Interferometric Observations of an Artificial Satellite

Abstract. *Very-long-baseline interferometric observations of radio signals from the TACSAT synchronous satellite, even though extending over only 7 hours, have enabled an excellent orbit to be deduced. Precision in differenced delay and delay-rate measurements reached 0.15 nanosecond (≈5 centimeters in equivalent differenced distance) and 0.05 picosecond per second (≈0.002 centimeter per second in equivalent differenced velocity), respectively. The results from this initial three-station experiment demonstrate the feasibility of using the method for accurate satellite tracking and for geodesy. Comparisons are made with other techniques.*

During a 7-hour period on 13 October 1969, very-long-baseline interferometric (VLBI) observations were made of the radio signals from the TACSAT I communications satellite, which was in a synchronous, nearly equatorial orbit. The three ground stations involved were located at Tyngsboro, Massachusetts; Green Bank, West Virginia; and Owens Valley, California. The satellite's transmitter radiated noise with an effective power of 1 kw, centered at 7257.5 Mhz and extending over a 10-Mhz bandwidth. The signal was so strong—nearly six orders of magnitude greater than those from natural celestial sources—that the low-noise front-end amplifiers were bypassed to avoid saturation (*1*).

The electronic systems and data-taking procedures employed were nearly identical to those used by Hinteregger *et al.* (*2*), with the following exceptions. (i) The 10-Mhz bandwidth of the received signal was sampled at eight places by cyclically shifting the 360-khz recordable bandwidth. (ii) In processing each pair of magnetic tape recordings, account had to be taken of the very small, but nonnegligible, declination motion of the satellite.

Simultaneous observations at all three sites were attempted 18 times and yielded a total of 30 independent measurements of the differenced delay and 32 of the differenced delay rate (*3*). To estimate the precision of the delay measurement, a pair of tapes was separated into 94 independent subsets of data, each 1.6 seconds long (one complete frequency-switching cycle), and the delay was computed for each subset separately. The resulting distribution of delays has a root-mean-square scatter of 1.4 nsec; the standard deviation of the mean is about 0.15 nsec (about 5 cm in differenced distance) and corresponds to the precision of the delay estimate from a single 150-second observation. The precision of the delay-rate measurements, governed by the phase stability of the system and the 2.5-minute duration of each recording, was estimated to be about 0.05 psec/sec in most cases.

The determination of the satellite's orbit from the VLBI data was accomplished with a double-precision computer program (*4*). The sensitivity of the measurements required that a sophisticated force model be employed. All known accelerations of 10^{-8} cm/sec^2 or larger were considered. These included the effects of the earth's second through fourth zonal and tesseral harmonics, the gravitational perturbations of the sun and the moon, and the pressure of direct sunlight. The sunlight pressure introduced the major uncertainty because of the difficulty in modeling its effects accurately (*5*). The influences of the charged and neutral constituents of the propagation medium were estimated, respectively, from Faraday rotation and surface meteorological data obtained near each site.

To test the reliability of the deduced orbit, the data were divided into nonoverlapping sets, one containing only differenced delays and the other only differenced delay-rate data. The orbital elements were then estimated separately from each set. The results are shown in Table 1 and are compared there with the corresponding, but less accurate, orbital elements determined by routine Air Force tracking of the satellite (*6*). The uncertainties associated with three of the angle elements (Ω, ω, and M_0) are relatively large because these elements are not well defined for an orbit like TACSAT's with small inclination and eccentricity. In addition to the orbital elements, the epoch offsets between the clocks at the different sites were also estimated from the differenced delay data. Since the very low orbital inclination of TACSAT made these estimates much less precise than those from the VLBI observations of quasars made in contiguous time periods (*2, 7*), the latter were used to obtain one of the solutions in Table 1.

The postfit residuals from the solutions are about half an order of magni-

Table 1. Comparison of VLBI estimates of the orbital parameters of the TACSAT satellite, for the epoch 0 hour U.T. 13 October 1969. The numbers in parentheses are the standard deviations and apply to the last digit or digits. For each estimate the standard deviation is based on a uniform weighting of the observations so that the measurement errors equal the root-mean-square values of the postfit residuals. In determining distances it is assumed that the speed of light c is 299,792.5 km/sec. The standard deviations associated with the differences in parameter estimates are calculated by taking the square root of the sum of the squared standard deviations of the individual parameter estimates.

Data set	Semimajor axis a (km)	Eccentricity e ($\times 10^4$)	Inclination i (deg)	Right ascension of ascending node Ω (deg)	Argument of perigee ω (deg)	Initial mean anomaly M_0 (deg)
Differenced delay data only (1)*	42,164.96(4)	2.059(6)	0.3128(2)	292.12(2)	250.2(2)	91.6(2)
Differenced delay data only (2)†	42,164.90(5)	2.08 (2)	0.3133(4)	294 (1)	247 (3)	95 (2)
Differenced delay rate data only (3)	42,164.83(2)	2.082(3)	0.3130(1)	292.5 (3)	249.6(7)	92.1(6)
Routine radio tracking data (4)	42,164.4 (4)	2 (1)	0.31 (2)	292 (2)	280 (70)	62 (70)
Differences in estimates						
|(1) − (2)|	0.06(6)	0.02 (2)	0.0005(4)	2 (1)	3 (3)	3 (2)
|(1) − (3)|	0.13(5)	0.023(7)	0.0002(2)	0.4 (3)	0.6(7)	0.5(6)
|(1) − (4)|	0.6 (4)	0.0 (10)	0.00 (2)	0 (2)	30 (70)	30 (70)

* The Haystack-Owens Valley clock epoch offset was taken from the analysis of quasar observations (*15*). The Haystack-Green Bank offset was estimated from the TACSAT differenced delay data along with the orbital parameters. A slight incompatibility in the two sets of reduction programs may account for the somewhat high value of a and low value of e obtained in this solution. † Both clock epoch offsets were estimated from TACSAT differenced delay data along with the orbital parameters.

tude larger than would be expected solely on the basis of the measurement precision. Explanations for these residuals are still under investigation; they are due partly to drifts in the characteristics of some of the components of the receiver system (*8*) and partly to errors in the corrections used for the propagation medium.

Even allowing for these systematic errors, we find that the VLBI observations determined the east-west position of the satellite, relative to the ground sites, to within about 3 m. The uncertainty in the corresponding north-south position was almost an order of magnitude greater because the baseline had correspondingly small components in this direction. The third component of position, the altitude, was determined primarily from the dynamics, through Kepler's third law, with an uncertainty of about 20 m. The accuracy here was limited by the short arc of tracking, which extended over less than one-third of the satellite's orbital period. A similar analysis shows that the main component of velocity is determined to within about 0.5 mm/sec. These accuracies are degraded from the corresponding ones of the differenced delay and delay-rate measurements by approximately the ratio of the satellite's altitude to the length of the appropriate baseline component.

In principle, VLBI observations of satellites can also be used to estimate the vector separations, or baselines, between the ground sites. However, variations in the differenced delays and delay rates are required to determine the baselines from VLBI data. For a truly synchronous equatorial orbit no such variations will occur. Therefore, the TACSAT orbit, which has an inclination of only 0.3 degree (approximately 0.005 radian) and an eccentricity of only 0.0002, is very poorly suited for baseline determinations. Detailed covariance analyses support this qualitative argument.

We conclude that, with only minor improvements in the ground equipment, VLBI can be used for highly accurate tracking of satellites. The accuracy limit will be determined primarily by the errors in the corrections for the propagation medium. With satellites in suitable orbits, such tracking can yield useful geodetic and geopotential information as well. It is therefore of interest to compare the VLBI technique with conventional radio and laser tracking of earth satellites. The wide-band VLBI measurements of one-way differenced group delay correspond very closely to the differences in the direct measurements of two-way delay made simultaneously at two sites, either by radio with ranging transponders aboard the satellite or by laser with retroreflectors on the satellite. For equal accuracy of individual measurements, the direct delays are relatively much more useful than the differenced delays the farther away the satellite is. If the altitude of the satellite and the length of the interferometer baseline are approximately equal, then the differenced and direct delays are almost of comparable usefulness (*9*). At present, VLBI differenced group delay measurements are one and two orders of magnitude more accurate, respectively, than the corresponding laser and radio-transponder measurements of delay, and so can be useful even for synchronous altitude satellites. Improvements in laser and radio-transponder technology could certainly narrow the gap and possibly reverse it.

The VLBI fringe rate, or differenced phase-delay rate, is analogous to the difference in the direct Doppler shift measured simultaneously at two sites with the use of satellite radio transponders. Again, the availability of the direct Doppler shift, in addition to the difference, is an important aid in orbit determination. With transponders, one usually measures the Doppler shift continuously over a full pass in a manner that preserves knowledge of the relative phases—the so-called counted Doppler observable. The difference of such observables measured simultaneously at two sites is identical to the fringe phase determined continuously by VLBI (*10*). Even if the propagation medium were nondispersive, these phase delays would not be equivalent to the group delays discussed above because phase-delay measurements lack a constant of integration. The initial phase is uncertain by the delay equivalent of an integral number of phase cycles.

Thus, in principle, a ranging and Doppler transponder can provide substantially more information than can VLBI observations of a wide-band noise source or free-running oscillators on the satellite. In practice, the VLBI technique has the advantages that (i) suitable noise sources or free-running oscillators are cheaper to implement than transponders; (ii) the ground-based equipment required is much simpler; and (iii) in regard to group-delay measurements, transponders with a sufficiently wide-band response to be competitive have not yet been developed.

Although laser tracking does not provide phase information, it does have advantages over radio methods: (i) The required retroreflectors on the satellite, being purely passive, will most likely have longer useful lifetimes than the radio devices (*11*). (ii) Atmospheric water vapor introduces a much smaller uncertainty into the laser measurements of delay because the index of refraction of water vapor is far less at optical wavelengths than at radio wavelengths. Conversely, because the radio devices are active, the signal-to-noise ratios are usually much higher and can allow relatively much smaller apertures in the ground equipment. A further advantage of the radio approach is its usefulness under all weather conditions; lasers, by contrast, are of no use for tracking in rain or even in cloudy weather.

We may also intercompare the utility, for geodetic applications, of VLBI observations of satellites and extragalactic sources of continuum radiation. The celestial sources have one essential advantage: They have negligible proper motions and hence provide an inertial reference frame; a single determination of the relative source positions suffices for all time (*12*). Having the radiation sources on the satellite allows the baselines to be located with respect to the center of mass of the earth (*13*), and provides sensitivity to the earth's gravitational potential. But the latter characteristic is also a hindrance for the determination of baselines because of deficiencies in the theoretical model of the potential.

Perhaps the most promising approach is to make use simultaneously of both natural and artificial sources. The satellites can then be located accurately with respect to a stellar frame; relative errors could be as low as fractions of a milliarc second if the satellite passes close to, and slowly by, one of the natural sources that constitute the inertial frame (*14*). One can even envision a hierarchy of ground terminals for geodetic use: The most sensitive installations can be used to observe both satellites and natural sources, while small, portable terminals observe only the much stronger signals from satellites. With the orbits determined precisely relative to the inertial frames by the large installations, the VLBI observations by the portable ones can be used to determine geodetic ties directly. An important role can also be played here by radio emissions from spacecraft in interplanetary flight and in orbit about, or emplaced on, other planets.

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References and Notes

1. The received signal was so strong that very small microwave horns (less than 1 m in diameter) could have been employed in place of the large parabolic antennas that were available at the sites.
2. H. F. Hinteregger, I. I. Shapiro, D. S. Robertson, C. A. Knight, R. Ergas, A. R. Whitney, A. E. E. Rogers, J. M. Moran, T. A. Clark, B. F. Burke, *Science* **178**, 396 (1972). Definitions given there for specialized terminology are not repeated here.
3. By differenced delays and differenced delay rates, we mean, respectively, the differences in group delay and in phase delay rate for the propagation of signals from the satellite to the different ground sites. The measurement totals follow since (i) a few observations at Green Bank were either unsuccessful or lacked phase calibrations, and (ii) the third baseline provides only redundant data. The constraint of closure insures that the sum of the three differenced delays or delay rates from each of the three baselines must vanish.
4. The Planetary Ephemeris Program of the Massachusetts Institute of Technology, developed largely by M. E. Ash, was modified for this purpose.
5. For a detailed discussion, see R. A. Preston, thesis, Massachusetts Institute of Technology (1972).
6. The orbital elements are not referred to the midpoints of the observations, but have been extrapolated backward in time through an interval somewhat greater than the total extent of the tracking session.
7. We note that a 10-degree orbital inclination would have resulted in a thousandfold improvement in the epoch offset estimate.
8. The phase calibration signals (*2*) were only recorded at the beginning of each observation. From a comparison of the calibration results from neighboring observations, we conclude that at times there may have been uncompensated drifts in the receiver phase characteristics large enough to account for the observed residuals.
9. Of course, VLBI observations require substantial common visibility of the source from the participating ground sites; this visibility will decrease as the satellite's altitude decreases. Also, atmospheric effects are harder to model accurately the lower the elevation angle of the source as seen from the ground site.
10. Some of the VLBI observations of the TACSAT signals were separated by only 9 minutes, and it may be possible to connect the values of the fringe phase unambiguously between these measurements and thus obtain the analog of the counted Doppler observable (*5*).
11. Radar tracking of passive (metallic) satellites could also yield very high echo-delay accuracies, but large ground facilities are required to obtain a sufficient antenna gain. The far shorter wavelengths at which lasers operate allow even small optical telescopes to have much larger gains.
12. This ideal situation is tempered by the fine structure and internal kinematics of distant natural sources of continuum radio radiation. But these usually are found to be of the order of 10^{-3} arc second and are of little consequence for geodetic applications [C. A. Knight, D. S. Robertson, A. E. E. Rogers, I. I. Shapiro, A. R. Whitney, T. A. Clark, R. M. Goldstein, G. E. Marandino. N. R. Vandenberg, *Science* **172**, 52 (19[illegible] A. R. Whitney, I. I. Shapiro, A. E. E. Rogers, D. S. Robertson, C. A. Knight, T. A. Clark, R. M. Goldstein, G. E. Marandino, N. R. Vandenberg, *ibid.* **173**, 225 (1971)].
13. Such ties to the earth's center of mass degrade with the decrease in parallax accompanying an increase in the altitude of the satellite relative to the length of the baseline.
14. For satellites in orbit about other planets, VLBI observations from the earth of both the satellites and extragalactic radio sources in neighboring parts of the sky can serve to orient the solar system with respect to the inertial frame formed by these sources.
15. A. R. Whitney *et al.*, in preparation.
16. We thank the Tri-Service Test Directorate for cooperation in scheduling; R. Levinson, Aerospace Corp., and W. Snyder and L. Riley, Hughes Aircraft Co., for providing TACSAT orbit determinations based on Air Force data; and J. Klobuchar, Air Force Cambridge Research Laboratory, and M. J. Davis, Stanford Electronics Laboratories, for providing estimates of the electron content of the ionosphere. We also thank W. E. Howard, III, National Radio Astronomy Observatory, and D. L. Jauncey, Cornell University, for the use of the Mark I VLBI recording systems; and H. Peters, Goddard Space Flight Center, for aid with the hydrogen-maser frequency standards. The experimenters at Massachusetts Institute of Technology were supported in part by the National Science Foundation and in part by the Advanced Research Projects Agency. Research at the Haystack Observatory is supported by NSF grant GP-25865 and NASA grant NGR22-174-003, contract NAS9-7830. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation. The Owens Valley Radio Observatory is operated by the California Institute of Technology with support from the National Science Foundation.

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Incised River Meanders: Evolution in Simulated Bedrock

Abstract. *A flume 60 feet (18.28 meters) long was employed to study the controls of lateral and vertical incision of a sinuous stream in simulated bedrock. When 100 percent of the available sediment load was entrained the flow incised vertically at bends. When less than 100 percent of the load was entrained the flow downcut laterally outward at bends. The effects of helicoidal currents and shear stress localization explain the loci of erosion and deposition.*

Meandering rivers that have incised in bedrock and yet have maintained a sinuous pattern may be of two basic types: (i) those which have slip-off convex spurs and undercut concave banks at bends (lateral incision), and (ii) those which have vertical concave and convex banks at bends (vertical incision). Nearly 80 years ago *Science* published a classic debate between Davis (*1*) and Winslow (*2*) concerning the incised Osage River of Missouri and how its incised meander pattern was related to the geologic history of the surrounding region. A major question was whether the existing meander pattern was closely related to a previous pattern (inheritance through superposition), or whether lateral incision had markedly altered a previous pattern. The field studies of Davis and Winslow depended largely on interpretations of valley morphology and alluvial deposits; thus, only inferences could be drawn concerning the crux of the problem—the mechanics and controls of vertical and lateral incision. Through the years, the reasons for the differences between the two types of meanders and their significance have remained an unsolved problem (*3, 4*).

In the work reported here, erosion at meander bends was studied by using simulated bedrock consisting of 70 percent sand, 19 percent original silt clay, and 11 percent added kaolinite clay. This mixture was poured as a slurry into a tilting, recirculating flume 60 feet (18.28 m) long by 4 feet (1.22 m) wide (Fig. 1). The slurry was leveled and allowed to dry and harden for 2 weeks. After drying, the material was cohesive and capable of maintaining vertical banks 1.5 feet (45.75 cm) high. Under the imposed flow conditions erosional grooves, scour channels, potholes, and erosional ripples developed in a remarkable simulation of features in natural bedrock channels.

A sinuous channel was manually excavated in the simulated bedrock (Fig. 1), and incision was induced through an increase of flume slope. The channel morphology at bends and crossings shown in Fig. 2 evolved during 73 hours at a discharge rate of 0.10 cubic foot per second (0.0028 m^3 sec^{-1}), sand feed rates from 30 to 50 g/min, and a maximum slope of 0.0167. Initial erosion was a maximum at the inside of the bends, and the channel was incised vertically (Fig. 2, a and c). The maximum erosion continued at the inside of the bends (convex bank) until scour had so decreased