MICROARCSECOND ASTROMETRIC INTERFEROMETRY

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ABSTRACT. A small astrometric optical interferometer, Mini-POINTS, which would fit fully assembled in about one-third of the Shuttle bay, could measure the angle between stars about 90° apart. For 10^{th} magnitude stars, an observation time of about 20 minutes would yield a measurement uncertainty of 5 microarcseconds. When compared to an astrometric telescope of comparable size which observes the same target for the same period of time, such an interferometer would achieve a greater accuracy by two to three orders of magnitude. Five design criteria lead to an instrument that achieves high precision by employing photon statistics for fringe splitting and achieves high accuracy by means of continuous internal metrology with laser interferometers. The high throughput of Mini-POINTS permits a mission design that addresses a wide variety of scientific questions.

Freed from the distortions of the atmosphere, an optical instrument using currently available technology could achieve microarcsecond (μas) astrometric precision with brief observations of widely separated stellar targets. Such an instrument would have numerous astrophysical applications including a deep search for other planetary systems. In 1974, I. I. Shapiro noted that the classical light deflection experiment of general relativity could be performed to second order in the solar potential by means of an optical astrometric interferometer in space. In response to that idea, the design concepts for Precision Optical INTerferometry in Space (POINTS) were developed. POINTS was intended to perform μas astrometric measurements with observing times of a few minutes.

The more recently designed Mini-POINTS is intended to reach 5 μas astrometric precision with a 20-minute observation of a pair of 10th magnitude stars. In this paper, I start by showing that an astrometric interferometer offers a substantial advantage over an astrometric telescope of comparable size. I then discuss the current criteria for Mini-POINTS and the design that results from their application. Finally, I discuss the astrometric precision and

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accuracy of this instrument and some aspects of a mission that might be flown with it.

Space-based astrometric instruments should achieve a measurement uncertainty far lower than the so-called diffraction limit. Thus, it is convenient to separate that uncertainty into two parts: the "intrinsic precision" S_o and the improvement factor which is determined by both instrument design and photon statistics. In an idealized model of a large class of astrometric instruments, the light is collected and manipulated to pass through two exit ports where detectors may be illuminated by intensities I_1 and I_2. (In some designs, only one port is accessible.) Then we may conveniently define the intrinsic precision by

$$S_o = I_o \left[\frac{\partial\Delta}{\partial\alpha}\Big|_{max}\right]^{-1}$$

where $\Delta = (I_1 - I_2)/2$, $I_o = I_1 + I_2$, and α is an angle of rotation of the instrument. If there are N photons detected during a given interval and if a fraction, f, is seen by one detector, then for N sufficiently large, the corresponding standard deviation of f is

$$\sigma(f) = \left[f(1-f)/N\right]^{1/2} .$$

If the instrument is centered, i.e., $f \sim 0.5$, then

$$\sigma(\alpha) = \frac{I_o}{2\sqrt{N}} \left[\frac{\partial\Delta}{\partial\alpha}\Big|_{max}\right]^{-1} .$$

It is easily shown that for an interferometer $S_o = \lambda/\pi L$ where λ is the wavelength of the detected signal and L is the length of the baseline or telescope separation. The corresponding expression for an astrometric telescope of diameter D is $S_o = \lambda/QD$, where it can be shown that $Q = 8/3\pi \approx 0.85$. The resolution ratio, $R \equiv \sigma(\text{telescope})/\sigma(\text{interferometer})$ provides a useful measure of the advantage of an interferometer over a telescope in astrometric applications. If we compare instruments with equal photon rates, e.g., equal light gathering areas and efficiencies, then $R = 3\pi^2 L/8D \approx 3.7L/D$. We can reduce R to a number if, for example, we require the instruments to be of similar size; if the interferometer baseline is equal to the telescope focal length, then typically $R \approx 50$.

The preceding analysis can be extended to include the instruments' fields of view which determine the expected brightness of the available reference stars and hence the likely photon rates for the reference (Reasenberg 1983, unpublished). This extended analysis considers an ordinary telescope and not a HIPPARCOS-type instrument which has a split field of view and depends on its own smooth rotation to relate the positions of sequentially observed stars. For instruments of comparable size, and with some assumptions about the kinds of observations, an interferometer will yield an astrometric measurement that is 100 to 1000 times more accurate than will an

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astrometric telescope. The price paid for this advantage is greater complexity, as is discussed below.

In the radio domain, the advantage of interferometers (both connected element and very long baseline) over single telescopes has been long established. In the optical domain, the effect of the atmosphere has prevented the advantage from being as significant and hence as widely appreciated. If we are to make good use of the option to observe optically from space, interferometry will become imperative for both imaging and astrometry.

What kind of space-based interferometer should be built first? The resolution of an imaging instrument is determined by the diffraction limit of its aperture. Deconvolution and related techniques cannot, in general, yield substantial improvements, even in the case of a high signal-to-noise ratio. With an astrometric instrument, however, it is possible to split fringes or centroid an image to achieve a resolution far better than the diffraction limit. Thus, if we are limited to instruments that fit fully assembled in the Shuttle bay, an imaging instrument cannot offer as much as an order of magnitude advance beyond the resolution of Space Telescope. Yet an astrometric interferometer can offer a two to three order of magnitude increase in accuracy over HIPPARCOS which should perform comparably to Space Telescope. (Space Telescope is limited to observations of stars separated by no more than 18 arcmin in a field of view that is generally determined by the requirements of other kinds of measurements. Since very little of its time is expected to be available for astrometry, Space Telescope cannot be considered a potentially important astrometric facility.) Thus, the first space-based optical interferometer will probably be a small astrometric instrument, using principally existing technologies. Such an astrometric instrument would not only provide an engineering test bed for later and more ambitious astrometric and imaging devices but would also provide a significant advance in observing capability.

Having considered its advantage, we can now turn our attention to the realization of an astrometric instrument. There are currently five criteria which comprise the basis for the design of Mini-POINTS:

(1) In order to avoid the cost of assembly and alignment in space, as well as the associated complexity, the first instrument to be built and flown should fit fully assembled and aligned in the bay of the Space Shuttle.

(2) The instrument should be capable of measuring the angular separation between a pair of stars that are widely separated in the sky. This criterion is essential for the achievement of the relativity objective and also valuable for the determination of absolute parallaxes; it enhances the number of reference stars available for a given target star and thus increases both mission flexibility and, on average, measurement speed. With a nominal

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instrument angle of 90°, the number of reference stars is maximized; a set of four measurements can provide 360° closure and thus determine the angle measurement bias.

(3) For a given target, the instrument should have high "throughput," $T = \rho/\sigma^2$, where ρ is the observation rate, the number of observations per unit time, and σ is the standard deviation of the astrometric measurement. Note that, given the target, T is independent of σ over a large range of observation rates for instruments that are limited either by photon statistics or by white measurement noise on incoherent data. Additionally, the instrument should function well with stars as bright as $m = 5$ in order to be able to take advantage of the higher measurement rate possible with a bright star. High throughput implies that the optical bandwidth should be made large. A large bandwidth would also make the instrument usable with a wide variety of targets.

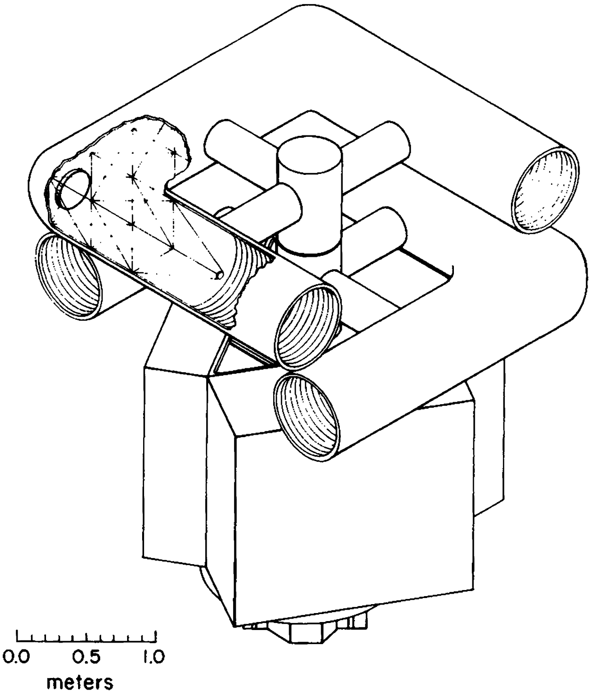

Figure 1. An artist's rendition of a Mini-POINTS with 2 m separations between pairs of 25 cm telescopes. The instrument comprises two U-shaped interferometers joined by a bearing which permits φ, the angle between the principal axes of the interferometers, to vary from its nominal of 90 deg. The Multimission Modular Spacecraft is shown mounted under the instrument.

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(4) The instrument should be relatively insensitive to pointing error and it should achieve this tolerance without the need for high-precision moving parts within the instrumentation. The importance of this criterion is supported by the recent history of the development of Space Telescope.

(5) The instrument should have a life of at least three years, and preferably more than ten years. Since scientific results would come from measuring changes in the apparent positions of targets, long life is essential. The high throughput and measurement accuracy, however, make it possible for Mini-POINTS to do useful science on a time scale short compared to that usually required for astrometric studies. Further, even a short mission would establish benchmarks that would be useful in the analysis of data from a later implemented instrument.

Figure 1 shows an artist's rendition of the current Mini-POINTS design. Two U-shaped optical interferometers are shown mounted above the Multimission Modular Spacecraft (MMS) which could be used to provide telecommunications, conditioned power, and attitude control for the spacecraft. The MMS could also house the control, preanalysis, and sequencing computer. The outer shield of the upper interferometer is shown cutaway, revealing one of the two primary mirrors and its secondary. A rotating joint between the two interferometers allows the angular separation φ between their principal directions to be varied by a few degrees with respect to the nominal 90° separation. In this design, the primary mirrors are 25 cm in diameter and are separated by 2 m.

Figure 2 shows some aspects of the optical design. A pair of afocal telescopes collects samples of the starlight and directs them toward the fringe forming and detecting assembly. In the latter, a beam splitter combines the two signals. At the exit ports of the beam splitter, the light is dispersed and focused onto a pair of linear arrays of detectors. When the instrument's principal axis is aligned with the apparent direction to the star, the signal at a given wavelength has equal intensity at the two beam-splitter exit ports. With misalignment, constructive interference for a given wavelength at one port is complemented by destructive interference at the other port. At each port, an alternating pattern of constructive and destructive interference is found. The resulting complementary channelled spectra, which are detected by the linear arrays, form the basis for determining δ, the angular separation between the apparent direction to the star and the principal axis of the interferometer. If each detector array had 1024 elements and the optical band pass were from 0.2 to 1.0 μ, then the fringes on the arrays would reach the Nyquist limit at $|\delta| = \delta_N = 13$ arcsec. At $\delta = 0.5\,\delta_N$, the fringe visibility is 0.97; at $\delta = \delta_N$, 0.90; at $\delta = 1.5\,\delta_N$, 0.78; and at $\delta = 2\,\delta_N$, zero. Thus, in principle, the instrument can continue to gather information at a useful rate even when $|\delta|$ is greater than δ_N. In practice, it would not likely be necessary to permit nearly so large a pointing error.

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The angular measuring precision of such an interferometer is easily calculated if a few simplifying assumptions are accepted. Initially, we assume that the precision is controlled by photon statistics, that the targets are black bodies, and that the optical bandwidth is unrestricted. Then it can be shown that (Reasenberg 1978, unpublished)

$$\frac{\sigma(\delta)}{5\mu as} = \frac{10^{(m_b-10)/5}}{\left[\frac{\tau}{470\ \mathrm{sec}}\ \frac{T}{7000K}\ \frac{\eta}{0.02}\right]^{1/2}\frac{D}{25\mathrm{cm}}\ \frac{L}{2\mathrm{m}}}$$

where $\sigma(\delta)$ is the measurement uncertainty of one interferometer, m_b is the bolometric magnitude of the target, τ is the observation time, T is the temperature of the target, and η is the optical efficiency of the interferometer. For Mini-POINTS, the estimated angular separation θ between the pair of observed stars is the sum of three components, $\theta = \delta_1 + \delta_2 + \varphi$ (see below); the error budget must be shared among the two interferometers and the metrology system. However, since the system is expected to work effectively for stars as bright as m = 5, the contribution from the metrology system should be negligible for the present case; the required observation time is about 16 minutes. If the unrestricted optical band pass is replaced by a finite one, the required observation time is increased. For a 7000K star, an optical band pass from 0.2 to 1.0 μ increases the required observation time by a factor of 1.1; at 4000K and 12500K the factor is 1.5. If we include the effect of a reasonably limited optical band pass and time for rotating the instrument and acquiring the targets, then a plausible average measurement rate is about 60 per day for $m_b = 10$ and $\sigma(\theta) = 5\mu as$.

The offsets, δ_1 and δ_2, are determined by the individual interferometers as discussed above. The separation φ between the interferometer optical axes must be determined by internal systems using laser metrology. These metrology systems are of three kinds. In the first, a null interferometer drives a servo which maintains constant separation between a pair of reference points. The second is a modification of the first. Provision is made to allow the separation between the reference points to be varied episodically by an integer multiple of one half of the laser wavelength. Such a system will be used to control the rotation of one interferometer with respect to the other. The third, and by far the most complicated kind of metrology system, is used to determine the average surface positions of extended optical elements.

A scheme for the "full-aperture metrology" to determine the positions of extended elements is shown in Figure 3. The metrology light source A injects a signal through mirror B into the primary beam splitter and backward through the optical trains of the two telescopes. Upon reflection from a telescope primary mirror, most of the signal is sent as a collimated beam toward the target star. On the surface of each primary mirror, however, there is a low contrast

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zone plate which diffracts a small fraction of the metrology signal (say 1%) and causes it to come to a focus at the focal point of the metrology subreflector C (or C′). The signals are sent from these subreflectors to the metrology beam splitter D where the interference fringes are detected. An additional null interferometer, not shown in the figure, is used to maintain the constancy of the path length difference between DC and DC′. Although the metrology signal travels backward through the optical train with respect to the starlight, one expects that there will be sufficient scattering to cause strong laser signals at the starlight detectors. Because of the narrow-band nature of this interference, it will be easily identified and disregarded.

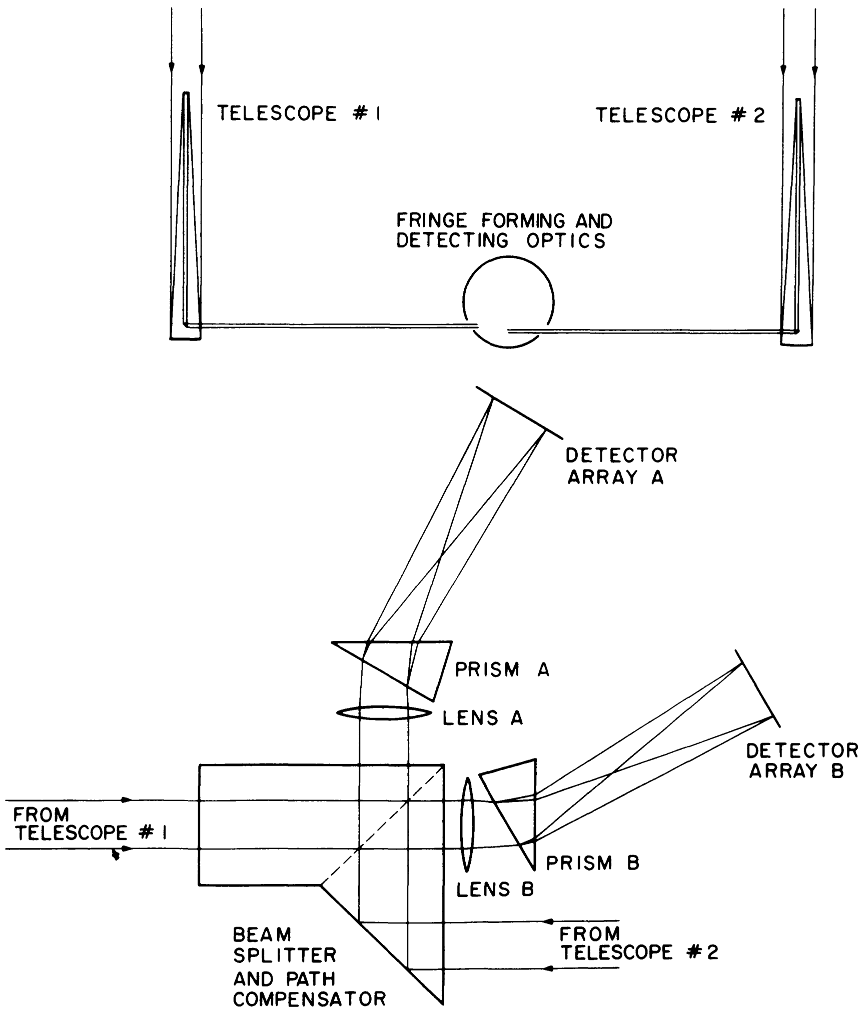

Figure 2. Optical design. Top: general scheme. Bottom: fringe forming and detecting optics.

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The full-aperture metrology allows a pair of small optical components "fiducial blocks" to be held by a closed-loop servo on a perpendicular to the interferometer's axis. Point-to-point interferometers are used to position two additional fiducial blocks near the principal mirrors so as to complete a square. The fiducial-block squares of the two stellar interferometers are aligned as parallel planes separated in a direction perpendicular to the plane. The rotation of one stellar interferometer with respect to the other is determined by additional laser interferometers that measure the distance along the sides of the fiducial block squares between one stellar interferometer and the other.

Although the above described metrology system is capable of providing the required precision, it contains many finite-size optical components, each of which will introduce a bias into the measurement of the angle φ. The bias in φ will have to be determined by independent means, as discussed below. A more serious problem is the possible temporal drift of this bias. Such a drift could be caused, for example, by a thermally induced change in the geometric relations among the multiple mirrors and retroreflectors in a given fiducial block. The thermal drift can be kept acceptably small by making the fiducial blocks compact, by fabricating all of them from a single piece of Cer-Vit or ULE fused silica, and by carefully controlling the temperatures of the blocks.

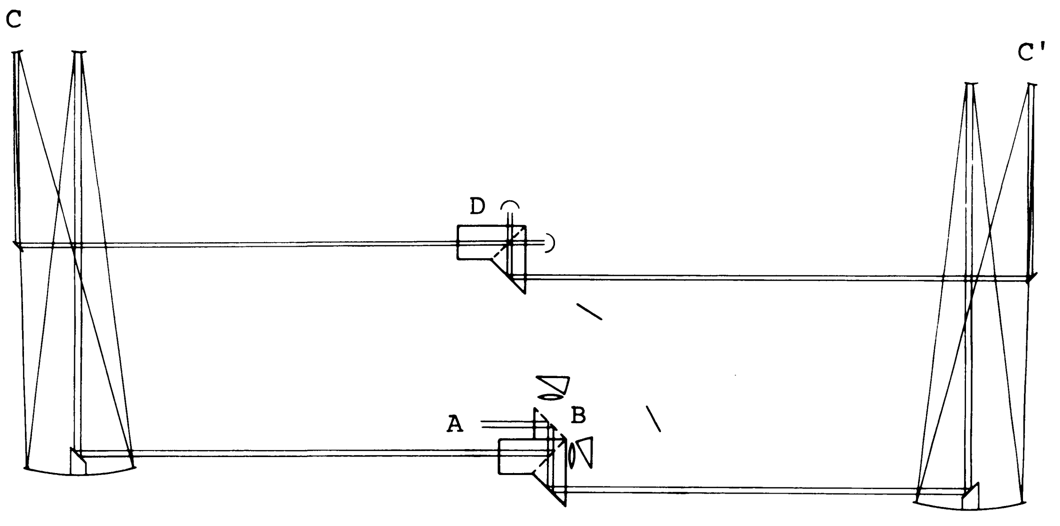

Figure 3. Full-aperture metrology. Optical paths shown are for the metrology signal only.

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Finally, we consider briefly some aspects of the use of the instrument. In a plausible Mini-POINTS mission, a grid of a few hundred bright stars would be selected with near-uniform coverage over the sphere. The interferometer would be used periodically to perform a fixed measurement series: to measure the angular separation between a set of pairs of mutually visible grid stars. Specialized measurement sequences, such as would be required for the relativity experiment, could be interspersed within the fixed series or placed between series. A rich and diverse set of astrophysical objectives could be achieved in an observation program limited to a subset of the 1.7×10^7 objects no dimmer than 15^{th} magnitude. The scientific return from the mission would probably be maximized by observing principally objects no dimmer than 10^{th} magnitude of which there are over 10^5.

Sensitivity studies of star-grid observing sequences have shown (Chandler and Reasenberg 1981, unpublished) that when the average number of measurements per star is five, the a posteriori estimated separation between about half of the pairs of stars (including those not measured directly) has an uncertainty $\bar{\sigma}(\theta)$ less than the measurement uncertainty $\sigma(\theta)$; for less than 5% of the pairs, $\bar{\sigma}(\theta) > 3\sigma(\theta)$. The stars of such a grid would be used as the reference stars for the majority of the scientific applications of Mini-POINTS. Their apparent motions would be analyzed both for the intrinsic scientific interest and to improve the stability of the resulting reference frame. The sensitivity studies have further shown that when the observations are combined in a least-squares estimate of the individual stellar coordinates, it is possible to estimate simultaneously the instrument bias parameter without significantly degrading the stellar coordinate estimates.

It would be natural to include the observation of a small number of bright quasars ($12 < m \leq 15$) in the standard measurement series. The quasar observations could be performed a large number of times per series to compensate for their larger magnitude. These quasar observations would serve two purposes. First, they would measure or bound the quasars' relative motions which are ordinarily assumed to be negligible. Second, they would stabilize the reference frame against uniform rotation and help identify in successive observation series the proper motions of the grid stars.

In a plausible scenario, there would be 300 stars and 5 quasars in the grid; each quasar would be observed 5 times as often as the typical star. The number of observations per series would be 5 times the number of stars plus 50 times the number of quasars. Such a series of 1750 observations would require about a month and could be repeated several times per year to determine the parallax, proper motion, and nominal coordinates of each object. If the series were repeated four times per year for a decade, the nominal uncertainties would be about 0.4 μas, 0.4 μas/year, and 0.6 μas, respectively and would require less than 35% of the instrument observing time. Additional stars could be observed in disproportionally less time.

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SUMMARY. Mini-POINTS is a design concept for a dual astrometric optical interferometer which could be carried fully-assembled in about one-third of the Shuttle bay. It nominally would yield an uncertainty of 5 μas for the measurement of the angular separation of a pair of 10^{th} magnitude stars which are about 90° apart in the sky. The corresponding observation rate is about 60 per day. Mini-POINTS would use a system of internal laser metrology to maintain and track the alignment of the principal optical components. It would have numerous astrophysical applications including a significant new test of general relativity. The instrument would serve as a test bed for technology for future space interferometers.

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Discussion:

McALISTER: Does this require an astronaut to operate it from the Shuttle bay?

REASENBERG: No. It can be put in orbit and used for a long time. That's the mode in which I'd like to see it operating.

McALISTER: How much would it cost?

REASENBERG: I had a preliminary estimate from some engineers at the Draper Lab. The larger instrument would run between 100 and 250 million dollars. This is presumably a less expensive device. Quantity discounts could, of course, be negotiated.

HUGHES: Is the metrology for active control or to derive corrections?

REASENBERG: We have active control and we are generating corrections beyond what the servos are able to do.

HUGHES: Since there is some control envisioned I'm sure you have considered the unfriendly temperature environment? Do you wish to comment?

REASENBERG: The best thing to do would be to enclose the spacecraft. Beyond that, it appears one does not need active thermal control.

ROSER How do you guarantee the stability of the right angle between the interferometers in space?

REASENBERG: The laser interferometry on board provides the stability needed which is comparable to the measurement precision.

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