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"Statistical Description of Tectonic Motions"

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Introduction

Over the period of this award, several distinct topics have been investigated. Since the results have largely been published, either in journal articles or in PhD theses, this report only summarizes these briefly, giving somewhat fuller descriptions of other topics not yet published.

Statistics of Crustal Deformation

One area of study the behavior of stochastic processes whose power spectra are described by power-law or piecewise power-law behavior. Agnew (1992) gives the details of the analysis and the conclusions reached. This analysis can be extended to compare the detection capabilities of different measurement techniques (e.g., gravimetry and GPS for the vertical, and seismometers and GPS for the horizontal), both in general and for the specific case of the deformations produced by a dislocation in a half-space (which applies to seismic or preseismic sources).

If the source of deformation can be approximated by a dislocation in a halfspace, the average displacement $\bar{x}$ at a distance Δ from a source with moment M_0 is very nearly $\bar{x} = K_x M_0/\Delta^2$, for distances of more than a few source dimensions. Similarly, the average displacement gradient (strain or tilt) $\bar{\varepsilon}$ can be approximated by $\bar{\varepsilon} = K_\varepsilon M_0/\Delta^3$. (At close distances these expressions overestimate the effects). For vector horizontal displacement and maximum extension around a vertical strike-slip fault, we find $K_x = 5\times10^{-12}$ and $K_\varepsilon = 10^{-11}$ (Δ in m, M_0 in N-m).

Even though strains and tilts decay much faster with distance than displacements do, the much higher resolution with which strain can be observed over short times makes such observations considerably more sensitive to rapidly-changing sources. Suppose that over a time t we can resolve changes in strain of $\varepsilon(t)$ and in displacement of $x(t)$. Then we can, for example, detect strain changes from a dislocation that releases a moment $M_0(t)$ for distances less than Δ_ε, where $\varepsilon(t) = K_\varepsilon M_0/\Delta_\varepsilon^3$. We can compute a similar distance Δ_x for displacement measurements. The ratio of areas within which the moment release is detectable then reflects the relative density of measurements needed to attain the same detection capability. This is

$$A(t, M_0) = \frac{\Delta_\varepsilon^2}{\Delta_x^2} = \frac{K_\varepsilon^{0.67}}{K_x} \frac{x(t)}{\varepsilon(t)^{0.67}} M_0^{-0.33}$$

Using the values of K_x and K_ε given above, and the short-term resolutions of 10^{-10} for strain ($\varepsilon(t)$) and 2×10^{-3} m for planned continuous GPS systems ($x(t)$), we find A to be about 100 for $M_0 = 10^{18}$ ($M_w = 6$); for such rapid changes, a single strain installation could be expected to cover the same area as 100 geodetic stations. The scaling with moment means that the area "covered" by strain measurements exceeds that for displacement measurements even for the largest earthquakes. For larger t this ratio of areas will not be as great, but for any t, the smaller the source, the greater the relative advantage of measuring displacement gradient rather than displacement. To take an example for a small event, the maximum surface displacement expected from a magnitude 4 earthquake at 10 km depth is only 15 microns, while its strain is an easily detectable 2×10^{-9}.

Earth-Rotation Studies

Another area of investigation was the study of various polar-motion series using multi-taper spectrum analysis techniques applied to both space-geodetic data and conventional astrometric estimates of the earth's polar motion. King and Agnew (1991) found that estimates of the annual wobble of the earth's rotation axis were seriously corrupted in the older data. The newer data however give consistent results, doubling the number of parameters to be fit, and showing that none of the available models are completely adequate.

King (1990) also looked at various earth-rotation series using multitaper spectrum analysis techniques. She examined both space-geodetic data, conventional astrometric series, and historical estimates of changes in the length of day (Δlod), with the following results.

VLBI Data

The IRIS LODR and LOD series are not quite stationary. Power spectra for 4 year-long segments vary for frequencies higher than about 30 cycles per year. The power spectra of these data sets fall off approximately as f^{-2} for frequencies between about 5 and 30 cycles per year.

The GSFC data is an independent reduction of the IRIS data, with CDP observations included as well. The GSFC data is stationary, except in 1984 for frequencies near 30 cycles per year. The power spectra of year-long segments are similar for IRIS LODR and GSFC, except in 1986 near 30 cycles per year. For the entire time period of each data set, the power spectral densities of IRIS LOD and GSFC data are similar for all frequencies.

The JPL TEMPO Δlod, the longest time series, is not stationary since the data quality improves so much over the 10 year time period. Later, high-quality data requires less smoothing. Below about 10 cycles per year, the TEMPO power spectrum is similar to other VLBI spectra. Because of the smoothing applied to the TEMPO data, the TEMPO spectrum fall off more rapidly above that frequency,

IRIS intensive Δlod is stationary at high frequencies. The annual and semi-annual variations are not resolved separately for this short time series. The M_m, M_f, and M_{tm} tides emerge clearly above the continuous background.

LAGEOS Data

Since the LAGEOS data quality improves so much over time, none of the three estimates of Δlod from LAGEOS is stationary. Power spectra of CSR LAGEOS and GSFC LAGEOS LODR are flatter for earlier data. For GSFC LAGEOS, on the other hand, the early data is highly smoothed and the power spectra of later data rise at high frequencies as the smoothing is relaxed. After 1984, the power spectra of CSR

LAGEOS, GSFC LAGEOS, IRIS LODR, and IRIS intensive data are similar. IRIS intensive and CSR LAGEOS spectra validate each other out to the CSR LAGEOS Nyquist frequency of 60.875 cycles per year. Power spectra of GSFC LAGEOS agree with the IRIS LODR spectrum even if the early, noisier data is included.

Combined Data

The JPL COMB87D.CHI and SPACE87D.CHI time series, like the space geodetic data used as input to derive them, are not stationary. The spectra of later data tend to rise at high frequencies, as data quality improves and the Kalman filter smooths less.

There are peaks at 45, 90, and 135 cycles per year, which may be artifacts of the Kalman filter. The power spectra of SPACE87D.CHI and COMB87D.CHI are similar out to about 10 cycles per year. The JPL power spectra agree with spectra of unsmoothed VLBI and LAGEOS Δlod for frequencies below 10 cycles per year. This is consistent with the transfer function of the Kalman filter.

The BIH data (1962 through 1980) are not stationary, since spectra of one-year segments vary significantly for frequencies between 10 and 50 cycles per year. However, the variation is not systematic with time. BIH/IERS data is consistent with JPL combined data, and space geodetic data sets, for frequencies below 10 cycles per year.

Lunar Occultation Data

The power spectrum of Morrison's unpublished monthly lunar occultation data is consistent with the spectrum of JPL SPACE87D.CHI for frequencies below 3 cycles per year. At higher frequencies, the lunar occultation power spectrum tends to be above the JPL spectrum, although the differences are not statistically significant.

The choice of smoothing the older lunar occultation data of Morrison from 1860 to 1942, is unimportant for frequencies below 0.1 cycle per year, but is crucial for higher frequencies. The power spectrum of McCarthy and Babcock's version of the data is similar to the power spectrum of JPL COMB87.CHI, filtered and decimated to 5 day samples. This suggests that their smoothing is appropriate.

Composite Power Spectrum

Combining several power spectra gives a composite spectrum that spans 4 orders of magnitude in frequency. The work with individual data sets in the previous sections allows us to choose an appropriate power spectrum for the intermediate frequency bands. At low frequencies (0.01 to 1 cycle per year), we use the McCarthy and Babcock data from 1860 through 1984. Between 0.04 and 10 cycles per year, we use the power spectrum of JPL COMB87.CHI, filtered and decimated to 5 day samples. At high frequencies, we use the power spectrum of IRIS intensive data with seasonal and tidal variation removed. The composite power spectrum spans the frequency range 0.01 to 182.625 cycles per year. There is a subtle bend in the spectrum around 1 cycle per year. Below this frequency, the power spectrum falls off as approximately f^{-2}. If we extend this power law, it lies systematically below the high frequency half of the power spectrum. We interpret this bend as the transition between core and atmospheric excitation.

GPS Studies

One activity not foreseen at the start of this award was the amount that would be contributed by GPS to the goals of the CDP. The PI and students played a major role in helping these activities commence in southern California. In the nature of crustal deformation studies, the results have taken some time to come out. Dixon *et al.* (1990) describe the first large-scale GPS experiment in southern California, in June 1986. This included the first measurements to the offshore islands of California. Results from this and other experiments (under combined NSF and NASA funding) were described by Larson and Agnew (1991) and Larson *et al.* (1991). The first paper describes the errors estimated from the repeated measurements; the second one describes the systematic effects of varying the fiducial network. Finally, Larsen *et al.* (1993) describe a GPS/EDM comparison across the Santa Barbara Channel, showing substantial rates of NS compression.

Another part of the contribution to GPS studies has been the development of high-stability geodetic monuments, for use with GPS or other space-geodetic techniques. The basic form of the monument is:

1. A ground-level base that is anchored to depth, and decoupled from the surface, as well as possible, using a support-rod arrangement that follows class A rod-mark design by having the rods anchored at depth, and as unconstrained as is reasonably possible toward the surface.
2. An antenna-mount that can be precisely positioned on this base, and can also support other types of measurements, ideally by being able to be removed and precisely reset.

Using a specially-built tripod as the antenna mount allows the antenna to be located well off the ground if this is required for good visibility. The first two tripods built are 6 feet high; their feet have V-grooves which sit on round-end bolts screwed into the base; this is a kinematic mount, which precisely relocates the tripod while not subjecting it to any stress. The bolts (and some screws in the tripod head) must be adjusted when the tripod is first set up to make the top of the tripod level and to position the center hole of the top plate vertically over the mark; once this is done, these screws are locked in place permanently. The system has been designed so that these are not then easily accessible, to minimize possible tampering. The antenna is centered on the tripod by laterally adjusting the tripod cap and locking it into place. The height measurement from the mark to the upper surface of the top plate (on which the antenna rests) need only be made once, and can be done to high accuracy.

The base on which the tripod rests is a stainless-steel triangle frame, embedded in concrete. The reference mark is welded to the frame's center, and the screw-plugs for the tripod support bolts are welded on the apices. (More screw-plugs are welded on the sides of the triangle as part of the system that holds the tripod down.) The installation plan (variable from site to site) is to get several rods or pipes placed as deeply as possible (either driving them or using a small drill rig), weld the triangle to these (adjusting it to be level), and finally encase the whole thing in cement. This, or something like it, should give the best coupling to depth, and the least coupling to material near the surface. The end product is a stabilized pad with only six screw holes and the marker visible; this should be unobtrusive enough to be left in place if the tracker (and tripod) were relocated.

A much simplified version of this multiple deep-anchoring scheme is possible. Without the need for a removable antenna tripod, the antenna stand/monument can be made directly from the anchoring pipes.

For the highest stability we need to install a framework of pipes to several meters in depth this required drilling 3½"-diameter holes about 10-12 m. For such shallow holes, conventional "blasting" hole-drilling equipment (a crawler-drill) is ideal, since drilling at angles up to 45° is a relatively simple matter for this equipment.

Our aim is to fix the position of each corner of the pad's stainless-steel triangular frame with three support rods: one in a vertical hole, and two more in angled ones. Three rods at each corner are wanted because the rods provide essentially no lateral support, but are quite rigid longitudinally. Various estimates of the different modes of elastic yielding of 1¼" Schedule 80 wrought-iron galvanized pipe indicate it should be reasonably stiff longitudinally (300 lbs. per 0.1mm) even over the 6-m-long unrestrained lengths involved, so that having nine pipes welded to the frame will make it quite rigid. While the pipe can buckle, this should have a minimal effect as long as the pipe is moderately well confined laterally. Even with the maximum possible motion our design allows, 2 cm at the midpoint of a 6-m-long unsecured section, we expect only 0.1 mm of longitudinal motion, and this will be suppressed by the elastic strength of the other support pipes.

Monuments of this design, and modifications of it, have been installed (with varied funding) at the Scripps, Piñon Flat, and Vandenberg GPS sites, and also at Monument Peak.

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