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TDA Progress Report 42-111

November 15, 1992

N93-1 ... 00

p. 18

Systems Analysis for Ground-Based Optical Navigation

G. W. Null, W. M. Owen, Jr., and S. P. Synnott
Navigation Systems Section

Deep-space telecommunications systems will eventually operate at visible or near-infrared regions to provide increased information return from interplanetary spacecraft. This would require an onboard laser transponder in place of (or in addition to) the usual microwave transponder, as well as a network of ground-based and/or space-based optical observing stations. This article examines the expected navigation requirements for future missions, as well as possible ground-based optical observing systems to meet these requirements. Special emphasis is given to optical astrometric (angular) measurements of stars, solar system target bodies, and (when available) laser-bearing spacecraft, since these observations can potentially provide the locations of both spacecraft and target bodies. The role of astrometry in the navigation system and the development options for astrometric observing systems are also discussed.

I. Introduction

Eventually, deep-space telecommunications will operate at optical or near-infrared wavelengths to provide increased information return; development plans and current progress toward a prototype optical system are described in [1]. The Deep Space Optical Reception Antenna (DSORA) ground system would employ a large, segmented 10-m mirror for reception and a smaller (perhaps 1-m) transmitter telescope. Of course, deep-space communications would require a transmitter/receiver capability on each interplanetary spacecraft.

These laser-based communications links can also be used for spacecraft navigation. This is analogous to the current microwave situation with a very important difference: in addition to the possibility of ranging, Doppler, and interferometric observations to a spacecraft, the optical system will allow ground-based observations of target bodies relative to each other, to a laser-bearing spacecraft, or to the star background. These "ground-based optical navigation" observations can potentially provide information comparable to the existing onboard optical navigation (OPNAV) system. This will be a new capability for the DSN, opening up the possibility that, for some missions, the entire navigation task can be performed with DSN data alone.

For instrument development purposes, the instrument characteristics required for accurate angular observations of a laser-bearing spacecraft with respect to target bodies or stars are similar to the instrument requirements for observing faint solar system objects against a star background. Therefore, as will be discussed, instrument development will make extensive use of target-body observations.

The realization of optical communications systems for interplanetary missions is still a number of years off. However, preliminary versions of the required astrometric observing systems can be developed and used today to improve mission navigation by reducing target ephemeris errors. This target-body observation capability can provide important navigation benefits for current missions, such as Galileo and Cassini, and it will also be required for future missions which employ laser transmitters. In summary, target-body tracking is of primary importance, both for instrument development and for mission navigation support.

Examples of requirements on ground-based optical navigation for current and future missions are discussed below, as are the possible observing systems to meet those requirements. Both near-term and long-term prospects will be discussed, but the emphasis here is on long-term technology development trends and prospects for the next 10 to 15 years.

Some cost-effective development options were identified for narrow-field telescopes with large format charge-coupled-device (CCD) detectors, and these instruments can potentially provide significant navigation benefits. These near-term options will not be described in detail here, because a full discussion is already available in [2], including a description of ongoing CCD observation programs being conducted as a target location technology demonstration. This work is a collaborative effort with the U. S. Naval Observatory (USNO) Flagstaff Station. For readers unfamiliar with CCDs, a CCD is a silicon-based two-dimensional array of "pixels"; pixels are small individual detectors which very efficiently convert visible light photons to countable electrons.

A very high-level overview of the possible ground-based optical observing scenarios is shown in Fig. 1, which depicts the possible observed objects and types of observatories. The term "filled aperture" is used here to denote conventional single-telescope observing systems. "Stare-mode" systems are guided so that stars are essentially fixed in the field of view; "scan-mode" systems are guided so that stars appear to move at a controlled rate across the field [3]. The challenge to the designer of the ground-based optical navigation system is to find an effective mix of observables (bottom of Fig. 1) to provide accurate astrometric positions for the observed objects (top of Fig. 1) so that the navigation requirements can be met.

This article is divided into seven major sections: Introduction, Observing Strategy, Navigation Requirements, Astrometric Observing System Overview, Filled-Aperture Instruments, Interferometric Instruments, and Summary and Conclusions. Section II examines the observational roles of target-relative astrometry and of optical counterparts to conventional radiometric observations. Section III demonstrates that there are significant navigation requirements for 25-nrad observational accuracy. A generic introduction to observational systems is provided in Section IV, including an explanation of the important relationship between instrument development plans and star-catalog positional accuracy and density. Then, filled-aperture and interferometric instrument development choices are discussed, including several candidate observation systems which potentially could provide the required 25-nrad accuracy. Finally, the most important results are briefly reviewed in Section VII.

II. Observation Strategy

Optical counterparts (optical ranging, Doppler, and differenced range) to current microwave radiometric observables have been investigated by Folkner and Finger [4]. As discussed in [4], these optical methods potentially can provide spacecraft positional accuracy roughly comparable to radio metric techniques, but this must be verified by actually building and testing a prototype system. A key part of this concept is that the angular information from differenced ranging is referenced to the well-known Earth orientation, and so does not require direct observations relative to optical stars. However, these techniques require a spacecraft transponder and are not suitable for stars and target-body observations. For this reason, there will be a navigation requirement for astrometric observing, so that the target bodies can be located relative to the spacecraft.

Although observational systems for optical ranging, Doppler, and differenced range can employ narrow filters to observe laser-bearing spacecraft within a few degrees of the Sun, astrometric systems cannot, because this would usually eliminate too much of the optical signal from stars and target bodies. Therefore, ground-based astrometric systems currently can obtain accurate observations only at night, at geocentric angles of roughly 50 deg or more from the Sun, and it appears likely that this will also be the situation for future systems. This implies that accurate astrometric observations of a given object will be limited to a roughly 260-day span per year. Space-based optical astrometric systems will also have a solar-exclusion constraint, which, depending on sun-shade design and other factors, may be less than 50 deg.

Fortunately, accurate target-body orbits can be determined from observations obtained during these 260-day intervals, and then these deterministic orbits can be accurately extrapolated into the solar exclusion regions. As discussed in [5, pp. 33–34], a 200-day extrapolation can be accomplished with acceptable accuracy. Spacecraft, however, are subject to unpredictable nongravitational forces which preclude a sufficiently accurate trajectory extrapolation; therefore laser-bearing spacecraft must be observed to within a few degrees of the Sun, as is routinely accomplished for spacecraft with microwave transponders.

In summary, an acceptable ground-based optical observing strategy is to obtain astrometric observations of stars, target bodies, and laser-bearing spacecraft at night, but, during solar exclusion periods, obtain angular positions for the laser-bearing spacecraft with differenced range or other suitable narrow-filter techniques.

III. Navigation Requirements

A complete survey of all possible requirements for ground-based optical measurement systems is beyond the scope of this article. However, two examples of the most important applications of ground-based optical navigation will be discussed and are shown in Fig. 2.

A. Planet or Asteroid Approach

For the planetary approach case shown in the left panel of Fig. 2, the typical radio-only delivery into orbit will be limited primarily by the a priori planetary ephemeris error, which can be assumed to be about 100 to 150 km for Jupiter during the Galileo approach and several hundred kilometers for Saturn. These planetary ephemeris errors cannot be significantly improved with conventional ground-based optical observations, which have errors of 1000 nrad (roughly 750 km at Jupiter; 1500 km at Saturn) or more.

Onboard optical observations will reduce the angular two-dimensional (2-D) error in the plane of the sky to a few tens of kilometers or smaller (i.e., roughly 25 geocentric nrad at Jupiter). If the ground-based optical data are to provide the same level of Jupiter navigation accuracy as onboard imaging, the ground-based optical system must also achieve 25-nrad 2-D measurement accuracies. Note that since the onboard and Earth-based observations usually have different lines of sight, combining these two complementary 2-D observation types will provide a quick three-dimensional (3-D) target-body position fix at roughly the same 25-nrad accuracy.

If the spacecraft carries a laser transmitter and if observing conditions (e.g., instrument field, spacecraft–target angular separation, and Sun angle) are suitable, the ground-based observation will directly measure the angular coordinates of the spacecraft relative to the target. Otherwise, this information can be obtained by an indirect technique, using separate observations of the spacecraft and target body.

As shown in the right panel of Fig. 2, the planet or asteroid target can be observed relative to stars. Observation over at least one-half of the target orbital period will enable an accurate extrapolated orbit determination for the target body. As previously discussed, this can be accomplished without any requirement for daytime observations. Spacecraft observations with radiometric techniques (or optical counterparts for laser-bearing spacecraft) can then provide accurate 3-D spacecraft orbits. Finally, a combination of spacecraft and target-body information yields an accurate 3-D spacecraft–target encounter position to roughly the same accuracy as the direct method.

As will be discussed, the indirect method is dependent on the availability of suitably accurate star catalog positions, with sufficient numbers of stars for a given instrument field, and there are several possible near-term sources for this catalog. Direct target-relative observations of a laser-bearing spacecraft are much less dependent on an accurate star catalog, since only the instrument scale and orientation may depend on this information; also, it may be possible to develop suitable scale and orientation techniques [2] which do not require accurate catalog positions.

B. Intersatellite Observations for Planetary Orbit Phase Navigation

In Fig. 2 (center panel), direct measurements of the intersatellite positions (relative angular measurements between satellites) are indicated. As discussed in later sections and in [2], very near-term technology developments in optical detector systems are the goal, and these potentially can provide ground-based intersatellite measurements of the Jovian or Saturnian systems with about an order of magnitude greater accuracy than can be achieved with the usual photographic techniques. Measurements with these systems would be acquired for several years, ending just prior to spacecraft orbit insertion at the planet.

These observations can potentially reduce the intersatellite and planet-centered ephemeris errors from the 100-km level to the 15-km level, competitive with errors found in onboard data. For both Galileo and Cassini, this satellite ephemeris improvement can have a major impact on the number of onboard optical navigation frames required, thereby saving more downlink capacity science data and reducing navigation tracking coverage requirements.

Note that this major benefit accrues without a laser-bearing spacecraft and with the same type of optical imaging system that would be needed for direct target-relative astrometric measurements of a laser-bearing spacecraft in the optical communication era. This would appear to be a nearly ideal situation, one in which development and extensive testing occur under essentially the same conditions as those that will apply when a new component is added (the laser source on the sky).

Achievable optical astrometric measurement accuracy for natural satellites will probably be limited by the difficulty in accurately modelling satellite shape, and, most importantly, brightness distribution and reflection properties. As discussed in [2], the JPL Optical Systems Analysis Group is currently analyzing Voyager images of the Galilean satellites and expects to calibrate brightness variations to support 25-nrad ground-based astrometry. Further improvements may be possible, but this will require overcoming the effects of incomplete spatial and spectral coverage and other systematic errors.

IV. Astrometric Observing System Overview

This section presents background information on optical astrometric observing systems, preparatory to later, more detailed descriptions of filled-aperture and interferometric observing options. The emphasis here is on generic considerations, which are applicable to all observing systems. Star-catalog positional accuracy and star-relative astrometric accuracy for current systems are reviewed and shown to be inadequate for navigation purposes.

Potential sources for accurate global (all-sky) catalogs are reviewed, and several good candidates are identified. These include the European Space Agency (ESA)/Hipparcos star catalog (available in the mid-1990s), as well as catalog improvements from ground-based observing systems, such as optical interferometry or optical observation of radio sources tied to the quasar catalog. Catalog densification techniques and atmospheric limitations to astrometric accuracy are also discussed. An instrument development strategy is presented, taking into account expected catalog improvements.

There is a vast literature about ground-based optical astrometry, but much of this is not current or does not supply an adequate error description for moving-body astrometry. A good background for the present article is provided in a recent (1988) survey of astrometric techniques and instruments by Monet [3], but, as will be discussed, Monet's accuracy estimates are usually given in the context of parallax or proper motion solutions; for moving-body astrometry, these accuracy estimates should be interpreted as reproducibility (precision) estimates. The present article does not attempt to duplicate this survey, but instead concentrates on the instruments and techniques required for accurate astrometric observations of moving bodies.

A. Current Astrometric Accuracy for Moving Bodies

Optical astrometry of moving objects (targets and laser-bearing spacecraft) currently has very limited accuracy compared to the 25-nrad observational accuracy goal. At present, the best star-relative observations have errors of at least 500 nrad and the best satellite–satellite observations [2] have errors of about 200 nrad; typical performance is usually much worse.

B. Current Star-Catalog Positional Accuracy

The importance to navigation of an accurate global star catalog is that it allows the connection of high-accuracy observations through large angles on the sky or, in the inner solar system, around the whole orbit of an object such as an asteroid. Also, a sufficiently accurate, dense catalog facilitates an easy, accurate determination of instrument scale and orientation.

Currently available star catalogs provide relatively poor positional accuracy for individual stars; the most accurate catalog (the fundamental FK5 global catalog of 1535 stars) has positional standard errors at a 1990 epoch of about 200 to 250 nrad [6] and provides only about 0.035 stars per square deg. Other catalogs usually provide more stars, but often with nearly an order of magnitude reduction in accuracy.

Of course, these inaccuracies enter directly into the absolute angular coordinates (right ascension and declination) computed from star-relative observations of moving bodies. Catalog positions are also usually required to determine the instrument scale (conversion from linear units on the detector to angular units on the sky) and orientation; potential catalog-independent methods are being tested in a near-term development effort [2], but these are difficult and the outcome is still uncertain.

C. Potential Near-Term Global-Catalog Improvements

Although the positional accuracy of current global catalogs is definitely unsatisfactory, there are excellent prospects for a dramatic improvement in catalog accuracy within the next few years. The ESA Hipparcos mission, currently flying, will produce a global catalog with roughly

2.5 stars per square deg; catalog delivery is scheduled for the mid-1990s. Astrometric errors for an individual star at an early 1990s epoch are expected to be about 10 nrad, but these errors will grow as the stellar proper-motion errors (about 10 nrad/yr) integrate over time [7]. However, it may be possible to significantly reduce the effect of individual star errors by observing target bodies or spacecraft relative to many Hipparcos stars.

By early in the next century, there will be a need for accurate star positions at a second epoch; the long interval between catalog epochs will then provide improved accuracy for star proper motions. The second-epoch positions could be obtained by a second Hipparcos mission or some other method with comparable accuracy, possibly ground based.

Two other techniques may also provide accurate, but sparse, global star catalogs. The first of these is optical filled-aperture observations of radio sources that have accurate positions in the quasar catalog. Some radio stars and quasars are bright enough (roughly 17th magnitude) to be observed with optical instruments [3]. The second technique is optical interferometry (to be discussed later) which can potentially provide an accurate (sub-50-nrad) global catalog of a few hundred stars.

Thus, there are several potential methods for constructing a global catalog of accurate star positions, and some of these methods do not require the Hipparcos catalog. However, these other methods produce sparse catalogs which must be densified with other wide-field instruments.

D. Catalog Densification Methods

As discussed in [2], accurate astrometry of moving bodies usually requires simultaneous observation of two or more stars whose angular positions are accurately known. Since even the Hipparcos global catalog is too sparse for easy use with existing narrow-field instruments, it will usually be beneficial to observe faint stars relative to stars from a global catalog and construct a suitably dense, accurate local star catalog. Other, more sparse global catalogs must be densified for navigation use.

All these densification techniques require a wide-field instrument. As discussed later, two filled-aperture techniques (scanning CCDs and wide-field stare-mode instruments) appear to be most suitable for this task. However, scanning CCD performance is still relatively modest compared to the required accuracy of 25 nrad or better, and suitable stare-mode instruments would require a major development effort. Obviously, assessment of the suitability of the global catalog and of the need for development of a wide-field instrument will be strongly influenced by the availability of a suitable catalog densification technique.

E. Observational Reproducibility Versus Accuracy

At this point, it is useful to briefly explore the effect that current catalog limitations have had on today's astrometric observing systems and procedures. For this purpose, the key concept is the distinction between astrometric reproducibility (i.e., precision) and accuracy.

Reproducibility can be measured by repeated observations of the same star field, taking care that each star is always positioned approximately at the same position on the detector and that the hour angle for each observation is approximately the same. These observations are reduced to the same scale and orientation by using star-catalog positions, which need only be known to a few arcsec. As will be discussed, reproducibility at the 25- to 50-nrad level has been demonstrated for some instruments with modern detectors.

Night-to-night reproducibility is sensitive to the signal-to-noise ratio, to image jitter caused by atmospheric fluctuations, and to star properties that change between observations. The best-known examples of changing star properties are star parallax and proper motion, which can be accurately determined from the small changes in positions of the target star.

Astrometry for moving targets or for star-catalog generation cannot be performed with the restrictive assumptions used for reproducibility observations, and, therefore, there are many additional error sources that affect astrometric accuracy, but not reproducibility. These include all the astrometric errors induced by star properties that do not change between observations (i.e., star catalog position errors, star brightness, color, and image position in the detector field).

These properties are different for each star and also there are errors in their numerical values. For both reasons, these effects can induce errors in such calibrations as instrument aberration (distortion), instrument scale-value and orientation, atmospheric dispersion, differential refraction, and detector defects. Also, moving-body observations require significant changes in zenith and hour angles, which cause additional errors for calibration of atmospheric effects and instrumental gravity flexure.

Thus, errors affecting accuracy (but not reproducibility) have had a significant effect for astrometry. Limitations caused by star-catalog position have seriously affected both the ability to calibrate these other errors and the motivation to do so. Fortunately, this star-catalog limitation may soon be effectively removed.

F. Effect of Earth's Atmosphere on Astrometric Accuracy

The Earth's atmosphere affects astrometric accuracy primarily from the effects of atmospheric dispersion (i.e., changes in index of refraction with incident wavelength [8,9]) and image jitter caused by fluctuations in the atmosphere. However, the astrometric effect of the atmosphere can be reduced through proper observational procedures, consistent with a 15-nrad atmospheric contribution to a 25-nrad error budget.

Atmospheric dispersion can be reduced by the use of narrow filters and by obtaining adequate knowledge of the spectral characteristics of each observed object. Narrow filters create a requirement for larger aperture telescopes and/or higher efficiency detectors, especially for the observation of faint objects. Further discussion is beyond the scope of this article.

Image jitter can be averaged down by increasing the integration (exposure) time T; for relative astrometry (i.e., for simultaneous observations of two objects in the same instrument field), astrometric error caused by jitter is proportional to $T^{-1/2}$ [10,11]. Equations relating time T, angular accuracy (considering only atmospheric effects), and angular separation S were experimentally verified by Lindegren [10] and Han [11], using different data sets; their results were roughly comparable. Lindegren's theoretical expressions indicate a significant advantage for very small values of S, but there are no observational results to check this.

Figure 3 displays curves of integration time T versus required angular accuracy σ, based on Han's results. Each curve is for a different angular separation S between observed sources. These results are for stare mode; there are no comparable results for scan mode. Results at $S > 0.5$ deg are extrapolated and may be increasingly in error at larger separations. As discussed, Fig. 3 may be too pessimistic for $S \leq 0.01$ to 0.02 deg.

As can be seen, T increases significantly for larger values of S or smaller values of σ. For example, if $S = 5.0$ deg and $\sigma = 25$ nrad, then $T \approx 2$ to 3 hours. Integration times of a few hours are tolerable for target-body observations, but, for certain time-critical observations of laser-bearing spacecraft, it may be necessary to reduce the effective integration time by combining observations from many sites and instruments. For spacecraft observations, this would probably be necessary in any case for weather-related reasons.

For very small angular separations $S \leq 0.01$ deg, such as might exist between two laser-emitting spacecraft at Mars, the curves in Fig. 3 predict that 5-nrad astrometric accuracy can be achieved within 1 hr or less. Since most of the nonatmospheric contributors to the astrometric error budget will also decrease for small separations, there could eventually be very accurate (few nrad or better) optical navigation using multispacecraft observations. In terms of navigation capability, this could possibly be analogous to recently developed "single-beam" radio interferometry techniques [12]. Further discussion is beyond the scope of this article.

G. Instrument Development Strategy

Assuming that an accurate star catalog will be available by the mid-1990s, one may ask, "What is an appropriate instrument development strategy to support accurate observations of moving bodies?" Several possible themes can be described. First, as improved catalogs become available, the complete set of astrometric errors would be calibrated; this may not an easy task with some of these calibrations. Instrument design would have to provide the capability for adequate minimization or calibration of these effects.

Second, improved methods of star-catalog construction and/or densification would be developed. The developments for densification will trade off to some extent with efforts to widen the fields for narrow-field instruments, since wider fields require less catalog densification. The optimum trade-off can be found only through actual observational system development and testing. A wider field is desirable for another reason, namely to directly observe laser-bearing spacecraft relative to target bodies.

Finally, at least for near-term purposes, methods of determining scale and orientation without an accurate catalog could be tested; this is currently underway for intersatellite observations [2]. This may provide some insurance against possible problems with catalog densification and would be applicable to observations of laser-bearing spacecraft relative to target bodies.

V. Filled-Aperture Instruments

Two possible filled-aperture observing techniques are listed at the bottom of Fig. 1. As discussed, stare-mode operation moves the telescope in angle to keep stars fixed in the field of view. In the scanning mode, the telescope is moved at a fixed angular rate so that the images move across the detector. For some systems, image motion in right ascension is achieved by turning off the telescope drive, but declination is not changed.

Image motion (smear) is a problem that must eventually be addressed for all these systems, since stars and moving bodies have different angular rates. Astrometric error induced by image motion is typically much less than the image motion itself, because the image motion is essentially symmetric about the center of the image. As a rough rule, the resulting astrometric errors can be held at acceptable levels if the image motion is less than one point-spread radius (i.e., roughly 0.5 to 1.0 arcsec for ground-based observing).

There are several potentially viable ways to obtain accurate astrometry in the presence of smear. For CCDs, these typically involve implementing instrumental and procedural changes to limit image motion to less than 0.5 arcsec (for example, by expanding the point spread by dithering or defocussing the telescope [13], by obtaining many short exposures, or by developing new data reduction and analysis methods to process smeared images). Further discussion of image smear for CCDs is beyond the scope of this article. As will be discussed, for Ronchi instruments the best approach appears to be movable photometers, under automatic computer control.

A. Stare-Mode Systems

1. Wide-field Instruments. A stare-mode instrument with a wide field (for example, a 5-deg field) would make it possible to avoid the requirement for Hipparcos catalog densification, to observe enough Hipparcos stars to "average down" the proper motion error, and to simultaneously observe a laser-bearing spacecraft and a target body, at desirably large encounter distances. Also, this instrument could produce a densified local star catalog for narrow-field use.

As will be discussed, it appears that suitable wide-field optical telescopes can be found, but a major problem arises in finding suitable visible light detectors to cover a wide field for stare-mode astrometry of moving bodies. A narrow-field instrument would avoid many of these detector difficulties, but would probably require some type of star-catalog densification, possibly with scan-mode observations of star fields.

Although the tentative goal is a 5-deg field, high-accuracy 25-nrad astrometry has never been accomplished over even a 1-deg field. To assess whether there could be an optical telescope capable of achieving such accuracy for a 5-deg field (again, assuming a perfect detector), Owen and Shaklan [14] performed a ray and wave trace analysis of a wide-field astrograph, based on an optical prescription for a USNO telescope that was designed for accurate astrometry, but not constructed.

This 36-cm refractor (a multielement lens system) is shown in Fig. 4. Owen and Shaklan's analysis has shown that this optical system is capable of producing an essentially symmetric point-spread function (analogous to a beam pattern in the radio) over the whole 5-deg field. An asymmetric point-spread function can cause significant amplitude-dependent image-centroid errors, which are difficult to calibrate. In addition, it was found that the position shifts due to optical system aberrations (distortions in the mapping from the sky to the detector) can be calibrated to the 5-nrad level. These aberrations were found to be essentially temperature invariant.

Assuming a perfect detector, a few-hour integration time, and (for dispersion calibrations) a narrow 0.02-μm filter, this telescope is large enough to allow accurate observation of 13th-magnitude objects, such as a small asteroid, a spacecraft at Saturn, or faint stars for a densified catalog. It might be possible to design an astrograph with a slightly larger aperture (say 0.5 m). However, adequate wide-field astrometry with low-efficiency detectors probably would require an even larger telescope. If this becomes necessary, the best choices appear to be reflectors with a modified Schmidt or Ritchey-Chrétien design [15,16,17]. However, these designs lead to much more severe aberration problems than those for the 36-cm wide-field astrograph, and this probably would significantly increase the difficulty of telescope design and construction.

Narrow-field Instruments. As discussed in Section V.C., the size, expense, and technological difficulty of making wide-field detectors forces consideration of narrow fields, perhaps as small as 0.5 deg. With a narrower field, the number of CCD chips would be dramatically reduced and the aberration problem incurred in using a larger telescope aperture for a Ronchi detector would also be reduced.

In this case, the best alternatives are to use a densified catalog or to acquire observations during those time-critical opportunities when the moving body can be imaged with two or more stars from the Hipparcos catalog, which will probably be the only accurate global star catalog with sufficient density for this time-critical option.

B. Scan-Mode Systems

An approach to reducing the wide-field detector problem while at the same time achieving fields of many degrees employs a telescope which can be slewed at a nonsidereal rate, as indicated in Fig. 5. In this case, the images of the observed objects are not fixed on the detector. In a stare-mode CCD-based observation, the images are fixed to allow signal integration in a few pixels before the image is electronically read out. In the scanning mode with a CCD detector, the telescope slew rate is set to allow the images to move across the CCD at the same rate at which the signal is transferred between CCD pixels during a normal readout. In effect, this allows the signal to be built up during readout. The sky is scanned with a relatively small array of CCDs. High-accuracy reference star positions, shown as images labeled with an H in Fig. 5, can then be used to accurately refer one scan position to another across a wider field than that covered instantaneously by the CCD array.

Currently, reproducibility for these systems is at the 200- to 500-nrad level [18,19]. Monet [3, p. 432] indicates that the ultimate performance for the USNO 0.2-m CCD scanning instrument could be as good as 50 nrad, and, of course, larger telescopes and larger format CCDs could potentially provide significant performance improvements.

CCD scanning instruments typically observe each object for only a few minutes per night, so that adequate averaging of the image jitter caused by the atmosphere may require many (perhaps 10) nights. This mode of operation is well suited to star-catalog densification, but may not be suitable for time-critical observations of moving bodies, particularly of laser-bearing spacecraft.

C. Detector Considerations

Photographic detectors are commonly used for both wide- and narrow-field applications, but these detectors do not meet the accuracy requirements [2] and will not be discussed further in this article.

The two major classes of modern detectors for optical filled-aperture astrometry are charge-coupled devices (CCDs) and Ronchi rulings coupled with photometers. As discussed, a CCD is a silicon-based two-dimensional array of "pixels," that is, an array of small (10 or 20 μm) individual detectors which very efficiently convert visible light photons to countable electrons.

A Ronchi ruling is essentially a mask with alternating opaque and transparent parallel bars. Two or more photon detectors (photometers), usually photomultiplier tubes, are placed behind the ruling to measure the oscillations in the visible signals as the ruling is scanned across the objects in the astronomical field of interest. Figure 6 is a diagram of a Ronchi focal plane for observation of an asteroid and a single star (both shown in open circles, to represent photometers). Since the a priori position of observed objects is almost always known to better than one ruling line, the difference in modulation phase can be transformed into a differential angle between the asteroid and star.

The literature describing both of these astrometric devices is extensive and no attempt will be made to duplicate the full content of those descriptions. Night-to-night reproducibility of roughly 20 to 25 nrad has been achieved both for CCDs [20] and Ronchi devices [21,22].

1. CCDs. Because CCDs are an increasingly popular detector for astrometry and the technology is improving at an impressive rate, the present description will describe the technology trends, but not attempt a detailed prediction of its future progress. However, if current trends are extrapolated, significant future progress is likely both for CCD chip arraying and for fabrication of larger format devices.

For CCD instruments in stare mode, the difficulty for wide fields is primarily one of arraying large numbers of CCD chips. This can possibly be accomplished by either a brute force method ("tiling" the desired field with CCD chips) or by more selective techniques, such as placing a CCD chip under each observed object and accurately measuring the relative position and orientation of these chips.

Optimistically assuming CCD astrometric precision of about 1/100 pixel (slightly beyond the current state of the art [3]), then centroid accuracy of 15 nrad (to meet a total error budget of 25 nrad) requires a pixel angular dimension of 1500 nrad (about 0.3 arcsec) or smaller. The largest format CCD made today is a 4096 × 4096 chip [23], which could provide roughly a 0.34- × 0.34-deg field. Under these assumptions, about 225 chips would be required to tile a 5-deg field. Each chip currently costs many tens of thousands of dollars. Even with cost reductions over the next decade, the acquisition of 225 CCD chips would be a great expense. A narrower 1-deg field would require only about nine 4096 × 4096 chips.

Larger format CCDs require increasingly long readout times, which may be impractically long for extremely large formats. Chip formats of 8192 × 8192 pixels are potentially feasible, but these may take about 43 minutes to read out [23]. Therefore, at some point, it may be preferable to array chips rather than increase the number of pixels per chip.

At present, verification of astrometric stability has not yet been demonstrated with even two chips! However, work is in progress at the USNO Flagstaff Station [20, pp. 663–664] and the University of Hawaii [24] to array several CCD chips.

Placing a chip under the focal plane image of each object would require movable chips whose positions and orientations must then be very accurately determined to about 0.1 μm, perhaps via a complex laser-metrology system. In either case, full tiling or movable CCDs, the next step in wide-field CCD detector development would be a major, and very expensive, effort.

However, for narrow fields, there are some very significant potential applications of CCD technology. For near-term development, the most cost-effective options appear to be large-format single CCD chips and eventually, with more capability and cost, an array of several chips. As discussed, these CCD systems are being developed by astronomers for their own purposes. If cooperative arrangements can be made with these observers, then technology development questions for moving-body astrometry can be addressed by actually acquiring and analyzing the appropriate ground-based observations. As discussed, JPL has an ongoing cooperative arrangement with the U. S. Naval Observatory Flagstaff Station [2].

2. Ronchi Ruling Devices. The wide-field Ronchi situation is depicted in Fig. 6 for a stare-mode instrument. For each object to be observed in the field, a photodetector must be positioned behind the ruling to record the modulation of the light caused by the ruling. Again, some implications of extending the field of these devices to a 5-deg field will be examined.

Although the ruling can be made to cover a 5-deg field, it must be very precisely ruled so that false frequencies are not artificially embedded in the data. For a typical wide-field telescope, with a 50-arcsec/mm scale value, a ruling precision of roughly 0.04 μm is required to achieve 10-nrad astrometric accuracy; this requirement primarily refers to long-period variations across the ruling.

Since this is approximately the ruling precision required for a proposed space mission, ground-based astrometry may eventually be able to take advantage of the high precision required for space. The required ruling precision has already been demonstrated for small (few-cm) gratings as part of a development effort for the Astronomical Imaging Telescope (AIT) [25]; work is continuing to extend this precision to meet flight requirements of 10 by 25 cm. Since the present ground-based application (5-deg field with 50-arcsec/mm scale) implies a grating size of roughly 36 cm in height and perhaps twice that in the direction of grating motion, the necessary grating precision probably is more difficult to obtain than in the AIT case.

Ronchi systems are inherently less efficient light collectors than CCD-based systems, in part because the half-opaque ruling throws half the light away, and in part because the photodetector probes are less efficient than CCDs (by a factor of 3 to 5). This inefficiency implies that a larger telescope must be used to capture more light or that dramatically longer integration times will be necessary than for a CCD-based system. Finally, the Ronchi device must be scanned separately in right ascension and declination to measure both sky coordinates, thereby requiring yet additional telescope resources.

All these considerations tend to drive Ronchi instrument design to larger telescope apertures. As discussed, this type of low-efficiency detector increases the technical difficulty for telescope design and fabrication.

As with CCDs, it may be possible to observe faint moving objects in a narrow-field instrument (either CCD or Ronchi) and then densify the star catalog with a wide-field instrument (again, Ronchi instrumentation is one of the choices). This would ease the requirements on the wide-field instrument by reducing the requirements for faint-object observations from about 16th magnitude to about 13th magnitude.

However, even for catalog densification, there are many other wide-field development problems. For catalog densification, it would be desirable to observe all the Hipparcos stars in the field (to reduce the proper-motion errors by averaging errors for many stars) and also to perform the densification by observing many fainter stars. The large number of probes required, 50 to 100 of them at tens of thousand of dollars each, guarantees that a wide-field Ronchi approach will be expensive as well. For observations of moving bodies, the probe or probes for the target objects must be movable during an observation to account for the object's motion relative to the stars. This technology would require a significant development.

Technology development of a narrow-field Ronchi instrument would be significantly easier than for the wide field, because the narrow field would require only a small subset of the probes required for a 5-deg field and would significantly ease the requirements for ruling precision.

VI. Interferometric Instruments

Interferometric navigation observables are possible in the visible and infrared (IR) regions as they are in the radio. The basic idea is the same. The extremely narrow field of an interferometer allows it to observe, in general, only one object at a time. In the radio regime, these objects are quasars and spacecraft. In the visible or IR, the objects would be stars, spacecraft, and some solar system bodies. However, observations of stars and solar system objects may be limited to nighttime hours, just as for filled-aperture astrometry.

In the radio regime, the position of the "fringe" is measured electronically as the value of a time shift in a cross-correlation device. In the visible or IR, the position of the fringe could be measured from the locations of the bright and dark bands of the sinusoidal interference pattern on a CCD or some other array detector.

Fringe ambiguity resolution for the optical or IR case will be complicated by the essentially monochromatic character of a spacecraft laser transmission. Although this problem can possibly be circumvented by using either multiple wavelengths or multiple baselines, there are potentially serious development difficulties. First, the use of multiple laser wavelengths increases the complexity of both the spacecraft and ground stations, and may not be suitable for the communications development. Second, use of multiple baselines for ambiguity resolution of a monochromatic signal is an untried concept, whose implementation may require major changes in hardware and data processing.

Solar system objects pose a special problem for interferometry because usually they are not point sources; typically these objects subtend angles equivalent to many fringe cycles. (As an example, a 10-m optical baseline will result in more than 100 fringes across Io.) As shown in Fig. 7, because the fringe patterns from many incoherent points on the object's surface overlap, the fringe contrast (visibility) will be extremely low on the detector and can become totally lost in the noise. Visible light interferometry can be used with only a few small solar system objects.[1]

Fringe spacing is given by wavelength divided by projected baseline length, so that increasing the wavelength from the visible (roughly 0.5 μm) to IR (about 10 μm) will decrease the number of fringes per body radius by about a factor of 20. Since this increases the pool of observable solar system objects by about the same factor, IR interferometric observations of solar system bodies, particularly in the 10-μm atmospheric window, may be found to be more generally useful for navigation than those in the visible.

If, as seems likely, the laser communications are at visible wavelengths, then an IR interferometer would not be able to observe the spacecraft. However, as discussed in the IR interferometry subsection, the instrument builders expect to achieve enough sensitivity for observation of a large set of target bodies.

As will be discussed, the present optical and IR interferometry instruments do not provide the sensitivity (and in the IR case, the astrometric capabilities) to observe either target bodies or laser-bearing spacecraft. New systems with significantly improved sensitivity and astrometric capabilities are being proposed by the astronomical community, and may be built during the 1990s, at a multimillion dollar cost for each system.

Filled-aperture instruments can also potentially achieve these goals, so there is no navigation requirement for construction and successful operation of an optical or IR interferometric system. However, from a systems viewpoint, it is important to understand the potential development challenges and observational capabilities of these systems, since they can still potentially play a role in a future navigational system.

A. Optical Interferometry

For navigation, optical interferometry is of some interest as a possible observing capability for angular observation of laser-bearing spacecraft relative to the star background and for construction of a sparse global catalog of bright stars.

Representative current and expected future optical interferometric capabilities will now be examined. The current best optical interferometric system at Mt. Wilson provides a reproducibility of about 50 nrad for repeated observations of 6th-magnitude stars over angles as large as 90 deg [26], but extensive new observations will be necessary to assess the astrometric accuracy.

The USNO optical interferometer, consisting of several telescopes (initially 0.5-m apertures, with possible future upgrade to 1-m apertures) [19,27], may become operational in the mid-1990s. This instrument may have the necessary sensitivity (13th magnitude or better for 0.5-m apertures) for useful astrometric experiments involving

[1] G. W. Null, "Astrometric Optical-Interferometry for Solar-System Bodies," JPL Interoffice Memorandum 314.5-1309 (Revised) (internal document), Jet Propulsion Laboratory, Pasadena, California, November 17, 1988.

small solar system objects, such as asteroids or the Martian satellites. The Infrared-Optical Telescope Array is a similar system being developed at Mt. Hopkins, Arizona, by a consortium of universities and research laboratories [28]. This system initially will operate with two 0.45-m telescopes with observations both at visible (0.8- to 1.0-μm) and IR (1.0- to 2.4-μm) wavelengths. The eventual goal is operation with several larger elements, perhaps the seven 1.8-m mirrors scheduled for removal from the Multi-Mirror Telescope (MMT).

As previously discussed, these systems could also potentially construct a sparse global catalog to 25-nrad or better accuracy, which then could be densified with suitable techniques (perhaps with a scanning CCD instrument).

B. Infrared Interferometry

For navigation, infrared interferometry could potentially provide accurate angular observations of most target bodies relative to bright stars from the Hipparcos star catalog or other suitable global catalogs.

The present infrared interferometry discussion is restricted here to small target bodies, such that β, the number of fringes per body radius, is less than 0.6 (i.e., on the main lobe). As shown by experience with microwave interferometry, this will potentially provide suitably high fringe visibility for accurate angular measurements.

For example, Muhleman et al. [29] obtained interferometric observations of Jupiter's Galilean satellites at microwave wavelengths ($\lambda = 2$ and 6 cm) at the range of β values above. These satellites have nearly spherical shapes but have significant albedo variations. Muhleman et al. were able to obtain 150-nrad accuracy for the satellite positions and their analysis indicated that effects of albedo variations were fairly minor.

Asteroids appear to be especially suitable objects for infrared observations. Although the solar radiation at the asteroid is much less at infrared than at visible wavelengths, there are compensating effects that ensure that the energy flux is roughly constant from the visible out to about 20 μm, as discussed by Lebofsky and Spencer [30]. Specifically, asteroids tend to be dark bodies (visible albedo < 0.3), and so the energy received in the visible band is mostly converted to heat and re-emitted in the infrared. Obviously, this is very favorable for IR observations of low-albedo solar system bodies.

M. Shao is collaborating with C. Townes, U. C. Berkeley, to update Townes' IR interferometer at Mt. Wilson by adding laser metrology and other improvements.[2] This array currently uses two 1.65-m telescopes. For the updated system, Shao indicates that a single night's observations could potentially reach S/N = 10 (sufficient to accurately measure fringes) for a 12.4 magnitude star at 2.2 μm, a 7.8-magnitude star at 5 μm, or a 3.7-magnitude star at 10 μm. These magnitudes (m) are given for spectral classification A0; by convention, the A0 magnitude of a given star is the same at all wavelengths. Eventual IR astrometric accuracy is difficult to predict, but might be comparable to that at visible wavelengths, i.e., 25 nrad or better. Plans call for operation of a prototype two-element version of this IR system by the mid-1990s.

Figure 8 provides a rough plot of energy flux above the Earth's atmosphere versus IR wavelength. Flux values are shown as dashed lines for asteroids [30] and as black lines for A0 stars [31]; Shao's S/N = 10 sensitivity limits expressed in flux units are marked by large $\times$'s. The plotted asteroid fluxes have not been reduced to compensate for finite-body visibility losses, which are insignificant for most portions of these flux curves. The single exception is for the 2.2-μm window for a 100-km asteroid at 5 AU; for this case, $\beta \approx 0.14$ and the squared visibility is slightly reduced to roughly 0.8. As can be seen, asteroid flux is relatively constant as wavelength increases, but the stellar flux decreases significantly. However, since IR interferometry can be performed at large angular separations, bright stars from a sparse catalog are acceptable background sources.

As shown, 10-km asteroids at 1 AU would be marginally observable at 2.2 μm and easily observable at 5 and 10 μm. A more distant asteroid (or low-albedo satellite) at 5 AU from the Sun with radius $R = 100$ km would have a signal-to-noise ratio of almost 10 (marginally observable) at 2.2 and 10 μm. Some of Jupiter's Galilean satellites may also be observable at 10 μm, since, for a 2.5-m baseline, $\beta \approx 0.50$ to 0.81. Their large radii (roughly 1550 to 2650 km) may provide enough flux to sufficiently compensate for fringe visibility losses and for reductions in IR emissions caused by higher visible albedos. If not, then accurate Galilean satellite observations would require improved sensitivity and/or longer wavelengths ($\geq$20 μm).

VII. Summary and Conclusions

This article has examined both the long-term and near-term development prospects for the astrometry of stars

[2] M. Shao, personal communication, Optical Sciences and Applications Section, Jet Propulsion Laboratory, Pasadena, California, August 1991.

and moving bodies. For the near-term, large-format CCD detectors have been identified as the most cost-effective means to obtain early, useful narrow-field observations of solar system bodies. CCD technology is being actively developed by the astronomical community for their own purposes, and there are strong, continuing trends toward larger format devices and chip arraying. Therefore, collaborative arrangements with astronomers can potentially provide accurate observations of moving bodies, which can provide valuable information for navigation observing system design. Of course, CCD technology will also be important for long-term navigation development, both for conventional spacecraft and those with laser transponders.

One near-term activity, currently in progress, involves a cooperative effort with the U. S. Naval Observatory Flagstaff Station. The Flagstaff instrument, a 1.55-m astrometric reflector with a 2048 × 2048 CCD chip, provides an 11-arcmin field that is large enough for efficient observation of Jupiter's Galilean satellites. Details of this effort and its potential navigation benefits for the Galileo project are provided in [2].

For long-term purposes, the primary goal has been to identify important development trends and their potential applications for accurate astrometry of spacecraft and target bodies. What conclusions can be drawn from the material just presented? First, no single instrument is likely to be superior for all the different observational requirements (such as catalog densification, observation of very faint 16th- to 17th-magnitude objects, observation of moving bodies, and time-critical observations of spacecraft). This suggests that the best strategy is to employ several instruments for complementary purposes.

Second, although some of these instruments have provided reproducibility consistent with our 25-nrad navigation accuracy goal, none has demonstrated suitable accuracy. Typical demonstrated observational accuracy is roughly 10 to 20 times worse, primarily because of errors in available global star catalogs.

For the near-term navigation observation program, the focus has been on intersatellite observations, since accurate astrometry with these observations may not require an accurate catalog. However, star-relative observations will always require accurate catalog positions.

Fortunately, the ESA/Hipparcos Earth-orbiting observatory (now in orbit since November 1989) is expected to provide an accurate global catalog of roughly 2.5 stars per square deg by the mid-1990s, and ground-based scanning CCD instruments may be able to accurately densify this catalog or possibly to densify directly from optically observable radio sources. Thus, by the end of this decade, it may be possible to obtain an adequate observational verification of astrometric accuracy for each candidate observational system.

For navigation development, the long-term task is to cooperate with instrument builders and observers to investigate, improve, and observationally verify the performance of these systems for navigation purposes, including moving body observations and catalog densification. As appropriate, there could also be instrument development of dedicated navigation instruments, possibly for use in the DSORA facility.

Turning now to specific instruments, what were some highlights described in this article? First, as just discussed, CCD development is giving promising results and is being energetically pursued by astronomers. Use of narrow-field CCD or Ronchi instruments with a densified star catalog is an attractive development option.

Second, wide-field (5-deg) astrometry with filled-aperture stare-mode instruments appears to require a major CCD or Ronchi detector development; this would probably require navigation support, since there are no other plans for such an instrument. Studying this capability is important, since it potentially would provide direct angular observations of laser-bearing spacecraft relative to target bodies and it could also densify a global catalog. CCD scanning instruments, now being upgraded by astronomers, could possibly perform these tasks, but these instruments may be less well suited to time-critical navigation observations.

Third, optical and IR interferometry instruments with suitable sensitivity and sufficient baselines to support moving-body astrometry appear to be major, high-cost developments that are probably 5 to 10 years away. Optical interferometry may provide accurate observations of laser-bearing spacecraft, if adequate methods of fringe-ambiguity resolution can be devised. However, these ambiguity-resolution methods present potentially serious development difficulties. IR interferometry could possibly observe many asteroids and satellites with the desired 25-nrad accuracy. However, neither of these systems will usually be capable of directly observing a spacecraft relative to a target body.

As with CCDs, optical and IR interferometry techniques are being actively developed by astronomers for scientific purposes, not for spacecraft navigation. However, at the appropriate times, it may be possible to arrange cooperative arrangements to investigate the navigation-related development questions.

Finally, what is the answer to the bottom-line question, namely, "Can suitable observational systems be developed for 25-nrad astrometry of laser-bearing spacecraft, target bodies, and stars?" At this point, it is difficult to be sure of the answer, but the availability of many promising development paths and the progress being made by astrometric instrument builders gives credence to the prognosis that the desired capabilities will eventually be attained, possibly within the next 10 to 15 years. However, this will require navigation support and involvement, so that the particular problems for moving-body observations are adequately addressed, both to ensure timely development and to provide an adequate operational capability for mission navigation. Reliable acquisition of time-critical observations involving spacecraft and target bodies will probably require construction of DSN astrometric observing facilities.

Acknowledgments

The authors gratefully acknowledge helpful conversations about Ronchi instruments (G. Gatewood, J. Stein, and M. Castelaz at Allegheny Observatory, Pittsburgh, and A. Buffington, UCSD), about CCD instruments (D. Monet, U. S. Naval Observatory Flagstaff Station), and about optical and IR interferometry (M. Shao, JPL). They also thank J. Ulvestad of JPL for helpful suggestions about this article.

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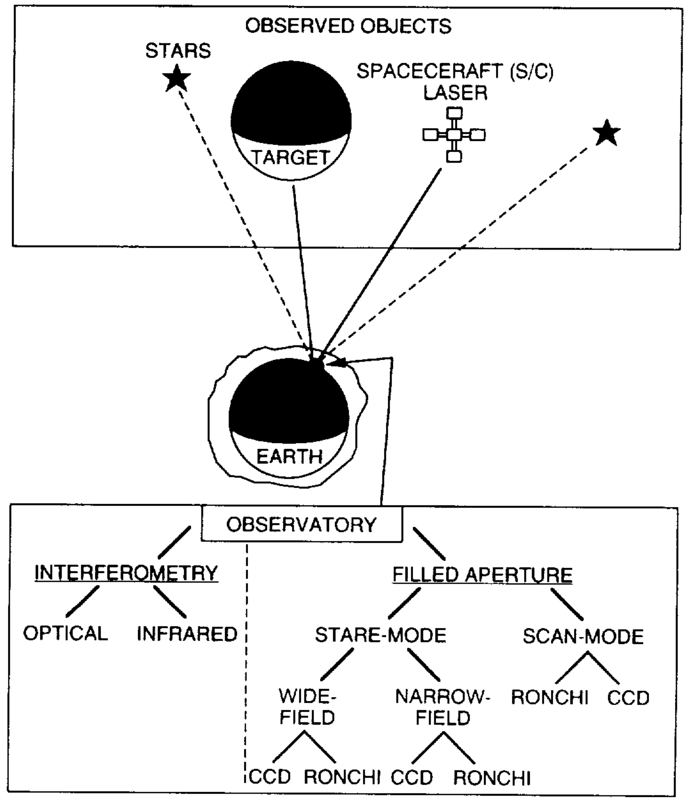

Fig. 1. Systems overview of ground-based optical astrometry.

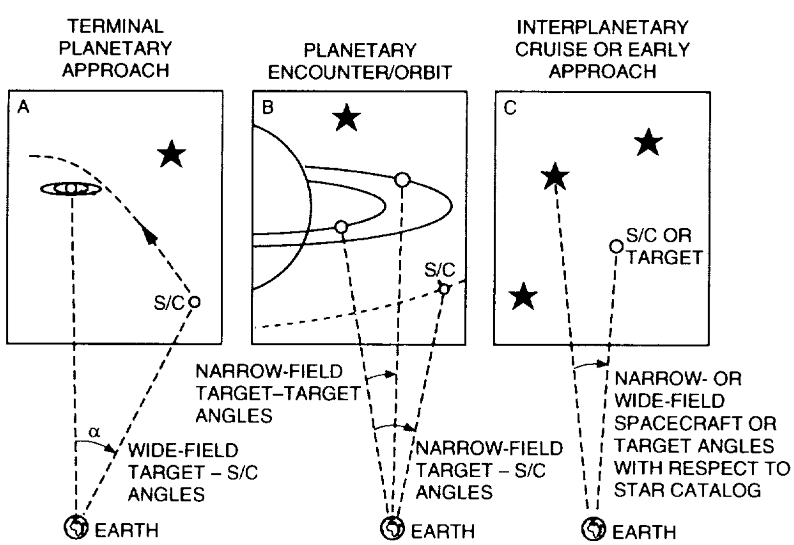

Fig. 2. Possible optical astrometric observations.

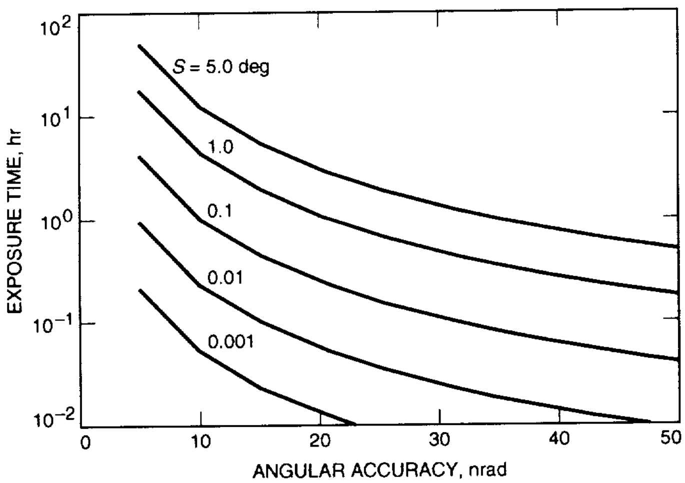

Fig. 3. Exposure time versus angular accuracy and angular separation. (Astrometric effect of atmospheric jitter based on Han [11].)

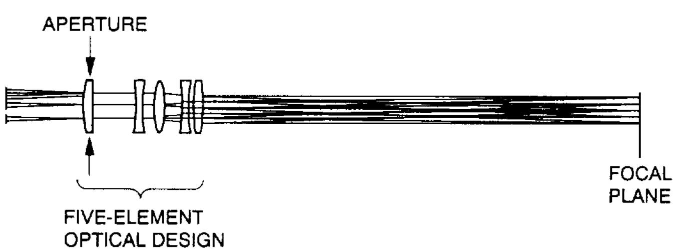

Fig. 4. Schematic diagram of a 5-deg wide-field astrograph.

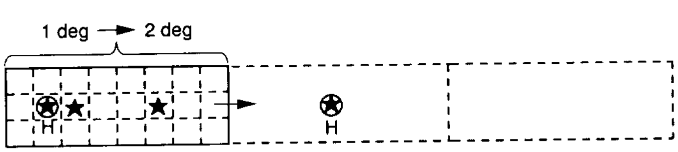

Fig. 5. Star observations with a scanning telescope and CCD detector. (Hipparcos stars are marked with an H.)

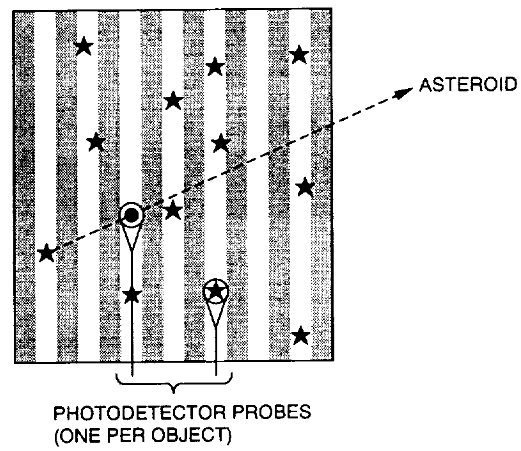

Fig. 6. Focal plane of Ronchi instrument (for stare mode). (Open circles represent photometers under asteroid and one star.)

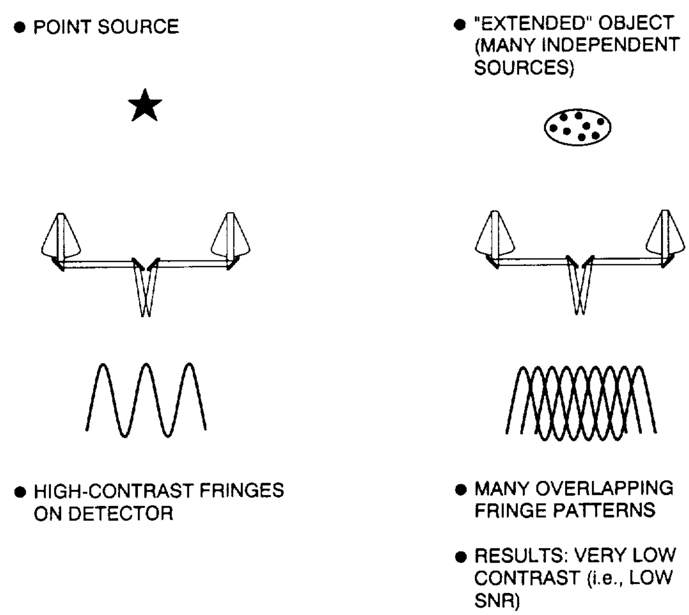

Fig. 7. Optical interferometry for solar system target objects.

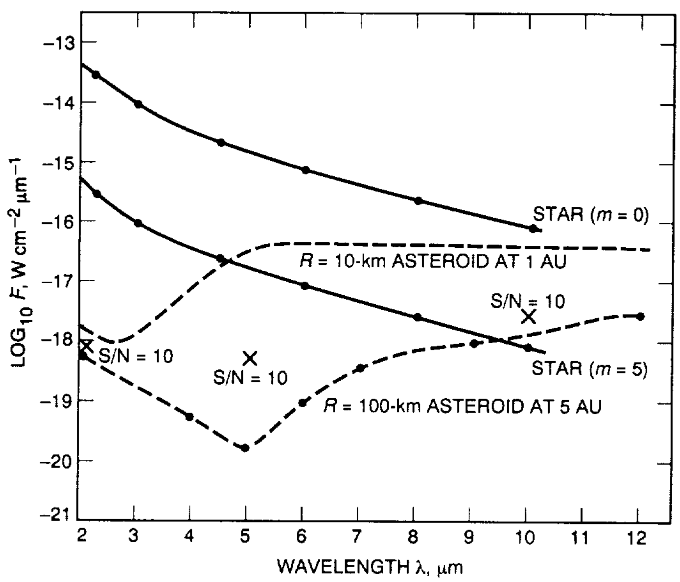

Fig. 8. Energy flux *F* for stars and asteroids versus wavelength.