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A SURVEY OF ATTITUDE SENSORS FOR SPACECRAFT

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PREFACE

During the past few years, an exceedingly large number of designs and concepts for determining the attitude of spacecraft relative to the earth, other planets, the moon, and stars, have been proposed. One notable effect of this proliferation of designs is that it is often difficult to become and to remain reasonably well informed in the attitude sensor field. This effect can be unfortunate, since the success of an increasingly large number of space missions depends upon the performance of the attitude sensors used, which in some cases has been poor. The purpose of this report is to alleviate the difficulty in understanding attitude sensors by describing the fundamental principles of operation of many designs which have been developed to the extent that their potential usefulness is clearly indicated. Several unique concepts are also mentioned. Included are moving-part and no-moving-part horizon scanners, sun sensors, star trackers, space sextants, and map matchers. Current areas of research are listed and certain problem areas are indicated. In addition, the performance of many sensors in space is mentioned.

INTRODUCTION

An extraordinarily large number of spacecraft attitude sensors and attitude sensor concepts have evolved recently, including earth sensors (horizon scanners), sun sensors, star trackers, space sextants, map matchers, magnetic field sensors, yaw gyroscopes, and impact sensors. Interestingly, many of the designs have evolved without specific applications. Apparently, the attempt has often been made to design sensors which are sufficiently versatile to be applicable to many or all space missions.

Although the importance of a particular sensor's characteristics depends largely upon its intended application, certain design goals apply for all sensors. Accuracy, low power consumption, small size, reliability, and insensitivity to planetary or celestial bodies other than the one it seeks are, of course, sought in all designs. In addition, the ability to operate within wide altitude limits, wide-angle capture capability, and long life are often required.

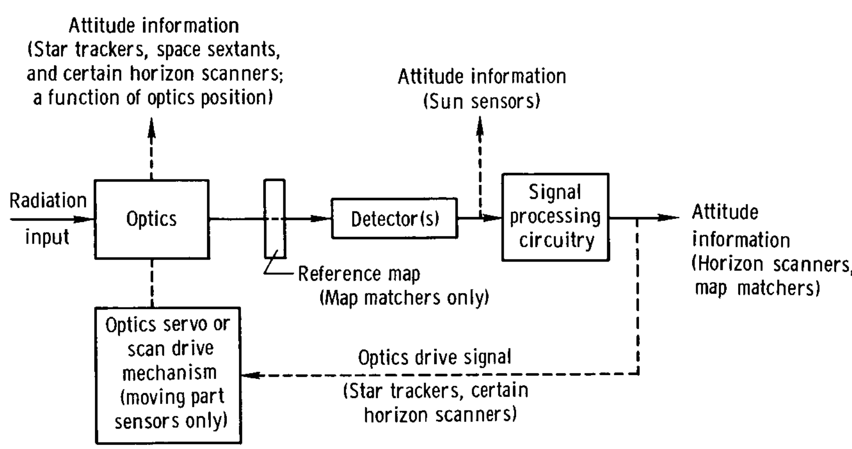

Figure 1.- Basic functional elements of optical-radiation-sensitive attitude sensors.

Figure 1 illustrates schematically the basic functional elements of optical (visible and infrared) radiation sensors. For sun sensors, it is seen that only an optical system and light detectors are normally required and, in many cases, the optics consist merely of a light shield or of a particular method of orienting the detectors in the sensor. For infrared horizon scanners, however, more complicated optics in addition to signal processing circuitry is normally required. If the scanning function requires optical motion (as is usually the case) rather than electronic scanning, a scan drive mechanism is also required. Map matchers, on the other hand, require an additional functional element – a reference map. For star trackers, automatic space sextants, and certain horizon scanners, all elements except the map are used and attitude is determined by reading-out the position of the optics. A closer examination of the various sensors reveals that the functional elements used in a particular class of sensors often differ markedly in design and operation – a fact that is particularly true for horizon scanners.

The specifications listed in the figures for attitude sensors are those stated by the manufacturers and are normally accurate under ideal laboratory conditions.

HORIZON SCANNERS

The terms horizon scanner, scanner, and horizon tracker have been applied indiscriminately to several types of attitude sensors which have in common only the characteristic that they determine spacecraft attitude relative to a planetary or lunar target. The implied scanning function is often not employed; nor do horizon scanners always utilize only the horizon in determining attitude, although the discontinuity in emitted infrared radiation which exists between space and several small areas on the horizon of the target is most often used by this class of sensors.

Infrared scanners that are currently operational belong to one of the following categories: (1) pulse generators, (2) conical scanners, (3) planar scanners, (4) point scanners, (5) edge trackers, (6) electronic-scan scanners, and (7) static heat balancers. In addition, visible-radiation sensors are often used as planet sensors. Reference 1 describes in detail many examples of the scanner types discussed in the following sections. Reference 2 lists complete specifications for some 30 specific scanners.

Pulse Generators

The simplest infrared scanner is the pulse generator. (See ref. 1, pp. 101-115.) This device uses the spinning motion of the vehicle to provide the necessary scanning action. (See fig. 2.) It has only a simple lens for collecting and focusing incident infrared radiation on a thermistor bolometer radiation detector (heat sensitive resistor) and a bolometer output amplifier. In operation, it produces a pulse (at t_1) when its field of view crosses the planet from space, and then another pulse (at t_2) when the field of view goes from planet to space. The midpoint between the pulses (t_1 - $t_2/2$) defines a plane passing through the planet's center (if it is assumed that the planet is spherical). A somewhat less accurate indication of vehicular attitude in a second plane can be revealed by an examination of pulse width (ref. 3). To date, a large number of pulse generators have been used in space.

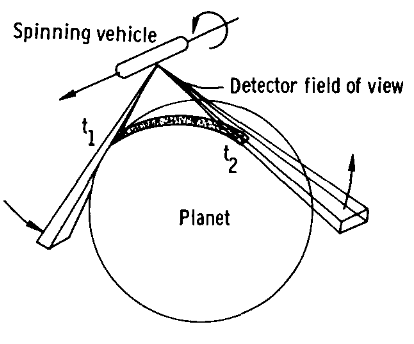

Figure 2.- Pulse generator. Typical specifications: Mass, 0.1 lb (0.05 kg); volume, 15 in^3 (2.47×10^{-4} m^3); power, 0.8 watt; accuracy, 0.1°.

Conical Scanners

In basic principle, the scanner type shown in figure 3 is a variation of the pulse generator having a built-in scanning mechanism and a means of electronically locating the bisectors of the included angle between the two opposite horizon-intersection directions (ref. 1, pp. 55-71). A pulse is produced while the field of view is on the planet. The midpoint of the pulse defines a plane passing through the planet center. Two units are required for two-axis attitude sensing. Conical scanners have been flown on several ballistic vehicles and on the Mercury spacecraft. They performed adequately on Mercury except during the early flights when they incorrectly interpreted cold clouds as a departure from earth to space and, consequently, were in error by as much as 20°. These scanners were subsequently modified, as explained later, and apparently functioned adequately on later Mercury flights.

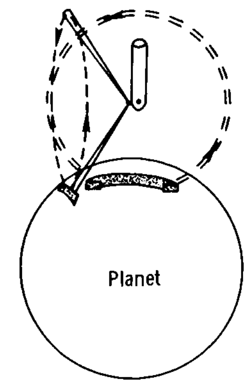

Figure 3.- Conical-scan horizon scanner. Typical specifications: Mass, 6 lbs (2.73 kg); volume, 150 in^3 (2.47×10^{-3} m^3); power, 6 watts; accuracy, 0.25°.

Planar Scanners

Several scanners have been devised to determine attitude by scanning in orthogonal planes across the infrared discontinuity at opposite sides of the horizon. In one such device, shown in figure 4, the fields of view are rotated through wide arcs and in such a manner that the angles between the fields of view in each plane and the primary axis are equal at all times. Horizon crossover signals are produced at times t_1, t_2, t_3, and t_4. In this design (ref. 4), the time difference between crossing opposite sides of the horizon in each plane indicates attitude in that plane.

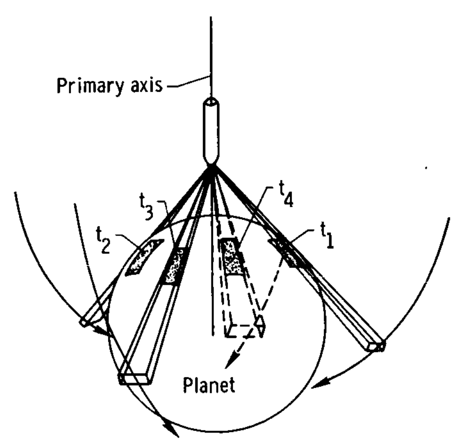

Figure 4.- Planar scanner type. Typical specifications: Mass, 4 lbs (1.82 kg); volume, 75 in^3 (1.23×10^{-3} m^3); power, 4 watts; accuracy, 0.1°.

The scanners in figures 3 and 4 incorporate high-speed moving parts, however, and would probably be incapable of operating reliably for long periods of time in space. Several designs have evolved, therefore, which require neither gears nor high-speed bearings in their normal operating modes. Such designs are either point trackers, edge trackers, electronic-scan scanners, or static heat balancers.

Point Trackers

Point trackers (fig. 5) consist of three or four separate scanning mirrors and their associated drive mechanisms which, after the target has been acquired, oscillate the detector fields of view across points on the horizon (ref. 1, pp. 117-131). The optics position indicates attitude. The oscillatory motion is caused by electromagnetically vibrated mirrors which are attached to the scanner frame by torsion bars. When four, rather than three, scanning heads are used in point trackers, the system offers potentially greater reliability, since it can be made to operate with any one of the heads incapacitated.

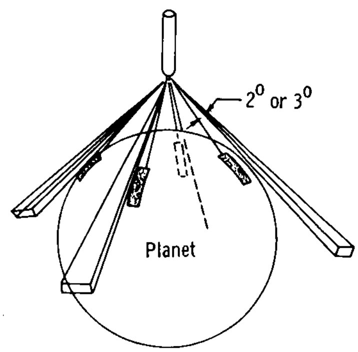

Figure 5.- Point tracker. Typical specifications: Mass, 12 lbs (5.5 kg); volume, 500 in^3 (8.2×10^{-3} m^3); power, 10 watts; accuracy, 0.05^0.

Point trackers were used on the orbiting geophysical observatory (OGO) satellites. Although the OGO-C scanners apparently misinterpreted cold clouds as space, those on OGO-B were modified and apparently functioned well.

Edge Trackers

The significant difference between point trackers and edge trackers (sometimes called limb trackers) is that the latter incorporate an additional mechanism which rotates the field of view of only one detector around the horizon (fig. 6). The horizon is crossed many times. Under most conditions, edge trackers permit better accuracy than can be expected from other designs because the effects of target oblateness, variations in effective altitude of the emitting radiation source, and variations in temperature of the source tend to be averaged out because of the relatively large number of points on the horizon which are crossed. (See ref. 1, pp. 133-157.) The scanners used on the Gemini were of this type. In general, they performed well except on Gemini V when the primary scanner failed, and during the immediate time of sunrise and sunset on all Gemini missions when intermittent losses of track occurred.

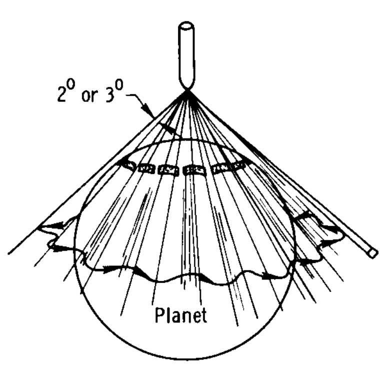

Figure 6.- Edge tracker. Typical specifications: Mass, 10 lbs (4.54 kg); volume, 200 in^3 (3.28×10^{-3} m^3); power, 10 watts; accuracy, 0.1^0.

Electronic-Scan Scanners

Electronic-scan scanners (sequential samplers) (fig. 7) normally contain four arrays of infrared detectors (thermistors or thermopiles). These detectors are located in the focal plane of either a refractive or a reflective optical system in such a way that an equal number of detectors in each of the four arrays are covered by the planet image when the instrument is pointed toward the planet center (ref. 1, pp. 217-229). Conversely, if a pointing error exists, the number of detectors covered by the image in the arrays will be different. The outputs of corresponding detectors in each of the arrays are sampled and compared simultaneously, starting with the outermost detectors in the arrays. An output difference indicates an image shift and, consequently, a pointing error in that plane. Normally, each array consists of 90 or more infrared detectors.

Sequential samplers require a heat source in the detector area to prevent the ambient temperature of the detectors from varying significantly; otherwise, small differences in temperature-responsivity characteristics of the individual detectors could produce output signal differences that exceeded the expected difference between the outputs of a detector in the planet's image and one outside the image. Recent research under the direction of the Jet Propulsion Laboratory has yielded promising methods of substantially reducing the current weight, volume, and power requirements listed in figure 7 for electronic-scan scanners. To date, sequential samplers have not been used in space.

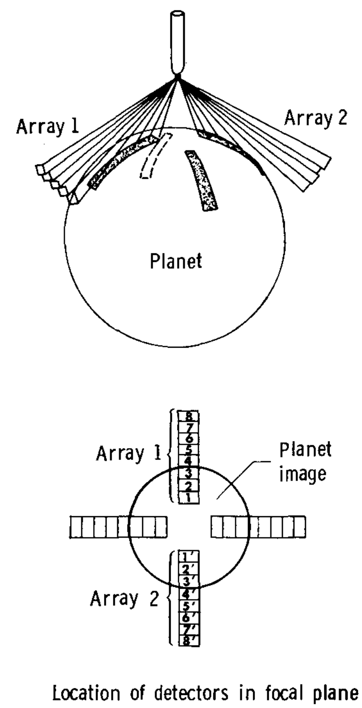

Figure 7.- Electronic-scan horizon scanner. Typical specifications: Mass, 25 lbs (11.4 kg); volume, 1100 in^3 (1.8×10^{-2} m^3); power, 13 watts; accuracy, 0.5^o.

Static Heat Balancers

Static heat balancers (ref. 1, pp. 175-193, 205-215) are the simplest and potentially the most reliable planet sensors for stabilized vehicles. They simply compare the levels of infrared radiation within opposite fields of view to detect attitude (fig. 8). Pointing error is indicated by difference in output level of detectors in each plane. Thermistors, thermopiles, or resistance wire may be used as detectors. Figure 9 illustrates a proposed technique for reducing the traditionally large pointing errors in heat balancers due to temperature differences over the source (ref. 1, pp. 195-203). In this design, the vertical position of the horizon in fields of view A and B are determined by the relative outputs of detectors A and B. Attitude is determined by comparing the horizon position in units viewing opposite sides of horizon.

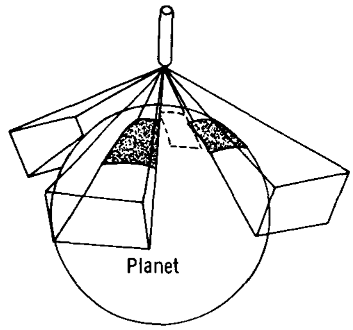

Figure 8.- Static heat balancer. Typical specifications: Mass, 6.5 lbs (2.95 kg); volume, 200 in^3 (3.28×10^{-3} m^3); power, 4 watts; accuracy 3°.

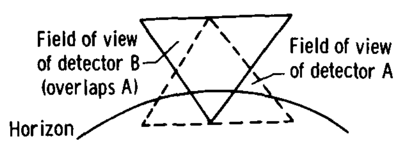

Figure 9.- Technique for improving accuracy of static heat balancers.

Visible-Radiation-Sensitive Planet Sensors

Light-sensing "scanners" normally use photoconductive or photovoltaic detectors to sense the center of illumination of the target. For high-altitude operations, where errors due to partial illumination are small, such sensors have proven to be very satisfactory. They were used on the Mariner and the Ranger spacecraft in orienting communications antennae toward earth and as primary attitude sensors on all Ranger and Mariner spacecraft except the Mariner IV Mars probe.

Problem Areas

Horizon scanners have in several instances performed poorly in space. High-altitude cold clouds have often been responsible for these problems. For instance, the conical-scan types used on the early Mercury missions interpreted such clouds as space and, as a result, produced highly erroneous outputs (ref. 5). These scanners were subsequently modified by adjusting their triggering thresholds and were accurate to better than $\pm 1^{\circ}$ on the later Mercury missions. As previously mentioned, cold clouds are thought to have been responsible for loss of track of the point trackers used on OGO-C. However, modifications to their triggering thresholds and changes in their optical bandpass apparently eliminated these problems.

The sun can also be a serious problem to many scanners. Most designs incorporate a signal-amplitude detection mechanism which grounds the scanner's output when the input radiation level exceeds some threshold level, as occurs when the sun is scanned. The sun can still cause errors, however, when it appears next to the horizon or when only a small part of it is scanned. Angle discriminating techniques (ref. 4) might be used in certain scanner designs to discriminate against the sun or other unwanted sources.

Uncertainties and variations in temperature and altitude of the emitting source relative to the center of the planetary source are also sources of error. Several flight experiments (refs. 6 to 10) have been performed to determine more precisely the nature of the infrared radiation at the earth's horizon and at least one sophisticated infrared radiation investigation program is underway (ref. 1, pp. 233-239).

Areas of Current Research

Although few entirely new scanner concepts have been proposed recently, a considerable amount of work is underway to improve existing designs. For example, a new infrared detector that should have better and flatter response to the far infrared than current thermistors is being investigated under the direction of the NASA Langley Research Center. The NASA Ames Research Center is investigating a planet tracker which is required to track the circumference of a planetary target that subtends only 60 arc-seconds to yield pointing accuracies of 1 second of arc. The tracker uses an image-tube light detector.

A point tracker incorporating instantaneous switching of the field between space and horizon is also being investigated (ref. 1, pp. 159-174). One significant advantage of instantaneous field switching is that it could increase the signal-noise ratios in point trackers.

In addition, various schemes of improving the accuracy of nearly all horizon scanner types have been explored. Many of these are discussed in reference 1.

SOLAR SENSORS

Sun Sensors

Sun sensors have been widely used in space for solar energy collection and for attitude determination. Because of their ruggedness and simplicity, they have functioned accurately and reliably. For each axis of operation, sun sensors normally consist of a pair of silicon photovoltaic or cadmium sulfide photoconductive cells which are connected in a bridge configuration so that their outputs are bucked. The physical arrangement of the cells in the instrument is such that a pointing error in one plane produces a difference in the amount of sunlight falling on the cells in that plane. This arrangement, in turn, produces a net output which is indicative of error. Coarse sun sensors having fields of view of up to 360° are usually used to bring the sun into the fields of the fine sensors. Figure 10 shows the design of the sensors used on Ranger and Mariner to orient the solar panels properly and to provide an attitude reference for midcourse and terminal guidance.

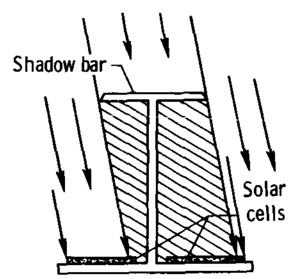

Figure 10.- Simple sun sensor.

Often, some technique is used to increase the slope of the bridge output in the vicinity of zero pointing error, since accuracy is most necessary in this region. Figure 11 illustrates one simple and successful method of accomplishing this increase (ref. 11). The combination of a small angle between cell surfaces and the use of shadow bars produces a steeper output slope around zero pointing error than the simple sun sensor and increases the saturation angle. The sensor shown in figure 12 has an extremely steep output slope about zero error (ref. 12). The solar cell output is minimal around zero pointing error because of internal reflection in the prism. At small error angles, reflection at one cell ceases and the cell output increases abruptly.

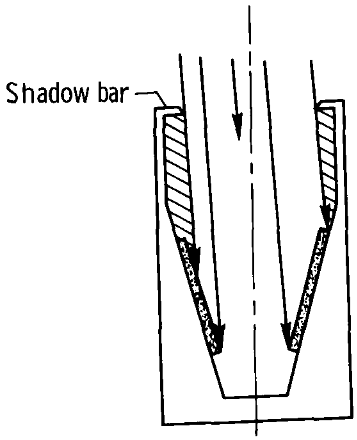

Figure 11.- Sun sensor with steep output slope. Typical specifications: Mass, 0.375 lb (0.17 kg); volume, 12 in^3 (1.97×10^{-4} m^3); power, none; accuracy, 1 min of arc.

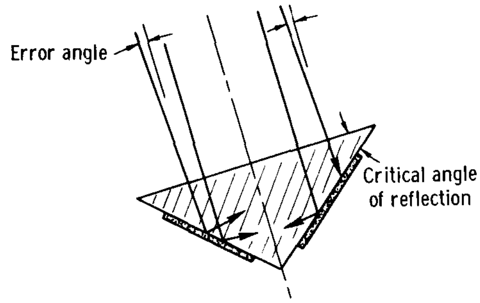

Figure 12.- Prism sun sensor.

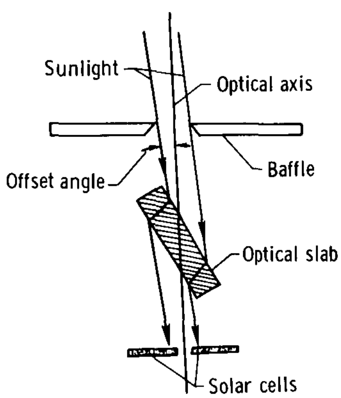

Figure 13.- Sun sensor for offset pointing.

The sun sensor which was designed for the proposed Advance Orbiting Solar Observatory (ref. 13) is unique in that it can be used to orient a spacecraft precisely at some offset angle with respect to the sun. Precise orientation is accomplished by means of rotatable optical slab which is placed in the field of view of the detector elements, as shown in figure 13. The optical slab is rotated to a prescribed angle relative to optical axis to displace the light bundle at detectors. The spacecraft is pointed at a corresponding offset angle relative to the sun to null detector bridge output. The slab can be rotated by command to a prescribed angle relative to the sun. This rotation, in turn, moves the light bundle at the detectors by a small distance and thus produces a net detector output. In order to null the output, the spacecraft is oriented at an offset angle. This sensor is reported to have an accuracy of better than 2 seconds of arc.

Unequal solar cell aging, which would create an offset bias in the detector bridge, can be a major problem in sun sensors. The application of radiation shields on the cells and the usage of light baffles and N on P cells are used to reduce aging. The problem of unequal aging is substantially reduced by selectively choosing cells from a preirradiated lot, since continued degradation would follow the same exponential curve (refs. 14 and 15).

Solar Aspect Sensors

Solar aspect sensors are used primarily for providing a record of spacecraft attitude relative to the sun rather than for attitude control. They are normally used on spinning vehicles and provide a digital output (ref. 16). Figure 14 shows schematically a digital solar aspect sensor with a fan field of view. A number of photo-duodiode light detectors are placed behind a coded mask which gives the detectors different fields of view, as shown. The azimuth and elevation angles of the sun relative to the sensor are determined, provided attitude about the third axis is known, by noting which detectors are producing an output.

Solar aspect sensors have been used on several vertical probe vehicles. In addition, the Explorer X magnetic field probe satellite contained a sensor of this type which sensed the earth and the moon, in addition to the sun, to provide trajectory-position information as well as attitude information. Solar aspect sensors and infrared earth sensors were successfully used on the S-6 aeronomy satellite to determine attitude in three axes (ref. 17). The solar aspect sensors contained a sun-moon switch for use in sensing the moon-reflected sunlight as well as the light of the sun.

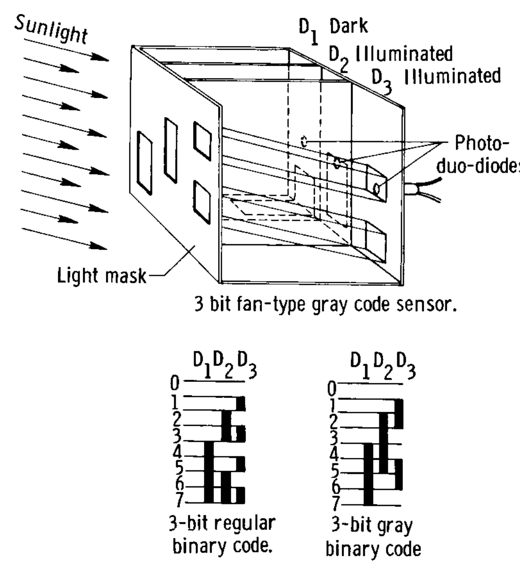

Figure 14.- Digital solar aspect sensor with a gray code light mask.

STAR SENSORS

Star Trackers

Star trackers provide precise vehicular attitude information for use in spacecraft guidance and orientation. To date, star trackers have been used on a number of ballistic vehicles and for midcourse guidance and terminal phase orientation on the Mariner, Surveyor, and the Lunar Orbiter spacecraft.

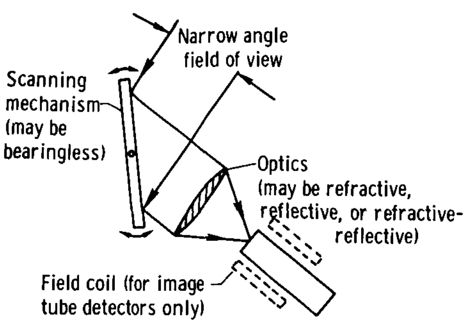

Figure 15.- Star tracker.

Figure 15 illustrates the basic operating principles of star trackers and star scanners. In star trackers using photomultiplier tubes, the field of view is oscillated by oscillating a mirror or a reticle located in the field. Torsion bars may be used to eliminate bearings. The field of view is centered on the desired star. The optics angle transducer determines the direction toward the star. In trackers using image-tube detectors, the image position in the focal plane determines attitude. The primary difference between star trackers and star scanners is that the latter scan through larger angles than trackers to locate the target star with the result that star scanners have a greater probability of locating the star within a given time period but with lower probable accuracy. After the target star has been detected, by means of its brightness, tracking systems attempt to lock on the star (refs. 18 and 19). The attitude-error signal, which is a function of displacement of the star from the center of the scan-arc limits, is used to drive the optics, or a field stop within the optics, in a way which will minimize the error signal. Spacecraft attitude relative to the star is then determined by reading out the angular orientation of the tracker optics relative to the spacecraft axes.

In trackers using photomultiplier tube detectors, the field of view is often oscillated through small amplitudes about a star to provide the necessary radiation-chopping function and for locating the position of the star. In other trackers using photomultiplier tubes, the incoming radiation is separated into two parts by beam-splitting techniques. Each part is then chopped in perpendicular planes by vibrating reeds which are driven at different frequencies in order that one photomultiplier detector may be used for two-axis attitude determination (ref. 20). Where image-orthicon tubes, vidicons, or image-disector tubes are used as detectors, the direction toward the target star is fixed by locating the star image on the sensitive surface of the tube by means of an internally scanned electron beam.

A single-axis Canopus star tracker (ref. 21) has been used on all the Mariner, Surveyor, and Lunar Orbiter probes. On each probe, one axis of the spacecraft was first oriented toward the sun and then the spacecraft was rolled about this axis until Canopus was detected. On the Mariner IV Mars probe, the attitude-sensing system had an accuracy capability of 18 seconds of arc.

Six gimbaled star trackers are used to bring the experiment optics of the Orbiting Astronomical Observatory into their operating range (ref. 22). The accuracy requirement of these trackers is 22 seconds of arc whereas that of the experiment optics, which will then become a part of the control loop, is as high as 0.1 arc-second.

Star Field Mappers

Star field mappers scan a star field mechanically or passively (on a spinning vehicle) to provide a map, or record, of the stellar objects it sees as a function of time. Spacecraft attitude is computed by comparing the map of the star field with a reference map of the celestial sphere.

Figure 16 shows a simple, but potentially accurate, star field mapper which is being used on the NASA Project Scanner infrared radiation investigation vehicle (ref. 23). An opaque reticle with two groups of transparent slits is placed within the field of view of a photomultiplier detector to provide a coded output which indicates the azimuth and elevation of the scanned stars relative to the vehicle.

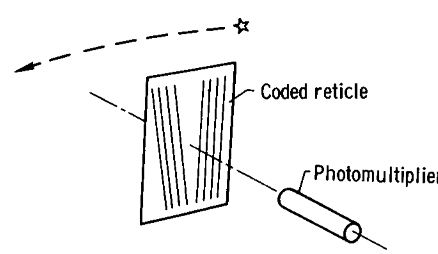

Figure 16.- Star field mapper for spinning vehicles. Typical specifications: Mass, 190 lbs (8.56 kg); volume, 1600 in^3 (2.62×10^{-2} m^3); power, 1.7 watts; accuracy, 0.01°.

The slotted reticle causes groups of pulses to be produced as the field of view sweeps across a star. The time of pulses, spacing between groups, and pulse amplitude are correlated with known star fields to determine attitude.

Problem Areas

One of the problems that must be eliminated in star sensors is that of reflected sunlight. As an example of the critical nature of the problem, reflected sunlight from dust particles that were knocked from the Mariner IV by micrometeoroids are thought to have been responsible for a temporary loss of track of Canopus on the Mars flyby mission. Multiple baffles for field-of-view restriction are often used to combat the problem. Proper star identification is another problem. The combined factors of detector aging and shot noise in photomultipliers can cause star trackers to choose an incorrect target star. Detector aging can be compensated for, however, by automatically and periodically sampling the detector's sensitivity and then by increasing amplifer gain in accordance with detector fatigue. The utilization of spectral analysis in star trackers has been proposed as a supplementary star identification technique (ref. 24).

Recent research under the direction of the Langley Research Center is being done on solid-state detectors for use in star trackers. If perfected, they would offer the advantages of reliability, simplicity, fast response, long life, and low weight and power requirements.

SPACE SEXTANTS

The automatic space sextant measures the angle relative to the spacecraft between two or more known celestial objects or landmarks to determine spacecraft attitude and position, as shown in figure 17. The objects which may serve as attitude reference sources are stars, the sun, the moon, a planet, or landmarks on the moon or a planet. Where a star and the moon or a star and a planet are used, the sextant is essentially a star tracker, an extended-source planet tracker, and a means of measuring the angle between the trackers combined into a single instrument.

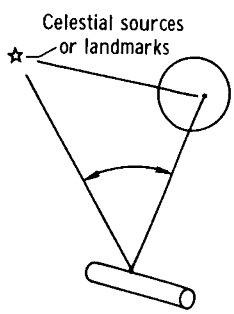

Figure 17.- Space sextant.

Space sextants might be used to perform a wide variety of functions. For example, one suggested application would use a space sextant for tracking stars, the moon, planets, or lunar and planetary landmarks (ref. 25). This sextant would consist of a multipurpose tracker with a phototube detector tied to an electrostatic free-rotor gyro reference frame. A primary error-producing factor in space sextants is that the reflected radiation from the earth or moon would usually have a crescent shape, as seen by a sextant at a relatively close range. For ideal conditions, however, accuracies of a few seconds of arc are predicted for some designs.

MAP MATCHERS

Map matchers determine spacecraft attitude relative to either star fields or lunar or planetary landmarks. Although map matchers are complicated in their mechanization, their operating principles are simple. They compare the features of a reference map stored within the instrument with the features of a star background or a lunar or planetary surface observed within their fields of view. The degree of similarity between the area viewed and the stored map reaches a maximum when the area viewed exactly corresponds to the map.

Basically, map matchers consist of three parts – a sensor which produces an image of the area viewed, a reference map, and a correlator which compares the map and the image. Either radar or optical scanning techniques may be used. Where radar scanning is used, an image of the area viewed is formed on a cathode-ray tube which is scanned internally by an electron beam. The image is thus converted to a pulse train which is compared by the correlator with a stored map (pulse train) representing the target area. When the correlation function exceeds some threshold value, the area viewed is assumed to be the target field. This information can then be used to determine spacecraft attitude relative to the desired field. If movement of the field relative to the spacecraft is rapid enough, velocity can also be determined.

In systems using optical scanning techniques (fig. 18), a telescope is used to superimpose an image of the field on a photographic transparency of the target area. The light energy transmitted by the map is then integrated optically and focused on a phototube detector, the output of which is the correlation function. Map matchers have not yet been used in space.

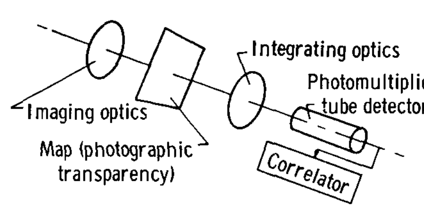

Figure 18.- Optical map matcher.

MAGNETIC FIELD SENSORS

Magnetic field sensors (fig. 19) measure the orientation of the spacecraft relative to the earth's magnetic lines of force. The sensors contain three mutually perpendicular coil-wound rods of high permeability. An alternating current is applied to the coils to magnetize the rods first in one direction and then in the opposite direction. Orientation of the rods relative to the earth's magnetic field (and thus spacecraft orientation) is indicated by an unbalance in the alternating current output from the coils with respect to zero voltage. Since the output voltage is proportional to the cosine of the misalinement angle of the rod to the earth's magnetic field vector, attitude sensing accuracy is variable, and it is maximum at 90° to the magnetic field vector. Magnetometers can only provide attitude information about two axes; thus, a sun sensor is normally used to provide attitude information about the third axis of the vehicle.

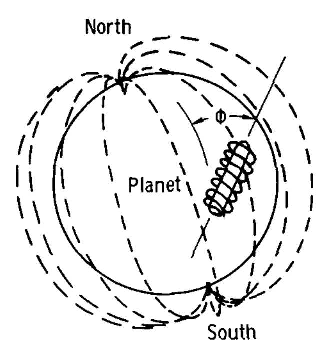

Figure 19.- Magnetic field sensor. Typical specifications: Mass, 2.5 lbs (1.14 kg); volume, 135 in^3 (2.2×10^{-3} m^3); power, 2 watts; accuracy, $<1^{\circ}$.

Magnetometer attitude sensors have been used successfully on several spacecraft, including the several transit navigational satellites and the TRAAC satellite (ref. 26) for which very good attitude sensing accuracy was not necessary.

OTHER SENSORS

Rate-Integrating Gyroscopes

Rate-integrating gyros have been useful for sensing spacecraft attitude in yaw. For this application, the rotational axis of the gyro is oriented perpendicular to the orbital plane. Yaw is indicated by an angular displacement of this axis relative to the spacecraft yaw axis (ref. 27, pp. 252-256).

Pressure and Impact Sensors

Several concepts have been suggested which would determine the attitude of planet-orbiting spacecraft by measuring either the residual atmospheric pressure or the impact rate at different points on the spacecraft of micrometeors, cosmic rays, or natural radiation (ref. 27, pp. 343-347). The area of maximum impact of micrometeors would be near the top of the spacecraft, whereas maximum impact area for residual atmospheric pressure, cosmic rays, ions, and neutral particles would be the frontal area (fig. 20). Ion-detecting attitude sensors were flown as an experiment on Gemini X. Although the results were encouraging, the experiment sensor indications went off-scale while the thrusters were firing because of the varying charge on the vehicle and/or the contamination in the immediate vicinity of the spacecraft. Neither pressure sensors nor impact sensors have been used in space for attitude control.

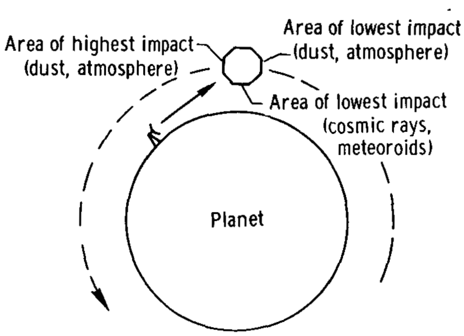

Figure 20.- Pressure and impact-rate sensors.

Other Concepts

Other concepts include attitude sensor instruments which would utilize the gravity gradient (ref. 28), radio or laser frequency radiation emitted by ground stations, the earth's airglow, ultraviolet radiation, and planetary-emitted radio frequency radiation. None of these concepts have been used in space.

CONCLUDING REMARKS

Existing and proposed attitude sensors are both numerous and diverse. Infrared radiation planet sensors exibit particularly wide variations in design and they incorporate either planar, conical, point tracking, edge tracking, radiometric balancing, or electronic scanning techniques. Solar interference and cold high-altitude clouds have caused serious problems in horizon scanners.

Sun sensors, on the other hand, have performed accurately and reliably. Although most sun sensors are simple in design, those which are required to orient a spacecraft at an offset angle relative to the sun or to function with extremely good accuracy are more complex. Solar cell aging is a severe problem associated with sun sensors.

Digital solar aspect sensors provide a digital time-based history of the azimuth and elevation of the sun relative to the spacecraft from which attitude can be determined.

Star trackers, which are categorized as either trackers or scanners, according to their scanning mode, have been successfully used on a number of missions. Precise attitude sensing in three axes can be achieved by using more than one star or by the use of a sun sensor in addition to the star tracker. Star field mappers perform basic functions which are similar to those of solar aspect sensors in that they provide a time-based record of the elevation and azimuth of the scanned stars from which vehicular attitude can be computed.

Automatic space sextants function similarly to other sextants whereas map matchers compare the features they scan with the features on a stored map to determine spacecraft attitude. Neither map matchers nor space sextants have been used in space.

Yaw-sensing gyros and magnetic field sensors have been used successfully on several space missions. Magnetic field sensors determine spacecraft attitude relative to the earth's magnetic field by measuring the current induced in a coil surrounding a rod of high permeability.

Atmospheric pressure sensors, particle impact sensors, and several other attitude sensor concepts have been proposed but not yet used as primary sensors in space.

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