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NASA-GSFC's Geodetic VLBI Program: a Twenty-year Retrospective

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Abstract. Our geodetic VLBI group at the Goddard Space Flight Center was constituted in 1974 and has been active ever since. The earliest VLBI data in our archives were taken in 1972 with the Mark I VLBI system. In the analysis of these data the formal errors in the length of 4000-km baselines spanning the U.S are typically 70 mm. Today - ~25 years later - with the Mark IIIA VLBI system we are obtaining formal errors under 1 mm for the best comparable baselines. There have been similar improvements in the estimates of UT1 and polar motion based on VLBI. These improvement came about as a result of continuous improvements in data acquisition hardware, correlators, experiment planning and data analysis.

Geodetic VLBI has produced numerous important scientific results. It has verified that the motions of the stable plate interiors are in very good agreement with motions predicted by plate motion models based on data sensitive to effects on the geologic time scale. It has shown that there are broad regions of deformation along the plate boundaries and it has detected discontinuous motions associated with earthquakes. The Earth orientation results showed that space geodetic techniques could completely replace classical techniques for monitoring Earth orientation. Earth orientation results from VLBI have been used to study the Earth's core/mantle interface and ocean tidal currents.

Starting in 1999 our group will be a part of an international consortium measuring Earth orientation on a continuous basis with 24-hour observing sessions scheduled every day and using the Mark IV VLBI system.

1 Introduction

This article is based on a paper at the 1997 Spring Meeting of the European Geophysical Society presenting a review of the history, current status and plans of the geodetic VLBI (Very Long Baseline interferometry) team at NASA's Goddard Space Flight Center (GSFC). This discussion will largely focus on the achievements of what is informally known as 'the East Coast VLBI group', so called because its original members came from GSFC, the Massachusetts Institute of Technology (MIT), and the Haystack Observatory (Haystack). We will mention only briefly the activities of 'the West Coast VLBI group' centered at the Jet Propulsion Laboratory (JPL), which was a VLBI team also funded by NASA. Except for a short period in the early 1980's when the two groups combined forces to pursue mobile VLBI, the groups have operated independently. The authors of this article joined GSFC's VLBI team in 1974 and have worked exclusively in this effort for more than twenty years.

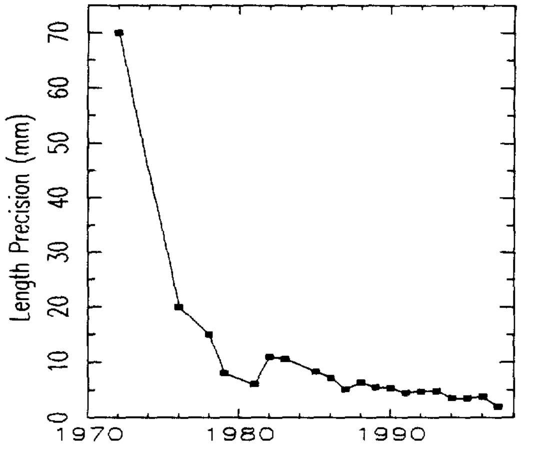

Fig. 1. The evolution of geodetic VLBI baseline length precision for a 4000 km baseline - 1972 to 1997.

2 The evolution of baseline length precision

Figure 1 shows the evolution of the formal precision of VLBI length measurements on 4000-km-long baselines made with the Mark I and Mark III VLBI systems. The individual values are 1-σ errors. Here and in the discussion to follow the 1-σ errors are the formal errors produced by our Mark III Analysis System based on modified observation errors from the correlator. The correlator values are modified by adding in a root-sum-square sense additional noise so that normalized observation residuals for each session in a fully parameterized solution are near unity. We have evidence that, at least for baselines, the actual accuracy is approximately 1.5 times these 1-σ errors (Ryan et al., 1993a). Through 1979, when there were very few sessions, the values are taken from the results from specific sessions. For 1980 to 1992 they are average annual 1-σ values for various California to Massachusetts baselines; from 1993 to 1996 they are similar values on an Alaska to Hawaii baseline; and the 1997 result is taken from a very successful session involving the Very Long Baseline Array (described below). No figure better characterizes the technical evolution of geodetic VLBI. Experiments in 1972 with the Mark I obtained a formal precision of ~70 mm; current formal precision is under 1 mm for the best baselines. In essence, VLBI formal precision has improved by a factor of nearly 100 in the last 25 years, but most of that was achieved by 1979. Nonetheless, the improvement has continued even in the most recent years, albeit slowly. The reasons for this improvement are many and diverse, including better antennas, receivers, data acquisitions systems, correlators, hardware and environmental calibrations, and schedules. The data analysis has also greatly improved in the last 20 years, but the current analysis system was applied to the entire data set to produce these results.

3 The early days - The Mark I era

The concept of radio interferometery over great distances with independent frequency standards, VLBI, was developed for astronomical purposes in the late 1960's in the U.S. (Bare et al., 1967; Moran et al., 1967) and Canada (Broten et al., 1967). Geodetic VLBI is a direct outgrowth of this development. For astronomy errors in the coordinates of the antennas are a nuisance that interferes with the creation of accurate radio source maps, but geodesy they are the signal. Some of the earliest experiments were carried out in the late 1960's by Irwin Shapiro's students at MIT and Thomas Clark at GSFC (Shapiro et al., 1974; Whitney et. al., 1976). By 1972 this group developing the hardware at Haystack Observatory had finished the Mark I VLBI data acquisition terminal (DAT) and correlator.

In geodetic VLBI two antennas receive a broadband radio noise signal from a celestial radio source usually in the 2 to 10 Ghz range; the VLBI observable, called the delay, is the difference in arrival time of the signal at the two antennas. The task of the DAT is to down-convert the signal (using a hydrogen maser frequency standard), digitally sample it, and write the samples to magnetic tape with extremely precise time tags (also derived from the hydrogen maser.) The tapes are sent to a correlator where the signals are cross-correlated to produce the delays. The Mark I was a single-frequency (X-band) system using 1/2" computer tape recording at 720 kbits/sec (Whitney et al., 1976; Ryan et al., 1986).

In 1976 all geodetic VLBI activity at GSFC was combined into a single VLBI activity called the Pacific Plate Motion Experiment (PPME) (although not a single observation from a site on the Pacific plate was acquired under its auspices). The goal of the PPME was technical, specifically to perfect a new generation of hardware and software to be used in Earth science programs of the 1980's. At the outset our team at GSFC entered into a major collaboration with our colleagues at Haystack Observatory and the U.S. National Radio Astronomy Observatory (NRAO). They developed the new generation of VLBI technology called Mark III VLBI (DAT and correlator), participated in Mark I experiments with antennas at Haystack and NRAO, and operated the Mark I correlator. Our group designed the Mark I experiments and developed the Mark III VLBI Analysis System using the Mark I observations as a test bed (Ryan et al., 1986). (The Mark II VLBI system was developed at NRAO, but was never used by our group.)

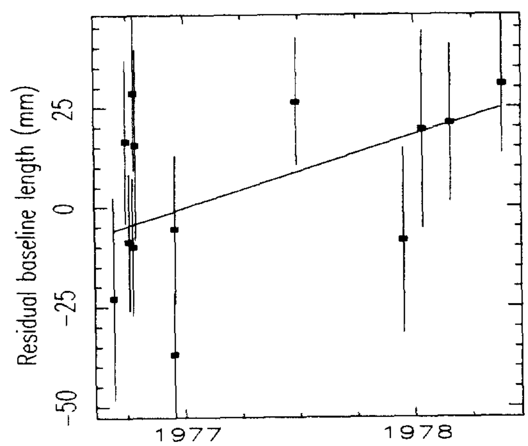

Fig. 2. Evolution of the length of the 4000-km Haystack (Massachusetts) to Owens Valley (California) baseline - 1976 to 1978. The mean length has been removed; error bars are 1-σ.

Between September 1976 and May 1978 the PPME carried out fifteen Mark I experiments with various combinations of the antennas at Haystack Observatory (Massachusetts), the Owens Valley Radio Observatory (California), NRAO (West Virginia), and the Onsala Space Observatory (Sweden) (Ryan et al., 1986). Figure 2 is a time-series plot of the residual length of the ~4000-km Haystack to Owens Valley baseline with 1-σ error bars. The solid line shows a weighted linear fit through the 13 values; the weighted-rms about the line is 19 mm and the slope of the line is 18±15 mm/yr.

Considering the formal error, this is a non-detection of tectonic motion. However, had we actually used an antenna on the Pacific plate, where the motions are a few cm/yr relative to North America, we would almost certainly have detected plate motion.

The baselines between the sites in the U.S. and Onsala were our first to cross a plate boundary, the North Atlantic Ridge separating the North American and Eurasian plates. Unfortunately, there were only 3 experiments spanning 20 months - insufficient data and time span to have any hope of detecting plate motion.

The Mark I era ended in May 1978. Looking back and considering how fervently we wished to detect actual site motion it is ironic that the facilities we used most extensively at that time, Haystack, NRAO, and Owens Valley (all on the North American plate) were connected by what would later prove to be among the most stable baselines that we could have measured (Ryan et al., 1993b). The Mark I era did achieve important milestones that reinforced NASA's commitment to geodetic VLBI. It established that VLBI could routinely measure trans- and intercontinental baselines with precision of a few centimeters. Moreover, it was clear that with this level of precision the measurement of interplate motions, in some places predicted to be many cm/yr (Minster and Jordan, 1978), would become possible within a few years once antennas in the right locations came into use.

4 The arrival of the Mark III

The deployment of the Mark III system in 1979 revolutionized geodetic VLBI. Its dual-frequency receivers (S- and X-band) produced simultaneous delays that could be combined into a delay that was essentially free of ionospheric error and had the random error of the X-band delay. The Mark III had many other improvements compared to the Mark I. It could sample and record up to 28 2-Mhz-wide channels, which produced more precise delays. Honeywell one-inch instrumentation tape drives replaced the computer tape drives of the Mark I. This greatly increased the recording density and made it possible to vary the lengths of the scans and to tailor their lengths to record only the minimum number of bits to ensure an adequate signal-to-noise ratio. Finally the Mark III was designed to operate under computer control, which made much more complicated schedules possible (Rogers et al., 1983).

A Mark III interferometer is inherently a much more sensitive instrument than its Mark I predecessor. In the Mark I era our source catalog contained only 24 of the brightest quasars and in any session the number actually used was typically half that. Our schedules seriously undersampled the sky over the antennas and as a result we could only generate crude estimates of tropospheric refraction and clock parameters. Moreover, many of these bright quasars were large and the locations of their centers of brightness varied depending on the observing geometry, resulting in errors which the analysis could not adequately model. The Mark III could observe much weaker sources. The catalog now has more than 500 quasars with 70 used in routine operations, and most of the Mark I era quasars have been eliminated from routine geodetic use.

The Mark III correlator is much more powerful and efficient than its Mark I predecessor. In its first implementation it could simultaneously process three baselines in near real time, completing a one-day, three-station session in just over one day. In the Mark I era sessions with two and three antennas were the norm and no session had more than four antennas. With the Mark III four or more antennas was usual for NASA-organized sessions and in the past few years there has been a series of 'global' sessions that routinely had 10 or more antennas.

5 The early years of the Crustal Dynamics Project - 1979 to 1984

In 1979 NASA established the Crustal Dynamics Project (CDP), a crucial management milestone because its project status guaranteed long term funding. The VLBI scientific goals of the CDP included measuring large-scale plate motion with antennas located deep in plate interiors, plate motion and deformation in the western U.S. (especially California) and later in Alaska with mobile VLBI systems, and Earth orientation. The CDP also had an equivalent satellite laser ranging scientific program and funded Global Positioning System receiver development. Originally the CDP was to end in the mid-1980's, but because the funding was less than had been planned it was extended in increments until 1991. This longer but lower level of activity proved to be quite fortunate because the longer time span allowed the effects of plate motion to accumulate and be much more accurately detected (Bosworth et al., 1993).

The first extended test of the Mark III took place during the MERIT (Monitor Earth Rotation and Intercompare Techniques) Campaign in September and October 1980, a set of fourteen sessions in two one-week-long bursts using antennas in the U.S. (Haystack, Owens Valley, and the Harvard antenna at Fort Davis (Texas)) and three in Europe (Onsala, the 100-m antenna in Effelsberg Germany, and a 25-m antenna in Chilbolton, England) (Wilkins and Feissel, 1982). This campaign, which lasted less than two months, produced 10,649 observations while the PPME-Mark I era, which lasted four years, produced 5,568 observations. The data were very good, and being free of systematic ionosphere errors, their inherent accuracy is much more like the data taken today than the Mark I data taken only two years earlier.

The National Geodetic Survey (NGS) is the U.S. government agency tasked to monitor polar motion for national needs and in the late 1970's NASA supported NGS in the development of an operational polar motion monitoring system with VLBI (Carter and Strange, 1979). The primary VLBI goal of MERIT was to establish Mark III VLBI as an accurate Earth orientation parameter (EOP) measurement system. In the late 1970's EOP values from the BIH based on classical optical techniques were accurate at the 30-cm level with 5-day resolution (Carter and Strange, 1979). The MERIT one-day EOP values typically had 1-σ uncertainties of 600 μarcsec in pole position and 30 μs for UT1, both of which correspond to ~2 cm level of accuracy (Ma et al., 1995).

From November 1980 through the end of 1983 NGS carried out the POLARIS (POLar-motion Analysis by Radio Interferometric Surveying) program for routine EOP monitoring (Carter and Strange, 1979). It consisted of a weekly series of mostly one-baseline sessions using either the Haystack or Westford antenna and the Fort Davis antenna with the Onsala antenna participating a few times per year. Since most POLARIS sessions were one-baseline they could not be used to measure all three components of EOP. Nonetheless, they did provide high accuracy EOP information in two directions and allowed NGS to gain experience with an operational VLBI program (Carter et al., 1985).

Following MERIT, data acquisition by our GSFC-led team slowed considerably while we digested the MERIT data, established Mark III capability at new antennas, and prepared for the mobile campaigns planned for the western U.S. A major technical development of this period was the instrumentation of fixed antennas in California to act as base stations for the mobile sessions. These were the Hat Creek antenna in north-central California and the Mojave antenna in NASA's Goldstone complex near Barstow (both 1983). The Goldstone-Venus antenna of the Deep Space Network was also instrumented in 1983 by JPL.

After MERIT we continued with regular sessions with the Haystack-Onsala and Westford-Onsala baselines connecting the North American and Eurasian plates. Based on data from 34 of these sessions acquired between August 1979 and May 1984 the first successful detection of tectonic plate motion with VLBI was published (Herring et al., 1986a). The rate was 17±2 mm/yr for the Haystack to Onsala baseline. Figure 3 is a plot of baseline length from a recent solution based on twelve years of data. The vertical line in mid-1984 shows the cutoff for sessions used in Herring et al. (1986a). The estimate of the rate in Figure 3 is 17.8±0.6 mm/yr based on 43 sessions.

In the early 1980's mobile VLBI became a major component of our program. This technique was first developed at JPL in the 1970's in a program called ARIES (Astronomical Radio Interferometric Earth Surveying) (Ong et al., 1976, Thomas et al., 1976). The ARIES mobile system consisted of a transportable antenna with a single-frequency receiver and the NRAO-developed Mark II DAT (Clark, 1973) modified for geodesy. The ARIES program validated the concept of mobile VLBI by successfully obtaining observations, but because it was single frequency the data had limited geodetic use. NASA mandated that the East and West Coast VLBI groups join forces to develop mobile VLBI. The East would provide Mark III technology and the West (specifically JPL) would develop the mobile antennas and equipment transport systems. By mid-1982 JPL had fielded two systems - the MV-1 system with the refurbished 9-m from the ARIES program (used mostly as a base station at Vandenberg AFB) and the entirely new 4-m MV-2 system. In 1983 the 5-m MV-3 system was added.

The first CDP mobile sessions took place in October 1982 with the fixed antennas at Owens Valley and Fort Davis, MV-1 located at JPL, and MV-2 located first at Monument Peak (southeast of San Diego) and then at Quincy (north-central California). The Monument Peak and Quincy sites were selected for these critical first sessions because their baseline was the so-called SAFE (San Andreas Fault Experiment) baseline. SAFE was an NASA experiment in the early 1970's in which satellite laser ranging data first detected plate motion (Smith et al., 1985). Monument Peak

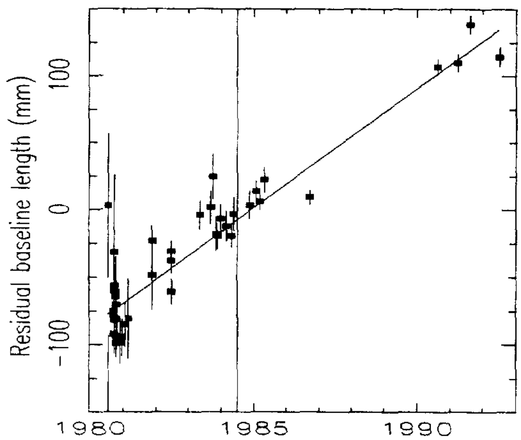

Fig. 3. Evolution of the length of the 5600-km Haystack (Massachusetts) to Onsala (Sweden) baseline - 1980 to 1992. The mean length has been removed; error bars are 1-σ.

and Quincy are on opposite sides of San Andreas faul and the baseline is aligned so the baseline length detects mcst of the expected motion occurring on the fault. Between 1983 and 1988 this baseline was surveyed thirteen times with a mobile system at each end; the measured rate was -25.4±3.3 mm/yr compared to the NUVEL-1 plate model rate of -45.3 mm/yr (Ma et al., 1995; DeMets et al., 1994). The lower measured rate was evidence that the motion between the Pacific and North American plates is not limited to the San Andreas fault but takes place in a broad zone of deformation (Ward, 1988). Following the October 1982 sessions mobile operations did not resume until February 1983, but thereafter there were mobile campaigns nearly every few months until the end of the CDP in 1991.

One surprising result from the early Mark III sessions was the detection of significant errors in the conventional nutation theory, the IAU 1980 model, adopted at the beginning of the decade (Wahr, 1981; Herring et al., 1986b). Figure 4 is a plot of the session-by-session offset corrections to the nutation in obliquity from the Mark III geodetic sessions from 1980 through the end of 1996. The pattern, which is more than 4 millarcseconds peak-to-peak, became very clear as the frequency of sessions increased, but it was evident as early as 1985. One interpretation of this deviation is that "it is the effect of a departure of the core-mantle boundary from its hydrostatic figure." (Gwinn et al., 1986)

The major milestones of the early Mark III era were technological and programmatic. They marked the evolution of all elements of the VLBI hardware, software, and analysis, as well as the establishment of new cooperative relationships. Additional Mark III DATs were fabricated and deployed, the correlator matured into a system capable of heavy sustained use and in 1982 the correlator was upgraded to process six baselines simultaneously. In 1983 the German Mark III correlator in Bonn become operational and began processing international sessions.

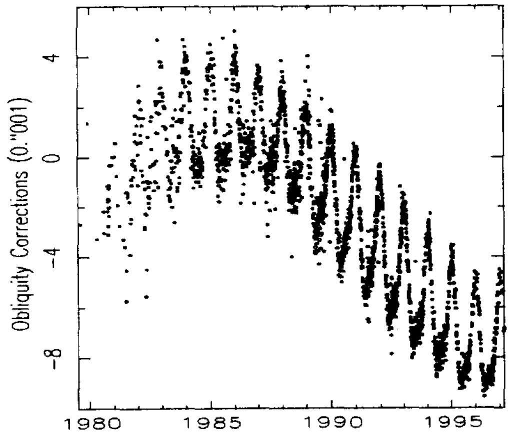

Fig. 4. Corrections to nutation in obliquity from the IAU 1980 model for 2437 VLBI sessions.

6 CDP VLBI as a mature program - 1984 to 1990

In January 1984 the newly-constructed 20-m antenna in Wettzell, Germany and the refurbished 18-m antenna of the U. S. Naval Observatory (USNO) in Richmond, Florida began routine Mark III operations. The four facilities - Wettzell, Westford, Richmond, and Fort Davis - comprised the observing elements of the IRIS (International Radio Interferometric Surveying) Earth rotation service. IRIS, a collaboration of NGS, USNO, and German university and government agencies, replaced POLARIS in January 1984. (The name IRIS was later replaced with IRIS-A to distinguish it from IRIS-P and IRIS-S, two other VLBI EOP programs.) The 26-m antenna in the National Oceanographic and Atmospheric Administration (NOAA) facility in Gilmore Creek, Alaska, reentered service in July 1984 (after a hiatus of 13 years). All of these antennas were dedicated Mark III geodetic VLBI facilities and the Wettzell antenna was built specifically to be the German anchor of IRIS and to become a fundamental geodynamical station. Gilmore Creek was refurbished by NASA as a permanent base station for Alaskan mobile operations and for Pacific Basin sessions. The arrival of these dedicated facilities marked the arrival of Mark III VLBI as a mature system. Figure 5 shows the number of Mark III geodesy sessions per month from 1980 through 1997 including both NASA and non-NASA sessions. During 1984 the number doubled from 5 to 10 sessions per month and the volume increased continuously until 1990 when there was nearly one session per day.

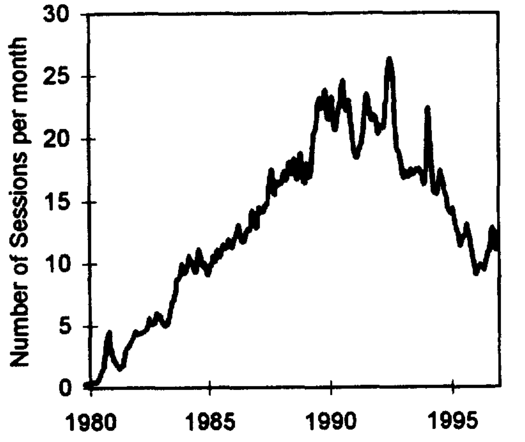

Fig. 5. Smoothed (three-month window) plot of the number of geodetic VLBI observing sessions per month by the GSFC VLBI team and by its associates.

In January 1984 the 26-m antenna at Kashima, Japan began operations with a Japanese-developed, Mark III-compatible DAT; in July 1984 the 12-m antenna at NASA's tracking facility on the island of Kauai, which had been an element of

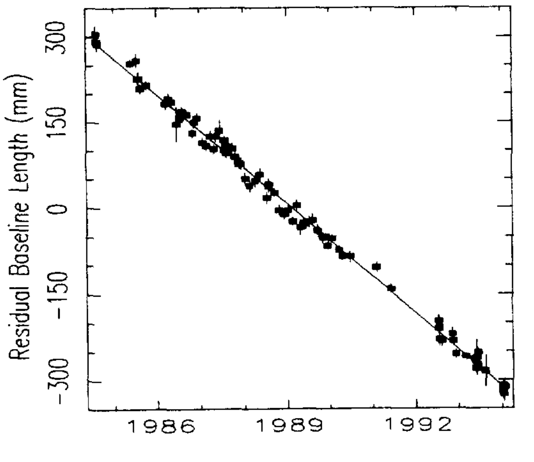

Fig. 6. Evolution of the length of the 5700-km Kashima (Japan) to Kauai (Hawaii) baseline - 1985 to 1994. The mean length has been removed; error bars are 1-σ. The slope of the line is -63.5$\pm$0.8 mm/yr (1-σ).

NASA's Unified S-band System in Apollo Moon program, began a new life as a Mark III VLBI facility. The Kauai antenna finally established geodetic VLBI on the Pacific plate far from the North American/Pacific plate boundary in the U.S. In 1984 routine data acquisition across major portions of the Pacific plate began. Figure 6 is a plot of the length of the Kashima to Kauai baseline spanning 1884 to 1994. The tectonic signal seen in the baseline rate is very large; the slope is -63.5±0.8 mm/yr, a nearly 100-σ detection of motion and a robust confirmation of the motion of the Pacific plate relative to Japan.

Mobile VLBI activity in the western U.S., especially in California, was a large component of the CDP VLBI activities from 1984 to the end of the CDP in 1991. There were a total of 183 sessions involving 23 mobile sites in U.S. and southern Canada (Gordon et al., 1993). These sessions measured the motion along the San Andreas fault using sites within a few kilometers of the fault as well as more distant sites. The data clearly established that the North American/Pacific plate motion occurs in a zone many tens of kilometers either side of the fault (Ward, 1988). Sites outside California established that there is no deformation greater than ~6 mm/yr in the western U.S. except in the deformation zone near the plate boundary (Gordon et al., 1993).

One of the most striking results obtained from these sessions was a measurement of the displacement caused by the Loma Prieta earthquake (October 18, 1989). For some time the CDP had been making mobile VLBI measurements at sites in the Fort Ord military base near Monterey, California, only a few tens of kilometers south of the Loma Prieta epicenter. Five days after the earthquake a mobile system was sent to Fort Ord, and nine sessions involving Fort Ord and the California base stations were acquired within a few weeks. An analysis of the VLBI data showed that the Fort Ord site had moved 49±4 mm at an azimuth of 11±4 degrees as a result of the earthquake (Clark et al., 1990).

In the summer of 1985 the CDP began a major campaign of mobile sessions in Alaska that was designed to measure the deformation associated with the subduction of the Pacific plate under the North American plate that occurs off the Alaska coast (Ma et al., 1990). The campaign continued each summer through 1990 producing 65 sessions. Three sites (Sand Point, Cape Yakataga and Kodiak Island) were on the southern Alaskan coast, two sites (Sourdough and Whitehorse) were inland in southeastern Alaska and the Yukon (Canada), and the fifth site was at Nome on the Bering Sea coast. The Gilmore Creek facility in central Alaska was the primary base station for these sessions, but other sites in the contiguous U.S. also participated. The most striking motion detected occurred on the Gilmore Creek to Cape Yakataga baseline. Figures 7a and 7b are plots of the baseline length and transverse. (For this baseline the transverse is essentially the motion of Yakataga relative to Gilmore Creek in the horizontal plane and perpendicular to the line connecting the two sites (positive to the right)). In the winter of 1987-88 there were two large earthquakes in the Gulf of Alaska south of Cape Yakataga. The plot clearly shows the long term smooth motion caused by the interaction of the Pacific and North American plates as well the jump associated with the earthquakes. The long term trend is that Cape Yakataga is being pushed into the Alaska mainland nearly directly at Gilmore Creek. The motion detected at Kodiak is 11.7±1.0 mm/yr at an azimuth of 315±5 degrees, so its motion is nearly parallel to Yakataga's but much slower. No other site showed motion outside its 99% confidence interval (Ma et al., 1990).

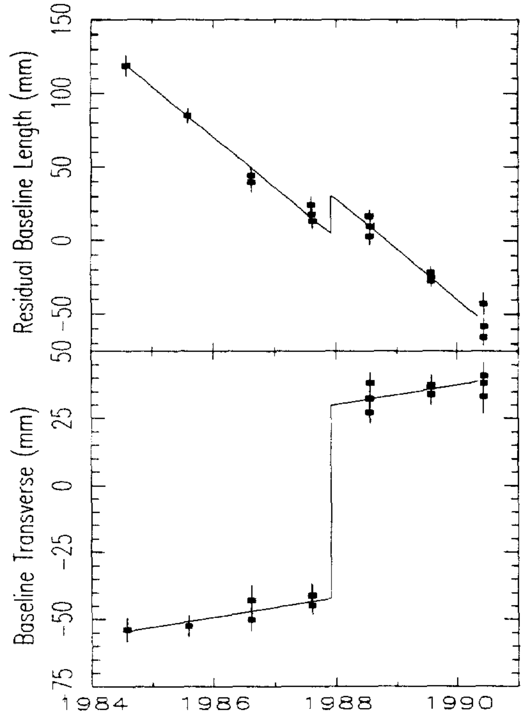

Fig. 7a and 7b. Evolution of the baseline length and transverse of the 600-km Gilmore Creek to Yakataga (both Alaska) baseline - 1984 to 1990. In the length plot the mean has been removed; error bars are one 1-σ. The slopes are -34.4±1.8 and 3.7±0.9 mm/yr (1-σ) and the offsets at the time of the earthquakes are 26.8±5.5 and 72.0±2.9 mm (1-σ) for length and transverse, respectively.

1984-1991 was also the time of numerous Mark III hardware and overall system improvements. These include: the introduction of new Mark III correlator at USNO (1986), the instrumentation of the radio telescope at Hartebeesthoek, South Africa, as the first southern hemisphere geodetic VLBI site (1986), the instrumentation of the 25-m telescope near Shanghai, China (1988) as the first antenna in the Far Eastern part of the Eurasian Plate (not counting one session in 1986 with a 6-m antenna in Shanghai), the implementation of High-Electron-Mobility (HEMT) amplifiers in the receivers (1986), the introduction of the Mark IIIA DAT and correlators with a 14-fold increase in tape-usage efficiency (1988), the instrumentation of DSS-45 and the Hobart antenna in Australia (1989), and the establishment of USNO's own program of VLBI sessions (1990). Also, during this period three antennas in Italy began regular participation in geodetic VLBI sessions: the 32-m Medicina antenna near Bologna (1987), the 32-m Noto antenna in Sicily (1989), and the 20-m Matera antenna just north of the Gulf of Taranto (1990). Medicina and Noto are operated by Istituto di Radioastronomia del Consiglio Nazionale delle Ricerche primarily for astronomy, while Matera was built by the Italian Space Agency specifically for geodetic VLBI.

Until Kashima began operation in January 1984 all Mark III sites were in the contiguous U.S. and Europe. The geophysical analysis of the data from these sites concentrated almost exclusively on measuring relative site motions and interpreting the motions considering tectonic plate motion models. Between early 1984 and the end of 1991 the number of sites that had produced Mark III data increased from 31 to 99 and most the large plates had been sampled. With these data it became possible to move beyond merely measuring relative site motions to defining a global terrestrial reference frame (TRF), that is, a set of geocentric site position and velocity vectors. (VLBI itself has no sensitivity to the initial epoch frame tie between the geocenter and the station positions and that information must be supplied externally. However, the motion of the center of the VLBI frame can be tied to the geocenter through the use of a so-called no-net-translation-rate constraint.) Using data through 1991 our group produced a global terrestrial reference with 95 sites and 1-σ errors generally less than 4 mm in position and less than 2 mm/yr (Ma et al., 1993).

In 1990 AUTOSKED, a VLBI schedule generation program, was introduced. It automatically creates observation schedules based on starting conditions, rules for observing, and statistical estimates. It was conceived and initially developed by the VLBI group at the Geodetic Institute of the University of Bonn and was perfected by the GSFC group. Prior to AUTOSKED each observation was 'hand picked' by an analyst with the aid of SKED (a program which displayed possible observations) and intuition - a tedious and only marginally scientific process. AUTOSKED could generate an entire schedule of observations using objective scientific criteria with only a few minutes of computer time. This was a breakthrough which produced schedules that were much more robust. AUTOSKED was a critical advance which must be ranked as equal with the hardware improvements of the 1980's.

The CDP ended in 1991 having substantially exceeded all its VLBI technical goals. Its scientific goals had also been achieved: the correctness of the global plate models had been verified for the gross motions of the plates, zones of deformation at the plate boundaries had been detected and measured, and VLBI had established one of the most accurate global terrestrial reference frames. Also, VLBI had been established as a state-of-the-art system for measuring Earth orientation and as the only 'space-geodetic' system capable of measuring nutation and UT1 in the inertial reference frame. Notwithstanding this success, by 1990 it was clear that much of what VLBI had been doing so successfully would soon be done with the Global Positioning System (GPS) at much lower cost and with greater efficiency. A first effect of the arrival of GPS as a scientific tool was the termination of NASA's mobile programs in the western U.S. and Alaska. The mobile systems were then made available to our European colleagues and saw limited use in Europe through 1992. As of 1998 MV-1 is fixed in Yellowknife, Canada, MV-2 has been scrapped, and MV-3 is fixed at Goddard.

7 The post-CDP era

After the end of the CDP in 1991 our group established the technical goal of developing a new generation of VLBI hardware - the Mark IV DAT and correlator. However, because of NASA's limited funds the development of the Mark IV became a joint development of NASA and other agencies. The consortium funding the Mark IV consists of NASA, the USNO, the Smithsonian Astrophysical Observatory, the Bundesamt fuer Kartographie und Geodesie (BKG, Germany, formerly IfAG) and the Joint Institute for VLBI in Europe (JIVE, the Netherlands). Haystack Observatory in the U.S. and JIVE in Europe are leading the development. The Mark IV takes advantage of the many advances in microelectronics since the early 1980's when the Mark IIIA was developed. Two critical advances are a gigabit/second recording system and a correlator architecture which supports the simultaneous correlation of all baselines from up to 16 antennas. To date there have been successful tests of various components of the Mark IV and the full system is expected to be in operation by late 1998. With the Mark IIIA system the cost of operating the correlators limited the number and complexity of VLBI sessions we could schedule; the much more powerful and efficient Mark IV correlator will remove this limitation entirely. (See the VLBI World Wide Web site at http://lupus.gsfc.nasa.gov/vlbi.html for more information about the Mark IV.)

In the post-CDP era we have successfully pursued a number of scientific objectives. We have continued to improve the global terrestrial reference frame with the addition of new antennas, by lengthening the observing span of the old antennas, and by improved scheduling and analysis. Thirty new antennas have participated in at least two sessions since 1990. Some locations not previously mentioned are: Kashima, Japan (a new 34-m antenna, 1990); Santiago, Chile (1991); O'Higgins, Antarctica (1993); Fortaleza, Brazil (1993); Kokee Park, Hawaii (the new USNO 20-m antenna, 1993), Urumqi, China (1994); Siemez, Ukraine (1994), Ny Ålesund, Spitsbergen (1994), Green Bank, West Virginia (the USNO 20-m antenna, 1995), and the 25-m antennas of NRAO's Very Long Baseline Array (VLBA). The VLBA consists of ten antennas - eight in the contiguous U.S. plus antennas in Hawaii and the Virgin Islands.

Figure 8 is a world map showing our VLBI horizontal velocities for a selected set of antennas in the NUVEL-1A no-net-rotation (NNR) reference frame and the corresponding NUVEL-1A velocities (DeMets et al., 1994). The VLBI values were taken from a recent solution which included virtually all data available to us through early 1997. The vectors with arrowheads show the VLBI values and those with a crossed line show the NUVEL-1A model values. An inspection of this figure shows that at this resolution many VLBI and model values are virtually identical. However, sites in deformation zones show large differences. See, for example, the sites in China, Japan, Italy, California and Chile. (A tab-

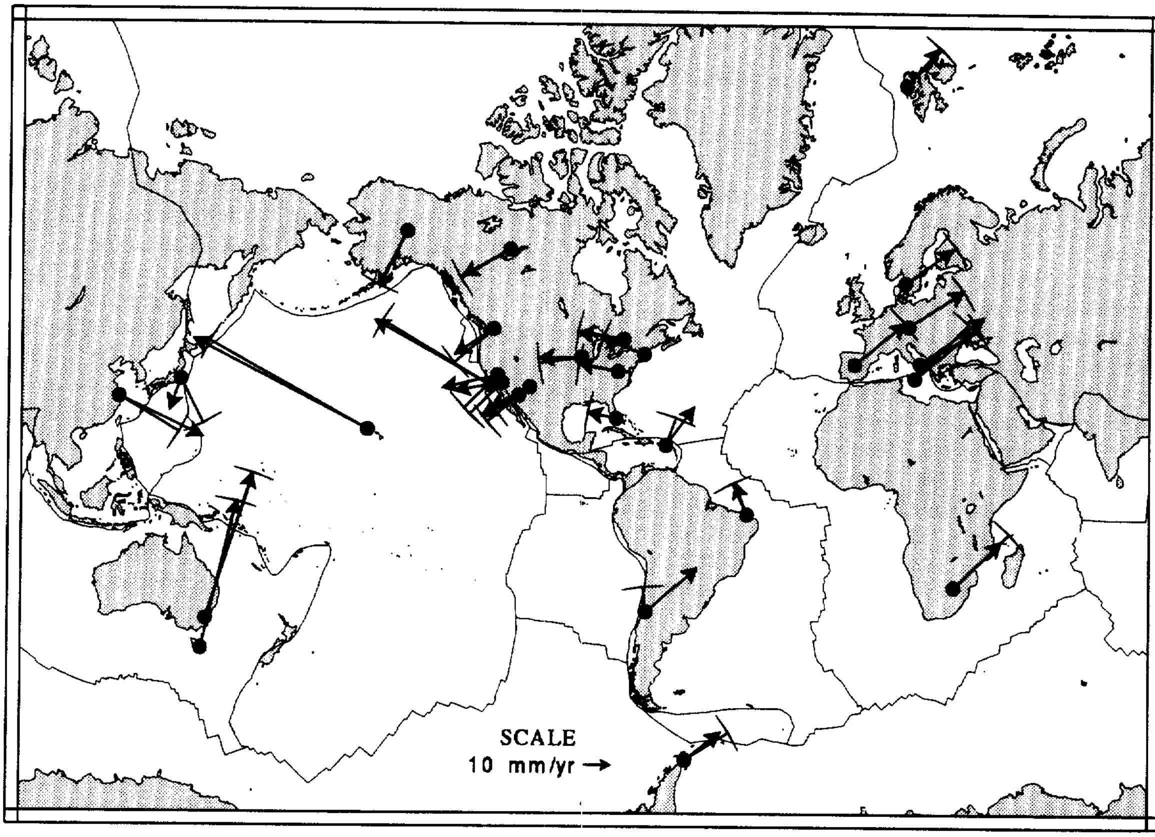

Fig. 8 World map showing VLBI and NUVEL-1A horizontal motion vectors. Lines with arrow heads are VLBI estimates and lines with crossbars are the NUVEL-1A values. The underlying frame is the NUVEL-1A no-net-rotation frame. No error bars are shown.

ulation of the values can be found in our most recent VLBI Annual Report on our Internet site at http://lupus.gsfc.nasa.gov/vlbi.html). The site motions detected with VLBI reflect effects spanning no more than 17 years, while the NUVEL-1A model is based on data spanning the geologic time scale (millions of years). The very good agreement in the measurement of motions of sites in the plate interiors between VLBI and NUVEL-1A is one of the most significant and remarkable results of NASA's space geodesy program.

Recently published geophysical modeling studies have provided estimates of site motions caused by postglacial rebound from the last ice age (James and Lambert, 1993; Mitrovica et al., 1994; Peltier, 1995) and a number of VLBI sites in North America and Europe are located in the rebound zones. Figure 9 is a plot of the vertical component of the Algonquin Park (Ontario, Canada) to Westford (Massachusetts) baseline. According to Peltier (1995) Algonquin Park is rising 2.2 mm/yr, Westford is sinking 1.6 mm/yr, and the Algonquin Park to Westford baseline vertical rate is 3.9 mm/yr. The VLBI measured vertical rate is

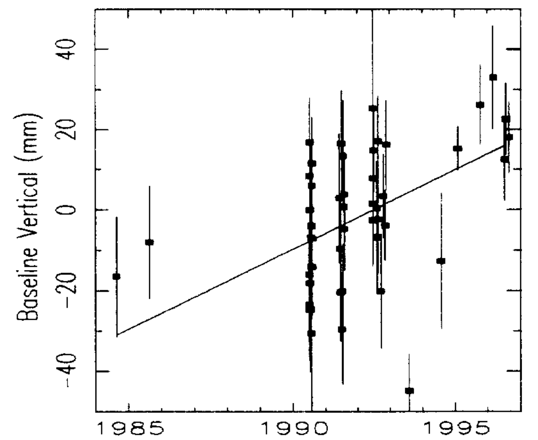

Fig. 9. Evolution of the baseline vertical of the 640-km Algonquin Park (Ontario) to Westford (Massachusetts) baseline - 1985 to 1995; error bars are 1-σ.

4.0±1.5 mm/yr. The solid line in Figure 9 shows the VLBI rate measurement and if we were to plot the Peltier rate it would be indistinguishable. The VLBI-measured site vertical rates are +2.1±0.8 and -1.6±0.5 mm/yr for Algonquin Park and Westford, respectively. This result as well as similar results for Gilmore Creek, Yellowknife, Onsala, and Wettzell have shown that VLBI can effectively measure the subcm/yr postglacial rebound motions.

VLBI has now advanced to the point where it can not only measure EOP each day with great accuracy but also measure changes in EOP continuously within one day (Clark et al., 1997). Figure 10 is a plot of hourly variations in UT1 (from a smoothed *a priori* model) estimated with data from a 24-hour VLBI session which began on November 21, 1996. The points with 1-σ error bars are the VLBI estimates and the sinusoidal line without error bars shows values from a set of tidal parameters derived from years of VLBI data (Gipson, 1996). A mean offset between the estimates and the model has been removed. The sources of these variations are diurnal and sub-diurnal oceanic mass redistributions and currents (Ray et al., 1994; Chao et al., 1996)

From the beginning of POLARIS in 1980 and well into IRIS, NASA acted in support of the operational EOP programs of NGS, NOAA and USNO but was not a part of the international consortium organizing those programs. The operating agencies purchased Mark III technology, funded the antennas, organized the observations, and correlated and analyzed the data. We developed the technology, supplied software, obtained their data and used it in our scientific analysis. Our support role changed in July 1992 when the NASA-supported Gilmore Creek antenna became a routine element of the IRIS-A network. In May 1993 IRIS-A ended and was replaced by NEOS (National Earth Orientation Service). NEOS was superior to IRIS-A because it used a much more widely spaced network. IRIS-A used sites in the contiguous U.S. and Europe (and Alaska in the last year), while NEOS added sites in Brazil and Hawaii. NASA supplied two of the five antennas routinely participating NEOS (Gilmore Creek and Kauai) and became a full member of the consortium organizing operational EOP activities. This was a key milestone in the transition of NASA's geodetic VLBI program from observing tectonic motions to Earth orientation.

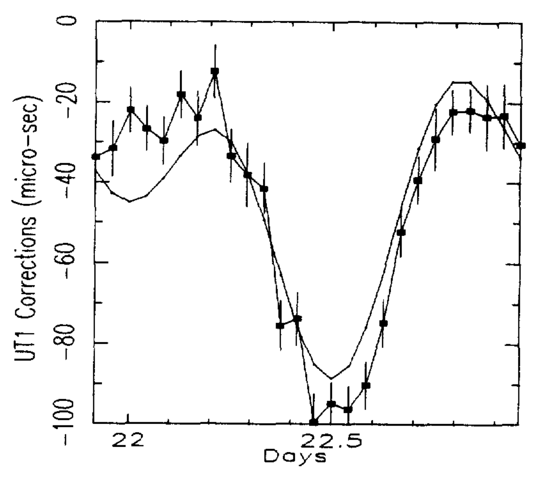

Fig. 10. Hourly corrections in UT1 to a smooth UT1 time series. The line with error bars connects the VLBI estimates and the line without error bars shows the model. The session began near 2200 on November 21, 1996.

8 Evolution of the MARK III VLBI analysis system

The evolution of the Mark III VLBI Analysis System does not fit neatly into the eras defined above because it was continuous and proceeded by many small increments. From 1975 through the present the development of the analysis system has been a major responsibility and activity of the GSFC group. Hardware development, while a major concern of and funded through our group, has mostly taken place elsewhere, primarily at the Haystack Observatory. The earliest incarnation of the analysis system (1976) was based on the VLBI-3 program developed at M.I.T. in the early 1970's, that in turn came from PEP (the Planetary Ephemeris Program), developed at M.I.T. in the 1960's. The advancement of the analysis system has been as far reaching as that of the hardware. Improvements can be divided into two types: better models and more sophisticated parameter estimation.

The improved models include: general relativity, nutation, ionospheric and tropospheric refraction, solid Earth tides, and ocean and atmosphere loading of the solid Earth.

The improvements in parameter estimation require description. Initially troposphere errors were estimated with a constant offset for each location and clock errors by a few low-order polynomials. In the mid-1980's T. Herring at M.I.T. developed a Kalman filter for VLBI analysis (Herring et al., 1990). The breakthrough realization was that VLBI had adequate information content to estimate rapid (as short as a few minutes) fluctuations in these effects so long as the changes were constrained to be physically reasonable. Using Herring's idea we achieved similar signal tracking capability in the Mark III Analysis System through the use of constrained, continuous, piecewise-linear functions. A like improvement was made to the estimation of Earth orientation parameters.

Initially the analysis was limited to processing a single observing session. To detect long term site motions, the single-session baseline results were accumulated and analyzed in an second step that produced baseline rate parameters. In the early 1980's the ability to combine very large, multi-session data sets in a single least-squares estimation using 'arc-parameter elimination' was added to the analysis system (Ma et al., 1990). This process produces a terrestrial reference frame in which site motion estimates, which are critical for geophysical interpretation, are the result of a single step without the loss of information that was inherent in the two-step process. We are now implementing an improved method of matrix handling called B3D developed at the Institute of Applied Astronomy in St. Petersburg, Russia (Petrov, 1997), which should decrease the time required for a large solution by a factor of 5 to 10. Currently the Mark III data set, consisting of more than 2700 sessions and nearly 2,500,000 observations, can be processed through regression analysis in about 15 hours. We expect with B3D and data management improvements already being designed processing time will be cut to a few hours. This projection does not include the effect of advances in computer speeds. For at least the next ten years, even when VLBI data acquisition returns to the level of a session every day, the computer time used to perform regression analysis the entire Mark III/IV data set will be reckoned in hours not days.

9 The future of geodetic VLBI at GSFC

The current plan for geodetic VLBI at GSFC has two major components: exploiting and advancing the development of the Mark IV system, and leading a VLBI observing program called CORE (Continuous Observations of the Rotation of the Earth), which is aimed at continuously measuring EOP over a multi-year period. When fully operational CORE will measure with millimeter resolution all EOP signals from a few hours to years. The data will be a probe of the whole Earth providing information on broad-band effects such as momentum exchanges among the oceans, atmosphere and the solid Earth and periodic effects such as ocean tidal currents and mass redistributions. The nutation information will continue to provide information about the Earth's deep interior through the measurement of the free core nutation. Currently CORE is planned to be fully operational by 2002 when the Mark IV correlators and antennas with Mark IV DATs will be in place. NASA will provide the Westford and Gilmore Creek sites, USNO the Green Bank and Kokee Park sites, and all other sites will be provided by the international VLBI community without which CORE would be impossible. The data will be correlated at USNO, Haystack Observatory, and the Mark IV correlator in Bonn, Germany.

The CORE program is currently in a transition phase carrying out two sessions every two weeks using Mark IIIA technology. One set of sessions, called CORE-A, is simultaneous with weekly NEOS sessions; the second set, called CORE-B, is on days adjacent to the NEOS days. Because both CORE-A and CORE-B measure EOP simultaneously with or adjacent to NEOS they will provide powerful diagnostics to probe the accuracy and systematic errors in our EOP results. The precision goals for CORE in the current phase are 3 μs for UT1 and 100 μarcsec for polar motion with one-day resolution. The CORE goals for 2002 are 1 μs for UT1 and 25 μarcsec for polar motion with one-day resolution. (For more information see the CORE description on our World Wide Web site mentioned above.)

In the late 1980's VLBI was a state-of-the-art system for virtually all aspects of scientific geodesy. The mobile systems were used to measure short to medium scale baselines (up to a few thousand kilometers) and the fixed sites were used to measure baselines spanning the Earth and to measure Earth orientation. Now GPS with its much lower user costs has taken over virtually all short to medium length baseline tasks and is competitive with VLBI for global scale tasks. Geodetic VLBI has been pushed into a niche, but it is a niche in which it is wedged very securely because it has unique attributes:

1) VLBI is the only system tied to the extragalactic, inertial reference frame and so it is the only system for monitoring long term UT1, precession, and nutation as well as defining the celestial reference frame.

2) The terrestrial reference frame from VLBI is state-of-the-art and is a key contributor the International Terrestrial Reference Frame (ITRF), which is the fiducial frame in which GPS data are reduced. Site motions in the VLBI frame have been used to measure post-glacial rebound in North America and Europe.

3) As discussed above, the entire set of all geodetic VLBI data ever taken can be re-analyzed through regression analysis in a few hours and completely reprocessed through model generation from the raw observations and regression analysis in a few days of computer time. This will continue to be so for the foreseeable future as the analysis methods improve and computers become faster. As such, VLBI is ideally suited to the study of effects which require observations spanning decades and the most up-to-date models.

VLBI currently samples only a small fraction of the wide-band radio noise from quasars so that as microelectronics develops in the coming years it will be possible to record more bits with a larger bandwidth, making VLBI observations more precise.

We foresee no reason for the improvement in the accuracy of geodetic VLBI to end in the years to come and there are many important scientific questions which only more accurate VLBI can address. Mark IV should produce much more accurate results than Mark IIIA, but Mark IV is certainly not the end. To use the NASA vernacular, geodetic VLBI will continue to become 'faster, better, cheaper'.

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