Tracking Geosynchronous Satellites by Very-Long-Baseline Interferometry

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Four approaches to radio interferometric tracking of geosynchronous satellites are analyzed and compared. Quasar-based differential very-long-baseline interferometry (ΔVLBI), which requires a very sensitive receiver, can achieve meter-level position accuracy with a two-baseline system. Satellite-based ΔVLBI gives somewhat lower accuracy with a compact, inexpensive receiver. Nondifferential VLBI, using less precise media and clock calibrations obtained by observing the satellites of the Global Positioning System (GPS), still gives 5-10 m position accuracy with two baselines. For a sufficiently inclined orbit, all interferometric approaches can yield six-component satellite state, with position at these accuracies, from a single baseline.

Introduction

FOR several years a group at the Jet Propulsion Laboratory (JPL) has been working to apply a powerful new technique of radio astronomy known as very-long-baseline interferometry (VLBI)[1-3] to navigation in deep space. The navigation technique is called ΔVLBI because in order to reduce measurement error it employs the difference between two VLBI observations, one of the spacecraft and one of an extra-galactic reference source. ΔVLBI is now operating successfully, providing an angular accuracy of about 50 nrad for the Voyager 2 cruise to Uranus, and promises further improvement for the upcoming Galileo mission to Jupiter. This accuracy, equivalent to 40 km at Jupiter, represents roughly an order of magnitude improvement over that of conventional two-way Doppler tracking. Moreover, ΔVLBI requires less tracking time, does not exhibit the zero-declination singularity,[6] and requires no uplink. These attributes make ΔVLBI-based strategies attractive candidates for the precise tracking of geosynchronous Earth orbiting (GEO) satellites.

One example of a GEO satellite that can benefit from more precise tracking is NASA's Tracking and Data Relay Satellite (TDRS) which itself will be used to track low Earth orbiting (LEO) satellites. The current method for tracking TDRS involves two-way range measurements from widely separated points on Earth. That system, as it is currently specified, is expected to yield TDRS orbits accurate to about 100 m, and this will in turn allow the tracking of low orbiters via TDRS to about 30 m.[7] This is not adequate for certain scientific (e.g., SEASAT, TOPEX) and other LEO satellites that require meter level tracking; thus large ground networks must be maintained for these users. Reducing TDRS orbit errors below 10 m will enable a tenfold improvement in LEO tracking by TDRS.[7] ‡

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‡This result depends on the mid-1980's state-of-the-art assumptions used here for the errors in mass of Earth, gravity harmonics, and solar radiation pressure. Conservative assumptions such as those used in Ref. 13 will indicate LEO orbit accuracy limited at 20-30 m by systematic modeling error.

Another GEO mission that has been proposed in various forms and would require precise tracking is an Orbiting Deep Space Relay Station (ODSRS)—in effect, an orbiting version of one of the three NASA deep space tracking stations. Such a station in geosynchronous orbit could in principle remove the need for two of the present three deep space stations. To fulfill its deep space tracking function, and to contribute to such other pursuits as astronomical radio source mapping and position determination, the ODSRB will require its position known to about 2 m. (Current deep space station positions are accurate to about 20 cm.) One possibility under study is that NASA's Tracking and Data Acquisition Satellite (TDAS), which will be a follow-on to TDRS, could perform some of the tasks of an ODSRS, and would thus require precise tracking. For these reasons NASA has funded the preliminary study presented here, and a follow-on demonstration now underway, of VLBI tracking of geosynchronous satellites.

In the VLBI technique examined here, a wideband source is observed simultaneously by two radio telescopes separated by several thousands of kilometers. The difference in signal arrival times, or delay, is determined by matching up (cross correlating) the received signal at one station with that at the other. This is illustrated in Fig. 1 and explained in greater detail in Ref. 4. The delay is a measure of the angle between the baseline and the source; two baselines are needed to get both angular components of source position.

Since each signal is time-tagged by the clock at its station, a significant error in the delay measurement is the time-synchronization error between the two clocks. However, that error can be removed if delay measurements on two sources, taken in quick succession, are differenced. The resulting differential delay is a measure of the angle between the two sources. If the sources are angularly close, transmission media and baseline errors will be largely common to the two observations and therefore greatly reduced in the difference. Finally, if the position of one source (the reference) is well known, the precise differential angle measurement yields a precise position for the other or object source.

In the application to deep space navigation, extra-galactic radio sources (quasars), of which there are many with positions known to better than 50 nrad, are the reference sources. In adapting the technique to high Earth orbiters several variations are being examined including the use of Earth satellites for reference and the use of nondifferential VLBI with clock synchronization and media calibration achieved by other means.

The Candidate Systems

Our objective is to devise a low-cost interferometric tracking system for HEO satellites. The stations should be

Table 1 Key system characteristics

	System A	System B	System C	System D
Antenna size, m	6	0.6	0.6	0.6
Baseline length, km	6000	6000	6000	100
Clock	Atomic	Quartz	Quartz	Quartz
Noise temperature, K	60	300	300	300
Method of clock and media calculation	ΔVLBI (quarsars)	ΔVLBI (satellites)	GPS receivers	Connected elements
Bit transmission (or record) rate, bps	3×10^7	1000	1000	1000
Receiver bandwidth, MHz	100	1	1	20

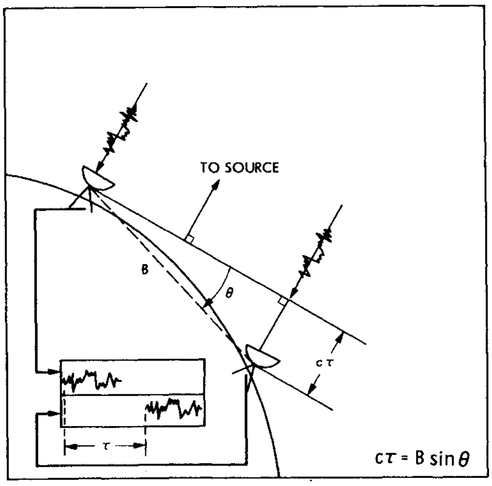

Fig. 1 VLBI delay measurement.

compact, versatile, and unattended, yet the system should retain, as much as possible, the high accuracy of deep space ΔVLBI. Four candidate systems have been studied, one to perform each of the following:

A) ΔVLBI with quasars as reference;

B) ΔVLBI with Earth satellites as reference;

C) VLBI with clock synchronization and ionosphere calibration by the satellites of the Global Positioning System (GPS);

D) Short baseline interferometry with connected elements.

Table 1 summarizes the principal features of each system.

System A, with the demanding job of detecting faint quasar signals, is considerably more sensitive (and costly) than the others, requiring larger antennas, better clocks, lower noise temperatures, and vastly higher bit rates. System B is the simplest but depends on the availability of reference satellites with accurately known positions and which transmit at the same frequency as the object satellite. To overcome the frequency limitation, system C dispenses with the differential observation and instead has a special receiver with which it calibrates the ionosphere and clock offset using the dual L-band transmissions of the Navstar satellites of the GPS.[8] In the analysis we assume these calibrations are performed each time a satellite observation is made.

System D is a departure, employing a short (100 km) baseline with stations physically connected, e.g., by fiber optics or buried coaxial cable, and driven by a common clock. This eliminates the synchronization problem and, because of the nearly cancelling raypaths to the closely placed stations, greatly reduces media errors as well. However, since angular sensitivity is proportional to baseline length, good performance with a short baseline requires extremely tight control of delay error. Moreover, the required stable link between stations results in a costly and inflexible system.

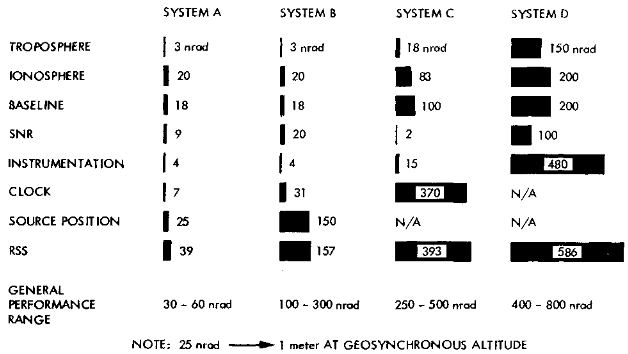

Fig. 2 Breakdown of angular position errors (1σ).

System Performance

First we examine the single observable (delay or differential delay) error for each system. To do this we have selected the example of a geosynchronous satellite centered over the baselines. This is a convenient choice for later orbit analysis since a geosynchronous satellite can be continuously tracked with a single baseline or baseline pair. For a meaningful comparison between systems with different baseline lengths, delay error is presented here in terms of the corresponding angular position error for each system. For ΔVLBI measurements, the reference source position error is included in the total error. Table 2 summarizes the assumptions used in evaluating these errors.§

Figure 2 gives the angular position errors for each system, broken down into their various components. In addition to the net root-sum-square (RSS) errors, Fig. 2 gives loose performance ranges for each system based on a wider range of assumptions. The ranges are a more realistic representation of potential system performance.

System A which, of the four, most closely resembles the deep space ΔVLBI system, is clearly the top performer. System B, while retaining the efficient self-calibration of ΔVLBI, is limited severely by reference position error, assumed here to be 150 nrad. Indeed, if provided a set of reference satellites with position errors at the quasar level as may well be possible by the end of this decade,[9] system B would perform nearly as well as system A at a much lower cost. The nondifferential measurement of system C is limited first by clock sync error, assumed here to be 7 ns, and then by baseline error. Recently a group at the National Bureau of Standards[10] demonstrated approximately 3 ns clock synchronization by GPS over a 3000 km baseline, giving some credibility to the 7 ns assumption. The performance of system D, apparently the poorest, is also the most uncertain since, with a short baseline, angular accuracy is extremely sensitive

§Although ionosphere error is reduced in the differential observations of systems A and B, at S-band it would not reach the required accuracy without calibration; the 40 cm specified in Table 2 assumes some external ion calibration.

to small changes in delay error. It could be argued that with dual-frequency reception for ion calibration, water vapor radiometers for wet troposphere calibration, and highly stabilized and continuously calibrated instrumentation, system D could be made to perform at the 100-200 nrad level. The estimates here are based on currently implemented and demonstrated capabilities at the Deep Space Network. However, future developments in connected element interferometer tracking bear watching.

Orbit Accuracy

The results in the previous section represent only the instantaneous (i.e., measured over ~10 min) angular position error of these systems. Two baselines are needed to get both angular components instantaneously; satellite altitude is not directly observed. In this section we evaluate the final orbit accuracy achieved using only the interferometer delay observable, from both single- and dual-baseline systems, around a complete 24-h orbit. The dynamics of the orbit are used to solve for all six components of satellite state.

The analysis was performed with the covariance analysis program COVAN at JPL.[11] Only systems A and C were evaluated. The baseline geometry is shown in Fig. 3, while the orbital and baseline parameters and some additional error sources are given in Table 3. Note that when at an orbital node the satellite is centered over the baselines. At those points the delay analysis given above applies unaltered. However, for inclined orbits, when the satellite is away from the nodes, station elevation angles are different and thus media errors are different. Moreover, away from the node the satellite sees a shortened baseline and thus a given delay error results in a larger angular position error. The analysis software accounts for these effects. In all analyses only the six components of satellite state were estimated; all other errors were "considered."

The measurement equation can be written as

$$\underset{\sim}{z}=\underset{\sim}{A}\underset{\sim}{x}+\underset{\sim}{C}\underset{\sim}{p}+\underset{\sim}{n}$$

where $\underset{\sim}{z}$, $\underset{\sim}{x}$, $\underset{\sim}{p}$, and $\underset{\sim}{n}$ are vectors of observations, of estimated parameters, of consider parameters, and of data noise accompanying the observations, respectively. The matrices $\underset{\sim}{A}$ and $\underset{\sim}{C}$ are the partial derivatives of the observations with respect to the estimated and consider parameters, respectively. In our analysis we assume that all observations are independent and uncorrelated. Hence $\underset{\sim}{n}$ is a vector of uncorrelated white noise. The effects of such data noise on the maximum-likelihood estimate of $\underset{\sim}{x}$ are given by the computed

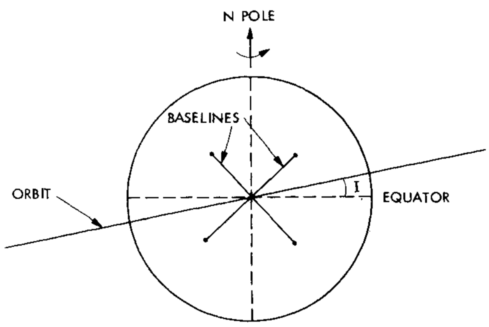

Fig. 3 Geometry for orbit determination analysis.

Table 2 Assumptions used in delay error analysis

All observations at S-band
Satellite at geosynchronous altitude (~36,000 km)
Satellite centered directly over baseline
Zenith troposphere error = 6 cm (seasonal model)
Zenith ionosphere error = 40 cm (Faraday or GPS calibration)
Baseline errors: 60 cm, systems A-C; 2 cm, system D
Source separation (systems A and B only): 10 deg
Reference position error: 25 nrad, system A; 150 nrad, system B
Clock sync error (system C only): 7 ns
Frequency offset: $\Delta f/f = 10^{-12}$, system A; 10^{-11}, system B
Frequency stability: $\sigma_{\Delta f/f} = 10^{-13}$, system A; 10^{-11}, system B
Object satellite: transmitted power, 2.5 W; antenna gain, 34 dB
All errors 1σ

Table 3 Assumptions used in orbit determination analysis

Satellite	Area/mass = 0.00925 m^2/kg	
	Solar reflectivity = 1.77	
Orbit	Circular	
	Radius = 42161.55 km	
	Inclinations: 0-45 deg	
Baselines	1: (22.2°W, 20.7°S) to (22.2°E, 20.7°N)	
	2: (22.2°W, 20.7°N) to (22.2°E, 20.7°S)	
Length	6368 km	
Data span	24 h	
Error sources	(see also Table 2)	
	GM of Earth:	10^{-7}
	Solar radiation:	5%

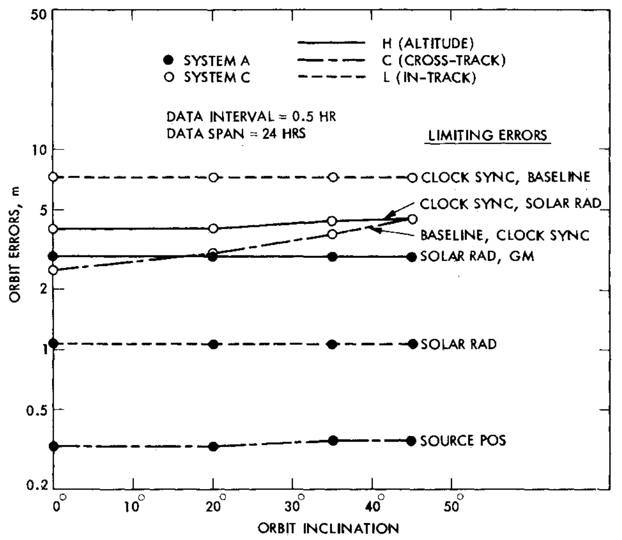

Fig. 4 Satellite position errors at ascending node, two baselines (1σ).

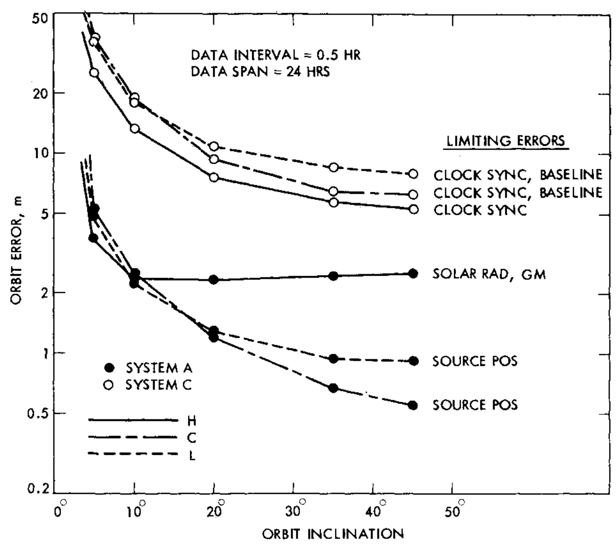

Fig. 5 Satellite position errors at ascending node, single baseline (1σ).

covariance P_x, $\quad P_x = (A^T P^{-1} A)^{-1}$

where P is the covariance matrix of the data noise n. In the case of ΔVLBI (system A) we assume that an independent reference source is used for each observation. Hence, all error sources listed in Table 2 can be treated as equivalent data noise, the effects of which are given by P_x. The ionospheric error in the case of VLBI (system C) is treated the same way. However, other error sources behave systematically on the observations and must be treated differently. With the systematic errors included, the covariance matrix of the estimates becomes

$$P_x^c = P_x A^T P^{-1} C P_c C^T P^{-1} A P_x + P_x$$

where P_c is the covariance matrix of the consider parameters p. For VLBI (system C) the consider parameters include troposphere error (scaled by elevation angle), clock sync error (constant bias), frequency offset (linear drift), frequency stability (approximated by quadratic drift), baseline error, Earth mass times gravitational constant (GM), and solar radiation. For ΔVLBI (system A), only the last two error sources are included as consider parameters; the rest are treated as equivalent data noise.

In the first case we examined, each system performed a two-baseline observation every 30 min over a full orbit; the 24-h data arc was then used to solve for satellite state at the ascending node. The resulting three-component position error as a function of orbit inclination is given for both systems in Fig. 4. System A achieves meter-level accuracy for all inclinations. It is limited in altitude and in-track accuracy primarily by the 5% solar radiation error. System C, hampered by the clock synchronization and baseline errors that are largely eliminated by system A, yields a still creditable 2-8 m accuracy.

We next looked at the orbit accuracy achieved with a single VLBI baseline, relying more heavily now on orbit dynamics to recover the six-component state. Again observations every 30 min were assumed. Figure 5 gives the resulting position errors at the ascending node. At zero inclination the problem is singular; inclination and eccentricity parameters are not separable with information from a single baseline resulting in a coupling between in-track and cross-track position errors. As can be seen in Fig. 5, at zero inclination the errors for both systems blow up. For an inclined orbit the elements are separable, and increasingly so with increasing inclination. At an inclination of just 5 deg system A achieves 5 m accuracy and above 20 deg it is back at the meter level, again limited in altitude accuracy by solar radiation. System C is somewhat less powerful, needing a 10 deg inclination for 15-20 m accuracy and 20 deg for 10 m accuracy. However, below a 20 deg inclination system C is dominated by clock synchronization error; improving synchronization to 3 ns would cut those errors in half.

Finally, we investigated the effect on the two-baseline, zero-inclination case of reducing the number of observations from one every 30 min to one every 2 h and one every 6 h. The results are shown in Fig. 6. The degradation is modest even at the lowest observation rate with system A achieving 1-3 m accuracy and system C 6-11 m accuracy.

Discussion

To illuminate the key features of VLBI tracking we have employed an ideal geometry; perfectly orthogonal baselines centered perfectly under the satellite at two points in the orbit. In principle, a two-baseline system formed from a triangular arrangement of three stations would perform virtually as well; however, placing those stations within a limited selection of available sites might pose a challenge. Although each arrangement would have to be analyzed individually, it is our experience that any reasonable positioning—one with relatively large orthogonal components, relatively near the satellite track—will perform well. We believe that the figures presented here are realistic, within perhaps a factor of two, for a practical system.

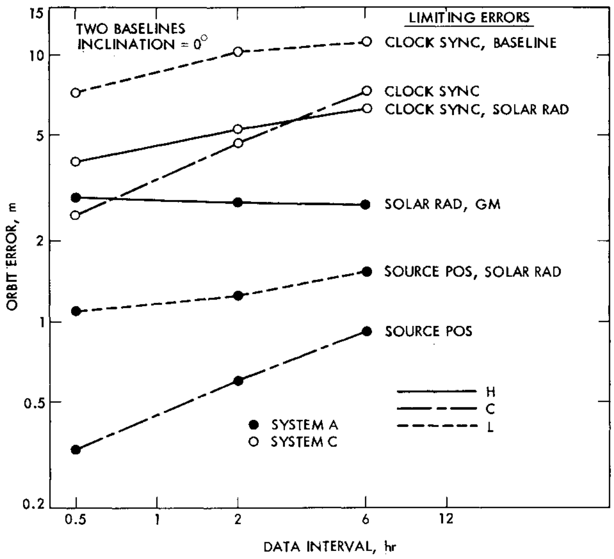

Fig. 6 Orbit error as a function of data interval.

One of the ancillary benefits of VLBI tracking mentioned in the Introduction is that it requires no uplink from the tracking stations. It will be noted, however, that to form the VLBI delay-observable data from two stations must be brought together—thus the data must somehow be sent. A valuable property of a spacecraft signal with known structure (e.g., subcarrier harmonics, known code sequences) is that the received signal can be modeled and its phase measured in the receiver. All that then must be sent is a phase measurement perhaps every second or every 10 s. This will require at most a few tens of bits per second which can be handled easily by commercial phone channels. Thus there is no need for direct broadcast from the ground or for a coherent transponder on the satellite. In a recent experiment conducted at JPL, observations were made of a military satellite transmitting encrypted telemetry. Embedded in the signal were pure, unmodulated tones observable over an 8 MHz band. These tones can be tracked by the receiver and their phases transmitted at intervals with a data rate of about 100 bps. Yet an 8-MHz-wide signal can be reconstructed from these phases by a process called bandwidth synthesis[4] to yield subnanosecond VLBI delay precision.

The purely random quasar signal cannot be modeled and reduced in the receiver (although with bandwidth synthesis only portions of the received bandwidth need to be sampled), hence the high bit rate shown for system A in Table 1. The 1000 bps rates shown for systems B-D are deliberately conservative, as are the 1 MHz received bandwidths indicated for systems B and C. The actual bandwidth needed will depend on the strength of the signal in question; in the case of TDRS, 1-ns delay precision, corresponding to ~50 nrad SNR contribution to angle error, will require a bandwidth of about 100 kHz with a transmitted power of 0.5 W. It should be noted that while systems B-D require only very small antennas, for many satellite applications a larger antenna will be required somewhere for telemetry reception and commanding.

Orbit accuracies currently achieved for geosynchronous satellites are typically hundreds of meters. The 100 m accuracy expected of the TDRS tracking system has already been cited. The Satellite Control Facility operated by the U.S. Air Force can determine GEO orbits to about 400 m, and that only when "the total ground system is dedicated to a particular satellite, which rarely occurs."[12] The INTELSAT communications satellites are tracked by range and angle measurements from a *single* station with accuracies of a few kilometers. These performances reflect no intrinsic deficiency in the tracking systems themselves—only the comparatively modest requirements placed on them. The ranging precision of various existing systems, excluding lasers, is typically tens of meters, limited primarily by instrumental biases and measurement bandwidth. If higher precision were required these systems could be improved with increased bandwidth and continuous instrumental calibration. They would also require precise position determination and media calibration. Such measures could reduce range errors to perhaps a few meters and yield orbit accuracies comparable to those presented here, although radio ranging would still lack the passive operation and inherent self-calibration of differential VLBI. As noted earlier, whatever errors remain from media, instrumentation, station locations, and Earth orientation are nearly the same for the two observations of a differential VLBI measurement and therefore cancel in the difference. Consequently, ΔVLBI can largely dispense with delicate and costly external calibration and still provide superior performance.

Another technique, laser ranging, is capable of subdecimeter range precision and requires only a reflector rather than an active transponder on the satellite. The accuracy of laser tracking is thus limited primarily by station location, Earth orientation, solar radiation, and instrumental calibration errors, and should be capable of 100 nrad performance. However, systems for laser ranging are costly and complex, while their operation is exacting and limited to cloudless conditions. At present we are unaware of any efforts to achieve meter-level orbit accuracy for GEO satellites by either radio or laser ranging. Over the next two years JPL will be seeking to demonstrate such accuracy using VLBI systems, originally developed for geodetic measurement and deep space tracking, applied to existing geosynchronous satellites.

Conclusions

VLBI tracking, which today is providing operational angle measurements accurate to about 50 nrad for the Voyager 2 cruise to Uranus, is an attractive candidate to provide ultraprecise orbit determination for geosynchronous satellites at low cost. Three approaches described here show particular promise: 1) quasar-based ΔVLBI, 2) satellite-based ΔVLBI, and 3) nondifferential VLBI with clock sync and media calibration by GPS. Of these, the first is potentially the most precise, able to provide meter-level position accuracy; however, it is also the most costly. Satellite-based ΔVLBI is in many respects the most attractive approach, offering accuracy near that of quasar ΔVLBI with a system featuring 2-ft antennas, quartz clocks, and ultra-low bit rates. Indeed, as reference satellite position errors are brought below 50 nrad, the performance of satellite-based ΔVLBI will match that currently achieved only with quasars.

In principle, other tracking schemes such as two-way laser or radio ranging could offer comparable accuracies, given sufficient attention to the (generally laborious) calibration of significant errors. Whether such approaches can be cost-competitive with VLBI remains to be examined. In any case, VLBI has the virtue of passive operation, requiring neither an uplink to, nor cooperation from, the satellite in question; and given suitable reference sources, differential VLBI is to all intents and purposes self-calibrating.

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