N93-19422

Deep-Space Navigation Applications of Improved Ground-Based Optical Astrometry

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Improvements in ground-based optical astrometry will eventually be required for navigation of interplanetary spacecraft when these spacecraft communicate at optical wavelengths. Although such spacecraft may be some years off, preliminary versions of the astrometric technology can also be used to obtain navigational improvements for the Galileo and Cassini missions. This article describes a technology-development and observational program to accomplish this, including a cooperative effort with U.S. Naval Observatory Flagstaff Station. For Galileo, Earth-based astrometry of Jupiter's Galilean satellites may improve their ephemeris accuracy by a factor of 3 to 6. This would reduce the requirement for onboard optical navigation pictures, so that more of the data transmission capability (currently limited by high-gain antenna deployment problems) can be used for science data. Also, observations of European Space Agency (ESA) Hipparcos stars with asteroid 243 Ida may provide significantly improved navigation accuracy for a planned August 1993 Galileo spacecraft encounter.

I. Introduction

There is an active technology development effort [1,2] at JPL, supporting possible implementation of a ground-based Deep Space Optical Reception Antenna (DSORA), consisting of a 10-m segmented receiving mirror for the downlink and a smaller, roughly 1-m, uplink telescope. This system would provide laser communications between the DSN and interplanetary spacecraft. Although the primary purpose of the DSORA would be to improve deep-space downlink communication, optical tracking systems could also provide new capabilities for interplanetary navigation.

For example, it may eventually be possible to directly image the spacecraft relative to solar system target bodies, thus providing ground-based optical navigation roughly comparable to the current onboard optical navigation capability, and with approximately the same linear accuracy at the distance of Jupiter. This will eventually require significant improvements in existing astrometric instruments and techniques. Since laser-emitting spacecraft will probably not be available in the 1990s, it is necessary to develop astrometric systems for observing these spacecraft without initially being able to observe them. Fortunately, a suitable astrometric replacement is to observe natural bodies (satellites or asteroids) together with background stars.

As the instrument development proceeds, the improved instruments can also provide improved mission target location accuracy for conventional radio metric missions, such

as Galileo. Such improvements are especially important since, as will be discussed, target location is the limiting error source for the most critical portions of these missions. Two potentially significant improvements are identified in this article: supporting navigation of the Galileo–Jupiter orbit tour and a possible Galileo flyby of asteroid Ida. Similar benefits may be possible in the future during the Cassini–Saturn orbit tour.

Most long-term development options are expensive and technically difficult, but some simpler near-term options have been identified for filled-aperture instruments with narrow (<1 deg) fields. These near-term options and their potential navigation benefits are the subject of the present article. It will focus on optical astrometry for target location, i.e., measurement of the angular sky-plane position of solar system objects relative to one another or to background stars.

One option, which is being actively pursued in cooperation with the United States Naval Observatory (USNO) Flagstaff Station (NOFS), is to observe Jupiter's Galilean satellites with NOFS's 1.55-m astrometric reflector and a modern, large format 2048×2048 charge-coupled device (CCD) detector. Although the 11-arcmin field is unusually large for a CCD detector, it is quite small as compared with a conventional photographic field.

The near-term goal is to achieve per-night accuracy of roughly 50 nrad (≈0.01 arcsec), although useful results can still be achieved with larger errors. This goal represents an appropriate trade-off between mission needs and near-term observational limitations, as will be explained later. If this observational goal can be achieved, then the Galileo–Jupiter tour navigation performance can be significantly improved.

The key technology challenge with an 11-arcmin CCD field[1] is to accurately determine the instrument scale (for CCD's, in arcsec/pixel measured on the focal plane), even though, within this field, existing star catalogs do not provide an adequate number of stars with accurately known positions. Observations of star fields are currently being acquired and analyzed by NOFS so that candidate scale-determination techniques can be assessed. These techniques are discussed in Section IV.A.

Five major sections are included in this article: Introduction, Navigation Overview, Instrument Overview, Galilean Satellite CCD Observation Techniques, and Summary and Conclusions.

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[1] D. G. Monet, personal communication, NOFS, February 12, 1992.

II. Navigation Overview

A. Galileo–Jupiter Orbit Tour

The Galileo spacecraft will be injected into orbit about Jupiter in late 1995, followed by a series of close encounters with Jupiter's Galilean satellites. Unfortunately, the spacecraft high-gain antenna did not fully deploy and currently is completely unusable. The low-gain antenna is available, but the data rate from Jupiter allows transmission of only a few full-field CCD science or onboard optical navigation (OPNAV) pictures per encounter (there is one encounter per 14–28 day orbit). Obviously, it would be beneficial to take more science and fewer OPNAV images, provided that mission navigation requirements can still be met.

Before the antenna deployment problem, roughly 30 onboard OPNAV pictures were planned for each satellite flyby, but now, even with data compression, there is a strong benefit if the number of pictures can be significantly reduced. Also, having both OPNAV and ground-based optical information can provide increased navigation reliability, and can also provide a quick, accurate three-dimensional target-location position fix by combining angular observations from two different lines of sight.

Close-up OPNAV satellite images can provide an accuracy of about 15 km (about 25-nrad, geocentric). If the 50–100 km a priori position accuracy of the Galilean satellites can be improved to the OPNAV accuracy levels, then the originally planned spacecraft navigation accuracy can be achieved with just a few OPNAV pictures to locate the spacecraft relative to the already well-known position of the target satellite.

As will be discussed later, the orbit improvements would be made with ground-based intersatellite observations. Figure 1 shows a schematic representation of typical observing geometry for these observations. Figure 2 shows an actual CCD frame containing four exposures of the Galilean satellites, taken with the NOFS 1.55-m telescope. The shutter was closed and the pointing was offset between each exposure. The leftmost satellite of the leftmost exposure is outside the field; otherwise, Jupiter and all four satellites are imaged for each exposure, and they are nearly collinear, roughly in the ecliptic plane. The satellites appear at a shallow, roughly 30-deg angle from the horizontal; the leftmost three satellites are somewhat below the Jupiter location.

The outermost Galilean satellite (Callisto) has a longer period and larger intersatellite angular separations than

the other Galilean satellites and, therefore, its data coverage, particularly for eclipses [3] and mutual events [4], is significantly less complete. Thus, it is not surprising that Callisto actually has the least accurate orbit of any Galilean satellite, with a longitude standard error[2] of about 90 km, and there is a high priority on improving the Callisto orbit. Since the angular diameter of the Galilean system is about 16–20 arcmin, larger instrument fields (10 arcmin and greater) are advantageous. This will influence the choice of telescope and detector.

B. Galileo Flyby of Asteroid Ida

The key information provided by orbit determination with long arcs (half an asteroid orbit period or more) of ground-based angular star-relative asteroid observations consists of accurate target ephemeris coordinates in three orthogonal directions [5; pp. 31–34]. When coupled with accurate DSN radio tracking of the spacecraft, this enables accurate determination of the spacecraft's time of arrival, which is orthogonal to the spacecraft-target sky-plane, and so is poorly determined by onboard OPNAV imaging. Because of time-of-flight uncertainties, the Galileo Project must schedule a picture mosaic to be sure of capturing a close-up picture of the asteroid. Since most of these pictures will capture only blank sky, there is a definite need to improve the ground-based asteroid observational accuracy so that the near-encounter picture budget can be used for actual observations of the asteroid.

Galileo has already successfully concluded a historic first encounter with asteroid 951 Gaspra on October 29, 1991. Pre-encounter ground-based astrometric observations obtained by the astronomical community and analyzed at JPL[3] provided critical Gaspra target-location improvement to enable accurate Galileo spacecraft instrument pointing. Recent star-relative observations of Gaspra from the NOFS 1.55-m sidereal CCD instrument and 0.2-m CCD transit instrument were a major contributor to the success of the encounter navigation, which achieved orbit prediction errors of less than 100 km (similar to the standard errors from the solution covariance matrix). This provided improved instrument pointing accuracy and enabled successful acquisition of several close-up images of Gaspra.

There will also be a close encounter with asteroid 243 Ida on August 28, 1993. An observation program similar to the Gaspra program is being conducted for Ida. All these observations are limited by inaccuracies in the available star catalogs, so that the star-relative observation noise is about 1450 nrad (0.29 arcsec)—a large value when compared with the technology development goal of 25–50 nrad per night. This motivates an effort to obtain a more accurate star catalog, both to support navigation technology development and to improve the Ida target prediction accuracy.

Fortunately, the European Space Agency (ESA) Hipparcos Earth-orbiting observatory has been acquiring star observations for a global star catalog since late November 1989. Recent estimates [6] of expected catalog accuracy, assuming three years of data, predict star positional accuracies better than $10 \text{ nrad} + (10 \text{ nrad/yr}) T$, where T is the time in years past the end of the catalog data span. Catalog density would be about 2.5 stars per square degree, roughly in an even distribution over the celestial sphere. Eventually, of course, a second Hipparcos mission would be required to reduce the effect of the 10 nrad/yr star proper motion errors, but, in any case, the Hipparcos catalog is expected to enable dramatically improved astrometry.

A special Hipparcos input catalog (not based on Hipparcos data) was obtained from ESA, containing approximate coordinates of 50 Hipparcos stars lying near the Ida track on the sky. Further processing[4] at JPL identified about nine stars within 10 arcmin of the Ida track during the Spring 1992 observing season, including an opportunity to observe Ida simultaneously with two Hipparcos stars for over a week during the post-opposition stationary point.

Observations of Ida relative to several of these Hipparcos stars were obtained by the NOFS 1.55-m telescope (CCD with 11-arcmin field), including observations taken over several days capturing Ida and two Hipparcos stars. The appearance of two stars with Ida during an Ida stationary point was a fortuitous but highly unlikely event, which may allow accurate scale and orientation calibrations for these observations and thus provide accurate angular positions of Ida, possibly with 50 nrad or better accuracy.

One of the actual NOFS CCD observations, taken in early 1992, is shown in Fig. 3. Ida is the faint (magnitude

[2] D. W. Murrow, "Integrated Covariance for the Galilean Satellites from E3," JPL Interoffice Memorandum 314.3-779 (internal document), Jet Propulsion Laboratory, Pasadena, California, January 21, 1988.

[3] D. K. Yeomans, P. W. Chodas, M. S. Keesey, W. M. Owen, Jr., and R. N. Wimberley, "Ground-based Ephemeris Development for Asteroid 951 Gaspra," JPL Interoffice Memorandum 314.6-1417 (internal document), Jet Propulsion Laboratory, Pasadena, California, March 24, 1992.

[4] W. M. Owen, Jr., "Opportunities for Observing 243 Ida Relative to Hipparcos Stars," JPL Interoffice Memorandum 314.8-819 (internal document), Jet Propulsion Laboratory, Pasadena, California, January 20, 1992.

$m_v = 14.0$) object surrounded by the cursors, and the two Hipparcos stars ($m_v = 8.3$ and 8.8) are the brightest and largest star images in the field. While the large difference in brightness between Ida and the Hipparcos stars may possibly degrade the measurement accuracy, it is important to note that the NOFS 2048×2048 CCD is the first astrometric CCD with wide enough dynamic range to enable these measurements. For example, an 800×800 CCD of the type used by Galileo or the Hubble Space Telescope would have been saturated by more than a factor of 6 under similar circumstances.[5]

Initial ESA plans were for a four-year data-reduction interval between the last Hipparcos observation (which depends on the spacecraft's lifetime) and final catalog release. The Galileo Project has requested preliminary catalog positions for the observed stars (based on actual Hipparcos data), but it is still not known whether it is feasible to obtain these positions prior to the August 1993 Ida encounter.

If early catalog delivery is not possible, then there will be no navigation benefit for the Ida encounter. However, for technology demonstration purposes, catalog delivery after Ida encounter would still provide a useful demonstration, since Ida's heliocentric orbit will be known very accurately after the encounter, so that computed residuals for the Hipparcos-relative observations could be used to verify the data accuracy.

III. Instrument Overview

This section reviews the characteristics of current photographic, Ronchi, and CCD astrometric instruments, reviews their capability to accurately observe the Galilean satellites, and provides the rationale for choosing a CCD instrument for the present Galilean-satellite observing-technology demonstration.

For readers desiring more information about CCD or Ronchi systems, there is an excellent astrometric review by Monet [7]. Readers who wish to accept the outcome of this section (i.e., the choice of the NOFS CCD for a Galilean satellite technology demonstration) can skip to Section IV, Galilean Satellite CCD Observation Techniques, without losing any information required for understanding the rest of this article.

A. Photographic Instruments

Photographic detectors have serious systematic defects (nonlinear response and emulsion shifts), and their quan-

tum efficiency is only a few percent. In practice, the non-linearity leads to magnitude-dependent, position-dependent changes in star image locations; adequate calibration of these effects is very difficult. Nevertheless, photographic techniques enable observation over wide fields; these techniques have been extensively used for Galilean intersatellite observations since the early 1900s, with errors in the best cases as small as ±250 nrad (0.05 arcsec) [8].

Recent NOFS photographic observations and analyses by Pascu et al. [9] show Galilean intersatellite errors of about 200 nrad for angular separation $S < 100$ arcsec, and of about 550 nrad for a complete set of measurements, including many at larger separations. The latter value is more applicable to the present navigation application, since, as discussed, it is important to observe the entire region out to $S \leq 600$ arcsec.

Pascu et al. attribute this error pattern to scale errors, whose effect is proportional to S. This can be confirmed by acquiring repeated observations of bright star fields, then examining the night-to-night reproducibility of the plate-constant solution residuals. Such results effectively remove all errors that are functions of star position, color, or brightness, and therefore the reproducibility is an underestimate of the actual observational errors.

For example, photographic observations of the star field surrounding 51 Andromedae were acquired and analyzed by Stein and Castelaz[6] in support of the present JPL technology development effort. This work, performed with the Allegheny Observatory 0.76-m reflector (a different telescope from the Allegheny 0.76-m refractor used for Ronchi-ruling observations), showed night-to-night reproducibility of about 100 nrad. Stein and Castelaz also found that repeated photographic observations of Galilean satellites (all taken within about 1 hour) showed reproducibility of about 150–250 nrad, after being reduced to a common scale value and extrapolated for satellite motion. Observations of asteroid 243 Ida ($m_v = 15$) were unsuccessful because of various difficulties in observing such a faint object with the 0.76-m photographic reflector.

All these results suggest that it might be possible to achieve 100- to 200-nrad photographic single-observation accuracy for the Galilean satellites, if accurate calibrations can be made for instrument scale and systematic

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[5] D. G. Monet, op. cit.

[6] J. W. Stein and M. W. Castelaz, *Acquisition and Data Analysis of Ronchi Ruling and Photographic Data and Crossing Point Measurements of Asteroids*, Final Report on Proposal IC-6-8063, work performed for the Jet Propulsion Laboratory, at the Allegheny Observatory of the University of Pittsburgh, Pittsburgh, Pennsylvania, 1991.

errors. However, navigation system development eventually will require 25-nrad observational accuracy and a capability to observe faint sixteenth-magnitude objects, and this accuracy appears to be well beyond the capabilities of photographic techniques. Therefore, modern photoelectric detectors appear to provide the best opportunity for a technology demonstration that could support long-term development plans and potentially provide better accuracy than with photographic detectors.

B. Ronchi Ruling Instruments

Ronchi ruling devices receive the light from each object (star or solar system body) in a separate photometer. This light is modulated by a moving grating, consisting of precisely ruled alternating opaque and clear strips. The difference in modulation phase between the various observed objects can be analyzed to provide accurate angular differences in the direction of grating motion. Two observers are actively using Ronchi astrometric instruments. The first, A. Buffington [10] (Table Mountain Observatory), has a fixed meridian-transit instrument (0.29-m reflector), which currently can observe only in right ascension and is very sensitive to scattered light from bright sources, such as Jupiter. The second, G. Gatewood [11] (Allegheny Observatory), has a sidereally guided 0.76-m refractor, but this instrument would require major modifications to keep the image of the moving satellites in the photometers during an exposure. Since observations in both right ascension and declination are required, moving bodies must be observed, and major near-term instrument renovations should be avoided, neither of these instruments is suitable for the present target-location applications.

C. CCD Instruments

Finally, CCD instruments potentially can accurately observe the Galilean satellites. These instruments have high quantum efficiency, essentially linear response, and a stable, precise metric. However, as discussed, it is important to have a very large format CCD, so that a good trade-off of field size and pixel size can be achieved. The NOFS 1.55-m instrument, which NOFS recently upgraded with a 2048×2048 chip for their own purposes, is currently unsurpassed in this regard, with an 11-arcmin field and a small, roughly 0.3-arcsec pixel size. Therefore, the technology demonstration for Galileo is being conducted with this instrument.

IV. Galilean Satellite CCD Observation Techniques

This section presents an overview of narrow-field CCD observational techniques, in the context of obtaining accurate ground-based intersatellite observations of the Galilean satellites. Some analysis results will also be presented. As discussed, the 1-σ accuracy goal is about 50 nrad per night.

A. Scale-Determination Techniques

Ground-based instrument scale changes significantly with temperature and other environmental conditions, with nightly changes in fractional scale [8, p. 75] of as much as 10^{-4}. This would induce unacceptable 300-nrad errors for 600-arcsec angular separations.

By scale-change calibration with measured temperatures and coefficients of expansion for the focal plane surface, it may be possible to improve this situation slightly for instruments such as the NOFS 1.55-m telescope, which has flat secondary mirrors. For example, analysis of three seasons of 51-Andromedae star field observations, taken with the Allegheny Observatory 0.76-m refractor and Ronchi instrumentation, showed[7] that variations in temperature-calibrated fractional scale had a standard error of about 3×10^{-5}. This corresponds to about 90 nrad (0.018 arcsec) over a 600-arcsec field, still not accurate enough for present purposes. Since environmental calibrations do not appear to provide sufficient scale accuracy for the 50-nrad per night accuracy goal, it will be necessary to determine the scale roughly coincident with each astrometric observation.

Traditionally, astronomers have determined the instrument scale value by simultaneously observing two or more stars, whose positions must be available from a star catalog. Then, the scale in arcsec/pixel can be computed, because for each star both the angular position (in arcsec, from the star catalog) and linear position (in pixels, from image centroids) are available. Figure 4 shows a multistar sky-plane observing geometry with three stars. Since this geometry provides a large angular separation in two orthogonal sky-plane directions, the instrument scale is well determined in all directions.

However, narrow-field CCD instruments usually cannot observe any stars without overexposing a bright target such as a fifth-magnitude Galilean satellite (stars with dim asteroids are much easier to observe). Even if the instrument is pointed away from the target so that long exposures bring up stars, then the observed faint stars will usually not have accurate a priori positions.

[7] G. W. Null, "Preliminary Analysis of Allegheny MAP Data (51-Andromedae Star Field)," JPL interoffice memorandum 314.5-1404 (internal document), Jet Propulsion Laboratory, Pasadena, California, February 1, 1990.

NOFS is investigating various combinations of two generic techniques to overcome these narrow-field scale-determination problems.[8] The first uses catalog densification with another, wider field instrument, and the second observes image motion across the CCD field.

Catalog densification involves observation of numerous faint stars relative to a few stars whose catalog positions are accurately known. This provides a densified catalog with many accurately known stars, which in turn provides three or more well-distributed, accurately known stars in the same CCD field with the target body. Then the scale can be computed. Densification usually requires a wide field to capture sufficient numbers of bright stars.

NOFS is performing catalog densification with the NOFS 0.2-m transit instrument [7, pp. 428 and 432] which clocks out the CCD charge at the sidereal rate. This instrument potentially could achieve 50-nrad accuracy.

Image motion scale-determination techniques take advantage of the fact that, although the angular position of a star or target body may be poorly known, angular motion expressed as the difference of positions at two epochs is usually accurately known. This angular motion can either be from target motion relative to the star background [12] (since target mean motion is usually well known) or apparent motion induced by stopping and starting the telescope drive[9] (thus making use of the Earth's well-known rotation rate). In either case, the time interval between observations is usually chosen so that the image moves across most of an instrument's field of view. Then the scale is obtained by the ratio of the angular change (in arcsec, from the product of the time interval and angular rate) to the linear change (in pixels, from the brightness centroid at each epoch).

When possible, there should be observations of two or more stars in the field (not necessarily with accurate catalog positions), so that observations taken during the image motion can all be accurately reduced to the same scale. Otherwise, it is necessary to rely on scale stability during this interval.

B. Orientation-Determination Techniques

If two or more catalog stars are in the field of view, then the instrument orientation (i.e., angular orientation about the optical axis) can be determined. Otherwise, the orientation can be obtained by the previously discussed image-motion observations.

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[8] D. G. Monet, op. cit.
[9] Ibid.

C. Calibration for Albedo Variations

Analysis [5, p. 21–23] of digitized Voyager Galilean satellite mosaic maps [13] obtained centroid shift versus satellite rotational longitude; the maximum centroid shift caused by albedo variations was about 0.05 satellite radius. The error in extrapolating these results from Voyager's vidicon (strong blue response) to a CCD (strong red response) was found to peak at about 0.01 radius.

These results were obtained using moment centroid algorithms; analysis of simulated ground-based CCD images for the NOFS 1.55-m instrument indicate that when a two-dimensional Gaussian is used for the centroid fit, the maximum effect is reduced by about a factor of three, i.e., to 0.017 radius. This corresponds to about 25 to 45 km, depending on satellite radius, still somewhat larger than the desired 15-km (25-nrad) orbit accuracy. The two-dimensional Gaussian is roughly comparable to centroid fitting functions actually used at NOFS.

Although mosaic maps could be used for albedo-shift calibration, recent analysis[10] has indicated that seams in these maps create unacceptable errors. Work is in progress[11] to perform the necessary calibrations with fit-every-pixel techniques applied to the original Voyager satellite images. This effort will be verified by using some Voyager images to predict albedo shifts for other Voyager images. If successful, it should be possible to adequately calibrate the ground-based Galilean satellite images.

V. Summary and Conclusions

This article has described some near-term technology development to support future optical astrometric tracking of laser-emitting spacecraft, target bodies, and stars. Since there currently are no such spacecraft, a good development substitute is to track target bodies relative to each other or to the star background.

A narrow-field CCD observing option has been identified, which can be tested without a major development effort and which potentially can provide significant navigation target-location benefits to the Galileo mission. A cooperative arrangement has been made with USNO Flagstaff Station to obtain and analyze observations with

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[10] P. J. Dumont, personal communication, Optical Systems Analysis Group, Jet Propulsion Laboratory, Pasadena, California, April 15, 1992.

[11] J. E. Riedel and P. J. Dumont, personal communication, Optical Systems Analysis Group, Jet Propulsion Laboratory, Pasadena, California, April 15, 1992.

a 1.55-m telescope, whose CCD detector provides an 11-arcmin field of view.

The key technology challenge is to demonstrate that it is possible to accurately calibrate the instrument scale, since the narrow field will usually not capture enough catalog stars for traditional scale-determination methods. To test scale-calibration techniques, observations of stars, now in progress, will be analyzed with two alternative scale-determination methods. First, catalog densification with the NOFS 0.2-m CCD transit instrument will provide a local star catalog with enough stars to enable scale determination for the sidereal instrument. Second, image motion across the 11-arcmin CCD field will be used to determine the scale.

Then, after demonstration of adequate scale-determination methods, intersatellite observations will be acquired for Jupiter's Galilean satellites. The 50-nrad per night accuracy goal for these intersatellite measurements appears to be potentially achievable. If acceptable accuracy is achieved, then these observations will be included in the Galilean satellite ephemeris determination.

The ephemeris goal is to reduce the positional standard error (currently 50–100 km) down to about 15 km (about 25 nrad), by combining many observations. This would have an important navigation benefit for the Galileo–Jupiter tour, since an accurate position of the spacecraft relative to the target satellite could be obtained with a much smaller set of onboard-optical pictures than would otherwise be required. This would enable more science pictures to be transmitted to Earth with the currently restricted spacecraft antenna configuration.

Current efforts to obtain NOFS CCD observations of Galileo asteroid target 243 Ida relative to the ESA Hipparcos star catalog were also discussed. A few nights of observations containing 243 Ida and two Hipparcos stars were obtained; these observations potentially could provide very accurate angular positions of this asteroid. If the Hipparcos output catalog is available prior to Galileo's August 1993 encounter with Ida, these data could provide valuable navigation improvements; in any case, it probably will be possible to conduct a technology demonstration to demonstrate the accuracy of Hipparcos-relative observations.

Acknowledgments

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[5] G. W. Null, *Deep Space Target Location With Hubble Space Telescope and Hipparcos Data*, JPL Publication 88-4, Jet Propulsion Laboratory, Pasadena, California, February 15, 1988.

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[8] D. Pascu, "Astrometric Techniques for the Observation of Planetary Satellites," *Planetary Satellites*, J. A. Burns, ed., Tucson: University of Arizona Press, 1977.

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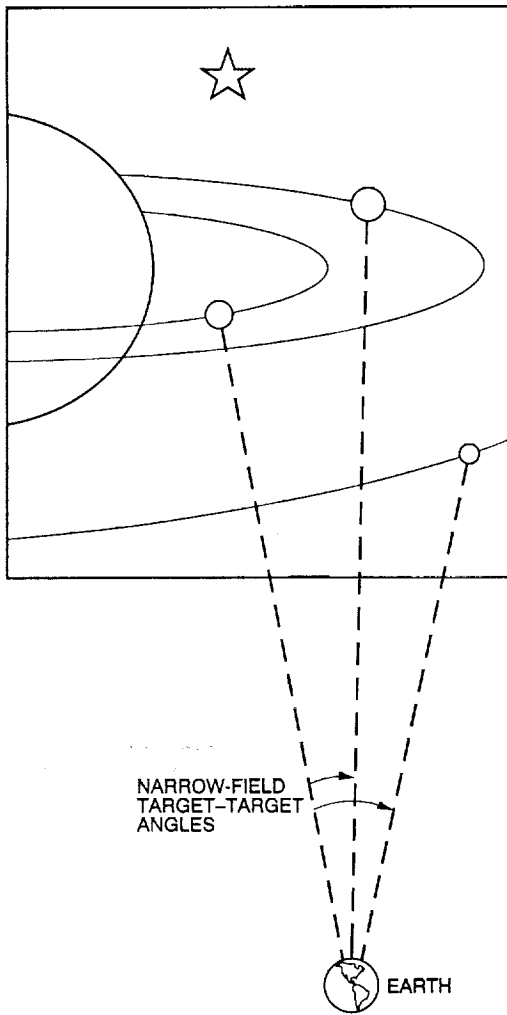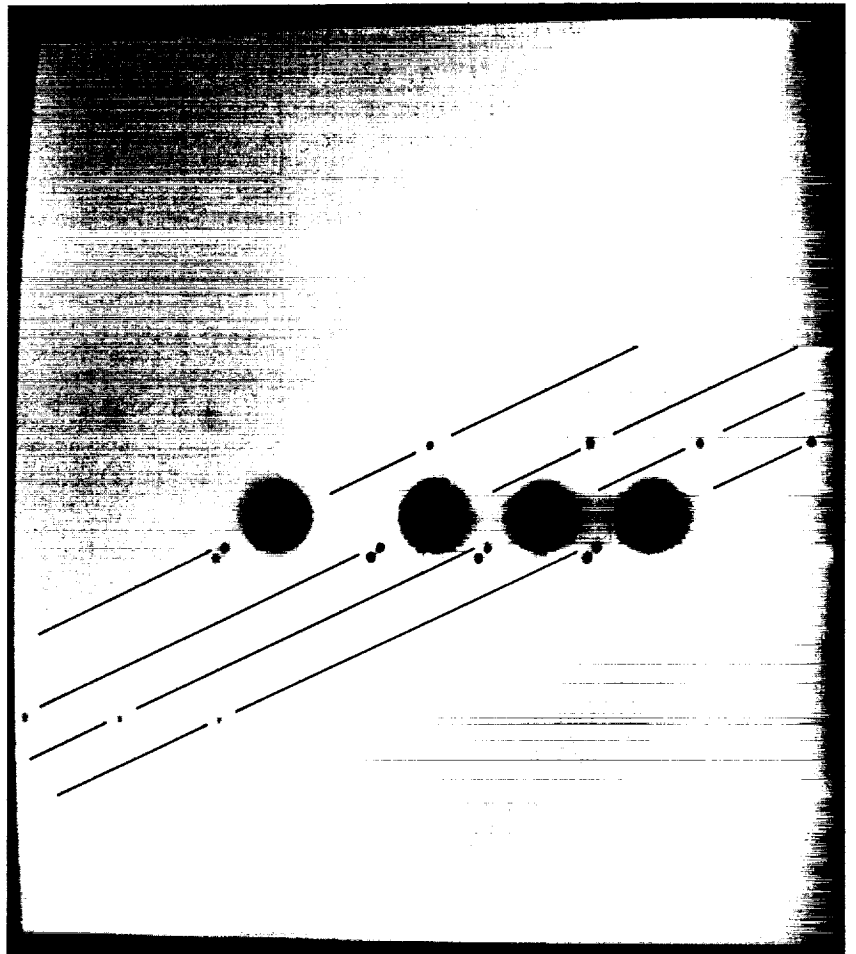
Fig. 1. Galilean satellite observing geometry.

Fig. 2. NOFS multiexposure CCD picture of Jupiter's Galilean satellites (courtesy of D. G. Monet, NOFS).

In Fig. 1, the diagram labels include:

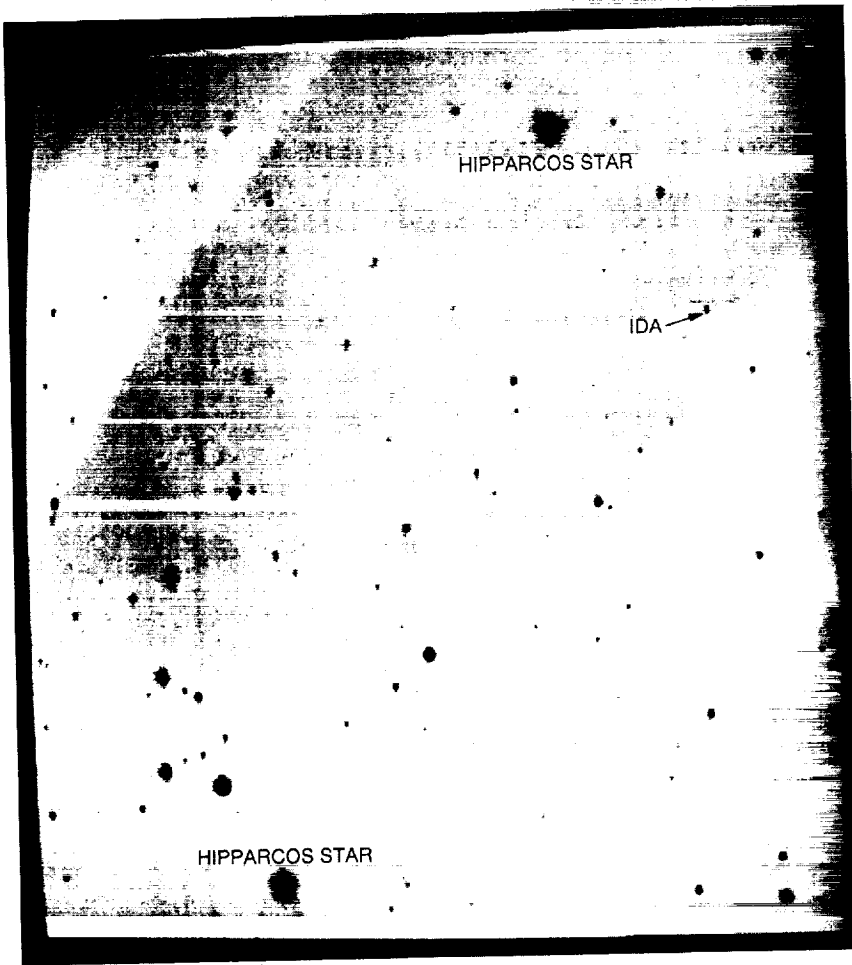NARROW-FIELD
TARGET–TARGET
ANGLES

EARTH

Fig. 3. NOFS CCD picture of asteroid 243 Ida with two Hipparcos stars (courtesy of D. G. Monet, NOFS).
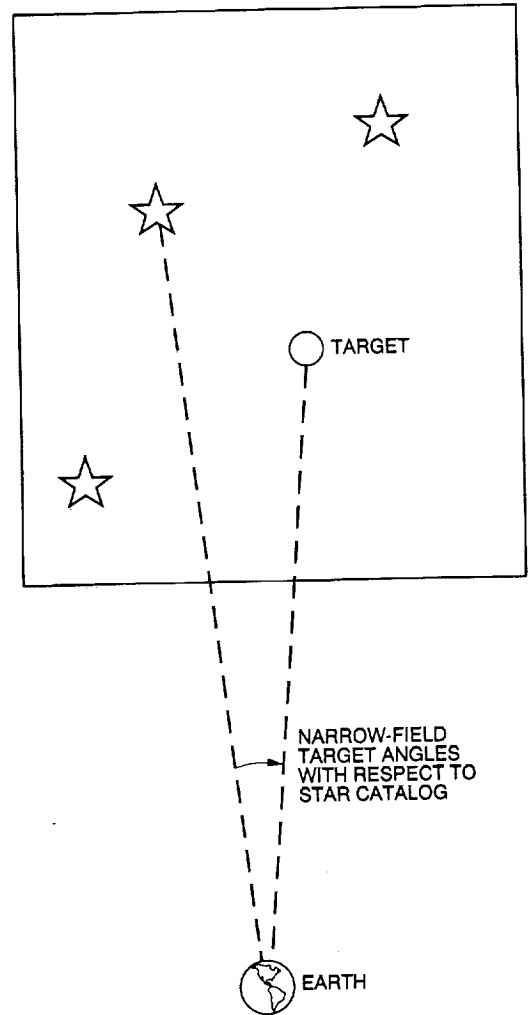

Fig. 4. Target-body observation relative to star background.