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Deep Space Target Location With Hubble Space Telescope and Hipparcos Data

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ABSTRACT

Interplanetary spacecraft navigation usually requires accurate a priori knowledge of target positions. This report presents a concept for attaining improved target ephemeris accuracy using two future Earth-orbiting optical observatories, the European Space Agency (ESA) Hipparcos observatory and the NASA Hubble Space Telescope (HST). Assuming nominal observatory performance, the Hipparcos data reduction will provide an accurate global star catalog, and HST will provide a capability for accurate angular measurements of stars and solar system bodies. The target location concept employs HST to observe solar system bodies relative to Hipparcos catalog stars and to determine the orientation ("frame tie") of these stars to compact extra-galactic radio sources. The present report will describe the target location process, discuss the major error sources, predict the potential target ephemeris error, and identify possible mission applications. Preliminary results indicate that ephemeris accuracy comparable to the errors in individual Hipparcos catalog stars may be possible with modest numbers of HST observations and that accuracy improvements of two to four may be possible with a more extensive HST observing program. The eventual need for a second Hipparcos mission is discussed, and possible future ground and space-based replacements for the HST and Hipparcos astrometric capabilities are identified.

ACKNOWLEDGEMENT

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ACRONYMS

CCD	-	Charge Coupled Device (detector)
DSN	-	NASA/Deep Space Network
ESA	-	European Space Agency
FGS	-	Fine Guidance System (on the Hubble Space Telescope)
HST	-	Hubble Space Telescope
JPL	-	Jet Propulsion Laboratory/Calif. Institute of Technology
NASA	-	National Aeronautics and Space Administration
OPRECS	-	Earth-Orbiting Optical Receiving Station
PC	-	HST Planetary Camera CCD instrument
RSS	-	Root-sum-square
VLA	-	Very Large Array (Socorro, New Mexico)
VLBI	-	Very Long Baseline Interferometry
WF	-	HST Wide Field Camera CCD instrument

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I INTRODUCTION

This report will present a discussion of the potential navigation target location accuracy which can be obtained using space-based optical measurements of solar system target bodies relative to the star background and will identify some possible deep space mission navigation applications. The associated target location technology development will also be briefly described. The goal of this target location activity, which would employ data from the future (1989 launch) ESA/Hipparcos and NASA/Hubble Space Telescope (HST) Earth-orbiting observatories, is to provide accurate a priori target ephemerides for 1990's era interplanetary missions.

As discussed in Section II.A, target accuracy improvements can provide significant mission benefits including more accurate near-encounter instrument pointing and far-encounter probe release operations. These improvements also may permit some missions to be navigated without an onboard imaging system. Since this "radio-only" navigation capability would not require scan platforms or onboard imaging, it might facilitate development of inexpensive, reduced-weight spacecraft for missions to targets which have obscuring atmospheres or which have been adequately imaged by previous missions.

The results to be presented here assume nominal observatory performance as defined by the observatory designers, and since the actual post-launch performance may differ, then target location accuracy may change correspondingly. As discussed later, target ephemeris accuracy comparable to the Hipparcos catalog accuracy can usually be achieved with a relatively modest amount of HST data, and additional data may permit a factor of two to four improvement.

As discussed in Section III.A, ESA scientists expect to obtain catalog star random positional errors of the form a + bT, where a = 10 nanoradians (nrad), b = 10 nrad/year, and T= time in years past the end of the nominal 2.5 year Hipparcos mission lifetime; the catalog regional errors are expected to be about a factor of four smaller. For large T values, the catalog error is primarily caused by the bT (proper motion) term. Hipparcos catalog star proper motion error is approximately inversely proportional to mission lifetime. If, as has often occurred for other missions, the actual Hipparcos lifetime significantly exceeds the nominal lifetime, then the catalog accuracy would be correspondingly improved.

The purpose of this report is to describe the target location process, to identify the most significant error sources (assuming nominal performance), and to roughly estimate expected ephemeris accuracy vs. HST data volume. Also, alternative ground and space-based observing techniques are identified which might, after development, be able to replace some (or possibly all) of the HST and Hipparcos target location capabilities.

As discussed in Section II.B, an important motivation for this target location activity is to provide target accuracy commensurate with the increasing astrometric accuracy of NASA/JPL Deep Space Network (DSN) very long baseline interferometry (VLBI) measurements of spacecraft relative to compact extra-galactic radio sources. These sources, which include both quasars and other similar objects, will all be called quasars for the present discussion.

This report is divided into nine sections: Introduction, Target Location Overview, Hipparcos Catalog Characteristics, HST Astrometric Characteristics, Target Image Calibrations, Frame Tie between Quasar and Optical Star Catalogs, HST Observational Strategy, Post HST Space Based Alternatives, and Conclusions.

II TARGET LOCATION OVERVIEW

A brief description of the HST/Hipparcos target location process, its use for deep space missions, and a comparison with existing and possible future ground-based target location techniques will now be presented. However, discussion of space-based alternatives will be deferred until Section VII. Subsections to be presented here include: Mission Rationale, Target Location Technology Goals, Current Target Observation Methods, Future Ground-Based Optical Observation Methods, HST-Hipparcos Target Location Concept, and Data Acquisition Plans.

A. Mission Rationale

Several deep space mission applications of improved target positional accuracy have been identified. First, accurate three dimensional (3-D) target position information (with two dimensions from HST angular observations of targets relative to optical stars and the third dimension from target orbital dynamics) could be used with conventional spacecraft tracking (which provides accurate 3-D spacecraft positions) to predict the near-target spacecraft instrument pointing for mission flyby applications. This capability would be especially useful for flybys and/or orbit insertion for asteroid or comet missions since the small mass of these objects does not give a good "gravity tie" with the spacecraft. Another alternative capability being developed at the Jet Propulsion Laboratory (JPL) is a target body tracker instrument (Ref. 1), which would provide interplanetary spacecraft with an autonomous pointing capability. Onboard imaging and target body tracker data provide poor positional information in the spacecraft-target direction and therefore, the target body tracker must obtain this information through changes in the near encounter observing geometry. This occurs so close to encounter that the near encounter instrument pointing must be performed autonomously. Since accurate 3-D target data would permit prediction of the spacecraft-target position far in advance, the target body tracker might not be necessary for some missions.

A second potential target location application is to provide a navigation capability for missions without onboard imaging. This would enable low-cost, reduced weight "radio only" missions to targets which are obscured by clouds or have previously been adequately observed with onboard imaging. Removal of the onboard imaging system may facilitate removal of the scan platform from some spacecraft, thus providing an even greater weight reduction.

Finally, navigation accuracy at large spacecraft-target distances (for example, some trim maneuver and probe release operations) is often limited by poor onboard optical system linear accuracy. Therefore, the capability described here might provide more accuracy for these cases.

B. Target Location Technology Goals

Plans for the target location technology development have been driven by the need to provide target accuracies commensurate with the excellent spacecraft orbit accuracy expected from NASA/JPL Deep Space Network (DSN) differential-VLBI angular measurements relative to nearby quasars. These measurements will be denoted as spacecraft-quasar measurements. Expected spacecraft-quasar VLBI accuracy (Ref. 2) with the Galileo transponder is about 50 nanoradians (nrad) (one standard error) for source separations up to thirty degrees and about 25 nrad for source separations less than 10 degrees. (For readers accustomed to arcsecond units, 50 nrad $\approx$ 0.01 arcsec). There is also an on-going effort (Ref. 3) to achieve 5-nrad spacecraft-quasar accuracy using improved ground station equipment and spacecraft transponders. This 5-nrad angular accuracy translates into impressive linear accuracy for outer planet missions (for example, it corresponds to approximately 4 km at the average Earth-Jupiter distance).

C. Current Target Observation Methods

Since mission navigation requires knowledge of both spacecraft and target body positions, there has been a corresponding effort to improve the a priori target location accuracy. Differential quasar-relative VLBI radio interferometric measurements by Muhleman, et. al. (Refs. 4,5) of 15-Ghz thermal emissions from Jupiter's Galilean satellites, Saturn's satellite Titan, and the planet Uranus with the Very Large Array (VLA) have provided angular positions of these bodies which, at present, have formal standard errors of about 100-150 nrad. Future single measurement performance is not expected to improve significantly, but multiple measurements might yield a factor of two improvement. [1]

Similar VLA measurements of the asteroids Ceres and Pallas by Seidelmann, et al. (Ref. 6) had an accuracy of about 250 nrad, and it may be possible (private communication, K.J. Johnston, Naval Research Laboratory, Dec. 1987) to make measurements with 100-200 nrad accuracy for

[1] Private communication, D. Muhleman, California Institute of Technology, December 1987.

D. Future Ground-Based Optical Observation Methods

1. Concept

Since current ground-based observation methods do not provide the desired data accuracy, target selection, and global coverage, new optical observation methods with improved capabilities are definitely of interest. Discussion of possible future capabilities is unavoidably somewhat speculative, since these capabilities depend on currently undeveloped instruments and, as will be discussed, the development must achieve accuracy in the presence of significant systematic errors.

It is possible, however, to define some characteristics of a desirable ground-based optical observing system. Ideally, such a system should provide good astrometric accuracy and a wide field of view (say 1 degree by 1 degree) so that the target body can easily be observed relative to bright reference stars. It should provide large data volumes so that systematic errors can be overcome to the maximum possible extent and should, if possible, be a dedicated instrument.

Current star-star astrometric observation methods usually have the goal of determining small relative motion (parallax and proper motion) of one star relative to other nearby stars. As will be discussed, it is possible, by proper selection of observing conditions, to obtain accurate relative motion determinations which avoid (by approximate cancellation) most of the systematic errors which affect the relative angular positions of these stars. However, this strategy does not accurately determine relative angular positions and, of course, accurate relative star-target angular positions are definitely required for target location purposes. Therefore, the key development requirement for an advanced ground-based capability is to overcome these systematic errors and obtain accurate relative angular positions.

2. Relative Motion Determination Example

Since the systematic errors are primarily independent of detector choice, these choices will not be presented. Instead, to provide a specific introduction to the general observing problem, astrometric results from a representative wide field detector will be discussed.

The chosen detector is described by Gatewood (Ref. 10), who obtained accurate photoelectric measurements of the relative motion of stars within small local regions. His observing technique employed a moving Ronchi grating to modulate the stellar signal before it arrived at these bodies. These experimenters expect to be able to observe 250-km diameter asteroids (i.e., the 15-20 largest asteroids) at opposition, but not around the rest of the orbit. Of course, this is only a tiny fraction of the more than 2500 numbered asteroids. Since the VLA is oversubscribed, it has been difficult to obtain large numbers of VLA thermal emission measurements for either the natural satellites or the large asteroids.

The VLA capabilities just described provide a valuable target location capability which does not rely on optical star catalogs. However, this technique appears to have definite accuracy and observability limits and, therefore, new observation methods are still needed to obtain 25-50 nrad (or better) accuracy for a wider set of targets (also including comet nuclei and small asteroids and satellites).

Ground-based optical imaging and Voyager onboard imaging measurements provide another alternative. Current ground-based inter-satellite data accuracies (Ref. 7) are usually about 500 nrad. There are also rare opportunities to obtain ground-based measurements of satellite mutual events to an accuracy of about 150 nrad (Ref. 8). Excellent 15-30 km (25-50 geocentric nrad at Jupiter) satellite angular accuracy is available (Ref. 9) from close-up Voyager spacecraft onboard imaging.

However, these infrequent data provide only a local planetocentric satellite ephemeris "fix"; to provide accurate planetary ephemerides, these data must be combined with more global (i.e., more uniform coverage) observations taken relative to an inertial coordinate system. For the planets beyond Mars, these global data primarily consist of thousands of ground-based optical meridian transit observations, which typically have accuracies of about 2500 nrad. These observations are supplemented by more accurate, but infrequent, data, such as the previously discussed VLA measurements. The use of global data for target location will be described in Section VII.C.3.

the photometric detector. Results were obtained for four reference stars forming a reference grid about a target star. These indicated that, for 8th magnitude stars and a 20 minute exposure, the standard error of the target star about its linear motion was about 23 nrad for a 13 by 18 arcmin reference frame and about 38 nrad for a 28 by 28 arcmin reference frame. These results may give an indication of the potential accuracies which could be achieved if the desired relative angular separation observations could be adequately calibrated.

3. Ground-Based Observation Systematic Errors

Currently identified systematic effects include anomalous atmospheric refraction (primarily differential color refraction), instrumental errors (telescope flexure caused by Earth gravity, thermal effects, etc.), and sloping background light levels caused by scattering of the planet light by the Earth's atmosphere. The extent to which these effects can be calibrated and/or minimized will determine the astrometric accuracy of the target angular data.

Differential color refraction (Ref. 11) is a significant effect, which, for wavelength offsets from a 6500 Å (angstroms) base wavelength, can amount to about (130 tan Z) nrad per 100 Å , where Z is the zenith angle. Since observing solar system targets near zenith (Z=0) would require an impractical number of observing locations, it is necessary to find other methods to reduce differential color refraction. One obvious possibility is to use narrow filters to reduce the astrometric effect. Since signal strength is roughly proportional to filter width, it is a challenging problem to obtain sufficiently strong signals with a narrow filter. If adequate spectral curves for observed objects can be obtained, then it may also be possible to remove much of the differential color refraction effect through calculation. This also might require detailed information about color variations across target body surfaces. More analysis and observational verification is needed to predict the astrometric accuracy and operational feasibility of these methods.

Gatewood (Ref. 12) has proposed an alternative instrumental technique to reduce differential color refraction so that the difference between the actual image and a monochromatic image is only 1-2 nrad. The proposed method places a horizontal vacuum or helium-filled window in front of the telescope, and then tilts the window to approximately cancel the differential refraction. Actual astrometric performance, which might be degraded by the glass window, still remains to be demonstrated.

Summarizing, differential color refraction is a significant systematic effect, but there may be techniques which can reduce the astrometric error to acceptable levels. However, these techniques are currently untested and require further analysis and observational verification. Similar efforts will also be required to quantify and overcome the instrumental and planet scattered light errors.

Although differential color refraction and instrumental errors significantly affect target location angular measurements, these errors have a much reduced effect on stellar parallax/proper motion determinations. For this latter case, the observing program is usually designed such that, for a given star field, observations are all taken near the meridian and at approximately the same zenith angle. This insures that these systematic effects will primarily have a constant (but poorly known) effect on each inter-star angular measurement. This constant offset then approximately cancels out of the desired inter-star motion determination.

4. Systematic Error Assessment with Target Data

To assess the effect of these errors, it would be desirable to image objects whose relative angular positions are already accurately known or whose orbital motion can be accurately modelled. Current star catalog accuracies cannot support this effort, but inter-satellite images used in a least squares orbit improvement might be suitable. The main limitation on this error assessment is likely to be the offset between the target body center of light and center of mass; as discussed later in this report, this effect can usually be calibrated to 20 nrad or better.

5. Ground-Based Observation Summary

Summarizing, if a ground-based wide field detector could provide global coverage to 25-50 nrad accuracy, then it would certainly provide a valuable target location capability. It appears that a complete feasibility assessment will require a significant technology development effort (including additional analysis, instrument development, and observational verification) which would have to be supported by the target location activity. Achievable ground-based angular accuracy is difficult to predict and there presently are no plans to carry out the technology development/assessment. Therefore, to increase the probability of having at least one good 1990's era target location method, it seemed advisable to investigate space-based observing techniques, which would be free of the disturbing effects of the Earth's atmosphere.

E. HST-Hipparcos Target Location Concept

Space-based optical observations of targets relative to background stars could potentially provide the desired accuracy for mid 1990's interplanetary missions. Hipparcos and HST provide complementary capabilities which may make this possible. Hipparcos is a geosynchronous spinning spacecraft which interferometrically observes over 100,000 stars; ESA scientists then compute an accurate global optical star catalog (Ref. 13). HST (Ref. 14), with its large 2.4 m diameter reflector, will provide a capability to accurately image solar system bodies relative to stars with charge-coupled devices (CCD's) and (for a few small satellites and asteroids) with the interferometric Fine Guidance Sensor instrument. The target location concept employs HST observations to provide angular positions of interplanetary mission target bodies relative to the catalog stars and to provide the orientation ("frame tie") of the optical catalog to the JPL quasar catalog.

As discussed, observatory performance predictions made today are subject to possibly major future revisions. However, assuming nominal performance, it is possible to perform a rough analysis of the potential target location accuracy achievable with this data and to identify the most important error sources. As will be discussed, this analysis indicates that the dominant error source is the Hipparcos catalog star locations and that a reasonable goal for the overall target location process is in the range of 25-50 nrad.

F. Data Acquisition Plans

Two major target location prerequisites are first, that HST be capable of providing sufficient high quality data and second, that enough HST observations are actually allocated to the target location effort. The first prerequisite is the primary focus of this report, but, since HST will be a valuable, heavily oversubscribed scientific resource, the second prerequisite is also a major concern. Fortunately, however, the HST data volume required for target location can usually be held to relatively modest levels by combining HST data with other existing data types. Results of an analysis of data volume vs. ephemeris accuracy will be presented in Section VII.C.3.

Normally, HST data is acquired either on the basis of peer-reviewed scientific proposals or from data archives at the Space Telescope Science Institute (Ref. 15). For a one year period all data is reserved for the exclusive use of the successful proposer and then it is placed in the data archives. Upon approval of an archival proposal, this data would then be available for other use. Archival data acquisition could include not only star-star data and planned CCD solar system body images, but also images of "extra" bodies which happen to be in the field of view. Although the above data acquisition methods may possibly provide good HST astrometric calibration data and some useful target location data, it appears that a more formal arrangement would be required to carry out actual deep space mission target location support.

Acquisition of the Hipparcos catalog, on the other hand, should pose no problem except that catalog construction may take several years after the end of the 2.5 year data span. The eventual catalog release may not be until 1995 or 1996 and is therefore expected to be the pacing item for the target location technology development. HST lifetime is difficult to predict; O'Dell (op. cit., Ref. 14) indicates that HST refurbishment at five year intervals will permit a very long lifetime and that operations should continue as long as the returns justify the cost. The design lifetime is 15 years.

III HIPPARCOS CATALOG CHARACTERISTICS

Since the target location concept employs the Hipparcos star catalog, it is important to examine the skyplane number density, visual magnitude range, and astrometric accuracy of these stars. The catalog discussion will be divided into five parts, namely: Catalog Astrometric Error Budget, Double Star Effects, Observation Strategies to reduce Catalog Error, Need for a Second Hipparcos Mission, and Catalog Characteristics Summary.

A. Catalog Astrometric Error Budget

The Hipparcos optical catalog is described by Kovalevsky (Ref. 16). Briefly, this global catalog will contain, on average, about 2.4 stars/square degree, and will include stars as faint as magnitude 11. It is based on Hipparcos observations of stars over a nominal 2.5 year span; this short observation span limits the proper motion accuracy and causes significant secular errors in the angular positions of stars. Assuming nominal Hipparcos performance, these star locations are expected (op. cit., Ref. 16) to have random errors of the form a+bT, where a=10 nrad, b=10 nrad/year, and T is in years past the end of the nominal 2.5 year Hipparcos data set, and regional errors (i.e., errors common to stars in a large angular area) about 1/4 as large as the random errors. The corresponding random and regional errors at T=9 years are, respectively, 100 nrad and 25 nrad; these errors are the largest target location error source. Of course, if Hipparcos exceeds its nominal lifetime, then the catalog accuracy would probably be significantly improved.

As discussed, the orientation and rotation of the Hipparcos catalog relative to the quasar catalog must be obtained by performing a "frame tie" between the two catalogs. Establishment of the frame tie will be presented in more detail in section VI.

B. Double Star Effects

Hipparcos catalog star position errors introduced by undetected main-sequence double stars have been analyzed by Lindegren (Ref. 17). He concluded that about 10 % of all magnitude 9 stars are unresolved binaries whose resulting proper motion errors are greater than 10 nrad/year, but that only 0.2 % of these stars will have proper motion errors greater than 50 nrad/year. These results assume that Hipparcos cannot detect double stars with separations less than 0.25 arcsec. One obvious possibility for improvement is to observe double stars with HST, and, in fact, the HST

Fine Guidance System instrument can detect double stars which differ by less than about 3 visual magnitudes with separations as small as 25 nrad (Ref. 18). The more sensitive Fine Guidance System detection capability and the fact that normally the double star "wobble" (i.e., the distance from the center of mass to the photocenter) is much less than the separation distance, should greatly reduce the number of "problem" unresolved double stars. As a final resort, redundant HST star-target data residuals from the target location ephemeris determination can be used to identify unusually large star position errors.

C. Observation Strategies to reduce Catalog Error

One obvious observing strategy is to observe the target relative to many stars, thus driving the target location error down toward the regional star location error level. The size of the "regions" and the extent to which this strategy will work remains to be determined with actual HST measurements of Hipparcos catalog stars. However, based on the just discussed estimate of catalog regional error, it may be possible to achieve accuracy improvements by a factor of two to four. Some strategies for obtaining these observations in the relatively narrow HST instrument fields of view will be presented in Section VII.C.1.

D. Need for a Second Hipparcos Mission

The secular increase in catalog errors suggests that within 10-15 years another Hipparcos mission (or other equivalent mission) will be required to maintain the catalog positional accuracy. If this occurs, then the accurate angular star positions at the epochs of the two missions will permit a reduction in the secular errors by about a factor of 4-6.

E. Catalog Characteristics Summary

Summarizing the catalog discussion, Kovalevsky (op. cit., Ref. 16) estimates that the star average random error is about 10 + 10 T nrad and the regional error is about 2.5 + 2.5 T nrad, where T = years past the end of the nominal 2.5 year catalog data span. It may be possible to achieve target location errors at the catalog regional error level by obtaining a number of HST observations and taking advantage of square root of N improvement. After 10-15 years, a second Hipparcos mission will be needed to reduce the catalog star proper motion errors.

A significant fraction of the catalog stars are double, but, as discussed, HST Fine Guidance System observations can probably reduce the problem stars to a manageable fraction and, as a last resort, multiple HST astrometric observations can eliminate stars which could not otherwise be detected.

IV HST ASTROMETRIC CHARACTERISTICS

HST astrometric characteristics provide important constraints on the HST-Hipparcos target location process. These characteristics will now be presented in three subsections, namely: Instrument Overview and Focal Plane Layout, CCD Astrometric Accuracy Characteristics, and Fine Guidance System Astrometric Accuracy Characteristics. As will be discussed, preliminary analysis indicates that it should be possible to achieve 25-nrad target centroid accuracy (exclusive of Hipparcos catalog star errors and target image calibration errors). Both the CCD's and the Fine Guidance System are important to the target location process, the former because it can observe a wide variety of targets, and the latter because its larger field of view can obtain more target-star measurements for a limited set of small targets.

A. Instrument Overview and Focal plane Layout

The location of the CCD and Fine Guidance System instruments in the HST focal plane is shown in Figure 1. As shown, the CCD pickoff is located in the center, and the Fine Guidance System operates over three sectors on the outside of the telescope field of view. Each sector is approximately 4 minutes by 18 minutes in angular extent and contains an interferometric sensor which can be sequentially placed over star (or small solar system body) images to determine their astrometric angular position. Two sectors lock onto guide stars and thus provide telescope line of sight and roll orientation, while the third, as shown, can be used to provide relative angular positions between images in its field of view.

CCD detectors have become the standard imaging detector for future JPL interplanetary missions and were also chosen for HST because of their excellent imaging performance. Each CCD detector contains a grid of small detecting areas (pixels) which generate a charge approximately proportional to the number of photons collected during the exposure interval. Measurements of this charge then provide an accurate measure of the light falling on each pixel. A good description of CCD principles and recent detector development (including that for HST) is given by Janesick and Blouke (Ref. 19).

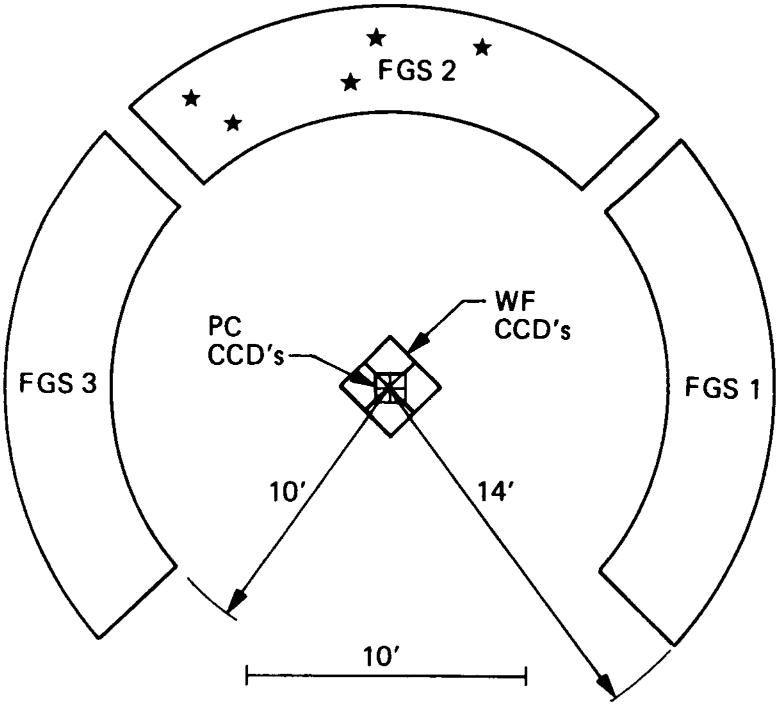

Figure 1. HST Focal Plane Location of the WF, PC, and FGS Instruments

The specific characteristics of the two HST CCD instruments will now be described. These instruments (which differ only in magnification) are the Wide Field (WF) and the Planetary Camera (PC) instruments. Both instrument detectors consist of four 800 by 800 arrays of square contiguous pixels with each 800 by 800 array forming a quadrant of a larger square area. Pixel side length for the WF instrument is about 0.1 arcsec (500 nrad) and for the PC instrument is 0.043 arcsec (215 nrad). Single quadrant fields of view are about 77 x 77 arcsec for the WF and 33 x 33 arcsec for the PC instrument.

The astrometric instruments just described will give excellent astrometric accuracy for the skyplane angular distance component (i.e., for the component which is invariant to an orthogonal rotation). However, uncertainties in telescope rotational orientation (caused by the expected 0.33 arcsec HST Guide star positional errors and possible uncalibratible temporal variations in the orientation of the CCD's relative to the Fine Guidance System) will significantly degrade the measured accuracy of the orthogonal ("position angle") skyplane angular component. This is not a serious problem, since target motion through the field of view can usually provide accurate angular distances in differing target-star skyplane directions and thus can provide reasonably good two dimensional angular information. However, it does indicate the desirability of observing stars close to the the target track, so that significantly different position angles can be obtained.

B. CCD Astrometric Accuracy Characteristics

Achieving good CCD centroiding accuracy requires several telescope/detector characteristics. Some of the most important include good geometric accuracy and stability, good pointing stability, and adequate sampling (i.e., a point spread over several pixels).

Geometric accuracy and stability within an 800 by 800 pixel grid has been verified in ground tests to about 1/20 to 1/40 pixel (except for distortion near the corners which is not expected to occur on HST) and HST in-flight performance is expected (after calibration) to be good to at least 1/20 pixel[2]. This pixel accuracy corresponds to about 10 nrad for the PC and 25 nrad for the WF instrument. Pointing jitter (op. cit., Ref. 15, p 27) is expected to be about 0.007 arcsec (35

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[2] private communication, Ken Seidelmann, WF/PC team member affiliated with the United States Naval Observatory, December 1987

nrad), but it tends to cancel out for inter-object astrometry and the higher frequency ($\geq$ 1 Hz) components (which are expected to have the largest amplitudes) tend to average out for exposures longer than the corresponding jitter wavelength. Thus the corresponding inter-object astrometric error should usually be much less than 25 nrad.

To analyze the photon-noise limited error, HST CCD diffraction-limited star images were simulated for 36 different star locations within the center pixel and then shot noise, read noise, and quantization noise were added to the data. After simulation, the data was fit with a moment algorithm, and the actual error was obtained by comparing the centroid solution to the known "true" solution. The "full well" pixel electron level was 30,000 electrons.

Results for the PC instrument for discrete wavelengths ranging from 5000 to 10,000 Å (suitable WF/PC filters are available for these wavelengths) showed average errors of less than 5 nrad at strong signal levels and about 10 nrad for a weak 600-electron signal. On the other hand, the WF results were wavelength dependent, with the best accuracy obtained using long wavelengths to increase the ratio of point spread to pixel length and thus obtain adequate CCD image sampling. For a strong 10,000-electron signal and wavelengths of 6000 to 10,000 Å, the centroid error decreased linearly from 75 nrad down to 15 nrad, and for a weak 1000-electron signal at 10,000 Å the error was about 35 nrad.

Similar simulations of natural satellite images (obtained by diffraction point spreading of a uniformly bright satellite disc) showed that the PC instrument can achieve about the same accuracy level for stars and satellites, but the WF instrument performed much better for satellites than for stars. The improved WF satellite accuracy is produced by improved image sampling created by the finite satellite disc.

Obtaining a suitably strong signal for multiple images may sometimes require two separate exposures. Although the jitter will have more effect on the astrometric errors for this case, these errors can be minimized by lengthening the exposure times until the jitter and image smear errors are approximately equal. As discussed, this will "average out" the higher frequency jitter components.

Summarizing, PC instrument astrometric errors should be less than 25 nrad for a wide range of wavelengths and signal strengths, but achieving good star centroid accuracy with the WF instrument will require a long incident wavelength and a strong signal.

C. Fine Guidance System Astrometric Accuracy Characteristics

As discussed, one of the Fine Guidance System field of view sectors is available for astrometric measurements. A detailed description of the characteristics of the Fine Guidance Instrument and its potential astrometric accuracy is given in the Fine Guidance Sensor Instrument Handbook (op. cit., Ref. 18). It specifies that stars as faint as 17th magnitude and solar system bodies as faint as 15.5 magnitude can be observed; however the extended bodies must have apparent diameters less than 0.04 arcsec.

The 0.04 arcsec diameter restriction corresponds to a linear equivalent of about 29 km per astronomical unit (AU). Examination of the sizes and apparent magnitudes of natural satellites indicates that the following satellites can be observed: Mars (Phobos and Deimos), Jupiter (Amalthea), and Saturn (Hyperion). A similar examination for asteroids reveals that the smaller asteroids provide many potential observing opportunities.

Recent pre-flight HST Fine Guidance System calibrations (Ref. 20) predict astrometric accuracies of about 15 nrad for observations meeting the above restrictions. These accuracies apply to a 4 by 5 arcmin field of view within the sector; accuracies for images in the rest of the sector may be worse than described here. Nevertheless, this 4 by 5 arcmin field of view is much larger than that provided by the CCD instruments.

V TARGET IMAGE CALIBRATIONS

Target surface characteristics can have significant effects on target body astrometric accuracy. As will be discussed, the most important target surface characteristic is albedo variations, although the phase illumination effects and body shape irregularities also must sometimes be included in the calibrations. The analysis for these effects is divided into three parts. First, target centroiding methods will be described and it will be shown that centroid errors caused by albedo variations can be calibrated by comparison of results from selected centroid determination methods. Second, experience with Voyager spacecraft close-up imaging of natural satellites is presented and it is shown that the maximum offset between the Europa or Io center of brightness and center of mass is about 0.05 satellite radii (115 geocentric nrad). Finally, results are presented which indicate that Voyager data could be used to calibrate centroid shifts for the larger satellites to about 20 nrad (or better).

A. Target Centroiding Methods

Target albedo variations over target body surfaces and irregularities in target shapes can cause significant offsets between the photocenter(center of brightness) and the center of mass. Since target location requires accurate astrometric measurement of the center of mass, it is important to calibrate this effect or to devise centroiding methods which are insensitive to it. Astrometric accuracy depends greatly on the angular size of the imaged body and the technique used for the centroid solution. Techniques which fit a shape to the image of the target edge (limb) are effective for targets with nearly circular shape and large angular extent (i.e., target radii greater than 10 CCD pixels) and are relatively insensitive to albedo variations. Preliminary HST PC instrument simulation results suggest that it may be possible to directly determine the mass centers of Titan and the Galilean satellites (which meet the 10-pixel radius requirement for the PC) to about 25-nrad accuracy using the previously discussed limb fitting techniques. However, more analysis is needed to definitely confirm this.

Limb fitting techniques are not suitable for targets whose limbs cannot be adequately sampled (i.e., targets with apparent radii less than 3 pixels) and, except for the planets, Titan, and the Galilean satellites, all other HST target images fall into this category. At present, all known

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centroid methods for intermediate sized bodies are sensitive to albedo variations and therefore must be calibrated for them. On the other hand, very small "star-like" bodies do not require calibration. The remainder of this section will primarily concentrate on an examination of albedo effects and their calibration.

B. Voyager Experience

Onboard imaging data taken by the Voyager spacecraft during its close approach to the Jupiter, Saturn and Uranus systems provides satellite images with 10-pixel (or greater) radii for a large number of satellites. This provides a good opportunity to determine actual centroid offsets and also provide information which can be used to calibrate HST CCD centroid shifts.

Comparison of Voyager Galilean satellite (Io and Europa) image centroids obtained[3] with limb fitting (to obtain approximate center of mass) and with moment algorithm fitting (to obtain approximate center of brightness) indicates that the offset between these centers varies with sub-Earth location and has a maximum value of about 0.05 satellite radii (115 geocentric nrad). The magnitude and wavelength dependence of these results was investigated by examining centroid shifts for different filter wavelength choices and sub-Earth points. This analysis (for Io and Europa Voyager images) indicated that the maximum centroid change induced by a 1000 Å wavelength change was about 0.01 satellite radii and that the average value was about 0.005 satellite radii, i.e., about 8-10 km. Since the wavelength difference between the peak response of the Voyager and HST detectors is about 1000 Å, wavelength effects do not significantly affect the use of Voyager information to calibrate HST centroids.

Some indication of the offset measurement accuracy can be obtained be examining previous navigation analyses of onboard imaging data. Analyses of close-up Voyager imaging of the Galilean satellites (op. cit., Ref. 9) indicate that optical navigation encounter images had a limb fitting centroid accuracy of about 15 km. Since this capability does not depend on the Earth-target distance, it should be roughly applicable to all the planetary systems visited by Voyager.

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[3] G. Null, "Preliminary Error Budget for Space Telescope Inter-Satellite Data", Interoffice memorandum 314.5/85-891 (internal document), Jet Propulsion Laboratory, Pasadena, Calif., April 11, 1985

C. Calibration of Large Satellites using Voyager Information

The preceding analysis suggests that moment algorithm centroid solutions could determine the center of brightness of HST CCD satellite images and then interpolated Voyager centroid shifts for these satellites could be used to compute the center of mass. This calibration would be needed primarily for the larger satellites (Jupiter 1-4, Saturn 3-6 and 8, Uranus 1-4, Neptune 1). The 15-km centroid offset accuracy corresponds to about 20-nrad calibration accuracy for the Galilean satellites. Other planetary systems are further away but have poorer Voyager satellite imaging coverage, so calibration accuracy probably would range from about 20 nrad at Saturn to 7 nrad at Neptune. More sophisticated satellite image calibration techniques under development for onboard navigation [4] may provide an additional factor of two accuracy improvement.

D. Calibration of Very Small and Very Large Bodies

Small asteroids and satellites sometimes have significant shape irregularities and therefore may have centroid shifts exceeding the 0.05-radii values just discussed. However, most of these objects are so small that the resulting astrometric error can be tolerated. At the other end of the size spectrum, accurate direct imaging of planets would require calibration to very small fractions of a planet radius, and this may be difficult to achieve. Adequate evaluation of this possibility will require analysis of real HST data.

E. JPL Image Calibration and Centroiding Capabilities

In addition to centroid shifts induced by albedo and shape variations, the effect of non-zero phase illumination angles must also be represented. For reasonable variations in assumed phase law, the error after phase calibration will not be a major contributor to the over-all centroid error. Calibration of phase effects is one portion of an extensive JPL image processing capability developed for ground processing of Voyager and Galileo mission onboard optical navigation measurements of stars and targets. Current plans are to use this capability for much of the HST image processing discussed here.

[4] S. Synnott, JPL Navigation Systems Section, private communication

VI FRAME TIE BETWEEN QUASAR AND OPTICAL STAR CATALOGS

A. Frame Tie Concept

As discussed, the HST-Hipparcos target location method requires that angular offsets and angular rates between the quasar catalog and the Hipparcos optical star catalog be accurately determined. The quasar catalog is important, not only because delta VLBI data is quasar-relative, but also because quasars are (presumably) extra-galactic sources and therefore are assumed to have negligible proper motions. Thus they provide a good approximation to an inertial coordinate system.

Of course, frame tie accuracy will be limited by the 2.5 + 2.5 T nrad Hipparcos catalog regional errors and, therefore, the immediate goal to drive the frame tie error down to this error level. Some methods which potentially could achieve this goal will now be described.

B. Methods proposed by the Astronomical Community

Several different techniques have been proposed to determine the quasar-optical catalog "frame tie". One promising technique involves HST observation of faint optical companions of quasars. These faint companions would then be observed with HST relative to bright stars in the Hipparcos catalog, and the frame tie could then be determined. Another technique involves quasar-relative VLBI microwave observations of radio stars. These stars are optically bright enough to be in the Hipparcos catalog, but they are weak and variable radio sources. A detailed description of these two techniques and a survey of current frame tie observational plans are given by Argue (Ref. 21), who indicates the potential of obtaining frame tie accuracy comparable to the catalog regional errors.

C. Galileo Frame Tie Method

Another alternative technique, involving the Galileo spacecraft during its Jupiter orbit phase, could also be useful. This technique would utilize the target location method described in this report to obtain accurate angular positions of the Galilean satellites relative to the Hipparcos optical catalog and would then use ground-based DSN radio metric observations of the Galileo spacecraft and onboard Galileo observations of Galilean satellites to locate the spacecraft relative to the satellites. Thus the geocentric angular position of the spacecraft relative to the optical catalog could be indirectly determined. Radio quasar-relative delta VLBI observations taken by the DSN would determine the geocentric angular position of the Galileo spacecraft relative to the quasar catalog. Finally, since the spacecraft orbit would now be determined relative to both catalogs, it would be possible to eliminate the spacecraft from the problem and determine the desired quasar-optical catalog frame tie. Preliminary analysis indicates that this method probably could provide accuracy comparable to the previously discussed Galileo spacecraft delta-VLBI data accuracy (i.e., about 25 nrad exclusive of Hipparcos catalog errors). The nominal two-year Galileo lifetime in Jupiter orbit does not provide a very long time span for frame tie angular rate determination, but, of course, other planet orbiting or lander spacecraft could be observed to extend the time span.

D. Frame Tie Summary

Summarizing, it seems likely that one or more of these frame tie methods will provide accuracy comparable to the Hipparcos catalog regional errors.

VII HST OBSERVATIONAL STRATEGY

The target location process will require acquisition of three data types, namely star-star data for telescope/detector calibration, satellite-satellite data for determination of planetocentric satellite ephemerides, and target-star data for planetary ephemeris determination relative to an inertial system. Target-star data acquisition, which is limited by field of view size, Hipparcos catalog star density, and HST data allocation priorities, can provide only a limited number of observations. As discussed, Hipparcos catalog star random errors (which grow linearly with time) are the main target ephemeris error source, and these errors can only be reduced by taking many target-star measurements. This strong need for observations coupled with marginal data availability creates the primary limitation on target ephemeris accuracy. The observing strategy and the ephemeris product and/or calibration result for each data type will now be presented.

A. Star-Star Imaging

After HST has been launched and good astrometric performance has been verified by the WF/PC and Astrometry (FGS) instrument teams, the development activities described here can be carried out with real data. Although some indication of post-launch Hipparcos performance may also be available, catalog release and definitive catalog error assessment will probably be some years away. HST astrometric activities will commence with instrument team analysis of star-star data and, since this data is needed for telescope/detector astrometric error calibration, it will be obtained throughout the entire HST mission. After a one year proprietary period, this data can be used to gain "hands on" experience and to perform whatever error analyses are needed to supplement those performed by the instrument teams. As discussed, these analyses are needed to accurately define the observation data characteristics.

B. Satellite-Satellite Imaging

After preliminary star-star results are available, the next logical step is to acquire satellite-satellite data and to use this data to perform a detailed analysis of target body data characteristics. Analysis of residuals resulting from least squares data fitting with N-body numerical integration and/or accurate orbital theories would form an important part of this activity. One important product of this analysis would be improved planet-relative ephemerides for the observed satellites.

These orbits would quickly reach (or exceed) HST data accuracy except for a "node in the sky-plane" near-singularity caused by the previously discussed position angle errors. This node error could easily be removed either by observing the satellites over 1/4 planet orbit period to gain orthogonality or (when available) by observing one or more satellites relative to nearby stars and including these measurements in the orbit fit.

From the previous discussion of HST data error sources, it appears that a reasonable estimate of HST inter-image data accuracy is about 35 nrad. Corresponding planetocentric ephemeris accuracy would benefit from "square root of N" improvement, and thus 25-nrad (or better) accuracy is possible.

C. Target-Star Imaging

When the Hipparcos catalog is available, it will be possible to obtain accurate target-star observations. Since satellite-satellite data will have already given accurate planet-relative satellite orbits, the planet orbit can be obtained by making star-relative observations for at least one satellite. As discussed, acquisition of target-star observations is limited by narrow HST instrument fields of view and this, in turn, limits the possible ephemeris accuracy. The analysis will examine acquisition probabilities, target-star data error, and ephemeris accuracy vs. data volume. As will be seen, the secular Hipparcos catalog star errors dominate the error process, and thus the target ephemeris accuracy depends on the interval between the HST star-relative observations and the end of the original Hipparcos catalog data span.

1. Acquisition Probabilities

As discussed, it is desirable to obtain a large number of target-star measurements to reduce the effect of random Hipparcos catalog star errors, and so it is important to examine the probability of obtaining these measurements in the instrument fields of view. Assuming "guaranteed accuracy" fields of view which are definitely expected to have good astrometric accuracy (i.e., single CCD quadrants for the WF and PC instruments and a 4 by 5 arcmin section of the FGS field of view), the acquisition probabilities can be roughly determined.

Data volume calculations were performed using the largest angular distance which will fit in each field of view (384 arcsec for FGS, 113 arcsec for WF, and 45 arcsec for PC) and assuming the average Hipparcos catalog star density (2.4 stars/square deg) and the HST 50 degree Sun viewing constraint. Other effects, such as unusable Hipparcos catalog double stars and possible lost HST observing opportunities (from unsuitable guide stars, etc.) were ignored, and therefore the results may be somewhat optimistic. The calculations indicated that the average number of stars which can be imaged relative to a single satellite (per planet orbital period) is 133 for the FGS, 40 for the WF and 16 for the PC instrument. Since outer planet periods are fairly long (Jupiter 12 yr, Saturn 29 yr, Uranus 84 yr, and Neptune 165 yr) it can be seen that (per year) the PC opportunities are very rare (only 2/year for a Jupiter satellite) and that the FGS instrument provides the most numerous opportunities. Asteroids typically have periods of about 4-5 years and therefore should provide more frequent star-target observation opportunities.

Since the Mars, Jupiter, and Saturn planetary systems each contain at least one satellite which is observable with the FGS instrument, one likely strategy is to obtain FGS star-satellite data for these satellites and then to use this data to provide the the desired planet ephemeris information. Asteroids could also often be imaged with the FGS. Another possibility is to expand the field of view by using all four CCD quadrants, by using an entire FGS field of view sector, or by imaging a star with the FGS and simultaneously image a satellite with a CCD instrument. These observation modes would provide much larger fields of view, but real HST data will be required to establish whether the inter-instrument stability will permit sufficiently accurate astrometric measurements. Current predictions of FGS-CCD stability vary from 35 nrad (op. cit., Ref. 18) to 50-100 nrad (Ref. 22), while CCD inter-quadrant stability is unknown.

2. Target-Star Data Error

From the previous analysis, the star-target data error can be roughly approximated as a statistical combination of the 35-nrad HST inter-image centroiding error and the Hipparcos catalog random errors (which are approximately 10 + 10T nrad, with T in years past the end of the catalog data span). The combined error is approximately the root-sum-square (RSS) of these two errors, i.e., RSS(36,10T) nrad, which for large T, is approximately the Hipparcos star random error level. A comparison of data errors for the HST satellite-satellite, HST target-star, and the previously discussed conventional ground-based data types is shown in Figure 2.

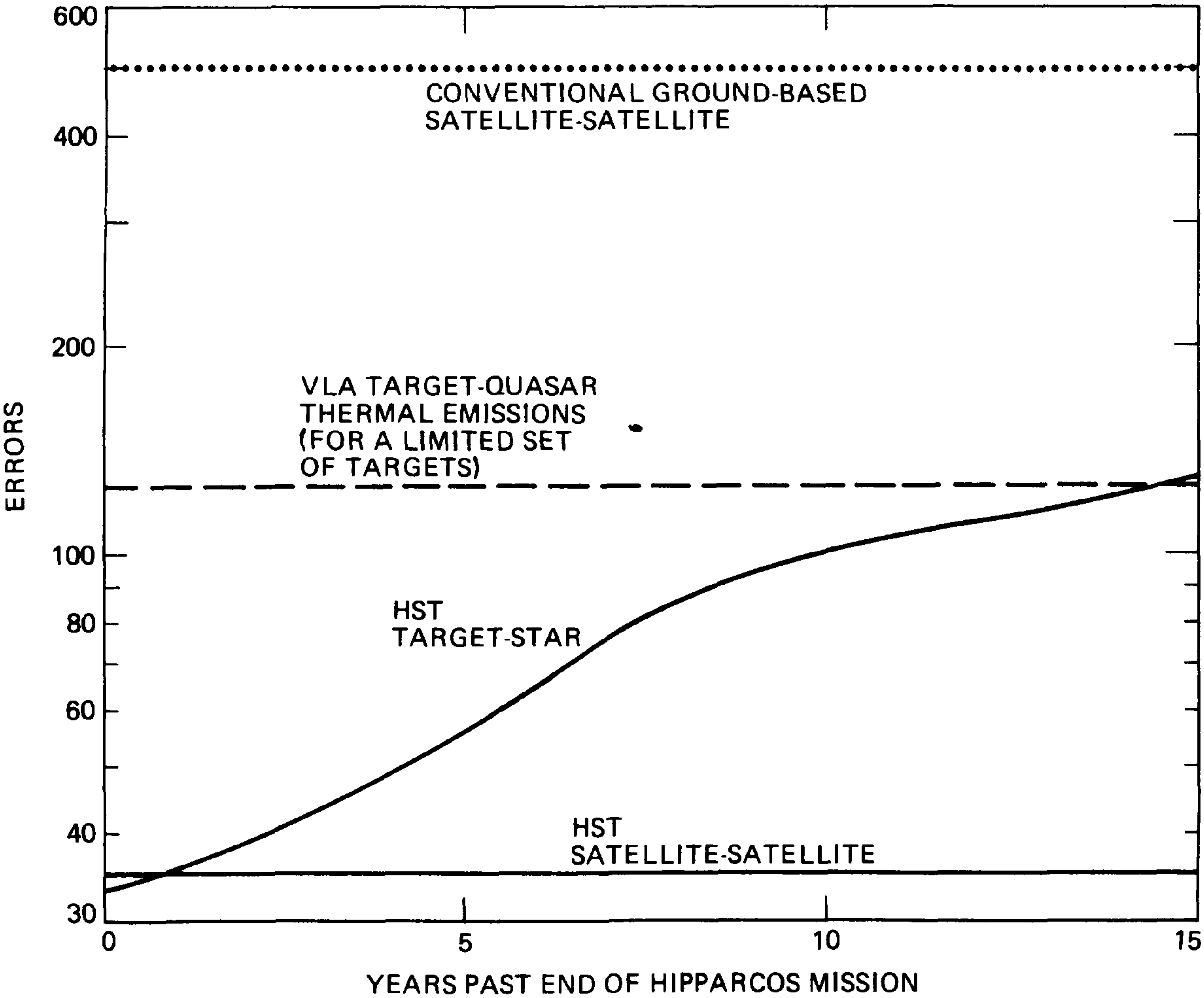

Figure 2. Data Errors vs. Years Past End of Hipparcos Mission

As shown, the accuracy of the HST satellite-satellite and target-star data is significantly better than the ground-based data accuracy. However, the HST target-star accuracy gradually degrades because of the Hipparcos catalog proper motion errors.

3. Ephemeris Accuracy vs. Data Volume

A covariance analysis was performed with simulated data to roughly assess the HST data volume required to achieve target ephemeris accuracy comparable to the HST measurement accuracy and to provide some initial understanding of expected planetary and asteroid ephemeris error characteristics. However, the more detailed results needed to optimize HST data patterns were beyond the scope of the present effort. The covariance analysis indicated that HST data volume can be significantly reduced by adding other existing Earth-based and deep space spacecraft astrometric data to the solution set. The goal of the analysis was to provide approximate answers to three questions. First, what accuracy can be attained with only HST data? Second, what accuracy can be achieved with a single HST observation combined with other data types? Finally, what accuracy is possible when other data is combined with a larger HST data volume? In the subsequent discussion, these last two data combinations will be denoted as "single-point" and "multi-point" cases.

Each HST target-star observation was assumed to be relative to a unique star, to have equal accuracy, and to consist of two exposures with orthogonal angular distance directions. Assumed HST target-star accuracy was a constant 100 nrad, corresponding to the Hipparcos catalog error 10 years after the last catalog data. This uniform HST data weighting assumption was adopted to simplify the analysis; it is definitely over-conservative, since the data errors for the last HST data are being applied to the entire data span and, as discussed, the earlier data is actually more accurate.

All covariance results were mapped to 200 days after the last HST data; this time was chosen to allow ample time for data reduction and for the interval between command transmission to the spacecraft and the actual mission event. Trajectory errors will be given in multiples of the HST observation error and are composed of an angular component (larger of the right ascension and declination errors) and an orthogonal radial component. HST data was spread evenly over the planetary data spans but, for asteroids, was concentrated at Earth oppositions and at the end of the data span.

Available observational data for the planetary ephemeris has been described by E.M. Standish[5] For the present combined planetary data simulation, HST observations were combined with 100 optical meridian transit measurements (data span= 40 years; std. error = 2500 nrad). This data pattern was conservative in two respects. First, 80 years of good transit data are available, and second, over 1000 transit observations are available for each major outer planet. The purpose of the conservative data pattern was to permit use of a readily available 40 year ephemeris and, pending a more detailed analysis, to avoid a strong reliance of the ephemeris accuracy on "square root of N" improvement from the transit data. If the full data span and volume are to be assumed in future analysis, it will be necessary to also analyze the systematic errors affecting this data.

Combined cases for asteroids had the same assumed ground-based data accuracy and span as the planetary transit data, but included only 20 photographic plate observations to reflect the typically poorer asteroid data coverage. A geocentric range normal point (std. error = 10 km) was included for every Voyager planetary flyby to reflect information gained from the Voyager-planet gravitational interactions. For Jupiter, information from the Galileo spacecraft gravitational interaction with Jupiter was also added to the solution. This data included 50 angular observations (std. error = 25 nrad) at the previously discussed spacecraft VLBI accuracy and 50 geocentric range observations (std. error = 10 km). The Galileo data was assumed to have a two year span and to occur 10 years before the last HST observation.

Heliocentric coordinates for the Earth were obtained directly from the JPL ephemeris, heliocentric planet coordinates were obtained from a conic fit to the ephemeris coordinates, and the heliocentric asteroid coordinates were computed from input conic elements. The use of conic partial derivatives for planet or asteroid orbits is an acceptable approximation for the present covariance analysis. Since the Earth ephemeris is known to a few kilometers, the Earth conic elements were

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[5] Private communication, E.M. Standish, JPL, January 1988; article to be submitted to Astronomy and Astrophysics - "Observational Data in the Planetary and Lunar Ephemerides of the Astronomical Almanac".

assumed perfectly known and solutions (without a priori information) were performed for the target ephemeris elements.

For the "HST-only" analysis, target-star observations over at least one target system (i.e., asteroid or primary planet) orbital period were optimal for determination (from the mean motion using Kepler's 3rd law) of the heliocentric orbit scale distance and so enabled the radial error to be determined more accurately than the angular error. As an example, the variation of ephemeris accuracy with data span is shown in Table 1 for 16 evenly spaced observations.

Table 1 "HST-only" Saturn Ephemeris Errors vs. Data Span with 16 Observations (expressed in multiples of the HST data error)

DATA SPAN (YEARS)	ANGULAR ERROR	RADIAL ERROR
2	1.1	5.4
5	0.9	4.7
10	1.0	2.7
15	0.9	1.4
20	0.8	0.9
30	0.7	0.3

As can be seen, shorter data spans degraded the radial accuracy significantly. For example, the radial error increased to 2.7 when the Saturn data span was reduced to 10 years (i.e., to about 1/3 of the 30 year Saturn orbital period).

"HST-only" target trajectory mapping results for 6 HST observations spanning a single target orbital period are shown in Table 2 for an asteroid, Jupiter, and Saturn. Although the Uranus and Neptune mappings were not computed, results for these bodies would probably be similar to those shown for Saturn. The tabulated results indicate that approximately 6 HST observations over one target orbital period are sufficient to determine the mapped trajectory components to the HST data accuracy. Assuming a "square root of N" error law, then 24 observations could provide a factor of two improvement and 96 observations could provide a factor of four improvement.

Table 2 "HST-only" Target Errors for 6 Data spread over one Target Orbital Period (expressed in multiples of the HST data error)

TARGET BODY	PERIOD (YEARS)	ANGULAR ERROR	RADIAL ERROR
ASTEROID	4.7	1.0	0.6
JUPITER	11.9	0.9	0.4
SATURN	29.5	0.8	0.4
URANUS	84.0	-	-
NEPTUNE	164.8	-	-

Since it is usually not feasible to wait for 30 years or more to obtain an accurate 3-D planetary orbit, it is important to examine the accuracy which can be obtained by combining a short span of HST data with existing planetary ephemeris data. As will be discussed, this data combination requires significantly fewer HST observations than the "HST only" case. The "single-point" combination of one HST observation with other data types will be used to roughly illustrate the accuracy characteristics for this situation. Mapped ephemeris accuracies for an asteroid, Jupiter, Saturn, Uranus, and Neptune are shown in Table 3.

As can be seen, significant improvement occurred for all targets except Jupiter, whose ephemeris was already well determined by Galileo information. These results demonstrate that a few HST observations can immediately reduce the planetary angular trajectory error components to the HST data error level. This strategy does not work as well for asteroids, presumably because of the weaker nature of the assumed asteroid ground-based data coverage. Therefore, asteroid ephemeris accuracy is probably best defined by the "HST-only" values from Table 2. However, improved ground-based data coverage might permit better ephemeris accuracy than shown here.

Table 3 Target Errors for One HST Observation Combined With Other Data (expressed in multiples of the 100-nrad HST data error)

TARGET BODY	ANGULAR (NO HST)	ANGULAR WITH HST	RADIAL (NO HST)	RADIAL WITH HST
ASTEROID	13.5	5.1	5.2	5.0
JUPITER	0.7	0.5	0.1	0.1
SATURN	3.4	0.9	0.8	0.7
URANUS	3.7	1.0	6.4	4.9
NEPTUNE	6.5	1.1	3.9	3.8

Other "single-point" analyses, with various assumed HST data accuracies, yielded angular component results (in units of the assumed HST data accuracies) which were similar to the Table 3 values. On the other hand, the radial component errors (also expressed in multiples of HST angular errors but primarily determined from the other data) were approximately inversely proportional to the HST data errors.

As discussed, available data includes over 10 times the transit data volume and twice the transit data span assumed here, and future analysis with this larger data set will require a careful representation of systematic transit data error sources. This analysis may lead to planetary "single-point" and "multi-point" radial accuracies which are significantly better than those given here. Also, accurate VLA and HST data could provide significantly improved planetary mean motions and scale distances within 10-20 years.

Of course, more than one HST target-star observation is required to identify and eliminate bad observations (about three observations are required to provide sufficient redundancy) and to drive the trajectory error down toward the Hipparcos catalog regional error level. If it were possible to obtain all the HST observations in a short time span (say 50 days) then, assuming square root of N improvement, it would then be possible to obtain angular component accuracies of 0.5 with 4 HST observations and 0.25 (the Hipparcos regional catalog error level) with 16 observations.

However, the narrow HST instrument fields of view cannot provide the required data sampling rate, and therefore the data spans must be expanded to accommodate the achievable data rates. Results from this "multi-point" analysis are difficult to generalize and need further analysis. As a rough indication of possible accuracy, results for 16 HST observations are shown in Table 4:

Table 4 Target Errors for 16 HST Observations combined with Other Data (expressed in multiples of the 100-nrad HST data error)

TARGET BODY	ANGULAR (NO HST)	ANGULAR WITH HST	RADIAL (NO HST)	RADIAL WITH HST
ASTEROID	13.5	0.7	5.2	0.4
JUPITER	0.7	0.2	0.1	0.1
SATURN	3.4	0.5	0.8	0.5
URANUS	3.7	0.8	6.4	3.2
NEPTUNE	6.5	0.6	3.9	2.3

The data span for the five bodies in this table was, respectively, 4.7, 2, 4, 10, and 10 years. As seen, these 16 HST observations yield excellent 0.2 HST data standard error accuracy for Jupiter. For the other bodies, the errors are larger, but still significantly improved as compared to the corresponding Table 3 "single-point" case results.

This analysis has not provided an optimum HST observing strategy, since more analysis is required and the secular target-star errors must be represented. Further analysis will probably yield improved strategies to reduce the required HST data volume. Also, the previously discussed HST multi-instrument fields of view may provide more observing opportunities, and thus, by concentrating data at optimum times, will reduce the data requirements. Clearly, the observational strategy should include both a concentration of data near the desired trajectory prediction time and also a long arc of data to take advantage of smaller star catalog errors and to determine the mean motion and orbit scale.

4. *Target-Star Summary*

Summarizing the target-star imaging discussion, target accuracy is primarily limited by Hipparcos catalog star location errors and, to a lesser extent, by HST centroiding errors. If HST observations are combined with other existing data types, then three HST observations can provide mapped (to 200 days after the last HST observation) outer-planet angular component accuracy equivalent to the data error. Asteroid solutions to this accuracy usually will require about 6 HST observations spread over several years.

The radial errors for Uranus and Neptune are much larger than the angular component errors, but these radial errors eventually can be improved by more extensive analysis of the existing ground-based transit data and by acquisition of long arcs of HST and VLA data. On the other hand, asteroids, which can be observed by HST for one or more full orbital periods, will have radial errors which are much smaller than the HST angular measurement error.

Since the most important data errors appear to be essentially random, the target location accuracy can be improved by increasing the number of target-star measurements, and therefore, accuracy improvements of two to four appear possible. This latter error level represents Kovalevsky's (op. cit., Ref. 16) estimate of the Hipparcos catalog regional errors. The target-star analysis indicated that the best trades of data volume and accuracy were obtained for Jupiter, whose ephemeris can be determined to 0.2 HST data standard errors by combining Galileo and Earth-based data with 16 HST observations. Although not analyzed in this report, HST observations of Mars satellites Phobos and Deimos would be easy to obtain and, combined with the extensive existing Mars data, should provide excellent Mars ephemeris accuracy.

As discussed, acquisition in the "guaranteed accuracy" fields of view becomes increasingly difficult for larger Earth-target distances, but multi-instrument extended field of view observations (if sufficiently accurate) will provide significantly more observations. The resulting frequent observing opportunities would then permit good ephemeris prediction accuracy with a relatively small number of HST observations.

VIII POST HST SPACE-BASED ALTERNATIVES

Some current deep space communications development activities at the Jet Propulsion Laboratory may provide an improved post-HST target location capability. This capability and its relationship to the target location process will now be presented.

A. Optical Receiving Station Concept

As discussed, HST provides a potentially accurate method of observing solar system bodies, but adequate data acquisition may be difficult and the target location process is limited by Hipparcos catalog star errors. However, optical deep space to Earth orbit communications capabilities now being studied at the Jet Propulsion Laboratory (Ref. 23) may eventually relieve some of these difficulties. The optical communications concept involves high data rate laser communications from the interplanetary spacecraft to an Earth orbiting Optical Receiving Station (OPRECS) and then a microwave link to the ground. The OPRECS would have both a large (perhaps 5-10 m diameter), relatively imprecise mirror for light bucket data reception and also a smaller (perhaps 1 m diameter) diffraction limited mirror for uplink command transmission and astrometry. This 1 m mirror, when used with the previously discussed Ronchi grating detector, could furnish a wide field of view (perhaps 1 degree by 1 degree) and could serve as a dedicated HST-quality astrometric instrument. The increased target-star data volume and improved observing geometry provided by this observatory could potentially provide better target location accuracy than provided by HST.

B. Optical Receiving Station Development Schedule

The proposed development schedule calls for the OPRECS instrumentation to be installed on a low Earth orbit Space Station for a late 1990's technology demonstration followed by interplanetary mission operational support after the year 2000. However, no definite deployment decision has been made. In addition to target location capabilities, the OPRECS could also directly determine the angular location of the interplanetary spacecraft relative to stars and solar system targets which are in the same field of view. Further discussion of this spacecraft-relative imaging capability is beyond the scope of the present report.

C. Target Location without the Hipparcos Catalog

Target location methods which do not require the Hipparcos catalog could be very important if Hipparcos catalog accuracy is worse than expected or if star proper motion errors are not reduced with a second Hipparcos mission. The OPRECS wide field of view and ability to image faint objects could possibly permit accurate target location without an accurate star catalog by measuring, at different times, the location of more than one solar system body relative to the same star. Since the observations would be in error by the propagated star proper motion error, dim stars (to minimize proper motion) and small time differences are desirable. This skyplane "crossing point" technique is described by Hemenway (op. cit., Ref. 22). In principle,"crossing point" measurements of planets, satellites, and asteroids combined with accurate planetocentric satellite orbits from inter-satellite observations could determine the orbits of these solar system bodies relative to a dynamic reference frame. The frame orientation relative to the quasar catalog could then be determined by making delta VLBI measurements of planet-orbiting spacecraft and then using the orbital dynamics of the spacecraft to determine the planet's quasar-relative angular location.

Another possibility is to make OPRECS star-solar system body measurements (including the crossing point measurements) and to use these data to construct a local star catalog. This local catalog could then replace the Hipparcos catalog in the target location activities.

All these methods would also be possible with the previously discussed advanced ground-based techniques, but adequate accuracy would probably be more difficult to obtain. Of course, HST could also make such observations.

IX CONCLUSIONS

As discussed, significant mission benefits from improved target ephemeris accuracy have been identified. These include support of navigation functions such as near encounter instrument pointing prediction, low cost "radio only" mission navigation, and far encounter probe release and trim maneuver operations. Target location goals were driven by the need to match (to the best possible extent) the expected 5-nrad angular accuracy provided by DSN quasar-relative VLBI spacecraft measurements.

The Hipparcos/HST target location concept employs HST observations to provide angular positions of solar system bodies relative to Hipparcos catalog stars and to provide a "frame tie" of the Hipparcos optical catalog. Each HST observation is defined to consist of two target-star exposures (both with the same star), sequenced to provide the maximum possible orthogonality between the skyplane target-star vectors. Assuming nominal HST and Hipparcos observatory performance, an accurate quasar-optical catalog frame tie, and a modest number (about 3) of HST observations, this data (combined with other available astrometric target location data) potentially can give quasar-relative target ephemeris root-sum-square (RSS) angular component accuracies of about RSS(36,10T) nrad, where T is time in years beyond the end of the original catalog data span. The ephemeris angular component error is defined as the larger of the trajectory errors in the right ascension and declination directions. These errors are for a target trajectory prediction 200 days past the last HST observation, allowing an ample time margin for data processing and trajectory delivery as required for mission operations.

As discussed, for the asteroids, Mars, and Jupiter, the radial (geocentric range) trajectory component accuracy is better than the angular component accuracy. For Saturn these accuracies are similar, and for Uranus and Neptune, the radial accuracy is significantly worse. However, the Uranus and Neptune radial errors eventually can be improved by more extensive analysis of existing ground-based optical data and by acquisition of long arcs of HST and VLA data.

If more HST data is available, then, as shown in Table 4 for 16 observations, additional ephemeris accuracy improvement by a factor of 2-4 may be possible, thus providing RSS(18,5T) to RSS(9,2.5T) nrad accuracies for the trajectory angular component. Although these trajectory accuracies will not quite reach the 5-nrad goal, they could meet the mission navigation requirements for many potential future interplanetary missions and would provide significantly improved target ephemeris accuracy.

Required HST data volumes can be significantly reduced if the HST multi-instrument fields of view provide sufficient accuracy; this can only be verified by in-flight HST performance. Additional analysis will probably identify more opportunities to minimize the data volume required for specific mission applications. Although identification of an optimal data sequencing strategy will require further analysis, some aspects of this strategy are already known. Specifically, data acquisition should begin as soon as possible, thus taking advantage of smaller Hipparcos catalog errors and eventually providing improved mean motion and orbit scale determinations. It is also desirable to obtain several observations close to the desired trajectory prediction epoch.

The ephemeris accuracies just presented are primarily controlled by the Hipparcos catalog star proper motion errors, which, as discussed, are expected to be the limiting HST target-star error source for ephemeris applications. Hipparcos catalog proper motion errors are approximately inversely proportional to the mission lifetime. If, as has often occurred for other missions, the Hipparcos lifetime exceeds its nominal length, then proper motion errors would be correspondingly reduced.

Since star proper motion errors will gradually degrade the target ephemeris accuracy, a second Hipparcos (or equivalent) mission is needed within 10-15 years. Proper motion errors from the combined missions would then be reduced by a factor of 4-6, resulting in a significantly improved RSS(36, 2T) nrad planetary ephemeris angular accuracy for three HST observations.

Two alternative optical observing techniques were identified which also could possibly provide a dedicated target location observational capability with accuracies comparable to that provided by HST. This capability could potentially reduce (or eliminate) target location requirements for data from the heavily oversubscribed HST observatory and, if necessary, could possibly provide accurate quasar-relative target locations without an Hipparcos catalog. Both these observing techniques utilize wide field of view detectors and, like HST, could observe target bodies relative to the Hipparcos star catalog. Either, if successfully developed, would provide an accurate, highly valuable target location capability.

The first technique, a potential future ground-based method, would probably require development support from the target location activity. As discussed, the principal challenge for this method is to reduce the astrometric effect of several difficult-to-calibrate systematic errors. The required instrument development and observational verification activities appear to require a significant effort whose success cannot be confidently predicted. There presently are no plans to develop this capability.

The second technique, which utilizes an Earth orbiting optical receiving station, potentially could provide better target location ephemeris accuracy than HST. However, no deployment decision has been made and, in any case, the optical receiving station would not provide interplanetary mission support until after the year 2000.

Thus, the technology forecast includes both a near-term target location observing capability with the soon-to-be-launched Hipparcos and HST observatories and possible improved, longer term alternative capabilities. These techniques could potentially provide an increasingly accurate target location capability for future interplanetary missions.

REFERENCES

1) E.W. Dennison, R.H. Stanton, and K. Shimada, "Astros: High Performance CCD Tracker for Spacecraft," Proc. of the 15th International Symposium on Space Technology and Science (Tokyo), Vol. 2, pp1131-1142, AGNE Publishing Inc., Tokyo, 1986.

2) B.K. Trinkle and S.M. Lichten,"Differential Very Long Baseline Interferometry for 50 Nanoradian Deep Space Navigation: Results from Quasar Pair Experiments," paper AAS 85-311, presented at the AAS/AIAA Astrodynamics Specialist Conference, Vail, Colorado, August 1985.

3) R.N.Truehaft,"Astrometry in Local Reference Frames for Deep Space Navigation," Proc. IAU Symposium No. 129, May 1987, to be published.

4) D.O. Muhleman, G.L. Berge, and D. Rudy, "Precise VLA Positions and Flux-density of the Jupiter System", Astron. J., Vol. 92, No. 6, pp1428-1435, December 1986.

5) D.O. Muhleman, G.L. Berge, D.J. Rudy, A.E. Niell, R.P. Linfield, and E.M. Standish, "Precise Position Measurements of Jupiter, Saturn, and Uranus Systems with the Very Large Array," Celestial Mechanics, Vol. 37, pp329-337, 1985.

6) P.K. Seidelmann, G.H. Kaplan,K.J. Johnson, and C.M. Wade, "Observations of Minor Planets with the Very Large Array," Cel. Mech., Vol. 34, pp39-48, 1984.

7) D. Pascu, "Astrometric Techniques for the Observation of Planetary Satellites," in Planetary Satellites (ed. J.A. Burns), Univ Arizona Press, pp63-86, 1977.

8) K. Aksnes, F. Franklin, R. Millis, P. Birch, C. Blanco, S. Catalano, and J. Piironen,"Mutual Phenomena of the Galilean and Saturnian Satellites in 1973 and 1979/80," Astron. J., Vol. 89, No. 2, pp280-288, 1984.

9) J.K. Campbell, S.P. Synnott, and G.J. Bierman, "Voyager Orbit Determination at Jupiter," IEEE Trans. on Automatic Control, Vol. AC-28, No. 3, pp256-268, March 1983.

10) G.D. Gatewood, "The Multichannel Astrometric Photometer and Atmospheric Limitations in the Measurement of Relative Positions," Astron. J., Vol. 94, No. 1, pp213-224, 1987.

11) C.W. Allen, Astrophysical Quantities, 3rd edition, Univ. London, Athelone Press, pp124-125, 1973.

12) G. Gatewood, J.H. Kiewiet de Jonge, J. Stein, and L. Breakiron, "A Helium Filled Astrometric Telescope," Amer. Astron. Soc. Bulletin, Vol. 17, No. 2, pp582-583, 1985.

13) J. Kovalevsky, "Global Astrometry by Space Techniques," Celestial Mechanics, Vol. 22, pp153-163, 1980.

14) C.R. O'Dell, "The Space Telescope Observatory," Special Session of Commision 44, IAU, 18th General Assembly, Patras, Greece, 1982, pp20-27, August 1982.

15) "Call for Proposals - General Observer Program - Edwin P. Hubble Space Telescope," Space Telescope Science Institute, Baltimore, Md., pp1-21, October 1985.

16) J. Kovalevsky, "Hipparcos and the Dynamics of the Solar System," Celestial Mechanics, Vol. 26, pp 213-220, 1982.

17) L. Lindegren, "Detection and Measurement of Double Stars with an Astrometry Satellite," Colloquium on European Satellite Astrometry, Padova, Eds. C. Barbieri and P.L. Bernacca, Univ Padova, pp117-124, 1979.

18) "Fine Guidance Sensor Instrument Handbook," Space Telescope Science Institute, Baltimore, Md., October 1985.

19) J. Janesick and M. Blouke, "Sky on a Chip: The Fabulous CCD," Sky and Telescope, pp 238-242, September 1987.

20) A. Fresneau, "Fine Guidance System (FGS), Space Telescope Science Institute Newsletter, Vol. 3, No. 1, p14, January 1986.

21) A.N. Argue, "Hipparcos - Link with Extragalactic Reference Sources," Highlights of Astronomy, J.P. Swings (ed.), pp719-722, published by the IAU, 1986.

22) P.D. Hemenway, "The Use of the Hubble Space Telescope for Global Reference Frame Work," Highlights of Astronomy, J.P. Swings (ed.), pp719-722, published by the IAU, 1986.

23) M.M. Sokoloski and J.R. Lesh,"Deep Space Optical Communications," Proc. SPIE, Vol. 810, Optical Systems for Space Applications, pp172-177, 1987.

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16. Abstract

Interplanetary spacecraft navigation usually requires accurate a priori knowledge of target positions. This report presents a concept for attaining improved target ephemeris accuracy using two future Earth-orbiting optical observatories, the European Space Agency (ESA) Hipparcos observatory and the NASA Hubble Space Telescope (HST). Assuming nominal observatory performance, the Hipparcos data reduction will provide an accurate global star catalog, and HST will provide a capability for accurate angular measurements of stars and solar system bodies. The target location concept employs HST to observe solar system bodies relative to Hipparcos catalog stars and to determine the orientation ("frame tie") of these stars to compact extra-galactic radio sources. The present report will describe the target location process, discuss the major error sources, predict the potential target ephemeris error, and identify possible mission applications. Preliminary results indicate that ephemeris accuracy comparable to the errors in individual Hipparcos catalog stars may be possible with a more extensive HST observing program. The eventual need for a second Hipparcos mission is discussed, and possible future ground and space-based replacements for the HST and Hipparcos astrometric capabilities are identified.

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