JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 19, No. 6, November–December 1996

Preliminary Star Catalog Development for the Earth Observation System AM1 (EOS-AM1) Mission

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Star catalogs are essential for determining the expected performance of stellar-inertial attitude determination systems, such as that planned for the Earth Observation System AM1 (EOS-AM1) mission. That spacecraft will use the CT-601 star trackers to maintain long-term attitude knowledge and gyros to measure short-term motion. To determine the sky seen by the CT-601 star trackers, extensive star catalog generation capability has been developed for EOS-AM1 attitude determination studies. The present study begins with the Goddard Space Flight Center SKYMAP catalog as the source and continues with tracker star separation and spectral response properties. It rejects stars that are not usable because of excessive variability in intensity or excessive position error or for which accurate spectra are not available. This study also assesses properties of the resulting star field, including statistics of position errors, brightness (detector magnitude), variability, and spectral class. The resulting catalog is combined with models of the lunar and solar motion and EOS-AM1 star tracker and orbital geometries to determine gaps in the star field induced by lunar blockage of the star trackers. The history of total star gaps over one year of EOS-AM1 operations is assessed, with periods of both minimum and maximum gaps defined, as well as gap statistics. The geometry of the worst-case gap is illustrated. Additionally, the potential for planetary corruption of star measurements is assessed.

Introduction

THE Earth Observation System (EOS) AM1 spacecraft uses the CT-601 solid state star tracker (SSST). This can track stars as dim as sixth visual magnitude; however, the EOS-AM1 mission plans to use stars of fifth magnitude or brighter. Numerous sky surveys contain star data at fifth and sixth magnitudes; however, to meet tracker performance requirements, stars as dim as ninth magnitude must be considered in the vicinity of potential catalog stars. Comprehensive star data to ninth magnitude are more difficult to obtain. Fortunately, the Goddard Space Flight Center maintains a master star catalog, SKYMAP,[1] which combines the best available data from numerous other star catalogs and which contains data down to 10th magnitude, albeit with some missing data for the dimmest stars. Position, spectral type, luminosity class, and brightness data contained in this master catalog are all used in developing a star catalog tailored to the CT-601. In addition, the unique EOS-AM1 orbital geometries and spacecraft layout influence the specific stars observed by the EOS-AM1 SSSTs. As the sun-synchronous EOS-AM1 orbit precesses to follow the mean annual motion of the sun, the path of the trackers in the star field changes. Additionally, as the moon orbits the Earth, it blocks SSST observations of the stars twice each month. When the lunar blockage coincides with extended gaps in the star pattern, star sightings can be blocked for more than one-quarter of an orbit. In addition to lunar blockage of stars, the motions of the planets (and even the bright moons of Jupiter) can cause corruption of star observations. All of these constraints must be considered in developing a practical star catalog.

In the present study, the process of developing the catalog is defined and applied to the source SKYMAP catalog. The properties of the resulting nominal operational catalog for EOS-AM1 are assessed, leading to the definition of the worst-case star gap expected during 1998 (the anticipated first operational year of EOS-AM1). Additionally, the potential for planetary obscuration of stars is assessed.

Relevant CT-601 Properties

Before a star catalog can be developed, relevant properties of the CT-601 must be defined. This tracker is guaranteed to meet its performance specifications only against well-separated stars. Additionally, the spectral response of the tracker must be considered.

If stars are too closely spaced, the tracker cannot resolve the separate images and tends to report the intensity-weighted centroid. Accordingly, stars for which the CT-601 can deliver accurate measurements must be separated from other stars. The star separation criteria for the CT-601 are illustrated in Fig. 1. As can be seen, three separate criteria apply. Firstly, no star within 0.1 deg can be brighter than four magnitudes dimmer than a usable star. Similarly, no star within 0.2 deg can be brighter than three magnitudes dimmer than a usable star. Further, no star brighter than first magnitude can

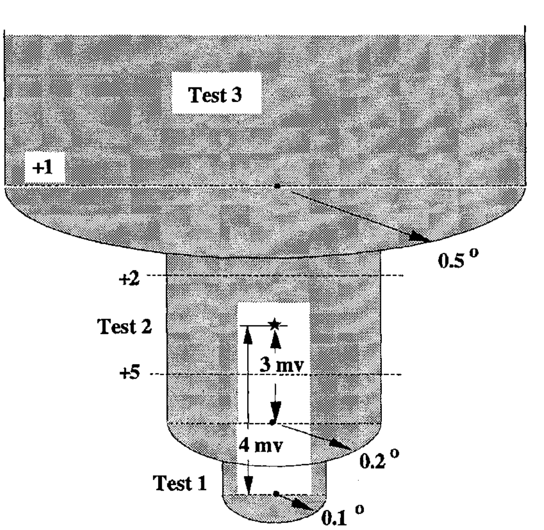

Fig. 1 CT-601 separation criteria.

Received June 17, 1994; presented as Paper 94-3619 at the AIAA Guidance, Navigation, and Control Conference, Scottsdale, AZ, Aug. 1–3, 1994; revision received June 10, 1995; accepted for publication May 10, 1996.

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be within 0.5 deg of a usable star. Since EOS-AM1 intends to use stars down to fifth detector magnitude, stars down to ninth magnitude must be considered. Fortunately, SKYMAP contains data on stars to 10th magnitude. However, the data for the dimmer stars are incomplete.

In addition to the separation of potential stars, the spectral response of the tracker must be considered. Although the ultimate accuracy in spectral response can be obtained by convolving the complete spectral response of the SSST with the complete spectrum of each star, a reasonable approximation[2] is to use spectral type as an indication of stellar spectra. With this approximate approach, a color index curve for silicon (the detector used in the CT-601) is developed.[2,3] This color index modifies the visual magnitude to determine the effective detector magnitude.

Star Selection Process

Given basic properties of the SSST and the master catalog, a nominal operational star catalog can be generated. The present process, illustrated in Fig. 2, begins with version 3.5 of SKYMAP, which contains 248,563 stars. Format conversion and selection of relevant data are the first step. The next step is filling in missing brightness data for dim stars. Some of the dim SKYMAP stars have no photovisual magnitudes. Since photovisual magnitude and V magnitude are similar (though not identical), a star with just the V magnitude reported is assumed to have the same photovisual magnitude. Uncertain stars, possessing neither documented photovisual nor V magnitudes, are assumed to be bright, a conservative assumption that will drop any stars near such uncertain stars from the catalog. The direct impact of this assumption on the final catalog was not investigated, since it was sufficient to meet all performance requirements.

Next, star magnitudes are corrected to detector magnitude using the color index curve for silicon, and all stars brighter than ninth detector magnitude (165,324 stars) are retained for further processing. Because the CT-601 is restricted to use stars dimmer than second magnitude, and because the EOS program wants to include only stars of fifth magnitude or brighter (as a result of the noise characteristics for dimmer stars), and because the color correction curve is only defined from O to M stars, only the 1578 stars meeting those criteria are accepted as candidate stars. Note that the attitude determination performance is not appreciably sensitive to the number of stars.[4] Hence, stars dimmer than magnitude +5 were not included, because the dimmer stars have a worse signal-to-noise ratio. For this set of stars, the three separation tests of Fig. 1 are applied, resulting in 1310 stars. Finally, stars with unacceptable position errors, brightness variability, or peculiarities are dropped. The final catalog contains 1223 stars. Certainly, further reduction of this catalog could be accomplished; for example, thinning in star-dense regions could be accomplished. However, for present EOS purposes, supporting attitude determination performance predictions,[4] this set of stars is sufficient.

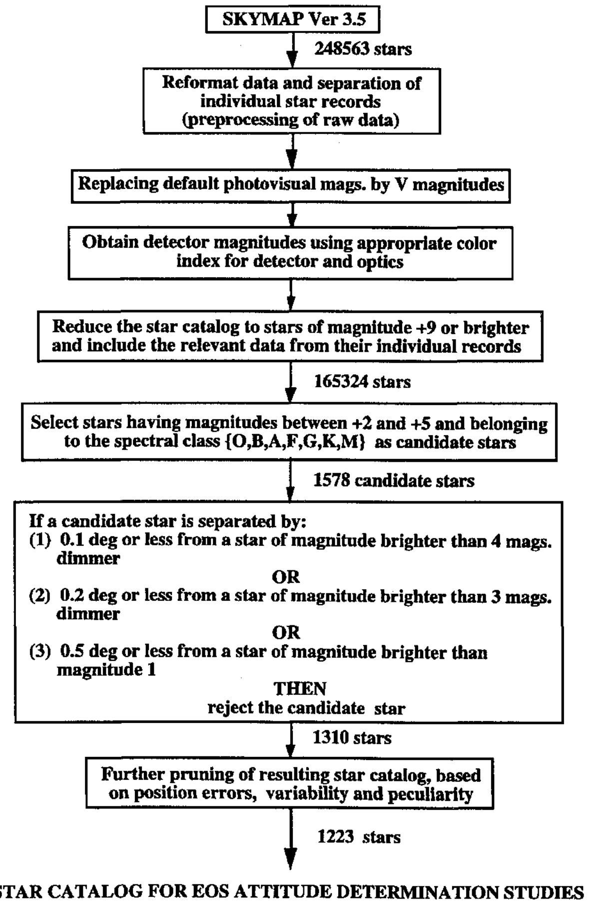

Fig. 2 Star catalog development flow diagram.

Catalog Properties

In the final stages of star selection, star variability and position uncertainty were considered. Additionally, because of the relative abundance of dimmer stars, the catalog brightness is biased toward the dim end. Similarly, because of the sensitivity of the silicon charge-coupled device to near infrared energy, the catalog has a bias toward redder stars.

A magnitude variability of one-half magnitude was used as a criterion in generating the catalog. As shown in Fig. 3, the 41 variable stars retained in the catalog all have magnitude variations less than 0.4 magnitudes, and 37 have less than 0.3 magnitude variability. Even if the variability were restricted to 0.1 magnitude, an abundance of usable stars would be left.

Given the nature of practical astrometry, precise positions of all catalog stars are not available. As shown in Fig. 4, half of the stars retained in the catalog have position errors of 0.1 arcseconds (arcsec) or less. Thus, lowering the position uncertainty criterion from 0.5 to 0.1 arcsec would remove approximately 600 additional stars.

The magnitude distribution of the final catalog (Fig. 5) shows a bias toward dimmer stars. In fact, nearly half of the stars in the catalog are dimmer than approximately magnitude 4.3, whereas fewer than 10% are brighter than magnitude 3.0. This bias toward dimmer stars is expected since the number of stars increases inversely with the brightness. Every magnitude is a factor of 2.5 decrease in brightness, and the number of stars added by lowering the limit one magnitude increases roughly by the same factor.

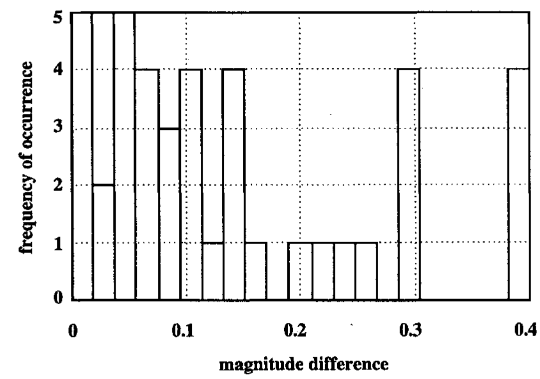

Fig. 3 Magnitude variations of the 41 variable stars in the final catalog.

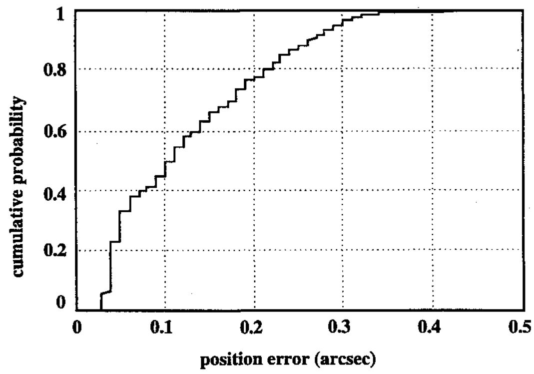

Fig. 4 Position error distribution of the final catalog stars.

The spectral distribution (Fig. 6) demonstrates the bias toward redder stars. Relatively cool spectral class K and (red) M stars represent nearly half of the stars in the final catalog. Note an additional set of 45 extremely red stars (spectral class R) were rejected because of a lack of color correction data at present. Given the red sensitivity of the silicon detectors, further studies could increase the number of red stars available. The hotter, bluer stars (classes O and B) represent approximately 15% of the catalog.

Star Gap Assessment

In addition to the physical properties of the stars, the relative orbital motions of the Earth, moon, and spacecraft also influence

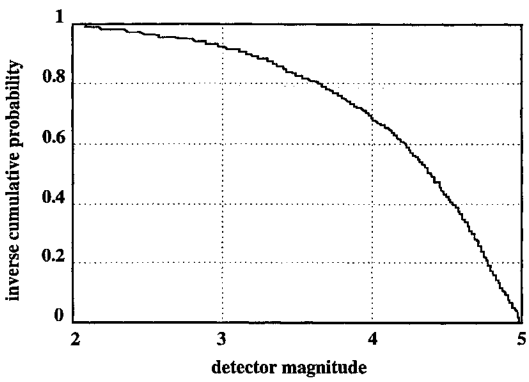

Fig. 5 Detector magnitude reverse distribution of the final catalog stars.

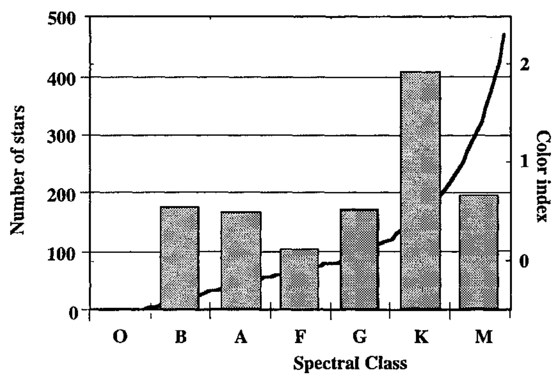

Fig. 6 Distribution of the final catalog stars by spectral class.

the availability of stars. The star trackers are fixed to the spacecraft, which is controlled to track nadir, implying that the tracker fields of view sweep out conical swaths against the field of stars. As the moon orbits the Earth, it moves in a fixed trajectory against the star field, repeating its path in approximately 29 days. As the star trackers sweep their conical swaths in the star field, they cross the plane of the lunar orbit, and during extended periods twice each month will pass close enough to the moon that star measurements can be corrupted by the energy reflected from the moon.

Neglecting the star field temporarily, this basic geometry is resolved in spacecraft coordinates in Fig. 7. The coordinate frame is defined with the spacecraft velocity vector going into the center of the page. Nadir, the direction toward the Earth, is at the bottom of the diagram. The spacecraft pitches about the axis of the spacecraft at −90-deg clock (azimuth in the spacecraft roll/pitch plane relative to the roll axis) and 0-deg cone (declination relative to the yaw axis). The trajectory of the moon for a single orbit on Jan. 1, 1998, is labeled "1" on the left half of the diagram, near −75-deg clock and −40-deg cone. The trajectory of the moon for a single orbit on Jan. 4, 1998, is labeled "4" and shows that the moon is nearly along the orbit normal (at −90-deg clock and 0-deg cone). The lunar geometry changes relatively slowly between orbits but makes one complete cycle in spacecraft coordinates approximately every 29 days. As can be seen in Fig. 7, by Jan. 13, the lunar trajectory is within 25 deg of the tracker boresights (labeled ST1 and ST2). Since the light reflected from the moon floods the tracker field of view and erodes star position accuracies, whenever the moon is within this 25-deg cone, star measurements are suppressed, resulting in a lunar blockage region. As can be seen from the intersection of the star tracker cones with the lunar trajectories, the lunar blockage only occurs during a portion of each orbit. As can be further seen, the period of blockage lasts several days—from Jan. 13 through Jan. 16 and again from Jan. 22 through Jan. 25.

The lunar motions illustrated are typical of any month; however, the exact phasing of the lunar motion varies throughout the year. In addition to the once per month motion of the moon about the Earth and the once per 98-min orbit of the trackers, the precession of the spacecraft orbit continuously varies this phasing. When these motions are all combined and mapped against the field of stars, the actual gaps in the star field encountered by the trackers can be determined. Figure 8 represents the results of such analysis for 1998 and the EOS-AM1 orbit and tracker geometry. For this study, a simulation of all of the geometries was stepped in 10-s intervals for an entire year. The twice per month lunar blockage is evident in the double peaks in star gaps every month. The overall maximum gap is near day 250, with day 167 a close second. Figure 8 also shows

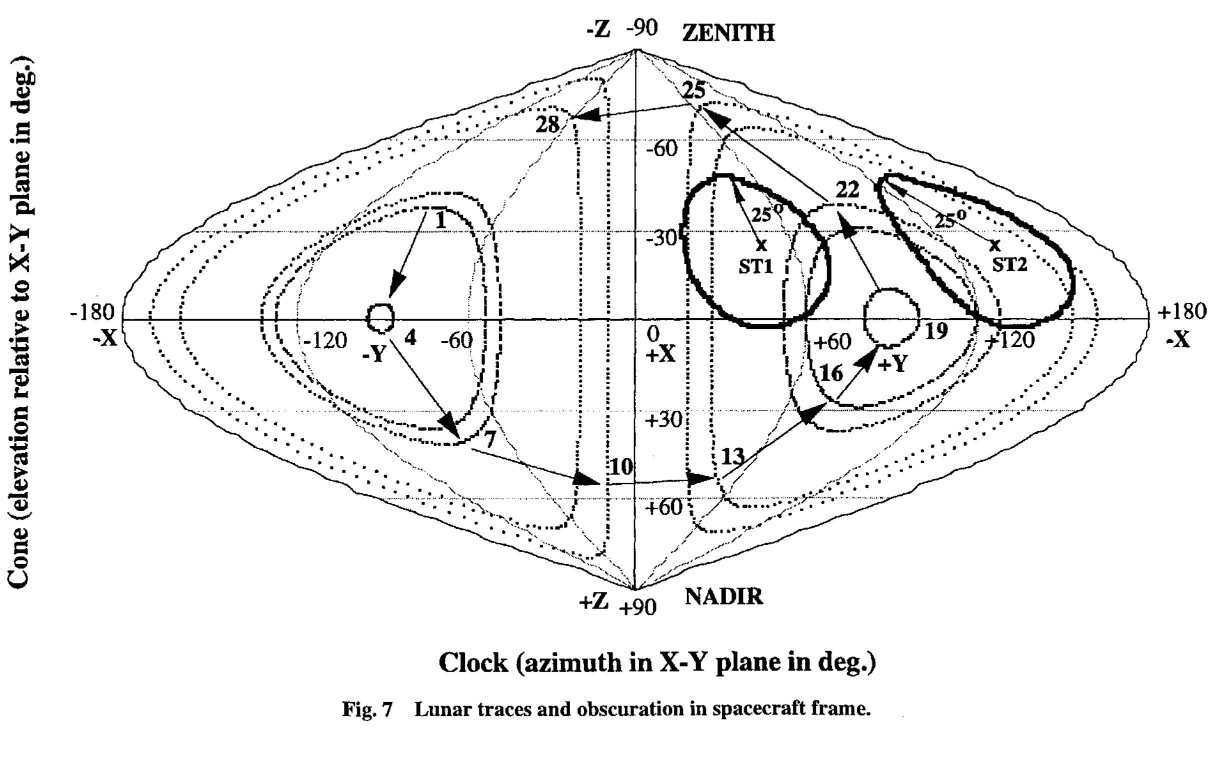

Fig. 7 Lunar traces and obscuration in spacecraft frame.

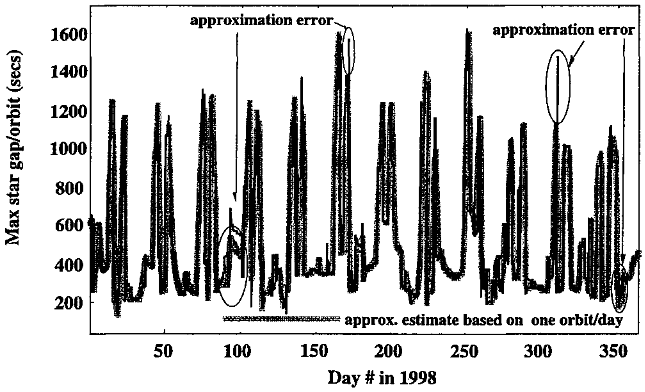

Fig. 8 Comparison of actual and approximate star gap profiles.

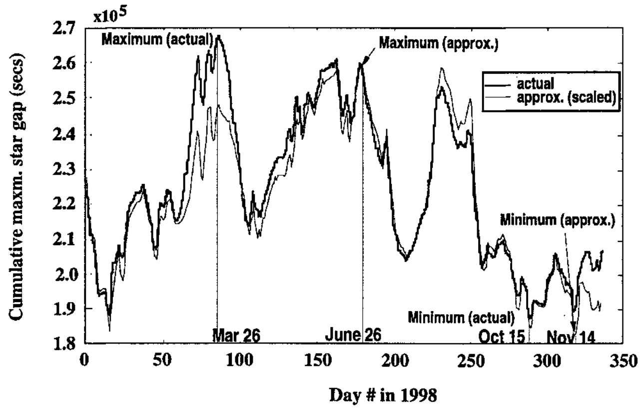

Fig. 9 Comparison of actual and approximate cumulative maximum gap (with 29-day window).

a set of approximate predictions, based on considering only one orbit each day. As can be seen, this approximate gap assessment is inaccurate (for instance, around day 90 through day 100) because it misses the effects of individual stars moving in and out of the tracker field of view.

Further insight into the periods of longest gaps can be gained by considering cumulative gap time over a month. Figure 9 illustrates the results of using a 29-day gap accumulation window. The accumulation of the approximate (one orbit per day) data is also illustrated (the dotted curve in Fig. 9). As can be seen, the approximate solution defines a distinctly different date for the worst cumulative gap. Thus it is important to consider every orbit in this sort of star gap analysis. The 29-day accumulation window, using data from every orbit for the year, is recommended as being the most representative of cumulative gap over the lunar cycle. These data imply that March 26, 1998, is the first day of the period with the largest cumulative gap, whereas Oct. 15, 1998, is the first day of the period with the smallest cumulative gap.

As was observed from Fig. 8, the gap lengths in any orbit range from approximately 150 to over 1600 s. Additional insight is given by the distribution of the gaps provided by Fig. 10. As can be seen, for more than half of the orbits, gaps of less than 400 s occur. However, the distribution function is distinctly non-Gaussian—as demonstrated by the plateau from 700- to 800-s gap, the slope from 900 to 1200 s, and the final tail from 1200- to 1600-s gap duration. Thus a purely Gaussian approximation to gap length is not representative of reality.

To demonstrate the occurrence of star gaps caused by lunar interference, a frame of reference must be established. For the present work, J2000 Earth-centered inertial (ECI) coordinates are assumed. This coordinate frame is illustrated in Fig. 11, with the x axis lying along the line of intersection between the equatorial and ecliptic planes. The ECI frame is related directly to the Earth's latitude and longitude system at the epoch. Right ascension (RA) is measured along the equator, positive in the direction of rotation of the Earth. Declination is the elevation angle from the equatorial plane, with positive declination describing stars in the northern hemisphere.

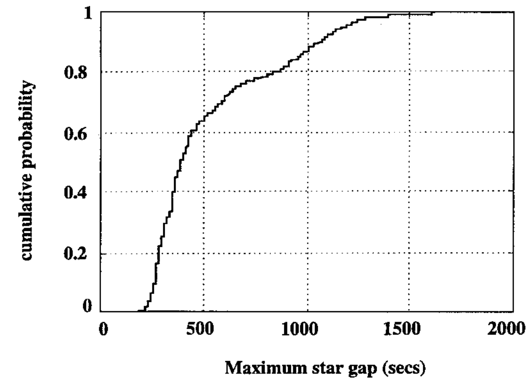

Fig. 10 Distribution of actual per orbit maximum star gaps for 1998.

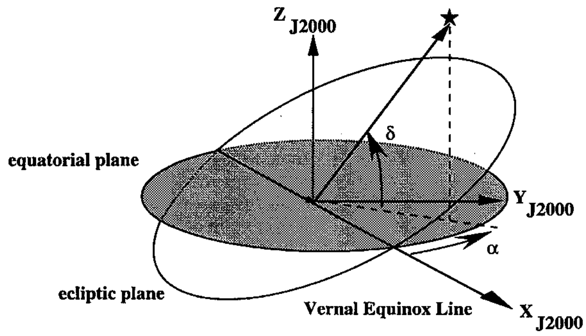

Fig. 11 Definition of α, right ascension and δ, declination.

The absolute worst gap encountered in the present study is illustrated in Fig. 12. The lunar exclusion cone has obscured a substantial portion of the sky near the origin of the J2000 coordinate frame. The tracker boresight trajectory is plotted against the star field and penetrates the lunar exclusion cone. In addition to being blocked by the moon, the tracker encounters substantial gaps on both sides of the lunar blockage, with the worst natural gap near −45-deg declination and 45-deg RA. In this worst-case geometry, the lunar blockage has extended the natural gaps in the catalog substantially. Note also that this worst-case gap is a direct function of the EOS-AM1 orbit and tracker mounting geometry. Trackers for other programs would sweep a different path in the sky. Thus although the basic star catalog development process is essentially mission independent, this sort of detailed geometric blockage study is mission specific.

Planetary Obscuration Assessment

As seen in the preceding sections, star measurements can be corrupted by light reflected from the moon. Additionally, they can also be corrupted by the bright planets. In fact, with fifth magnitude catalog stars, even the moons of Jupiter are sufficiently bright to be of concern. With many of the outer planets, it would be sufficient to exclude stars along the ecliptic; however, the inner planets require special care.

In the context of star separation test 3 (Fig. 1, star separation of 0.5 deg from any other objects of magnitude +1 or brighter), the positions of Mars, Jupiter, and Venus should all be compared with catalog stars. Likewise, Saturn must be considered for test 2 and Uranus and Neptune for test 1. Fortunately, Saturn, Uranus, and Neptune have relatively slow orbital motion. Over the entire five-year EOS-AM1 mission, they only progress a few degrees along the ecliptic. Simply deleting stars near the tracks of these planets would be sufficient to preclude star measurement corruption by these planets, without inducing unacceptable gaps in the catalog. Venus only moves 46.5 deg away from the sun (as viewed from the Earth), and so it will not be visible in the star trackers in normal, nadir tracking operations.

Mars generally stays near the ecliptic but deviates when the Earth approaches most closely to Mars. Figure 13 illustrates this motion, with hour angle increasing from 0 h on the right to 24 h on the left across the chart and with +90-deg declination at the top. Figure 13 was generated using the Voyager II, version 1, sky simulator from

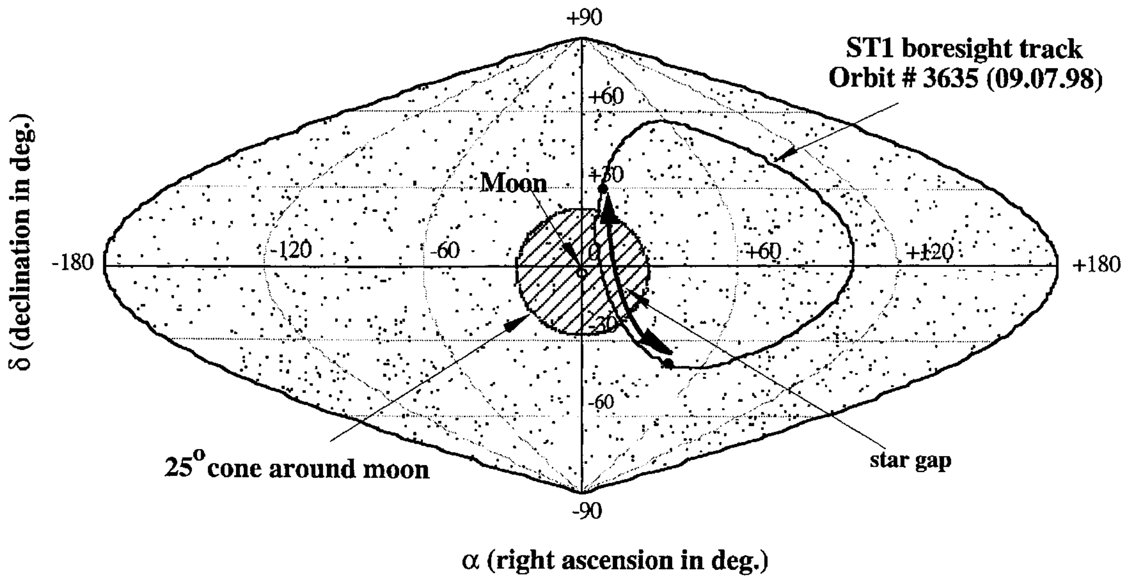

Fig. 12 Moon location and ST1 boresight trace for peak star gap.

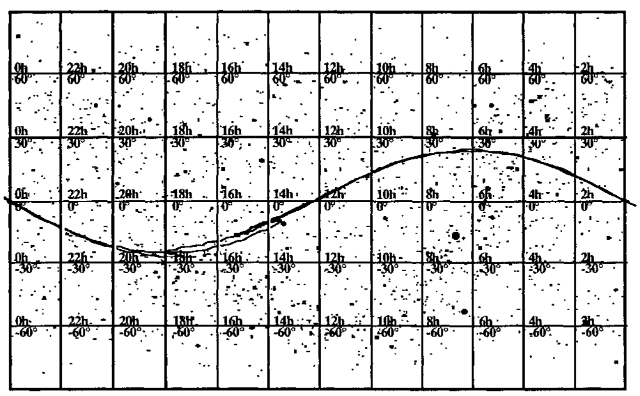

Fig. 13 Trajectory of mars against fifth magnitude stars (1998–2003). © Voyager II sky simulator (Carina Software).[5]

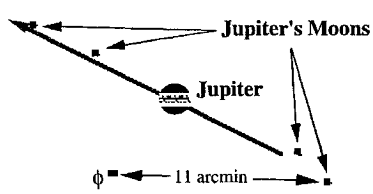

Fig. 14 Jupiter and its moons near Phi Aquarii at 22:00 UTC on April 18, 1998. © Voyager II sky simulator (Carina Software).[5]

Carina Software.[5] As currently conceived, the flight software checks for both the position and the intensity of a star, thereby reducing, though not precluding, the possibility of misidentifying Mars as a star. The simplest means of accounting for Mars' effect would be to exclude all stars along the ecliptic and further to delete stars near Mars' excursion path. A more elegant approach would be periodic exclusion, whereby stars near Mars' trajectory for a short period would be excluded, with the exclusion determined again near the end of that short period. The ultimate approach would be to carry a martian ephemeris on board and to compute star exclusion continuously. These alternatives will be investigated in follow-on studies. In any case, stars near the trajectory of Mars must be excluded.

Jupiter presents a different sort of challenge. Jupiter traverses nearly half of the ecliptic over the nominal EOS-AM1 mission. Further, an examination of the excursions of Jupiter's bright moons (ranging from +4.6 to +5.6 magnitude) indicates that the region that must be excluded around Jupiter increases by ±0.2 deg. To further illustrate the concern, Fig. 14 shows the actual geometry near Phi Aquarii (+4.2 magnitude) at 22:00 UTC (universal time) on April 18, 1998. As Jupiter approaches Phi Aquarii, Jupiter's bright moons precede it by up to 0.2 deg, whereas as Jupiter departs, the moons trail by up to 0.2 deg. Thus, in addition to the normal 0.5-deg zone of exclusion about Phi Aquarii (for objects brighter than +1 magnitude), an additional ±0.2 deg must be added to account for Jupiter's moons.

Thus, some means of accounting for planetary obscuration of stars must be provided. Finding a way to accomplish this without increasing ground operations cost (through frequent manual updates to the star catalog) will be the subject of future studies.

Conclusions and Recommendations

A process for developing star catalogs for the CT-601 star trackers has been defined. The process uses the GSFC SKYMAP star catalog (version 3.5) as the source and applies a variety of star separation and quality tests, in addition to correcting for the magnitudes of the stars as seen by the silicon detectors. The properties of the resulting catalog, in terms of position uncertainty, magnitude variability, and spectral type and brightness (magnitude), were defined. The gaps in the star field, including EOS-AM1 specific orbital and star tracker geometry, as well as lunar and solar motion, were studied over an entire year, with minimum and maximum gap periods defined. The need for accounting for planetary obscuration of stars was also demonstrated, documenting the need for more refined future studies. The star catalog that results from this process is used in related attitude determination studies.

Acknowledgments

This work was supported by NASA Goddard Space Flight Center (GSFC) Contract NAS5-30363, under task 710-16A. Many thanks to J. Bolek (GSFC EOS-AM1 Guidance, Navigation, and Control Systems Manager), R. Ho (GSFC EOS-AM1 Spacecraft Manager), K. Grady (GSFC EOS-AM1 Deputy Program Manager), and C. Scolese (GSFC EOS-AM1 Program Manager) for their support throughout this work.

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