Astronomical Applications of Differential Interferometry

Abstract. *Intercomparison of radio signals received simultaneously at several sites from several sources with small mutual angular separation provides a powerful astrometric tool. Applications include tracking the Lunar Rover relative to the Lunar Module, determining the moon's libration, measuring winds in Venus's lower atmosphere, mapping Mars radiometrically, and locating the planetary system in an inertial frame.*

In most applications of very-long-baseline interferometry (VLBI) the most serious limitations on the accuracy of the results are imposed by unknown, variable phase errors introduced by both the neutral atmosphere and the ionosphere above the receiving sites, and by fluctuations in the rates of the oscillators that provide phase references at the separate sites. These limitations may be largely removed in differential measurements, in which signals received simultaneously from different radio sources located close together in the sky are compared. If atmospheric and independent oscillator phase shifts affect observations of each source equally, their effects will cancel when differences between observations are examined. In this report we discuss several scientific applications of differential interferometry (*1*), as well as the actual tracking of the Lunar Rover performed during the Apollo 16 mission.

Because differential interferometry involves taking differences not only between receiving points but also between transmitting points, it follows that any potential source of error will cancel if it is common either to all receivers or to all transmitters. This simple principle will be shown to have important consequences for astronomical measurements. One such consequence relates to observations of artificial transmitters for which the carrier frequency may be uncertain and variable. Noninterferometric one-way Doppler tracking of such objects is ordinarily of little use because changes in the received frequency due to the Doppler shift cannot be distinguished from changes in the frequency of the transmitter itself. In interferometry, however, transmitter (and any other) frequency changes that appear equally at all receivers have no direct effect on the ability of the interferometer to determine relative angular positions. In fact, artificial radio sources make particularly convenient objects for interferometry because conventional Doppler counting techniques can be used to keep track of the phase of the carrier signal received at each site. Wide-bandwidth group-delay interferometry also may be done efficiently with artificial sources if the carrier wave is suitably modulated, for example, with a pseudorandom wave form of the kind often employed for two-way radar ranging (*2*). As in the case of one-way Doppler tracking, one-way radar ranging is ordinarily useless if either or both of the transmitter and receiver time bases are unstable. But for either phase-delay or group-delay observables, the effects of transmitter instability cancel when the difference is taken between receiving sites (thus forming an interferometric observable), and the effects of receiver instability cancel when the difference is taken between a pair of transmitters (forming a differential interferometric observable).

We shall now discuss some of the potential scientific applications of differential interferometry. First, however, we describe one technical application already successfully carried out: Earth-based tracking of the Apollo 16 Lunar Rover relative to the Lunar Module. Three tracking stations (*3*) were employed so that two independent baselines were formed. Thus, two components of the motion of the Rover relative to the Module were determined from the changes in phase of the two differential interferometric observables. From the initial separation of the Rover and the Module and the constraint that the Rover remained on the lunar surface, it was possible to determine its entire path (Fig. 1). After a traverse of over 4 km, the final position computed from these data differed from the actual position by about 30 m, or about 0.015 arc second at the distance of the moon (*4*). The main source of error was relative phase drift between the two receivers (one each for the Rover and the Module) used at each site in this trial experiment. In an operational system this error would be eliminated by using a single receiver for both signals. The basic technique appears capable of reducing tracking errors to the meter level, a limit imposed by unmodeled lunar topography.

A related scientific application involves the accurate determination of the moon's libration by monitoring simultaneously from several tracking stations the ALSEP (*5*) telemetry transmitters located at three well-separated sites, such as those of Apollo 14, Apollo 15, and Apollo 16. Here, because the ALSEP's are fixed on the lunar surface,

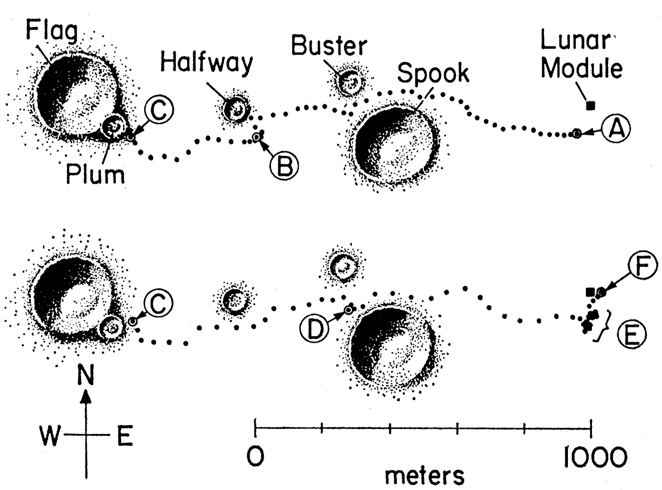

Fig. 1. The path of the Apollo 16 Lunar Rover is shown as determined by Earth-based differential interferometric tracking on 21 April 1972. Individual dots mark the positions obtained at 20-second intervals, beginning at 20:52:40 U.T. from point *A*. Craters given names by the astronauts are included for reference, although their locations are known only approximately. The Rover was stopped at point *B* for 6^m20^s, at *C* for $1^h9^m40^s$, and at *D* for 27^m0^s; several brief stops were made at *E*. At 23:03:40 our tracking indicated that the Rover had stopped finally at *F*, 30 m east of the Lunar Module; the Rover had actually parked at the Module. Some of this error may reflect a corresponding error in the assumed starting position, *A*. However, tracking data obtained while the Rover was known to be stopped occasionally showed systematic drifts as large as 2 or 3 cm/sec (see text). Random noise was less than 1 m. At all times during the traverse, position readings from the navigation system on board the Rover agreed within 100 m (approximately the limit of precision of the onboard system) with these differential interferometric tracking results.

their relative positions must be determined by monitoring changes in the phases of the differential interferometric observables over a sizable fraction of a day. Lunar libration causes these apparent positions to vary over the course of a month, and longer. The differential nature of the observable sharply reduces the effects of errors in the lunar ephemeris, tracking station coordinates, and so forth, and should yield at least an order of magnitude improvement in our knowledge of the libration [present uncertainty about 10 seconds of selenocentric arc (6)].

Differential interferometric tracking of planetary probes, landers, and orbiters will yield results in many cases more accurate than can be obtained from tracking satellites of the earth. This seemingly paradoxical conclusion follows because the usual limitation is set not by signal strength but by systematic effects of the atmosphere and ionosphere, and sometimes by receiving-system phase instabilities. These effects cancel in the differential interferometric observable. A planetary application of differential interferometry which is analogous to, but more complicated than, the Lunar Rover–Lunar Module situation involves tracking a number of small probes descending simultaneously into Venus's atmosphere (7). By differential tracking of the free-falling probes relative to a parent spacecraft it should be possible to detect horizontal winds at the level of a few meters per second. Differential interferometry could also aid in the interpretation of occultation data (8). Additional applications of differential interferometry to both orbiters and landers are too numerous to be elaborated here; for example, improved estimates of the planet's gravity model parameters, rotation vector, and landing site or orbit parameters may be expected [see, for example, (8)]. Whenever the planet passes close to the direction of an extragalactic radio source, differential interferometry may be used to determine the earth-planet direction relative to that of the source to about 0.001 arc second. Such measurements could be used to determine precisely the orientation of planetary orbits with respect to an inertial frame and, for example, to monitor the perihelion precessions to further test general relativity. For ground-based radiometric mapping of the terrestrial planets, differential interferometry can overcome the effects of instrumental, atmospheric, and ionospheric phase drifts, which limit the application of aperture-synthesis techniques. A phase reference could be provided, for example, by the specular echo of a radar signal sent at the appropriate frequency (9). Such mapping appears especially important for Mars where the distribution of small amounts of surface water (or ice) might be discernible from millimeter-wavelength observations (*10*).

In summary, the technique of differential interferometry seems capable of solving a wide range of astronomical problems.

C. C. COUNSELMAN, III
H. F. HINTEREGGER
I. I. SHAPIRO

Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge 02139

References and Notes

1. This principle has already been applied in lunar and planetary radar experiments, in mapping the relative positions of closely spaced sources in the sky, and in the detection of the differential gravitational deflection of radio signals by the sun. Our discussion concerns new applications, especially ones in which a carrier signal is available from each source.
2. A matched-filter receiver could then be used to estimate the delay at each site, in the same way as for two-way ranging. See, for example, J. V. Evans and T. Hagfors, Eds., *Radar Astronomy* (McGraw-Hill, New York, 1968), pp. 500–509. The value obtained at one site would not, by itself, be significant, but the difference between sites would. Phase delay could be measured simultaneously with group delay if a Doppler counter were also available at each site. In addition to not requiring direct recording of the signals for VLBI, artificial sources have an enormous signal-to-noise advantage over natural sources because they are coherent.
3. These stations (in Madrid, Spain; on Ascension Island; and at Cape Kennedy, Florida) belong to the Spacecraft Tracking Data Network (STDN) of the National Aeronautics and Space Administration (NASA), and are managed by Goddard Space Flight Center.
4. A detailed discussion of the algorithms used is presented by us in "The STDN Metric Tracking Performance Apollo 16 Final Report," No. X832-72-203, available from the Librarian, Goddard Space Flight Center, Greenbelt, Maryland 20771.
5. ALSEP is an acronym for Apollo Lunar Surface Experiments Package.
6. Observations of the ALSEP's to determine the lunar libration are now being considered by the STDN (3) (I. Salzberg, personal communication).
7. Space Science Board, *Venus, Strategy for Exploration* (National Academy of Sciences, Washington, D.C., 1970), pp. 33–34.
8. W. H. Michael, Jr., D. L. Cain, G. Fjeldbo, G. S. Levy, J. G. Davies, M. D. Grossi, I. I. Shapiro, G. L. Tyler, *Icarus* **16**, 57 (1972).
9. This application of differential interferometry is similar to the phase-calibration technique used for unambiguous radar delay-Doppler mapping of Venus by A. E. E. Rogers and R. P. Ingalls [*Science* **165**, 797 (1969)].
10. C. Sagan and J. Veverka, *Icarus* **14**, 222 (1971).
11. The Lunar Rover tracking results shown here resulted in part from the programming and related aid performed at Goddard Space Flight Center by E. S. Shaffer and D. Shnidman of the Bendix Company. Invaluable support was also provided by the Metric Data Branch at Goddard, and especially by the Tracking Data Evaluation Section. The Lunar Rover tracking project was headed by I. Salzberg.

19 June 1972

A Scanning X-Ray Microscope Using Synchrotron Radiation

Abstract. *Focused synchrotron radiation collimated by means of a pinhole has been used to construct a scanning x-ray microscope capable of making stereoscopic element-discriminating pictures of relatively thick specimens in an atmospheric environment.*

We have constructed an element-discriminating microscope with the soft x-ray portion of the synchrotron radiation from the Cambridge Electron Accelerator (CEA) as a source. In this report we describe the prototype design and present some results obtained during the initial weeks of operation. It is our hope that some of the microscope's unique characteristics might be useful in a variety of disciplines, and we encourage those interested in possible applications of the microscope to communicate with us.

The CEA, which is currently being used in electron-positron colliding beam experiments, is a source of synchrotron radiation. The radiation emitted by relativistic electrons of energy γmc^2 (where m is the rest mass, c is the speed of light, and γ is the "Lorentz factor" E_{total}/mc^2) moving in a circle of radius R, observed outside the orbit and in the orbital plane, consists of a series of short electromagnetic pulses spaced apart by the orbital period $2\pi R/c$. The radiation is confined to a fan-shaped beam within an angle of order $\theta \simeq 1/\gamma$ of the orbital plane, and has a spectrum (power per unit energy interval at a photon energy E) which is essentially a continuum proportional to $E^{1/3}$ up to a peak photon energy $E_P \simeq \gamma^3 \hbar c/R$ (where $\hbar$ is Planck's constant), and dropping rapidly at higher energies (*1*).

With the CEA operating at 3 Gev, the synchrotron radiation spectrum has its peak at about 2 kev and emits copiously in the spectral region from 100 ev to 5 kev, where elements of low to moderate atomic number have their K absorption edges. Furthermore, the x-ray power emitted per unit solid angle in this part of the spectrum exceeds by three to six orders of magnitude that available from conventional x-ray tubes,