An Innovative Approach to Determine the Alignment of the Star Camera System for the Clementine Spacecraft

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Abstract

The Clementine spacecraft has the requirement to provide accurate inertial pointing of the mission sensors toward celestial objects, perform precisely-oriented propulsion maneuvers, and steer the body-fixed high-gain downlink antenna. The baseline for the spacecraft's inertial knowledge is derived from the on-board star camera system. This paper describes the methods employed to derive the critical alignment of the two star cameras with respect to the spacecraft. The primary alignment combined conventional optical metrology to orient the star cameras relative to the spacecraft axes with outdoor alignment of the star cameras using the night sky. The end-to-end verification of the fully-integrated spacecraft was done entirely using the night sky. These techniques were unique in that they were designed to provide a fast, accurate, and complete end-to-end alignment without costly and time-consuming hardware and test fixture setups.

Introduction

Clementine is a three-axis stabilized spacecraft designed, built, and operated by the Naval Research Laboratory to map the Moon and photograph the asteroid Geographos. In flight, the Clementine spacecraft derives its attitude entirely from two CCD star cameras and a star-matching algorithm implemented on the spacecraft computer. From a single star image from either star camera the complete three-axis orientation of the spacecraft can be determined.

The star camera system possesses an implicit, internal coordinate system, and when the star camera system determines an attitude using the stars it actually determines the orientation of this internal coordinate system relative to the celestial coordinates. Of course, it is necessary to know the orientation of the camera internal coordinate system relative to the spacecraft axes in order to use the star camera system to determine the spacecraft attitude. This paper discusses using the stars in the night sky to determine this orientation. The estimated uncertainty in the alignment using this method was 0.01°. In addition, this paper will discuss using the night sky to perform an end-to-end validation of the star camera and star matching system on the completely integrated spacecraft. Finally, these tests provided a reassuring opportunity to operate the star camera system using actual, rather than simulated, star fields.

This paper describes both the theory and practical aspects of aligning a star camera system using the night sky. The analysis makes use of Earth-based and celestial coordinate systems. The reader is referred to Bowditch [1] for a general discussion of these coordinate systems and time measurements, and Seidelmann [2] for additional discussion and the specific almanac data required for these measurements.

Clementine Attitude Determination System and Requirements

The attitude of the Clementine spacecraft is determined during flight by taking a star image with either of two star cameras and processing the image on the spacecraft computer to determine the spacecraft attitude. The cameras were designed and built, and the algorithm was developed, by the Lawrence Livermore National Laboratory. Each of the two, identical cameras has a relatively wide field of view of 28 by 42 deg, and can detect stars to visual magnitude approximately 4.5. Therefore, a single star image from either camera is sufficient to provide a complete three-axis attitude determination including the roll angle about the camera line of sight. Two cameras pointing in different directions are carried on Clementine because for some spacecraft orientations the Sun will blind one camera or the other, and the alternate is used.

The primary attitude knowledge requirement to know the pointing direction of the science imaging cameras to 0.03°, one sigma. However, this requirement did not have to be met before launch, and the science payload alignment measurements were performed in flight by imaging stars using the science cameras. The in-flight measurements demonstrated that the spacecraft met the pointing knowledge requirement of 0.03°. An additional, pre-launch three axis attitude knowledge requirement for the Clementine spacecraft was 0.1°, one sigma. This pre-launch requirement was fixed by the need to orient the spacecraft to fire the solid rocket motor to leave low Earth orbit and begin translunar flight. The alignment measurements discussed in this paper easily meet this pre-launch requirement, with an estimated uncertainty of 0.01°, one sigma.

Star Camera Alignment Using the Night Sky

In principle, determining the coordinate reference frame for a star camera system using the night sky is straightforward. First, mount the star camera outdoors viewing the stars overhead, and measure the orientation of the star camera body relative to the local Earth frame. Second, take and process a star image to yield the orientation of the star camera internal reference frame relative to the celestial reference frame. Third, by knowing the location on the Earth's surface and the time at which the image was taken, compute the orientation of the local Earth frame relative to the celestial frame at the instant the image was acquired. These can be combined to give the orientation of the camera reference frame relative to the star camera body, which is the information needed to use the star camera system information. In this section these measurements will be expressed symbolically in terms of rotation matrices and commonly-used coordinate systems, although other coordinate systems and coordinate transformation representations such as quaternions can be used.

The star camera system can be assigned two Cartesian coordinate systems; the first is the implicit, internal coordinate system relative to which the star camera system measures attitude, and the second is a coordinate system referred to the camera's mechanical body. These will be called the internal and body coordinate systems, respectively. The specific purpose of the alignment measurements described in this paper is to determine the three-dimensional rotation matrix $\mathbf{R}_{\text{internal to body}}$ which rotates the internal coordinate system into the body coordinate system, so that the results from the star camera system can then be related to the spacecraft axes.

A commonly-used Cartesian coordinate system for the celestial frame has the x-axis pointing toward the vernal equinox in the constellation Aries, which is the point in the sky at which the Sun crosses the projection of the Earth's equator as the Sun appears to travel from the southern to northern hemisphere in the spring. The z-axis projects from the Earth's north pole, and the y-axis completes a right handed coordinate system. When the star camera system determines an attitude, the output is the three-dimensional rotation matrix $\mathbf{R}_{\text{internal to celestial}}$ which rotates the internal frame into the celestial frame.

The celestial coordinate system used to specify the direction to individual stars is defined using the projection of the Earth's equator and poles. Because the Earth's poles precess relative to the fixed stars, this celestial coordinate system moves relative to the fixed stars. This is a significant effect, and is much larger than the proper motion of the stars. Stated differently, the coordinates of the stars change with time due to the precession of the Earth's poles, and a catalog of star coordinates must specify the date for which the coordinates are valid. This date is called the epoch of the catalog; a commonly-used epoch is the year 2000.

A star camera system used for attitude determination uses the coordinates of the stars in its internal catalog, so that during spacecraft operations all attitude specifications and commands must take into account the epoch of the star coordinates in the internal catalog. In using the night sky to align a star camera system, it is important to note that the attitude determination matrix $\mathbf{R}_{\text{internal to celestial}}$ resulting from a star image is based on the star positions for the epoch of the internal catalog, not for the stars positions at the current epoch. Therefore, a rotation matrix $\mathbf{R}_{\text{epoch}}$ must be included in the analysis to account for the three-dimensional rotation of the celestial coordinate system relative to the stars, between the epoch of the alignment measurements and the epoch of the star camera system's internal catalog.

Finally, a Cartesian coordinate system can be assigned to the Earth at the location where the measurements are taken. For Clementine the Cartesian coordinates represented by true east, true north, and gravity vertical were used. This will be designated the Earth reference frame, and there is a three-dimensional rotation matrix $\mathbf{R}_{\text{celestial to Earth}}$ which rotates the celestial frame into the Earth frame. Similarly, there is a three-dimensional rotation matrix $\mathbf{R}_{\text{Earth to body}}$ which rotates the Earth frame into the star camera body frame.

Using this notation, the desired rotation matrix $\mathbf{R}_{\text{internal to body}}$ can be found by combining the other rotations which can be measured individually, using

$$\mathbf{R}_{\text{internal to body}} = \mathbf{R}_{\text{Earth to body}} \bullet \mathbf{R}_{\text{celestial to Earth}} \bullet \mathbf{R}_{\text{epoch}} \bullet \mathbf{R}_{\text{internal to celestial}}.$$

Alignment of the Clementine Star Camera System

The plan outlined above was implemented for the Clementine star camera system. The bodies of the Clementine star cameras did not have alignment surfaces. Therefore, each star camera was fastened to a mounting plate which carried a reflecting alignment cube, and the camera body frame was defined by the reference cube. Of course, the camera was not removed from the alignment plate following the measurements.

For the alignment of the Clementine star cameras, a large, precision, machinist's rotary table was mounted outdoors on stands and electrically grounded. The rotary table was leveled relative to the local gravity field using a precision machinists level so that the table's rotary axis was vertical. Then, a flight star camera was mounted on the rotary table so that the camera reflecting cube was visible and accessible to a theodelite. The camera was completely wrapped and taped in antistatic plastic before leaving the clean area, for protection. The optical baffle opening, which was not a static-sensitive area, was covered with taut *Saran Wrap* plastic, which produces a good optical window. The boresight of the camera was nominally vertically upward to minimize the effects of the atmosphere, but it was not necessary that the camera boresight be exactly vertical. The camera was connected to a power and data acquisition system which emulated the spacecraft interface.

The elevation and azimuth of the normal to two of the camera reflecting cube faces was measured using a theodelite autocollimator. For these measurements, the rotary table was first positioned so that a reflecting cube face was visible to the theodelite. The elevation of the normal to this face relative to local gravity was determined using the theodelite's internal bubble level, and the azimuth of the normal relative to true north was determined by sighting Polaris with the theodelite and correcting for Polaris' actual position. Then, the rotary table was rotated approximately 90° to bring a second cube face into view of the theodelite, and the measurements were repeated. These measurements, including the rotation of the rotary table, are sufficient to define the body Cartesian coordinate system, and to determine the rotation matrix $\mathbf{R}_{\text{Earth to body}}$ for any position of the rotary table. In fact, the complete set of these measurements overdetermines the body coordinate system, and for the Clementine alignment measurements the elevation and azimuth of the normal to the first face, and the elevation of the normal to the second face, were used to construct the body coordinate system.

Using this system, a set of star camera images was acquired at known times for the beginning position of the rotary table, and processed using the star matching algorithm to yield the instantaneous attitude of the star camera reference frame relative to the celestial frame. The rotary table was rotated by accurately-known angles of approximately 90, 180, and 270 degrees, and at each position the set of images and analysis were repeated. For each image, the three-dimensional rotation matrix $\mathbf{R}_{\text{internal to celestial}}$ was computed. Of course, all of these matrices were different, not only because of the different positions of the rotary table, but also because of the rotation of the Earth which caused the orientation of the internal frame to change with time with respect to the celestial frame.

The measurements at multiple positions of the rotary table provide a very important opportunity to detect systematic errors in the measurement of the latitude, the longitude, or the times of the images. Except for random errors, the rotation matrices $\mathbf{R}_{\text{internal to body}}$ must be the same for all positions of the rotary table A systematic difference in the matrices $\mathbf{R}_{\text{internal to body}}$ for different rotary table positions is a clear indication of a systematic error.

The epoch of the star coordinates used in the Clementine star camera system is the year 2000, whereas the epoch of the alignment measurements made in October 1993 was 1993.9. Therefore, the rotation matrix $\mathbf{R}_{\text{internal to celestial}}$ reported by the star camera system was slightly incorrect, because the star

camera system used the celestial coordinate system as it will be in the year 2000, not the current celestial coordinate system. Therefore the rotation matrix $\mathbf{R}_{epoch}$, which is the three-dimensional rotation of the celestial coordinate system relative to the fixed stars between 1993.9 and 2000, was included to compensate for this difference. The reader is referred to an astronomical almanac formulas giving this rotation, from which the explicit rotation matrix can be constructed.
The orientation of the local Earth reference frame of east, north, and gravity vertical at the position of the star camera, relative to the celestial reference frame, was determined by knowing the latitude, longitude, and time of the image. The latitude and longitude of the star camera were determined using a basic GPS receiver, which also provided a Universal Time reference. The required rotation matrix which rotates the Cartesian celestial frame described in the previous section into the local Cartesian Earth frame can be computed with the aid of the familiar celestial coordinate system defined by the lines of declination and right ascension.

Declination and right ascension, commonly used in astronomy and celestial navigation, form a coordinate system analogous to latitude and longitude [1]. The lines of declination are analogs of lines of latitude, where the line of zero degrees declination, or the celestial equator, is the projection of the Earth's equator onto the celestial sphere. The celestial poles are projections of the Earth's north and south poles, and at the celestial poles the declination is positive or negative ninety degrees. The declination of a point in the sky, measured in degrees, is simply the angle between the celestial equator and that point. Except for the effects of local gravity anomalies, which are negligible for the Clementine alignment measurements, the celestial declination directly overhead as defined by the gravity vertical is exactly equal to the local latitude.

It is important to note that no corrections are required for the oblateness of the Earth or the "centrifugal force" due to the Earth's rotation, because the latitude which is used for mapping on the Earth's surface already includes these effects [1]. The conventional latitude used for mapping at a point on the Earth's surface is defined as the angle between the normal at that point to the average geoid of the Earth, which is the surface defined by a smoothed effective gravity horizontal, and the Earth's equatorial plane. In particular, latitude on the Earth's surface is *not* equal to the angle between the equatorial plane and a line drawn from the center of the Earth to the point on the surface. Since the definition of the average geoid takes into account the oblateness of the Earth and the effects of centrifugal force, the celestial line of declination directly overhead is by this definition exactly equal to the latitude, except for local gravity anomalies.

The lines of right ascension extend from celestial pole to celestial pole, and are analogs of lines of longitude. The lines of right ascension are conventionally designated by hours, minutes, and seconds of right ascension. The line of zero hours of right ascension intersects the celestial equator at the vernal equinox described in the previous section. Right ascension increases by one hour for each fifteen degrees in an easterly direction along the celestial equator. Because of the rotation of the Earth in inertial space, the celestial sphere appears to rotate about the Earth, carrying the lines of right ascension with it. The rate at which the lines of right ascension pass overhead is almost but not exactly equal to one hour of right ascension per hour of elapsed civil time, where the difference is due primarily to the Earth's orbit around the Sun.

In the absence of a local gravity anomaly, the line of right ascension directly overhead as defined by gravity vertical is known as the local meridian.

Again, the local gravity anomaly was negligible for the Clementine alignment measurements, Of course, the local meridian changes constantly as the celestial sphere rotates overhead, and the right ascension of the local meridian is equivalent to the local sidereal time. The local sidereal time, and so the right ascension of the local meridian, is computed by referring to a current celestial almanac [2] to find the sidereal time at the Greenwich meridian for the Universal time of interest, and adjusting this for the latitude difference between the local longitude and Greenwich by adding one hour for each 15 degrees of longitude east of Greenwich. The reader should consult the almanac for the specific formulas used in this computation.

Using these definitions the relationship between the Cartesian Earth frame of true east, true north, and gravity vertical, and the Cartesian celestial frame defined in the previous section can be constructed. Neglecting the local gravity anomaly, gravity vertical in the Earth frame points toward a celestial declination equal to the local latitude, and a celestial right ascension equal to the local sidereal time. At this point it is convenient to convert the conventional hours of right ascension to degrees of right ascension by multiplying the hours by fifteen, in order to compute the rotation matrix. The true north axis of the Earth coordinate system lies in the plane defined by the projection of the Earth's poles and the gravity vertical.

In the Cartesian celestial reference frame, the x-axis points toward the vernal equinox at zero degrees declination and zero degrees right ascension, and the z-axis points toward the north celestial pole. Using this information it is straightforward to write the three-dimensional rotation matrix $\mathbf{R}_{\text{celestial to Earth}}$ for each image. Because of the rotation of the Earth, the rotation matrices for the different images are all different.

Therefore, for each star camera image this set of measurements determines the four rotation matrices $\mathbf{R}_{\text{internal to celestial}}$, $\mathbf{R}_{\text{epoch}}$, $\mathbf{R}_{\text{celestial to Earth}}$, and $\mathbf{R}_{\text{Earth to body}}$. The four matrices for each image are combined to produce the desired rotation matrix $\mathbf{R}_{\text{internal to body}}$ for that image. Note that the individual rotation matrices $\mathbf{R}_{\text{internal to celestial}}$ will all be different; the rotation matrix $\mathbf{R}_{\text{epoch}}$ will be the same for all images because the star coordinates do not change significantly on the time scale of a single set of measurements; the rotation matrices $\mathbf{R}_{\text{celestial to Earth}}$ will all be different; and the rotation matrices $\mathbf{R}_{\text{Earth to body}}$ will be different for different positions of the rotary table. However, the matrix product $\mathbf{R}_{\text{internal to body}}$ will be the same for each image, except for statistical scatter in the measurements.

Any systematic differences in the computed matrices $\mathbf{R}_{\text{internal to body}}$, such as a systematic change in the matrix as a function of the time at which the image was taken, or a systematic difference in these matrices for different positions of the rotary table, are indications of an error in the procedure. If there are no systematic errors in the procedure, then the individual rotation matrices should be averaged to produce the required matrix $\mathbf{R}_{\text{internal to body}}$.

Estimation of Alignment Uncertainties

The sources of uncertainty in the alignment of the Clementine star cameras are: uncertainties in the latitude, longitude, and time of the images; uncertainties in the orientation of the camera relative to the Earth coordinate system; and the local gravity anomaly. These are listed in Table 1 on the next page, which also gives the estimated uncertainty resulting from each source. The resulting three-axis uncertainty in the Clementine alignment is 0.01°, one sigma. The individual sources of uncertainty are discussed below.

Source of Uncertainty	Estimated Uncertainty
camera latitude	0.001°
camera longitude	0.001°
time at which image is taken	0.005°
camera body orientation about east-west axis	0.003°
camera body orientation about north-south axis	0.003°
camera body orientation about vertical axis	0.006°
local gravity anomalies	0.004°

Table 1. The sources and estimates of the uncertainty in the Clementine star camera system alignment measurements. The total uncertainty is 0.01°, one sigma.

A basic GPS receiver can conservatively determine position of the Earth's surface to 50 m. In the Washington, D.C. area this corresponds to an uncertainty in latitude and longitude of less than 0.001°. This is a negligible uncertainty for the Clementine star camera alignment measurements.

The Universal Time for each exposure was provided by the GPS receiver, and was recorded to the nearest second, which corresponds to an uncertainty of approximately 0.005°. It is interesting to note that when the GPS receiver was compared to a time standard, the GPS receiver was found to indicate a time several seconds earlier than the standard clock. This indicates that the Universal Time reported by a basic GPS receiver must be checked against a time standard.

The ability of a theodelite to determine the orientation of a reflecting cube relative to gravity level is measured in seconds of arc. Therefore, a conservative uncertainty of 0.003° was assigned to the measurement of the camera body orientation about the east-west and north-south axes of the Earth reference frame.

The orientation of the camera body reflecting cube about the vertical Earth axis was measured using the theodelite, by sighting Polaris to determine the direction of true north, and autocollimating off the reflecting cube to measure its orientation. Polaris is only approximately overhead at the Earth's north pole, and travels in an apparent circle once every sidereal day with a radius of approximately three quarters degree. Therefore, the time at which Polaris is sighted must be recorded, and the actual azimuth of Polaris must be determined for the time of sighting using a celestial almanac. The total uncertainty assigned to measuring the orientation of the reflecting cube about the vertical Earth axis is 0.006°.

The vertical defined by local gravity will in general differ by a small angle from the normal to the average geoid because of local mass concentrations. In the Washington, D.C. area this gravity anomaly is negligibly small for the Clementine alignment measurements, so that no correction was made for the local gravity anomaly, and the gravity anomaly was simply included as a source of uncertainty of 0.004°. The local gravity anomaly is never greater than one arc minute in the continental United States [1], however this is large enough that in some cases the local gravity anomaly would have to be included in the analysis of the calibration data.

The total uncertainty from these sources, computed by taking the root square sum of the individual uncertainties, is 0.01°.

End-to-End Verification of the Star Camera System

Following spacecraft integration, the alignment and performance of the Clementine star camera system was tested at the launch site. These measurements used the complete flight spacecraft and software, and were a complete end-to-end test of the flight system.

For these measurements, the entire spacecraft was wrapped and taped in antistatic plastic, and the star camera baffle openings were again covered with taut *Saran Wrap* plastic. The spacecraft was mounted on an electrically-grounded rotary fixture, and placed outdoors at night so that the star cameras could view the stars. The axis of the rotary fixture was vertical. The reference reflecting cubes for the star cameras and primary spacecraft axes were not visible on the completely-integrated spacecraft. Therefore, the orientation of the spacecraft was inferred by leveling the rotary fixture using a precision machinists level, and measuring the orientation of the fixture about the vertical axis using a theodelite and sighting Polaris.

A set of star camera images were acquired for several positions of the rotary fixture. The images were processed by the spacecraft computer, and the resulting spacecraft attitude quaternions were relayed to the ground support equipment for display. Using the measurements, the orientation of the spacecraft in celestial coordinates could be determined, and compared to the spacecraft orientation reported by the attitude determination system.

These measurements verified that the overall coordinate transformations converting the star camera attitude measurements to spacecraft attitude were correct, and verified the overall performance of the star cameras and algorithm using the flight hardware.

Conclusion

There is often an understandable reluctance to test flight hardware outdoors, out of the controlled environment of a clean room or integration area. However, for the alignment measurements required for the Clementine star camera system, and considering the schedule under which the measurements had to be performed, the night sky was clearly the best alignment source. By wrapping the star cameras, the measurements could be performed outdoors without risk of contamination. In addition, using the night sky for the alignment measurements and for the end-to-end verification of the sky camera system clearly demonstrated that the system operated correctly when viewing the actual star field. The alignment measurements of the Clementine star camera system were a complete success, and demonstrate that the night sky can readily align a star camera system to 0.01°.

References

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