Comments on NGS Proposed CORS Monumentation

Duncan Carr Agnew, Yehuda Bock, Frank Wyatt

Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego

1. Introduction

The National Geodetic Survey (NGS) Process Action Team 20 has developed a design for site monumentation for Continuously Operating Reference Stations (CORS) of a national GPS network. This design is described in admirable detail in the Team's final report of 20 December 2000 (hereafter the ''Report''). It does not appear that any input from outside of NGS was sought during the development of the design; this note is an attempt to offer such input, with the perspective of a long involvement with issues of stable monumentation, and particularly close knowledge of the monumentation adopted for the Southern California Integrated GPS Network (SCIGN).

Since much of this note will raise some objections to the NGS Report, it should be said at the outset that it represents a step towards an important goal, namely better CORS monumentation. Certainly, this design is likely to be an improvement over some of the systems now in use (for example, mounting the antenna on a roof). Also, it can be installed at relatively low cost.

A summary of the comments made in more detail below would include the following points:

- The aim of a single design does not seem appropriate, given the range of geology in which a monument may need to be set.
- The criteria for monument stability used in the Report do not match those determined from other studies.
- The design given requires drilling a relatively large hole. Such drilling (unless done with fairly massive equipment) is likely to stop at the first moderately hard material (probably not ''bedrock''), thus ensuring that the monument will not be coupled to stable material.
- The emphasis put on avoiding all metal in construction is not justified. Concrete also will scatter the signal, and tests of metallic monuments show that they can be built to have no significant effect on GPS positions.
- The Report does not include any discussion of the desirability of a stable electromagnetic environment.
- The cost estimate for the CORS monument does not show the total cost; when all costs are included the cost ratio between this and other monuments is not large, especially given the long lifetime expected for a geodetic monument.

2. Monument Stability

As stated in the Report (p.34), ‘‘First and foremost, the monument should be stable. It should hold its position well over daily, seasonal, and multi-year time scales.’’ We very much concur: if the positions of CORS sites are to serve as a geodetic framework, these positions must be predictable from past measurements, which requires a stable position. However, it appears to us that the design process emphasized issues of cost and possible modification of the GPS signal over known procedures for ensuring stability, and, in particular, did not take into account the range of geological settings likely to be encountered and the resulting need for a variety of solutions.

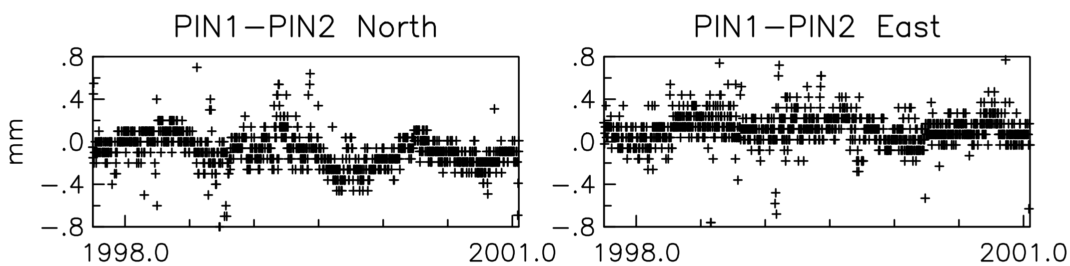

Figure 1

2.1. Evaluation of Stability

The report shows many past designs, but does not compare their stability except to note (p.3) that the team was shown ‘‘positional time-series plots from three National CORS stations.’’ Unfortunately, such time-series plots are rarely adequate for evaluating monument stability, unless this stability is very poor, simply because the scatter inherent in even precise GPS position estimates is driven largely by other sources of noise, such as unmodelled atmospheric effects, orbital errors, and reference frame uncertainties. As an example, we show in Figure 1 time series for the baseline btween two stations (PIN1 and PIN2) in southern California; because they are only 50 m apart, this baseline can be very precisely estimated using the L1 and L2 carrier phases independently rather than the LC (L3) combination. What is clear is that the true variability in this measurement baseline is only 0.3 mm (much of this in an annual cycle); so small that the quantization of the analysis (0.1 mm) is apparent, and much less than the scatter of 1 to 1.5 mm seen in even the best positional series (R. Nikoliades, pers. commun.). The danger of using positional time series to evaluate monument stability is that such series cannot distinguish between the very stable and the less stable: to rely on such data is to run a severe risk of deciding, falsely, that different monument designs give the same results when in fact they do not.

2.2. Designing for Stability

It is not clear what design criteria the Team used to ensure stability, except for the statement (p.29) that ‘‘most concerns about the subsurface character of a site can be adequately addressed by designing a monument that is of sufficient breadth and depth that it provides the required stability,’’ and (p.33) ‘‘A ratio of 2:1 of the depth-to-height provides good stability, with the monument’s center of mass located well beneath the mid-point of the structure.'' These two criteria are appropriate for evaluating the resistance of a rigid unconstrained block to being overturned; but these measures of stability are not appropriate for a geodetic monument, which is embedded in the Earth and is subject to applied stresses caused by soil motion.

If there is one general rule available for monument stability, it would come from the universal experience of geotechnical and geophysical measurements (Wyatt 1982, 1984; Zumberge and Wyatt 1998; Agnew 1986; Bilham 1993) that the deeper the material, the more stable it is. A stable monument should thus be (1) attached to as great a depth as possible, and (2) as unattached to the shallower material as possible—with the further proviso (3) that since some near-surface disturbance is probably inevitable, the monument should move as little as possible when such disturbance occurs.

An early application of these principles was by Burford and Harsh (1980) who, in their alignment arrays, found that a rod driven to 1.5 m and isolated from the soil to a depth of 0.5 m was significantly more stable than the cast-in-place concrete monument typically used for the Coast and Geodetic Survey triangulation points (Gossett 1959). Another early example was the work of Riley (1970, 1986) in designing vertical extensometers for compaction measurement; he found that supporting the surface reference point on an array of sleeved piles gave better results than using a massive concrete pad.

An application of these principles to geodetic monuments, worked out in great detail, was the NGS Class A rod mark for vertical control (Floyd 1978), which included complete isolation to 0.5 m, vertical sleeving to depths from 1 to 10 m (depending on geology) with the rod set deeper than the sleeving, and at least to 4 m. The subsequent extension of this to a ''3-D rod mark'' was perhaps less wise, since it violated the third principle stated above: a rod is very stiff along its length but easily deflected perpendicular to it, so a vertical rod is not very stable if even a small horizontal force is applied to it.

It is not clear to us that these principles were taken into account in the design of the CORS monument. The large mass of concrete will certainly be stiff both vertically and in bending, so it will tend to move as a rigid block. However, it is in no way isolated from the near-surface material, nor does it go very deep (only 3 m). The location of the antenna 1.5 m above ground also means that any tilting of the monument will produce an apparent displacement—and such tilting is a common mode of motion for shallow monuments (Wyatt 1982, Langbein *et al.* 1995).

The braced monument design used in the SCIGN network (though shown in the Report only for the BARGN network) was a deliberate attempt to extend the design of Floyd (1978) to provide horizontal as well as vertical stability. Drawing in part on the ''optical anchor'' of Wyatt *et al.* (1982) it uses a quincuncial arrangement of rods (one vertical and four inclined) to form a truss. For most of the SCIGN installations the rods go to a depth of 10 m and are isolated above 5 m depth. Since any motion of the intersection (where the antenna is mounted) involves a change in length of at least one rod, the intersection point is held very stiffly relative to the deep attachment points. This design also has the advantage of attaching to a very large volume of material, which is another source of stability.

2.3. Dealing with Real Geology

The large diameter of the subsurface part of the CORS design appears to us to raise serious concerns—not by itself, but because of the way in which this affects the drilling process, and how (in turn) the drilling will be affected by geology. It seems crucial that any design for a National CORS monument should work well in diverse geology; it does not seem likely that this design will. The only discussion of geology given is that if ‘‘bedrock’’ is encountered the monument should be tied to it. This appears to reflect a common, but incorrect, view that the surface of the earth consists of rock with a layer of soil on it. Unfortunately, the complexities of weathering and other geological processes mean that real depth profiles of the regolith (as the weathered layer is called) are vastly more complex (see Ollier and Pain, 1996 for a geological view, and Legget and Karrow, 1983, for many engineering examples, presented very readably).

In particular, it is rare for the depth profile to consist of a soft layer overlying intact rock with a sharp contact between them. And it is also not that usual for the hardness to increase smoothly with depth. An obvious example is any material containing boulders, notably the glacial tills which cover large parts of the northeastern US; another is the caliche layers found in the arid southwest. Even in areas of nominally exposed rock, it is not uncommon to find softer material (created by weathering along subhorizontal fractures) under harder rock. A specific example from our experience occurred during the installation of the SCIGN monument at Monument Peak, California. This is also the site of a satellite laser ranging system, for which several ‘‘Nelson’’ piers had been installed by NASA, all encountering ‘‘bedrock’’ (in the local metamorphic rocks) when jackhammered to 1 m or less. But the drilling for the SCIGN monument went through this and showed several thick layers of well-weathered material below it to a depth of 6 m.

This story also illustrates the interaction between drilling and geology which makes us concerned about the CORS design. The more power per unit area delivered to the drill bit, the harder the material that can be drilled (at reasonable speed); but the more total power, the more expensive the drill rig. Using a small, inexpensive rig to drill a large hole—which is what is recommended for the CORS monument—means that only the softest materials can be drilled. The auger system described in Appendix A of the Report worked well in the deep clays of the Corbin site but in a glacial till it would be stopped by the first large rock it hit—and this would very likely not be bedrock. The smaller size of the holes used for the braced-rod mark mean that even fairly modest drilling equipment (e.g., the hand drill used in the shallow version developed by Hudnut, or a jackhammer) can penetrate relatively hard material. The percussion rig used at many of the SCIGN sites can drill through virtually any hard rock, while an auger rig is used in softer materials. Essentially the only setting to which the braced-rod monument has not been adapted is very loose materials, from the difficulty of keeping the hole open—but this would be a problem in excavating for any type of geodetic monument.

3. Radiometric Issues

One notable feature of the NGS CORS monument is the complete avoidance of metal, down to using nonmetallic rebar and making the antenna mount from Delrin. Obviously, there is a considerable contrast with the SCIGN braced-rod monument and antenna mount (the D3 adaptor) which are entirely metallic. This avoidance of metal has led to choices which are suboptimal in other ways; for example, the NGS antenna mount, unlike the D3 adaptor, provides neither security against the antenna being removed, nor forced orientation of the antenna. It therefore seems important to ask how important it actually is that the monument be nonmetallic.

The Report (p.28) is not very specific on this point, saying merely, ''The presence of metal in close proximity to the antenna is a potential source of signal degradation. Although the process is not completely understood, evidence exists that the presence of metal beneath the antenna can alter the radiometric properties of the antenna.'' This information appears to be derived from a briefing by Dr. Gerald Mader; the Report also refers to a paper ''GPS Antenna Calibration at the National Geodetic Survey'' but the version of this available on the Web does not address the distorting effects of metal.

There is a modest geophysical literature on the effect of GPS antenna mounts on received GPS signals (Schupler 2001; Jaldehag *et al.* 1996; Elósegui *et al.* 1995) and it is indeed fair to say that the subject remains less well understood than it might be, partly because of the complexity of modelling electromagnetic-wave scattering by arbitrary shapes. It is certainly true (Schupler 2001) that ''Almost anything you put near an antenna affects its response,'' but it may be possible to be a little more specific by constructing a simple model.

3.1. Microwave Properties of Materials

Before doing so, however, one general point is worth making, namely that metal is not the only material that can affect the GPS signal. At microwave frequencies metals approximate ideal conductors (the skin depth of aluminum at the L1 frequency is a fraction of a mm) and thus reflect (scatter) all the energy that falls upon them. But nonconducting materials will also reflect and scatter microwaves, provided that they have a dielectric constant different from air—and they usually do. (Hence the difficulty of building stealth aircraft.) In particular, typical concretes have a reflection coefficient at normal incidence of around 0.5, (Rhim and Büyüköztürk 1998) not a lot less than the 1.0 of metals. Very crudely, we might expect equal amounts of scattering from a concrete monument with twice the cross-section of a metal one. Elósegui *et al.* (1995, p.9932) noted that they reduced the scattering effect of their antenna mount and monument if they covered either the metal plate or the concrete beneath the antenna with microwave absorbent: both areas contributed to the distortion.

3.2. A Model for Monument Effects

In order to discuss the possible effects of an antenna mount, it seems useful to introduce a simple model for the distortion of the GPS signal. For geodetic positioning the observable of interest is carrier phase, and we may write the direct signal at some point and from a particular satellite as

$$U_0 e^{2\pi i f t}$$

which at some particular time has phase ϕ_D. Given a directional antenna with no phase distortion we could measure this, but for actual antennas the signal we measure is more complicated. Though the full response of the antenna and mount requires solving a complete boundary-value problem, we may make the simplifying assumption that the antenna and environment contribute separately. Given this assumption, we may write the signal as

$$U_0 e^{2\pi i f t}[e^{i\phi_A(\theta_0,\beta_0)} + \int_{\Omega^-} A(\theta,\beta)R(\theta,\beta)e^{i\phi_R(\theta,\beta)} d\theta\, d\beta] \qquad (1)$$

Here ϕ_A is the phase shift introduced by the antenna itself, as a function of the elevation angle θ_0 and azimuth β_0 of the incoming signal; this shift includes any offset of the antenna "phase center" from the reference point on the antenna. The integral term is meant to include all the "multipath" contributions, and so is an integral over Ω^-, which denotes the unit sphere excluding the direction of the direct wave. The integrand includes the relative amplitude R and phase shift ϕ_R of the multipath signal arriving from (θ, β), scaled by the relative antenna gain A in that direction. If we could evaluate this integral we could, from (1), find the phase of the carrier as received, which could be expressed as

$$\phi(\theta_0, \beta_0) = \phi_D + \phi_A(\theta_0, \beta_0) + \phi_M(\theta_0, \beta_0) \qquad (2)$$

which is to say, a phase shift ϕ_A from the antenna, and ϕ_M from the antenna and the surrounding environment. The antenna phase shift ϕ_A is what we would expect to measure in an anechoic champer (Schupler *et al.* 1994), which approximates having the antenna suspended in free space.

In geodetic GPS processing, ϕ_A and ϕ_M are dealt with in two different ways. If the same antenna is used at two stations, ϕ_A drops out of the final solution; if different antennas are used, ϕ_A is usually removed by applying estimates of ϕ_A made in special tests—most often the estimates provided by Dr. Mader of the NGS. Since ϕ_M depends on the environment, it cannot be differenced or calibrated; instead, it is assumed to average out over time as the satellites occupy a wide range of θ and β.

Having set up this framework, we can now address more precisely what affects a GPS antenna mount and monument (which together we call the antenna support) might have on the measurement. There are three possible contributions:

A. The antenna support can alter ϕ_A from the form it has for an isolated antenna, or one on some other type of support (for example, a tripod).

B. The support can alter $A(\theta, \beta)$ to make the antenna less resistant to multipath; for example, increasing A for $\theta < 0°$.

C. The support can increase $R(\theta, \beta)$ by scattering more energy from below the antenna.

Consistent with the simplification we have made, we would say that contributions (A) and (B) relate to the antenna, and hence to parts of the support within a few wavelengths of it, while (C) relates to parts more distant.

3.3. Testing for Monument Effects

To actually evaluate any of the components of (1) is not easy because of the complex geometries involved; even the design of such metallic elements as the choke ring (Tranquilla *et al.* 1994) uses approximations. A consideration of equation (2) suggests some procedures whereby we can at least estimate the effects that an antenna support might produce. The important point is to recognize that for GPS analysis all we care about is $\phi(\theta_0, \beta_0)$, and that we might expect the contributions of ϕ_A and ϕ_M to this to depend differently on θ_0 and β_0; in particular, we expect different smoothness (that is, different spherical harmonic degree). Because ϕ_A is affected by reflectors close to the antenna sensing element (less than a wavelength away) we would expect it to vary quite smoothly with θ_0 or β_0: that is, to be representable by low-order harmonics. By contrast, ϕ_M includes contributions from reflectors many wavelengths away, and so would vary rapidly with θ_0 or β_0.

This different behavior of ϕ_A and ϕ_M suggests the following strategy, an extension of that used by Elósegui *et al.* (1995), for testing the effects of an antenna mount. For a test, we need to have three GPS systems close enough together that atmospheric and ionospheric contributions will be the same for all of them, and the local multipath environment at least similar in a statistical sense. Two systems (A and B) should use a ‘‘standard’’ antenna support, either approximating to a free-field antenna, or to some setup that would be commonly used in the field, such as a tripod or fixed-height pole. The third (C) should use the same antenna and receiver but have the antenna mounted on whatever type of monument is to be tested.

The first analysis is essentially that of Elósegui *et al.* (1995), namely to compute the baseline A-C for different amounts of elevation-angle cutoff using conventional static positioning (without zenith-delay estimation). Changes in the vertical component of the baseline with cutoff angle θ_C imply that ϕ_A differs systematically (as a function of θ) between the standard and test support. The baseline A-B, being between identical supports, should show no change with θ_C.

The second test is to analyze the baselines A-C, A-B, and B-C using the single-epoch positioning mode of Bock *et al.* (2000). Much of the fluctuation in such baseline estimates is known to be caused by multipath effects (ϕ_M, in our terms) because it repeats, like the satellite configuration, with a period of one sidereal day. Any increase in the variability of ϕ_M for the test mount and monument would thus be reflected in an increased scatter of the single-epoch solutions for the baselines including C, compared with the one that does not.

3.4. A Test of the SCIGN Monument

We have available data which may be used, through the tests just described, to evaluate the SCIGN monument and antenna mount (though the data were collected for another purpose). For day 60 of 2001, data are available from three setups at Piñon Flat

Observatory, one of which (PIN2) is the prototype SCIGN monument, including a D3 adaptor and SCIGN tall dome. There is also data from two tripod-mounted antennas: P102, about 30 m from PIN2, and PINY, about 350 m away (and set up over the Pinyon Flat VLBI mark). All three setups used Ashtech Z-12 receivers and Ashtech versions of the Dome-Margolin antenna with choke ring.

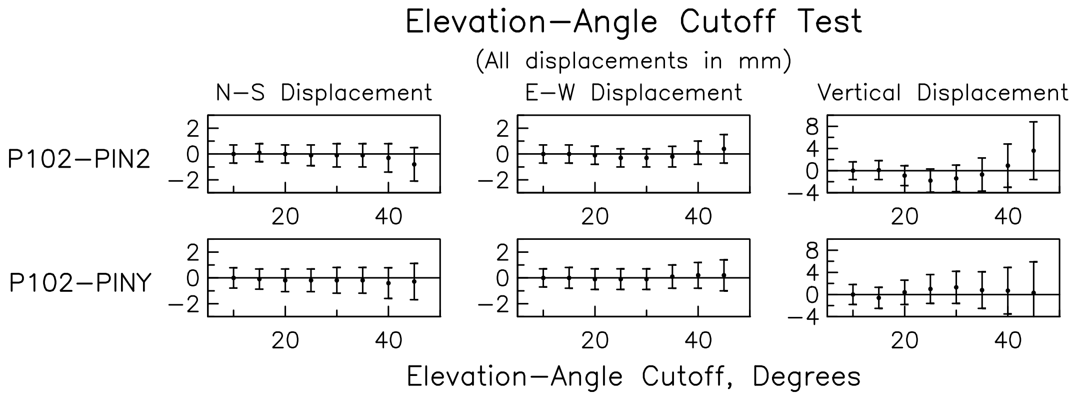

Figure 2

Figure 2 shows the results of an elevation-angle cutoff test, for 24 hours of data analyzed using the GAMIT software: the LC observable was used, with no zenith delays estimated. The components of the baseline P102-PINY (identical setups) do not vary with θ_C, as would be expected. The vertical component of P102-PIN2 (but not the horizontals) does suggest a slight systematic variation with θ_C, but much less than the changes seen by Elósegui *et al.* (1995), who found a vertical change of 30 mm for $\theta_C = 45°$ for the (then) IGS-standard antenna mount. It thus appears that the SCIGN adaptor and monument do not in fact much distort the phase pattern of the antenna, a not unexpected result given that both, quite intentionally, have a diameter much less than the antenna for the parts that are closest to it.

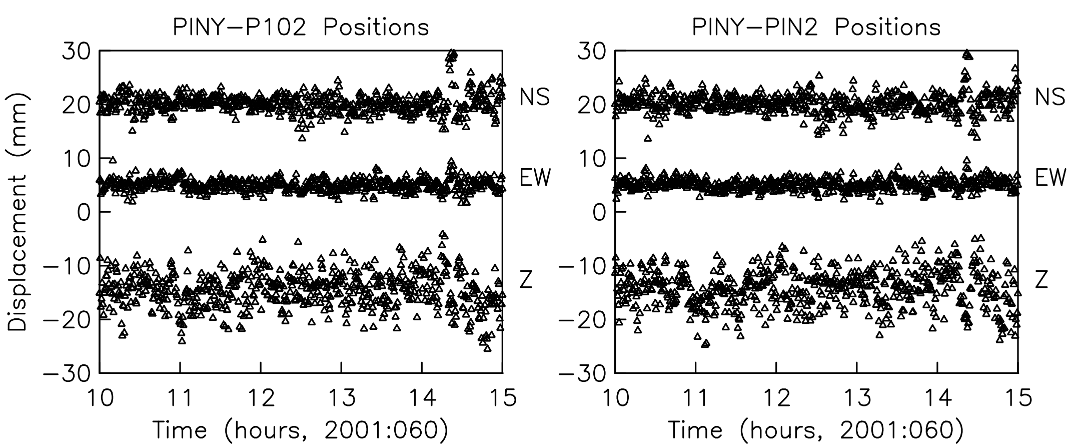

Figure 3

We have also computed single-epoch positions for the two baselines PINY-P102 and PINY-PIN2, which are of similar length and have similar multipath environments at their two ends. Figure 3 shows the resulting time series, using by using the L1 and L2 independently, which has a much smaller scatter than the LC combination does over this short a baseline (335 m). It is not evident that the series including PIN2 has much more variation. A robust estimate of scatter is the interquartile range (IQR), which is given for all components of each series in Table 1. It is apparent that there is no difference in scatter between the two baselines (if anything the one to PIN2 has less scatter in LC), which certainly suggests that the SCIGN monument neither degrades the signal, nor increases multipath, relative to an antenna on a fiberglass tripod.

Table 1: Interquartile Ranges of Single-Epoch Solutions

	LC Observable			L1/L2 Observable		
Baseline	NS	EW	Vertical	NS	EW	Vertical
PINY-P102 (tripod-tripod)	6.8	5.5	17.9	2.3	1.7	5.1
PINY-PIN2 (tripod-SCIGN)	7.0	5.2	16.8	2.3	1.8	5.3

All values are in mm.

3.5. Electromagnetic Environment

One final point may be made using equation (1), namely that multipath signals from the environment, ($R(\theta, \beta)$) could be very important in long-term stability, something not discussed in the Report. Changes in the multipath, whether from nearby construction or (quite often) from the growth and pruning of vegetation, can produce apparent long-term shifts in GPS position. Figure 4 shows an artificial example from a test at Piñon Flat, for the baseline between PIN2 and PIN1 (PIN1 is another permanent site 50 m away from PIN2). On alternate days, a small tree (cut off and mounted on wheels) was placed close to PIN2, producing the offsets shown. These diminish with time as the dead tree dries out.

Less controlled but equally large effects have been seen at some SCIGN sites; certainly the experience of the SCIGN project has shown that sometimes vegetation cannot be avoided. However, any specifications for CORS sites should certainly emphasize that a stable surrounding environment is as important as a stably attached monument. Ideally, CORS sites would place their monuments in open, and unchanging, settings.

4. Cost of Construction

Finally, there is the important, and difficult question of the cost and complexity of construction—difficult because a precise estimate of true costs can be very hard to determine. Supplies, materials, and contracted costs are easy to determine, but true labor costs are not, especially in ‘‘one-off’’ situations. The Report gives a cost for purchased items of about $700, and estimates 24 staff hours of NGS employees, which could easily be another $1-2K (and note that this does not include time and equipment volunteered by the USGS). A minimum cost of $2K seems reasonable; and as Appendix A of the Report makes clear, this is a fairly straightforward project—assuming that the drilling goes well

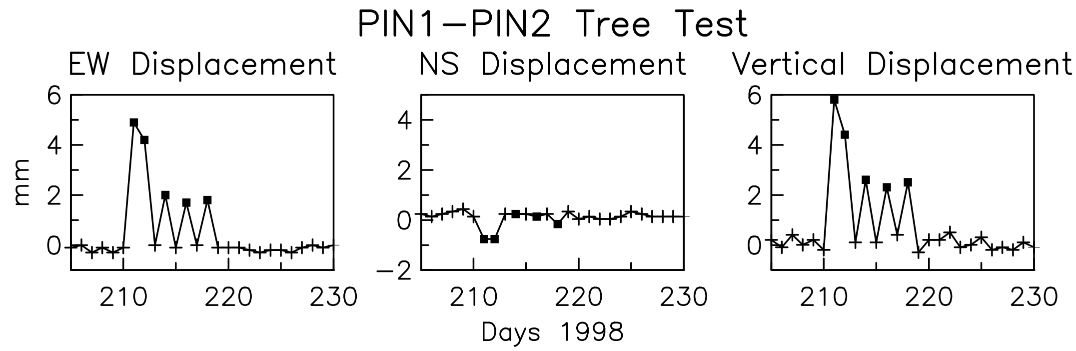

Figure 4

and the hole stays open.

For comparison, we estimate the cost of a deep-braced SCIGN monument to be about $7K. This is not the full cost of the site, which averages about $23K, but just the cost of building the monument—of, so to speak, providing a 5/8-11 thread for the antenna to attach to. Of the monument cost, about $3K is the cost of drilling, the rest being materials (steel and cement), grouting, and construction. The adaptors cost about $300 in the limited production runs SCIGN has used.

It should be said at once that this monument cost is lower than what it would be for a single installation: with increasing experience has come less time spent and decreased labor costs. It is also true that the SCIGN monument requires more care to build, and more specialized abilities, than the simple concrete-pouring of the proposed CORS monument. This should be no surprise: better performance usually does require greater expense. Whatever monument is built for CORS will, we may hope, have a very long lifetime, so that (on an annualized basis) the construction cost of even an ‘‘expensive’’ monument will be the least of the costs of operating a CORS site. Given that many government agencies do not depreciate their assets, and so count any expenditure as part of that year’s budget, the temptation to minimize costs on capital equipment is great. But it would seem to be a false economy, and not one to encourage if the aim is to make CORS a high-quality national GPS reference system.

References

D. C. Agnew, “Strainmeters and tiltmeters,” *Rev. Geophys.*, 24, p. 579−624 (1986).

R. Bilham, “Borehole inclinometer monument for millimeter horizontal geodetic control accuracy,” *Geophys. Res. Lett.*, 20, pp. 2159-2162 (1993).

Y. Bock, R. M. Nikolaidis, P. J. De Jonge, and M. Bevis, “Instantaneous geodetic positioning at medium distances with the Global Positioning System,” *J. Geophys. Res.*, 105, pp. 28223-28253 (2000).

R. O. Burford and P. W. Harsh, “Slip on the San Andreas Fault in central California from alinement array surveys,” *Bull. Seismol. Soc. Am.*, 70, pp. 1233-1261 (1980).

P. Elósegui, J. L. Davis, R. T. K. Jaldehag, J. M. Johansson, A. E. Niell, and I. I. Shapiro, “Geodesy using the Global Positioning System: the effects of signal scattering on estimates of site position,” *J. Geophys. Res.*, 100, pp. 9921-9934 (1995).

R. P. Floyd, "Geodetic Bench Marks," Manual NOS NGS 1, U. S. National Ocean Survey (1978).

F. R. Gossett, "Manual of Geodetic Triangulation," Special Publication 247, U. S. Coast and Geodetic Survey (1959).

R. T. K. Jaldehag, J. M. Johansson, B. O. Rönnäng, P. Elósegui, J. L. Davis, I. I. Shapiro, and A. E. Niell, "Geodesy using the Swedish permanent GPS network: effects of signal scattering on estimates of relative site positions," *J. Geophys. Res.*, 101, pp. 17841-17860 (1996).

J. O. Langbein, F. Wyatt, H. Johnson, D. Hamann, and P. Zimmer, "Improved stability of a deeply anchored geodetic monument for deformation monitoring," *Geophys. Res. Lett.*, 22, pp. 3533-3536 (1995).

Robert F. Legget and Paul F. Karrow, *Handbook of Geology in Civil Engineering, 3rd ed.*, McGraw-Hill, New York (1983).

C. Ollier and C. Pain, *Regolith, Soils and Landforms*, p. 316, John Wiley and Sons, New York (1996).

H. C. Rhim and O. Büyüköztürk, "Electromagnetic properties of concrete at microwave frequency range," *ACI Materials J.*, 95, pp. 262-271 (1998).

F. S. Riley, "Land-surface tilting near Wheeler Ridge, southern San Joaquin Valley, California," *U.S. Geol. Surv. Prof. Pap.*, 497-G (1970).

F. S. Riley, "Developments in borehole extensometry" in *Proceedings of the Third International Symposium on Land Subsidence*, pp. 169-186, Internat. Assoc. Hydrology., Venice, Italy (1986).

B. R. Schupler, "The response of GPS antennas−how design, environment and frequency affect what you see," *Phys. Chem. Earth A*, 26 N6-8:605-611 (2001).

B. R. Schupler, R. L. Allshouse, and T. A. Clark, "Signal characteristics of GPS user antennas," *Navigation: J. Instit. Navig.*, 41, pp. 277-295 (1994).

J. M. Tranquilla, J. P. Carr, and H. M. Alrizzo, "Analysis of a choke ring groundplane for multipath control in global positioning system (GPS) applications," *IEEE Trans. Antenn. Prop.*, 42, pp. 905-911 (1994).

F. Wyatt, "Displacement of surface monuments: horizontal motion," *J. Geophys. Res.*, 87, p. 979−989 (1982).

F. Wyatt, "Displacements of surface monuments: vertical motions," *J. Geophys. Res.*, 94, pp. 1655-1664 (1989).

F. Wyatt, K. Beckstrom, and J. Berger, "The optical anchor − a geophysical strainmeter," *Bull. Seismol. Soc. Am.*, 72, p. 1707−1715 (1982).

M. A. Zumberge and F. K. Wyatt, "Optical fiber interferometers for referencing surface benchmarks to depth," *Pure Appl. Geophys.*, 152, pp. 221-246 (1998).