MEASUREMENTS OF CRUSTAL MOTION

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In this chapter I will describe what is being done in the making of precision geodetic measurements with very long baseline interferometry (VLBI). A few months ago a number of practitioners of geodetic VLBI tried to assess our error budgets; the composite chart in Figure 12-1 is the result. John Spencer (in Chapter 9), in referring to polar motion and UT, used the right-hand column and took the optimistic view that we had water vapor radiometers (WVRs). Please note that the wet troposphere is the dominant error term in each of the sums shown and that much of the uncertainty arises because WVRs are only now coming into use in an experimental way for calibrating data. They are not available for all stations and do not yet constitute a proven geodetic tool, although they have produced some interesting results.

We are reaching a point at which the baseline measurement seems to be good to about a fringe. Once we reach the level of a fringe, and can trust our calibrations to get to the level of a fringe, then another step forward will be possible. We should then make use of the actual fringe phase on the sky as a much finer ruler within which to make geodetic measurements. We have attempted to use that technique. Several years ago, between the Haystack and Westford observatories (a 1.24-km baseline), we showed that with that technique, even with independent oscillators, we could achieve millimeter-level measurements. However, we must have calibrations commensurate with those numbers.

The current levels of achievement are in the 1- to 3-cm range, except for the local vertical, where the troposphere acts as an additional corrupting agent. Uncalibrated tropospheric contributions, especially on short baseline measurements, essentially raise and lower the apparent level of the station.

The scientific community wants to improve measurements in the vertical to follow the response function of the lithosphere—the perturbations in the crust following earthquakes—and to try to find out more about the nature of the fluid down there. Improving measurements in the vertical is currently a major activity.

Let us now discuss measurements on motion (or nonmotion) seen with VLBI. Peter Bender showed in Chapter 7 a chart of our Haystack to Owens Valley measurements, which now extend over more than 6 years, with some 50 observations. We have detected no motion at levels of...
### CONTRIBUTIONS TO "BOTTOM LINE" BASELINE RESULTS

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<tr>
<th></th>
<th>400 KM VERTICAL</th>
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<td><strong>1.4-2.0</strong></td>
<td><strong>1.4-1.7</strong></td>
</tr>
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(1) FIRST NUMBER ASSUMES WVR, SECOND ASSUMES THE USE OF MODELING OR SURFACE METEOLLGICAL DATA

(2) ASSUMES 10-20 CM A PRIORi DATA (E.G. POLARIS, SLR OR LURE)

**FIGURE 12-1 VLBI error source summary: crustal dynamics project** configuration based on one-day measurement sessions (consensus of VLBI working group in preparation for Oct 82 investigators meeting).

under 1 cm/yr; it is about 3 mm/yr, with 1- formal standard error. None of us believes 1- formal standard errors, so I have called it less than one.

The Westford-Fort Davis Baseline, which resulted from the POLARIS measurement effort that William Carter alluded to in Chapter 8, has also shown a nondetectability of baseline motions at levels of about 1 cm/yr. This finding is based on about 2 years of data, including approximately 100 observations.

With these two sets of 50 and 100 repeated determinations, we are better able to consider the VLBI as a geodetic tool, and to ask, regardless of the size of the formal standard error, how do measurements repeat? If one assumes that there were no motions at the baselines, the RMS repeatability of measurements is at the 2-cm level; it is in accord with the error chart that I showed.

Another baseline for which we have some 10 years of observations and some 35 measurement points extends from Haystack to Green Bank, 850 km; findings there are under 1 cm/yr of motion. In addition, as was reported at a meeting just before this one, the triangle comprising an antenna at the Jet Propulsion Laboratory (JPL), the Owens Valley antenna, and an antenna at Goldstone was also showing under 2 cm/yr of motion on any of the legs of the triangle, ranging from 200 to 400 km. The findings are based on about six to eight observations per baseline.

All the stations, with the exception of Puerto Rico and Hawaii, are located on the North American Plate (8 of the 10 stations). The
proposed Puerto Rican station would be located on the Caribbean Plate, which is moving to the right at about 2 cm/yr velocity, while the Hawaii station would be located on the Pacific Plate.

Let us look now at some regional aspects of tectonics. The two New Mexico observatories are on opposite sides of the Rio Grande Rift. The Rio Grande River is a rifting river caused by separation of the plate across that boundary. Clearly, there is still some current geological activity; the mountains in the area have shown fairly recent volcanic activity, and hot springs and hot vents are prevalent throughout the Rio Grande Valley area. With the connected-element radio link between these observatories and the Very Large Array (VLA), it should be possible to measure spreading across the Rio Grande Rift, which in this epoch is unlikely to be more than 1 or 2 mm/yr but could prove to be an interesting technique synthesis.

The Owens Valley site is located within a few kilometers of the largest earthquake in North America, which occurred in 1872. The extensive volcanic activity and block faulting that occurred as a result of the 1872 earthquake, extending from Lone Pine nearly to Bishop, are easily observed. Because of the antenna located in Owens Valley, some interesting data for aperture synthesis might be obtained. Furthermore, at the moment a large amount of volcanic activity is anticipated slightly to the northwest of the Owens Valley Observatory at Mammoth Lakes, where a hot puddle of molten rock seems to be extruding upward.

Not all earthquake activity is in California. In 1803, one of the highest energy earthquakes that ever occurred in North America was at New Madrid, Missouri. It was felt, and broke glass, as far away as Pittsburgh.

To provide a slightly larger perspective on the VLBA, I took Figure 12-2 from an old document: it includes many of the right stations. Based on conventional tectonic wisdom, where the velocities are derived with time constants of hundreds of thousands to millions of years, the expected velocities between certain stations are of some interest. The Hawaiian station would be expected to move 3.1 cm/yr. The pole of rotation of the Pacific Plate as it moves up goes through New England, so the velocity in length with respect to Haystack is quite small, but the Hawaiian station would be expected to move at velocities in the 1 1/2- to 3-cm/yr range with respect to the rest of the VLBA. Therefore, fairly frequent recalibrations of the array should be planned, and there is the possibility of some interesting free aperture synthesis.

Let us now discuss some geophysical problems relevant to the array. The use of polar motion and UT as a means of measuring global atmospheric circulation has been mentioned by Peter Bender. Since the total angular momentum of the spinning earth system has to be conserved, the earth must slow down as the atmosphere increases speed. By measuring the earth's slowing, one can determine how the integrated winds are blowing. Meteorologists might find this information useful, if for no other reason than as a way to check their independent determinations of integrated winds over the surface of the earth. There are many gaps in their measurement strategy because they lack observatories in a number of places where they would be desirable.
FIGURE 12-2 Interplate velocities (in centimeters per year) for proposed VLBI baselines. Calculations by G. Mead (NAS/GSPC) based on model of Minster and Jordan.

Water distribution on the earth might become detectable through polar motion and UT. For example, if the Eurasian Plate had heavy snowfall one year and North America had only light snowfall one winter, the distribution of mass on the surface of the earth would change, causing the earth to tilt with respect to the inertial rotation axis.

The core-mantle interface and the dynamics of the core are of continuing interest; polar motion and UT will provide information about them.

Finally, quake precursors or postcursors and the response of earthquakes are additional kinds of VLBA data and output that could have great impact on society.

In regard to plate deformation, I mentioned the spreading across the Rio Grande Rift and that Owens Valley is a dynamic area. One of the fundamental assumptions of plate tectonics is that certain parts or lumps of plates are fairly rigid entities. If they were found to be slushy, then much of plate tectonics theory would have to be revised. The VLBA will present some intriguing possibilities for plate motion determinations. The VLBA would provide a very good antenna for Hawaii and the Pacific Plate. The Crustal Dynamics Project attempted to find an available site in Hawaii. Such a site would be advantageous. If there is any choice in the order in which antennas for the VLBA are built, I would like to see one in Hawaii before termination of the Crustal Dynamics Project in 1988.

The Caribbean Plate is another focus of interest. Based on the Caribbean Basin Initiative, NASA has augmented the Crustal Dynamics Project to permit extensive measurements in the general Caribbean Basin area. Arecibo, or the Puerto Rican area, would complement that program.
Measurements to many other points on the earth would also be advantageous, as Robert Coates emphasized in Chapter 11.

Let us consider how geodesy will be done in the 1990s. First, I believe that there will be polar motion and UT networks of the type described by William Carter in operation (see Chapter 8), and that every few days, independent of the array, these will deliver polar motion determinations at accuracies of better than 1 milliarc sec and UT1 at better than 40 microtime seconds. Those networks, combined with radio astronomy facilities and tracking stations around the world, including the VLBA, could be linked a few times a year to form special grids for measuring global-scale plate tectonics. These measurements should be at the 1 or 2 cm level by the 1990s.

Velocities, as I showed earlier, are measured in centimeters per year. Therefore a measuring program to follow plate motions would be possible; it would probably be a little too long a program for a graduate student project. Whether it would be undertaken as a calibration for the VLBA or as a scientific measurement in its own right would have to be decided.

In addition, sparse transcontinental-scale (1000-4000 km) measurements will be made a few times a year with VLBI, using all existing stations, to collect data on the stability of the plates and to serve as fiducial points to co-locate receivers and systems as part of the Global Positioning System (GPS) or its successor to do routine surveying on a dense scale. Measurements on the sparse transcontinental scale are needed only a few times a year because there would be a set of GPS satellites that essentially define a stable geometric grid. As long as the plates are not moving, one could rely on the integrity of that grid and use the co-located GPS stations daily for calibrating the orbit of the satellites.

My view, then, on the frequency of use of the VLBA for geodetic purposes is that only a few measurements a few times a year would be needed. However, even on those time scales it could be quite useful. More dense measurements in time for polar motion and UT, and more dense measurements in space for geodetic grids, would be done by other networks in conjunction with the VLBA.

In conclusion, a few words about what the geodetic community will need from the VLBA. Because the geodetic community will have its own networks, some degree of compatibility between the instrumentation chosen by the VLBA and that used by the geodetic community will be required. At present, that would mean MARK III and S and X band frequencies. Those are not necessarily numbers to be maintained in perpetuity, but they would be current requirements for compatibility. Further, in planning the VLBA there should be a philosophical commitment to achieving proper calibration of the data, using phase calibrators, and WVRs, allowing for two frequency measurements for the removal of ionospheric biases, and the like.

Routine VLBA calibrations, both reduced baseline data (possibly on polar motion and UT) as well as the raw VLBI data (the delay-rate observables) should be made available to those in the geodetic community who may be working with much more precise models of the earth for their analyses than might be in place in the array. Thus from the
outset data should be exportable, not only at the baseline level but also at the more fundamental level coming from the correlator.

The VLBA should be usable in international networks. International networks are essential not only for astronomy but also for geodesy, because global-scale plate tectonics issues are worldwide concerns. Sites of particular geophysical interest include Hawaii, which is the only good radio telescope on the Pacific Plate; Puerto Rico, because it would be a unique facility on the Caribbean Plate; and the linkage between the VLA and the two sites in New Mexico. Various subelements of the array will present opportunities for geophysical measurements of intrinsic interest. The ability to make use of these subelements will be important.

I assume that time on the VLBA will be allocated on the basis of competitive proposals, as has been done at other national facilities. The geophysical sciences should be considered as competitive sciences for the purpose of proposal evaluation. I anticipate that members of the geophysics community will submit proposals for use of the array for geophysical measurements.

I also think that it would be desirable to allow for co-location of GPS at the VLBA sites, or at least at several of the VLBA sites. It will be important to have some representation of the geophysics community on steering and advisory committees for management and operation of the array.

Finally, I agree with William Carter that the VLBI community, which will be working independently, will need the source maps, source fluxes, source coordinates, and other data coming out of the array.

DISCUSSION

CANNON: I want to congratulate you on a complete picture of what would be required in the array installation. I would like to add one comment: The great strength of these techniques for geophysical applications is that they are insensitive to the gravity field. In a sense, that is also a weakness, for much classical geodesy is related to determining the shape of the geoid—interpreting the geoid in terms of subsurface structure. In the Canadian proposal, we are considering co-locating absolute gravimeters at selected sites as well, because both Global Positioning System Network (GPSN) and the VLBA technique will not tie to the gravity field at all.

CLARK: They don't have to be co-located. But if you are going to have a facility, it might as well be at the same site.

HEILIGES: When you say the Crustal Dynamics Project will end in 1988, what does this mean?

CLARK: Current plans call for ceasing operation in 1988, when R&D activity should have reached a state where instrument systems will have been turned over to agencies that are more responsive to operational needs. The same was true for weather satellites: NASA did the early developments. When they became operational tools we turned them over to NOAA.
FLYNN: The geodynamics program will continue past 1988. That is, we are writing a program plan for continuation of these types of measurement activities to complement what will be done in operational agencies to which we are turning over some--not all--of the equipment.

COATES: One thing both Dr. Clark and I neglected to mention is that the measurements we are talking about for baselines are a few parts in $10^9$ in the precision; there is no good way to calibrate that a priori. We will have to continue to use competitive systems. The Crustal Dynamics Project is using satellite laser-ranging to make the same baseline measurements in 30 percent of the cases for direct intercomparison to calibrate both systems. They have different error sources, so running them together is quite useful. In the future for global and even local measurements, there should be provision for other techniques as part of the calibration program.

CLARK: Yes. There are investigators from the geophysical sciences and geodetic measurement sciences who may want to be able to obtain additional information for special purposes. We may need more ground around each antenna.

SHAFFER: The sites should have some established reference point. That is, VLBI astronomers tend to think of the antennae as theirs, but there should be some fiducial mark on the site so that others can bring in a device and locate, too, without a great deal of difficulty.

CLARK: That service has been provided by the National Geodetic Survey (NGS). Dr. Strange might address this when he talks about the National Crustal Motion Network.
III. Astrometry