THE OPTICAL SLIT SENSOR AS A STANDARD SENSOR FOR SPACECRAFT ATTITUDE DETERMINATION

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The idea for using an optical slit sensor as a standard sensor for spacecraft attitude determination arose during a brainstorming session of the First Goddard Standardization Meeting on June 6, 1975. This paper describes the basic concept of the slit sensor, indicates what information is available from a single sensor and from two sensors, describes one possible standard sensor package, and compares the standard sensor package with the attitude package flown on the first Synchronous Meteorological Satellite (SMS).

The slit sensor concept is one which has exciting potential as a standard attitude sensor for an enormous variety of missions, specifically, any mission using a spinning spacecraft or where rotating sensors or mirrors could be used. At present we are still in the stage of analytic studies–no experiments or design studies have been made. However, past experience suggests that such sensors are feasible and should be relatively easy and cheap to build.

The basic idea of a slit sensor is simple, as shown in figure 1. It consists of one, or perhaps two, narrow slits with a 180° field of view capable of triggering on both the earth and the sun and distinguishing between them. There is no angle measurement per se. There is simply a voltage change or pulse as the sensor crosses the sun or enters or leaves the disk of the earth. The slit scans the sky by being mounted parallel to the spin axis on a spinning spacecraft, by rotating itself, or by looking into rotating mirrors on a nonspinning spacecraft.

The major advantage of such a sensor is that it sees the entire sky. If the earth and the sun are visible, it will see them. Equally important, however, is that the slit sensor returns a wealth of attitude data that is both easy to interpret and particularly amenable to sophisticated analysis techniques.

It is important to keep in mind that the idea presented here is a standard sensor concept rather than a single piece of hardware; that is, we are interested in standardization of style and in manner of use. This implies great cost reduction, with little or no loss, and, in fact, possibly some gain in the versatility for individual missions.

The greatest economy probably comes from the fact that there is only one ground processing package, thus reducing the development costs. On the other hand, the experience base that is gained provides economy, reliability, and confidence. There will be some degree of package duplication, and this will certainly reduce hardware costs for some missions. At the same time, the mission planner is free to adjust a variety of physical parameters to meet his needs, or to take advantages of advances in hardware or software design. In addition, the mission attitude analyst is free to concentrate his efforts on improving quality and accuracy of results without constantly having to start over by developing new models or combining a variety of old models for each new mission.

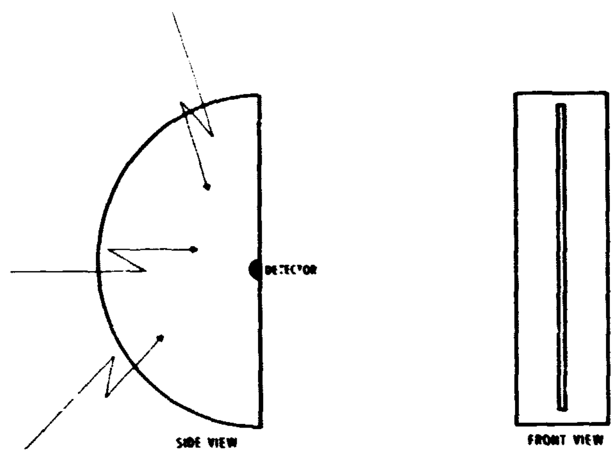

Figure 1. Optical slit sensor.

It has been indicated that a wealth of attitude information is available from the slit sensor or sensor package. Next I will briefly describe the type of information obtained, and then compare it with that available from sensors actually flown on the recently launched SMS-A.

In examining the information available from a single sensor as shown in figure 2, the most obvious data is a dihedral angle from the sun to the earth, measured to the earth midscan (D). However, this could also be measured to earth-in or earth-out for purposes of redundancy. A second type of data is the nadir angle, or the angle from the spin axis of the spacecraft to the center of the earth, which is available from earth-width measurements. Figure 3 is a plot of nadir angle versus earth-width angle, with nadir angle along the vertical axis and earth width along the horizontal axis. As can be seen from the figure, as the earth moves toward the sensor poles, it will subtend a larger dihedral angle. Therefore, the earth-width angle can be used as a measure of the nadir angle.

There are two regions where there is some difficulty with this measurement: In the vicinity of the spin plane, the earth-width measurement is relatively insensitive to the nadir angle, and, in the vicinity of the poles, the sensor never leaves the disk of the earth. Thus, there is not particularly good attitude information in two regions—along the Equator and in the region of the poles. However, there is a large region in between where high quality attitude information is available.

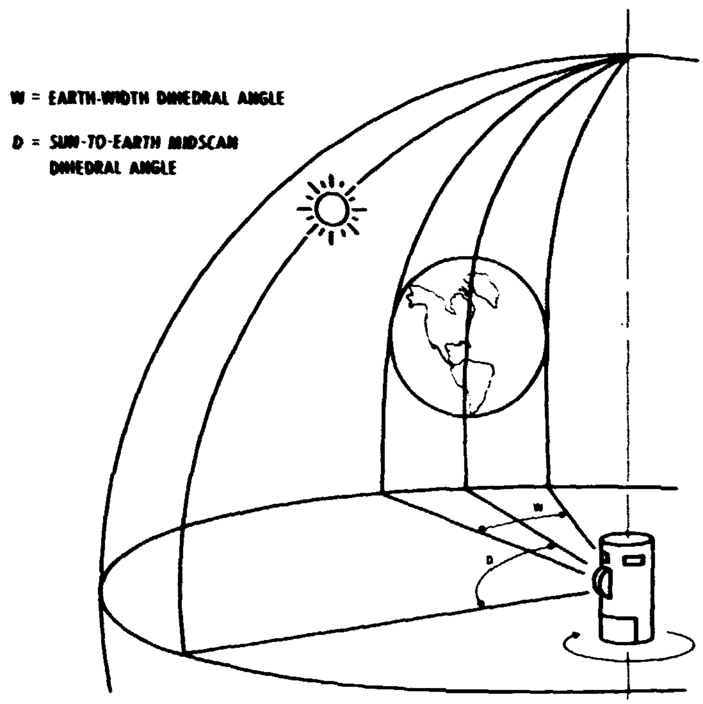

Figure 2. Information available from a single sensor.

Both of these measurements are available from just the presence of simple pulse. If the total illumination following on the slit sensor is monitored, then additional information is available which can provide the nadir angle in the vicinity of the poles. That is, specifically, if the total illumination output from the slit sensor is monitored, then this will be a sinusoidal oscillation. The amplitude of the sine is a measure of the nadir angle, and the phase of the sine relative to the sun is a measure of the dihedral angle from the sun to the center of the earth.

This information alone is sufficient for attitude determination; therefore, we could stop with a single sensor. However, the information would be of relatively poor quality at nadir angles near 90°, which are relatively common, and near the poles the information depends on intensity measurements. Bias determination and in-flight calibration would both be difficult.

Thus, it is worthwhile to consider the nature of information available from a second sensor. In particular, if the second sensor is mounted at an angle to the first, rather than parallel to the spin axis, then there will be a great deal of additional information rather than just redundancy. Slightly different information would be available, depending on whether the second sensor looks into the same hemisphere as the first or is canted somewhat so it can see slightly up or down. For the sake of concreteness, the results of a 360° sensor will be considered, but this is by no means necessary to take advantage of the second sensor.

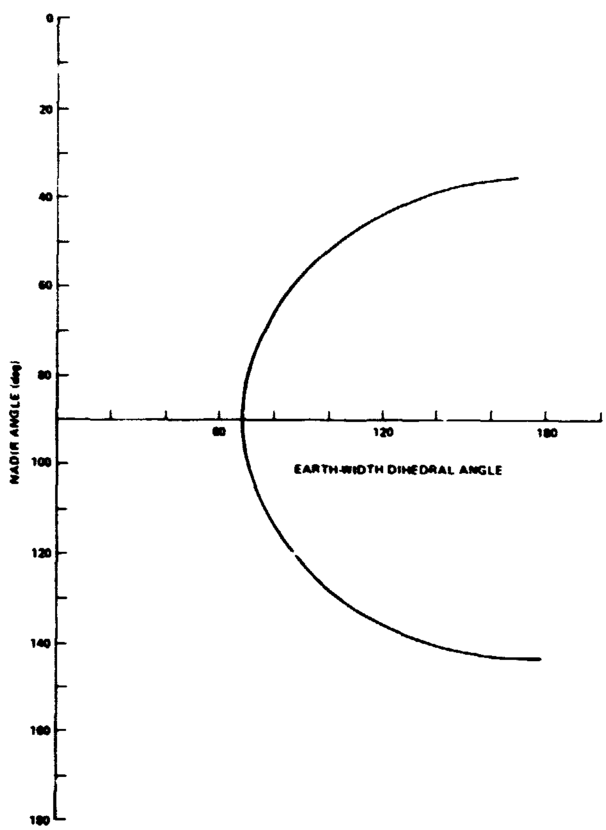

Figure 3. Nadir angle versus earth-width dihedral angle for vertical slit sensor and 70° diameter earth.

There are measurements available from a second sensor that are similar to those from the first sensor, but there are important differences as well. The dihedral angle from the sun to the earth is measured between two planes that do not contain the spin axis, and the nadir angle from earth widths (shown in figure 4) comes closer to the poles.

Specifically, if ρ is the angular radius of the earth and θ is the angle at which the second sensor is tilted to the first, then the nadir angle measurement will come within ρ-θ of both poles. Thus, full sky coverage in the nadir angle is available by tilting the second sensor at an angle equal to the angular radius of the earth at whatever distance the spacecraft is operating. The intensity measurements are the same at the pole as well, if we wish to use them; and the same problem exists around the Equator where the earth width is relatively insensitive to the nadir angle.

However, in addition to these two measurements, there are two measurements that are available from two slit sensors which are not available from either sensor singly. In particular, there is a sun angle from the sensor crossing times, and, as illustrated in figure 5,

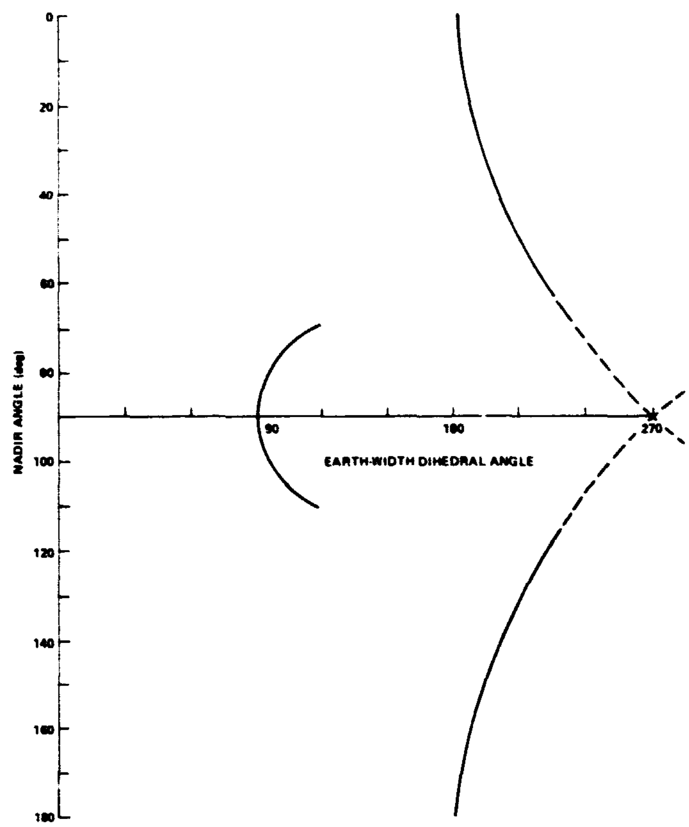

Figure 4. Nadir angle versus earth-width dihedral angle for 360° field of view slit sensor 35° from vertical and 70° diameter earth.

there is a third independent measure of the nadir angle from the midscan crossing times. Here again the nadir angle is the vertical coordinate and the midscan-to-midscan dihedral angle is the horizontal coordinate. It can be seen in the figure that there is now particularly good data in the vicinity of the Equator, with good distinction of the nadir angle. In addition, since the two hemispheres are different, we no longer have the problem of ambiquity about two possible solutions. Therefore, one needs no a priori information at all in order to use this procedure to find the attitude.

The following is a summary of the measurements that are available from two nonparallel slit sensors: There is one sun angle measurement, two independent measurements of the sun-to-earth midscan dihedral angle, and two earth-in measurements and two earth-out angles available for redundancy purposes. There are three independent measurements of the nadir angle. In addition, if we are willing to monitor the total illumination falling on the slit sensor, then there will be two additional independent measurements of the nadir angle available. So it is seen that two slit sensors provide essentially full sky coverage with abundant attitude data.

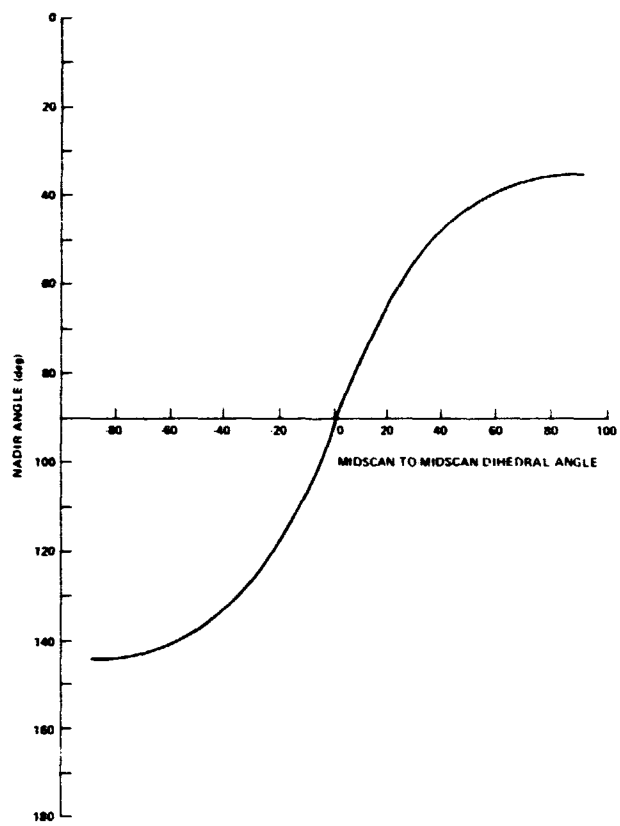

Figure 5. Nadir angle versus dihedral angle from midscan of vertical slit sensor to midscan of 35° off vertical slit sensor for 70° diameter earth.

Given the general concept of attitude determination with a pair of optical slit sensors, it should be possible to incorporate these sensors into a standard attitude package. The key to a standard sensor package is versatility; that is, a variety of sensitivity levels, a variety of spectral regions, and a variety of angular orientations. For example, the most likely spectral region for normal operation would be the infrared, since this provides well-defined earth horizons and intensity levels such that a single sensor could trigger on both the sun and the earth. At the same time, it is desired to incorporate the possibility of other intensity levels and other spectral regions for triggering on different celestial objects.

There are many possible configurations for a standard sensor package. One possible configuration, shown in figure 6, consists of three sensors mounted on a single plate: One sensor would be parallel to the spin axis of the spacecraft and two would be tilted at adjustable angles. In normal operation, the vertical sensor and one of the others would be used for attitude, and the third sensor used purely for purposes of redundancy. Any two sensors could provide high quality attitude information over all, or nearly all, of the celestial sphere, and any one could provide adequate information over most of the celestial sphere.

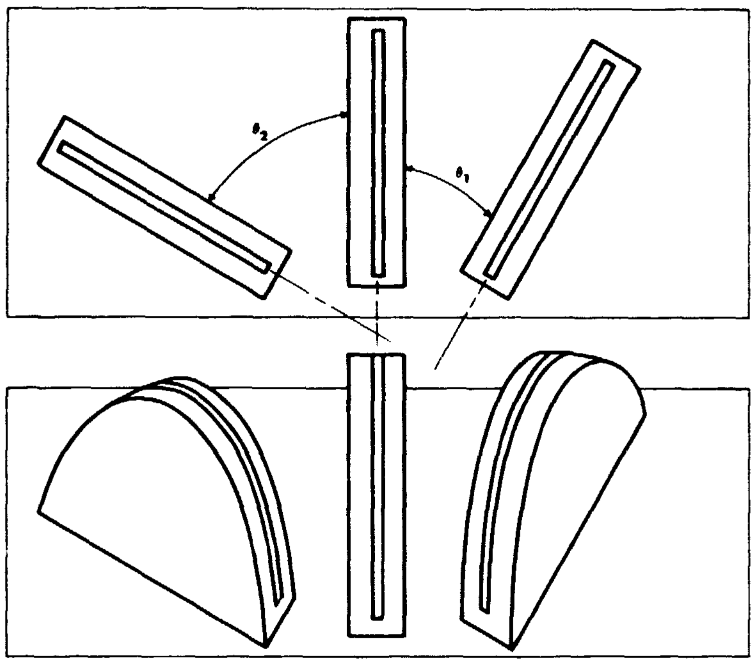

Figure 6. Slit sensor package.

So far we have discussed the general characteristics of slit sensor behavior. Now we will compare the analytic performance of a slit sensor package with the attitude package flown on the first SMS, which was launched on May 19, 1975, into a transfer orbit and was eventually placed in a circular synchronous orbit near the Equator. It should also be pointed out that, relative to Mr. Goad's presentation, we are interested here only in the attitude sensors themselves, and not attitude determination from the visible and infrared spin scan radiometer (VISSR).

There were seven attitude sensors actually flown on the SMS: two sun sensors, each with a field of view of 120° and five earth sensors: two primary earth sensors at 4° above and below the spin plane that were used for attitude determination in mission orbit and three other sensors that were used primarily for attitude in the transfer orbit. We will compare this with a slit sensor package consisting of three attitude sensors: one sensor that is parallel to the spin axis and two which are tilted, one at 8.5° and the other at 30° in the opposite direction.

Accurate spacecraft attitudes require that sensor biases be accurately known. Therefore, it is of interest to determine how many biases would need to be measured to use the sensor information with precision. In the package flown there are 20 total biases (two plane tilt, six azimuth, five triggering level, and seven elevation angle), which, as a purely practical matter, tells us that some selection will be necessary. There is essentially no chance of determining 20 biases from the data that are available from the spacecraft. The slit sensor package has a total of eight biases (three plane tilt, two azimuth, and three triggering level) that would need to be determined for all of the sensors to be utilized.

In normal circumstances, however, all the sensors in either package will not be fully utilized, and all of the biases will not need to be determined. Specifically, in both cases, a minimum of five biases is required for accurate attitude determination. However, it should also be pointed out that these five minimum biases for the sensor packages flown provide accurate attitudes only near the mission orbit and, in particular, do not provide accurate attitudes during most of the transfer orbit or during any other maneuvers or mishaps that might occur. On the other hand, since one sensor is fully redundant in the slit sensor package, the five minimum biases there provide accurate attitudes over the entire celestial sphere, including both the transfer orbit and the mission orbit.

Given the geometry of the sensor package, it is straightforward to calculate the portion of the celestial sphere covered by each sensor and the variety of independent measurements available for attitude determination. In particular, for the sensor package that is flown, there are two sun angle measurements over 50 percent of the sky and one sun angle measurement over the remaining 50 percent, such that the sun is fully covered with the package flown. In the slit sensor package, there are three sun angle measurements available over 87 percent of the sky, one measurement over 12 percent, and there is no sun angle measurement at all for 1 percent of the sky.

If the attitude is at orbit normal, and if the satellite is in an equatorial orbit, then in the package flown there are four sun-to-earth midscan dihedral angles available, and there are three such angles available with the slit sensor package. However, those three angles with the slit sensor package are available if it is required that the same sensor be used for both sun triggering and earth triggering. If you allow the sun to trigger with one sensor and the earth to trigger with another, then there are a total of nine sun-to-earth dihedral angles with the slit sensor package.

There are two earth-width dihedral angles over 9 percent of the sky with the sensor package flown: There is one measure over just slightly less than half of the sky, and there is no earth-width measurement at all over 42 percent. On the other hand, with the slit sensor package, there are three earth-width measurements over 93 percent of the sky, two over 6 percent, and one measurement over the remaining 1 percent, such that the sky is fully covered.

In addition to this, there are three midscan-to-midscan nadir angle measurements over 93 percent of the sky with the slit sensor package and one measurement over 6 percent. This measurement is not available at all from the attitude package flown.

Thus, the results here indicate that the slit sensor package has substantially more independent attitude measurements over more of the sky than the attitude package flown, even though the package flown has more than twice the number of sensors. From an analytic point of view, the slit sensor package should give better attitude results from this information.

Another characteristic of importance is sensor redundancy. That is, what information is left if the single most critical sensor for a particular measurement or a particular region of the sky is lost. With the sensor package flown, the loss of one critical sensor would be a moderately serious problem, since we are guaranteed coverage of the earth over only 9 percent of the celestial sphere. The sun presents fewer problems, since there we are guaranteed coverage over 50 percent of the sky. With the slit sensor package, the loss of one critical sensor would be essentially no problem, since one of the sensors was intended to be redundant in any case. The earth and sun sensing are 100 percent covered; the sun angle measurement is at least 87 percent covered.

The loss of two critical sensors would be a very serious problem for the attitude package flown. All of the sun or all of the earth observations could be lost. It would also be a problem for the slit sensor package. All of the sun angle and midscan-to midscan nadir angle measurements would be lost. However, the sun-to-earth dihedral angle and the earth-width angles would still be available over at least 87 percent of the sky. Thus, it should still be possible to do attitude determination. However, the accuracy or bias determination characteristics could be impaired.

If we lose three critical sensors in the slit sensor package, which has only three sensors, the spacecraft is obviously fully blind. In the attitude package flown, the spacecraft would be essentially blind. In some configurations, it is possible that there would be one observation still in existence, however, it is unlikely that attitude determination could be done with that one observation.

Lastly, there is the question of attitude accuracy, which requires a good knowledge of the sensor biases. A major factor in the accuracy with which biases can be determined is the coverage of the celestial sphere for each individual sensor. In the normal course of a mission, there are transfer orbits, inversion maneuvers, and so on. Each sensor will encounter a variety of geometries. As more coverage of the sky is available, more data from these different geometries will be provided, and the biases can be better determined, for two reasons. The most obvious, of course, is that there is more information available. In addition, there is a greater variety of geometries, and, in general, it is the variety of geometries which allows us to distinguish between sensor biases.

Thus, it is worth examining the sky coverage of individual sensors for purposes of bias determination. With the attitude package that was flown on SMS, the sun sensors both covered 75 percent of the sky. When sensing the sun, the slit sensor package would cover anywhere from 87 to 100 percent of the sky. (The parallel sensor would cover 100 percent; the +8.5° sensor, 99 percent; and the -30° sensor 87 percent.) Thus, the two packages would be essentially equivalent in this regard, with a very slight advantage, perhaps, going to the slit sensor package.

However, when sensing the earth, there is a major difference. With the attitude package flown, the earth sensors cover only 20 to 29 percent of the sky. (The ±4° sensors would cover 29 percent; the +20° sensor, 28 percent; the -25° sensor, 27 percent; and the -48° sensor, 20 percent.) However, when sensing the earth, the slit sensor package would cover 93 to 100 percent. With the parallel sensor, coverage would increase from 99 to 100 percent if an intensity measurement in the vicinity of the poles is used, rather than simply a pulse measurement. So it is clear from this information that the slit sensor package would provide much better bias determination, for two reasons: There are fewer biases to be found, and those which are necessary are easier to determine.

Thus, for SMS, it is seen that the slit sensor package has less than one-half the number of sensors that the flown package has, yet these would provide more independent attitude measurements over more of the sky, substantially greater redundancy, and far better bias determination characteristics than the flown sensors. One advantage of the slit sensor package is that it is inherently simple. (It is possible to envision a prototype made out of a tunafish can and a photocell). A second major advantage is that it is exceptionally versatile in two senses: It obviously has full sky coverage, which allows for more independence of mission details, but probably more important is the great mechanical versatility. That is, the same sensor can be used with changes in mechanical or electrical parameters to fit the particular mission at hand. Therefore, a single ground processing package could be used for a large number of missions.

For example, we could change the tilt of the second sensor to provide the best pole-to-pole coverage for a particular mission. On some missions, it might be possible to use a tilted sensor that has two stops for different conditions where accurate attitudes are desired. Also, the triggering levels could be changed to fit the particular needs at hand. In theory, the same sensors aboard the same spacecraft could be used in transfer orbit 322 km (200 miles) above the surface of the e... .n as halfway to Mars, by simply changing the triggering levels and triggering on Mars and Jupiter as point sources and measuring their nadir angles with respect to the spin axis of the spacecraft.

The slit sensor works on any spinning spacecraft. On any despun spacecraft, it can work by either rotating the sensors or by allowing them to look into one or more rotating mirrors.

It is difficult to find any disadvantages from an analytic point of view, although, of course, such a sensor system may be physically unbuildable. One minor disadvantage is that a slit sensor's response to the earth is not a square wave, as it is with point sensors. It rises to a maximum at the center of the earth and falls off toward the edges, which implies that the slit sensor might yield substantial triggering level biases. However, triggering level biases are by far the easiest to resolve by ground processing, and therefore this is unlikely to be a serious difficulty.

In summary, the optical slit sensor appears to be a versatile idea. It may be remarkably close to what is needed for modern space flight—a single standard attitude sensor with enormous versatility in its application.

ON THE DEVELOPMENT OF PRACTICAL NONLINEAR FILTERS

H. W. Sorenson
Applied Systems Corporation
San Diego, California

The general problem of estimating the state of a nonlinear, time-discrete system from noisy measurement data is considered from the point-of-view of developing feasible computational algorithms for evaluating the Bayesian recursion relations. Algorithms which have been proposed are reviewed, the computational implementaion of these algorithms is discussed, general conclusions coming from numerical studies are noted, and areas requiring additional research are defined.

CONVERGENCE CHARACTERISTICS OF BATCH AND SEQUENTIAL ESTIMATION ALGORITHMS

B. Schutz
University of Texas
Austin, Texas

The convergence rate and radius of convergence of the batch, and the extended sequential estimators are compared. The convergence behavior of the two processors in the presence of both observable and unobservable parameters is considered.

MANEUVER STRATEGY DESIGN FOR MARINER/JUPITER/SATURN AUTONOMOUS GUIDANCE AND NAVIGATION

T. Hagar
Jet Propulsion Laboratories
Pasadena, California

Candidate maneuver strategy algorithms for multiple and quasi-adaptive midcourse maneuvering are presented. Application of these techniques to the Mariner/Jupiter/Saturn 1977 mission, and as possible candidates for autonomous navigation and guidance, is discussed.

CONSIDERATIONS FOR LARGE SPACE TELESCOPE (LST) MISSION EFFECTIVENESS

J. Tuttle
Martin Marietta Corporation
Denver, Colorado

In designing the support systems module for the LST, consideration must be given to hardware limitations and mission design requirements. Special software has been developed to analyze these sometimes conflicting requirements. This talk will discuss the software and analysis made for the LST study.