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Final Report and Seminannual Reports 1, 2, and 3

This is the final report and semiannual reports 1, 2, and 3 for NASA Grant NAGW-1355 in response to our proposal P1870-1-88 for the study of "Planetary System Detection by POINTS." The grant covered the period from 15 June 1988 through 31 December 1989. The work during that period comprised the further development and refinement of the POINTS concept.

The status of the POINTS development at the end of the Grant period was described by Reasenberg in a paper given at the JPL Workshop on Space Interferometry, 12-13 March 1990, and distributed as CfA Preprint 3138. That paper, "POINTS: a Small Astrometric Interferometer," follows as Appendix-A. Our proposal P2276-7-09, dated July 1990, included a more detailed description of the state of the development of POINTS at the end of the tenure of Grant NAGW-1355. That proposal, which resulted in Grant NAGW-2497, is included herein by reference.

APPENDIX A

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POINTS: A SMALL ASTROMETRIC INTERFEROMETER

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Historical Introduction

The POINTS concept can be traced to 1974 when Irwin Shapiro was asked by NASA to provide some ideas for missions in the distant future. Among the concepts he offered was optical interferometry in space, which included both a large Earth orbiter (order 1 kilometer baseline) and a lunar-based interferometer with a multi-kilometer baseline. His proposed applications included a second-order deflection test of general relativity. A few years later, after completing some preliminary analysis and design, Reasenberg established a collaborative effort with Keto Soosaar *et. al.* at the C.S. Draper Laboratory. Their objective was to investigate an astrometric optical interferometer in space that was to be the forerunner of the current POINTS concept. From the beginning there were 2 interferometers, but initially they pointed 180° apart. The 90° separation angle was a suggestion of Leslie Matson of C.S.D.L., and was instantly recognized as an important improvement. By 1978, the baseline and aperture had shrunk to 10 m and 0.5 m, respectively. (Reasenberg and Shapiro, 1982) In 1979, a spherical enclosure was added to reduce the variation of temperature with instrument orientation, and to decrease the radiation temperature anisotropy, which we recognized would cause severe distortions of the precision structure. These versions of POINTS explicitly showed a long boom supporting the solar occulters that were clearly needed for the light-deflection test of general relativity.

In the early 1980's, David Black ran a series of workshops at NASA/ARC on planetary system detection. He enlisted Lockheed Missiles and Space Co. to do concept studies for two space-based astrometric instruments, one based on the astrometric telescope of George Gatewood *et al.* at Allegheny Observatory, and one based on an interferometer design by Mike Shao and David Staelin, both at MIT. Following a suggestion by Staelin, Wayne Metheny of Lockheed presented a scheme at a project review on 20 November 1981 for monitoring the optical path difference of an interferometer by fully illuminating the optical elements with an expanded laser beam. He used a linear grating on the final optical element, a flat siderostat mirror, to return the laser light to the beamsplitter. Unfortunately, this scheme measures the wrong quantity. It was, however, the inspiration for the Full-Aperture Metrology (FAM) system which is now an integral part of POINTS. The earliest version of FAM was described by Reasenberg in a memorandum (81-4, Astrometric Instrument in Space) to Black dated 9 December 1981. In that memo, a modified zone plate (equations in memo) on a flat siderostat mirror was used in conjunction with a small flat mirror and "auxiliary metrology [which] is required to determine the location of the small flat mirror." Although a primitive "fiducial block" was described by Reasenberg in a memorandum dated 15 August 1980, the memo to Black is the harbinger of the present fiducial block concept. Today, most of the FAM analysis assumes that the diffractive element is on the telescope primaries, since this approach removes the need for an extra large optical element on each telescope. However, no trade-off analysis has been done between this and the original scheme, which has the advantage that the diffractive elements are not inside the telescopes.

It was not until 1983 that the baseline and aperture reached their current nominal dimensions of 2 m and 0.25 m, respectively. The major shrinkage of the instrument nominal dimensions over a period of 5 years represents a growing realization of the importance of two considerations: (1) The cost of the spacecraft is closely related to size and weight, and only mildly dependent on technological complexity; (2) The richest scientific agenda is likely to involve (be dominated by) bright objects (*e.g.*, mag = 10) for which the integration time will be short even with small optics and a small baseline, if the nominal POINTS accuracy of 5 microarcseconds is assumed. More recently, the emergence of a rapidly growing community interested in optical interferometry has suggested that eventually several interferometers can be expected in space. Most of these will be imaging devices on a grand scale, with comparable price tags. Because they represent a new and complex technology, these "great observatory" class instruments are not likely to be flown without the benefit of a smaller, less expensive precursor instrument.

Instrument

POINTS (Precision Optical INTerferometer in Space) is a dual astrometric optical interferometer intended for Earth orbit. It is characterized by its small physical dimensions, internal laser metrology system providing real-time configuration determination and control, and its self-calibration *via* 360° closure. The instrument measures the angular separation of a pair of stars about 90° apart on the sky with a nominal 5 μas accuracy, which is reached after a 10 minute observation of a pair of 10th magnitude objects. After making allowances for slew and settling time, we estimate that 60 pairs of stars could be observed each day.

POINTS was originally developed as a means of performing the deflection test of general relativity to sufficient precision that the second-order contribution of the solar potential could be measured. However, it would have numerous other applications including the search for and characterization of extra-solar planetary systems and the direct determination of one of the lower rungs of the cosmic distance ladder. A list of scientific objectives that could be addressed by a POINTS mission is given in Table 1.

The nominal characteristics of the POINTS instrument and its mission are based on 25 cm optics for each of the 4 telescopes and a 2 m baseline length. For all calculations, we assume a 2% probability of detecting any photon that enters one of the starlight interferometers, and is within the 0.25 to 0.9 μm nominal bandpass. This detection probability is deliberately conservative, perhaps by a factor of 10, and is intended to amply cover a number of small corrections and problems not yet addressed (*e.g.*, part of the aperture is blocked by the secondary and the fiducial block, and we do

Table 1. Some Scientific Objectives of a POINTS Mission

- Search for extra-solar planetary systems
- Direct determination of the Cepheid distance scale
- Deflection test of general relativity
- Masses of stars in binary systems and those close enough to apply the method of perspective acceleration
- Parallax measurements yielding both absolute stellar magnitudes and, in conjunction with mass estimates and other data, a sharpened mass-color-luminosity relation.
- Vastly improved global reference frame tied to existing ones.
- Mass distribution in the Galaxy
- Strictly geometric (i.e., coordinate and parallax) determination of the membership of star clusters
- Bound or measure quasar proper motions
- Masses of many asteroids through observations of their mutual perturbations
- Masses of the major planets and their satellites through observations of the smaller of these satellites

not explicitly account for this approximately 20% reduction in aperture). Although itintended to amply cover a number of small corrections and problems not yet addressed (*e.g.*, part of the aperture is blocked by the secondary and the fiducial block, and we do not explicitly account for this approximately 20% reduction in aperture). Although it was conceived as a free flying spacecraft, we have considered the accommodation of POINTS on the Space Station. See Figs. 1 and 2.

For such an instrument, in addition to the myriad other, more detailed questions, there are three essential questions that must be addressed: (1) What is the measurement uncertainty $\sigma(\theta)$ and scientific "thruput" $\tau = N/\sigma^2$, where N is the number of observations per unit time? (2) How stable need the fringes be? and (3) How does one control systematic error? The first of these was addressed above in terms of the photon statistics with latitude for small, otherwise unidentified problems built into the deliberately low, assumed detection probability.

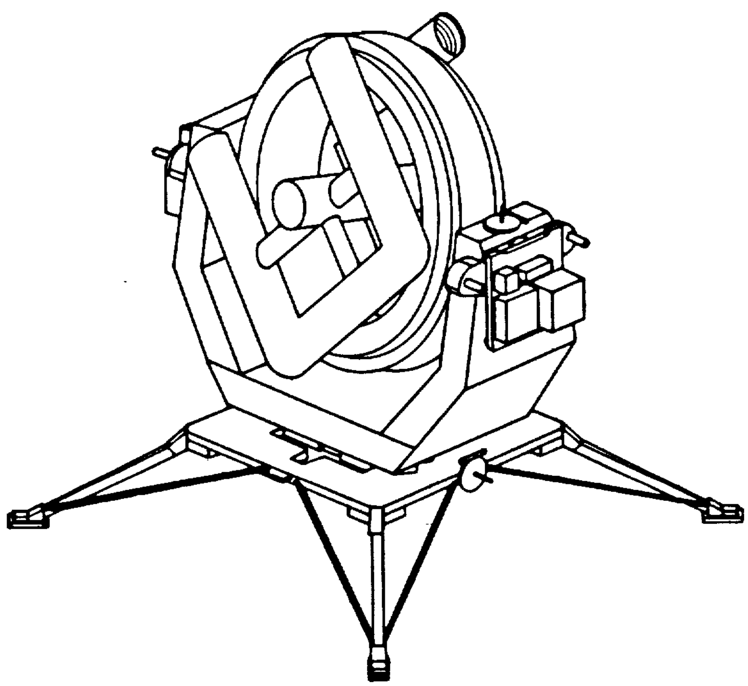

Figure 1. An artist's rendition of POINTS with 2 m separations between pairs of telescopes of 25 cm diameter, all mounted on the Space Station PPS. Between POINTS and the PPS is an isolation and pointing assembly which provides fine pointing, vibration isolation, and rotation in the plane of the elevation gimbal. The instrument comprises two U-shaped interferometers joined by a bearing which permits φ, the angle between the principal axes of the interferometers, to vary from its nominal of 90^o.

The question of fringe stability translates into limiting magnitude. We have investigated that question (Reasenberg, 1984) and found that under one plausible set of assumptions, the limiting magnitude is 17. These assumptions included that the angular motion of the instrument was determined by a star tracker of 10 cm diameter looking at a 7th magnitude reference object. If we use one of the interferometers instead of the telescopic star tracker, then we gain another 5 magnitudes; this makes the question of limiting magnitude all but irrelevant. (This study also assumed a 2% probability of detecting photons. Improving the detection efficiency would correspondingly improve the limiting magnitude.)

The question of systematic error is fundamental to precision astrometry and central to the architecture of POINTS, where it is addressed at three levels: (1) the use of stable materials in a thermally controlled environment, (2) real-time metrology, and (3) the use of the closure information content of the astrometric data to estimate, and thus eliminate, the effects of instrument biases. The stable materials with thermal control are used in two categories of components. First, there are the gross structural elements of the instrument. For these, stability serves to limit the scale of the deviation that must be detected and in some cases corrected by the metrology-actuator system. Plausible candidates include carbon-carbon and aluminized graphite epoxy. Second, there are the small, specialized components in the metrology system, whose stability bears directly on the results of the metrology, and which are therefore critical to its performance. We will encounter the latter below.

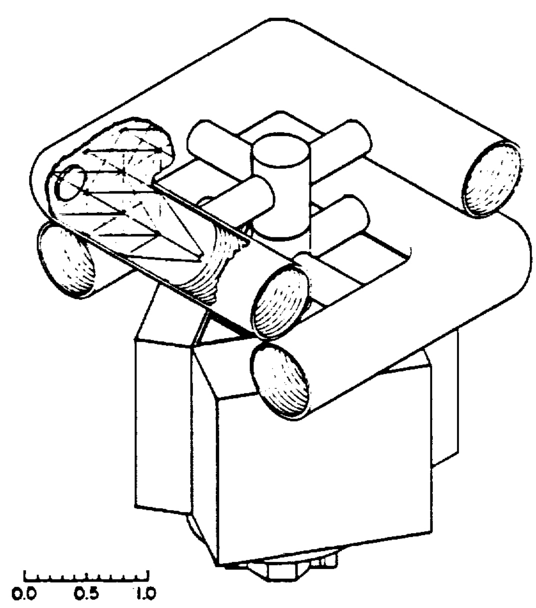

Figure 2. An artist's rendition of POINTS, as in Fig. 1, except mounted on the Multimission Modular Spacecraft.

The instrument relies on two kinds of laser-driven optical interferometers to determine changes in critical dimensions. The high-precision star-position measurement is made with respect to the optical axis of the interferometer. In turn, the position of this axis is determined by the positions of the optical elements used to transfer the starlight. In order to achieve the required pathlength measurement accuracy, variations in the optical pathlength through the system must be monitored to about 0.1Å. The metrology system must determine the average change in the starlight delay induced by all motions and distortions of all optical elements. Our approach is to use Full-Aperture Metrology (FAM), a novel technique discussed below. It provides three significant advantages over conventional approaches.

(a) FAM removes complexity. The usual metrology systems use a large number of laser gauges to determine the locations of the elements individually. From these measurements, the optical path through the system is computed. FAM directly measures the optical path through the system.

(b) FAM measures the correct quantity. Because the metrology signal fully illuminates the surface of each optical element that determines the starlight phase at the beamsplitter, the phase of the metrology signal is representative of the average starlight path through the system.

(c) FAM provides the basis for an operational definition of the direction of the interferometer baseline. It results in a pair of "fiducial points" located in front of each interferometer. These fiducial points, which lie on lines parallel to (or held at fixed small angles to) the interferometer baselines, are used to determine φ, the angle between the two interferometers' optical axes.

Figure 3 illustrates the technique. The key element is the set of primary mirrors which have shallow (phase contrast) zone plates on their surfaces: alternate zones are depressed about 100Å. The zones are approximately in the form of Newton's rings; each zone has about the same total area. We have shown that the required Zone-Plate Mirror (ZPM) can be made holographically.

Our colleagues at the Space-Sciences Division of Perkin-Elmer, now Hughes Danbury Optical Systems (HDOS), working under their IR&D program, have (1) developed a technology for making a phase contrast zone plate on a curved mirror surface and (2) made four of these, all of which have been studied at SAO and one of which remains on long-term loan to SAO. We have developed a test system at SAO for this ZPM and preliminary laboratory tests have shown that (1) the ZPM diffractive focus is close to the expected diffraction pattern, (2) the diffracted light represents the phase errors in the specularly reflected light with an error of under one part in 200 (Babcock *et al.*, 1988) for piston motion of the ZPM, and (3) the diffractive efficiency varies considerably over the ZPM surface, which makes the optical behavior under tilt

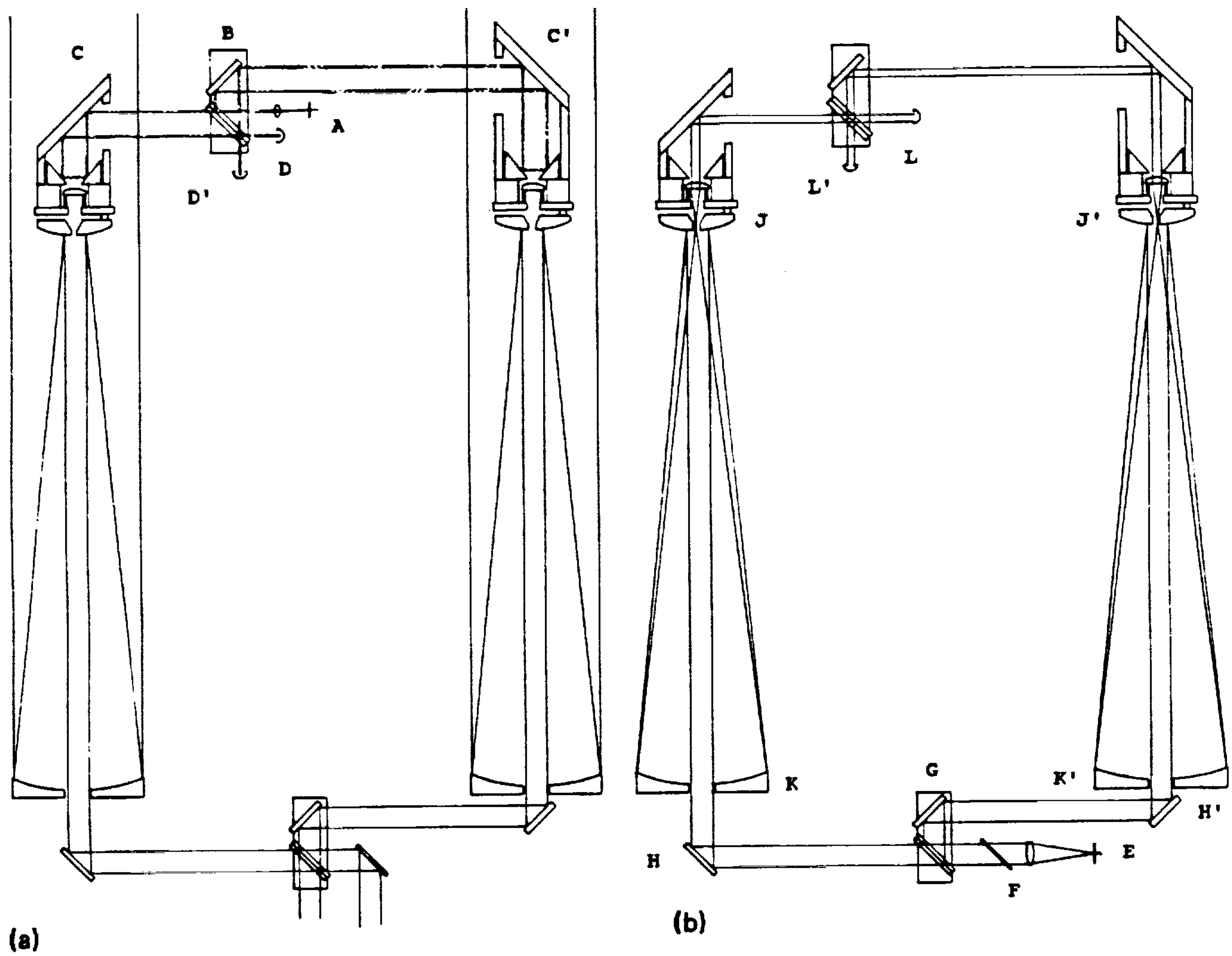

Figure 3. Interferometer optical paths. (a) Starlight and auxiliary null interferometer. For the latter, a laser signal passes through the spatial filter A and is divided by the metrology beamsplitter B to form beams that enter the fiducial blocks C and C'. Within each fiducial block, the beam is deflected by the 45° folding mirror, retroreflected by the hollow corner cube (axial retroreflector), and returned toward the metrology beamsplitter by the 45° folding mirror. The returning signals are combined at the metrology beamsplitter and fall on detectors D and D'. (b) FAM interferometer. A laser signal passes through the spatial filter E and injection beamsplitter F and is divided by the starlight beamsplitter G. The separated beams are reflected from the tertiary mirrors H and H' and secondary mirrors J and J' to fully illuminate the primary mirrors K and K'. The zone plates on the primaries diffract the signal to focal points in the holes in the secondaries and the athermal lenses collimate the diffracted light. Finally, the signals are reflected from the 45° folding mirror, are recombined at the metrology beamsplitter, and fall on detectors L and L'.

or distortion different for the reflected and diffracted light. In collaboration with HDOS, we are investigating new methods for making ZPMs with more uniform diffractive efficiency. Residual variations can be compensated by a mask near the diffractive signal detector. At present, the ZPM test rig is operating in our recently completed 100 ft^3 vacuum chamber.

The FAM technique requires two servos. The error signal from the auxiliary null interferometer (Fig. 3a) is used to shift the metrology beamsplitter so as to maintain a constant difference (of the order of a meter) between the optical paths from the metrology beamsplitter to the two axial retroreflectors inside the fiducial blocks. The error signal from the FAM interferometer (Fig. 3b) is used to shift the starlight beamsplitter so as to maintain a constant difference between the two paths from one beamsplitter to the other (*i.e.*, *via* the two telescopes and their fiducial blocks). With both servos working, there is a small (say under 2 mm) and constant difference between the distances from the starlight beamsplitter to the fiducial points, which are the apices of the axial retroreflectors inside the fiducial blocks. Under the assumption that these servos do not need to track path changes due to vibration, they can have small bandwidths. Since it is desirable to limit the contamination of the starlight by the laser signal (*e.g.*, *via* scattering from the surfaces of the optical elements), a minimum of laser light is used in the FAM servo and it is therefore the slower of the two. The fiducial blocks and the metrology beamsplitter assemblies are made of optically contacted stable material such as ULE (T.M., Corning Glass), and kept at a stabilized temperature. These devices pose the only critical materials problem identified.

At the workshop, the fiducial block was shown as a series of 24 color slides. Here, for practical reasons, we choose to show it as a line drawing, Fig. 4. The four retroreflectors are properly oriented for a POINTS configuration in which the fiducial points of each starlight interferometer lie on a line that passes through the instruments' articulation axis. While this configuration has an aesthetically pleasing symmetry, it has not been shown to offer a significant advantage in terms of control or reducing sensitivity to systematic error. In this computer-generated engineering sketch, there are four retroreflectors positioned such that their apices are coincident at the fiducial point. Only a small part of each cornercube retroreflector is included in the structure and would consist of two subassemblies: one, a flat mirror, and the other, a V-shaped mirror. Figure 5 is an exploded drawing of the fiducial block, showing how each retroreflector would be mounted on a flat plane before the subassemblies were joined together. Our current thinking is that all components will be optically contacted together, although an additional glue bead along the edges may be used to add strength during the early phase of the curing of the optical contact. (The glue may also add to the long-term reliability.) We are continuing to investigate the question of manufacturability for the fiducial blocks.

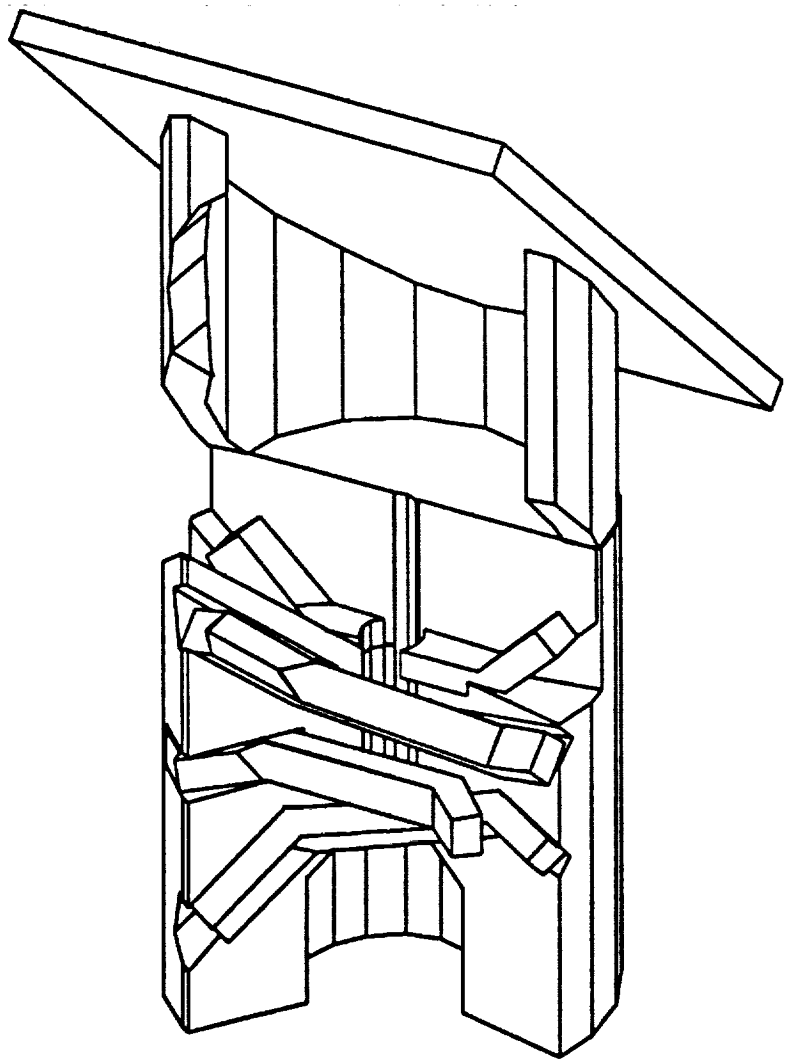

Figure 4. Cutaway view of a fiducial block. There are four "retro-strips," each a slice of a truncated cornercube retroreflector, and each to serve as the end point for a laser gauge. The apices of the cornercubes coincide at the fiducial point in this computer-generated engineering sketch. Although difficult to see in any one figure, there is adequate space between the retro-strips to provide good support. For clarity, each retro-strip is shown here as a U-shaped structure. In an actual fiducial block, the base of the "U" would not be present and the two side pieces would be optically contacted to a supporting plane. The cylinder diameter would be about 10 cm.

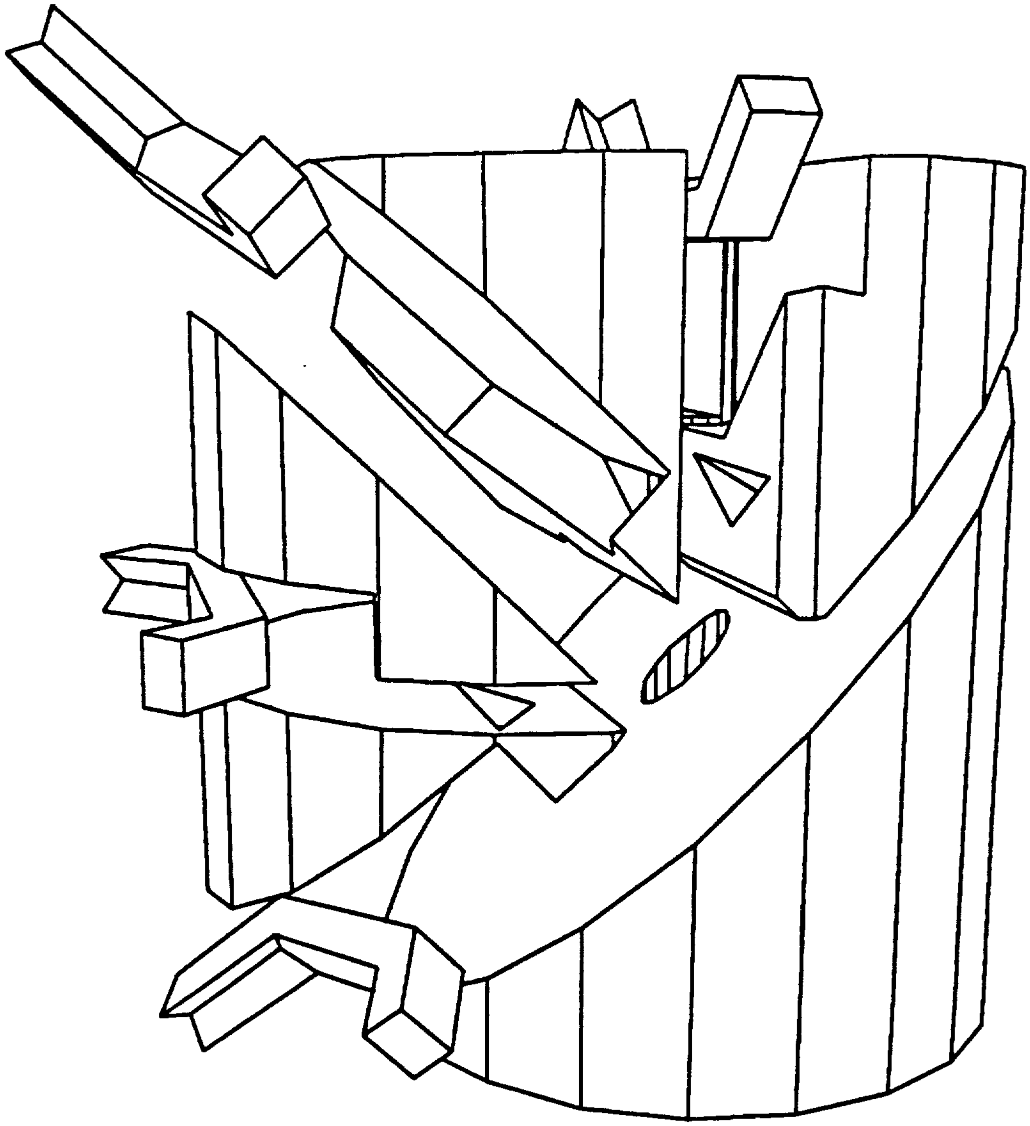

Figure 5. Exploded view of the fiducial block showing subassemblies. The 45° folding mirror is not shown. Each retroreflector would be assembled in two stages: In the first stage, the dihedral block and plane mirror block would be made; In the second stage, the blocks would be mounted on their respective support plates. As in Fig. 4, each retro-strip is shown here as a U-shaped structure. In an actual fiducial block, the base of the "U" would not be present.

The angle φ between the baselines of the two interferometers (*i.e.*, the instrument articulation) is determined by the measurements of the six distances among four fiducial blocks in the system. (See Figure 6.)

$$\cos\varphi = (d_2^2 + d_3^2 - d_1^2 - d_4^2)/2b_m b_f$$

Here d_i are the four distances between the fiducial points of one interferometer and the fiducial points of the other and b_m, b_f are the baseline distances for each interferometer, *i.e.*, each is the separation of the fiducial points of one interferometer. Each of the six distances is measured by a laser gauge. The development of suitable laser gauges is a prime objective of the POINTS technology development effort.

Instrument Operations

Our understanding of the characteristics of the instrument operations is based on a series of covariance studies and other analyses. Since POINTS is a "global astrometric instrument," all observed objects are available to contribute to the stability of the reference frame used for each observation. Each object that contributes to the reference frame stability can be studied astrometrically and its motions modeled. A small number of observations of quasars will connect the POINTS reference frame to the best

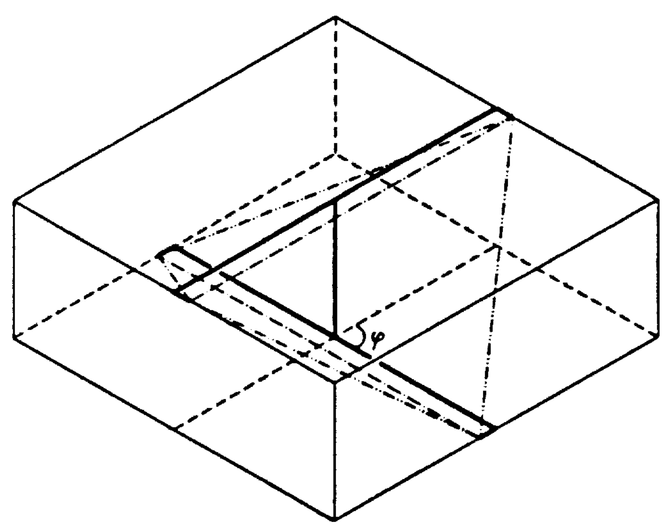

Figure 6. The angle φ is determined by measuring the six distances (b_i, dash-dot; d_i, dash-dot-dot) among the four fiducial blocks.

available candidate for an inertial frame. For any target, there is always a large number of bright (*e.g.*, mag 10) reference stars available so that observing time is not significantly increased by the reference-star photon rate.

When an observation set has sufficient redundancy, it can be analyzed to yield a rigid frame; it serves to determine the angular separation of all pairs of observed stars, even those that were not observed simultaneously. The redundancy is measured by M, the ratio of the number of observations to the number of stars observed. With moderate redundancy, M = 4.2, the uncertainty in the separation of any star pair is about equal (on average) to the instrument measurement uncertainty. The grid is essentially free of regional biases and will be further strengthened by additional data obtained when the grid stars are used as reference stars for additional science targets.

If we use 300 grid stars plus a few quasars and take M = 5, then the observation series requires about four weeks at the nominal rate of 60 observations per day. Such a series could be repeated four times a year to provide not only coordinates but proper motions and parallaxes for the stars. Our Monte Carlo covariance studies show that after ten years the coordinate uncertainties are ~0.6 μas, the proper motion uncertainties are ~0.4 μas per year, and the parallax uncertainties are ~0.4 μas (Reasenberg, 1986). Note that this parallax determination is a factor of 2 better than one would naively calculate from the coordinate uncertainties in a single series. The reason for this enhancement is that the 90° nominal angle of POINTS results in direct observations of absolute parallax. (See Appendix)

In other Monte Carlo covariance studies, we investigated the ten-year observing sequence with fewer observations. Based on this study, it appears that if at least one of the four-week observing series is complete (*i.e.*, M = 4.2), then observations can be deleted from the other series by a variety of random or systematic procedures yielding an increase in the mean parameter-estimate uncertainty which depends only on the square root of the total number of observations. Further, additional stars can be added to the observation sequence with a minimal number of observations (perhaps 20) per star. Thus, if the instrument were run full-time on a ten-year star survey, which included the above 300 star (M=5) quarterly observations, the survey could comfortably encompass 8000 stars in addition to the 300 grid stars, and would result in the knowledge of the positions, annual proper motions, and parallaxes of the 8000 stars at the 2 μas level. Independent of the target selection and scheduling, aberration would insure that the stellar grid would be connected to the Earth ephemeris frame with an uncertainty under a milli-arcsecond.

Appendix: Absolute Parallax

The traditional approach to measuring a trigonometric parallax π depends on narrow-field measurements with respect to a "zero parallax object," *i.e.*, an object (such as a QSO) so distant that its parallax is small compared to the angle measurement error. From the Earth's surface, this is the only reasonable approach since the best astrometric accuracy, which is essential for stellar parallax determinations, is obtained in a narrow field. In space, in the absence of atmospheric corruption, global astrometry becomes possible. Here we consider how this leads to absolute parallax, and thus liberation from the use of zero parallax objects.

We consider a right orthogonal frame with the ecliptic in the x-y plane and neglect proper motions, spacecraft motion with respect to Earth, and the eccentricity of Earth's orbit. Then the location of the observing spacecraft is r_s

$$r_s = a(\cos\phi,\ \sin\phi,\ 0) \tag{A1}$$

where a is the semi-major axis of Earth's orbit. Let there be a pair of observed stars. Their locations, in spherical coordinates $(d,\ \beta,\ \alpha)$ are given by

$$r_i = d_i(\cos\alpha_i\ \cos\beta_i,\ \sin\alpha_i\ \cos\beta_i,\ \sin\beta_i) \tag{A2}$$

where we further define a parallax:

$$\pi_i = a/d_i \tag{A3}$$

In the absence of parallax, the angle between the stars would be θ_o, where

$$\cos\theta_o = \hat{r}_1 \cdot \hat{r}_2 \tag{A4}$$

Including the effect of parallax, the measured stellar separation is θ, where

$$\cos\theta = (r_1 - r_s)\cdot(r_2 - r_s)/|r_1 - r_s|\ |r_2 - r_s| \tag{A5}$$

If we expand Equ. A5 and neglect terms of order π^2, then we obtain

$$\begin{aligned}\cos\theta = \cos\theta_o &+ \pi_1(\hat{r}_1\cdot\hat{r}_s\cos\theta_o - \hat{r}_2\cdot\hat{r}_s)\\ &+ \pi_2(\hat{r}_2\cdot\hat{r}_s\cos\theta_o - \hat{r}_1\cdot\hat{r}_s)\end{aligned} \tag{A6}$$

For POINTS observations, $\theta_o \approx 90^\circ$, which leads to some simplifications. Let $\theta = \theta_o + P$ and expand cos θ using $\sin\theta_o = 1$ and P small:

$$\cos\theta = \cos\theta_o - P \tag{A7}$$

Then, to a reasonable approximation, and for purposes of understanding the method by which absolute parallax becomes available, we obtain

$$P = \pi_1 \hat{r}_2 \cdot \hat{r}_s + \pi_2 \hat{r}_1 \cdot \hat{r}_s \tag{A8}$$

As one can see from Equ. A8, the two components of P will each vary sinusoidally with a one year period. Since the amplitude and phase of the coefficients of π_1 and π_2 are known, π_1 and π_2 can be determined from a set of measurements of P, except in the degenerate case that the stars lie on a great circle passing through the ecliptic pole. (It is also possible to make the problem degenerate by a bad choice of observing times: always at the same two solar longitudes that differ by 180°.) At first, this appears to suggest that one cannot determine the parallax of stars near the ecliptic pole since they will always be part of a pair that lies on a great circle (nearly) through the pole. However, (1) the parallax of the near-ecliptic reference star would easily be determined in conjunction with another near-ecliptic star, and (2) for an ecliptic reference star there is no poleward component of the parallax signature to be confused with the corresponding component of the motion of the near-polar target star. In general, for any set of three stars for which all three pairs are about at 90° separation on the sky, there is no degeneracy of the kind discussed above, independent of the placement of the set on the sky.

Acknowledgements

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