POINTS: A GLOBAL REFERENCE FRAME OPPORTUNITY

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ABSTRACT. POINTS is a space-based optical astrometric interferometer, capable of measuring the angular separation of two stars about 90° apart with 5-microarcsec (μas) nominal accuracy. During the intended ten-year mission, a repeated survey of a few hundred targets over the whole sky, including a few bright quasars, will establish a "rigid" reference grid with 0.5 μas position uncertainties. At that level, the grid will be free of regional biases and tied to the extra-Galactic frame that is our present best candidate for an inertial frame. POINTS will also determine parallaxes and annual proper motions at about the same level. Further, the planetary ephemeris frame will be tied through stellar aberration to the grid at about 300 μas. Additional targets of interest, to a limiting magnitude of greater than 20, will be observed relative to the grid, yielding determinations with uncertainties depending on the observing schedule. Measurement at the microarcsec/year level of the apparent relative velocities of quasars that are widely separated on the sky will severely test the assumption of cosmological quasar distances and may also constrain models of the early Universe.

1. Introduction

We consider a large-bandwidth optical astrometric interferometer to be operated in space. This interferometer (dubbed POINTS for Precision Optical INTerferometer in Space) would measure the angular separation of stars separated by about 90° on the sky with a nominal measurement accuracy of 5 microarcseconds (μas). The key to obtaining such accuracy is the use of stable materials in a thermally controlled environment, real-time metrology of critical instrument dimensions, and closure information from the astrometric data. We estimate the instrument would measure daily about 60 pairs of stars; a random set of such measurements, if suitably redundant, contains the closure information necessary to detect and correct time-dependent measurement biases to well below the nominal measurement accuracy. The 90° target separation yields direct observation of absolute parallax; we do not encounter the problem of finding zero-parallax reference stars which would be severe at the microarcsecond level.

The nominal limiting magnitude, m = 17, assumes moderate control of unmodeled changes in the instrument's angular acceleration. However, techniques exist for extending the range fainter by several magnitudes. The wide magnitude range permits an observing schedule that includes both bright stars and quasars. We have found that roughly one third of the observing time in a ten-year mission would allow the determination of relative positions, parallaxes, and annual proper motions below the 1-μas level for a set of several hundred reference objects. These well-observed stars and

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quasars would form a "rigid frame" and would serve as references for all additional target stars, as well as being targets of primary scientific interest. Because of the quasars in the observation set, all POINTS observations would be in a frame which is the best available realization of an inertial system. The remaining two-thirds of the observing time would be available for a wide variety of scientific applications.

The European astrometric instrument HIPPARCOS has ushered in the age of space astrometry. Initial progress reports for this survey instrument, including discussions of possible follow-on missions, appear elsewhere in this volume. POINTS is the natural interferometric descendant of HIPPARCOS: both combine stars from well separated fields in a single measurement; both use 360° closure for self-calibration; both yield a global star map that gains rigidity from a truss-like measurement schedule.

It is now widely recognized that interferometric instruments will play a major role in many aspects of space-based optical astronomy. (See, for example: Proceedings of the Workshop on High Angular Resolution Optical Interferometry from Space, Baltimore, June 1984, *BAAS* **16**, 1984; Proceedings of the Colloquium on Kilometric Optical Arrays in Space, Cargèse, October 1984, ESA SP-226, 1985; Report of the Workshop on Imaging Interferometry in Space, Cambridge, October 1985, distributed by Battelle, 1987.) Results of major importance will come from imaging interferometers with higher resolution and more light-gathering power than the Hubble Space Telescope (HST). However, such instruments must be large to achieve their advantage over existing ones. POINTS, which is small, could open new areas of astrophysical research and change the nature of the questions being asked in some old areas. It could be the first of a new class of powerful instruments in space and could prove the technology for the larger members of that class to follow.

In Section 2, we discuss briefly the design of POINTS. In Section 3, we discuss the operation of a POINTS mission. In Section 4, we consider the data analysis task for POINTS, and in Section 5, we discuss some of the expected results from a POINTS mission, with emphasis on the reference-frame aspects.

2. Instrument design

The POINTS instrument consists of two starlight interferometers mounted at a nearly right angle and a metrology system. The instrument determines the angular separation between two widely separated stars by measuring the (adjustable) angle between the interferometers and, independently, the offsets of the target stars from their respective interferometer axes. With proper selection of target stars and only a small adjustment capability in the interferometer angle, both members of a target pair of stars can be simultaneously within one second of arc of their respective interferometer axes. Consequently, off-axis distortions and the attendant biases are essentially eliminated. Central to the instrument architecture is the real-time monitoring of the angle between the interferometers and the metrology along the starlight optical path, each of which uses a laser interferometer scheme based on currently available technology.

Figure 1 shows an artist's rendition of the preliminary design for POINTS mounted on the Multimission Modular Spacecraft; Figure 2 shows a rendition of POINTS mounted as a Space Station Attached Payload. Each interferometer has a 2-m baseline separating two afocal telescopes,

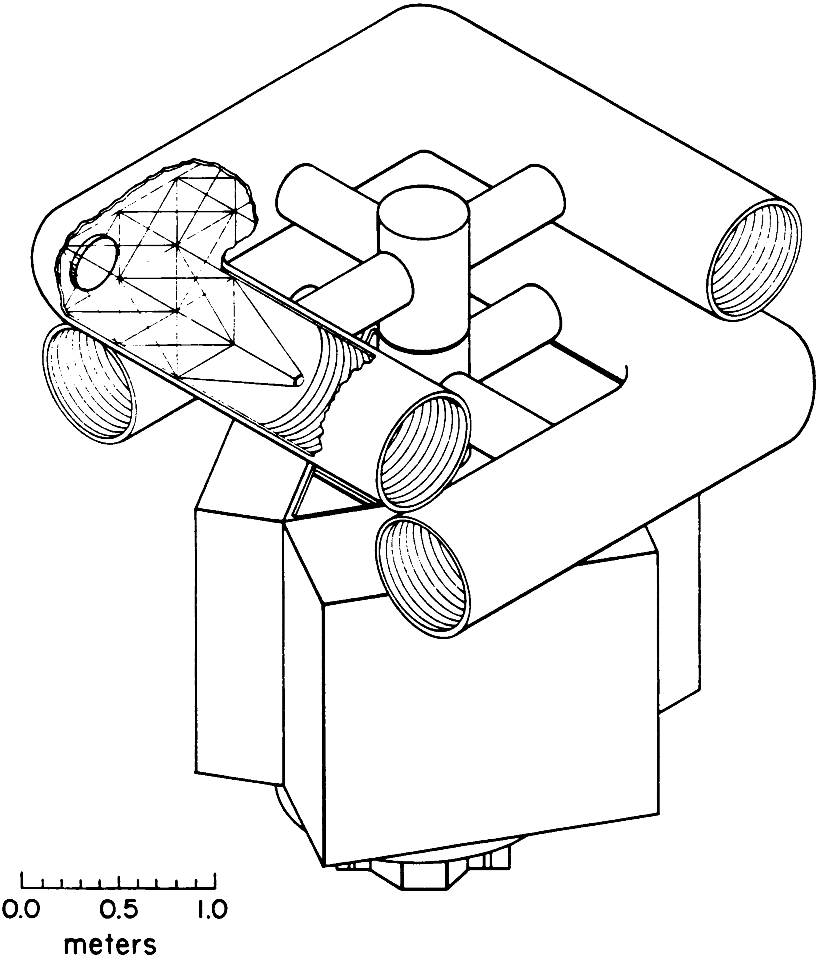

Figure 1. An artist's rendition of POINTS with 2-m separations between pairs of telescopes 25 cm in diameter. The instrument, shown mounted on the Multimission Modular Spacecraft, comprises two U-shaped interferometers joined by a bearing that permits the angle between the principal axes of the interferometer to vary by up to a few degrees from its nominal value of 90°.

each with a primary mirror 25 cm in diameter. The axes of the interferometers are separated by a roughly 90° angle adjustable within an articulation half-range presently estimated to be 3°. In each of the two interferometers, the afocal telescopes collect samples of the starlight and direct them toward fringe-forming and detecting assembly (not shown in either figure). After the compressed samples are mixed by a beamsplitter, the light is dispersed and focused to form a channeled spectrum, from which the astrometric information is extracted.

The determination of the interferometer angle is accomplished with an internal laser metrology system. For a 2-m baseline, the nominal 5-μas uncertainty corresponds to a displacement of one end of the interferometer by 50 picometer (pm). Since similar displacements of internal optical elements are also important, the instrument requires real-time metrology of the entire starlight optical path at the few pm level. This metrology does not pose an overwhelming problem because the accuracy need be achieved only after 100 sec and because a bias in the measurement is acceptable as long as it changes slowly on a time scale of hours, as discussed in the next section.

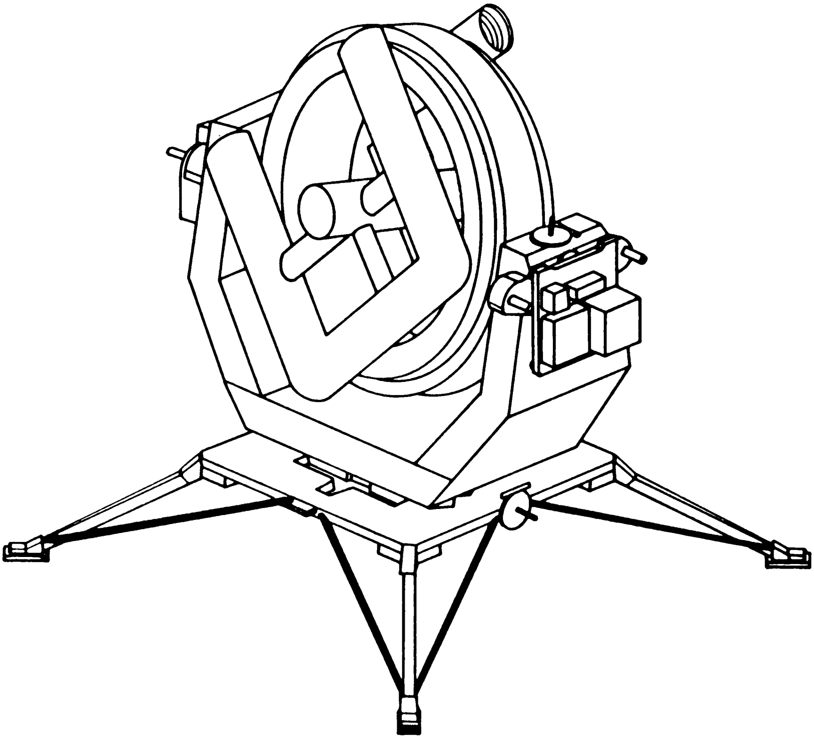

Figure 2. An artist's rendition of POINTS with the same specifications as in Figure 1, but mounted as an Attached Payload on Space Station. The attachment uses the Payload Pointing System (PPS) for coarse pointing. Fine pointing and vibration isolation are both provided by a magnetic suspension, which is shown as a ring mounted inside the PPS and holding POINTS.

3. Instrument operation

Our understanding of the characteristics of POINTS' operation is based on a series of covariance studies and other analyses. We have investigated several patterns for the distribution of target stars on the sky, including uniform Monte Carlo distributions, and have found no fundamental advantages for any particular pattern. We have, therefore, conducted most of the covariance studies with sets of uniformly distributed Monte Carlo stars.

Since POINTS would be a global instrument, it is natural to consider a global reference frame as the basis for interrelating POINTS observations. See Kovalevsky (1984) for a discussion of astrometric instruments in space and definitions of types of astrometry. This global approach, which is in sharp contrast to the use of local frames defined for classical small-field astrometric instruments, provides significant advantages. All observed objects, not just the stars of our primary reference grid, are potentially 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 modelled.

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 degree of redundancy is well characterized by M, the ratio of the number of observations to the number of stars observed. In a series of Monte Carlo covariance studies, we found that the minimum redundancy necessary for a rigid frame is about $M = 3.5$. 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. A solidly redundant observing schedule for 300 stars and 5 quasars (1500 star-star observations and 250 star-quasar observations to provide extra redundancy to compensate the quasar's higher magnitude), in which a roughly 30-day observation sequence would be repeated four times per year for ten years, would yield mean stellar parameter uncertainties of 0.6 μas in position, 0.4 μas/y in proper motion, and 0.4 μas in parallax (Reasenberg, 1986). Note that the parallax determination to 0.4 μas is better by nearly a factor of two than one would naively calculate from the coordinate uncertainties in a single series. The enhancement reflects POINTS' direct parallax observation. The star grid is free of regional biases by virtue of the global astrometry that determines it.

In other Monte Carlo covariance studies, we investigated the ten-year observing sequence mentioned above, but with fewer observations. From this study, it appears that if at least one of the observing series is complete (*i.e.*, $M \geq 3.5$), 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 (perhaps 20) of observations per star. Thus, if the instrument were run full-time on a ten-year star survey, the survey could comfortably include 7000 stars and would result in the knowledge of their positions, annual proper motions, and parallaxes 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 a 300-μas uncertainty.

Our studies have also showed that the 90° nominal interferometer angle is not crucial to the design of the instrument, but it minimizes the required articulation range. For POINTS to have plenty of reference stars available for each target, the product of the articulation range and the sine of the nominal angle should be as large as possible, since that product is proportional to the solid angle from which reference stars may be selected.

The metrology system mentioned in the previous section contains finite-size optical components, each of which will introduce a bias into the measurement of the interferometer angle. This bias will, of course, be time dependent at the microarcsec level. It is essential that we be able to determine and correct for the instrument bias, preferably without the introduction of additional hardware. The required determination and correction both naturally occur when the observations are combined in a least-squares estimate of the individual stellar coordinates (including proper motion and parallax), instrument model parameters, and the expected biases. In particular, our covariance studies have shown that even without the introduction of a special observing sequence, it is possible to estimate simultaneously the stellar coordinates and several instrument bias parameters per day without significantly degrading the stellar coordinate estimates. Thus, metrology biases and related errors can be allowed to change on a time scale of hours without significantly degrading the performance of the instrument.

This kind of calibration, which uses the astrometric data, extends even to the determination of the lengths of the interferometer baselines, which serve as the scale factors in relating fringe phases to angular offsets of the target stars from their respective axes. Observing the same pair of stars with successively different articulation angles allows the scale factors to be determined along with the total separation angle between the stars. The observation time scale of a few minutes largely decouples the baseline calibration from the rest of the data analysis, which must remove the effects of long-term drifts in the instrument.

Our performance analyses assume the target to be an isolated, unresolved point source, *i.e.*, one with no significant structure. In practice, this condition will not always be met. Star spots, flares, and the like will set a limit to the astrometric usefulness of the measurements of some targets. Of course, we may learn useful things about some stars from the motions of their centers of light. At 100 pc, the Sun has a magnitude of 10. A shift of the center of light by 1% of its diameter at this distance would cause an apparent astrometric shift of nearly 1 μas. Many of the targets are expected to be less than 20 pc away.

4. Data Analysis

Although the mission will support a large and diverse set of science objectives (Reasenberg *et al.*, 1988a), we picture the first stage of the data analysis as being done centrally because of the synergistic nature of the data: one investigator's target is everybody's reference star. The amount of effort required would depend on the degree to which we need to use spacecraft engineering data to elucidate systematic errors. In any case, it would not be a complex effort nor would it require special computing facilities. If the data were available today, the analysis could be done, for example, on a "super minicomputer" as a time-shared job or even on one of the high-power personal work stations now available. The software needed would be similar to that already in use for POINTS sensitivity studies, but with the more detailed instrument models that will be possible after we have a working instrument. The required algorithms are those of standard weighted least-squares parameter estimation and error analysis. Those algorithms and the equations of condition relating the measurements to the adjustable parameters are, of course, embodied in the existing software.

Early in the mission, the analysis would be limited to positions determined during observing periods of a few days to a month. Of course, the best *a priori* proper motions and parallaxes would be included in the analysis model, although these would have little effect. At about one half year, it would first become possible to estimate the full set of five parameters (two position, two proper motion, and one parallax) for each star. The stability of the solution should increase considerably during the following year. Because of this progressive refinement of the parameter set, the POINTS reference frame would, in effect, be available for experiments from the very beginning of the mission, despite the fact that the "final" reduction of data already taken would be delayed while the reference grid stabilized. Among the classes of early science from the mission would be a determination of the RR Lyrae and Cepheid distance scales, a study of the spiral arms of the Galaxy, a determination of the mass and mass distribution of the Galaxy from observations of the Magellanic clouds and of clusters, respectively, and a determination of stellar masses by parallax measurements of visual binaries.

After about two years of observation, the postfit residuals from the data reduction would be used to investigate irregularities in the motions of individual stars. These apparent motions would be analyzed both for their intrinsic scientific interest and to improve the stability of the resulting reference frame. At first, the position of each star would be determined with respect to the mean of the positions of all the stars. After the initial modeling of the irregularities in stellar proper motions, the position of each star would be determined with respect to the nominal modeled reference positions of all the stars. This iterative procedure is expected to converge quickly as long as the number of stars in the reference grid is large enough (*i.e.*, greater than 100).

One of the possible irregularities in stellar positions is the astrometric "wobble" due to planets orbiting the target stars. A series of numerical experiments has shown that suitably large planets could be detected through their astrometric signatures as seen by POINTS. These experiments involved a set of 100 nearby target stars, and in each experiment a subset of stars were chosen (blindly) at random to have a single planet each. The planet masses and orbital elements were all assigned with Monte Carlo distributions. Using the iterative procedure just described, planet-like signatures were sought in the Monte Carlo measurement noise over a ten-year simulated mission, and planet signatures with amplitudes above the noise level were invariably detected; this threshold is equivalent to 1% of the Sun's motion due to Jupiter as seen at a distance of 10 pc.

5. Applications

In this section, we discuss some of the scientific results that could be obtained from POINTS. They depend on the high astrometric accuracy and, in some cases, on the wide target separation that POINTS would provide. A brief list includes (a) a distance scale based on direct parallax determinations for a large number of Cepheids; (b) a determination of the masses of stars in binary systems and those close enough to apply the method of perspective acceleration; (c) parallax measurements yielding both absolute stellar magnitudes and, in conjunction with mass estimates and other data, a sharpened mass-color-luminosity relation; (d) a vastly improved global reference frame and a tie to existing ones; (e) the study of the mass distribution in the Galaxy; (f) a strictly geometric (*i.e.*, coordinate and parallax) determination of the membership of star clusters, especially useful in the case of "peculiar" stars; (g) a bound on or a measurement of quasar proper motions; (h) a light-deflection test of general relativity (Reasenberg *et al.*, 1988b); and (i) a search for other planetary systems.

No attempt has yet been made to develop a scientifically balanced allocation of the instrument observing time. The time required to perform all of the indicated studies far exceeds the time that would be available with a single ten-year mission. Further, additional uses are likely to be suggested when it becomes widely known that POINTS-type data will be available.

In any case, it is clear that, in one way or another, all the results hinge on the ability of a POINTS Mission to realize its goal of establishing a global reference frame. Defining a reference frame based on POINTS measurements requires that we select coordinate axes. Traditionally, these axes correspond to the mean equator and equinox of the Earth at some epoch, which seems a reasonable basis for a frame derived from observations from Earth's surface. However, POINTS represents a non-traditional approach to astrometry, freed from Earth's spin vector; the choice of axes can be made arbitrarily. For example, the coordinates and proper motions of all the reference stars could be tied by weak constraints to the values from a traditional catalog so that the ensemble of reference stars provides the link to classical optical catalogs. Similarly, the coordinates of the reference quasars could be tied by such constraints to the values from a radio-source catalog. Alternatively, three star coordinates, such as the right ascension and declination of one star and the position angle of a second star relative to the first, could be given defined values.

The new FK5 catalog, which is now the best of its type available, is characterized by statistical position errors of order 10 milliarcsec (mas) at the mean epoch of about 1940; errors in the proper motions are about 1 mas/y (Fricke *et al.*, 1988). Thus, the contemporary accuracy is ~50 mas. In addition to having these statistical errors, such catalogs are known to have systematic zonal effects resulting from instrumental flexures, the atmosphere, and the use of a variety of different instruments covering separate parts of the sky. These kinds of errors are discussed, for example, by Podobed (1965), and more theoretically by Eichhorn (1974). The most promising near-term effort to address the question of reference frames based upon quasars is the envisioned cooperative program involving HIPPARCOS, the Very Large Array (VLA), and the HST. HIPPARCOS is expected to produce a rigid framework of star positions requiring adjustments both to orient the system and to remove residual rotation rate. These adjustments are to be provided by VLA observations of radio stars observed optically by HIPPARCOS, and also by measurements of the relative separations of quasars and HIPPARCOS stars by HST.

Unfortunately, the expected HIPPARCOS proper-motion errors are as large as 3 mas/y because of the short time base of the observations and will be greater if the mission is cut short. These errors will degrade the HIPPARCOS catalog to the current level of the FK5 in an astrometrically brief period of under two decades. More important, this degradation will continue, making the HIPPARCOS catalog inferior to the FK5. The solution to this problem could be a second HIPPARCOS mission, as advocated by some members of the HIPPARCOS Team. POINTS would provide an independent check on the systematic errors of the HIPPARCOS catalog, including an immediate extragalactic link. The direct referral of star positions to an extragalactic reference by POINTS would furnish an extremely accurate grid of optical sources over a wide magnitude range, thus providing a practical approach to extending this reference to other objects. The use of a small POINTS catalog to enhance the much larger HIPPARCOS catalog needs to be investigated.

The radio and optical reference frames may be related by objects which emit detectable radiation in both spectral regions. There are discrepancies at the 0.3-arcsec level in the northern hemisphere between the FK4 optical reference frame and the radio reference frame (Johnston *et al.*, 1985). These discrepancies are believed to be due to systematic errors in the optical frame. In the southern hemisphere, the optical frame is significantly less accurate than in the northern hemisphere. POINTS would establish an optical reference frame free of such systematic errors and accurate to a few μas over the entire celestial sphere, as well as tied to the radio frame by redundant observations of bright extragalactic radio sources.

There is a limited number of known compact optical extragalactic sources showing radio emission. See Table 1 for a list of 36 quasars and BL Lac objects of magnitude 15.5 or brighter, extracted primarily from Veron-Cetty and Veron (1987) and first presented in this form by Reasenberg *et al.* (1988a). Instruments such as the VLA and the HST will extend this number to more than 100. The radio reference frame should be accurate to approximately 0.1 mas. POINTS' optical positions of radio objects would relate the optical and radio reference frames to the accuracy of the radio positional measurements or to the extent that the radio and optical emission are coincident. The POINTS reference frame could be used to help in finding and removing systematic errors in the radio reference frame so that the reference frames may be related on a submilliarcsecond scale. This data set could also be used to examine the coincidence of the radio and optical emission at the milliarcsecond level in the reference objects.

In addition, POINTS could tie its new reference frame to the existing one of the planetary ephemerides. At present, the latter rests primarily on spacecraft Doppler and range tracking and Lunar laser ranging data, which are all measures of distances or line-of-sight velocities, but which, by the application of planetary dynamics, allow the construction of a geometric framework with angular consistency comparable to the relative uncertainties of the distances. The uncertainty in the planetary reference frame depends upon the object and the epoch chosen, but a typical value is 1 mas. A knowledge of the Earth ephemeris is, in fact, necessary for taking into account the effect of stellar aberration. Indeed, Earth orbital parameters would be included in the parameter set for the data analysis, and the results would include a possible refinement of the ephemeris and a tie to the POINTS reference frame at roughly the 300-μas level from the aberration alone. Direct observation of small solar-system bodies with POINTS could provide an additional tie of even higher precision.

In the process of tying its optical reference frame to that of extragalactic radio sources, POINTS would perform an important check on quasar distances. Quasars ought to have motion relative to the local comoving frame comparable to the approximately 100 km/s seen for closer objects. Thus, the cores of quasars ought not to show relative motion if they are at cosmological distances and are not complicated by source structure variations; these hypotheses would be cast into doubt if such motions were to be seen. Recent work at radio frequencies has placed a 20 μas/y bound on the relative motion of the cores of two quasars separated by about 30 arcmin (Bartel *et al.*, 1986). With ten years of observing, POINTS should detect, at several standard deviations, an angular velocity of 5 μas/y for widely separated quasars. If, as generally expected, quasars are at cosmological distances, this angular velocity corresponds to relativistic relative velocities across the primitive universe. Indeed, although there is no consensus on the relevant cosmological deceleration constant, it seems possible that two observable quasars can be found that lie outside each other's event horizons. In the simplest case, two quasars each with a redshift Z=3 separated by 180° would lie just at each other's horizon (Field, 1990).

Table 1. Bright Quasars and BL Lac Objects

Name	*Right Ascension*	*Declination*	*V*	*Radio Flux (6 cm)*
	(1987.5)		*(mag)*	*Jy*
	h m s	° ' "		
III Zw 2	00 09 50.8	+10 54 07	15.4 (S)	0.42
PG0026+12	00 28 34.8	+13 11 56	14.8 (S)	0.002
TON S180	00 56 30.8	–22 26 00	14.4 (S)	
TON S120	01 21 14.7	–28 24 58	14.7	
Fairall 9	01 23 17.1	–58 52 16	13.2 (S)	
PKS0405–12	04 07 13.2	–12 13 34	14.6	1.990
0716+714	07 21 53.4	+71 20 36	13.2 (L)	1.121
1E0754+3928	07 57 09.5	+39 22 30	14.4	
PG0804+761	08 09 23.4	+76 04 56	15.1	
PG0844+349	08 46 55.4	+34 47 52	14.0	
OJ 287	08 54 48.9	+20 06 31	14.5 (L)	2.61
PG0953+415	09 56 06.5	+41 19 15	14.5	
PKS1004+13	10 06 45.9	+12 52 37	15.1	0.420
EX1059+730	11 01 45.7	+72 50 47	14.7	
PG1116+215	11 18 29.0	+21 23 24	15.1 (S)	
4C 29.45	11 58 51.8	+29 19 05	14.4	0.890
PG1211+143	12 13 39.4	+14 07 22	14.6	
Mk 205	12 21 11.6	+75 22 46	14.5	
W COM	12 21 31.7	+28 13 58	15.0 (L)	
3C 273	12 28 28.3	+02 07 17	12.9	43.4
OP–106	13 05 33.0	–10 33 20	15.2	1.28
B2 1308+32	13 09 52.0	+32 24 52	15.2 (L)	1.59
PG1351+640	13 52 53.4	+63 49 25	14.8	
PG1441+442	14 13 18.8	+44 03 43	15.0	
S4 1435+63	14 36 28.5	+63 39 52	15.0	1.240
AP LIB	15 16 55.8	–24 19 27	14.8 (L)	1.94
1519–65	15 21 45.6	–06 41 45	14.9	
PG1634+706	16 34 34.5	+70 33 04	14.9	
4C 39.49	16 53 52.2	+39 45 36	14.0 (L)	1.313
PG1700+518	17 01 07.0	+51 50 26	15.2	
3C 351.0	17 04 31.6	+60 45 31	15.3	1.21
PG1718+48	17 19 17.2	+48 04 59	14.7	
Mk 509	20 23 27.6	–10 47 02	13.2 (S)	0.004
PKS2155–304	21 58 06.9	–30 17 14	13.1 (L)	0.31
BL LAC	22 02 43.3	+42 16 40	14.7 (L)	2.96
4C 31.63	22 03 15.0	+31 45 38	14.5	0.298

Objects above marked with a (L) are BL Lacs, objects marked (S) are Seyfert 1's with bright stellar nuclei, all others are QSO's.

6. Discussion

We have described a small, novel astrometric instrument that could both perform several significant scientific studies and prove technologies which could eventually be useful for larger interferometers, both imaging and astrometric. A preliminary evaluation of the scientific uses of the instrument shows that the observing schedule for a ten-year mission could easily and usefully be filled. In fact, the large number of areas of research that POINTS would strongly impact would surely result in oversubscription of the observing time. Increased scientific throughput is possible by scaling the instrument. Serious problems with the scaling are not encountered for an instrument that fits in the Shuttle bay.

The principal technical challenge posed by POINTS is the control of systematic error. The architecture of the instrument has been developed around this problem, which we address at three levels: the use of highly stable materials and thermal control; real-time laser metrology of critical dimensions; and the correction of biases by means of the closure information content of the raw astrometric data.

POINTS would establish an optical global reference frame of unprecedented precision, tied to the frames of both the planetary ephemeris and extra-Galactic radio sources and free of regional biases at the level of precision. It would permit the evaluation of the radio frame for regional biases and would address the co-location of the centers of light and radio emission for several tens of targets.

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Discussion

BASTIAN: Did you really say that this instrument should be operated mounted on the Space Station? It would constantly be shaken and jolted. No such high-precision work would probably be possible.

CHANDLER: The Space Station is only one of the possible options. The first configuration I showed on the transparencies was a free-flying one. If POINTS is operated as a Space Station Attached Payload, then a major effort will indeed be required to provide both fine pointing and vibration isolation.

HØG: What is the technical level of your study? I ask because I miss a realistic picture of a baffle to limit stray light from the Sun. In fact your drawings do not look different from what you presented in 1984.

CHANDLER: The study is still in an early stage, and many technical details (including the necessary internal and external baffles for shielding the detectors from stray light) remain to be worked out. The primary emphasis of recent work has been in the area of laser metrology and sensitivity studies.

RÉQUIÈME: At the present time we have a lot of problems with the optical structure of radio stars used to link the VLBI and optical reference frames at the level of 10 mas. We also have difficulties with the radio structure of extragalactic sources at the level of 1 mas. How will you select your stars in order to obtain the microsecond accuracy? Are you certain that the optical reference frame obtained with these stars will be coincident with the VLBI extragalactic frame, even at the level of 0.1 mas?

CHANDLER: We will naturally choose sources as compact and as stable as possible, but we cannot assure coincidence of the radio and optical positions at the microarcsecond level. By observing as many radio sources as possible, we can expect to *test* the level of coincidence and to provide a means of calibrating the global consistency of the VLBI reference system.