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E. GLOBAL AND REGIONAL KINEMATICS WITH GPS

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INTRODUCTION

The inherent precision of the doubly differenced phase measurement and the low cost of instrumentation made GPS the space geodetic technique of choice for regional surveys as soon as the constellation reached acceptable geometry in the area of interest: 1985 in western North America, the early 1990s in most of the world. Instrument and site-related errors for horizontal positioning are usually less than 3 mm, so that the dominant source of error is uncertainty in the reference frame defined by the satellites orbits and the tracking stations used to determine them. Prior to about 1992, when the tracking network for most experiments was globally sparse, the number of fiducial sites or the level at which they could be tied to an SLR or VLBI reference frame usually set the accuracy limit [e.g., Feigl et al., 1993]. More recently, with a global network of over 30 stations, the limit is set more often by deficiencies in our models for non-gravitational forces acting on the satellites. For regional networks in the northern hemisphere, reference frame errors (or uncertainties) are currently about 3 parts per billion (ppb) in horizontal position, allowing centimeter-level accuracies over intercontinental distances (Figure 1) and less than 1 mm for a 100 km baseline (Figure 2).

The accuracy of GPS measurements for monitoring height variations is generally 2-3 times worse than for horizontal motions. As for VLBI, the primary source of error is unmodeled fluctuations in atmospheric water vapor, but both reference frame uncertainties and some instrumental errors are more serious for vertical than horizontal measurements. Under good conditions, daily repeatabilities at the level of 10 mm rms have been achieved (Figure 3), leading to the hope that with frequent or continuous measurements, long-term monitoring of geophysical changes in station heights can be accomplished at the millimeter level.

This paper will attempt to summarize the current accuracy of GPS measurements and their implication for the use of SLR to study regional kinematics. Readers not familiar with the fundamentals of GPS surveying, both field work and analysis, are referred to the recent reviews by Dixon [1991], King and Blewitt [1990], and Hager et al. [1991].

NON-ORBITAL ERRORS IN POSITIONING

There are four primary sources of GPS measurement error that are not related to the accuracy or stability of the reference frame: 1) operator setup error; 2) signal multipathing; 3) deficiencies in modeling the atmosphere; and 4) error or uncertainty in relating the effective phase center of the antenna to the ground mark. For horizontal measurements, each of these sources usually contributes between about 0.5 and 2 mm, so that the aggregate effect varies between 1 mm and 5 mm, with 2-3 mm typical. For vertical measurements, atmospheric effects dominate, at 10-50 mm, except on very short (<2 km) baselines.

Operator setup errors can be limited to about 1 mm in both horizontal and vertical with sufficient care by the field operator. Miscalibrated tribrachs, poor lighting, high wind, and poorly defined center points on the ground monuments can degrade the quality of the setup, but it would be unusual for the total error to exceed 2 mm. For permanent sites with antennas mechanically fixed to a ground mark, there is no significant setup error contributing to measurements of the *change* in position.

Multipath errors are strongly dependent on the environment of the site and the type of antenna used. They are also among the most difficult to assess since they tend to repeat from day to day and alias with atmospheric effects for low elevations. Often the most obvious multipath signature - high amplitude and frequency in the phase residuals - has minimal effect on position estimates, but the invisible low-frequency component may be introducing significant error. I know of no systematic study that quantitatively and reliably relates identifiable multipath to errors in horizontal or vertical position. Crude numerical experiments carried out at MIT, in which spans of high multipath are deleted from the analysis and the elevation cutoff varied, suggest that even several centimeters of high-frequency multipath usually affects horizontal position estimates at the level of only 1-3 mm. Since multipath is frequency dependent (dispersive), its effect is amplified when the ionosphere-free linear combination (LC or L_3) of the two GPS signals (L_1 and L_2) is formed; thus, it will introduce less error into the measurement of very short (<5 km) baselines for which the L_1 (and/or L_2) signal can be used directly.

Atmospheric errors are most serious in estimates of vertical position but can affect estimates of the horizontal if there are azimuthal asymmetries in either the atmospheric delay or the geometry of the satellite constellation. As for VLBI, both water-vapor radiometer measurements and stochastic estimation techniques have proven successful in improving estimates of vertical position [Tralli and Lichten, 1990], but the low elevation (<15 degrees) observations used with fixed VLBI antennas to separate atmospheric and height parameters are not as effective since GPS antennas are omnidirectional and thus subject to significant signal multipathing. To the advantage of GPS, however, are the larger number of "sources" to be observed and the low cost of frequent measurements. Since atmospheric errors for many (though not all) sites are nearly random, the accuracy can be improved by averaging over a large number of observations. This strategy is most easily followed with permanent tracking sites, which can observe continuously for months or years [Bock and Shimada, 1990].

The phase centers of all commonly used GPS antennas have elevation-dependent variations of 10 mm in the LC observable, and some are as large as 50 mm. These variations cancel when matched antennas are used over regional baselines, for which the elevation angle of the satellites from both sites is nearly the same. Alternatively, they can be modeled using anechoic chamber measurements of the antennas [Schupler et al., 1992]. The most serious problem occurs when antennas of different types are used in a survey [Braun et al., 1993; Mireault et al., 1993]. For the commonly used combination of Rogue (Dorne-Margolin with JPL choke ring) and Trimble antennas, horizontal errors of about 2 mm and vertical errors of about 4 mm remain even after modeling the variations [S. McClusky, personal communication, 1994]. Modeling also becomes more important for long baselines since the elevation angle of the satellites will be different for each station. For example, introducing a phase-center model to our analysis of 23 global sites with matched Rogue antennas from the 1991 "GIG" experiment changed estimated heights by 20-30 mm.

STABILITY OF THE GLOBAL REFERENCE FRAME FOR REGIONAL SURVEYS

With the current (43-station) tracking network of the International GPS Geodynamics Service (IGS) there may still be non-negligible reference-frame (baseline-length dependent) errors for regional surveys. The dense northern hemisphere network provides reference-frame control at the level of 1-4 ppb for horizontal, and 2-8 ppb for vertical positions [Blewitt et al., 1992; Heflin et al., 1992]. For the southern hemisphere, however, the density of tracking stations may not be sufficient to reach this level of stability. Analysis of the 1991 GIG experiment, which included 5 southern hemisphere stations, resulted in repeatabilities of 5-10 ppb for baselines between northern and southern hemisphere stations, and 15 ppb for southern hemisphere baselines [Heflin et al., 1992]. The current IGS network includes nine southern hemisphere sites (soon to expand by another five), and there is clear evidence that the stability of the reference frame has shown marked improvement [Heflin et al., 1993].

Although the GPS orbits are dynamically tied to the Earth's center of mass, their high altitude and perturbations by non-gravitational forces result in a significantly weaker tie than for lower laser geodetic satellites such as Lageos. While SLR currently provides a determination of the center of mass at the level of about one centimeter for monthly averages, the GPS estimate is no better than a decimeter [M.G. Heflin and T.A. Herring, personal communications, 1994]. By constraining the motion of the center of mass, however, a few ppb stability can be achieved without applying any further constraint in position or velocity from SLR or VLBI measurements.

SUMMARY AND IMPLICATIONS FOR SLR RESOURCES

For densification of regional networks less than 1000 km in extent, there is little question that GPS measurements equal or exceed the horizontal accuracy available from mobile VLBI or SLR and at a fraction of the cost. For large-scale regional and global kinematics, GPS seems poised also to supplant the older techniques, due principally to the relative economy of fixed, continuously tracking stations. There are some regions of the world for which the longer span of SLR plate motion measurements may warrant their continuation at one or two sites for a few more years [see, e.g., Oral, 1994]. These measurements are most valuable if they provide velocity constraints for the region at the level of a few mm/year.

The jury is still out on the ultimate accuracy and role of GPS in monitoring height variations. Like SLR and (at least mobile) VLBI, GPS seems stuck at the 10 mm level, which may not be sufficient for studying vertical tectonic motions and changes in global sea level. Among the most important experiments that can be carried out over the next few years are rigorous intercomparison of vertical measurements using the three techniques together with efforts to improve the accuracy of each.

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REFERENCES

Blewitt, G., M.B. Heflin, F.H. Webb, U.J. Lindqwister, and R.P. Malla, *Global coordinates with centimeter accuracy in the International Terrestrial Frame using GPS*, Geophys.Res.Lett., 19, 853-856, 1992.

Bock, Y., and S. Shimada, *Continuously monitoring GPS for deformation networks, in Global Positioning System: An Overview*, IAG Symp. No. 102, Y. Bock and N. Leppard, eds., Springer-Verlag, New York, 1990.

Bock, Y., *Permanent GPS Geodetic Array: Continuous measurement of active tectonics in S. California*, (abstract), EOS, Fall Meeting Suppl., 43-59, 1993.

Dixon, T. H., *An introduction to the Global Positioning System and some tectonic applications*, Rev. Geophys., 1991.

Braun,J., C. Rocken, and C.M. Meertens, *GPS antenna mixing and phase center corrections* (Abstract), EOS Full Meeting Suppl., 74, 197, 1993.

Feigl, K.L., D.C. Agnew, Y. Bock, D. Dong, A. Donnellan, B.H. Hager, T.A. Herring, D.D. Jackson, T.H. Jordan, R.W. King, S. Larsen, K.M. Larson, M.H. Murry, Z. Shen, and F.H. Webb, *Space geodetic measurement of crustal deformation in central and southern California, 1984-1992*, J.Geophy.Res., 98, 21677-21712, 1993.

Hager, B.H., R.W. King, and M.H. Murray, *Measurement of crustal deformation using the global positioning system,* Ann. Rev. Earth Planet. Sci., 19, 351-382, 1991.

Heflin, M., W. Bertiger, G. Blewitt, A. Freedman, K. Hurst, S. Lichten, U. Lindqwister, Y. Vigue, F. Webb, T. Yunck, and J. Zumberge, *Global geodesy using GPS without fiducial sites.*, Geophys.Res.Lett., 19, 131-134, 1992.

Heflin, M., G. Blewitt, D. Jefferson, Y. Vigue, F. Webb, D. Argus, T. Clark, J. Gipson, and C. Ma, *Global positions and velocities from one year of GPS data*, viewgraphs from paper presented at the 1993 Fall Meeting of the AGU, EOS, 93, 194, 1993.

King, R.W., and G. Blewitt, *Present capabilities of GPS for high-precision regional surveys, in Global Positioning System: An overview,* IAG Symp. No. 102, Y. Bock and N. Leppard, eds., Springer-Verlag, New York, 1990.

Mireault, Y., F. Lahaye, and P. Taylor, *Preliminary investigation of inter-receiver biases between Ashtech, Leica, Rogue, and Trimble GPS receivers*, viewgraphs from paper presented at the 1993 Fall Meeting of the AGU, EOS, 93, 197, 1993.

Oral, M.B., *Global Positioning System measurements in Turkey (1988-1992), Kinematics of the Africa-Arabia-Eurasia plate collision zone,* Ph.D. Thesis, MIT, Cambridge, MA, 343pp, 1994.

Schupler, B.R., R. Allshouse, and T. Clark, *GPS antennas - measurements and multipath*, DOSE Investigator Working Group Meeting, October, 1992.

Tralli, D.M., and S.M. Lichten, *Stochastic estimation of tropospheric path delays in Global Positioning System geodetic measurements*, Bull. Geod. 64, 127-159, 1990.

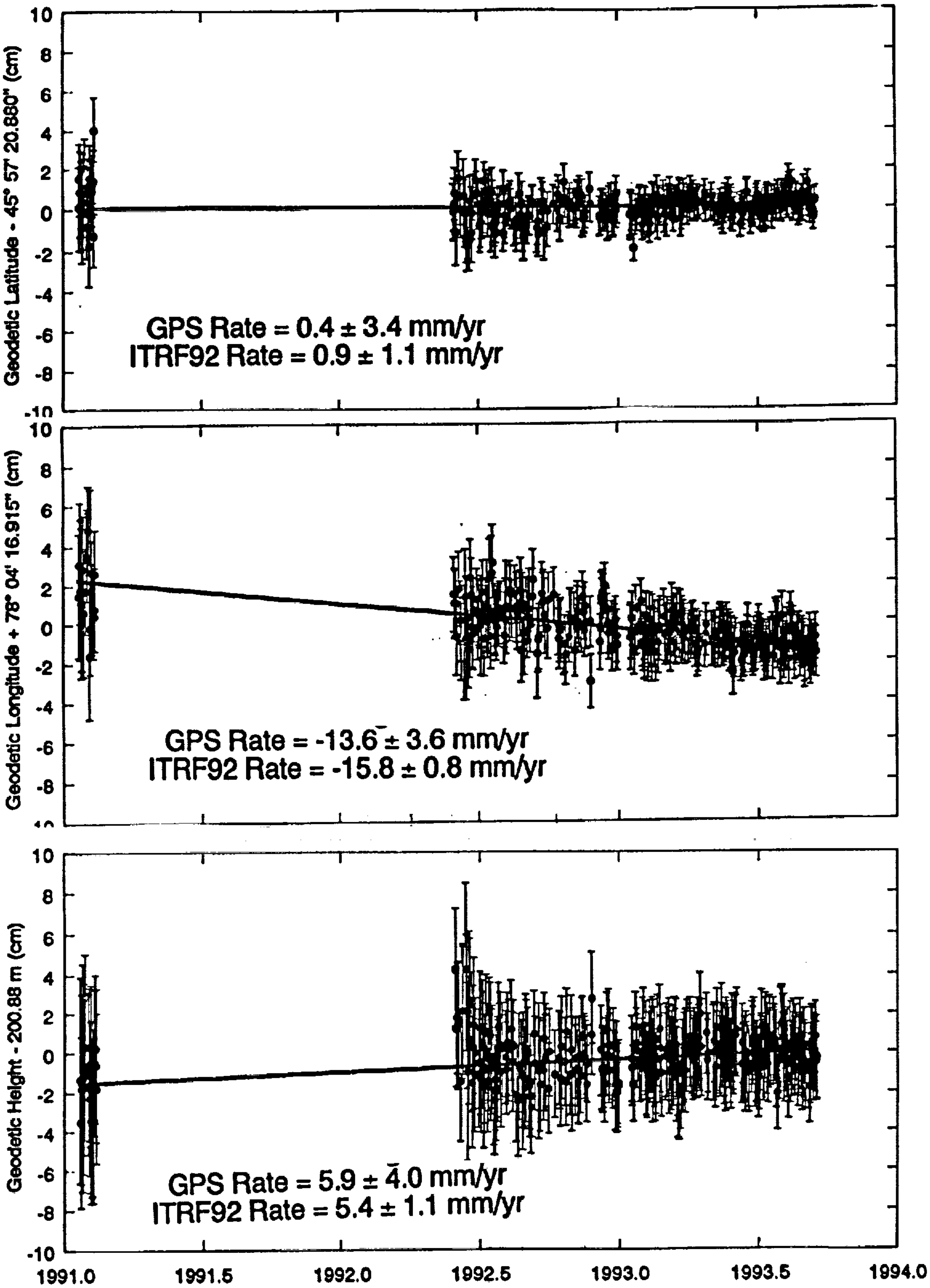

Figure 1. Time evolution of the north, east, and height of Algonquin from GPS estimates in GIG '91 and 1992–93 [*Heflin et al.*, 1993]. The reference frame is defined solely by the global network of GPS tracking stations.

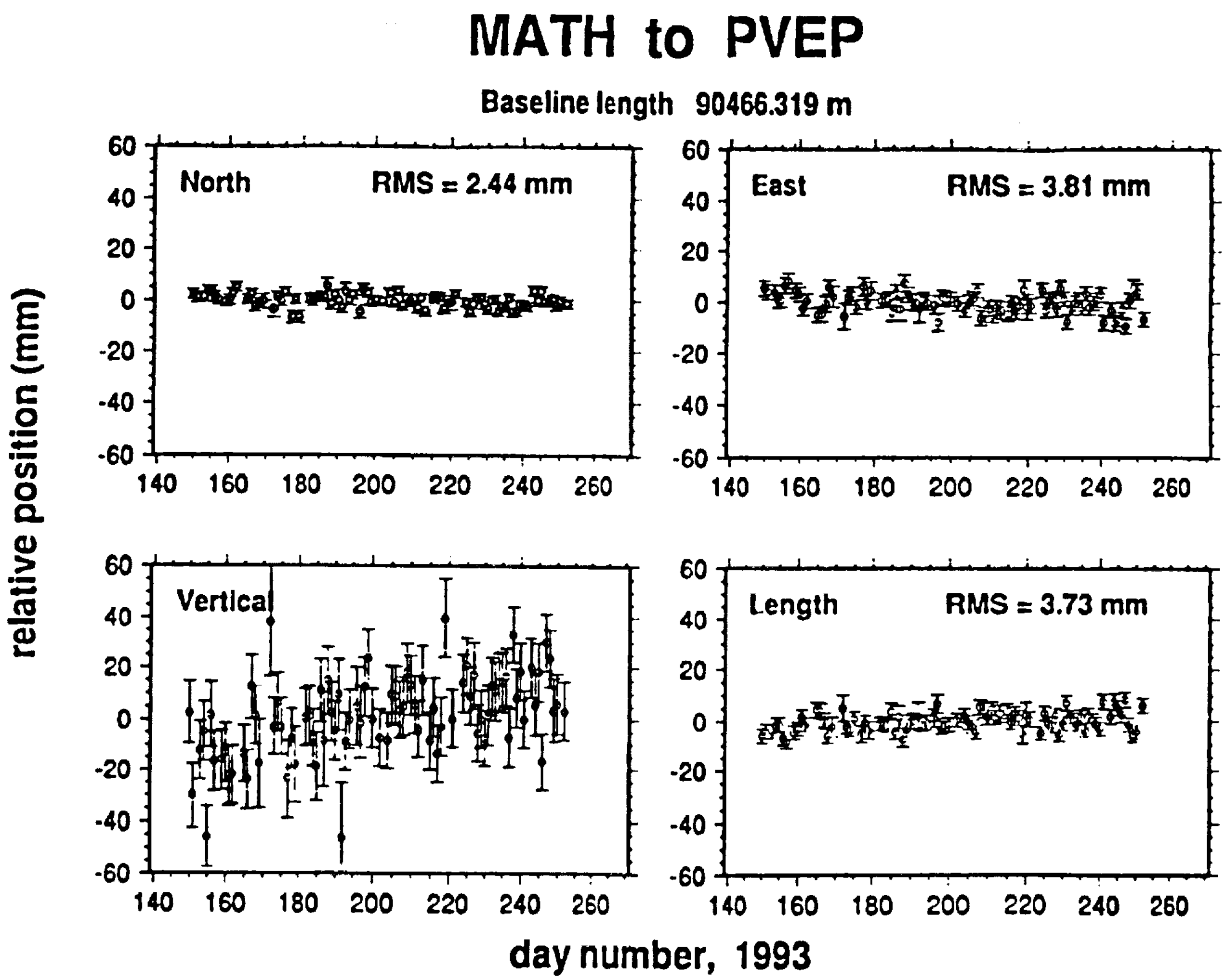

Figure 2. Daily baseline estimates for the relative position of PGGA sites at Lake Mathews (MATH) and Palos Verdes (PVER), June–September, 1993. A comparison of solutions using simultaneously estimated and extrapolated orbits indicates no significant contribution of orbital error for this 90-km baseline [*Bock*, 1993].

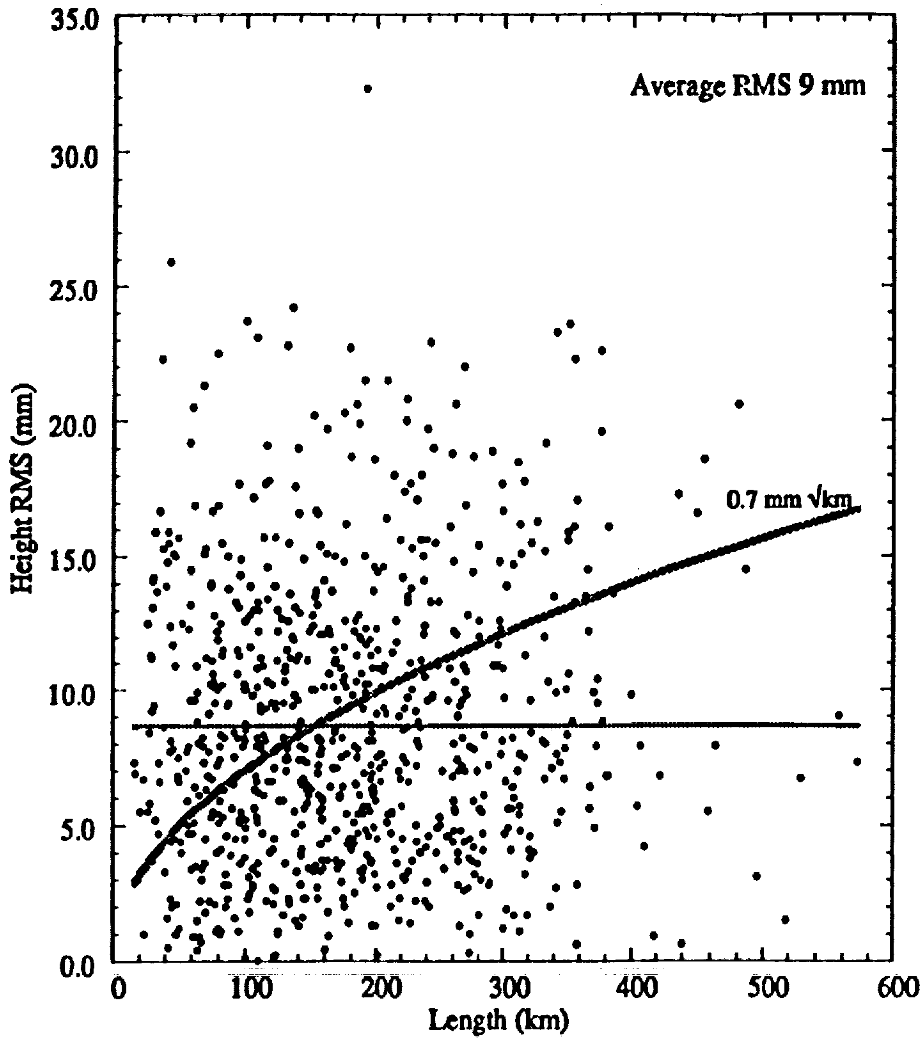

Figure 3. Vertical repeatabilities over 3 days for baselines in a 87-station network in Kazakhstan surveyed in July, 1993. The horizontal gray line gives the average value of the rms, and the lighter, curved line shows the expected error of first-order leveling. There is a large amount of (expected) scatter in the rms values since each is based on only 3 determinations. [T. A. Herring, personal communication, 1993].