REPORT OF TLS

(TERRESTRIAL LASER SCANNER)

WORKSHOP

8-10 SEPTEMBER 2008

NASA
GODDARD SPACEFLIGHT CENTER

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SUMMARY

This workshop was organized to bring together survey authorities from both within and outside the space geodesy community to examine the co-location vector issue and suggest ways to determine the necessary vectors. Co-location of space techniques is a fundamental tool for developing realizations of the terrestrial reference system and accurate determination of the inter-systems vectors is essential for proper combination of the measurements.

The original motivation for the workshop was to assess whether a small number of laser scanners, placed on properly designed geodetic pillars, could provide a data set that could characterize the space geodetic instruments with sufficient accuracy to determine the inter-system or co-location vectors. We concluded that although laser scanner technology is rapidly evolving, the present measurement accuracy is not sufficient and that many viewing aspects would be necessary, requiring either many instruments or a survey campaign with a few instruments.

With this in mind, the workshop decided to examine all of the candidate ground survey and in-situ monitoring techniques that might be applicable to determining the vectors and how to proceed with a measurement program to test a candidate configuration. This report summarizes our conclusions and recommendations.

INTRODUCTION: PEARLMAN

Space geodetic ground networks support a broad range of applications including precision orbit determination, Earth rotation, ground motions, gravity field (mass displacement) and the realization of the Terrestrial Reference Frame (TRF). The TRF is derived from combining data from the different networks. A crucial element in this process is the presence of sites with two or more co-located techniques, and accurate ties between the techniques. The TRF impacts all of the other applications and is the standard by which we measure global change over space, time, and evolving technology. The most stringent need for the reference frame is sea level, which changes by a few mm per year but whose secular behavior is clear – oceans are rising. Altimeters on spacecrafts (with orbits referenced to the TRF) measure the ocean surface. Careful measurements of this ocean rise will help us to better understand the full nature of the process and the timeframe of concern. Requirements for other application such as the Earth's ice budget and terrestrial topography are less stringent, but still very important.

The reference frame is modeled by a time history of station positions from a global network of geodetic stations. The more comprehensive the network, the better and more stable the model. Co-location of different instruments (VLBI, GNSS, SLR, DORIS) allows us to combine fundamentally different measurements with different error sources to exploit the strengths of each while diminishing the weaknesses.

Space geodetic techniques are now making measurements over global distances to mm precision, but one of the fundamental problems with the co-location regime is the measurement of the vector between the invariant reference points (intersection of axes, GPS antenna reference points, etc) on the co-located instruments. Invariant points are almost always inaccessible and the determination of these vectors includes a survey between accessible points on each instrument plus extrapolations to points that are not directly accessible. This extrapolation process includes careful examination of engineering drawings, laboratory measurements, dynamic local surveys, etc. We emphasize that these invariant points, which can be related to a local ground control network by use of survey instrumentation, are not necessarily the points realized from the analysis of space geodetic data. The correction from the phase center to the physical antenna point for a GPS antenna, for example, is a calibration issue that is not directly addressed by this workshop.

Sub-mm accuracy may require a monitoring component in order to understand what is happening in real or near real-time. Small motions may be corrupting our measurements and subsequently our realization.

Several organizations have undertaken network studies to better understand how we can address the sub-mm issue including the intersystem vectors for the reference frame and other applications. Activities by the US National Research Council and the IAG's Global Geodetic Observing System (GGOS) are two examples (See Appendix 1).

Current ground survey techniques can provide closure to properly configured ground monuments to mm accuracies. These measurements however tend to be very expensive and infrequent. In addition, as discussed in Ray and Altamimi (2005), survey measurements must be extrapolated to invariant reference points (i.e. intersection of the axes on SLR and VLBI and physical GPS antenna reference points) on each of the space geodetic instruments in order to provide closure. Physical and electrical conditions may vary over time, which further complicates the situation.

The question is how do we find an economical scheme that would measure or even monitor the inter-system vectors with sufficient spatial accuracy and temporal resolution to support reference frame requirements now projected at 1 mm accuracy and 0.1 mm/year stability?

With this in mind, the workshop participants decided to examine all of the candidate ground survey and in-situ monitoring techniques that might be applicable to determining the vectors and how we might precede with a measurement program to test a candidate configuration.

In this report, we examine several surveying techniques that may be applicable to co-location survey. The characteristics, capabilities and limitations of these techniques are summarized on the following page, and discussed further in the text. We then describe the various space geodetic techniques and particular features that affect surveying, including specific situations at GGAO. Finally we conclude with some specific observations and recommendations.

A series of appendices contains additional information which, although relevant to the general question of how to measure and monitor local site ties, falls somewhat out of the mainstream of this report. We include these appendices for completeness.

VISIT TO GGAO: GIPSON

The NASA Goddard Geophysical and Astronomical Observatory (GGAO) is a typical multi-technique geodetic site with a VLBI station (MV3), two SLR stations (MOBLAS7 and NGSLR), a GPS station (GODE) and a DORIS beacon. On the first day of the workshop, the participants visited GGAO to gain firsthand knowledge of the issues and challenges involved in co-location. In many ways, GGAO has the problems typical of most existing co-location sites. These issues are discussed in more detail in Appendix B. GGAO grew organically over time. The placement of the different instruments was driven more by cost and convenience than by surveying considerations. In large part this was because the instruments were considered independent, as opposed to be being part of an integrated system.

Figures 1 and 2 on the following page show the layout of GGAO.

Figure 1 Panoramic view from MV3.

To the immediate left in Figure 1 is the pedestal of the VLBI antenna MV3. In the center of the figure, near the road, is the GPS instrument GODE. In the distance are the two SLR stations: the next generation prototype NGSLR and the operational MOBLAS7. The DORIS station, which is behind the SLR instruments, is not visible in this photograph.

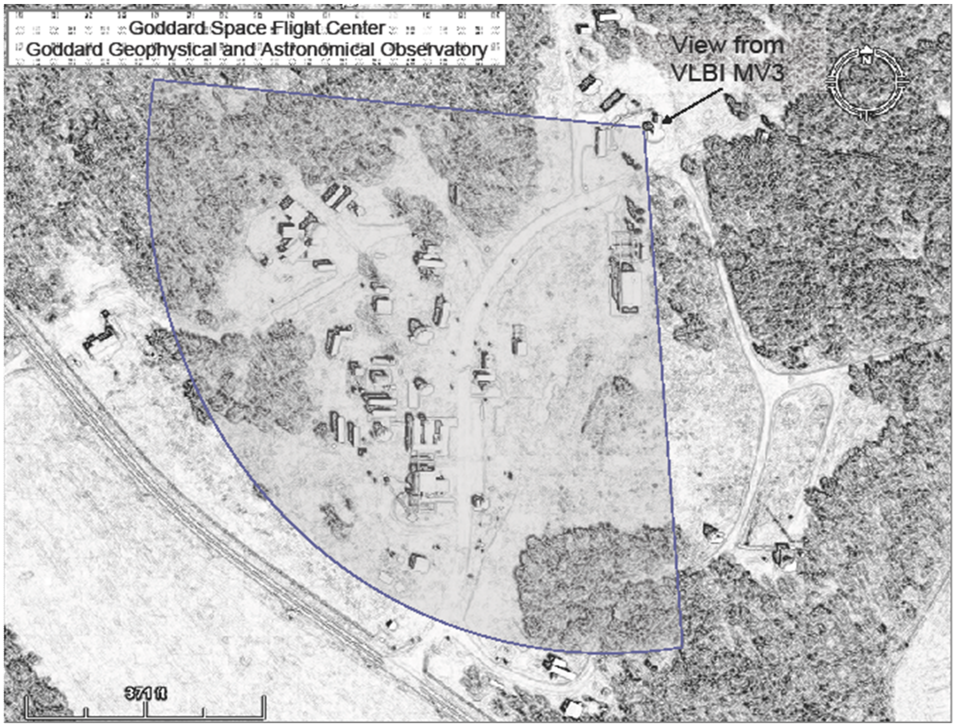

Figure 2 Aerial view of GGAO

Workshop participants toured the various instruments and were briefed on how the site is currently surveyed. The techniques are described in the following section, together with any technique-specific special issues. Following this is a discussion of site surveys for geodetic sites.

TECHNIQUE SPECIFIC ISSUES

GNSS/GPS: MEERTENS

DESCRIPTION OF GNSS/GPS SYSTEMS AND ANTENNAS

High precision GNSS receivers use microwave carrier phase and coded range data transmitted from constellations of orbiting satellites to calculate the position of the receiving antenna. The longest running systems are the fully operational U.S. Global Positioning System (GPS) and Russian GLONASS, which is being restored to full operations. Galileo is a new European global positioning system under current development. Other systems including QZSS (Japan), IRNSS (India) and Beidou-1 (China) are also being developed but are not considered here because they focus on regional, not global use (although China is experimenting with Beidou-2 or Compass for global applications). The French DORIS satellite system is fundamentally different from other GNSS techniques in that it is a ground transmit method as opposed to a receive system. DORIS has a lower accuracy (cm-level) than that of GPS (mm-level) and is used primarily for satellite orbit determination. The GPS system is currently in the process of being modernized by adding new codes and a new frequency. The modernization of GPS and the new GNSS systems will require significant changes to the global network over the next few years. One of the key issues will be changing from GPS-only to GNSS antennas and the impact on site position accuracy.

GPS high precision survey antennas consist of dual frequency antenna elements, a ground plane or choke ring, and a low noise amplifier. There are a variety of antenna elements in use including a microstrip patch, helix, and vertical dipole designs. In order to reduce multipath, typically a circular or square ground plane or choke ring is added. A protective antenna radome may be installed either directly on the antenna, integrated with the antenna mount, or separately installed on the geodetic monument. The GPS invariant reference point, i.e., physical antenna reference point (ARP) of the GPS antenna, is the intersection of the horizontal reference surface of the antenna (typically, but not always the base of the antenna) and the vertical axis of rotation defined by the threaded insert in the antenna base. GPS measurements are not determined by the physical ARP, but rather the electrical phase center of the GPS antenna. This is not a physical point and varies dependent upon the direction the GPS signal enters the antenna, principally upon the elevation angle. The phase center variation (PCV) is determined empirically either using relative calibrations on test ranges or a robot absolute calibration system. Uncorrected PCV errors are at the cm-level; with corrections this improves to the mm-level.

SURVEYING ISSUES WITH GPS ANTENNAS

The ARP is typically well defined for each antenna and can be related to a physical point on the survey monument, sometimes referred to as the marker reference point. Usually there is also an antenna mount between the monument and the antenna. With existing GPS stations, the antenna mount and monument, like the antennas and radomes installed on them, are of varying designs. Ultimately it is the marker reference point that is physically tied to other geodetic monuments and geodetic techniques.

In principle, GPS itself is the most precise means of achieving the local site ties between monuments and to orient these ties in a global frame. In many of the old site ties, classical astronomical observations were used for these transformations.

Sub-mm level precision can be achieved on short baselines at co-located sites. As noted, however, the primary issue with GPS surveys is not physical, but rather electrical. Antenna PCVs are affected by local site multipath, the presence of a radome, and the calibration of each individual antenna. All can significantly affect the accuracy of GPS observations. Note that the antenna calibration is dependent not only upon a specific model design, but also upon the consistency of manufacturing each individual antenna. For the widely deployed Dorne-Margolin choke ring the specification is +/-2 mm in the phase center variation from antenna to antenna. Currently the global network of GPS receivers, including those co-located with the other geodetic techniques, has a heterogeneous combination of antenna, antenna mount, survey monument, and radome configurations. They also have different in situ site conditions depending upon local ground and structures and time variability due to moisture, snow and ice accumulation. The variability of instrument and monument designs and site conditions all can affect the accuracy of site co-location determination using GPS at the mm-level or greater if the GPS antenna is very near structures such as VLBI antennas. It would therefore be desirable to make an independent measure of the marker reference point to other survey monuments using terrestrial techniques as has been done in the past.

In most cases local ties to GPS ARPs using an indirect approach based on redundant forward intersection can be successfully and accurately applied: see Sarti P, Sillard P, Vittuari L (2004). Where antennas are not accessible or radomes opaque or dimensions not accurately known, removing the radome or antenna is required so that an optical target or leveling rod can be placed directly on the marker. Invariably this results in an offset in the GPS coordinate time series due to difficulties in replacing the antenna and dome to the precise location they were in before. In order not to affect the long term time series of it has become common practice never to remove an operational antenna. While this has improved the precision of the time series, this makes it difficult to measure a local site tie and also makes it hard to access accuracy of the co-location site ties at existing sites. In future observations, it may be desirable to allow for at least one monument at a site where the GPS antenna can be deliberately changed. If even after using the best know antenna calibrations the solution time series is offset by >1mm then the accuracy needs to be reassessed.

OBSERVATIONS FROM THE FIELD TRIP TO GGAO

The GPS site “GODE” at GSFC GGAO highlights some of the issues mentioned above. This site has a “FLYNN” concrete pier monument with stainless steel plate on the surface that is used at many existing NASA GGN sites. The survey or marker reference point is a punch mark in the center of the plate. A fixed height pin connected to the antenna base rests in the mark and three leveling screws support and level the antenna. There is no forced orientation of the antenna. A 5-6 mm thick acrylic dome covers the JPL choke ring antenna and monument and is fixed to the monument itself. With the dome in place it would be difficult to use a laser scanner to image the antenna itself or the mark itself. The dome likely has a large (mm to cm level) affect on the PCV. Calibrating this in situ is not currently a viable option. More recent designs, such as the SCIGN radome with Dorne-Margolin choke ring, are coupled with the antenna. The radome becomes part of the antenna and its effect included in the PCV determinations. The physical dimensions are also well known allowing for scanning of the dome and relation to the marker determined. While using such an antenna/radome reduces the problem, site effects remain.

SATELLITE LASER RANGING: PEARLMAN

DESCRIPTION OF SLR SYSTEM

Satellite laser ranging uses short-pulse lasers to measure the precise distance from ground stations to retroreflector-equipped satellites. SLR stations range in size from small compact systems to some with telescopes with apertures as large as a meter. There is little standardization of the mechanical configuration, but most of the systems use some kind of Coude telescope to guide the optical beam out and the return back into the ranging machine. Some stations have rolling roofs that open to expose the whole system; others have rotating domes with windows or ports that permit ranging access, but otherwise shield the instrument. There is much more commonality in the laser and in the electronics components, but even here there is variation with some systems using 5 and 10 hertz pulse operation and others 2 KHz. We anticipate that the higher repetition rate will become more common with time. Most of the systems use ground targets at well surveyed distances to calibrate for internal path (range) delay; others use targets internal to the system. All of the systems periodically verify performance using ground targets. Most stations do not take into consideration the effects of temperature variations within the system (including cable lengths) on their range measurements.

SURVEYING ISSUES WITH SLR STATIONS

SLR measurements are made with respect to the system “invariant point” which is the intersection of the azimuth and elevation axes. There is no assurance that the optic beam in and out goes through this point at the sub-mm level. However the Coude alignment provides very strict constraints on the beam path. The intersection of the axes is not accessible, so its location must be extrapolated from survey measurements of the telescope through azimuth and altitude rotations. Detailed systems surveys measure everything from orthogonality of axes, target ranges, and position within the local station geodetic grid.

OBSERVATIONS FROM THE FIELD TRIP TO GGAO

At the GSFC GGAO we visited both the Moblas-7 legacy system and the New Generation SLR (NGSLR) now under development. The Moblas system has separate transmitting (16 cm) and receiving (76 cm) telescopes and a rolling roof. The NGSLR has a single 30 cm telescope housed within a dome with a window for ranging. In order to estimate the system invariant point, line of sight is required from external surveying points to different points on the telescope. The dome and the window severely restrict survey access to the NGSLR. The Moblas system has a roof that rolls back away from the instrument giving survey access for a wide azimuth range. Neither instrument has any permanent survey reference points on its structure.

VLBI: GIPSON

DESCRIPTION OF VLBI SYSTEM AND ANTENNAS

Very Long Baseline Interferometry geodesy measures the time it takes a radio wavefront from a quasar to reach pairs of VLBI sites and converts this to a baseline vector between the sites. VLBI antennas used for geodesy measure from 5 m to 100 m. The typical size of most geodetic VLBI antennas is in the 20-25 meter range. Because sensitivity is proportional to area and VLBI signals are very weak, smaller antennas can only be used in conjunction with larger antennas. The higher sensitivity of the larger antenna compensates for the lower sensitivity of the weaker antenna. The VLBI system at GGAO has a 5-meter dish. This dish is currently used primarily in VLBI2010 prototyping, where it observes in conjunction with the 14-m Westford dish. The minimum size for the VLBI2010 antennas is 12 m. The VLBI2010 system compensates for smaller antenna size by increased observing and recording bandwidth.

The VLBI observable is found by recording and cross-correlating the signal from two antennas. The frequencies and the bandwidths of the signals must be the same at both sites. Although there is some variation in the data-acquisition equipment at different sites, at a high level the equipment is functionally the same. The primary difference between the different hardware is that the recording format varies. The VLBI community has harmonized critical features by developing standards for ongoing developments (VSI-H, VSI-S etc.). VLBI systems do not have the degree of variation around the world as you see in SLR systems.

VLBI antennas are mounted on backup-structures that move the VLBI antennas to point at different parts of the sky. There are a variety of VLBI antenna ‘mounts’. All VLBI mounts have two axes: a fixed axis, and a rotating axis. GGAO is an AZ-EL mount, which is by far the most common type. The antenna rotates around the azimuth axis, which points straight up. The elevation axis is perpendicular to this. Rotation around the elevation axis causes the antenna to move up and down.

SURVEYING ISSUES WITH VLBI ANTENNAS

VLBI measurements are made with respect to the antenna invariant point, which is the projection of the moving axis on the fixed axis. If the axes intersect, the travel time of a radio signal to this point does not depend on which direction of the sky the antenna is looking. If the axes do not intersect, then an “axis-offset” correction needs to be applied to compensate for variation in delay as the antenna points at different elevations.

The results of a VLBI measurement are referred either to the intersection of axes or a geodetic marker on the ground; hence there must be a survey to connect the VLBI invariant point to the geodetic marker. As discussed in the section on Present Surveying Techniques, this is complicated because the invariant point is usually inaccessible.

Another complication for VLBI is antenna deformation due to thermal or gravitational deformation: the structure of the antenna changes with changing elevation angle. Antenna deformation is more of a problem on larger antennas. Because of their small size, it may not an issue with GPS or SLR. Antenna deformation may cause variations in the length of the signal path, which in turn leads to errors in the estimated station position. These can be compensated for if the deformation can be accurately measured or modeled.

OBSERVATIONS FROM THE FIELD TRIP TO GGAO

THE GGAO 5-m VLBI antenna has no permanently fixed survey markers. The initial site surveying process, as well as re-surveying, would have been made easier if these had been installed; surveying markers are relatively cheap. Surveying the physical axis offset would be helped by having a target at the center of the elevation axis, which the GGAO antenna lacks.

PRESENT SURVEYING TECHNIQUES: LONG

A number of experienced survey organizations from around the world perform the local site-tie surveys at co-location sites. While each organization has unique skills and expertise, the basic concept for the local tie or co-location vector surveys is quite similar. Current local tie surveys generally consist of periodic epoch campaigns at co-location sites to survey the surrounding ground control network and the invariant reference points of the space geodesy instruments. At best, the local tie surveys are done annually. Quite often, the time between surveys is 2-3 years or longer.

The survey observation procedures and equipment used are very much the same as for other high-precision control and metrology surveys, with some special enhancements for the unique application to space geodesy instruments.

For the space geodesy instruments that have steerable mounts to point at specific targets (SLR and VLBI), the invariant reference point is the intersection of the effective axes of rotation. Since the intersection of the axes is often not directly accessible the invariant point is determined by indirect methods. The general method is to install survey targets on the moveable part of the SLR telescope or VLBI antenna and then rotate the telescope or antenna systematically about one axis of rotation, while observing the target with survey instruments from multiple ground control standpoints. The center of the arcs scribed by the survey target points represents the axis of rotation. This process is repeated for the other axis of rotation.

For the space geodesy instruments (GPS and DORIS) that are not moveable, and whose invariant reference points are not accessible, simpler but still indirect methods are used. Generally, the GPS and DORIS antennas are located by forward intersection from the survey control standpoints by observing in the horizontal direction to specific points on the antenna (such as the tangent lines-of-sight to the outer edges of a GPS choke ring antenna). Well-documented, physical dimensions of the antenna are used to reduce the observations to the invariant reference point.

Nowadays, GPS equipment is used to orient the local topocentric survey observations within a geocentric system like ITRF. To do so, GPS instruments must occupy a minimum of three of the survey ground control network standpoints and take data for 3-to-5 days. In many of the old site ties, classical astronomical observations were used for the transformations.

All of the field survey data is reduced and adjusted with least-squares software to identify outliers and to verify the precision of the survey. Various software tools are used to rigorously analyze the determined arcs of rotation and solve for the rotation axes.

NEW SURVEY INSTRUMENTATION

In this section we describe a variety of survey instrumentation. The characteristics of these instruments are summarized in Table 1 on the following page. We also discuss each technique in more detail.

SUMMARY OF SURVEYING INSTRUMENT CHARACTERISTICS

	Cost $1000’s	Measurement	Accuracy	Comments
Theodolites	$15,000	Angle	0.5”=2.4 μ-radian	Traditional surveying instrument.
Total Station	$25,000	Angle Distance	0.5”=2.4 μ-radian ~ 0.5 mm + 1ppm	Adds range capability to theodolites. Accuracy depends on whether using refectorless prisms or not.
Robotic Total Station	$30-$60	Angle Distance	0.5”=2.4 microradian ~ 0.5 mm + 1ppm	Adds programming capability to total station.
Terrestrial Laser Scanners	$75-$200	Angle & Range of Point Cloud	Angle accuracy from 9-350 μ-radian depending on model. Range accuracy depends on target material and distance. Typical values are: 0 .25 mm for 1-10 M 1-10 mm for 25M 1-50 mm at 50 M 3-4 cm at 500 M	Similar to Total Station but measures 10,000s pts. Angles and distances not as accurate as TS. Time of flight instruments have longer ranges, slower rates and high accuracy. Phase instruments have short ranges, higher rates, lower accuracy. Maximum range depends on reflectivity. Divergence of beam width affects resolution. Longer distances only if you spend $200K.
Laser Tracker	$70 – 150	Δ Range Angle	$\lambda/2$ ~0.01 mm/m 0.5”=2.4 μ-radian	Range measurement uses interferometry. Accuracy limited by angle precision.
Digital Levels	$3-8	Height	~0.5 mm (range <60 m) 0.2 * sqrt(distance in km)	Consists of electronic level and staff, typically invar.
Electrolytic Tilt Meters	$10	Tilt	1-5 nanoradian resolution ~1 μ-radian stability	Used to monitor tilt of optical and radio telescopes.
Long Baseline Tiltmeters	$8+ $2/100M	Difference in water height	50 nanoradian 0.1 μ-radian stability	Uses level pipe half filled with water. Water level measured at ends and in middle.
Vertical Extensometers	$3	Changes in height/depth	0.1 mm	Uses invar rods. A) Used to monitor antenna height of VLBI antennas. B) Placed in boreholes at end of tiltmeters, monitors sub-surface stability.

TOTAL STATION & LEVELS: NOTHNAGEL

A total station surveying system consists of an electronic theodolite with an integrated Electronic Distance Measurement Instrument (EDMI), coupled with a precision retroreflector. (There are reflectorless total stations available, but they tend to measure distances with a lesser degree of precision.) Total stations have been in use by the surveying community since the 1970s and are a proven technology. While total stations are designed for outdoor usage and can be operated under all but the most extreme weather conditions, they should not be exposed to heavy precipitation. Some total stations have robotic capabilities, enabling remote or programmed operations. These should be applicable to automated co-location surveys or monitoring.

Those total stations possessing the highest level of precision are capable of measuring horizontal and vertical angles to 0.5 seconds and distances to the sub-millimeter level. There are various systematic errors associated with these instruments, most of which can be determined using established calibration techniques, while others can be eliminated by proper field procedures. When systematic errors associated with these survey instruments are identified and accounted for through instrument calibration and prescribed survey methodologies, sub-millimeter local accuracies are achievable.

DIGITAL LEVELS: FANCHER

A digital leveling system consists of an electronic level and a staff, or pair of staffs to improve efficiency. These instruments have been in use since the early 1990s and are a proven technology. They may continue to be useful for the local control network. The level contains a Charged Couple Device (CCD) imaging sensor. Staffs designed for higher level of precision have bar code scales superimposed upon invar strips. The CCD sensor takes an image of the barcode scale on the staff. This image covers a certain sector of the bar code scale both above and below the horizontal line of sight. On-board software compares this against an internally stored image of the entire scale and determines both a distance and a height difference.

There are digital leveling systems capable of height difference measurements at the sub-millimeter level. Systematic errors associated with both the level and staff can be identified using established calibration techniques. Proper field procedures and calibration can eliminate some of these errors, and sub-millimeter vertical accuracies are achievable. However, heights can only be transferred over longer distances by repetitive steps of about 60 m each and that remaining errors tend to accumulate systematically with every step.

TERRESTRIAL LASER SCANNER: AIKEN

TLS instruments are similar to total stations in that they combine a laser-determined range with accurate angles. They differ in that instead of measuring a few to ~100 points per session they typically measure hundreds to hundreds of thousands of points per second. The resultant dense cloud of laser points ("point cloud"), often numbering in the millions, is a characteristic of these devices. TLS instruments cost from $75K to $200K.

TLS instruments determine range by either phase or time of flight (TOF). Phase devices typically have ranges in the few tens of meters and are usually operated indoors. Their accuracy is millimeter to sub-millimeter in accuracy and they operate at rates in the hundreds of thousands of points per second. TOF devices can have long range (up to 2 km) laser rangefinders but tend to have lower accuracies and slower rate of operation (a few thousands of points per second).

The accuracy of the vertical and horizontal angle measurements determines the accuracy of these instruments. The resolution is determined by the minimum separation of points in the point-cloud, and the diameter of the laser beam, which increases with range. These characteristics must be considered when choosing a TLS for a particular application requiring very high resolution and accuracy. These specifications are improving all the time.

A dense point cloud allows details of a surface and any change to be defined at millimeter resolution with phase scanners and few millimeters with TOF devices. Deriving a model of a surface from the point cloud requires CADD type software or point cloud analysis capable software such as Polyworks (very expensive, ~$25k/seat). The addition of a coaxial camera attached externally or internally to the scanner allows the points in the point cloud to be colored by the image pixels from the camera. The camera and the lens combination determine the resolution. The point-cloud provides the geometry and the image provides RGB color information of the surface.

The University of Texas at Dallas (UTD) builds surface models from the point cloud, and applies texture maps from oblique close range photography using Cybermapping software. This software, which does not require coaxial cameras, provides a more general solution. UTD developed software called GeoDimensional Tools (GDT) to use ArcGIS (a specific geographical information system) as a platform to visualize and analyze 3D features including clouds and photorealistic surfaces. This package could be used to create new tools inside ArcGIS that could perhaps provide what is necessary.

TLS survey control is usually done by scanning positioned reflectors, which can vary from flat targets to 3D shapes such as balls and cylinders. How the scanner software handles these reflector shapes varies with the manufacturer, but this is an important factor if one is trying to use TLS instruments for co-location surveying. It is usually the case that relative changes in a surface or target can be identified through repeat scans at a higher accuracy than the absolute positions can be determined within a single scan.

The Optech Ilris3D scanner used during the workshop is a TOF survey device with long range, and a very fine beam diameter. UNAVCO has, or has access to, Optech Ilris3D and Riegl LPM

800i scanners. The LPM 800i has much lower accuracy and resolution than the Optech. Using or testing other scanners, especially phase types, would be recommended.

Although TLS technology is probably not appropriate for co-location surveys, it is very useful for deformation studies, or to detect changes in shape. The technology and methodology however should continue to be evaluated for all the required applications because the point clouds provide such an enormous amount of 3D information.

LASER TRACKER: NOTHNAGEL

Laser trackers work on the principle of interferometry. The laser beam is split into two parts. The tracker sends one beam to a retro-reflective target placed on the object being measured. The reflected beam reenters the laser tracker, where it is “mixed” with the other beam. This produces interference fringes. The fringe pattern changes as the distance to the object changes. Because the fringe pattern remains the same if the path distance changes by one wave length, the laser tracker measures only relative changes in position. The first laser trackers measured relative distances by tracking the position of a reflector as it moved from a predefined position to a target location. The laser tracker simultaneously measured the horizontal and vertical angle within a local reference system. The size of the overall system (tracker plus object) was typically limited to less than 10 meters. Currently, laser trackers can operate up to about 70 meters.

The precision of laser trackers is high, but depends very heavily on the distance. The precision is usually given in microns per meter. The instrument application is generally for engineering purposes indoors. The requirement for an uninterrupted view of the reflector at all times for the interferometric mode restricts the absolute distance measurements capability to about 0.5 mm out to a range of 50 meters.

Laser trackers require rectangular-mirror reflectors that limit the maximum deflection angle from the reflector's normal plane to about 10 degrees. Early instruments were large and heavy and mounted on their own pedestals, which would make using them on site problematic. More modern instruments are lighter (~25 kg) and smaller (largest dimension ~0.5 M), and should be able to use pillars designed for theodolites[1]. Special adapters may be required. Prices are in the $70K to $150K range but are expected to drop in the future. One problem with laser trackers is that the reflectors need to be oriented towards the instruments quite frequently. This limits their use on rotating structures such as VLBI antennas.

Laser trackers are probably not suitable for co-location survey.

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[1] See for example: http://www.faro.com/Faroip/Files/File/Brochures/UK_brochure_FARO_Tracker.pdf

TILT METERS & EXTENSOMETERS: MEERTENS

Tiltmeters have wide application for crustal and structure monitoring. The most common type has an electrolytic sensor and can be installed in shallow (~10 m) boreholes or on platforms. Tiltmeters are used at astronomical optical and radio telescopes for telescope zenith positioning and to monitor axis alignment and deformation of the telescope structure. Borehole or platform tiltmeter measurements are typically not used for long term site monitoring at geodetic fundamental sites due to the poor long term stability of these instruments caused by very local influences. They are used to measure active crustal deformation at volcanoes where larger motions are expected. The cost for electrolytic sensors and electronics is approximately $10K plus installation costs. Borehole tiltmeters intended for geodetic applications have a resolution at 1-5 nanoradians and microradian-level long term stability (depending on local site conditions).

Long baseline fluid tiltmeters overcome some of the limitations of point tiltmeters by averaging the tilt over a larger area, typically a half of a kilometer or more, and by employing vertical extensometers to reference tiltmeters to more stable materials at depth. The University of Colorado long baseline tiltmeter (Bilham, pers. Comm., 2008), is an example of such a system. The tiltmeter is a level pipe half filled with water that has two precise measuring points at the ends and one in the middle. The use of three sensors provides an unusual measure of signal integrity and immunity to spurious noise at any one sensor. The sensitivity of the tiltmeter sensor measurement of the water level is 50 nanometers. The long term stability of the system is at the 0.1 microradian level making this an effective instrument to monitor local site stability. The cost of long baseline fluid tiltmeter depends on its length (e.g., $2k/100 m), and the three water level sensors cost $2.5k each. The cost of the vertical extensometers depends on the depth of the hole. The sensors cost around $1k each.

The vertical extensometers co-located at the end points of the tiltmeter monitor the subsurface stability of the tiltmeter sensors. The vertical extensometer measures the motion of Invar or graphite rods anchored to the bottom of an approximately 20 meter deep borehole. The sensitivity of the vertical extensometer is at the sub-micron level and long term stability at the 0.1 mm level making this an excellent instrument to independently monitor vertical local site stability of any geodetic instrument. The cost of a vertical extensometer is ~$3K plus installation costs.

To date, tiltmeters have not been used for co-location determination.

PREVIOUS EXPERIENCE WITH TLS

VLBI: SARTI

Large VLBI telescopes undergo gravitational deformations that are functions of the elevation angle. These may change the incoming signal path. Clark and Thomsen (1988) identified three factors which may change the length of the signal path: i) the displacement of the receiver, ii) the displacement of the primary mirror (essentially described by its vertex's position) and iii) the change of focal length. They quantified the contributions of the three different effects for the Gilcreek VLBI antenna using a Finite Element Model (FEM) of the antenna.

Any change in telescope's focal length is strictly related to the shape of the primary mirror and its response to gravitational deformations. Any elevation-dependent change of the main reflector's geometry modifies the antenna optics and corrupts the observations.

In September 2005 TLS scanning surveys were carried out at the radioastronomical observatories of Medicina and Noto (Italy) to study the gravitational deformation of the primary reflector and to determine changes in the focal length. Both antennas have AZ-EL mounts and have 32 m parabolic mirrors. A GS200 Trimble-Mensi TLS mounted near the vertex surveyed the surface of the dish using a sampling interval of 2 cm at a distance of 15 m on the primary reflector. Each point cloud contained at least 1.3 million points, and was used to model the surface of the antenna. This process was done at six elevation angles ranging from 15° to 90° (in 15° steps). Survey procedures, data processing and results are summarized in a paper (Sarti et al.) in the Journal of Surveying Engineering. The main results can be summarized as follows.

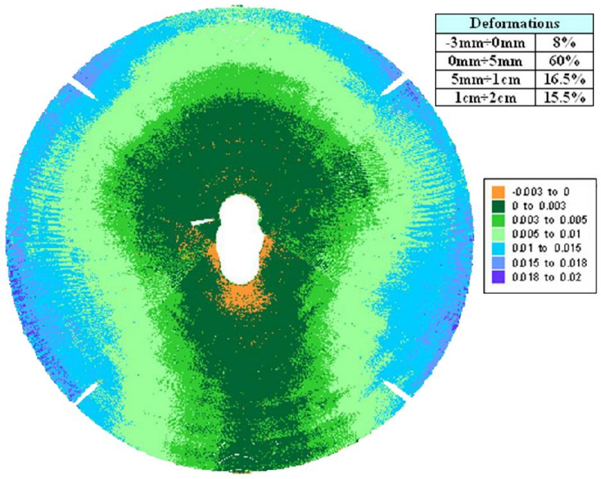

Figure 3 Difference in antenna deformation between 90° and the 15° as measured by TLS.

Laser scanner surveying proves to be an innovative and effective method to monitor the elevation dependence on gravity of the focal length. Measurements of the surface deformation by the laser scanner allow you to estimate the change in focal length. As illustrated in Figure 3, the relative deformations of the primary reflector can reach up to 2 cm (±0.1 mm) when comparing the 90° and the 15° elevation scans. The telescopes' structures react to gravity in a very similar manner: they fold inwards as the line of sight turns from zenith to the horizon. This behavior is not perfectly symmetrical at the edge: the lower part of the dish experiences a weaker inward folding than the upper part.

For both telescopes, the focal length change is approximately 4 cm as the elevation changes from 0° to 90°. The focal length becomes larger as the angle increases. It is important to note that this variation does not map directly into the signal path delay: it is multiplied by a constant coefficient dependent on the particular design of the telescope (see Clark and Thomsen, 1988).

The surveying design and planning are crucial to obtain the desired parameter with sufficient accuracy. A particularly important aspect is obviously related to the laser scanner instrument: its performances must meet the requirements of the survey in terms of precision and performance.

TLS WITH GPS TARGETS: FOSTER

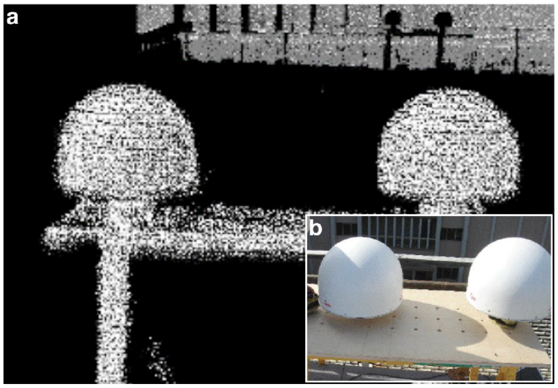

Figure 4 Test table for TLS and GPS. a) Example point cloud b) Photo of setup.

Researchers at the Pacific GPS Facility at the University of Hawaii have been investigating the potentials and limitations of automated target modeling using an Optech Ilris3d TLS and Leica choke ring antennas with the Leica snow radome. Because the upper portion of the radome is a 19 cm radius hemisphere it can be modeled in the point cloud as a sphere and the center related to the phase center of the GPS antenna. Aryal et al. [2007] performed controlled experiments by building a stable table with a grid of peg holes and estimating static offsets and translations of the Leica GPS antenna and radome. The radome was scanned from variable distances (50 - 350 m) and with variable spot spacing. The 3D point cloud data was used to model the center of the radome in a local co-ordinate frame. Preliminary results show that from over 1000 individual scans with spot-spacings of ~7 mm and over distances of 75-350 meters, the repeatabilities of estimates for the center of the radome had standard deviations of 2-6 mm, while displacements of up to 1 m were estimated with standard deviations of 9-14 mm.

CONCLUSIONS

The following are issues and recommendations that the committee points out in the quest for sub-mm co-location vector recovery:

1. Laser scanners are not currently suitable for determining co-location vectors with the required accuracy.

2. The optimization of the layout of space geodesy instruments and the supporting survey network for a new fundamental station should be studied.

3. Automation of co-location vector determination and monitoring using robotic total stations should be studied.

4. Specific issues and recommendations

    a. The invariant point on most SLR and VLBI systems is not readily accessible so its location must be extrapolated from survey measurements of the telescope through azimuth and altitude rotations and or very detailed as-built engineering information; (This is probably the most fundamental of all of the issues)

    b. Rotating instruments such as VLBI and SLR require survey access from several well-separated azimuth directions to define the vertical axis;

    c. Fixed, integrated survey targets should be permanently affixed to the space geodesy instruments for survey monitoring. Permanent markers should be affixed to GPS monuments, and on the elevation axis and on other moving parts of VLBI and SLR systems;

    d. Tilt meter and extensometer could help in the SLR and VLBI antenna to indicate motion;

    e. Temperature measurements at crucial locations and thermo-mechanical and electronic path modeling should be used to model the thermal deformation and other temperature effects on the performance of the systems;

    f. The simplest geometry would have four targets at different distances in the four azimuth directions for survey control and SLR calibration; The next step would be to arrange pillars so that they could serve more than one space geodesy instrument;

    g. Proper layout of the sites could reduce the ground survey burden by assuring lines of sight and common use of some pillars;

CONCRETE NEXT STEPS

The following are some steps to take in the near term.

1. Investigate feasibility and suitability of using robotic total stations to measure and monitor local site ties. This is discussed more in Appendix A.
2. Seek input and encourage cooperation with domestic and international partners who are interested in this issue. This may be in the way of borrowing equipment, e.g., total stations, or manpower, or using their expertise.
3. Do a design study of an ideal integrated geodetic station. This would include issues such as placement of geodetic instruments, survey markers, and auxiliary instruments such as extensionometers, tiltmeters, etc. It would include tradeoff studies to see how accuracy would be degraded if the number/type of instruments were reduced. It would also include studying how much of this could be adapted to existing stations, as opposed to starting *ab initio*.

REFERENCES

Aryal, A., B. Brooks, and J. Foster (2007), "Accuracy and Precision of Terrestrial LiDAR for Ground Deformation Monitoring", EOS Trans AGU, Fall Meet. Suppl., 88 (52), Abstract G51C-0615.

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Ray, J., Altamimi, Z., "Evaluation of co-location ties relating VLBI and GPS reference frames", J. Geod (2005) 79: 189-195.

Sarti P, Vittuari L, Abbondanza C "Laser scanner and terrestrial surveying applied to gravitational deformation monitoring of large vlbi telescopes' primary reflector." J Surv Eng, in press.

Sarti P, Sillard P, Vittuari L (2004) "Surveying co-located space geodetic instruments for ITRF computation", J Geod 78(3):210–222.

APPENDIX A. PROOF OF CONCEPT DEMONSTRATION WITH ROBOTIC TOTAL STATIONS

The original motivation for the workshop was to assess whether a small number of laser scanners, placed on properly designed geodetic pillars, could provide a data set that could characterize the space geodetic instruments with sufficient accuracy to determine the inter-system vectors. We concluded that although laser scanner technology is rapidly evolving, the present measurement accuracy is not sufficient and that many viewing aspects would be necessary, requiring either many instruments or a survey campaign with a few instruments.

On the other hand, many colleagues have successfully used robotic total stations. Robotic total stations have the advantage that they can be programmed to run automatically. Therefore, we recommend that a series of tests be undertaken at one of the current space geodesy sites with two or more robotic total stations to examine how such a complex could be configured, how the expert manpower hours for such a survey might be reduced or essentially eliminated, and how simultaneous measurements might allow us to better optimize the placement of the instruments, the instrument orientations, and the number of targets. This will require study and planning for a number of measurement options that can be explored. It will also require the development of some control and processing software.

This series of tests would be best undertaken with the cooperation of several interested agencies that could provide equipment, personnel, and experience. The participants in this workshop are interested. HTSI already has a robotic total station instrument in its ground survey team. If additional robotic stations are not available, we can simulate their performance with standard manned systems. The issue here is not the accuracy – the issue is how we take the survey in a more efficient, less costly, automated manner. The tests should also give us better insight into how the space geodetic instruments (VLBI, SLR, and GPS) should be designed in the future to better accommodate the ground survey tie measurements.

APPENDIX B. ISSUES WITH CURRENT GEODETIC SITES: NOTHNAGEL

In many cases, existing co-location sites suffer from the fact that the facilities have grown organically from single-technique installations to multi-technique observatories. The placement of instruments at sites is governed by considerations of topography, economics or politics, with little thought given to how to tie different instruments together. The fundamental problem is that the instruments are considered individually, and not as part of a larger entity, the "geophysical observatory". Because of this, only a very limited awareness of the importance of ground surveys for stability and eccentricity vector determinations exists.

In most case, local control networks are poorly planned and realized or do not exist at all. The number of survey monuments may be limited or placed in arbitrary locations. In addition, proper forced-centering devices for precise measurements are often missing. Another issue is the pillars themselves may not be stable, or they may be prone to thermal deformation due to asymmetric solar radiation due to the lack of protection against direct sun illumination.

On VLBI or SLR telescopes there is almost no provision made to accommodate survey targets at locations suitable for a good surveying geometry or even adequate visibility from the ground. For example, the end points of the elevation axis are often covered by a box containing the angle encoders for steering the telescope movements inhibiting a direct materialization of the elevation axis. Rails, ladders and the like often block the view from the ground to possible locations of surveying targets on the telescope support structures.

Telescopes under radomes present their own implicit difficulties with conventional techniques since the operating space under the radome is very limited. In the case of SLR telescopes, the view through the window in the dome is very limited.

In a more global context, a single GPS antenna at a co-location site is always sensitive to local effects like multi-path. More importantly, replacement of the antenna or adding a radome has a severe effect on the coordinates determined from the observations in a global network. The magnitude of these effects could only be recovered if more than one, preferably three, GPS antenna-receiver units would be in operation at each site permanently and be analyzed routinely in the IGS analysis framework.

APPENDIX C. POSSIBLE MULTITECHNIQUE SITE LAYOUT: NOTHNAGEL

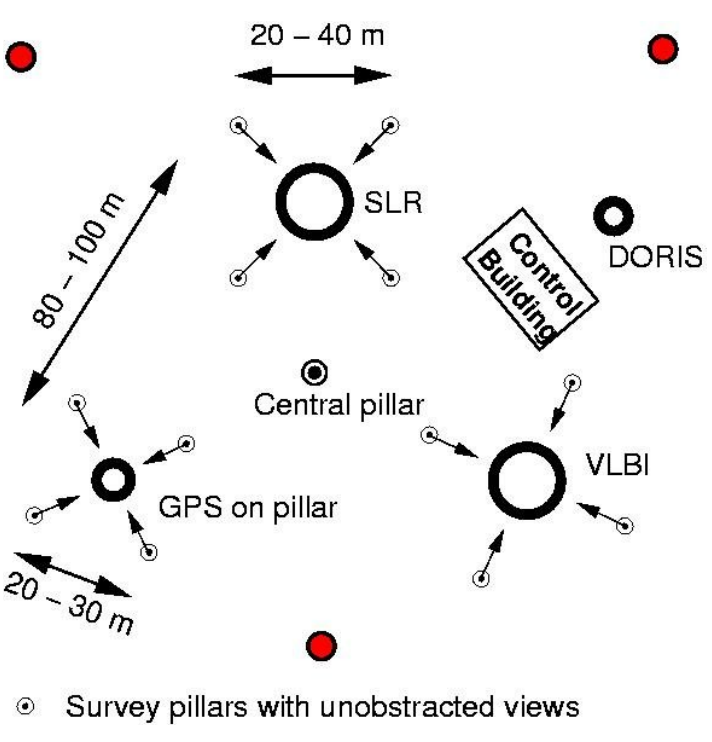

Figure 5 Possible site layout of fundamental station.

This figure illustrates one possible layout for a fundamental station (i.e., a station with all of the space geodetic techniques.) The size of the entire site is ~100 meters, about the size of GGAO. The techniques are separated far enough apart so that they do not interfere with each, but close enough together so that the errors in the local survey can be performed at the sub-millimeter level. There are adequate survey pillars and the visibility is good.

This diagram is not meant as a final recommendation, but rather as a starting point for further discussion. As drawn this diagram only includes provisions for conventional surveying. It does not include provisions for additional instruments such as tiltmeters and extensionometers which may be required for sub-millimeter accuracy. Including such instruments in the site design would lead to additional requirements and constraints. For example, including long baseline tiltmeters require relatively flat sites, and hence would not work at GGAO.

As discussed above, accurate and precise site surveys are necessary in order to combine results from space geodetic techniques. In principal, a single site survey might be sufficient. In practice, some sites are surveyed every few years. Sometimes this is done to resolve discrepancies between the techniques. In any case, this temporal resolution is inadequate to resolve local site effects at more rapid timescales. In this Appendix, we illustrate the necessity of more frequent measurements using the Pietown VLBA antenna as an example.

Figure 6 Pietown VLBA antenna with GPS antenna in foreground.

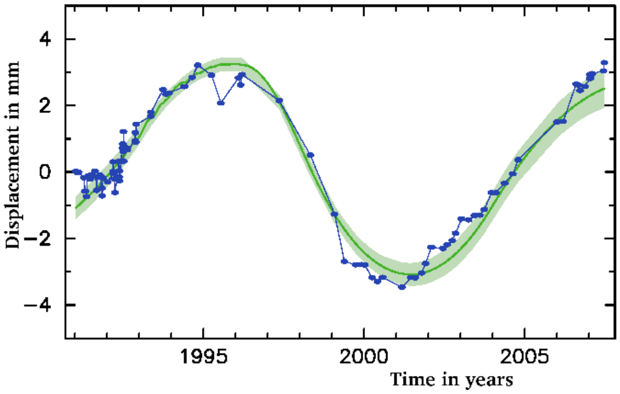

Figure 7 East displacement of Pietown measured by VLBI

Pietown is one of 10 VLBA antennas used primarily for astronomy. These antennas are regularly scheduled with other IVS antennas in order to tie them into the global VLBI network and hence into the ITRF. Most VLBA sites have co-located GPS antennas. The Pietown VLBA site exhibits anomalous non-linear motion. Figure 6 which plots the east displacement (curve with dots) measured by VLBI. The up and north displacements are of similar magnitude. As part of their regular observing programs, the VLBA makes regular measurements of antenna tilt at all sites. Antenna tilt shows up as changes in the station position. The tilt is due to ground settling. Although real, this effect is well localized. Without monitoring and correction, this would alias into the ITRF. The GPS antenna exhibits similar non-linear motion that is correlated with the VLBI. This indicates that the tilt is a site phenomenon, and not just the VLBI antenna and pad.

This example illustrates not only the importance of regular measurements, but also the inclusion of non-traditional measurements, in this case, antenna-tilt measurements. In the case of the VLBA, the tilt measurements are done without additional hardware by observing quasars. Including tilt measurements for other techniques would require additional hardware.

APPENDIX C. HOW SHOULD WE MONITOR THE LOCAL TIE? NOTHANGEL

Conceptually a local tie or co-location vector between different observing platforms like SLR and VLBI telescopes or GNSS antennas cannot be performed directly but needs intermediate steps employing fixed ground markers and/or pillars. The coordinates of the reference points of the individual observing techniques must be surveyed to link the reference points to the ground markers or surveying pillars, thus determining coordinates in a common locally defined system. From the differences in the coordinate components, the local tie vector is inferred in the local system and, after applying the necessary transformations, in the global system.

For GPS antennas, this is done by determining the local coordinates of a reflector which may be mounted underneath the GPS antenna and for which the eccentricity of the GPS invariant reference point, most often the "bottom of pre-amplifier", and the center of the target has been properly calibrated. Geoscience Australia designed such a device and implemented at the Mt. Stromlo site. This method can be adapted for other GNSS techniques like GLONASS and Galileo and also DORIS. The critical factor is that the multipath environment of the GNSS antennas may be affected and should be calibrated appropriately.

Since for VLBI and SLR the invariant reference points are defined by rotations around two axes and their intersection, respectively the projection of the moving axis onto the fixed axis, it is necessary to determine multiple points on the structure which describe circles around these axes when the telescopes are rotated. In an adjustment process, the axes can then be inferred and the invariant reference point be computed in the local coordinate system of the ground markers and pillars. The measurement technique for determining the coordinates of these points representing the structure of the telescope must be chosen carefully, and design considerations in the systems for surveying could make this job a lot easier.

APPENDIX D. PILLAR MOUNT DESIGN RECOMMENDATIONS: LONG

The survey ground control networks at space geodesy sites consist of a series of pillars that serve as standpoints for the survey instruments and survey targets. It is very important that the pillars be constructed to be very stable and also offer a universal mount fixture that will accept a large variety of types of survey instruments and targets.

The pillar should be constructed of reinforced concrete, with a minimum diameter of 0.3 meters. The pillars must extend below ground a significant distance to very stable soil or bedrock. The actual depth will depend on the geological soil characteristics of the site.

The concrete pillar should be protected from movement due the thermal effects of the sun by an outer cladding, possibly of PVC pipe material, with an annular insulation space between pipe and the pillar.

The mount system should consist of a stainless steel, self-centering fixture, such that any survey instrument or target placed on the fixture is automatically fixed planimetrically to a high precision. An example of such a fixture is a stainless steel plate with a 5/8”-11 threaded stud. It is equally important that the relative height of the survey instrument or target be precisely determined. A domed stud at the edge of the stainless steel plate would facilitate this measurement.

It would be useful to have the flexibility to mount a target and a survey instrument (or multiple types of targets) on a pier at the same time. As an example, a fixture that would support a survey prism under a GPS antenna would allow for constantly monitoring the stability of the pillar with GPS and also allow the survey prism to be used as an SLR calibration target or the a control point for the local tie survey effort.

An alternative to the reinforced concrete pillars in certain soil conditions are the drilled and braced GPS monuments developed for the GPS SCIGN programs. These have proven to be very stable.

APPENDIX E. MEETING AGENDA

TLS Workshop 2008

Meeting Agenda

Monday, September 8, 2008

09:00–10:30	**Session 1: Introduction {Mike Pearlman}**
09:00−09:20	Workshop logistics [Dirk Behrend]
09:20−09:40	Introduction to the co-location problem [Mike Pearlman]
09:40−10:00	Surveying around space geodetic instruments at GGAO [Jim Long]
10:00–11:00	**Drive to GGAO, Coffee break**
11:00–12:30	**Field Session 1: General Demonstration [all]**
12:30–13:30	**Lunch**
13:30–15:00	**Field Session 2a: Total Station / Laser Scanner Survey [two groups]**
15:00–15:30	**Coffee break**
15:30–16:30	**Field Session 2b: Laser Scanner / Total Station Survey [two groups]**
16:30–17:00	**Field Session Wrap-up {Chuck Meertens}**
18:00	**Workshop Dinner**

Tuesday, September 9, 2008

09:00–10:30	**Session 2: Geodetic space technique-specific issues {Chopo Ma}**
09:00−09:20	GNSS-specific issues and anticipated advancements [Chuck Meertens, Dave Stowers]
09:20−09:40	SLR-specific issues and anticipated advancements [Mike Pearlman]
09:40−10:00	VLBI-specific issues and anticipated advancements [Axel Nothnagel]
10:00–10:30	**Session 3: Overview on current survey techniques {Dirk Behrend}**
10:00−10:30	Co-location survey experience at Honeywell/NASA [Jim Long]
10:30–11:00	**Coffee break**
11:00–11:30	**Session 3 cont'd {Dirk Behrend}**
11:00−11:25	Co-location survey experience at Bonn University [Axel Nothnagel]
11:25−11:50	Co-location survey experience at IRA/INAF [Pierguido Sarti]
11:50−12:15	Software packages and comparisons of results [Pierguido Sarti]
12:15−12:30	**Wrap-up of Sessions 2 and 3 {John Gipson}**
12:30–13:30	**Lunch**
13:30–15:00	**Session 4: Survey instrumentation, new technologies {Chuck Meertens}**
13:30−15:00	Laser scanners [Gerald Bawden, Carlos Aiken]
15:00–15:30	**Coffee break**
15:30–17:00	**Session 4 cont'd {Chuck Meertens}**
15:30−16:10	Total stations [Carlos Aiken, Lionel White]
16:10−16:30	Targets [Chuck Meertens]

16:30−17:00	**Instrumentation session wrap-up [Chuck Meertens]**

Wednesday, September 10, 2008

09:00–10:30	**Session 5: Continuous monitoring {Axel Nothnagel}**
09:00−09:10	Motivation for continuous monitoring: reprise of key points [Mike Pearlman]
09:10−09:30	Laser tracker [Axel Nothnagel]
09:30−09:50	Vertical stability by tiltmeters and vertical strain meters [Chuck Meertens]
09:50−10:10	Monumentation [Jim Long]
10:10–10:30	**Session 6: Ideal site layout {Pierguido Sarti}** **General discussion and possible recommendation for measuring site vectors using laser scanners and ideal site layout**
10:30–11:00	**Coffee break**
11:00–12:30	**Session 6 cont'd {Pierguido Sarti}**
12:30 13:30	**Lunch**
13:30–15:00	**Wrap up and report writing {Mike Pearlman, Chuck Meertens}**
15:00–15:30	**Coffee break**
15:30–17:00	**Report writing cont'd {Mike Pearlman, Chuck Meertens}**
17:00	**Adjourn workshop**

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