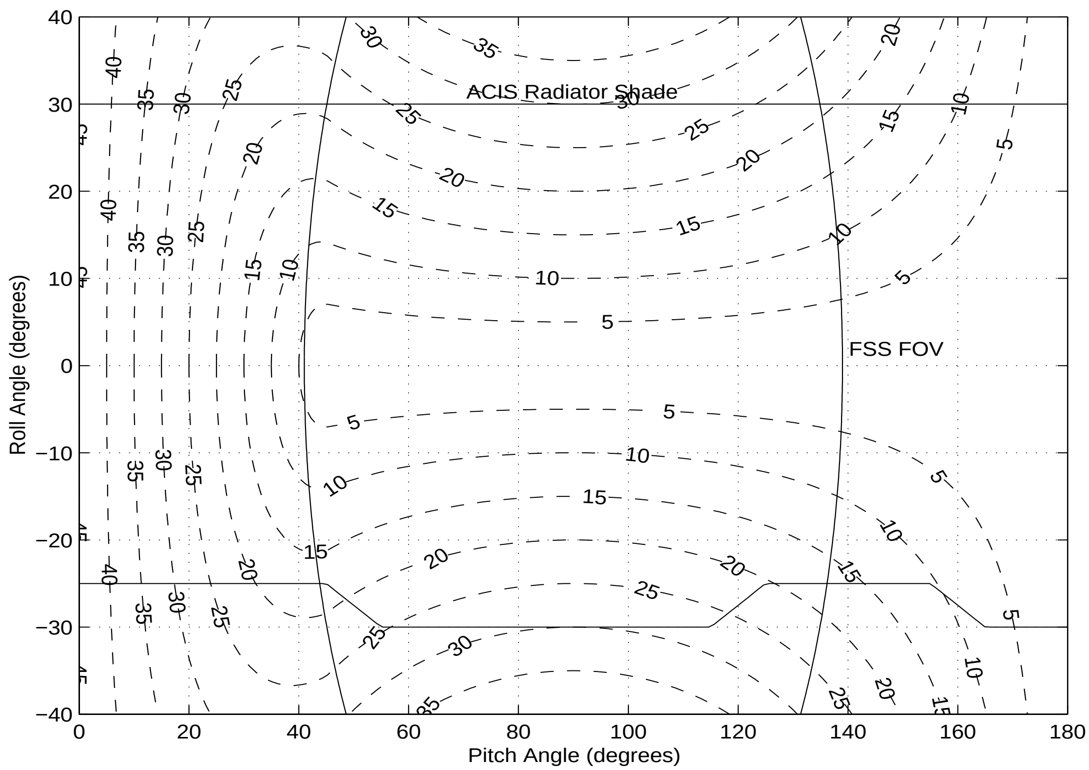
where i=1 for X < KP.Region_Bound and i=2 for X >= KP.Region_Bound.

4.4. Monitor Limitations

In determining the Commanded Attitude Monitor and Sun Position Monitor thresholds, consideration must be given to the relative accuracy with which the ephemeris based or measured position of the sun can be ascertained. To ensure sun protection, the monitor thresholds would have to be set assuming worst case sun position knowledge error. Further, although many of the Section 3 sun exclusion limits allow for sun excursion beyond those limits for certain periods of time, the Reference 15 flight software implementation of these monitors does not allow for discrimination with respect to periods of time allowed for sun positions beyond a given boundary. Therefore, if the monitor thresholds are to be set to protect the observatory from damaging sun attitudes, they should be set such that the monitor trips absolutely in the event that the sun position violates the physical constraints established. In this case, the monitor thresholds must be set such that a measured or calculated sun vector which is on the monitor bound is "inside" of the physical constraints in the observatory coordinate system by a closest angular margin equal to the maximum angular error of the calculated sun vector. Further, since the flight Software will use the same values of these thresholds for both monitors, the thresholds used must represent the intersection of necessary sun pitch and off-nominal roll constraints for each monitor.

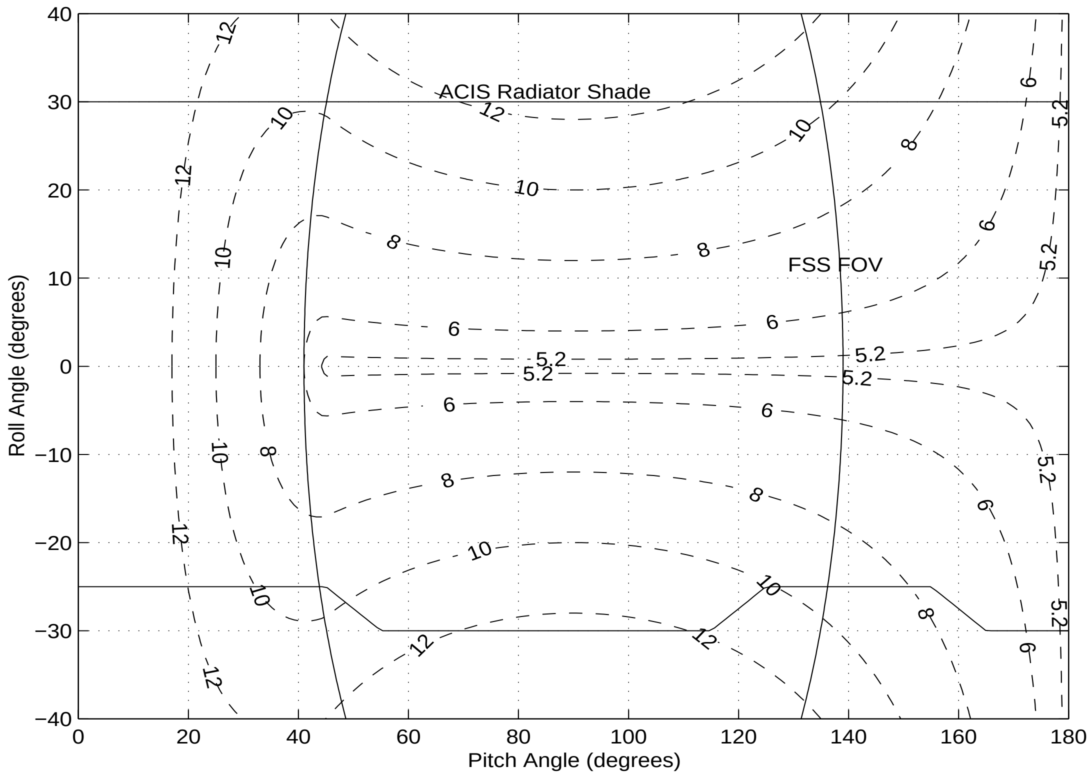
For the Commanded Attitude Monitor, the maximum angular error for ephemeris calculations is assumed to be less than 0.01^{o} as claimed by Reference 16. For the Sun Position Monitor, the

Figure 8. Angle from SA normal (degrees)



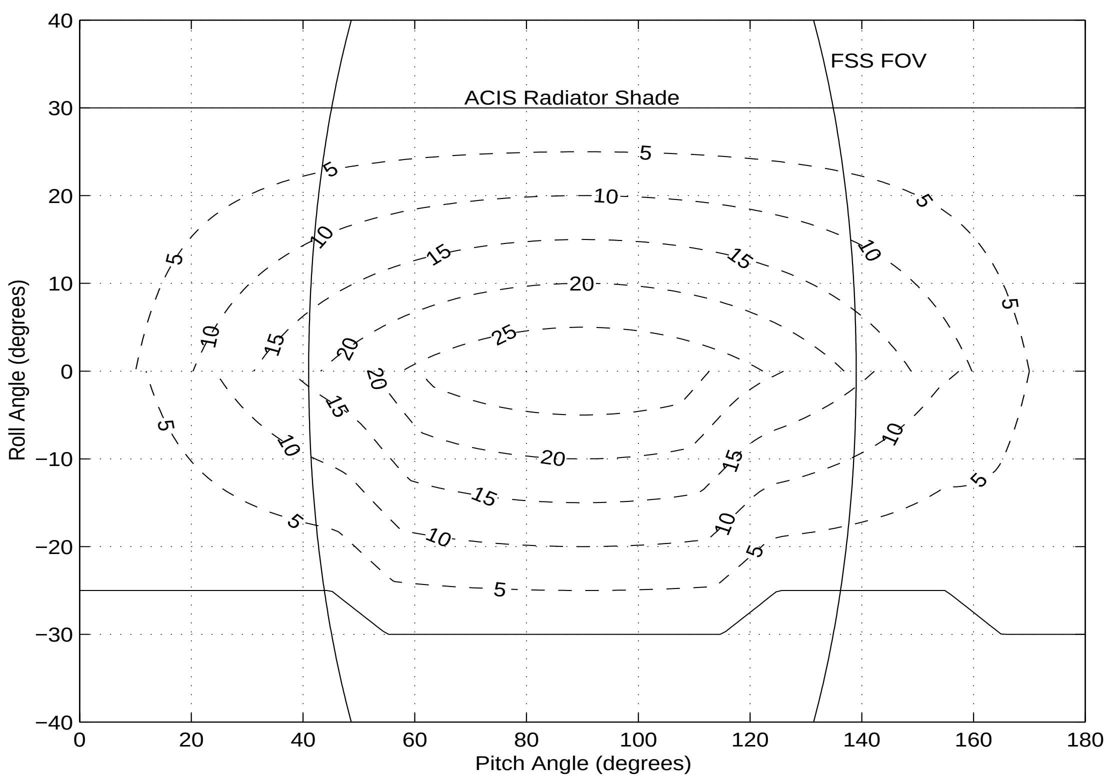
accuracy of the FSS and thus the sun vector calculated using FSS data is no worse than approximately 0.05^{o} (Reference 17). However, while the sun is outside of the FSS FOV, the sun vector in the observatory coordinate system is determined using CSS measurements. Indeed, the CSS determination of sun position has several sources of error. As discussed in Section 4.2 and Appendix A, the maximum error in CSS determination of sun vector position is significant and varies with the angle between the sun vector and the solar array normal. Given the relationship between sun pitch-roll coordinates and the angle to the solar array normal as depicted in Figure 8 and assuming a linear interpolation of CSS sun vector error, the maximum CSS error as a function of sun vector position can be calculated and is shown in Figure 9.

Figure 9. Maximum CSS Sun Vector Error (degrees)



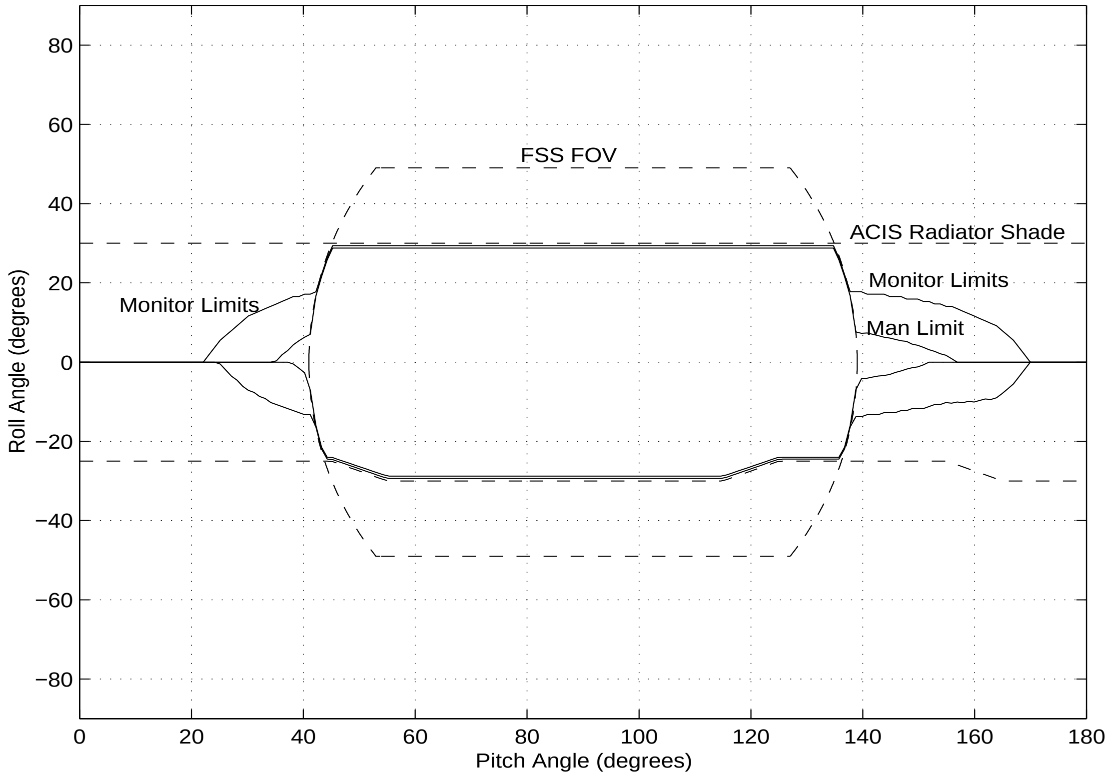
To illustrate the setting of the monitor thresholds such that the monitor absolutely detects

Figure 10. Angle to ACIS Radiator Shade Bound (degrees)



unacceptable sun positions, consider only the ACIS radiator shade constraint. The shortest angular distance to an ACIS radiator shade boundary of a sun vector as a function of its position in the observatory coordinate system is depicted in Figure 10. Assuming that the Sun Position Monitor

Figure 11. Monitor and Maneuvering Limits (after accounting for CSS error)



is used to detect any incursion of the sun into unacceptable attitude, then for a given pitch angle, the off-nominal roll constraint for the monitor threshold should be set such that the maximum error in the determination of sun position from sun sensor measurements is less then the shortest angle distance to the boundary. Considering only the ACIS radiator shade bound, the monitor limits would then need to be set as in Figure 11.

Further, in order to prevent an inadvertent trip of the monitor due to error in the determination of the sun vector, the constraints that restrict sun position during maneuver screening in the off-line system must themselves be set “inside” of the monitor bound by a margin again equal to the worst case error of the calculated sun vector. Considering only the ACIS radiator shade bound and its associated monitor bound developed above, the constraints for the nominal sun position during a maneuver that would be required are also shown in Figure 11. Hence, under the assumption that the Sun Position Monitor is to be used to detect any incursion of sun into a prohibited position in the observatory coordinate system, the region of allowable nominal sun positions outside of the FSS FOV is extremely small.

4.5. Analysis of Sun Exclusion Protection

Under nominal operations, all attitudes which are commanded by the ground will have been screened by the off-line system to ensure proper sun exclusion and that the observatory will have accurate onboard knowledge of its attitude. The use of the Sun Position Monitor derives from the need to protect the observatory in cases where an anomaly has caused it to attain a dangerous attitude with respect to the sun but other monitors have not been caused to trip. As discussed in Section 4.4, use of the Sun Position Monitor for sun exclusion protection significantly limits the region of allowable sun positions outside of the FSS FOV. The following discussion will justify a plan of operation which will ensure adequate protection for the observatory from damage due to the sun without the use of the Sun Position Monitor.

4.5.1. Anomalies Potentially Leading to Dangerous Sun Attitude

Two general categories of anomalies which could lead to an unacceptable sun position will be considered:

4.5.1.1. Accurate Onboard Attitude Knowledge

With accurate attitude knowledge present in the onboard estimated quaternion, there are several conceivable ways in which a dangerous attitude with respect to the sun could be attained:

1. Scenario: Due to an operational error, the ground commands a dangerous attitude with respect to the sun or an attitude which will become dangerous at some time during the length of an observation.

   Safeguard: The observatory’s Commanded Attitude Monitor will detect an improper commanded attitude and prohibits such a maneuver. In addition, the Commanded Attitude Monitor continuously checks the current ephemeris sun position in the target frame. Assuming that the observatory has maneuvered to the current target quaternion and that it represents the true attitude of the observatory, the Commanded Attitude Monitor would then trip if the sun later moved into an unacceptable orientation.

2. Scenario: A time error in the OFLS prior to an update of the onboard ephemeris time causes both the onboard sun ephemeris and the ground sun ephemeris to be incorrect. The observatory could then be commanded to an attitude such that the sun was in an unacceptable position without tripping the Commanded Attitude Monitor.

   Safeguard: Care must be taken when updating the onboard ephemeris time to ensure that the resulting onboard sun ephemeris matches the measured sun position by checking the consistency of the following items:

   - The sun vector calculated by the FSS, transformed to ECI using the current estimated quaternion.
   - The sun vector in ECI, calculated by the onboard ephemeris.
   - The sun vector in ECI, calculated by the ground system.

Thus, all of these possible anomalies are protected against by the Commanded Attitude Monitor and proper operating procedure with respect to sun exclusion constraints.

4.5.1.2. Inaccurate Onboard Attitude Knowledge

Many PCAD and safing subsystem functions assume accurate attitude knowledge in order to safely maneuver the observatory and properly exclude the sun from unacceptable attitudes. If the observatory where to have inaccurate onboard attitude knowledge, PCAD would control the observatory such that the estimated attitude would closely match the commanded attitude (and after maneuvering, eventually match the target attitude), but the estimated attitude would differ from the true attitude of the observatory. Thus, as planned by the ground, the sun might be at an acceptable attitude in the estimated frame (as well as the commanded and target frames), but at an unacceptable attitude in the true frame.

In transfer orbit, attitude determination with respect to the sun line is regularly ascertained by FSS data processed by the ground system and ground controllers. However, between updates by the ground to the onboard estimated quaternion, the estimated attitude of the observatory is susceptible to drift due to uncompensated errors introduced by gyro bias or undetected gyro faults. For on orbit operations, attitude determination is positively established while tracking stars using the Aspect Camera system and software, with concomitant updates by the Kalman filter to the onboard estimated quaternion and estimated drift rate. The only credible way in which the onboard attitude knowledge could become inaccurate during on orbit operations would be during a maneuver for an undetected fault which occurs in the gyro. During both transfer orbit and on orbit nominal operations, gyro bias will be estimated and corrected for to a relatively precise degree. Based on the Reference 18 conversation, there are several possible gyro failures that could cause significant errors in gyro estimation of observatory rates which, when integrated, would cause errors in estimated attitude:

1. Scenario: The Voltage to Frequency Converter (VFC) of a gyro channel or channels fail resulting in zero change in gyro counts for the channel(s).

   Safeguard: The IRU Monitor will detect the dead channel within 30 seconds and put the observatory into safe mode.

2. Scenario: A resistor in the capture loop of a gyro channel fails resulting in a change in the scale factor for that channel. This would predominantly cause an error in rate estimation during maneuvers.

   Safeguard: Such a failure is considered extremely unlikely, but has been seen once before by TRW in the temperature control loop for a gyro. Nevertheless, as developed in Reference 21, the miscompare check of the IRU monitor will detect significant changes in the bias of a single gyro channel. The monitor will also detect an equivalently error in the measured rate for a channel caused by a change in scale factor.

   For high rate gyro operations (transfer orbit), the IRU monitor miscompare check can only detect very large changes in gyro bias (much more than an order of magnitude larger than the Reference 19 specification limit of 7.2^{o}/hr). For a fault which results in a change in scale factor in high rate gyro operation, for a given maneuver and set of maneuver parameters there is no way to guarantee that the IRU monitor will detect the fault. Thus, the worst case possible angular error which can result from such a fault cannot be bounded.

As developed in Reference 21, for low rate gyro operation (on orbit), the IRU monitor miscompare check threshold is set such that the monitor will not trip for drift rates that change significantly in only one channel and by less than approximately the Reference 19 specification limit of 7.2^{o}/hr. Further, if the possible nominal changes in acceleration insensitive drift rate (AIDR) are considered, the present IRU Monitor limits might not trip until larger changes in the drift rate of a single channel occur (For this analysis, the maximum uncompensated drift rate that does not cause the IRU Monitor to trip will be considered to be 10^{o}/hr). If a fault occurred which changed gyro scale factor during low rate gyro operations yet remained undetected, the attitude error which might result during a maneuver will be assumed to be bounded by a rate of 10^{o}/hr integrated in the worst case orientation over the length of the maneuver.

3. Scenario: Mechanical degradation of the bearings in a gyro causes a change in the uncompensated drift rate in a channel(s).

   Safeguard: For low rate gyro operation, the IRU monitor miscompare check is configured to detect a condition under which the uncompensated drift rate in a single channel approximately exceeds the values enumerated in the previous scenario. This check may also detect significant changes in bias for both channels of a single gyro. Based on the Reference 21 analysis and depending on the polarity and magnitude of the changes in bias, detection by the IRU monitor is not guaranteed. However, this failure is not considered likely to occur suddenly, but would develop over a relatively long period of time. Further, as bearing degradation developed, noticeable changes in the gyro motor current would be expected, serving as a warning of a problem with the gyro. Thus, this failure is not considered likely as a source of significant, sudden and undetected attitude error.

Thus, a fault resulting in a change of scale factor for a given channel is considered the only credible anomaly which could remain undetected yet lead to significant attitude errors. However, for on-orbit operations, the worst case error which could result from an undetected change in scale factor would be approximately bounded by a rate of 10^{o}/hr integrated in the worst case orientation over the length of time of the maneuver.

4.5.2. Justification of Sun Exclusion Protection Without Sun Position Monitor

Assuming the analysis presented in Section 4.5.1, the protection of the observatory from dangerous sun attitudes without the Sun Position Monitor will be analyzed for transfer orbit and on orbit configurations.

4.5.2.1. Transfer Orbit

During most of transfer orbit, the observatory is configured in a sun pointed attitude with its -Z axis toward the sun. It will be assumed that during periods when the sun is in the FSS FOV, the ground has ascertained good observatory onboard attitude knowledge, consistent with respect to the sun line. Thus, the observatory onboard estimated attitude will be considered vulnerable to undetected and uncompensated changes in drift or scale factor during the time between ground confirmations of correct observatory attitude using FSS measurements.

The only time the sun is expected to be outside of the FSS FOV in transfer orbit is during earth scan maneuvers and burn sequences. Since the sun shade door is closed during transfer orbit thus protecting the HRMA and Science Instruments, the principle sun exclusion regions of concern involve solar array off pointing and shadowing and ACIS radiator shade protection. In these circumstances, the following conditions mitigate the need for use of the Sun Position Monitor:

1. The extreme unlikelihood of a fault which causes a significant and sudden undetected change in gyro bias or scale factor.

1. The observatory is nominally in ground contact throughout each earth scan. Therefore, anomalies which might cause dangerous observatory attitudes that do not trigger a safing action may be detected by ground control (e.g. gyro, thermal, Earth Sensor and CSS measurement telemetry) allowing ground intervention for corrective action.

2. Upon maneuvering to an earth scan attitude, receipt of the expected earth scan telemetry would provide corroboration that the observatory was at the correct attitude and had not experienced a loss of attitude knowledge during the maneuver due to a change in scale factor.

3. If at all possible, earth scan and burn attitudes are always selected to have nearly zero off-nominal roll. This would provide angular margin to sun exclusion violations.

4. The absolute time sequences (ATSs) which control these events in transfer orbit are always configured to command the observatory back to a sun pointed attitude after each event.

4.5.2.2. On Orbit

In order to meet Reference 4 viewing requirements, an operational plan is required for safe on orbit operation of the observatory which will allow sun positions in the observatory coordinate system outside of the FSS FOV. For on orbit operations, attitude determination is positively established while tracking stars through the Aspect Camera system and software with concomitant updates to the onboard estimated quaternion and estimated drift rate. Between periods of star tracking (such as during a maneuver), the onboard estimated attitude of the observatory is susceptible to drift due to errors introduced by gyro bias or faults. Once the observatory is at a scheduled viewing attitude after completing a maneuver, the Aspect Camera Processing subfunctions in the PCAD flight software will attempt to acquire stars loaded in the onboard star catalog by the ground. The flight software will command the Aspect Camera to look for the stars at the appropriate positions in the Aspect Camera FOV corresponding to where they would be expected for the given target attitude. If the flight software does not find a minimum of two stars at the expected location and with the expected magnitude after several iterations (taking no more than approximately 5 minutes), several things will occur:

1. SCS 28 will be called which will terminate all mission SCS’s.

2. A Bright Star Search by the Aspect Camera will be commanded, which will look for any stars in the Aspect Camera FOV. The flight software will then hold the attitude of the observatory

inertially fixed on those bright stars for an indefinite period of time.

3. If the Bright Star Search is unsuccessful (possibly due to high observatory rates) and the observatory is not in an eclipse, the PCAD mode will be commanded to Normal Sun Mode (NSM) (if in eclipse, the observatory will fail over to safemode under CPE control).

If the onboard attitude knowledge error at the end of a maneuver is small (less than approximately 100-200 arc-sec), then the Aspect Camera Processing flight software should find the stars that it intended to find, confirming its inertial attitude. The onboard estimated attitude and rate drift will then be further corrected by the Kalman filter. If the onboard attitude knowledge error at the end of a maneuver is larger than this, then the Aspect Camera flight software will not find the stars that it intended to find and thus will “detect” the attitude error no later than about 5 minutes after maneuvering to the viewing attitude. As illuminated in Section 3, the only sun exclusion constraints which are of concern for sun positions outside of the FSS FOV are solar array offpointing and ACIS radiator shade constraints. In order to assess the worst case sun exposure for sun positions outside of the FSS FOV, sun exclusion protection with respect to each of these constraints will be addressed:

4.5.2.2.1. ACIS Radiator Shade

In view of the Section 3.3 restriction on solar illumination of the ACIS Radiator Shades, the following assessment will bound the worst case duration of sun exposure of the inner surface of the ACIS radiator shades:

1. The only undetected fault which could cause a significant loss of onboard attitude knowledge is an extremely unlikely large change in gyro scale factor. As discussed in Section 4.5.1.2, the angular error arising from such a fault if undetected by the IRU monitor would be bound by a rate on the order of 10^o/hr integrated in the worst case orientation over the length of the maneuver. Assuming a worst case series of maneuvers between periods of star tracking consisting of a 180^o maneuver followed by a 135^o maneuver, such a sequence of maneuvers would last a total of 90 minutes and the worst case error due to an undetected change in scale factor during this time would be on the order of 15^o.

2. If SCS 28 were to be modified such that calling it resulted in PCAD mode being commanded to NSM (to return the observatory to sun pointed attitude in the event that the search for stars is unsuccessful), then the worst case period during which the sun could be outside of the exclusion boundary as a result of undetected change in gyro scale factor would be limited by:

    1. The time during which the observatory would be maneuvering to the erroneous attitude after the sun moves beyond the sun exclusion limits. For a worst case error in attitude of 15^o at the end of a maneuver, this would take on the order of 9 minutes.

    2. The time for the Aspect Camera Processing flight software to detect the attitude error (no greater than approximately 5 minutes).

    3. The time for the sun to move back within sun exclusion limits while maneuvering to

sun pointed attitude in NSM. Assuming:

1. The nominal pull-in rate in NSM of 0.1^{o}/sec.

2. The angular distanced traversed by the sun while it exits the ACIS radiator shade sun exclusion region may be longer than while entering the region (assume a factor of two margin).

then the worst case angle traversed by the sun while exiting the ACIS Radiator sun exclusion region would be approximately 30^{o} which would take approximately 5 minutes.

Thus, implementing a change which would command NSM upon transition of ACA Sequence to Bright would result in a worst case duration of illumination of the inner surfaces of the ACIS Radiator Shades of less than the References 9 and 10 specified constraint of 30 minutes.

4.5.2.2.2. Solar Array Offpointing

Unlike the sun exclusion constraint for the ACIS radiator shades, the solar array off pointing constraints discussed in Section 3.5 have no allowable time for which they may be violated. Using the analysis presented in Section 4.5.2.2.1, the worst case deviation from the planned maneuver trajectory due to an undetected fault will be assumed to be less than 15^{o}. The justification of sun exclusion protection with respect to solar array off pointing while the Sun Position Monitor is disabled will be based on limits imposed on maneuver planning such that the nominal planned position of the sun is never more than 5^{o} from the solar array normal while the sun is outside of the FSS FOV.

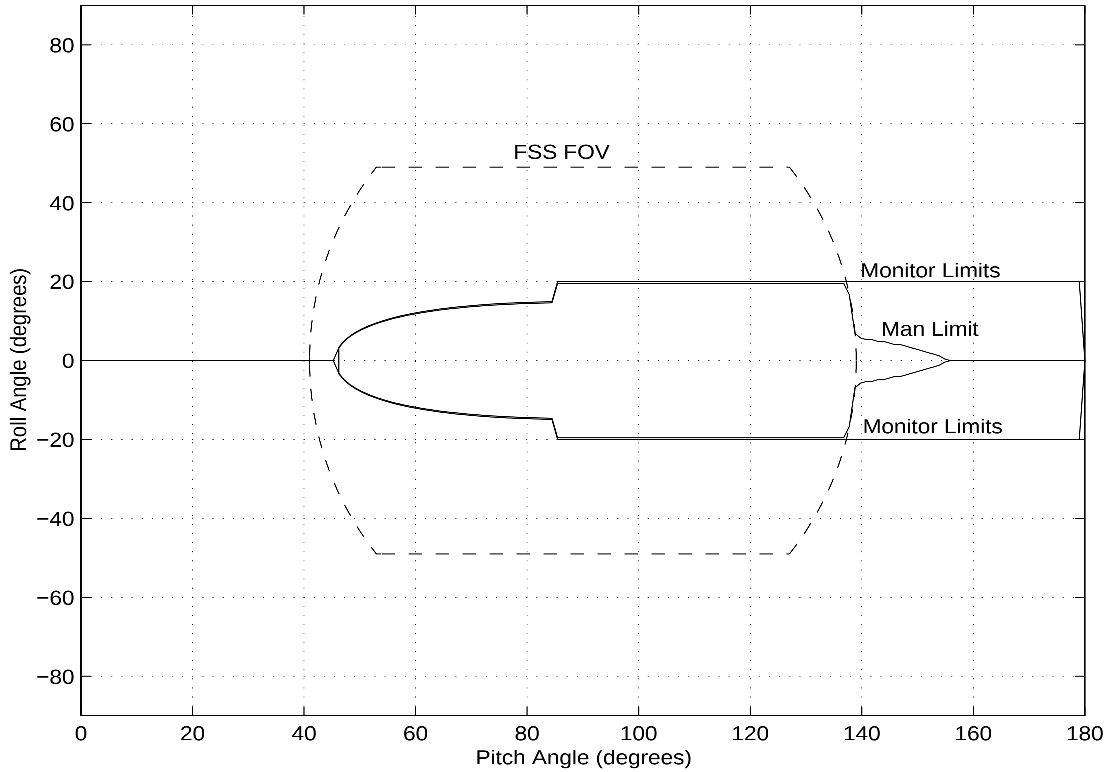
4.5.3. Possible Alternative for On Orbit Sun Position Monitor Operation

Two alternative ideas for continued operation of the Sun Position Monitor while the sun is outside of the FSS FOV have also been considered:

1. Leave the Commanded Attitude Monitor/Sun Position Monitor thresholds as they would otherwise be for the Commanded Attitude Monitor to provide sun exclusion protection from improperly commanded target attitudes. Subsequently limit maneuvers so as to prevent an inadvertent monitor trip due to CSS error. This would provide some protection with respect to sun exclusion but would also present a “region of vulnerability” of the Sun Position Monitor where the sun could be at an unacceptable attitude yet not cause a monitor trip due to CSS sun vector error. Assuming conservative CSS errors approximating those developed in Appendix A, the implementation of this plan would result in OFLS maneuver constraints shown in Figure 12 (for margin, the CSS worst case error was assumed to be 8^{o} when the sun is near the solar array normal up to approximately 25^{o} when the sun is 60^{o} off of the solar array normal). Clearly, if this plan were to be implemented, there would be little added range

of sun excursions allowed outside of the FSS FOV. Therefore, pursuit of this approach is not

Figure 12. Alternate Monitor and Maneuvering Limits (Proposal 1)



recommended.

2. Set the monitor thresholds such that for a full range of allowed off nominal roll angles, the Sun Position Monitor will not be falsely tripped due to CSS sun vector error. The Sun Position Monitor would then be effective for ensuring that large angular excursions of the sun into exclusion regions are detected. To implement such a plan would require monitor limits such as those presented in Figure 13. Such a plan is not feasible for several reasons:

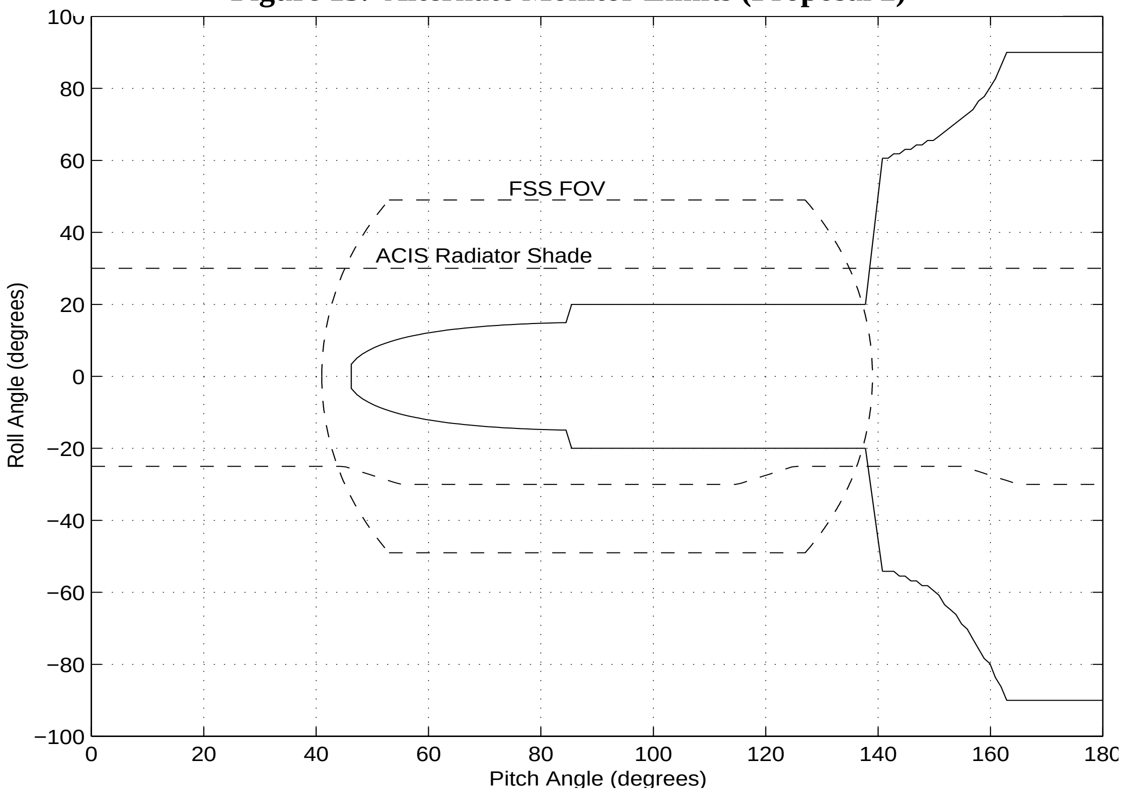
   - The Reference 15 flight software simple implementation of monitor exclusion regions using ellipses in the XY plane does not allow for definition of the unusual monitor region depicted in Figure 13.

   - Since the Reference 15 flight software implementation of monitor thresholds uses the same values for the Commanded Attitude Monitor and the Sun Position Monitor, changing the monitor thresholds to implement such a change would significantly degrade the Commanded Attitude Monitor's verification of correctly commanded attitudes.

5. Proposed Action

The following are the proposed actions regarding the operation of the observatory with respect to

Figure 13. Alternate Monitor Limits (Proposal 2)



sun exclusion protection:

5.1. Spacecraft Ephemeris and Estimated Attitude Update

As discussed in Section 4.5.1.1, care must be taken when updating the onboard ephemeris time or estimated attitude to ensure that the resulting onboard sun ephemeris matches the measured sun position by checking the consistency of the following items:

- The sun vector calculated by the FSS, transformed to ECI using the current estimated quaternion.
- The sun vector in ECI, calculated by the onboard ephemeris.
- The sun vector in ECI, calculated by the ground system.

5.2. Sun Position Monitor Implementation

1. Given the Section 4.4 analysis and observatory sun position measurement capability, the Sun

Position Monitor should be disabled while the sun is outside of the FSS FOV. As discussed in Section,4.5.2, the following action should be taken in order to ensure adequate sun exclusion protection while the sun is planned to be outside of the FSS FOV:

- Transfer Orbit:

  1. Maintain ground contact.

  2. If at all possible, select earth scan and burn attitudes which have nearly zero off-nominal roll. This will provide angular margin to sun exclusion violations.

  3. Configure SCS's which will command the observatory back to a sun pointed attitude after the event and also within 30 minutes of any loss of communication. This could be done by one of two methods:

     1. By ground command, periodically reactivating a Relative Time Sequence which contains 1) a delay and 2) a command to NSM. Thus, in the event of a loss of communication, the SCS would return the observatory to a sun pointed attitude within the period of time of the delay.

     2. Create two new events in the flight software event table corresponding to receiver lock in each of the two receivers. An SCS could be configured which would command the observatory to NSM in the event that receiver lock is lost in both receivers,

- On Orbit:

  1. Modify SCS 28 to command PCAD mode to NSM in the event of transition of ACA Sequence to Bright. This will ensure that the worst case duration of a violation of the ACIS Radiator Shade constraint due to an undetected fault will be less than the allowable 30 minutes. This could be effectively implemented for operation by implementing the following changes:

     1. Permanently modify SCS 28 to call a second protected SCS which itself calls SCS 79. (SCS 79, NSM Transition, will ensure that the proper actions are taken for a safing transition to NSM such as gyro to high range, ACIS/HRC power off, SIM Translation Table to safe position etc.).

     2. As part of ground scheduling, enable this second protected SCS whenever the sun is outside the FSS FOV and disable it otherwise.

  2. Limit the range of allowable off-nominal roll angles considered by ground scheduling such that when the sun is outside of the FSS FOV, the nominal sun position is always less than 5^{o} from the solar array normal. This will ensure that the worst case excursion of the sun vector from the solar array normal due to an undetected fault

will remain within the maximum allowable off pointing angle.

5.3. Commanded Attitude Monitor Implementation

As discussed in Section 4.1, if the Commanded Attitude Monitor trips, PCAD attempts to hold the observatory's attitude and SCS 28 is called to terminate mission SCS's. However, based on the operating philosophy recommended above, during on orbit operations, if the sun is outside of the FSS FOV when the commanded attitude monitor trips, the appropriate action should be to return to a sun pointed attitude. Implementing the modifications to SCS 28 recommended in the previous section will ensure that this action is carried out.

5.4. Flight Software Monitor Thresholds

The PCAD Commanded Attitude and Sun Position Monitor thresholds should be set to ensure that the Section 3 sun constraints are enforced. Although the Sun Position Monitor will be disabled while the sun is outside of the FSS FOV, both monitors use the same monitor thresholds in the Reference 15 flight software. Thus, for those attitudes where the sun is outside of the FSS FOV, the monitor thresholds still need to be set consistent with proper sun exclusion for the Commanded Attitude Monitor and the associated error in the onboard sun ephemeris calculation. The sun exclusion limits defined in Section 3 are implemented as follows:

5.4.1. Transfer Orbit

The sun exclusion limits that apply during transfer orbit are those in Section 3 which apply with the sun shade door closed. The aggregate of these physical constraints is depicted in Figure 15, Also included in Figure 15 is a proposed fit for Reference 15 monitor thresholds which satisfy these constraints. Since solar array off-pointing constraints define these limits, it is assumed that the ephemeris error of 0.01^{o} defined in Reference 16 is insignificant. Using the definitions given in Section 4.3, the associated Reference 15 flight software constants which implement these constraints are as follows:

KP.Plus_Z_Lim=[0.0002];

KP.Sun_Vec_X_Thresh=[2.0, -2.0];

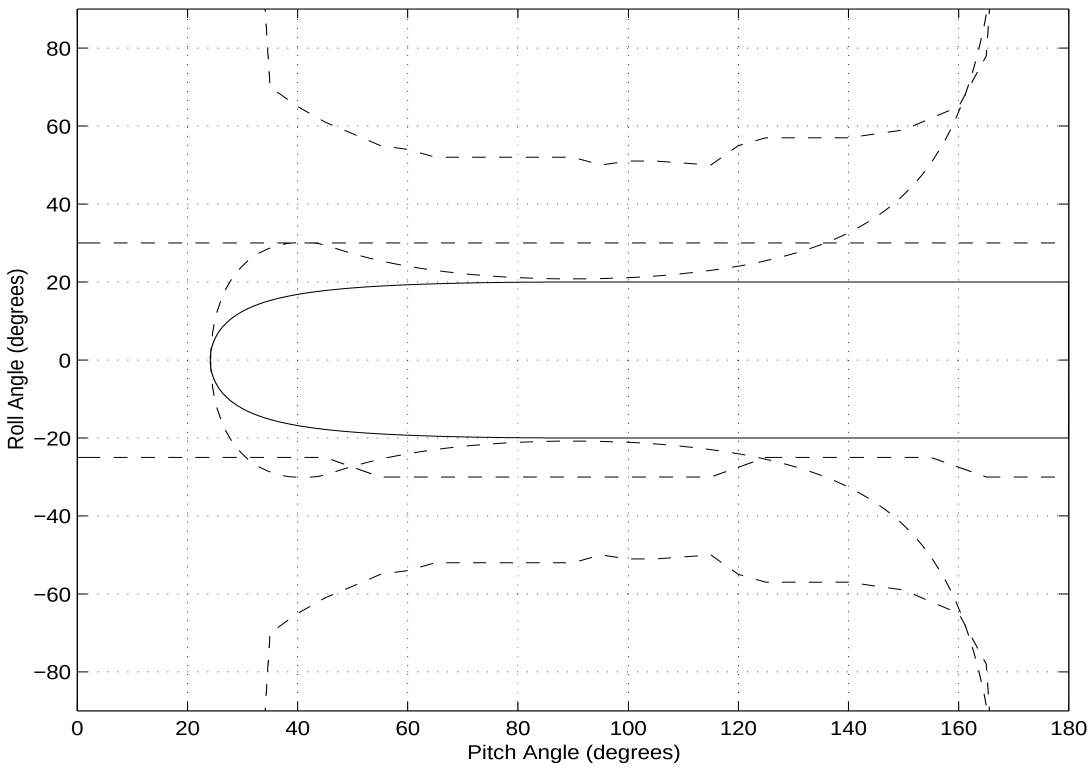
KP.X_Ellipse=[1.0, 0.91212];

KP.Y_Ellipse=[0.342, 0.342];

KP.Region_Bound=0.0;

Note that the value for KP.X_Ellipse(2) will limit the minimum sun pitch angle to 24.2^{o} to

Figure 15. Transfer Orbit Sun Exclusion and Monitor Limits



maintain Reference 13 constraints for solar array off-pointing during the summer.

5.4.2. On Orbit

The sun exclusion limits which apply after the sun shade door is opened are identified in Section 3. These physical constraints are depicted in Figure 16. Also included in Figure 16 is a proposed fit for monitor thresholds which satisfy these constraints. Based on the Section 3 discussion, monitor thresholds and maneuver limits will be set such that sun pitch angles will be greater than 46.0^{o} for on orbit operations so as to guarantee complete sun exclusion of the HRMA. For operation at sun pitch angles less than this and down to the theoretical minimum sun pitch angle, monitor thresholds should be changed accordingly.

Using the definitions given in Section 4.3, the associated Reference 15 flight software constants which implement these constraints are as follows:

KP.Plus_Z_Lim=[0.0002];

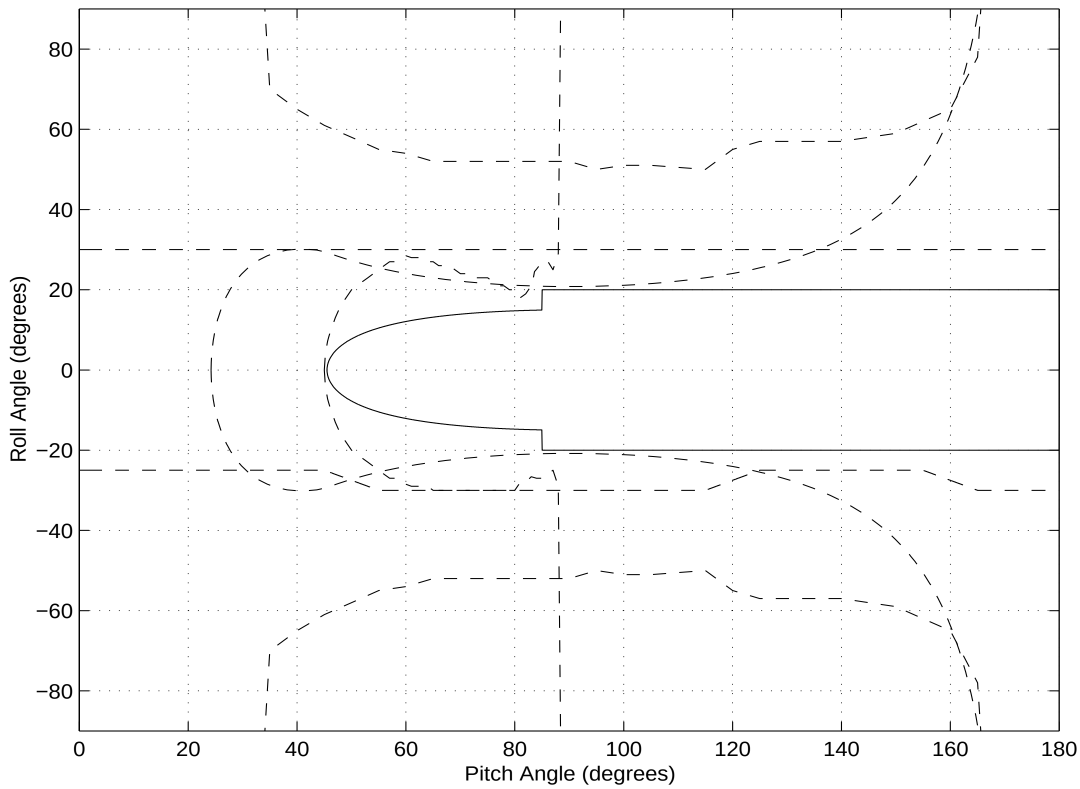
KP.Sun_Vec_X_Thresh=[2.0, -2.0];

KP.X_Ellipse=[1.0, 0.69466];

KP.Y_Ellipse=[0.342, 0.2588];

KP.Region_Bound=0.0872;

Figure 16. On Orbit Sun Exclusion and Monitor Limits



5.5. Data Base Constraints

The Chandra Off-line System scheduling software screens maneuvers and target attitudes to check that the sun position in the observatory coordinate system is acceptable at all times. The variables used in the algorithm to perform this check are defined in Reference 22.

5.5.1. Pitch Angle Constraint

The three element vector ODB_ANGSUN, defined in degrees, specifies minimum and maximum allowable sun pitch angles for maneuvers and observations scheduled by the off-line system. The Reference 22 definition of this vector and the values which ensure proper sun exclusion are listed in Table 3.

Table 3: OFLS Specification for Minimum and Maximum Sun Pitch Angle

ODB_ANGSUN	Reference Definition	Value (degrees)
Element 1	Minimum allowed angle between spacecraft LOS and the sun (sunshade door open)	46.10

Table 3: OFLS Specification for Minimum and Maximum Sun Pitch Angle

ODB_ANGSUN	Reference Definition	Value (degrees)
Element 2	Minimum allowed angle between spacecraft LOS and the sun (sunshade door closed)	24.21
Element 3	Maximum allowed angle between spacecraft LOS and the sun	180

5.5.2. Off Nominal Roll Constraint

The vectors ODB_SUNX_ANG and ODB_ROL_DEV_MAX, defined in degrees, are used to check the acceptability of an off-nominal roll angle ϕ, given a sun pitch angle θ, according to the rule:

if

$$\text{ODB\_SUNX\_ANG}(i) \leq \theta < \text{ODB\_SUNX\_ANG}(i+1) \tag{3}$$

then the off-nominal roll angle ϕ must satisfy:

$$|\phi| < \text{ODB\_ROLL\_DEV\_MAX}(i) \tag{4}$$

Assuming the operational plan proposed in Section 4.5 for disabling the Sun Position Monitor for observatory attitudes which place the sun outside of the FSS FOV, then the OFLS Characteristics & Constraints maneuver parameters should be chosen such that the maneuver limits are placed inside of the Section 5.4.2 Commanded Attitude Monitor and Sun Position Monitor limits by a margin greater than the angular error of the FSS determined sun vector or sun ephemeris model used. In addition, based on the discussion of Section 4.5.2.2.2, for sun positions outside of the FSS FOV, the nominal sun position should be restricted such that it is never further than 5^{o} from the solar array normal (as illustrated in Figure 8). Applying these criteria, acceptable values of ODB_SUNX_ANG and ODB_ROL_DEV_MAX are presented in Table 4.

Table 4: OFLS Specification for Maximum Off-Nominal Roll Sun Exclusion Checking

ODB_SUNX_ANG	ODB_ROL_DEV_MAX
46.0	0.000
46.2	1.269
46.4	2.052
46.6	2.635

Table 4: OFLS Specification for Maximum Off-Nominal Roll Sun Exclusion Checking

ODB_SUNX_ANG	ODB_ROL_DEV_MAX
46.8	3.111
47.0	3.517
47.2	3.942
47.5	4.501
48.0	5.192
48.5	5.771
49.0	6.268
49.5	6.726
50.0	7.142
55.0	10.043
60.0	11.753
65.0	12.894
70.0	13.659
75.0	14.182
80.0	14.523
85.5	19.899
137.08	7.334
140.0	7.775
145.0	8.697
150.0	9.979
153.0	11.021
157.0	12.785
160.0	14.628
163.0	17.153
166.0	19.999
170.0	19.999

The constraints presented in Table 4 are summarized in Figures 17 and 18.

Figure 17. OFLS Off-Nominal Roll Constraints

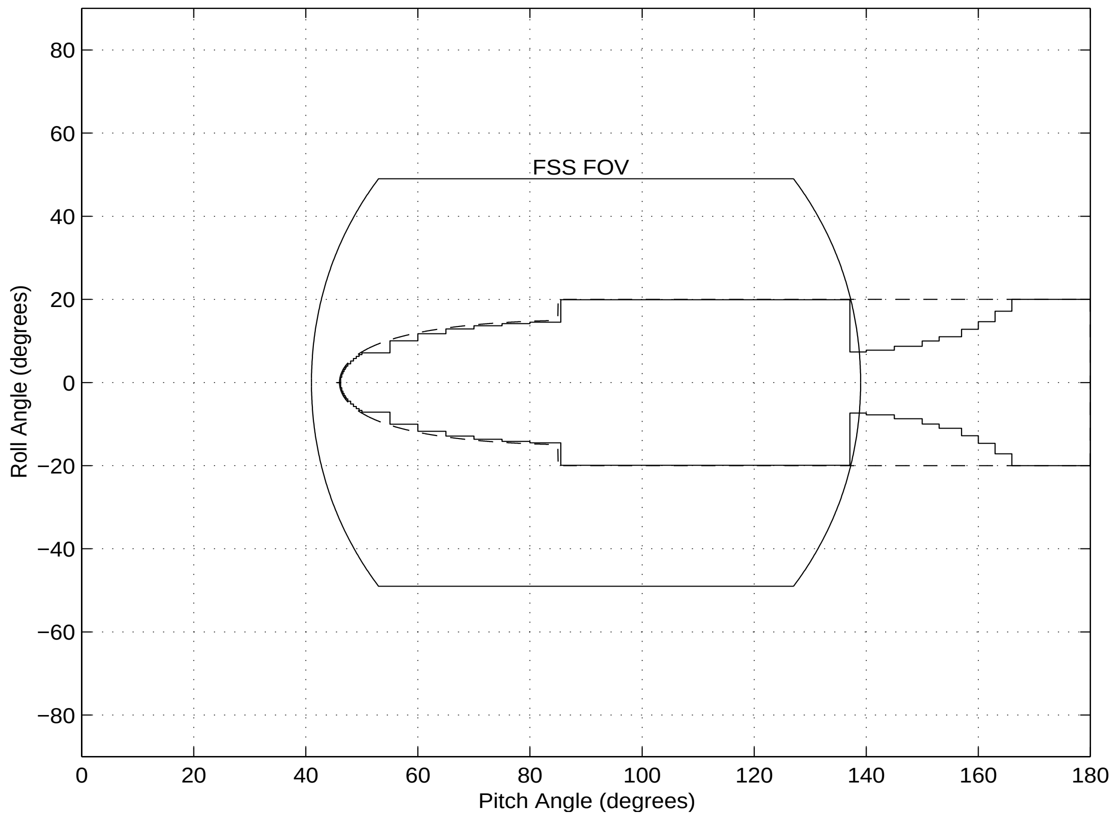
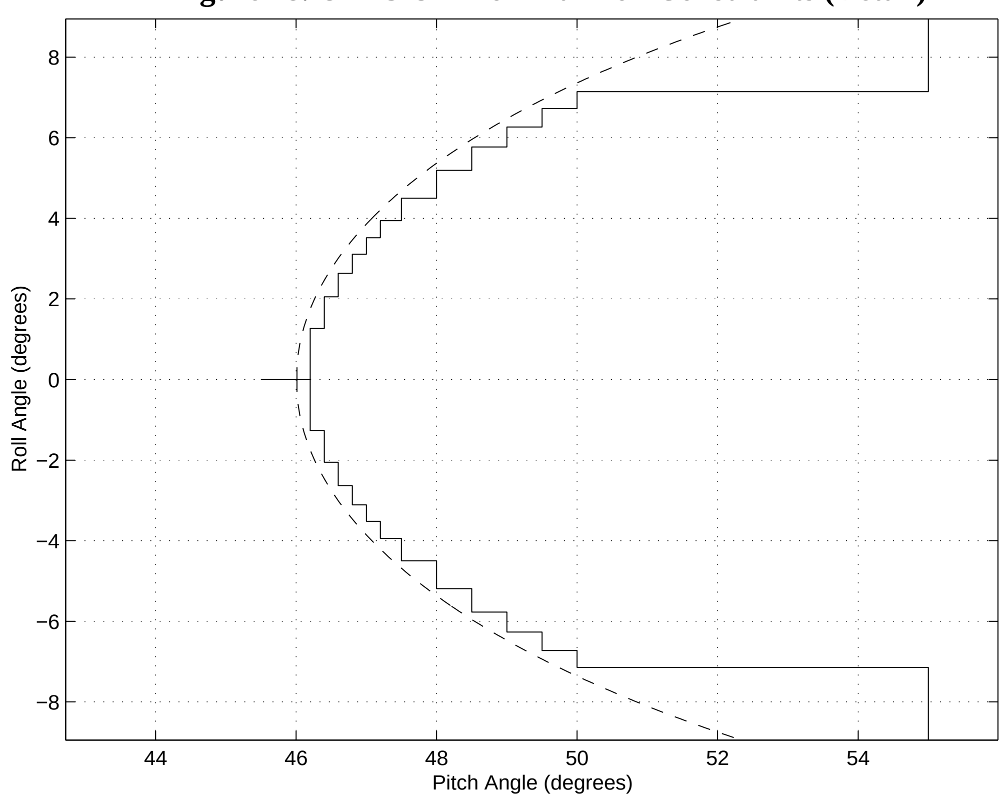


Figure 18. OFLS Off-Nominal Roll Constraints (Detail)



6. Conclusion

1. The Chandra Observatory can safely perform viewing with a sun limb avoidance angle of 45.27^{o}.

2. The Chandra Observatory can safely perform viewing with a sun pitch angle of 180.0^{o}.

3. Due to currently estimated maximum possible errors in the CSS determination of sun position, the Sun Position Monitor must be disabled during periods in which the sun position is outside of the FSS FOV. However, if appropriate modifications are made to operating procedures, the Chandra Observatory will retain adequate sun exclusion protection during such periods. After on orbit operations begin, the actual error associated with CSS determination of sun position can be assessed by periodic calibration and the need to disabled the Sun Position Monitor during periods in which the sun position is outside of the FSS FOV can be reassessed.

Appendix A. CSS Sun Vector Accuracy

While the sun is outside of the FSS FOV, the sun vector used by the Sun Position Monitor is calculated using CSS measurements. The Reference 15 Flight Software uses the following simple algorithm to determine the sun vector in the solar array coordinate system:

X = KP.CSS_SF(1) * (-CSS(1) + CSS(2) + CSS(3) - CSS(4)) (5)

Y = KP.CSS_SF(2) * (CSS(1) + CSS(2) - CSS(3) - CSS(4)) (6)

Z = +/-SQRT(1.0 - X*X - Y*Y) (7)

where KP.CSS_SF= (2.85592E-04, 1.64887E-04), CSS(i) is the output in counts of the i'th CSS and the sign of the Z component is determined from EPS determination of which side of the solar array the sun is on. The sun vector in the observatory coordinate system is then calculated by vector transformation based on the estimated solar array angle. The output of a CSS is approximately proportional to the projection of the sun vector onto the CSS normal. The scale factors KP.CSS_SF are based on the assumptions derived from unit testing that the maximum current output of each CSS with sun center directly on the CSS normal is 4.7 mAmps (and that 745 counts are produced by the Sensor Processor Electronics for each mAmp of CSS current). Equations 5-7 will give an exact determination of the sun vector position in the observatory coordinate system assuming:

- perfectly flat and aligned solar array geometry.
- perfect knowledge of the solar array angle.
- response of the CSS's that is exactly proportional to the projection of the sun vector onto the CSS face normal.
- maximum current output of each CSS is exactly 4.7 mAmps.

However, the calculation of the position of the sun vector in the observatory coordinate system is subject to variability. In particular, the CSS response can vary as a result of many factors. Table 5

Table 5: Sources of CSS Gain Deviation from Nominal

Source	Deviation from Nominal	Variability Between CSS's (estimated)	Variability Affecting All CSS's Jointly (estimated)
Temperature Effects	+3.6% to -11.5%	+/-2.0%	+2.0% to -10.0%
UV Radiation Effects	0% to -2.2%	0%	0% to -2.2%
Particle Radiation Effects	0% to -6.1%	0%	0% to -6.1%
Sun-Earth Distance Effects	+/-3.23%	0%	+/-3.23%
Measured Unit to Unit Variation	+/-2.0%	+/-2.0%	0%

Table 5: Sources of CSS Gain Deviation from Nominal

Source	Deviation from Nominal	Variability Between CSS's (estimated)	Variability Affecting All CSS's Jointly (estimated)
Value used for analysis		+/-4.0%	+5.0% to -20.0%

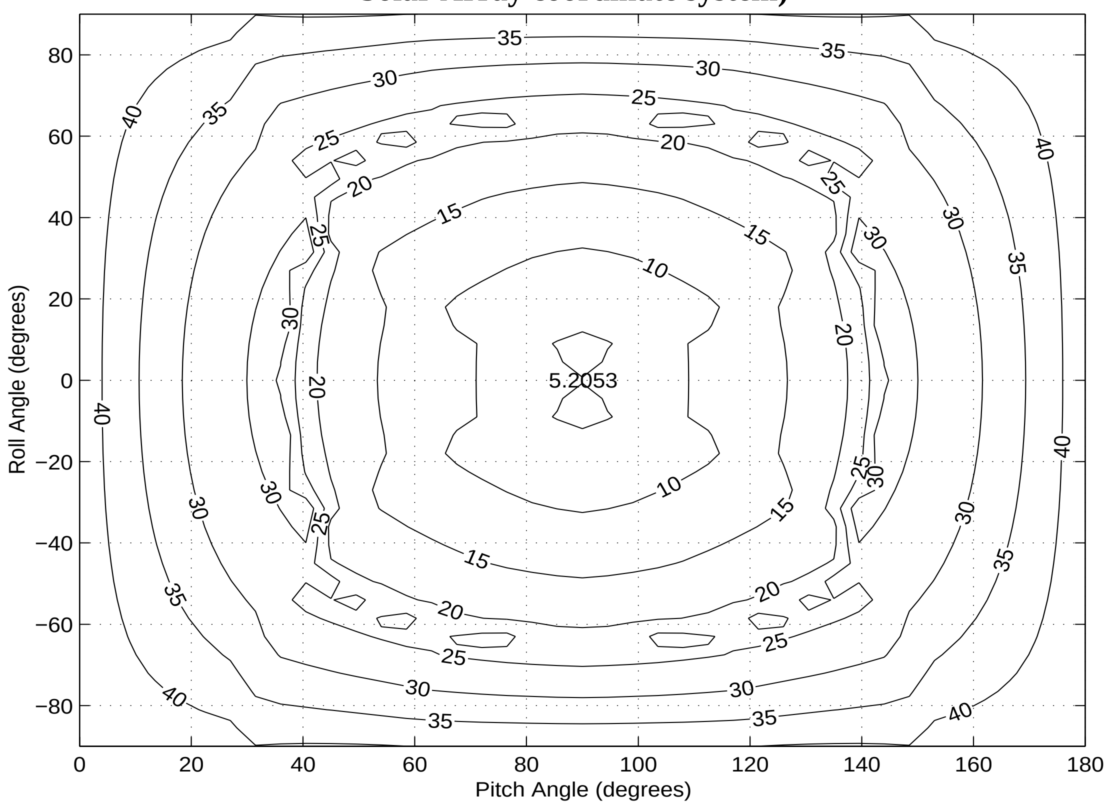
identifies the prime factors contributing to differences in CSS gain as defined in Reference 20 and the values assumed for the present analysis. Also the response of the CSS current is not exactly proportional to the projection of the sun vector onto the CSS face normal. In addition, the geometry of the solar arrays will not be perfectly flat, but may be deflected from nominal position. Further, the resolver angle used to establish the rotation angle of the array about the Y axis may not be aligned so as to accurately represent the orientation of the outer edge of the solar arrays in the observatory coordinate system. Reference 23 presents an assessment of the worst case configuration of the outer edge of the solar arrays relative to observatory coordinate system. The Reference 23 results are outlined in Table 6.

Table 6: Sources of CSS Alignment Deviation from Nominal

Source	Deviation from Nominal
Solar Array In-Plane Misalignment	+/-1.66^{o}
Solar Array Out-of-Plane Misalignment	+/-2.21^{o}
Solar Array Rotational Misalignment (about Y axis, including resolver misalignment)	+/-2.32^{o}

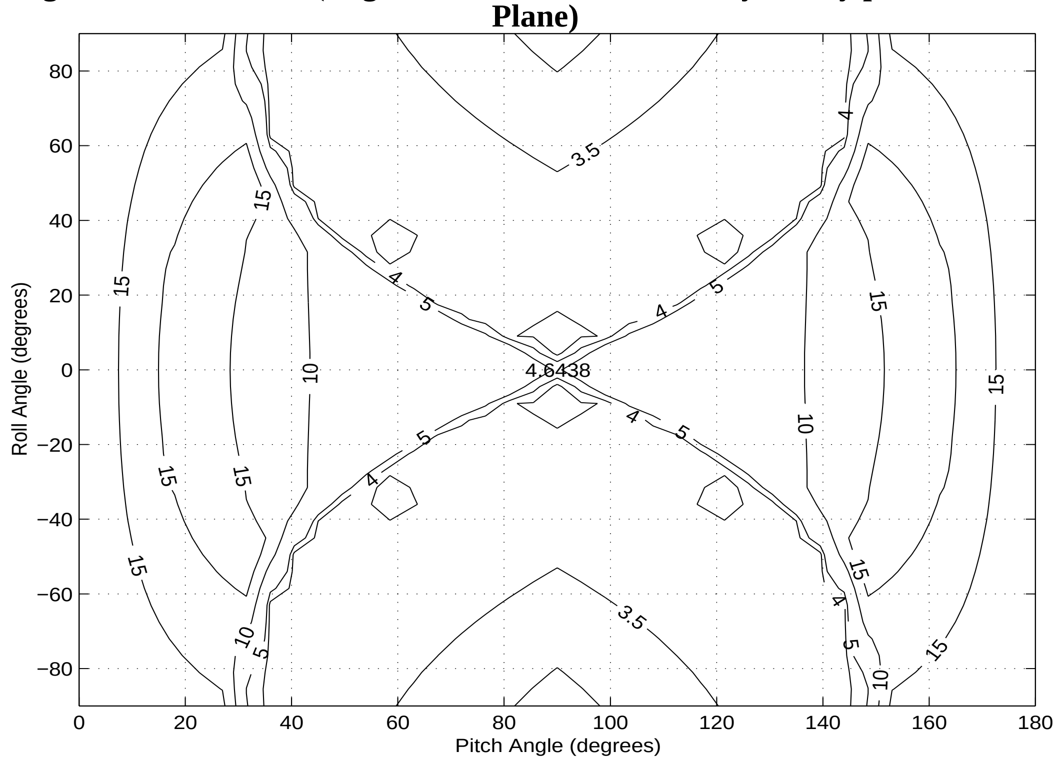
Using all possible permutations of the CSS gain variability and solar array misalignments presented in Tables 5 and 6, a worst case assessment was performed to establish the maximum angular error in determination of sun vector position in the solar array coordinate system using CSS data (for simplicity, the CSS current was however assumed to be exactly proportional to the projection of the sun vector onto the CSS face normal). The results are presented in Figure 20. In

Figure 20. CSS Sun Vector Error (Degrees, All Sources, Angles Relative to Solar Array coordinate system)



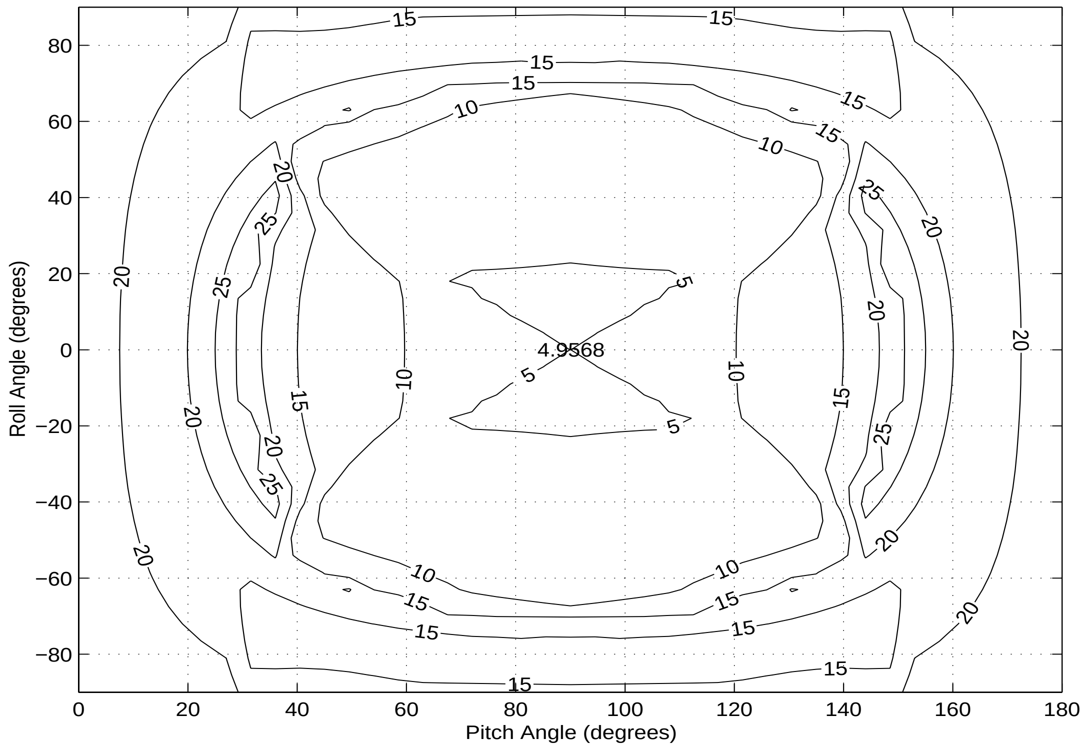
addition, the maximum errors in CSS determined sun vector position considering only solar array

Figure 21. CSS Error (Degrees, Rotation Sources Only, Array parallel to XY Plane)



misalignment errors are presented in Figure 21. Finally, the maximum errors in CSS determined sun vector position considering both the solar array misalignment errors and the CSS gain differences arising between CSS's are presented in Figure 22.

Figure 22. CSS Error (Degrees, Rotation and Inter CSS Difference Errors, Array parallel to XY Plane)



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