VERY-LONG-BASELINE INTERFEROMETRY APPLIED TO GEOPHYSICS

W.E. Carter and D.S. Robertson

Geosciences Laboratory
Office of Ocean and Earth Science
National Oceanic and Atmospheric Administration
Rockville, MD

ABSTRACT. Very-long-baseline Interferometry (VLBI) has opened for study a broad new spectrum of geophysical phenomena including: direct observation of the tectonic motions and deformations of the Earth's crustal plates, observations of unprecedented detail of the variations in the rotation of the Earth, and direct measurement of the elastic deformations of the Earth in response to tidal forces. These new measurements have placed significant constraints on models of the interior structure of the Earth; for example, measurements of the variations in the Earth's nutation have been shown to be particularly sensitive to the shape of the core-mantle boundary. The VLBI measurements will allow us to construct a global reference frame accurate at the centimeter level. Such a frame will be essential to studying long-term global changes, especially those changes related to sea-level variations as recorded by tide gauge measurements.

1. Introduction

The history of observational science is punctuated by the invention of revolutionary instruments such as the telescope and spectroscope for astronomy, the microscope for biology, the particle accelerator for physics and the seismometer for geophysics. These critical inventions often redefined whole branches of science by allowing the study of entirely new classes of phenomena. The effect of many of these new instruments was to increase attainable measurement accuracies by several orders of magnitude. Very-long-baseline interferometry (VLBI) is a recent example of such a revolutionary development in geophysical instrumentation.

By improving the accuracy and sensitivity of position determinations on the Earth by about three orders of magnitude over previously available techniques, VLBI allows us to greatly refine measurements of certain phenomena, such as polar motion and nutation, and to observe entirely new categories of phenomena such as the tectonic motions and deformations of crustal plates, the effects of core-mantle interactions on the rotation of the Earth, and the details of the angular momentum interchanges between the atmosphere and solid crust of the Earth. Many of these uses of VLBI were first pointed out by Shapiro [Shapiro, 1967; Shapiro and Knight, 1970].

2. Results from Fixed VLBI Networks

2.1. Plate Motions

One of the obvious uses of centimeter-accuracy transcontinental baseline length measurements is to monitor global tectonic processes, the determination of the motions and deformations of the continental-scale plates that comprise the Earth's crust. Classical determinations of plate motions have employed a variety of indirect geological/geophysical information that spans millions of years (magnetic data, transform fault strikes, etc.) to determine the long-term behavior of the crustal plates [Minster and Jordan, 1978; DeMets *et al.*, 1990], but VLBI observations have the capability of determining these motions directly from observations on time scales of a decade or less. Figure 1 shows the determinations of the length of the baseline from Westford, in Massachusetts, to Wettzell, in Germany. The observed increase in baseline

I.I. Mueller and B. Kołaczek (eds.),
Developments in Astrometry and Their Impact on Astrophysics and Geodynamics, 133–144.

length, 18.0 mm/yr, is in good agreement with the prediction of both the Minster-Jordan plate model (18.8 mm/yr) and the NUVEL model (18.9 mm/yr).

There are many other interplate vectors that have been measured with VLBI. Detailed studies have shown that the VLBI determined plate motions are generally in very good agreement with the geological models when the VLBI stations are located in the interior of plates well away form active subduction or fault zones. Attention is now shifting to areas along plate boundaries such as in California and Alaska, and to investigating other tectonic motions such as vertical rebound. The studies in California are particularly interesting because California is one of the rare locations where an extensive plate boundary can be studied on land. The motion of sites such as Vandenberg and Ft. Ord on the Pacific plate (west of the San Andreas fault) relative to sites in North America was found to be consistent with recent geological calculations for plate motions [DeMets *et al.*, 1990], and the spreading of the Basin and Range province was found to be at the level of 9-10 mm/yr [Argus and Gordon, 1990; Clark *et al.*, 1987; Gordon, 1988; Herring, 1986a,b; Herring *et al.*, 1986b; Ryan and Clark, 1988; Sauber *et al.*, 1988].

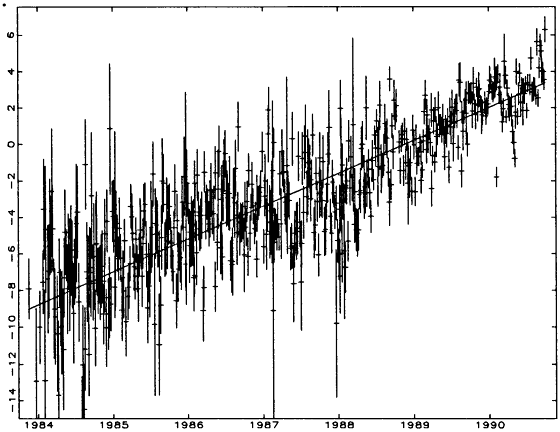

Figure 1. Westford-Wettzell baseline length differences from the weighted mean in centimeters. The vertical bars represent one-sigma formal errors. The best-fit straight line shown has a slope of 18.0 mm/yr.

2.2. Earth Rotation

Classical observations of the Earth's rotation that used optical observations of galactic stars had errors typically at the level of a few tens of milliseconds of arc or about a meter of equivalent displacement at the Earth's surface. In contrast VLBI determinations routinely achieve accuracies of a fraction of a millisecond of arc, or about a centimeter of displacement at the Earth's surface.

The geophysical implications of variations in the Earth's rotation were surveyed recently in Lambeck [1980], Wahr [1986] and Lambeck [1988]. The variations in the Earth's rotation are usually classified into three distinct components. The first component is termed polar motion or wobble, and is the change in the orientation of the Earth's crust relative to its spin axis. The second component is the Earth's total rotational phase angle, called universal time (UT1). Fluctuations in UT1 are sometimes expressed in terms of the length of the day (LOD), which is the negative of the time derivative of UT1. Changes in the orientation of the Earth's spin axis relative to an inertial reference frame in space are referred to as precession and nutation. (The best currently available approximation to such an inertial reference frame can be defined in terms of the locations of extragalactic radio sources observed with VLBI.) These orientation parameters have different sensitivities and responses to a variety of different geophysical phenomena, such as mass shifts of the atmosphere and ocean and interactions between the mantle and fluid core. Each parameter provides a different probe of the magnitude of these interactions.

2.3. Polar Motion

In his classic study of the rotation of rigid bodies Euler showed that if the spin axis of a rigid Earth were not perfectly aligned with its axis of symmetry the rotation axis would exhibit a free nutation about that symmetry axis with a period of about ten months. In the 1890s S.C. Chandler discovered that this polar motion actually had a period of about 14 months and an amplitude of a few tenths of an arc-second, and was mixed with an annual motion with a comparable amplitude. Simon Newcomb quickly showed that the increase in the period from ten to fourteen months could be explained qualitatively as resulting from the effects of the nonrigidity of the Earth.

The three fundamental geophysical problems that are associated with the Earth's wobble relate to the value of its period, the value of its damping factor, Q, and the nature of the excitation mechanism that maintains the motion against damping over geological time scales. These problems are tightly coupled, as it is difficult, for example, to determine the damping factor without knowledge of the excitation mechanism and vice-versa. Jeffreys [1958] and Smith and Dahlen [1981] noted that the Chandler wobble provides a probe of the anelastic properties of the Earth at a period (~435 days) far removed from the seismic frequencies that are commonly employed to determine the structure and rheological properties of the Earth. Recent determinations of the Q of the Chandler wobble using classical observations are in the range of 100-400 [Currie, 1974; 1975; Wilson and Haubrich, 1976; Ooe, 1978]. A full exploitation of the geophysical information provided by this motion of the Earth will require an accurate determination of the excitation mechanism(s).

If we start with an Earth whose spin axis is perfectly aligned with its principal axis of rotational symmetry, so that it exhibits no wobble motion, then virtually any mass shift within the Earth (other than the exceptional case of a mass shift that is symmetric with respect to the spin axis) will change the orientation of the axis of symmetry and move it away from the spin axis. The spin axis will then begin its slowly damped wobble about the new principal axis.

Geophysicists have speculated for years about the nature of the mass shifts that are required to maintain the wobble against damping. The mass shifts associated with large earthquakes were ruled out by Munk and MacDonald [1960, p. 163-164] using a simple argument based on crustal block movement that indicated that the tensor changes were about a factor of 100 to 10,000 too small. But Press [1965] pointed out that earthquake strain fields were much larger than had been realized. Mansinha and Smylie [1967; 1968] claimed to have found a correlation between the epochs of large earthquakes and corresponding shifts in the pole centroid. However, in Stacey's words: "Both convincing observations and realistic calculations indicating adequacy of the earthquake excitation have been difficult to produce." [Stacey, 1977, p. 69]. Chao and Gross [1987] concluded that, "The computed changes in the Earth's global geodetic/gravitational parameters induced by the earthquakes during 1977-1985 are in general two orders of magnitude smaller than the observed values that are available." Meteorological shifts of atmospheric masses are another possible source of the excitation mechanism that has received extensive study [Munk and Hassan, 1961; Wilson and Haubrich, 1976; Wahr, 1982; 1983; Barnes *et al.*, 1983; Hide, 1984]. A related possibility involves changes in the distribution of surface and ground water resulting from changes in rainfall and snow cover [Wilson and Hinnov, 1985; Hinnov and Wilson, 1987; Chao *et al.*, 1987; Chao and O'Connor, 1988; Chao *et al.*, 1988]. Lambeck noted that these meteorological effects are highly detrimental to the use of Earth rotation measurements for studying the properties of the solid Earth. He writes: "Without corrections for this meteorological noise, high precision and high resolution observations of the Earth's rotation lose much of their interest." [Lambeck, 1988, p. 15.] Interpretation of all of these excitation mechanisms is hampered in various ways by the difficulty in obtaining the necessary raw data, such as data concerning the detailed strain fields associated with earthquakes or snow cover depths over central Asia. The nature of the excitation mechanism for the Chandler motion remains one of the major unsolved problems in geophysics.

The major effect of the new VLBI observations on studies of the excitation of the Earth's wobble is to reduce the observational errors to the point that their magnitude is negligible compared to the effects of the forcing functions being studied. This eliminated observational error from the analysis of motion, but does not solve the problem of separating the various sources of the excitation. The VLBI determinations of the pole position from the IRIS 5-day sessions from January, 1984 to December, 1990 are shown in figure 2. The formal errors of the determinations are in the range of 0.5 millisecond of arc, and are shown as barely visible crosses in the figure. The spiral motion seen in the figure results from a 6-year beat phenomenon between the 14-month Chandler motion and a comparable magnitude 12-month motion caused by seasonal atmospheric effects.

To place a bound on the true accuracy of the VLBI pole position determinations we have compared them with comparable determinations from satellite laser ranging (SLR). The RMS differences between the two series have been found to be less than 2 milliseconds of arc [Robertson *et al.*, 1985a]. The differences are too small to display on the scale of figure 2, but figure 3 shows the VLBI and SLR residuals to a generalized pole position model, composed of two elliptical components with annual and Chandler frequencies, respectively, and two terms of a polynomial to account for possible long-term drift. It is clear that the residual (irregular) motion of the pole is at least an order of magnitude larger than the differences between the two separate determinations which bound the total observational errors. The amplitude of these irregular motions, about 30 milliseconds of arc, is roughly the size of the errors in the classical optical determinations of pole position. With the new observations the investigation of these irregular excitations can now proceed virtually unhampered by observational errors.

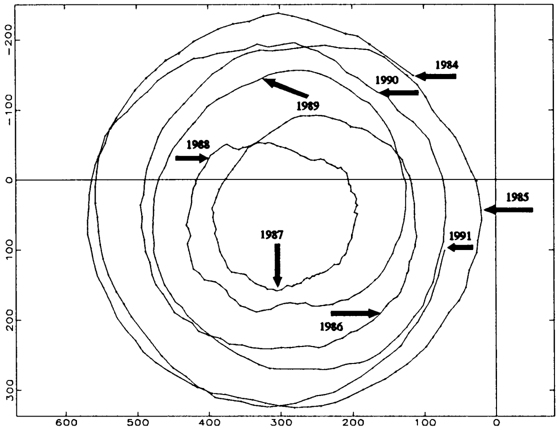

Figure 2. VLBI determinations of the pole position, 1984-1990. Scales are in milliseconds of arc. The linear scale of the spiral figure is about 15 meters across its widest diameter.

2.4. UT1

The physical causes of the variations in UT1 can best be understood in the context of the total angular momentum of the Earth, **L**. If we write **L** = **I**ω, where **I** is the inertia tensor of the Earth and ω is the spin vector, then it is clear that UT1 variations, which entail changes in the magnitude of ω, can be caused by either changes in the total angular momentum of the solid Earth, **L**, or changes in **I**, the inertia tensor. Both types of effect have important consequences for the observed variations in UT1.

The largest short-period changes in the inertia tensor of the Earth are caused by tidal effects. Both the Sun and Moon raise a tidal bulge in the solid Earth. Because those bodies are not restricted to the Earth's equatorial plane, the symmetry axes of the tidal bulges will follow the motion of those bodies into and out of the equatorial plane. Such motions of the tidal bulge will cause significant changes in the moment of inertia of the Earth, and will

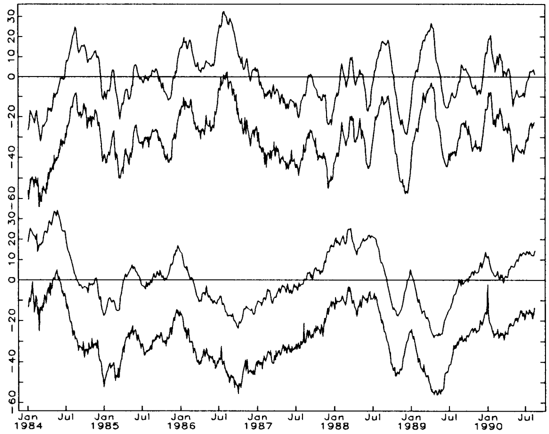

Figure 3. The X-component (top) and Y-component (bottom) pole position residuals in milliseconds of arc from VLBI observations and SLR observations. The SLR residuals have been offset by 30 milliseconds.

produce UT1 variations with amplitudes up to a millisecond of time with periods ranging from a few days to a year.

Figure 4 shows the theoretical tidal variations in UT1 as calculated by Yoder *et al.* [1983], superimposed on measurements of UT1 from daily 45-minute observing sessions using the Westford-Wettzell baseline [see Robertson *et al.*, 1985b]. The observed UT1 values have had a linear drift removed and have been high-pass filtered to remove variations longer than 100 days. The signature of the tidal variations, sinusoidal terms with amplitudes up to 1 millisecond of time (~40 cm) and periods ranging from a few days to months, can be clearly seen in the observations. It is equally clear that other variations (largely meteorological in origin; see below) are also present in the time series.

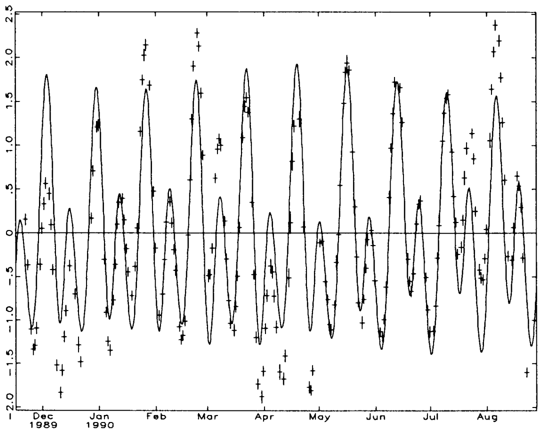

Figure 4. The solid curve shows the predicted Earth tide effects on UT1 in milliseconds of time. The crosses show the observed values from the IRIS daily observing sessions.

The geophysical significance of these tidal variations in UT1 lies in the fact that the driving force (tidal gravity) is well known, and the amplitude of the response to this force is sensitive to the rheological properties of the Earth. In particular, anelastic effects will tend to amplify the response of the Earth, because, other factors being equal, an anelastic Earth will experience slightly less restoring force than a purely elastic one, and its response to a disturbing force will therefore be slightly greater. Wahr has calculated the effects of anelasticity on the UT1 tidal amplitudes [Wahr and Bergen, 1986; Wahr 1988]. He comments that (similar to the polar motion effects) the tidal signatures in UT1 provide a probe of the anelastic properties of the Earth at a frequency range that is far from the range probed with seismic observations (or that of the Chandler wobble).

A study of the tidal amplitudes seen in the daily VLBI observations showed that the formal uncertainty of the estimated tidal amplitudes is at least an order of magnitude smaller than Wahr's calculated effects of anelasticity in the mantle [Robertson *et al.*, 1988]. In other words, the uncertainties in the VLBI observations are a negligible part of the problem. Unfortunately the study also showed that the variability of the tidal amplitudes estimated from different subsets of the data is large compared with the formal uncertainties and compared with the magnitude of the anelastic effects that are of interest. Tentatively at least part of these large variations have been ascribed to effects of ocean water motions on UT1. The oceans obviously respond strongly at the tidal frequencies. Separation of ocean effects from solid Earth effects will require detailed studies of ocean tidal motions, which have only recently been attempted [Brosche *et al.*, 1989].

The other important component of UT1 variation is caused by changes in the angular momentum of the solid Earth, which, of course, represent an exchange of angular momentum with other physical bodies. The most important of these exchanges involve interactions with the Sun and Moon through tidal torques, and momentum exchanges with fluid components of the Earth, especially the fluid core, the oceans and the atmosphere. The tidal torques produce a very slow decrease in the rotation of the Earth, important on time scales of centuries, for which the short time span of available VLBI observations is of little interest. Similarly, effects of the momentum of the fluid core are expected to have characteristic time scales of decades, beyond the period of the current VLBI UT1 results [see Stacey, 1977, p 65-67].

Momentum exchanges with the atmosphere are a different story. The atmosphere has been found to control most of the variability of the rotation of the Earth on time scales significantly shorter than a decade [Barnes *et al.*, 1983; Rosen and Salstein, 1983]; figure 5 shows the variations in length-of-day (LOD) and with the variations implied by changes in the total angular momentum of the atmosphere as calculated from detailed numerical models by the U.S. National Meteorological Center. A quasi-periodic 50-day variation is detectable in both curves [Langley *et al.*, 1981], as is variations at 3 to 5 years associated with the El Niño-Southern Oscillation phenomenon. Important atmospheric phenomena such as El Niño are also reflected in the rotation of the Earth [Carter *et al.*, 1984; Rosen *et al.*, 1984; Chao, 1989]. Recent studies have shown that nontidal variations in LOD with periods ranging from two years down to about 14 days are well correlated with observed changes in the angular momentum of the atmosphere. Below 14 days the correlation disappears [Rosen *et al.*, 1990]. Studies are ongoing to try to determine whether the lack of correlation at periods less than 14 days is due to inaccuracies in the numerical atmosphere models that the angular momentum calculations are based on, or whether some non-atmospheric phenomena, perhaps related to ocean effects, are beginning to dominate the rotational spectrum of the Earth at these periods.

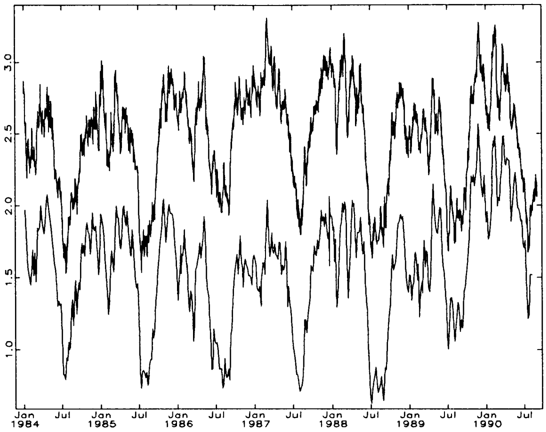

Figure 5. LOD variations inferred from atmospheric angular momentum calculations (top) and IRIS VLBI observations (bottom) in milliseconds of time. The curves are offset for plotting clarity.

2.5. Nutation

The Earth's nutations are similar to tidal variations in UT1 in that the driving mechanisms are well known. The nutations are caused by tidal torques of the lunar and solar gravity fields acting on the Earth's equatorial bulge. The theoretical effects of these torques on realistic models of the Earth have been calculated in great detail by Wahr [1981], whose model for nutation has been adopted by the IAU as the standard to be used for the reduction and analysis of precise astrometric measurements.

Figure 6 depicts the residuals of the VLBI determinations from the Wahr model. Small as they are, the residuals contain a wealth of information about the structure and behavior of the Earth.

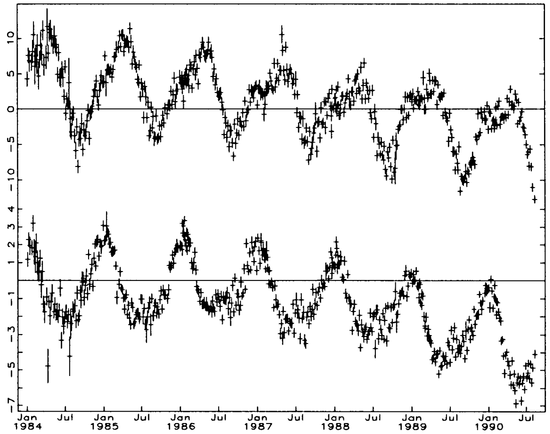

Figure 6. VLBI corrections to the IAU 1984 nutation series, in milliseconds of arc. Corrections in longitude at the top, obliquity at the bottom.

The obvious annual signature which results from a resonance with a natural nutation mode of the Earth, sometimes called the free-core nutation (FCN). This mode is caused by the presence of a fluid core in the Earth constrained within an ellipsoidal cavity defined by the core-mantle boundary (CMB). If the rotation axis of the fluid core were misaligned with the symmetry axis of the CMB then the rotating fluid would exert a torque on the boundary. This torque would cause a precession-like motion of the mantle with a period that was calculated to be about 460 days. (Because of conservation of angular momentum, the fluid core would experience an equivalent motion 180 degrees out of phase with the mantle and with an amplitude that scales by the ratio of the moments of inertia of the core and mantle. [See Toomre, 1974, and Rochester *et al.*, 1974.])

The Earth models used by Wahr to calculate the period of the FCN assumed that the shape of the CMB was such that the boundary was in hydrostatic equilibrium. Gwinn and his colleagues showed that if the CMB deviated from hydrostatic equilibrium by about 0.5 km, then the frequency of the FCN would shift to about 430 days, and this shift would bring the resonant frequency close enough to the 365 day nutation to significantly alter the response of the Earth at that frequency and produce the residual signature seen in figure 6. Part of the significance of this work is that geophysicists concerned with convection processes in the Earth's mantle had suggested that such convection would perturb the shape of the CMB away from hydrostatic equilibrium by about 1.5 km [Hager *et al.*, 1985]. The VLBI observations seem to completely rule out such a large deviation. The consequent change in the annual nutation would have been far outside the errors in the VLBI determinations of that amplitude [Herring *et al.*, 1986*a*; Gwinn *et al.*, 1986].

Fourier analysis of the residuals shown in figure 6 shows other periodic structures, especially at semiannual and 13-day periods. Investigations are currently underway to determine what modifications are needed in the detailed Earth structure models used in the theoretical nutation calculations to account for these deviations from the theory. The 13-day terms may result from effects of tidal motions of ocean water, which were not considered in the nutation theory, and part of the remaining discrepancies may result from effects of the Earth's solid inner core [Matthews *et al.*, 1991*a,b*; Herring *et al.*, 1991; de Vries and Wahr, 1991].

2.6. High Frequency Variations of Earth Rotation Parameters

Recent work has begun to focus on the essentially unexplored realm of sub-diurnal variations in the rotation of the Earth. VLBI observations have been shown to have sufficient sensitivity and time resolution to probe these variations. The observed sub-diurnal variations have amplitudes of a few hundredths of a millisecond of arc and frequencies characteristic of tidal interactions. Preliminary analysis seems to indicate that the effects may be caused by the mass shifts associated with tidal motions of the water in the oceans, although atmospheric effects cannot yet be ruled out [Dong and Herring, 1990].

2.7. Earth Tide Love Numbers

The elastic Earth is perturbed by the same component of the disturbing gravitational potential of the Sun and Moon that raises tides in the ocean. The response of the Earth to this disturbing potential is characterized by a set of scalar values called Love numbers that scale the response: h scales the vertical displacement of the surface and l scales the horizontal displacement. The magnitude of the solid earth displacement due to these tidal stresses is about 30 cm in the vertical direction, and 1-3 cm in the horizontal directions. Studies of estimates of the Love numbers from VLBI observations [Robertson, 1975; Herring *et al.*, 1983; Carter *et al.*, 1985; Ryan *et al.*, 1986; Herring, 1986*a*] have shown values that are in good agreement with theoretical values calculated from the known rheological parameters of the Earth [Wahr, 1981], but, as Herring put it, "The geophysically interesting aspects of Earth tide measurements . . . seem to be below the level where they can be reliably studied by using the VLBI. . . . Improvements in the VLBI models [*e.g.*, atmospheric refraction models] could allow such small displacements to be measured in the future." [Herring, 1986*a*, p. 183].

3. Mobile VLBI Units

3.1. Development

By the late 1970s it had become clear that mobile VLBI stations would be useful for studying regional tectonic problems, such as crustal motions in the highly faulted and tectonically active regions of the western United States. The Jet Propulsion Laboratory constructed three mobile VLBI units using Mark-II recorders [MacDoran, 1979; Davidson and Trask, 1985]. In the middle 1980s these mobile units were upgraded to Mark-III capability and transferred to NOAA.

3.2. Observations of Crustal Deformations Associated with Earthquakes

A series of joint NASA-NOAA observing campaigns in the western United States, Alaska, Canada, and Europe [Lyzenga *et al.*, 1986; Lyzenga and Golombek, 1986; Clark *et al.*, 1987; Ma *et al.*, 1990] were made during the 1986-1989 time frame. Three stations had been occupied by mobile VLBI observatories in the San Francisco area prior to the earthquake at Loma Prieta on October 17, 1989. Immediately following the earthquake the mobile observatories were dispatched to these sites for new observations. No significant offsets were observed for the Presidio and Pt. Reyes sites, the interpretation being that these sites were too far from the rupture zone. However the third station, at Ft. Ord near Monterey, showed a motion of about 4.5 cm in a north-south direction. Figure 7 shows the N-S coordinates of the Ft. Ord site relative to stations on the North American plate. The epoch of the earthquake is indicated by a vertical line. The slope that is seen in the station position before and after the earthquake results from the motion of the Pacific plate relative to the North American plate. (Ft. Ord, as noted above, is on the Pacific plate.) Of course, because there were no observations between May and October, it is not possible from these data to define the epoch of the motion more precisely than a 5.5-month window. However, the observations are consistent with the offset expected at this site from calculations of a coseismic slip model [see Clark *et al.*, 1990].

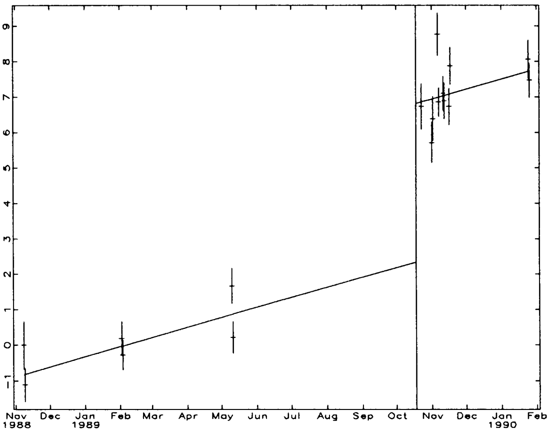

Figure 7. Mobile VLBI determinations of the N-S component at Ft. Ord, California, in centimeters, showing the offset seen at the time of the Loma Prieta earthquake indicated by the vertical line in October.

3.3. Glacial Rebound and Global Sea Level

One of the potentially detrimental effects of global warming is a rapid and large increase in the volume of the ocean, which would cause inundation of highly populated and developed coastal regions. Extracting global absolute sea level from tide gauge records requires removing vertical crustal motions caused by tectonic activity, glacial rebound, and local phenomenon such as subsidence caused by subsurface fluid withdrawal. Glacial rebound models predict millimeter per year or greater vertical crustal motions over the entire globe. In order to verify and help refine these models NOAA has initiated cooperative VLBI observing programs with Canada and Norway. Mobile unit MV-1 has been installed at Yellow Knife, Canada, and will remain at that site for several years to make a direct measurement of the contemporary rate of rebound (expected to be about 6 mm per year). MV-2, which is a newer and much more mobile unit than MV-1, has been assigned to measuring glacial rebound at a station near Trysil, Norway, where the expected velocity is 7 mm per year, and during summer periods to make campaigns to other stations, particularly locations near tide gauge stations.

The first observing season at Trysil was November 1991 to March 1992. A total of 12 observing sessions were completed, and the repeatability of the vertical component of the position are shown in figure 8. These observations represent the current state-of-the-art of mobile VLBI measurements. They were made using a spanned bandwidth at X-band of about 800 MHz, and were recorded at double the normal Mark-III tape speed. The RMS scatter in the up (local vertical) component is 17 mm, indicating that estimates of the vertical crustal rate of motion should be determined to better than 1 mm per year in 3 to 5 years.

4. Conclusions

VLBI observations have opened new windows onto a variety of interesting global phenomena that were too small to be observed with classical geodetic observations. Although the interpretation of many of these observations is still at a preliminary stage, important discoveries have already been made, especially concerning the effects of the shape of the core-mantle boundary on the nutation of the Earth. But perhaps the most important and exciting feature of the VLBI observations is that their accuracy has generally far outstripped our present ability to interpret them. They thus provide great incentives for theoreticians to construct the more detailed models of the Earth and its atmosphere and oceans that will be needed to explain the variety of phenomena seen with the VLBI observations. Unraveling the details of the complex interactions of the elastic and fluid components of the Earth is a difficult problem, but it is a problem that is well matched to the rapidly expanding number-crunching capability of modern computers. In some areas a great deal of progress has already been made. One of the more difficult tasks, computer modeling of the total angular momentum of the atmosphere, has already provided insight into the spectrum of the interactions between the atmosphere and the solid Earth. There is every reason to expect that as the detailed numerical models of the interactions between the atmosphere, oceans, and solid Earth become more sophisticated that further insight will be provided into the dynamics of the Earth and its constituent parts. In time the models should allow us to calculate the effects of these interactions at a level commensurate with the accuracy of the present VLBI observations.

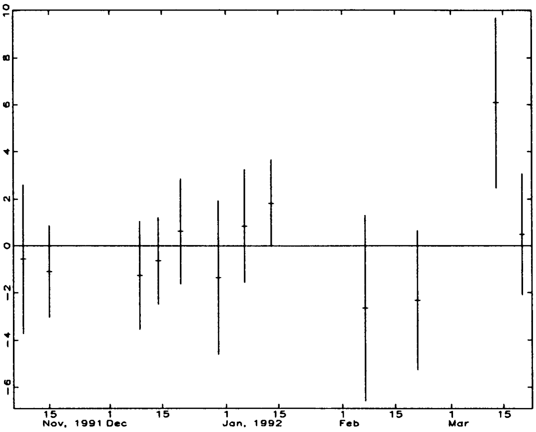

Figure 8. Vertical position determinations at Trysil, Norway, in Centimeters.

References

Argus, D.F., and R.G. Gordon, 1990, Pacific-North American Plate Motion from Very Long Baseline Interferometry Compared with Motion Inferred from Magnetic Anomalies, Transform Faults, and Earthquake Slip Vectors, *J. Geophys. Res.*, **95**, 17315-17324.

Barnes, R.T.H., R. Hide, A.A. White, and C.A. Wilson, 1983, Atmospheric Angular Momentum Fluctuations, Length-of-Day Changes and Polar Motion, *Proc. Roy. Soc. Lond.*, **A387**, 31-73.

Brosche, P., U. Seiler, J. Sünderman, and J. Wünsch, 1989, Periodic Changes in Earth's Rotation Due to Oceanic Tides, *Astron. Astrophys.*, **220**, 318-320.

Carter, W.E., D.S. Robertson, J.E. Pettey, B.D. Tapley, B.E. Schutz, R.J. Eanes, and Miao Lufeng, 1984, Variations in the Rotation of the Earth, *Science,* **224**, 957-961.

Carter, W.E., D.S. Robertson, and J.R. MacKay, 1985, Geodetic Radio Interferometric Surveying: Applications and Results, *J. Geophys. Res.*, **90**, 4577-4587.

Chao, B.F., 1989, Length-of-Day Variations Caused by El Niño-Southern Oscillation and Quasi-Biennial Oscillation, *Science*, **243**, 923-925.

Chao, B.F., and R.S Gross, 1987, Changes in Earth's Rotation and Gravity by Earthquakes, *Geophys. J. R. Astron. Soc.*, **91**, 569-596.

Chao, B.F., and W.P. O'Connor, 1988, Global Surface-water Induced Seasonal Variations in the Earth's Rotation and Gravitational Field, *Geophys. J. R. Astron. Soc.*, **89**, 263-270.

Chao, B.F., W.P. O'Connor, A.T.C. Chang, D.K. Hall, and J.L. Foster, 1987, Snow-load Effect on the Earth's Rotation and Gravitational Field, *J. Geophys. Res.*, **92**, 9415-9422.

Chao, B.F., W.P. O'Connor, and A.T.C. Chang, 1988, Snow-load Excitation of the Earth's Annual Wobble, in *The Earth's Rotation and Reference Frames for Geodesy and Geodynamics*, A.K. Babcock and G.A. Wilkins, (eds.), Kluwer, Dordrecht, Holland, 373-380.

Clark, T.A., D. Gordon, W.E. Himwich, C. Ma, A. Mallama, and J.W. Ryan, 1987, Determination of Relative Site Motions in the Western United States Using Mark III Very Long Baseline Interferometry, *J. Geophys. Res.*, **92**, 12741-12750.

Clark, T.A., C. Ma, J.M. Sauber, J.W. Ryan, D. Gordon, D.B. Shaffer, D.S. Caprette, and N.R. Vandenberg, 1990, Geodetic Measurements of Deformation in the Loma Prieta, California Earthquake with Very Long Baseline Interferometry, *Geophys. Res. Lett.*, **17**, 1215-1218.

Currie, R.G., 1974, Period and Q_w of the Chandler Wobble, *Geophys. J. R. Astron. Soc.*, **38**, 179-185.

Currie, R.G., 1975, Period, Q_p, and Amplitude of the Pole tide, *Geophys. J. R. Astron. Soc.*, **43**, 73-86.

Davidson, J., and D. Trask, 1985, Utilization of Mobile VLBI for Geodetic Measurements, *IEEE Transactions on Geoscience and Remote Sensing*, **GE-23**, 438-449.

DeMets, C., R.G. Gordon, D.F. Argus, and S. Stein, 1990, Current Plate Motions, *Geophys. J. Int.*, **101**, 425-478.

de Vries, D., and J.M. Wahr, 1991, A Solid Inner Core Nutational Normal Mode and Its Effects on the Earth's Forced Nutations and Diurnal Body Tides, *J. Geophys. Res.*, **96, B5**, 8275-8293.

Dong, D., and T.A. Herring, 1990, Observed Variations of UT1 and Polar Motion in Diurnal and Semi-diurnal Bands, *EOS, Trans. Am. Geophys. Un.*, **71, no. 17**, 482-483.

Gordon, D., 1988, Geodesy by Radio Interferometry: Determination of Vector Motions for Sites in the Western United States, in *The Impact of VLBI on Astrophysics and Geophysics*, M.J. Reid and J.M. Moran, (eds.), Kluwer, Dordrecht, Holland, 351-352.

Gwinn, C.R., T.A. Herring, and I.I. Shapiro, 1986, Geodesy by Radio Interferometry: Studies of the Forced Nutations of the Earth, Part II: Interpretation, *J. Geophys Res*, **91**, 4755-4765.

Hager, B.H., R.W. Clayton, M.A. Richards, R.P. Comer, and A.M. Dziewonski, 1985, Lower Mantle Heterogeneity, Dynamic Topography, and the Geoid, *Nature*, **313**, 541-545.

Herring, T.A., 1986*a*, Very Long Baseline Interferometry, in *Space Geodesy and Geodynamics*, A.J. Anderson, (ed.), Academic Press, London, 169-196.

Herring, T.A., 1986*b*, Precision of Vertical Position Estimates from Very Long Baseline Interferometry, *J. Geophys. Res.*, **91**, 9177-9182.

Herring, T.A., B.E. Corey, C.C. Counselman III, I.I. Shapiro, A.E.E. Rogers, A.R. Whitney, T.A Clark, C.A. Knight, C. Ma, J.W. Ryan, B.R. Schupler, N.R. Vandenberg, B.O. Ronnang, G. Lundquist, G. Elgered, J.A. Campbell, and P. Richards, 1983, Determination of Tidal Parameters from VLBI Observations, in *Proceedings of the Ninth International Symposium of Earth Tides*, J. Kuo (ed.)., E. Schweizerhart'sche Verlagsbuchhandlung, Stuttgart, 205-214.

Herring, T.A., C.R. Gwinn, and I.I. Shapiro, 1986*a*, Geodesy by Radio Interferometry: Studies of the Forced Nutations of the Earth, Part I: Data Analysis, *J. Geophys Res*, **91**, 4745-4755.

Herring, T.A., I.I. Shapiro, T.A. Clark, C. Ma, J.W. Ryan, B.R. Schupler, C.A. Knight, G. Lundqvist, D.B. Shaffer, N.R. Vandenberg, B.E. Corey, H.F. Hinteregger, A.E.E. Rogers, J.C. Webber, A.R. Whitney, G. Elgered, B.O. Ronnang, and J.L. Davis, 1986*b*, Geodesy by Radio Interferometry: Evidence for Contemporary Plate Motion, *J. Geophys. Res.*, **91**, 8341-8347.

Herring, T.A., P.M. Matthews, B.A. Buffet, and I.I. Shapiro, 1991, Forced Nutations of the Earth: Influence of Inner Core Dynamics III. Very-Long-Baseline Interferometry Data Analysis, *J. Geophys. Res.*, **96, B5**, 8259-8273.

Hide, R., 1984, Rotation of the Atmospheres of the Earth and Planets, *Phil. Trans. R. Soc. Lond.*, **A 313**, 107-121.

Hinnov, L.A., and C.R. Wilson, 1987, An Estimate of the Water Storage Contribution to the Excitation of Polar Motion, *Geophys. J. R. Astron. Soc.*, **88**, 437-459.

Jeffreys, H., 1958, A Modification of Lomnitz's Law of Creep in Rocks, *Geophys J. R. Astr. Soc.*, **1**, 92-95.

Lambeck, K., 1980, *The Earth's Variable Rotation: Geophysical Causes and Consequences*, Cambridge University Press, London.

Lambeck, K., 1988, The Earth's Variable Rotation: Some Geophysical Causes, in *The Earth's Rotation and Reference Frames for Geodesy and Geodynamics*, A.K. Babcock and G.A. Wilkins, (eds.), Kluwer, Dordrecht, Holland, 1-20.

Langley, R.B., R.W. King, I.I. Shapiro, R.D. Rosen, and D.A. Salstein, 1981, Atmospheric Angular Momentum and the Length of the Day: a Common Fluctuation with a Period Near 50 Days, *Nature*, **294**, 730-733.

Lyzenga, G.A. and M.P. Golombek, 1986, North American-Pacific Relative Plate Motion in Southern California from VLBI Measurements, *Science*, **233**, 1181-1182.

Lyzenga, G.A., K.S. Wallace, J.L. Fanselow, A. Raefsky, and P.M. Grouth, 1986, Tectonic Motions in California Inferred from VLBI Observations, 1980-1984, *J. Geophys. Res.*, **91**, **B9**, 9473-9487.

Ma, C., J.M. Sauber, L.J. Bell, T.A. Clark, D. Gordon, W.E. Himwich, and J.R. Ryan, 1990, Measurement of Horizontal Motions in Alaska Using Very Long Baseline Interferometry, *J. Geophys. Res.*, **95**, **B13**, 21991-22011.

MacDoran, P.F., 1979, High Mobility Radio Interferometric Geodetic Monitoring of Crustal Movements, *Tectonophys.*, **52**, 47.

Mansinha, L., and D.E. Smylie, 1967, Effect of Earthquakes on the Chandler Wobble and the Secular Pole Shift, *J. Geophys. Res.*, **72**, 4731.

Mansinha, L., and D.E. Smylie, 1968, Earthquakes and the Earth's Wobble, *Science*, **161**, 1127.

Matthews, P.M., B.A. Buffet, T.A. Herring, and I.I. Shapiro, 1991*a*, Forced Nutations of the Earth: Influence of Inner Core Dynamics 1. Theory, *J. Geophys. Res.*, **96**, **B5**, 8219-8242.

Matthews, P.M., B.A. Buffet, T.A. Herring, and I.I. Shapiro, 1991*b*, Forced Nutations of the Earth: Influence of Inner Core Dynamics 2. Numerical Results and Comparisons, *J. Geophys. Res.*, **96**, **B5**, 8243-8257.

Minster, J.B., and T.H. Jordan, 1978, Present-day Plate Motions, *J. Geophys. Res.*, **83**, 5331-5354.

Munk, W.H., and G.J.F. MacDonald, 1960, *The Rotation of the Earth*, Cambridge University Press.

Munk, W.H., and E.S.M. Hassan, 1961, Atmospheric Excitation of the Earth's Wobble, *Geophys. J. R. Astron. Soc.*, **4**, 339.

Ooe, M., 1978, An Optimal Complex ARMA Model of the Chandler Wobble, *Geophys. J. R. Astron. Soc.*, **53**, 445-457.

Press, F., 1965, Displacements, Strains and Tilts at Teleseismic Distances, *J. Geophys. Res.*, **70**, 2395.

Robertson, D.S., 1975, Geodetic and Astrometric Measurements with Very Long Baseline Interferometry, Ph.D. dissertation, M.I.T., 1975. Also available as NASA GSFC X-document No. X-922-77-228 and NOAA reprint, National Geodetic Information Center, Rockville, MD.

Robertson, D.S., W.E. Carter, B.D. Tapley, B.E. Schutz, R.J. Eanes, 1985*a*, Polar Motion Measurements: Sub-Decimeter Accuracy Verified by Intercomparison, *Science*, **229**, 1259-1261.

Robertson, D.S., W.E. Carter, J. Campbell, and H. Schuh, 1985*b*, Daily UT1 Determinations from IRIS Very Long Baseline Interferometry, *Nature*, **316**, 424-427.

Robertson, D.S., W.E. Carter, and F.W. Fallon, 1988, Earth Orientation from the IRIS project, in *The Impact of VLBI on Astrophysics and Geophysics*, M.J. Reid and J.M. Moran, (eds.), Kluwer, Dordrecht, Holland, 391-400.

Rochester, M.G., O.G. Jensen, and D.E. Smylie, 1974, A Search for the Earth's "Nearly Diurnal Free Wobble," *Geophys. J. R. Astron. Soc.*, **38**, 349-363.

Rosen, R.D., and D.A. Salstein, 1983, Variations in Atmospheric Angular Momentum on Global and Regional Scales and the Length of Day, *J. Geophys. Res.*, **88**, 5451-5470.

Rosen, R.D., D.A. Salstein, T.M. Eubanks, J.O. Dickey, and J.A. Steppe, 1984, An El Niño Signal in Atmospheric Angular Momentum and Earth Rotation, *Science*, **225**, 411-414.

Rosen, R.D., D.A. Salstein, and T.M. Wood, 1990, Discrepancies in the Earth-Atmosphere Angular Momentum Budget, *J. Geophys. Res.*, **95**, 265-279.

Ryan, J.W., T.A. Clark, R.J. Coates, C. Ma, W.T. Wildes, T.A. Herring, I.I. Shapiro, B.E. Corey, C.C. Counselman, H.F. Hinteregger, A.E.E. Rogers, A.R. Whitney, C.A. Knight, N.R. Vandenberg, J.C. Pigg, B.R. Schupler, and B.O. Ronnang, 1986, Geodesy by Radio Interferometry: Determinations of Baseline Vector, Earth Rotation and Solid Earth Tide Parameters with the Mark I Very Long Baseline Radio Interferometry System, *J. Geophys. Res.*, **91**, 1935-1946.

Ryan, J.W., and T.A. Clark, 1988, NASA Crustal Dynamics Project Results: Tectonic plate motion measurements with Mark-III VLBI, in *The Impact of VLBI on Astrophysics and Geophysics,* M.J. Reid and J.M. Moran, (eds.), Kluwer, Dordrecht, Holland, 339-340.

Sauber, J., T.H. Jordan, G.C. Beroza, T.A. Clark, and M. Lisowski, 1988, Constraints on North American-Pacific Plate Boundary Deformation in Central California from VLBI and Ground-based Geodetic Data, in *The Impact of VLBI on Astrophysics and Geophysics,* M.J. Reid and J.M. Moran, (eds.), Kluwer, Dordrecht, Holland, 353.

Shapiro, I.I., 1967, New Method for the Detection of Light Deflection by Solar Gravity, *Science*, **157**, 806-808.

Shapiro, I.I., and C.A. Knight, 1970, Geophysical Applications of Long-Baseline Radio Interferometry, in *Earthquake Displacement Fields and the Rotation of the Earth*, L. Mansinha, D.E. Smylie, and A.E. Beck, (eds.), 285-301, D. Reidel, Dordrecht, Holland.

Smith, M.L., and F.A. Dahlen, 1981, The Period and Q of the Chandler Wobble, *Geophys. J. R. Astron. Soc.*, **64**, 223-282.

Stacey, F.D., 1977, *Physics of the Earth*, Wiley, New York.

Toomre, A., 1974, On the 'Nearly Diurnal Wobble' of the Earth, *Geophys. J. R. Astron. Soc.*, **38**, 335-348.

Wahr, J.M., 1981, The Forced Nutations of an Elliptical, Rotating, Elastic and Oceanless Earth, *Geophys. J. R. Astron. Soc.*, **64**, 705-728.

Wahr, J.M., 1982, The Effects of the Atmosphere and Oceans on the Earth's Wobble - I. Theory, *Geophys. J. R. Astron. Soc.*, **70**, 349-372.

Wahr, J.M., 1983, The Effects of the Atmosphere and Oceans on the Earth's Wobble and on the Seasonal Variations in the Length of Day - II. Results, *Geophys. J. R. Astron. Soc.*, **74**, 451-487.

Wahr, J.M., 1986, Geophysical Aspects of Polar Motion, Variations in the Length of Day, and the Luni-Solar Nutations in *Space Geodesy and Geodynamics*, A.J. Anderson, (ed.), Academic Press, London, 281-313.

Wahr, J.M., 1988, The Theory of the Earth's Orientation, with Some New Results for Nutation, in *The impact of VLBI on Astrophysics and Geophysics, proceedings of IAU Symposium No. 129*, M.J. Reid and J.M Moran, (eds.), 381-390, Kluwer Academic Publishers, Dordrecht, Holland.

Wahr, J.M., and Z. Bergen, 1986, The Effects of Mantle Anelasticity on Nutation, Earth Tides and Tidal Variations in the Rotation Rate, *Geophys. J. R. Astron. Soc.*, **86**, 633-668.

Wilson, C.A., and R.A. Haubrich, 1976, Meteorological Excitation of the Earth's Wobble, *Geophys. J. R. Astron. Soc.*, **46**, 707-743.

Wilson, C.A., and L. Hinnov, 1985, Water Storage Effects on the Earth's Rotation, in *Proc. Int. Conf. Earth Rotation and the Terrestrial Reference Frame*, Dept. Geod. Science, Ohio State University, Columbus, Ohio, 415-433.

Yoder, C.F., J.G. Williams, and M.E. Parke, 1983, Tidal Variations of Earth Rotation, *J. Geophys. Res.*, **86**, 881-891.