Local Surveys of VLBI Telescopes

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Abstract

With geodetic VLBI techniques we are able to determine station coordinates and displacement rates at millimetre accuracy levels. These results are very sensitive to local telescope displacements caused by natural phenomena or by man-made modifications. In order to separate the local effects from those which are of interest like crustal movements, land uplift and subsidence, we need to measure the position of the telescopes in the local vicinity. Local networks in walking distance of the telescope should be complemented by extended networks which provide links to geologically stable areas. In this paper we introduce the holistic approach to footprints and geodetic monuments. In order to achieve millimetre precision, local effects such as slope movement, weathering and thermal effects can no longer be ignored. The geodesist must recognise and be aware of potential instabilities caused by such factors.

1. Introduction

In order to achieve the current objectives of geodesy, several space geodetic techniques are utilised at facilities all over the world. Very Long Baseline Interferometry (VLBI), Global Positioning System (GPS) and Satellite Laser Ranging (SLR) are the three main space geodetic techniques supported. Determining the stability of each geodetic fiducial site on a local scale, tie reference points and determine the eccentricities between these points, require small geodetic networks which surround the geodetic sites. These *footprint* networks cover a radius of some tens of metres to tens of kilometres. Conventional surveying techniques and instrumentation could be used, utilising optical instruments such as theodolites and electronic distance measuring instruments, or GPS equipment. All these techniques are capable of providing good results and it will depend to a large extent on a station's available equipment and expertise as to which instrumentation is used for the local surveys and ties. It is time however to adopt a new approach to footprints, using an holistic approach which could add more meaning to the term *footprint*. This paper does not allow a full discussion of the subject at hand so a more detailed version is to be published as an IVS monograph. The IVS monograph will contain detailed examples of both conventional (optical) and GPS procedures.

2. Footprints; an Introduction

This short introduction is partially based on an unpublished report by Bell et al. (1994) and personal communication received from C Noll (Crustal Dynamics Data Information System (CDDIS)) and R Allenby. Conventional geodetic surveys are usually performed to ascertain reference points of SLR and VLBI instrumentation and the relative positions of reference monuments or other collocated geodetic instruments within the immediate site area. 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.

As mentioned by Bell et al. (1994) the objectives of the NASA/GSFC Site Stability Program are:

- Assuring the integrity of geodetic measurements taken at principal space geodetic observing sites (VLBI, SLR, and GPS)
- 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)
- Repeating conventional surveys of the reference markers relative to the main observing monument (less than 1 km) to assure monument stability
- 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.
- Providing raw survey data and final geodetic results to NASA's CDDIS.

2.1. Conventional Site Surveys

Physical stability of the main observing monuments are assessed by conventional geodetic surveys of the reference markers. If a permanent tracking instrument (VLBI, SLR, GPS) is installed at the site, these conventional surveys determine the reference point of the fixed observing instrument, and the relative positions of reference monuments, an azimuth mark, as well as other collocated geodetic instruments within the site area. When a site contains a marker that is frequently used by mobile geodetic systems, a mark to mark survey is simply conducted. The relative station position estimates from these classical surveys generally agree at the several mm level.

2.2. GPS Footprint Surveys

From 1990 onwards, NASA's Site Stablity 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. Similar work has been done at other sites, including HartRAO. 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. The footprint encompasses a single tectonic feature which is occupied by the main site, whereas the regional strain network encompasses an entire deformation field including all of its regional characteristics.

3. The Footprint System in General

Basically the stability of the footprint area is inferred from the measured stability of the footprint reference points, referred to (in HartRAO's case) the SLR pad, radio telescope and the IGS station HRAO. Several of the reference points at HartRAO are located on rocky outcrops, which are essentially free of soil and can be regarded as continuous or nearly continuous bodies of exposed rock. These outcrops owe their form to the intact strength of the rock, the continuity, dip, strike and spacing of their partings. Any movement of the rock on which the monument is located might not be due to crustal instability in the footprint area, but might be the result of other natural factors which influence and even control the nature and extent of the dominant processes in rock slope evolution. The current form of such an outcrop is a result of long term evolution of the ridge on which the outcrop is located. Each outcrop will have its own inherent stability, dependent on the current state of balance with the dominant processes in its evolution.

Form is an important parameter in any footprint as the processes which created the form are the same processes which will cause movement of the monument. Therefore the footprint does not concentrate on the evolution of the form, but on the effect the processes have on the stability of the monument. 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 individual reference point as a system, and a combination of all these systems into the footprint system. These systems can be simply defined as structured sets of objects and/or attributes with specific relationships between them. In order to solve this particular geodetic problem, use should be made of all relevant disciplines, in a multi-disciplinary approach.

3.1. The Open Dynamic System

The type of system which is convenient to describe the footprint and its components is the **open dynamic system**, as its main matter component is the surface of the Earth, which is open to the flow of matter and energy. Using GPS as example, the system's main measurement component is GPS, which is open to influence from other systems, such as the ionosphere, troposphere and time. We have thus an external input, some processes internal to the system, such as rock movement or soil heave and an output consisting of radiated energy or matter which leaves the system. Each component in the footprint system can be described as a subsystem and this approach allows a methodical, structured approach which aids in describing the footprint system holistically.

The footprint as an open system, in the case of HartRAO can be described as having:

- **Boundaries**, an inner boundary set by the five inner monuments, an intermediate boundary, set by the four outer monuments and an outer boundary set be the three reference points of the outer network.
- A **focal point**, chosen as the main reference point, which is the area surrounding the radio telescope and which contains the radio telescope, the SLR pad and IGS reference point HRAO and monuments close (< 200 m) to the radio telescope.
- A **set of coordinates** which defines the boundaries and focal point. The focal point has fixed coordinates whereas the boundary reference points have dynamic coordinates. For instance, the IGS station HRAO was used as the 'fixed point' in the final adjusted values of the footprint.
- **Inputs and outputs** of varying nature such as energy, matter and information (e.g. satellite ephemerides), which crosses the boundaries of the system.
- **Processes** within the system which affect measurement accuracy and monument stability.
- A **steady state**, in which the footprint shows no signs of instability, it is in dynamic equilibrium. An **unsteady state**, where one or more reference points show instability, the system will either move towards a new state of equilibrium or return to its previous state. During the crossover from one steady state to the next, the footprint system is in a **transient state**.

The footprint is mostly a cyclic, dynamic system in which the energy and other factors which constitute the inputs increase and decrease in a cyclic manner. As an example the measurement system is affected by diurnal changes in total electron content and periodic repetition in the geometry of the GPS satellites. The Earth's surface, i.e. the crustal component, is affected by diurnal variation in incident solar radiation, which causes possible thermal expansion and contraction. This component is also affected by the drying and wetting cycle of summer rain and winter dry periods.

4. Footprint Geology and Geomorphology

Causes and factors involved in site stability are mentioned here as these should be taken into account during site selection and during the lifetime of the geodetic monuments. For instance, weathering can cause apparent site instability through affecting the stability of a monument by transport of surface material; or weathering of subsurface rock could lead to progressive settlement of a monument.

4.1. Natural slopes

The geodesist should be aware of the danger that slope movement presents to his footprint monument stability. This is especially true if the monument is located on a slope and not tied to bedrock. Many footprint areas over the world will be located on terrain which is not perfectly flat and not all sites will have zero slope movement. Slope movement and development is a common, natural occurrence in nature and is an important factor in footprint stability. Giani (1992) mentions some of the principal phenomena which can contribute to an increase in shear stress and/or to a reduction of shear strength, both being causes which determine sliding movement in a slope. Contributions to an increase in shear stress are mainly from the slope surface or toe weakening, or slope surcharging. Natural surcharging result from water percolation in rock discontinuities, rain water or snow weight. Man also play a role when constructing embankments, heavy buildings and other structures, and large water reservoirs.

Slope surface or toe weakening could be the result of erosion by streams, rivers, glaciers, waves, tidal currents, sub-aerial weathering, wetting and drying and frost action. Subsidence, previous rock fall, toppling, sliding and superficial scaling plays a role as well as phenomena connected to human activity such as excavations and mining. The main causes contributing to a decrease in shear strength, include soil texture rock fabric and structural defects, physical and chemical reactions as well as changes in intergranular forces. Slope studies should form part of the footprint systems approach, local movement will in most cases be due to some form of slope movement unless the footprint is situated in active earthquake zone. Even in earthquake zones, slope movement would still be very important as slope activity could be increased by seismic activity.

5. Monumentation and the Geodesist

Monumentation is one of the most important aspects of a geodetic installation, where long and short term stability is the main requirement. Using a tripod to locate a theodolite or GPS antenna is an inferior approach and should **not** be used for high precision work. Selfcentring devices which are permanently fixed to the monument should be used as reoccupation errors are tens of microns instead of a tripod's millimetres. In order to determine crustal stability or measure relative plate motions, conduct a footprint or measure Earth rotation, one needs to fix the geodetic monuments to be used to the Earth's crust.

The more interfaces we have between the geodetic reference point and the solid crust, the more leeway is allowed for indeterminate errors. If data are collected over a long time, local and short term effects which induce positional errors tend to be averaged out, which give some observers confidence in a weak interface. However, as is well known, statistically it is far better practice to have better data than more but poor data. It is obvious that the closer the monument is located to the crust, the better, but even the shortest interface can be weak if made from the wrong material or incorrectly constructed. All of this sounds like common sense but when one inspects some geodetic reference points, it is obvious that more regard has been given to other factors such as ease of installation, cost considerations, accessibility, safety and security of equipment and personnel. Before one can design and construct a suitable interface between the reference point and the crust, one must first decide how the crust, in our terms of reference (considering crustal dynamics and footprint networks) can be defined.

A monument located on soil, or on a buildings would be more unsuitable than one that has been built on the bedrock as the interface between the monument and the crust would be strengthened by limiting the material separating the monument and the crust. The upper layer of the crust may not necessarily be that fixed either, as sediments and crystalline basements exhibit the presence of cracks, joints, fractures and fissures for at least the first 10 km of depth, but the topmost 10 m or so is normally the zone where bedrock acts as parent material for soil. This is a zone which should preferably be bypassed when installing a geodetic monument. Using this simple introduction one can create a definition of the crust from a surveying point of view.

This crust varies in composition and physical characteristics. One could therefore write:

- *Monumentation crust = the layer of the Earth, overlaid by man made structures, water, vegetation and organic matter, soil and regolith. Its depth varies from the surface where it can be exposed, to depths exceeding 100 m. It is the thin layer that separates the soil forming part of the uppermost layer of the Earth from the more stable and subjected to significantly less weathering processes, solid crust and is normally the parent material for the soil.*

The rock close to the monumentation crust could be weathered to such an extent that a residual soil is formed, which could take the form of several layers of rock-like soil or soil-like rock transitions in between. This residual soil, or saprolite, should be bypassed by drilling until true bedrock is reached and not be confused with the monumentation crust. From a stability and accessibility point of view, the ideal location for a geodetic monument would be on exposed, unweathered bedrock. Regardless of the inaccessibility to the monumentation crust, maximum effort should always be exerted to have the reference point located as close to and connected as strongly as possible to this crust.

In the geotechnical field, rock and soil stability analyses are used to allow evaluation and prediction of instability, especially those caused by excavation and construction on natural slopes. The analyses are designed to support the safe and functional design of slopes to be cut, and incorporate features such as consolidation works (drainage systems, retaining walls) which can aid in stabilising a slope. Evaluation is made of the role played by design parameters such as excavation height and slope angle, in order to determine their role in the work excavation stability. Unless the researcher is placing his monument on an absolutely flat location, which is not a very likely scenario, it is being placed on a slope. Geotechnical engineering and geomorphology provide us with information which is useful when selecting a site for a geodetic monument. The purpose of this section is to describe, in a general way, what one should keep in mind when selecting a site from a stability point of view.

5.1. Field Investigation

Once a decision has been made on the geographical region for the monument installation and one has studied available geological and geotechnical data, a field reconnaissance should be undertaken to gather information on the proposed site. Note the presence of exposed bedrock, note the strike and dip of the rock, joint spacing and condition. One should draw a map of the site and its immediate surroundings, keeping in mind the requirements of a stable monument. Factors which might influence the stability of the monument on rock are:

- Presence of faults, joints, fractures, shear zones
- Varying ground water levels
- Rock slope instability, rock which could cause problems due to swelling, dissolving and shrinking
- Presence of cavities due to karstic formations, such as found in dolomitic regions
- Human engineering activity, gas,water and sewer pipes, drainage ditches.
- 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.

5.2. Monumentation Located on Rock

Rock mass strength is an important determinant of slope form, especially in the absence of structural controls. Rock properties such as intact strength, spacing of joints and other geological discontinuities determine to some extent the form of the equilibrium slope. Any changes in the slope form over time will affect the stability of the monumentation. Generally the emphasis in the literature has been on processes as controls of rock slope development, (Wood 1942), (King 1953), but more recently rock mass properties has been recognised as controls in rock slope evolution (Terzaghi 1962), (Moon 1985). The study of the properties of materials, although a relative newcomer to the field of geomorphology, emerged in recognisable form with the work of Yatsu (1966) and found its way into the mainstream of geomorphology by Whalley (1976). Compressive strength, the degree of rock weathering and elasticity have been found to effect control on morphometric variables such as valley slope gradients and drainage density (Cooks 1979, 1981, 1983). A technique to determine rock mass strength was developed by Selby (1980) which allows for the expression of rock mass strength on a scale from 25 to 100. Rock mass strength can be regarded as the resistance of a rock mass to surface processes and it being the foundation of the reference monument, it follows that rock mass strength is directly related to the longterm stability of the monument. Application of rock mechanics was taken further by Selby (1982) and Moon (1985) and lead to a better understanding of rock resistance and joint roughness as controls of the stability of different rock slopes. It is important to bear in mind the main finding that joint spacing and intact rock strength are some of the prime determinants of slope form. The detailed analyses of individual properties of rock masses will enhance the understanding of the development of rock slopes and consequently of long term monument stability. Study of the materials, or at least taking them into account in some way, will aid in evaluating potential stability or instability and has important implications for monument design and site selection. Rock mass classification systems exist which have been used extensively in correlation with parameters applicable to the design of rock foundations (ASCE 1996). The geodesist should be aware of these approaches, as they provide valuable insight as to the possible instabilities, especially in the long term, which could affect a monument's stability.

5.3. Monuments Located on Soil

Classical soil mechanics can be put to use to give one a good indication of the expected stability and movement of a mounument located on soil. There are two basic groups of calculations, *settlement calculations* and *stability calculations* which are commonly used in geotechnical engineering. Settlement calculations are of direct importance to us as it is concerned with the stiffness of the soil beneath the monument. Stability calculations are used to model complete failure of soil masses, where large deformations occur on rupture planes followed by collapse of the geotechnical structure. Useful calculations can be done for a given monument and examples as well as the mathematical theory supporting various approaches can be found in the literature (see for instance Lambe 1964, Bowles 1977).

5.3.1. Volumetric Variables

A large proportion of the volume occupied by soil consists of voids, normally filled by air or water (pore fluids). When deformed, large and often irreversible changes in volume can occur due to the change of relative positions of the soil particles. In contrast, rock is more homogeneous at the particulate level so it is easier to describe it in terms of stresses and strains. However, the geotechnical structure on which the monument is located is normally much larger than the individual soil particles and as long as we take into account the possibility of large volumetric changes, stresses and strains can be averaged over the soil. The soil particles form a highly redundant skeletal, cellular framework, so any changes in the volume of this particle structure leads to the flow of pore fluid through the soil. The mechanical behaviour of the geomaterial on which a monument is located depends on its state, which in turn is defined by its structure and texture.

State parameters are:

- porosity (density)
- water content (consistency)
- stress (stress level, degree of isotropy, stress path)
- strain
- time
- temperature

These parameters are not isolated and act in combination. It is outside the scope of this paper to give a detailed description of each parameter, but the geodesist should be aware of the following points:

- The stress fields of porous continuous materials are not homogeneous (Feda 1992) and sources of progressive failures at higher stress levels, different stress gradients, their distribution and intensity, depend on the pore-size curve, as well as the overall porosity and its homogeneity.
- An increase in water content can lead to structural breakdown or decrease in strength and peak shear resistance. Monuments should not be built in a depression where water can accumulate.
- The mechanical response of soils is related to the magnitude of their strain (Ishihara 1981, quoted by Feda 1992). The response is elastic for $\epsilon < 10^{-5}$; elastoplastic for $10^{-2} > \epsilon > 10^{-5}(\epsilon = 10^{-1}$ representing the approximate failure strain); loading rate and frequency becomes relevant when $\epsilon > 10^{-3}$. The value $\epsilon > 10^{-3}$ is the threshold for major structural changes before dilatancy and contractancy appear.

5.4. Monuments Located on Buildings

Many geodetic monuments are actually buildings. If one attaches a GPS antenna to a pole which is attached to a building, the pole is not the monument, nor is the antenna mount the monument, the monument is the building. Buildings are not necessarily bad monuments, they often meet requirements in respect of accessibility, safety, power and convenience. Hardly ever are they evaluated in terms of their long-term stability. Building foundations suffer from primary consolidation, which results in the pore- water pressure being diffused. The theory and calculations can be found in the engineering literature (see for instance Holtz and Kovacs 1981, ASCE 1996) and indicates that even for geodetic monuments, depending on soil type and state, some primary consolidation is to be expected. Secondary consolidation should also be taken into acount. All buildings will show some settlement, the best will be those which have had pilings done to bedrock. It is probably good practice to avoid using buildings as monuments. 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 results in settlement of structures. This is true for the monument as well to a certain extent. The total settlement of the monument or building foundation in general is given by

$$S = S_e + S_c + S_s \tag{1}$$

where S_e = 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.

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 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 the monument will be. So within reason, if one has to choose a building for a monument location, it becomes part of the monument and in general older buildings should be more stable.

6. Footprint Networks

In a way, footprints are like fingerprints, not one is alike and each footprint will show the influence of its owner. The smaller inner network should possibly be called the fingerprint, as it is usually given much more attention. At HartRAO, during the footprint planning stages, fair consideration was given to network geometry and accessibility to reference points. Using self-centring plates and existing standard trig beacons did lead to a suitable geometrical configuration and practical network which was cost effective. During the construction of the 26 m radio telescope and the years following, several beacons were constructed surrounding the telescope and some of these were very suitable for the inner network. The outer and intermediate networks were designed by using as a starting point, a topographical map on which the trig beacons have been marked. Some apparently suitable beacons were selected from the map. This was followed by a field investigation to ascertain their overall suitability, leading to a final selection of the existing footprint network. This consists basically of an outer network of three points, an intermediate network of four points and an inner network of five points with radii centred around the VLBI telescope of approximately 60 Km, 20 Km and 1 Km.

7. Conclusions

The footprint for a specific geodetic site is defined by the operations required to make it scientifically useful and is not determined by any one particular definition set up with special circumstances in mind. Footprints determine geodetic site integrity, identify local instabilities, determine eccentricities between different geodetic techniques, and can vary in scale from very local (tens to hundreds of metres) to several tens of kilometres scale or more, depending on specific local requirements. Footprints are not technique dependent, nor are they bound by particular disciplines and can be regarded as an open dynamic system. Footprints should include some investigation of the geology and geomorphology of the area encompassed by the footprint networks as well as a substantial area beyond these networks. Evidence of historical and present/future instability can be had from several sources such as faults, seismics and geomorphology. The main point to be stressed here is that one should approach the footprint study from an holistic viewpoint and one should take into consideration the history, structure and slow evolution of the Earth on which the footprint is located. Final results of a footprint or any other geodetic network depend to a large extent on the stability and suitability of the monumentation used.

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