LONG DURATION EXPOSURE FACILITY (LDEF) ATTITUDE MEASUREMENTS OF THE INTERPLANETARY DUST EXPERIMENT

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ABSTRACT

Analysis of the data from the Long Duration Exposure Facility (LDEF) Interplanetary Dust Experiment (IDE) sun sensors has allowed a confirmation of the attitude of LDEF during its first year in orbit. Eight observations of the yaw angle at specific times were made and are tabulated in this paper. These values range from 4.3 to 12.4 degrees with maximum uncertainty of ±2.0 degrees and an average of 7.9 degrees. No specific measurements of pitch or roll were made but the data indicates that LDEF had an average pitch down attitude of less than 0.7 degrees.

INTRODUCTION

The LDEF IDE was unique in providing a time history of impacts of micron-sized particles on six orthogonal faces of LDEF during the first year in orbit.[1] The value of this time resolved data depended on and was enhanced by the proper operation of some basic LDEF systems. Thus the value of the data is greatly enhanced when the location and orientation of LDEF is known for each time of impact. The location and velocity of LDEF as a function of time can be calculated from the "two-line elements" published by NASA Goddard Space Flight Center during the first year of the LDEF mission. The attitude of LDEF was passively stabilized in a gravity-gradient mode and a magnetically anchored viscous damper was used to dissipate roll, pitch, and yaw motions.[2,3] Finally the IDE used a standard LDEF Experiment Power and Data System (EPDS) to collect and store data and also to provide a crystal derived clock pulse (1 count every 13.1 seconds) for all IDE time measurements. All that remained for the IDE was to provide a system to calibrate the clock, eliminating accumulative errors, and also to verify the attitude of LDEF. The typical steady-state motion of LDEF was expected to be less than 2 degrees for pitch and roll oscillations but there was greater uncertainty about the yaw attitude.[4]

The IDE used solar cells on six orthogonal faces to observe the LDEF sunrise and provide data about the LDEF attitude. The data were recorded by the EPDS about 10 times per day for the first 346 days of the LDEF mission. These data consist of the number of IDE counts since the last LDEF sunrise and the status of the six solar cells (light or dark) at

the time of the last IDE pulse. The EPDS determined the time that the data were recorded and includes with each record the master EPDS clock counter (1 count every 1.638 seconds) that provided the range and resolution for time measurements. The IDE solar cells provided data for an excellent clock calibration, meeting their primary purpose, and this paper will present the time resolved LDEF attitude measurements that can be gleaned from this data.

THE EPDS/IDE CLOCK

All of the timing measurements of the IDE are derived from the EPDS crystal controlled clock which had a design frequency of 1.280 MHz. The EPDS circuitry used a 26 stage divider chain to provide a large selection of clock rates. The IDE used the twenty-first stage of this divider (a period of 1.638 seconds) as the master clock rate. The EPDS also had a 24 bit counter that was used to store the accumulated counts since the experiment was turned on and the value stored in this counter was written to the data tape as part of every IDE record. The master clock rate and the count in the 24 bit counter are referred to as the EPDS clock or count.

The IDE also used the twenty-fourth stage of the EPDS divider chain as a secondary clock rate with a period of 13.1 seconds. This clock rate and its related counts are referred to as the IDE clock or count and is used to provide 12 bit measurements of time relative to the 24 bit EPDS count. This clock rate is used to sample and hold the sun sensor status, and to measure the time since sunrise. The phase between the IDE and the EPDS clock counts was fixed such that when the EPDS count changed from 3 to 4 counts the first IDE clock pulse was generated. Thus the integer relationship between IDE and EPDS counts can be expressed as:

EPDS + 4 = IDE * 8

SENSITIVITY OF THE SOLAR CELL CIRCUIT

Since the primary purpose of the sun sensors was to detect the sunrise event independent of the LDEF orientation at the time of sunrise, the sensitivity of the light sensing circuit was intentionally high. Each sun sensor circuit consists of four solar cells in series. The photo-current was amplified by a single transistor and the output of the transistor was clocked by the IDE clock pulses into a storage register for use by the other digital circuits of the IDE.

THE CLOCK CALIBRATION

The IDE clock calibration datum is essentially the count in a 12 bit counter which continually counts IDE clock pulses and is reset whenever a sunrise has been observed. The reset pulse for this counter is derived in the following manner. All sun sensors data are combined in a logic OR gate so that each IDE clock pulse can be considered as a light or dark pulse depending on whether LDEF is in sunlight or not. After 46 dark pulses (10 minutes) a circuit is armed so that the next light pulse will cause the desired reset (note that this reset is synchronized to the IDE clock pulses). The most precise piece of information that can be calculated from this counter is the EPDS count that marks, not the

sunrise event, but the end of an IDE interval during which the sunrise occurred. This EPDS count can be calculated by converting the EPDS (24 bit counter) count, that marks the time of the record, to an IDE count (Integer) subtracting the sunrise count value, then converting back to an EPDS count. Four more counts were subtracted to obtain the EPDS count associated with the center of the IDE interval in which the sunrise occurred.

The clock calibration used for this paper was obtained in the following manner:

(1)   The geometry of the LDEF sunrise is defined as LDEF being on a line that is tangent to the earth and sun; the line bent at the earth surface by some small constant angle of deviation. The sense of this angle is in the direction of atmospheric refraction but it also accounts for the height of the sun's upper limb above the horizon to provide sufficient light for the IDE sun sensors.

(2)   The time of sunrise was calculated with a precision of 0.1 seconds using the LDEF orbital elements (NASA Goddard "two-line elements") reported during the first year in orbit and matched to the EPDS sunrise count as indicated above.[5,6]

(3)   Since the IDE was turned on about 3 hours before the LDEF was released and the first data was recorded while the LDEF was still attached to the shuttle, the first IDE record is not used in this analysis.

(4)   The EPDS time zero and a constant EPDS period was determined using a linear least squares method.

(5)   The deviation angle defined in (1) was varied to minimize the standard deviation of the total error of the least squares process.

The clock calibration constants that were determined and used in this report are as follows:

Average EPDS Time Zero:	98.594187 ±2.8E-6 Day of Year 1984
Average EPDS Period:	1.63770501 ±2.3E-8 Seconds
Deviation Angle:	0.00376 radians
Standard Deviation of Total Error:	3.63 $\sqrt{(\text{count} * \text{second})}$

LDEF POSITION AND ORIENTATION RELATIVE TO THE SUN

With the above clock calibration the position and velocity vectors of LDEF were calculated for the time when the sun sensor status was clocked into storage for each of the IDE data records. Also for these times the XYZ coordinates of the sun (in the same coordinate system) were calculated. This positional data of LDEF and the sun were then combined to form the following three parameters for each IDE record:

(1)   The angle between the LDEF position vector and the sun. This angle has its vertex at the center of the earth and is in a plane that contains the centers of LDEF, the earth and the sun.

(2)   The Beta angle, which is the angle between the plane of LDEF's
        orbit and the direction to the sun. The plane of LDEF's orbit is that
        plane which contains LDEF's position and velocity vectors. For
        LDEF the Beta angle is positive when the sun is on the north side of
        the orbital plane and negative on the south side.

(3)   A light level parameter which indicates whether LDEF is expected to
        be in sunlight or the earth's shadow based on the sunrise condition
        defined in the clock calibration procedure.

These three parameters form the essential data that indicate the position and orientation
of LDEF relative to the sun and sunlit earth. By comparing this data with the
corresponding observed sun sensor status data some conclusions about the LDEF yaw and
pitch angles can be made.

Figure 1 is a plot of the number of sun sensors illuminated as a function of the angle
between LDEF and the sun. The way this angle was defined, it can vary from 0 to
180 degrees and does not indicate whether LDEF is approaching a sunset or leaving a
sunrise. The complete IDE data set consists of 3,413 data points randomly distributed over
the range of 0 to 180 degrees; however, the figure plots only the data (642 points) between
85 and 115 degrees with the morning and evening data indicated by different symbols.
When the LDEF is greater than 115 degrees from the sun, all sensors are dark as LDEF is
in the earth's shadow. When the angle is less than 85 degrees, all sensors are illuminated
either by the sun or by sunlight reflected by the earth.

The first conclusion that was made about this data was that the sunlit earth was very
significant in determining the light or dark status of the sun sensors. The method of
determining the attitude of LDEF used in this investigation depends only on light coming
directly from the sun, and it was expected that when the sunlight was parallel to a sun
sensor surface that sensor would be dark. The determination of yaw depended on LDEF
being totally out of the earth's shadow and the sun sensors on both row 12 and row 6
being dark. A similar determination of pitch using the sensors on the space and earth end
was not possible because the earth end sensor is illuminated by light reflected from the
earth.

Some observations about the pitch attitude can be made by looking at the angle at which
the sun sensor on the space end of LDEF changed from light to dark near sunset as
compared to the dark-to-light angle near sunrise. It was expected that both these angles
would be less than 90 degrees and on average would be an indication of the resolution by
which the yaw measurement was made; also the difference between the angles would
indicate twice the average pitch angle. How well the IDE sun sensor status can be used to
define these angles can be a measure of the variability of the pitch. If the pitch is constant,
the angles will be well defined within the expected errors for determining an angle between
the LDEF and the sun.

To determine how well the sun sensor data and a linear clock calibration can be used to
indicate an angle between LDEF and the sun, the data of figure 1 was used to determine the
sunrise/sunset angle. The data between 111 and 113 degrees was replotted in figure 2 with
the observed sun sensor status indicating whether LDEF is in sunlight or shadow and the
symbols indicating the expected lighting based on the sunrise condition defined in the clock
calibration. For this analysis the exact angle of sunrise or sunset is not as important as the

spread of the observed lighting, identified as sunrise or sunset data scatter, and the symmetry of the two intervals. If the standard deviation of total error from the clock calibration is used to calculate error bars for this data the range of errors for angles near 112 degrees would be from ±0.16 to ±0.30 degrees with the maximum error at minimum beta angle (for the clock calibration the maximum residuals occurred at maximum beta angle). The interval identified as "sunrise data scatter" is only slightly greater than the maximum error bar for a single data point and includes five sunrise data points: two points have the expected lighting and three have lighting that is the opposite of expected. The greater interval identified as "sunset data scatter" includes 13 sunset data points: 8 have the expected lighting and 5 have opposite lighting. Of the total eight points that have lighting that is opposite to the expected lighting, five are less than 112 degrees and indicate LDEF in darkness when it should have been in sunlight, and three points above 112 degrees indicate sunlight when LDEF was expected to be in the earth's shadow. The symmetry of these intervals about the sunrise/sunset angle is a good indication that the linear clock calibration's starting time is probably correct since any error in the starting time would shift the sunrise and sunset points in opposite directions destroying the symmetry. The length of the total data scatter interval (0.9 degrees) can be used as a measure of the precision with which the angle between LDEF and the sun can be determined using this clock calibration.

LDEF PITCH ATTITUDE

The sun sensor data of IDE cannot measure the pitch of LDEF directly but can put some limits on what the pitch may have been during the first year in orbit. Figure 3 presents the sun sensor data for the space end of LDEF. The first obvious feature of this data is that the morning and evening data is offset from 0.5 to 1.4 degrees. This would indicate that for the first year in orbit LDEF had a slight pitch down that, on average, was at least 0.25 degrees but not more than 0.7 degrees. The scatter in this data is slightly greater than that in figure 2 and can be attributed to variations in attitude as well as variations due to the precision of the clock calibration. Both pitch and roll variations can cause scatter in this data. Either a constant or a varying roll would cause scatter in this data but probably would not effect the morning to evening offset. If the pitch was oscillating the amplitude of the oscillation would be reflected in the amplitude of the scatter. Even if all of the scatter is attributed to variations in pitch, then the pitch oscillations were less than 2.0 degrees.

LDEF YAW ANGLE

The LDEF yaw angle can be defined as the angle between two planes. One plane referred to as the LDEF body axes plane contains the LDEF long axis and the normal to rows three and nine. The second plane is the LDEF orbital plane. It is assumed that the LDEF position vector is coincident with the LDEF long axis which is defined as the yaw axis. The traditional definition of yaw is a clockwise rotation of a body about its vertical axis when viewed from above; thus when the velocity vector and orbital plane is in the quadrant between the normal to row nine and twelve, LDEF has experienced a positive yaw. Early observations of LDEF and the results of the pinhole camera experiment indicated a yaw of about +8.0 degrees.[7]

The IDE measurement of the yaw angle is time dependent though not too sensitive to clock errors. It depends on observing an alignment of the yaw angle with the beta angle. Figure 4 indicates the alignment of a positive yaw angle with a negative beta angle at a time near sunrise. In this figure the IDE sun sensors would indicate that the sun was in the LDEF body axes plane and the yaw angle would be equal to the beta angle (except for sign). A similar alignment near sunset would be a positive yaw angle with a positive beta angle. Because the orbit of LDEF regresses, the beta angle oscillates with a period of about 45 days and has a maximum rate of changes of 0.4 degrees per IDE record. For a constant yaw angle of 8.0 degrees there would have been about 12 morning alignments and 13 evening alignments during LDEF's first year in orbit.

In figure 1 there are eight points between 103 and 112 degrees where only two sun sensors are illuminated. In each case the sun sensor on the earth end was illuminated along with either the leading edge or the trailing edge. These points indicate yaw angle aligned with beta angle to at least ±2 degrees if we consider the sensitivity of the sensor near grazing incidence to be like that of the space end (figure 3). These points account for two of the expected morning alignments and six evening alignments. The yaw angle measurements from these points is presented in table 1.

There are two possible explanations for why only one third of the expected alignments were observed by the IDE sun sensors. The most likely cause is that alignments that would be observed when LDEF is less than 103 degrees from the sun are not observed because the light reflected by the earth illuminates both the north and south sensors. There is some evidence to support this explanation in the data of figure 1 between 99 and 101 degrees. Most of the points in this interval have only three sun sensors illuminated. Where four sun sensors are illuminated (11 points), the yaw and beta angles are near an expected alignment. The second explanation is that the yaw angle was oscillating. The data in table 1 show that the yaw was definitely not constant during the first 100 days of LDEF. If the yaw angle was oscillating, the time of some alignments would be prolonged and others shortened because of the relative phase of the beta and yaw angles; thus, some alignments would more likely be observed than others.

CONCLUSIONS

The sun sensors of the IDE were used to make eight measurements of the LDEF yaw angle at discrete times during the first year of its mission. These measurements indicate that the LDEF yaw angle was not constant but was oscillating about some average value. There is evidence that the oscillations were dampening but there is insufficient data to indicate the period of the oscillations or the dampening coefficient.

The determination of the LDEF pitch attitude was qualitative and indicates that LDEF had an average pitch down attitude of not more then 0.7 degrees with time variations less than ±1 degree during the first year.

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Table 1. LDEF Yaw Angle at Days in Orbit

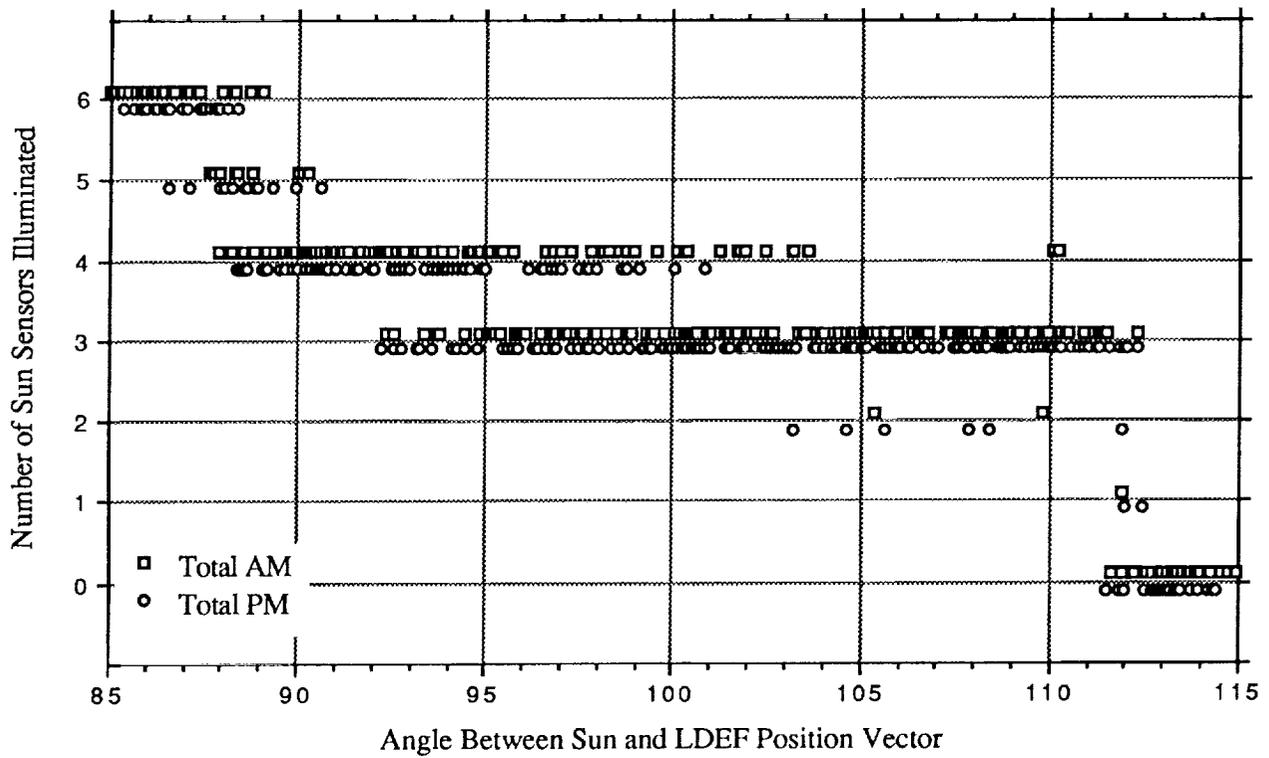| Day	Yaw Angle
4.15	6.9
75.77	12.4
91.77	4.3
163.69	9.8
167.44	5.2
205.43	9.5
238.04	9.2
288.69	5.9
Average	7.9

Figure 1. IDE sun sensor data at morning and evening for six orthogonal faces of LDEF.
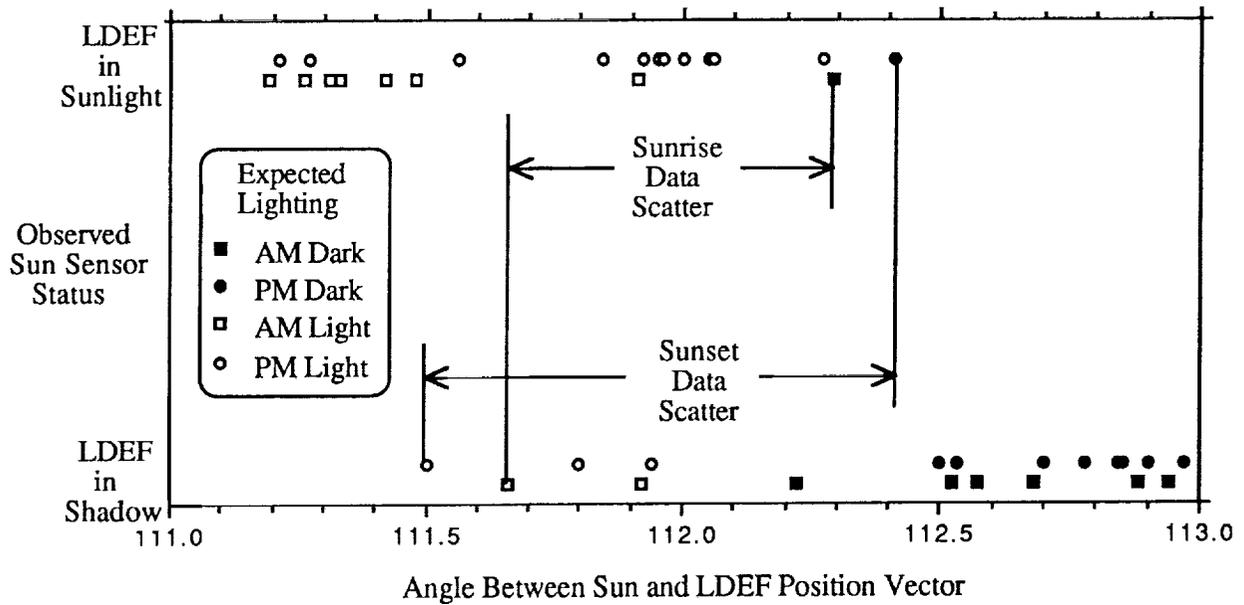

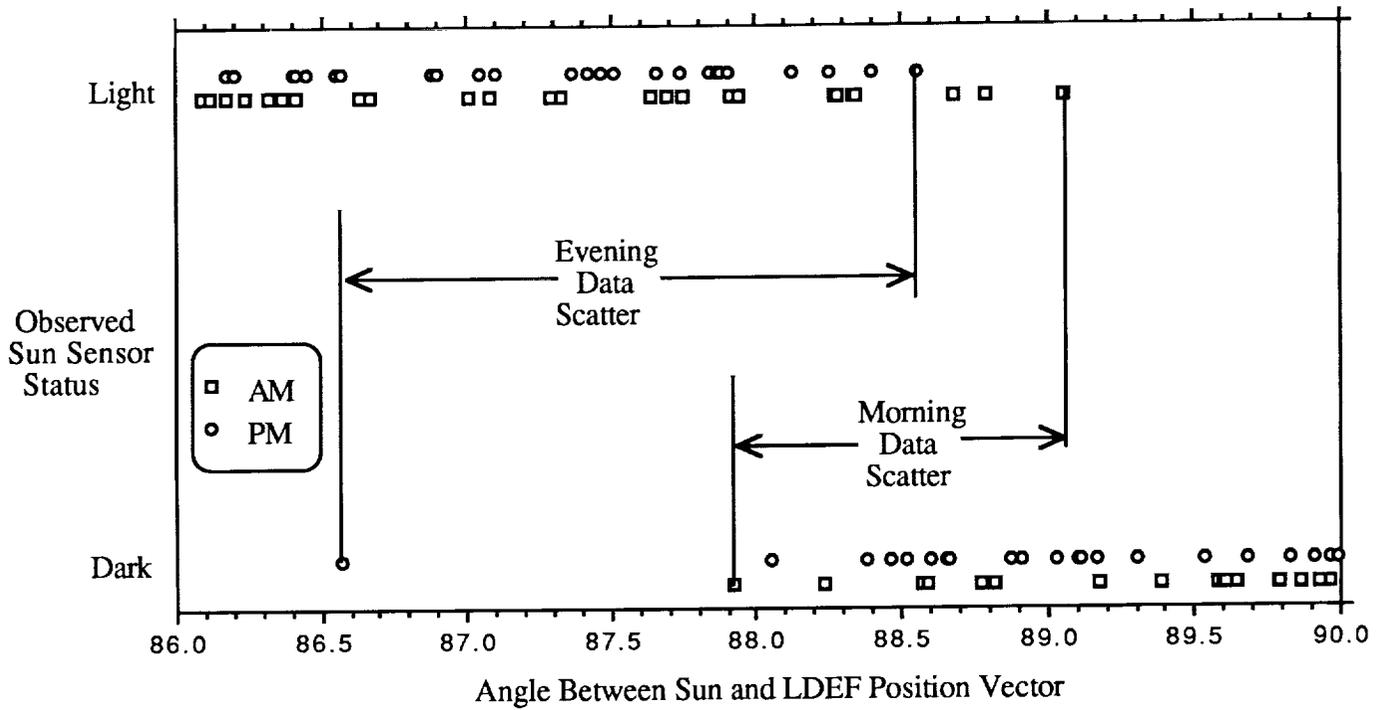Figure 2. Sun sensor data at sunrise and sunset geometry.
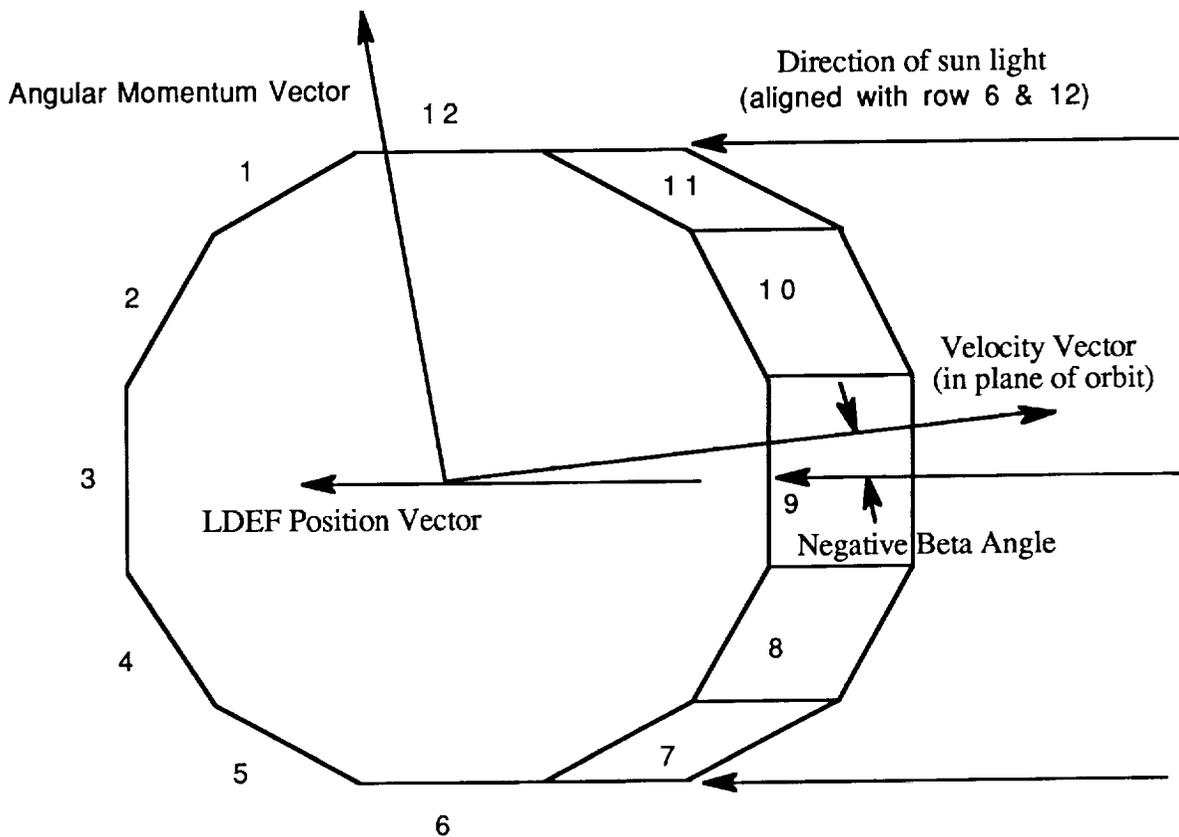
Figure 3. Sunlight on the Space End of LDEF.

Figure 4. Alignment of yaw and beta angles near sunrise.