CHALLENGES IN INTER-TECHNIQUE TIE SURVEYS – AN ENGINEERING PERSPECTIVE

Hansjörg KUTTERER, Harald VENNEGEERTS, Jens-André PAFFENHOLZ and Hans NEUNER

Geodetic Institute, Leibniz University of Hannover, Germany

Abstract: The determination of terrestrial and celestial reference frames is based on the combination of space-geodetic techniques such as Very Long Baseline Interferometry (VLBI), the Global Positioning System (GPS) and Satellite Laser Ranging (SLR). Today, impressive results for the determination of the site coordinates are already reached globally in the range of a few millimetres. For the inter-technique combination, co-location sites are maintained which provide at least two different space-geodetic techniques. The actual connection of the respective techniques is based on local surveys which is a typical task of engineering geodesy. In order to provide highly precise and reliable local ties, both scientific and technical issues have to be treated considering the available surveying technology. The goal of this paper is to show both the possibilities and challenges of inter-technique tie determination from an engineering viewpoint. The presentation is divided into three parts. First, the state of the art of local tie surveys is discussed. Some shortcomings of the present-day strategies are indicated. Second, the relevant sensors and systems are presented including high-end instrumentation such as laser trackers and laser scanners. Third, a more comprehensive dynamical monitoring approach is outlined and discussed regarding instrumentation and data analysis which can provide high-quality local tie products.

1. MOTIVATION

Global geodetic coordinate reference frames are an indispensable basis for a multitude of geo-applications in technology such as positioning and navigation as well as in science such as Earth system research. With the ITRF[1] 2005 (Altamimi et al., 2007) the most recent realization is available which provides for the first time consistent time series of station positions and Earth orientation parameters with high quality (mm-level). The ITRF 2005 has been derived as an inter-technique solution which integrates observations from four different space-geodetic techniques: GPS, VLBI, SLR, and DORIS[2]. Each of these techniques has its

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[1] International Terrestrial Reference Frame

[2] GPS: Global Positioning System, VLBI: Very Long Baseline Interferometry, SLR: Satellite Laser Ranging, DORIS: Doppler Orbitography Radiopositioning Integrated by Satellite

particular or even unique contribution in parameter determination. As an example, the link to an inertial system and hence Universal Time is observed by VLBI only.

In order to geometrically link the different space-geodetic techniques for a joint analysis, a number of co-location sites are maintained. At a co-location site at least two techniques are operated. For the ITRF 2005 solution 608 observation stations have been considered which are located at 338 sites. Among them there are 52 sites with two techniques, 26 sites with three techniques and 6 sites with all four techniques. In addition to the space-geodetic observations local 3D surveys are performed at co-location sites in order to obtain the coordinate differences between the space-geodetic instruments (Altamimi et al., 2007).

The need for good inter-technique ties in the combination of space-geodetic techniques is well-known. During the last years an increased number of papers in journals and proceedings volumes as well as technical reports were dedicated to the determination of inter-technique ties. An excellent up-to-date overview is given in the proceedings of the IERS workshop on site co-location which was held in Matera, Italy, in 2003 (Richter et al., 2005). However, there are still existing shortcomings and deficits regarding the recommendation of sub-mm accuracy according to Richter et al. (2005, p. 143) which will be addressed here.

The intention of this paper is to give an overview on the state of the art in inter-technique tie determination in order to provide a basis for the development and discussion of a more comprehensive method. Hence, the paper is organized as follows. In Section 2 the state of the art in inter-technique tie determination is briefly reviewed. Section 3 provides information on the surveying equipment which is typically used. In addition, alternative sensors are introduced which allow a higher accuracy or additional types of observation. Afterwards, a more general concept based on a system-theoretical approach is outlined in Section 4. Some recommendations are given in the Conclusions.

2. STATE OF THE ART IN INTER-TECHNIQUE TIE DETERMINATION

2.1. General remarks

Within the scope of this paper inter-technique ties are defined as follows. Each space-geodetic instrument observes with respect to a specifically defined reference point (RP). Hence, in case of sites with more than one technique there are small eccentricities between the different instruments ranging typically between some tenths or hundreds of meters. An inter-technique tie denotes and quantifies the 3D vector between two respective RPs. A synonymous notion is local tie (LT). The RPs are referred to each other by means of a local geodetic network (LGN) consisting of a number of control points. The LGN is observed with conventional surveying techniques using total stations or theodolites, geodetic GPS, and precise levelling.

2.2. Reference point and local tie determination

A recent reference regarding conceptual issues of RP definition for the relevant space-geodetic techniques and of a comprehensive surveying and data processing strategy is Sarti et al. (2004). The authors distinguish between two types of RPs – those which are physically realized and those which are not; the RP definitions are given in detail. GPS and DORIS are examples of the first case – their RPs can be accessed using targets in forced centring. In the paper a combined technique is described which does not require the removal of a GPS or

DORIS antenna.VLBI and SLR stand for the second case. Here, the RPs have to be recovered indirectly by observing a set of moving targets.

Dawson et al. (2007) describe an indirect approach for the determination of the RPs of VLBI or SLR telescopes. Leinen et al (2007) refer to VLBI only but they consider both the RP of the antenna and the orientation of the rotation axis. Besides the development and application of the proposed indirect determination method they discuss a variety of systematic errors due to external effects such as gravitational or wind-induced loading or thermal deformations. In all reported cases mm-accuracy (Leinen et al., 2007) or even sub-mm accuracy (Haas and Eschelbach, 2005) are stated for the RP determination. Note that the applied surveying procedures are all static and significantly time-consuming. There are typical repetition intervals of several years while the RP and LT observations are performed episodically (Schlüter et al., 2005) as these time-consuming surveying processes should not interfere with the space-geodetic observations.

For the combination of the different space-geodetic techniques, the respective RPs are referred to each other by means of the LGN which has to be established in a proper way; see Leinen et al. (2007) for a detailed discussion. The LGN is observed using precise local surveying techniques. The coordinates of the RP as well as the the coordinates of the control points which form the LGN are estimated based on a least-squares network adjustment. In addition, the variance-covariance matrix (vcm) of the RPs is obtained. In order to monitor the surroundings of a space-geodetic site so-called footprint observations are performed using geodetic GPS (Schlüter et al., 2006).

2.3. Tie treatment in inter-technique combination

In inter-technique reference frame combination the results of the adjustment of the LGN (estimated coordinates and vcm) at the different sites are used as independent observations together with the results of the space-geodetic intra-technique combination which are provided by the respective services such as IGS or IVS[3] (Altamimi et al., 2007). Note that several publications such as, e.g., Sarti et al. (2004) underline the importance of full vcms for local tie information.

For each local tie solution an empirical variance factor is estimated in inter-technique combination. From this combined adjustment, residuals are obtained for the local tie observations which can be analysed regarding the degree of agreement with the space-geodetic observations. Ray and Altamimi (2005) evaluate GPS-VLBI local ties. They show the need for local ties with the accuracy of 1 mm for a minimum of two to four sites. Altamimi et al. (2007) report discrepancies of more than 1 cm in the local ties of some important co-located sites such as Westford, U.S.A., or Fortaleza, Brazil. Such discrepancies are typically treated in a mathematical way: the local tie observations which yield normalized residuals exceeding the chosen threshold value (of 4) are down-weighted but not rejected.

[3] IGS: International GNSS Service, IVS: International VLBI Service for Geodesy and Astrometry

2.4. Requirements and shortcomings

If significant discrepancies in local tie observations are identified using adequate test procedures there are various possible causes which lie either in the local terrestrial or in the space-geodetic observations – or in both or in the data processing and analysis process. Some of these causes are rather technical, some others are rather fundamental. This is illustrated in a short example: For the testing, e.g., the estimated variance relations between the terrestrial and the space-geodetic observations are crucial – but they are just abstract mathematical quantities. As described above, the local tie observations are derived in a unique way from the observation and adjustment of local geodetic network using standard instrumentation and software. In contrast, the intra-technique combined solutions of the particular services are suboptimal as they are based on an improper stochastic model.

Note that all analysis centres within a particular space-geodetic service are using the same observation data as there is no possibility for independent observations. These observation data are pre-processed and analysed according to standards which are described in the conventions manual of the IERS. Besides, there are various degrees of freedom which typically lead to observation data which are modified individually during the processing steps. Hence, each analysis centre provides different results which are then averaged by the particular service. For this reason typical results are too optimistic as the respective vcms contain too small variances which do not reflect the original identity of the observation values (Kutterer et al., 2008). Thus, depending on the actual configuration which is described by the functional adjustment model and on the respective vcms of space-geodetic solutions and the local tie information, the obtained residuals may not be representative.

The influences of the above-mentioned causes cannot be separated by data analysis techniques only (Krügel and Angermann, 2005). Therefore, from an engineering perspective it is strongly required to assess these causes and to determine and improve the relevant components by further action in addition to a pure mathematical treatment and to perform all required instrumentation and observations keeping the sub-mm requirement for inter-technique ties into account. In the following, all problems which refer more or less to space-geodetic issues such as observation strategies and modelling are not considered. All others can be understood as local surveying tasks which can be treated by high-end engineering geodesy. As an example, Person and Michel (2005) describe general surveying competence which is available at the IGN Special Works Department and which is of interest for inter-technique tie determination. In order to take all relevant – and in general time-dependent – causes and mechanisms into account, a thorough system-theoretical analysis is required which is at least to our knowledge still missing. Section 4 is dedicated to this topic.

A last topic shall be addressed here which is fundamental in engineering geodesy. Notions like error, precision, or accuracy are often used and quantified in the context of local ties and the combination of reference frames. However, this is done neither in a precise nor in a unique way. Interested readers should refer to the GUM[4] (ISO, 1995) where the detailed analysis and documentation of the observation and derivation of measurement results are described together with unique measures of uncertainty. For a thorough discussion clear standards for uncertainty measures are indispensabile.

[4] Guide to the Expression of Uncertainty in Measurement

3. INSTRUMENTATION

3.1. Conventional instruments

The observations for the determination of the inter-technique ties are typically performed using conventional surveying equipment such as total stations, theodolites, geometric (spirit) levels, and geodetic GPS. Typical examples are the total stations Leica TCA 2003 or TDA 5005 (Person and Michel, 2005), the EDM device Mekometer 5000 together with a high-end theodolite Wild T 3000 (Schlüter et al., 2005), or the geodetic GPS receivers Leica SR 530 or of different type (Abbondanza et al., 2006). See Richter et al. (2005) and the reference therein for further information. With these instruments it is possible to determine the required reference point and possibly axis information as well as to observe the LGN.

Nothnagel (2005) reflects several surveying issues which are concerned with the use of total stations as main instruments in inter-technique tie determination which are self-evident for colleagues with a background in surveying but obviously not from all staff working at space-geodetic observation stations.

3.2. Instrumental alternatives

Depending on the particular tasks there are alternatives to the surveying equipment which has been described above. Bolli et al. (2006) explain and compare several surveying techniques such as photogrammetry and terrestrial laser scanning which are not standard in inter-technique tie determination. The main goal of their study is the determination of the actual shape of a VLBI dish in order to improve the performance of the antenna.

Today, close-range photogrammetry, terrestrial laser scanning and – in addition – laser tracking are promising techniques which have been used in various applications outside the present subject. Digital close-range photogrammetry allows the immediate determination of the surface of the dish by taking at least two photos from two different locations in order to recover the geometric 3D information. Note that a proper signalization is indispensable. The presented results show deviations between the observed and the theoretical shape of a dish in sub-mm range. Using terrestrial laser scanning, Bolli et al. (2006) scanned the dishes at Medicina and Noto but their actual results were not given.

In the following these instruments are characterized regarding their potential contributions to inter-technique tie determination. In photogrammetry, an adequate signalization is required to identify homologous points in order to calculate a 3D model from the 2D image observations. Then it is possible to derive surface geometries in the sub-mm accuracy range in very short time. Hence, repeated observations in a fast temporal sequence are available.

Terrestrial laser scanning (TLS) is an alternative for the determination of 3D surface geometries. The basic surveying principle is the observation of slant distances without artificial retro-reflectors together with horizontal directions and vertical angles. As these observations are performed with a high spatial resolution, 3D point clouds are directly obtained with a high level of detail and without any additional signalization – unless scans from different stations have to be registered (i.e., transformed into a unique local coordinate frame). Recent instruments are the Trimble GX 3D or the Zoller+Fröhlich Imager 5006. For TLS, the precision of single observed points is in the range of a few mm. If the huge number of scanned points is exploited for a proper filtering, an even higher precision is possible for the derived surfaces.

Note that the accuracy of the distance observations depends directly on the material characteristics of the scanned objects. This can yield systematic errors. Depending on the distance measurement principle (time-of-flight or phase-shift) a very fast repetition of the scans is possible. Kutterer and Hesse (2006) show the so-called kinematic application of TLS based on phase-shift distance observations in 3D mode and in profile mode which allow both to derive time series for defined object reference points.

As a third group of alternative instruments laser trackers such as the Leica LTD 640 or the FARO Laser Scanner LS are of interest. Laser trackers observe slant distances and two spatial angles just like laser scanners but now retro-reflecting prisms such as corner-cubes or cat-eyes are required. Distances are observed based on interferometry what yields a accuracy in the range of tenths to hundreds of μm on distances of a few tenths of meters. The observation repetition rate is about 1000 Hz what allows a very fast tracking of the prism. Although the high accuracy is based on interferometry which actually allows to observe distance changes only, absolute distances can be derived either using a reference point at the laser tracker or if an additional distance measuring device is provided.

The instrumental alternatives can be summarized as follows: digital close-range photogrammetry and TLS provide 3D surface information very fast which is mostly interesting in case of VLBI telescopes, and by laser tracking the position of signalized single points can be derived very precisely with high temporal resolution. Note that these instruments are not capable for an improved observation of the LGN. For this purpose, high-end total stations are still the best choice as – regarding sub-mm accuracy – geodetic GPS is not competitive.

4. TOWARDS A COMPREHENSIVE DYNAMIC MONITORING

4.1. System-theoretical analysis

Regarding the required sub-mm accuracy in inter-technique tie determination the present-day practice has to be extended and the different procedures existing in parallel have to be integrated. In order to guarantee adequate local tie products it is indispensable to widen the scope from a more or less technical perspective which is concerned with a sequence of closed, rather basic surveying tasks to a more scientific one. In order to provide a proper basis a thorough system-theoretical analysis is needed. This analysis has to comprise both the dynamics of the considered objects on the temporal and spatial scales as well as the possible instrumentations and the corresponding observation and analysis processes which are relevant regarding the required accuracy. See Welsch et al. (2000, Ch. 1) for a comprehensive description of a system-theoretical approach and further references.

The key question in local tie determination is directly concerned with the derivation and monitoring of the RP positions of space-geodetic devices co-located at a particular site. The RPs can be understood as being existent in a dynamic environment with several acting forces which are due to thermal and gravitational effects as well as loading caused by meteorological, hydrological and operational effects. The considered effects occur at least on sub-daily and seasonal temporal scales. The spatial scales refer to the dimensions of the devices themselves including their monumentation, to the set of co-located devices and the distances between, and to some extent to the range of the relevant environment. The observable effects depend mainly on the particular space-geodetic technique. As examples, VLBI and GPS are discussed below in some detail. In a refined analysis it is necessary to separate between physical effects and artefacts.

Leinen et al. (2007) provide a good overview and discussion on effects on VLBI antennas. Gravity-induced deformations of the VLBI parabola dishes during operation yield elevation-dependent changes of the optical path length between the RP and the antenna receiving system. Such deformations can be modelled using a finite-element model of the antenna and corrected with an elevation-dependent function. In contrast, Bolli et al. (2006) mention an active surface system based on electromechanical actuators which allows to recover the misalignement of panels induced by gravitational effects. Deformations which are due to temperature changes can be compensated by applying a thermal distortion model; see also Wresnik et al. (2007). Pointing errors of the telescope which are due to wind and wind gusts are in general highly variable and not compensated for (Leinen et al., 2007).

From the viewpoint of structural monitoring the RP of a VLBI telescope is not an isolated point in a 3D euclidean space but a physical point inside the telescope. In an ideal model it is considered as an invariant point. In practice, all effects on the telescope structure are more or less propagated to the position of the RP. Thermal and gravitational effects will lead to a bending and torsion of the structure. This holds for meteorological effects, too. Hydrological effects will show tilting and vertical displacements. It is certainly possible to model parts of these effects numerically to derive correction functions. However, a calibration of such models using observed data it indispensable.

Concerning GPS a number of effects has been reported. Also in this case, displacements and tiltings of the monuments have to be expected. Depending on the antenna, wind load could be relevant. Besides, multipath due to objects in the close vicinity of the antenna or near-field effects induced by the particular antenna mounting may occur (Dilßner, 2008). Here, these effects are considered as artefacts as they are not related to an actual physical displacement of the RP. However, as the magnitudes of both effects can be in the range of some mm they have to be taken into account.

Looking at the effects which have to be considered a dedicated observation configuration and processing strategy is required. The on-site space-geodetic devices have to be modelled and observed within a dynamic environment as extended physical structures which are sensitive to a variety of causes. From a general point of view the derived system model can be descriptive or causal. In case of a descriptive model it is only possible to provide a temporal or spatial prediction of the observed effects. In case of a causal model an input-output relation between influence and reaction parameters has to be estimated which can either be based on observable characteristics or on physical (differential) equations. This is done if, e.g., correction functions for the RP displacement due to thermal or gravitational deformations are derived using a finite-element model.

4.2. Observation configurations and processing strategies

In order to formulate a number of adequate correction models for the displacements of the RPs all required quantities have to be observed. These (preferably causal) correction models refer on the one hand to the respective space-geodetic devices and on the other hand to the relation between the co-located instruments. They have to account for displacements on sub-daily scales and on seasonal scales. Both types of effects cannot be determined effectively by conventional surveying techniques. In particular sub-daily effects require fast or highly resolved observations, possibly using permanently installed automated sensors or sensor systems which are continuously tracking.

Regarding the discussion in Section 3.2 there are several devices like terrestrial laser scanners or laser trackers which are partially capable for such a task – at least regarding episodically scheduled observation periods which are carried out through several days. However, for a permanent installation other sensors are better suited. Hydrostatic levels allow to automatically detect height changes between a number of observation points. Tilts and tilt changes, respectively, can be observed using tilt sensors or accelerometers. Displacement sensors, strain gauges or fibre-optic sensors may provide more useful information concerning the induced deformations of the considered space-geodetic device. In addition, the influence quantities have to be observed. Seasonal effects can be detected either using the just described equipment or by conventional surveying procedures which are optimized regarding efficiency in order to have minimum impact on the space-geodetic observation schedules.

The observed time series have to be analysed carefully in order to identify the immanent signals. A thorough modelling and propagation of uncertainty is strongly required. The data processing strategies have to include also the derivation of numerical models by integrating the physical knowledge on the structures – which is typically described using finite elements – and the actual effects observed through the monitoring process. The method developed by Lienhart (2007) for the integrated monitoring of a bridge can be used as a guideline. In intra-technique combination the determined displacements on sub-daily scales can be introduced as corrections within the processing of the observation data of single sessions. Seasonal effects have to be modelled both in intra-technique and in inter-technique combination.

5. CONCLUSIONS

In this paper the state of the art in inter-technique tie determination is reviewed which becomes increasingly important regarding the mm accuracy of the intra-technique combined global terrestrial reference frames. The consequent request for local ties with sub-mm accuracy demands a thorough analysis and discussion within a system-theoretical framework. Within this accuracy range the dynamical position changes of the reference points of space-geodetic devices have to be monitored on various temporal and spatial scales. As conventional surveying equipment is only to some extent capable to provide this required quality it has to be complemented with additional sensors. The observed data have to be integrated with physical knowledge on the object.

As far as we know this has not been done up to now. For this purpose it is worthwhile to study the problem of local tie determination as open-minded as possible. Therefore, the capability of engineering geodesy should be considered not only as technological competence but also as an important link between scientific issues concerned with space-geodetic observations and basic surveying procedures. Then it will be possible to significantly support the derivation of global terrestrial reference frames.

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Corresponding author contacts

Hansjörg KUTTERER
kutterer@gih.uni-hannover.de
Geodetic Institute, Leibniz University of Hannover
Germany