

IGS Network Systems Workshop  
November 2-5, 1998  
Annapolis

### Position Paper

## Physical Site Specifications: Geodetic Site Monumentation

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### Abstract

Monumentation is one of the most important aspects of a geodetic installation, whether it be for VLBI, SLR or a GPS installation. Currently a large number of different monument types, with varying designs, construction, quality and suitability are used in the IGS network. This chapter gives an introduction to the current approach to monumentation, some of the aspects of site selection and monumentation, with special emphasis on safety from vandalism, stability and collocation as seen from the GPS technique viewpoint.

### Introduction

Several different techniques are used in modern geodesy and currently there are several space geodetic techniques which are utilised at facilities all over the world. Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Positioning System (GPS) are three of the main space geodetic techniques supported at fiducial sites. The monumentation for each technique may differ as the instrumentation that needs to be supported is quite different. For instance there is a large difference in mass between a GPS antenna and a geodetic VLBI antenna. However, one wishes to achieve the highest possible stability of the monument in each case. Apart from stability, one needs to assess the site for other prerequisites such as low horizon, possible multipathing and vandalism which will determine whether the site is suitable. The nature of the site determines to a large extent the type of monumentation required.

In order to determine the stability of each geodetic fiducial site on a local scale, small networks are measured which surrounds the geodetic sites. These footprint networks normally cover a radius of hundreds of metres to tens of kilometres. For instance Goddard Space Flight Centre's (GSFC) Crustal Dynamics Project and now its successor, the NASA Space Geodesy Program has been involved in the acquisition of GPS data at footprint networks located around primary VLBI and SLR sites since 1990. Footprints may cover geodetic sites which support not only GPS, but other techniques such as VLBI and SLR. In this case one would want to tie the reference points of each geodetic system and this can be done simultaneously using GPS.

### GPS Monumentation

The IGS guidelines taken from their webpage has the following specifications for the geodetic monument and can be found under the section describing requirements for permanent stations:

#### Marker:

*The marker should fulfil standard requirements for a first order geodetic monument with respect to stability, durability, long-term maintenance, documentation and access. The marker description should be fully documented in the IGS site log file.*

The log file requests a full description of the monument. Table 1 describes the status of 44 IGS global stations (sampled alphabetically in sequence) log files as far as monumentation is concerned. More often than not it is not specified whether the monument is in fact founded on the underlying bedrock. Sometimes there is a GIF image which at least shows if the monument is located on a building, but the table reflects only the contents of the current log file as submitted. The GIF image, although adding useful information does not supply all the required information. It is obvious that the log file entries leave a lot to be desired and in many cases is totally useless in terms of describing monument, monument foundation, mounting plate and other relevant detail. This lack of detail needs to be addressed. It seems there are different interpretations of the terms monument, marker and mounting plate. The monument is a lasting, many times colossal, structure which serves as foundation for the marker. This monument can be in the form of a concrete pier, steel construction or rock outcrop, designed or selected to represent the earth's crust or as close as you can get to it. In the case of an antenna fixed to a roof of a building, the building is the monument and the pipe supporting the antenna is an extension of it. The reference marker is attached to the monument and serves as the geodetic reference point. This can be a brass or stainless steel pin or fitting with centred punch mark. Your antenna height is measured to the reference mark. The mounting plate supports the antenna, and could have as part of its construction a reference mark. The reference mark must however be fixed permanently to the monument. An adjustable reference mark is *not* a reference mark.

Station	Monument Type	Foundation Material	Monument Foundation Confirmed
ALBE	Concrete pier	Exposed bedrock	Specified
ALGO	Concrete pier	Exposed bedrock	Specified
ANKR	Pillar	Clay and Silt, Limestone	?
AREQ	?	Alluvium	?
ASCI	Building	?	Roof mount
AUCK	Concrete	Clayey soil, sandstone, mudstone	anged to refusal ?
BAER	?	?	?
BARB	Building ?	?	?
BOGT	Building ?	?	?
BRMU	Building ?	?	?
CASI	?	?	?
CEAT	Concrete pier	Clay,100 ft firm/waterlogged soil	Presumed ?
COCO	?	?	?
CBO1	Concrete pier	?	?
DAV1	?	?	?
DGAB	?	?	?
DBAO	Concrete pier	Exposed bedrock	Specified
EISL	Concrete pier	?	?
FAIB	?	Metamorphic rock	?
FOBT	?	?	?
GALA	?	?	?
GOL2	25 M microwave tower	Alluvium	?
GUAM	Building	?	Roof of observatory
HARK	?	?	?
HOB2	Concrete pier	Jurassic Dolerite	?
HRAO	Interlocking steel rod	Andesite	Specified
IISC	?	?	?
IBKT	Rock	?	Installed on 'a rock'
KELY	?	?	?
KERB	Concrete pier	?	?
KIT3	?	?	?
KOKB	Satellite tracking base	Magma	?
KOSG	?	?	?
KOUR	Concrete pier	?	?
KSTU	Pillar	Bedrock	Specified
KWJL	Mast on building	Coral reef formation	?
LEAS	Pillar on building	?	?
LPGS	?	Conglomerate	?
MAC1	?	Sedimentary bedrock	?
MAD2	No monument ?	Granite/sandy soil	?
MAG0	Steel rod	Bedrock	Specified
MALI	Concrete monument	?	?
MAS1	?	?	?
MATE	Pillar on building	Sedimentary bedrock	?

Table 1: IGS Global stations

UNAVCO has an excellent website which contains a large amount of interesting and useful details on monumentation. They have invested a large amount of time on monument stability and is a 'must read' for the investigator who is planning to construct and install geodetic monumentation. UNAVCO's preferred monument according to their webpage is the deeply anchored/braced monument designed by Frank Wyatt, Hadley Johnson and Duncan Agnew, as described in *Improved stability of a deeply anchored geodetic monument for deformation monitoring*, Geophysical Research Letters, Vol. 22, No. 24, Pages 3533-3536, December 15,1995. UNAVCO supports requests for monument consultation and design with details of some of these to be found on their website, such as the design for a monument using an Invar rod to withstand the climatic extremes of Greenland. Details of the UNAVCO levelling mount, GPS geodetic quality benchmarks and recommendations on sleeve depths for expansive soils can also be obtained on the website.

### Monument Types

A very informative monumentation specification table which characterizes various monuments in terms of approximate cost, multipath and physical attributes is on the website and is reproduced here for our benefit in Fig 1. One common attribute which is conspicuous in the UNAVCO table for most 'excellent' monuments is that these installations are difficult and time consuming. Even the stainless steel pin installed in bedrock, although listed as a simple installation, may require a thorough site investigation using geophysical techniques as 'bedrock' is sometimes not what it appears to be. The building type monument is not listed, but currently it is of a type that should be added to the list. If one attaches a geodetic monument to a building, the building in effect forms part of that monument.

## Monumentation Specifications Summary

### Monument Types

The following table provides a summary of various monument types used in the GPS community and under development and test at UNAVCO. All monuments require separate antenna mounts.

Monument type	Weight (lbs)	Cost (US \$)	Multipath	Stability	Thermal expansion	Installation	Usage	Other notes
Concrete Pillar	Note 1	Note 1	High (duplicates ground effects)	Good	Low	Deep anchors in bedrock or soil	NGS	Difficult and time consuming installation
Deeply Anchored GPS Monument (UCSD)	Note 1	Note 1	Low	Excellent	Very low	Deep anchors in bedrock or soil	Basin/Range (TB installed) and networks in CA (ZFO)	Difficult and time consuming installation
INVAR Rod with sleeve	Note 1	Note 1	Low	Good	Very low	Anchors in bedrock	Greenland perm. GPS station	INVAR is expensive
NGS Sleeve type monument	Note 1	Note 1	Low	Excellent	Very low	Deep anchors in soil	NOAA/NGS	Difficult and time consuming
Stainless steel pin	2	5	N/A	Excellent	Stainless steel (7-8 x 10exp-6 in/in/deg F)	Bedrock only	Majority of GPS campaigns	Simple installation

*Note 1. Can vary depending upon site conditions and amount of material.*

This is not a complete list. We welcome additional information to be added. Contact Field Engineering.

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Figure 1: UNAVCO monument specification table

### Finding a Good Site

For a footprint, it would be difficult to build a monument for each reference point in the footprint network which would have comparable or better stability than a site's main geodetic GPS monument, unless unlimited funds were available. However, for the main geodetic monument, one must do your best to ensure that instabilities of any kind have been minimized. If we could build a monument and tie it to bedrock, or be fortunate enough to find exposed bedrock, monument instability would be minimized.

Some of the requirements for a good primary monument site are:

- (1) shallow bedrock of high quality
- (2) clear horizon
- (3) safe from vandalism
- (4) clear of reflecting surfaces (fences, metal poles etc.)
- (5) not too far from receiver
- (6) ease of access
- (7) data accessibility
- (8) electric power
- (9) no local crustal instabilities
- (10) controlled vegetation (growing horizon elevators)

Of course not all these site qualities are easily found, or are economical or practical to achieve.

The type of monument normally depends on the site characteristics, as well as on the investigators eagerness to obtain as stable and durable a monument as possible. Don't build a monument flush with the earth's surface, apart from antenna interaction with (varying) conductive soil, humans and growing vegetation shadowing satellite signals, the antenna is 'overexposed' to its environment. Bugs will crawl into it, ants will nest in it, it might get flooded, trampled on etc. The UNAVCO site has some examples of monument types. Some interesting monuments exist, such as the massive monolith used by the University of New Castle (Geoff Blewitt's group).

To find a good site, one starts out with an idea as to where the GPS monument should be located, with the above mentioned requirements in mind.

### Horizon Mask

The horizon mask is defined as those areas of the horizon, when viewed from the antenna, that are obstructed so as to impede or block the satellite signal from reaching the antenna. Ideally there would be no obstruction above the horizon; however in a practical world it is rare that this optimum is achieved at the same time as meeting all other siting specifications. Significant blockage below certain elevations or in specific azimuthal quadrants can limit the usefulness of the data collected as well as constrain the user community to a select group rather than meeting the needs of a broader user group

"Solid" objects such as mountains and buildings as well as trees and structures can cause the blocking of the satellite signal. In the former case the signal will be lost for the duration of time the satellite(s) is/are behind or below the obstructing object. For example in deep valleys or within the boundaries of large cities, this can amount to a considerable amount of lost data. In the case of vegetation and other less "solid" obstructions, the loss may be of a more intermittent nature depending on the transparency of the obstruction to the satellite signal. The obstruction may also vary with time. Deciduous trees, which have lost their leaves, will provide less obstruction compared to fully foliated trees. The type of tree cover (thick rain forest vs. sparse needle forest) is important as is the capability of the receiver / antenna that are to be used at the site. Some receivers / antenna combinations are designed to track under tree cover while others are not. Trees will obviously also grow and thus affect the horizon mask with time. In a similar fashion urban growth or development in the immediate area of the reference station installation may affect the horizon mask with time. Intermittent blockages and site changes may also cause multipath problems.

It is important to select a site with minimal blockage and to ensure that the horizon will not undergo significant change with time. It may be necessary to determine the extent of

anticipated development from adjacent landowners. During the site reconnaissance stage, obstructions (current and planned), should be noted and prediction software used to determine the effect of the blockages on the data collection and thus the range of user applications of the data. Changes over time should be noted in the site log.

### Multipathing

Multipath can cause errors in GPS measurements, the severity of which is dependent on the extent and type of multipath. As the expression indicates, multipath refers to signals that arrive at the antenna via multiple paths, in this case caused by reflective surfaces in the vicinity of the reference station. Multipath causes interference or distortion, and therefore error, primarily on the code pseudo-ranges but also on the phase pseudo-ranges.

Different types of reflective surfaces can cause a multipath effect on the received signal. Most obvious are highly reflective surfaces such as the sides of buildings, solar panels, vehicles, etc.. Fluctuations in multipath levels can be caused by surfaces such as water whose reflective properties will change with time. Similarly the accumulation of snow or ice on nearby structures or on the surrounding ground can effectively change the properties of the reflected radio signal as a function of time. A diffused scattering of the satellite signal can be expected from metallic structures such as large radio towers and chain link fences.

The siting of the antenna installation and the monitoring of any changes in the surrounding area is very important. Prior to establishing the site, data should be collected using the same type of instrumentation that is to be installed and as close as possible to the exact location of the proposed antenna site. A longer test data set, for example 72 hours, when analyzed should provide a good indication of the impact of the site's multipath environment. It may be necessary to test several different antenna heights in order to judge the optimal height for the reference station antenna. The addition of ground planes and use of RF absorbing material may have to be considered. It should also be noted that reflective waves from surfaces below the antenna, such as the ground and the top of a concrete pier can also cause problems and steps may be required to minimize this source of near-field multipath.

### Buildings

If a building is being considered for your monument, installation is normally easier as there might be convenient access to power, clear horizon, security and other items on your wish list. Stability will to a large extent be dependent on the size of the building, its foundations, its age and nature of the site it has been constructed on. There might also be other RF equipment installed on the building, for instance VHF and UHF repeaters, with their accompanying RF harmonics radiating and causing interference in the L band which will degrade your installation. Sometimes there are metal structures which should be taken into account such as airconditioning plants, guard rails, water tanks and antenna towers. A solidly constructed building, with foundations on bedrock can be a good monument/site, but one has to be aware of its stability limitations. Large structures increases the room for instability.

### RF Environment

The radio frequency (RF) signal received by reference station satellite receivers can be detrimentally affected by the presence of interference from other RF sources. This interference can simply show up as additional noise in the data, cause intermittent or partial loss of lock or, in the more severe cases, render the reference station completely inoperable.

The close proximity of a transmitting facility (such as a TV station, microwave facility, etc.) can cause an overload in the front-end filters of the antenna / receiver. Other sources of RF include FM radio stations, cellular telephones, CB radios, radar, high voltage transmissions lines, etc. Some sources which are near-band w.r.t. the primary satellite signals are obvious sources of RF interference (RFI). However harmonics from other sources are not so obvious. It should also be noted that the close proximity of pseudolite ground transmitters can cause interference or jamming of the satellite signal in a reference station receiver.

It is therefore important to collect as much information about transmitters (current and planned) in the area as well as the use of any portable RF equipment prior to installing a site. The potential presence of RFI is another good reason to test a site thoroughly. In addition to collecting and analyzing a data set (72 hours if possible) a spectrum analyzer should be used to identify any RFI in the band allocated to the satellite signals. Ideally the spectrum analyzer would be connected to the satellite receiver's antenna via a splitter at the same time the test data set is collected.

### Field Installation

Once you have decided on the geographical region for your installation and have studied available geological and geotechnical data, a field reconnaissance should be undertaken to gather information on the proposed site. Look for possible exposed bedrock, note the strike and dip of the rock, joint spacing and condition. You would want to draw a map of the site and its immediate surroundings, keeping in mind that you want a stable monument. Factors which might influence the stability of your monument on rock are:

- (1) Presence of faults
- (2) Joints, fractures, shear zones
- (3) Varying ground water levels
- (4) Rock slope instability
- (5) Rock which could cause problems due to swelling, dissolving and shrinking
- (6) Presence of cavities due to karstic formations, such as found in dolomitic regions
- (7) Human engineering activity, gas, water and sewer pipes, drainage ditches.
- (8) The type and condition of the rock

The effect of these factors are quite obvious. For instance joints, fractures and shear zones may be filled with compressible soils such as expansive clay. During drying and wetting cycles, expansive minerals, for instance montmorillonite and anhydrite, shrink and expand, leading to a seasonal signal in your time series. Cavities develop in soluble rocks, especially dolomite, limestone, rock salt and gypsum. This might not have an immediate effect on your monument, but an existing cavity may lead to your monument disappearing into a sinkhole when the cavity roof collapses. Flow of water dissolves gypsum and can cause tilting of your monument. Certain types of rock are less suitable for a stable site, as the density of the rock is normally a factor in the swelling characteristics of the rock. Shales for instance are affected by moisture content, density, weathering and mineral structure.

### Boring

Sometimes one can find bedrock which is hidden below the soil by utilizing techniques of geophysics such as resistivity tests and gravimeter measurements. Once a point has been found that will be suitable, boring is the only viable tool which will directly reveal the condition of the subsurface conditions. At HartRAO for instance, during the installation of the SLR reference point, resistivity and gravimetry measurements showed large fluctuations in depth to bedrock. The mother material of the soil is andesite, which often weathers in such a way as to leave large boulders suspended in soil. This could lead to a monument bedded onto a suspended boulder instead of onto real bedrock. Core logging describes a permanent record of the rock mass conditions and is useful in estimating the depth to the weathered zone and fresh bedrock. After finding solid bedrock, one still has to drill through and clear off the weathered and fractured top section until fresh bedrock has been reached. This is the part to which you want to fix your monument. We eventually augered a 1 metre diameter 6 metre deep hole which was cut partially into the andesite to access fresh bedrock. The monument was isolated with foam from the soil and is a massive steel and concrete structure fixed to bedrock. Of course the number of borings and the depths would be limited if the rock mass conditions are of excellent quality and massive. Rock boring is expensive, so more time spent on locating an approximate position of the bedrock closest to the surface will be worth it. In the case of our IGS GPS station (HRAO) monument we drilled through exposed shale and then into bedrock and grouted a steel monument into the andesite by pressure pumping grouting down the steel tube. The tube had holes drilled in the bottom section, so that the grouting would be forced out into the joints and cracks of the rock, effectively like a tree sprouting roots. The steel was then isolated from the drilled hole via thick wall plastic tube and guided through a steel collar cemented onto a foundation installed on the slate. This allows the shale to breathe as it absorbs and loses water, without affecting the stability of the monument.

### Not Fixed to Bedrock ?

Not all monuments can be tied to bedrock, you might have to install a monument on sand, on top of a building, deep soil or expansive clay. What should be realised at the outset is that there are instabilities introduced the further your monument moves away from the bedrock. Expansive clay is not a stable foundation and great care should be taken when designing your monument. There are many GPS monuments which are not tied to bedrock and they produce good results. We must however be sure that we are measuring what we were originally planning to do and not perhaps thermal expansion, short and long term building foundation settlement, slope movement, local subsidence due to groundwater extraction etc.

### The 'Building Type' Monument

When a building is constructed, its foundations may or may not be fixed to bedrock. The load imposed by the structure at the foundation level will always be accompanied by strain which result in settlement of structures. This is true for your monument as well to a certain extent. The total settlement of the monument or building foundation in general is given by

$$S = S_i + S_c + S_s \quad (1)$$

where  $S_i$  = immediate settlement,  $S_c$  = primary consolidation settlement and  $S_s$  =

secondary consolidation settlement. In granular soils the predominant part of the settling is during the immediate settlement phase. In areas where saturated inorganic silts and clays occur the primary consolidation settlement predominates. If your monument is located on highly organic soils or peats the secondary consolidation settlement forms the major part of the settlement.

Of course the expected settlement is not easy to calculate due to the many variables involved such as modulus of elasticity, shear modulus and Poissons ratio obtained from triaxial tests, but reasonable estimates are possible. One can find many different approaches in the literature. If you are installing a monument on a newly constructed building, mortar shrinkage will also produce some instabilities, these last about 6 months. Typical primary consolidation over a period of 10 years is on the several cm level. The settlement depends a lot on how close the foundation is to bedrock, the closer, the more stable your monument will be.

The coefficient of secondary consolidation for thick clay is defined as

$$C_{\alpha} = \frac{\Delta H_t / H_t}{\Delta \log t} \quad (2)$$

where  $t$  is time and  $H_t$  is the thickness of the clay layer.  $C_{\alpha}$

decreases logarithmically with time and is directly proportional to the total thickness of the clay layer once secondary consolidation has started. So, within reason, if you have to choose a building for your monument location, the building becomes part of the monument and in general older buildings will most likely be more stable.

### Antenna Mounts

UNAVCO has done a considerable amount of work on suitable mounts and normally they attempt to address points such as:

- (1) relocation of a replacement antenna
- (2) ease of installation
- (3) stability
- (4) durability
- (5) tampering
- (6) levelling and orientation of antenna
- (7) multipathing
- (8) attachment to monument

UNAVCO has a summary of various antenna mounts on their web page. There are many different versions of the same type and it is often up to the ingenuity of your mechanical workshop as to how the mount is made. There are several good designs available. I recently saw a nice easy mount designed and built at SOPAC, which simplifies antenna installation and removal, making it very convenient for testing antennas. There is no ultimate mount, but there are some which you may want to throw out after some thought.

For all our installations, HRAO, HARK and our new HartRAO/JPL site for Namibia we use a similar design to UNAVCO's 'levelling mount'. These can be made up easily and are very stable, easy to align and durable. Mounts should use only marine grade stainless steel, marine grade aluminum or other stable and durable material. PVC and other material which do not withstand bushfire or intense solar radiation should be used with caution.

### Lightning and the Geodetic Monument

Many IGS and other GPS sites have been taken out by lightning, totally and partially, with damage occurring to the antennas, inline amplifiers, receivers and peripheral equipment. All sites should go to great lengths to ensure that their equipment is protected as best as possible as lightning damage is normally quite severe.

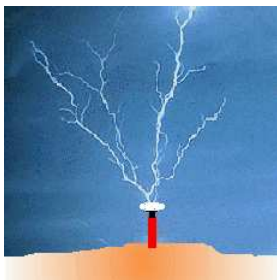


Figure 2: Your IGS station ?

UNAVCO has done a lot of work on lightning protection for monumentation and the associated equipment attached to the monument and a large amount of useful information and technical details is given on their website. Direct lightning strikes of monuments are in the minority when compared to damage resulting from EMPs (electro-magnetic-pulses). The EMP induces high voltages in unprotected coaxial cables and antennas which allows massive voltage spikes to enter anything else attached to the cables. At HartRAO, we have had several outages of HRAO as a result of lightning, all of the EMP type. We might have a more severe problem in this regard as most other sites, as this area (Johannesburg) is reputed to have one of the highest counts of lightning strikes per year in the world. Proper grounding rods at the monument, and at the other side of the coax and data lines, inline EMP protectors (Huber+Suhner), surge protection in RS232 lines and power lines are all necessary to reduce the chances of damage. The use of optical fibre links for data communication should be used if possible. One should not use any form of lightning protection unless it has been properly tested and screened, so it would be prudent to check with UNAVCO if your proposed system is suitable. There is a large amount of totally inadequate devices on the market which will not produce the required results.

### Surge protection devices

Surge protection devices (SPDs) are also known as 'surge arrestors', 'lightning protection units' and 'lightning barriers'. The SPDs which you want to protect your equipment with should ideally operate instantaneously to divert a surge voltage and current to ground, resetting automatically to restore normal operation and be ready for the next surge. Tests done by the IEEE have shown that many cheap type of SPD functions only the first time, but still has an indicator that pretends all is well. Advanced SPDs however combine a number of different surge-suppression components to utilize their different characteristics. Data line SPDs make use of high-current, high-voltage gas discharge tubes and low-voltage, low-current surge suppression diodes for rapid and accurate voltage control. UNAVCO is able to advise on suitable units.

### Vandalism

Vandalism is probably of concern to us all and some locations may have serious problems in this regard. Vandalism comes in different forms and from different sources and in varying degrees of intensity. Certain electronics companies recognize this, for instance those who make public telephones will advertise their equipment to be well designed, durable and dependable. They will also offer a wide variety of models constructed of heavy gauge stainless steel, lexan armored cables and tamper-proof securities. Do we have the same approach

for our GPS equipment ? In South Africa I have yet to discover a survey beacon flag that is not riddled with large calibre bullet holes. How tough are these radomes ?

Some IGS sites are particularly vulnerable in that they are easily accessible, with antenna and receiver a couple of metres apart. The receiver and small UPS may be enclosed in a metal box which is locked. Many times the box is fixed on a steel pipe, so that the casual vandal would not tamper with the equipment. The serious vandal however will saw off the pipe and remove the whole installation intact.

When a site selection and investigation is done, the vandal potential should be estimated and minimized. Vandalism is normally of human origin (except in South Africa where I take baboons into account), but rodents and heavy hoofed animals may wreck havoc with wiring and coax if exposed, even fire should be considered. During the site selection and monument design phase consider some of these points:

- (1) Is the site visible from public pathways and road ?
- (2) Is your color scheme for the monument and enclosures vandal yellow, or does it blend into the environment, making it less conspicuous ?
- (3) Is the monument constructed in such a way that the antenna is out of reach ?
- (4) Is the reference marker to be a nice, attractive, 2 Kg, beautifully machined and polished brass momento ?
- (5) If you are considering fencing, metal or (sometimes wet) wood, what about multipathing ?
- (6) The very casual vandal might be an innocent visitor, blocking off satellites because your antenna is below human height. Do you need loss of lock ?
- (7) Is your GPS site on the list of things all visitors must see ?
- (8) Are you incorporating some electronic alarm which will warn you if the equipment is being tampered with ?
- (9) Has the radome you are considering been checked for uniform thickness, rf transparency, does it retain these characteristics out in the sun ?
- (10) Should you consider additional insurance ?
- (11) Will the communication and rf cables be protected ?
- (12) Does the solar panel have reduced reflective surface ?
- (13) Are the equipment boxes really solid and can they be bolted from inside onto rock or buried stakes ?
- (14) Is the site plagued with bush fires ?

There is of course no complete list of what should be taken into account, each investigator will have to carefully assess his options and requirements.

#### Other Issues

Other issues to be concerned about when siting a new reference station include future site development and change in ownership, power requirements and communications issues. Evidently any major changes in terms of construction and possible future interference of the site will be of concern. Use and ownership issues are perhaps best dealt with through comprehensive land use agreements and contracts. Power and communication to the site have to be reliable. Design issues may include long term (backup) power and data storage in the event of major disruption to the local power and communication infrastructure (e.g. major seismic event).

#### Overview of Footprint Studies

When one attempts to find footprint information on IGS sites, it is obvious that very little has been done at most of the IGS sites. It is clear that footprints are not regarded as being high on the list of IGS site priorities. Footprints do take a lot of effort and on some sites it is also a difficult practical problem. In order to give a general background on previous and current footprint studies conducted by NASA, a short overview is given based on and using extracts from an unpublished report by Bell et. al. (1994) and personal communication received from C Noll (CDDISA) and R Allenby. A GPS site footprint is similar in all respects except that it is easier to refer the footprint network to the main GPS reference, than say the reference point of a geodetic VLBI antenna.

At the time of their report, two epochs of GPS data had been taken by NASA at footprint networks at six different observing sites. Three of these are in California (Quincy, Pinyon Flat and Monument Peak), two in the continental U.S. (Fort Davis, Texas and the GGAO in Greenbelt, MD) and one in Alaska (Sourdough). Conventional geodetic surveys are usually performed to ascertain reference points of fixed observing instruments such as SLR and VLBI and the relative positions of reference monuments or other collocated geodetic instruments within the immediate site area. The classical and GPS surveys are used at the local reference and regional footprint scale to determine each site's stability.

The measurements are done in order to differentiate between local instability effects (local groundwater fluctuations, soil movement or monument instability) and geodetically measured motion from larger scale effects. The larger scale effects include coseismic displacement during an earthquake, subsidence or uplift due to glacial or fluvial loading or unloading, steady state slip resulting from plate motion, or displacement due to volcanic eruptions. A footprint measurement can provide crucial information when a site suddenly exhibits anomalous displacement. This is supported by the case of the Pinyon Flat Observatory in California, which had footprint measurements taken in 1992 and 1994, before and after the Landers earthquake. This earthquake sequence ruptured an area which is located about 40 to 50 kilometres from the Pinyon Flat Observatory, during June 1992.

#### NASA/GSFC Site Stability Program

The site stability program of NASA/GSFC was initiated in the late 1980s with the aim to ensure geodetic site integrity as outlined by a special committee of principle scientific investigators of the CDP. Through collaboration with local specialists basic guidelines were established for selecting, monumenting and surveying 'footprint' or site stability networks around primary geodetic sites. The footprint measurements then provided a basis for the analysis of both the tectonic and physical stability of these sites. As mentioned by Bell et al. (1994) the objectives of the Site Stability Program are:

- (1) *Assuring the integrity of geodetic measurements taken at principal space geodetic observing sites (VLBI, SLR, and GPS)*
- (2) *Implementing and measuring local GPS networks around the main observing monument that are representative of the local tectonic environment they encompass (5-30 km scale)*
- (3) *Repeating conventional surveys of the reference markers relative to the main observing monument (less than 1 km) to assure monument stability*
- (4) *Providing first and second epoch GPS footprint measurements at many of the essential fiducial geodetic sites used in the worldwide global networks, beginning with the U.S.*
- (5) *Providing raw survey data and final geodetic results to NASA's CDDIS.*

#### GPS Footprint Surveys

From 1990 to 1994, NASA's Site Stability Program has implemented and measured local GPS networks (1-30 km scale) centred around main observing monuments with the aim to determine local stability of the area occupied by the main reference point. In comparison to the footprint survey, local GPS networks have been and are being measured by scientific teams in areas of tectonic interest to identify geological structures that are accommodating strain seen between and around geodetic fiducial sites. There is a basic difference between these two efforts however. The footprint encompasses a single tectonic feature which is occupied by the main site, the regional strain network encompasses an entire deformation field including all of its regional characteristics.

#### Concept of a Footprint System

At HartRAO we have been conducting a footprint study but on a slightly higher level. HartRAO has 3 primary reference points, and the stability of the footprint area is inferred from the measured stability of the footprint reference points, referred to the VLBI telescope, SLR pad, and IGS GPS receiver monument.

The footprint study is not a study concerned with only the baseline and relative position GPS measurements, in order to understand and correctly interpret small movements of the reference points one has to approach the footprint in a holistic way. Therefore, consideration needs to be given to the reference point as a system, and a combination of all these systems into the footprint system. During the formulation and slow process of setting up boundaries for a footprint study, it is clear that in order to solve this particular geodetic problem, use should be made of all relevant disciplines, in a multi-disciplinary approach. Free use should therefore be made of techniques and approaches used to solve problems in geodesy, geology, geophysics, electronics and other useful and sometimes seemingly unrelated sciences.

#### Collocation of Space Geodetic Techniques

An important part of the footprint is the determination of ties between the different geodetic reference points of each site. The IGS specifies that local ties to other markers on the site should be determined in the ITRF coordinate system to guarantee 1-mm precision in all three dimensions. Offsets should be given in delta-X, delta-Y, delta-Z, where X,Y,Z are the geocentric Cartesian coordinates (ITRF). This seems to be a reasonable request, but in practice may be difficult to achieve. This is particularly true when a geodetic VLBI antenna needs to be tied in. With such an antenna the reference point is the intersection of the axes, or when there is an axis offset, the projection of the declination axis onto the polar axis. At HartRAO we developed a technique to tie our VLBI antenna, SLR and GPS monuments simultaneously using GPS (Combrinck and Merry, 1997) with high accuracy. Due to possible errors being generated by the (mostly) elevation-dependent phase centre variations care has to be taken to use identical antennas on either end of GPS derived eccentricity vectors.

The advantage of using GPS for collocation and determining ties between the various reference points is that we need no intervisibility between the various instrument reference points. Not all sites have completed ties or footprints and many have yet to initiate such a project.

### Summary and Conclusions

What then is the current position of IGS GPS monumentation, antenna mounts, footprints, collocation ties and protection against lightning and vandalism ? The IGS does not specifically prescribe what should be used or how it should be done, nor does it give advanced information on designs and methods. Such a prescription would be impractical due to varying site characteristics, funds, access to engineering skills and different approaches. Heavy reliance is made on each site's ingenuity and interpretation of what a first order geodetic monument is and what sort of mounting plate is to be used.

### Where to From Here ?

Certainly no single station or installation has the final answer. There are nearly as many solutions (good and bad) as installations. UNAVCO seems to be the only site that offers solutions and informed help in an organised way to investigators aiming to set up an IGS station. Many sites have been set up using local expertise, approaches and designs. Some of these are documented but might not be readily available. Information on footprints is virtually nonexistent. Empty log files glare at us. Should we not forward more technical details, designs, footprint results, vandal and lightning protection measures and occurrences to a central point where it can be assimilated into an organised structure for the benefit of all ? Should we not have some sort of monument rating, however simple ? Do we not rate stations already in some way based on their receivers, reference clocks, geographical positions, data quality and select these for networks ? Should more emphasis be placed on higher quality monuments ? Should there not be a couple of 'small' rules before a station becomes an accepted IGS station, such as a complete and detailed monument design and installation description ?

### References

- Bell L., Bryant M., Nelson V. and Allenby R. *NASA's Space Geodesy Project: A Summary of GPS Footprint Results*. Fall AGU, 1994.  
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Tue Dec 1 14:44:02 SAT 1998