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Common Interests of the IGS and the IVS

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1. Introduction

With the advent of the International Laser Ranging Service (ILRS) and the International VLBI Service (IVS) all three major space geodetic techniques, GPS, SLR, and VLBI, have a dedicated service. The availability of these three services, IGS, ILRS, and IVS, will simplify the cooperation and exchange of information amongst the three services.

The routine availability of reference frame products, station coordinates and Earth rotation parameters with their full covariance matrix, from all three techniques will enable an accurate combination of the reference frames from the different techniques. This is very important because it has become clear over the last few years that there are biases between the techniques at the several centimeter level, e.g., a 5 cm bias has been observed between the SLR range observations from the GPS satellites and the computed ranges based on IGS orbits and ITRF SLR station positions [11]. Each of the three techniques has its own unique capability and none of the three techniques can provide all the answers we are looking for. Already each technique profits from the other, e.g., GPS and SLR rely on the VLBI based UT1, SLR may use the GPS and VLBI based X- and Y-polar motion, and GPS heavily relies on SLR based models like, e.g., the Earth's gravity field. When combining the three techniques we should be able to get the best out of each technique. Last but not least the availability of products from different techniques may help understanding and resolving technique dependent problems.

1.1. The International GPS Service

Over the last decade GPS started playing a major role in regional and global studies of the Earth. In view of a continued growth and diversification of GPS applications, the scientific community has made an effort to promote international standards for GPS data acquisition and analysis, and to deploy and operate a common, comprehensive global tracking network. As part of this effort, the International GPS Service (IGS) was established by the International Association of Geodesy (IAG) in 1993 and began official operation in January 1994. Usually, the International Association of Geodesy (IAG) General Meeting in August 1989 in Edinburgh, UK, is considered as the starting point for the IGS. The IGS planning committee was created shortly thereafter and the IGS call for participation was sent out in February 1991. At the XX$^{\text{th}}$ IUGG General Assembly in Vienna in August 1991 the IGS planning committee was reorganized and renamed IGS campaign oversight committee. This oversight committee organized the 1992 IGS Test Campaign scheduled from June 21 to September 23.

The 1992 operations were so successful, that data collection, processing, and product dissemination continued without interruption after September 23, 1992, first on a "best effort" basis, then, starting November 1, 1992, as the "IGS Pilot Service". During this pilot phase in 1993, the

IGS Terms of Reference were written and the current IGS structure was established. The official start of the IGS took place in January 1994. In December 1997 the name of the IGS was slightly changed. The original name was International GPS Service for Geodynamics. Due to the enormous expansion of the IGS the term “for Geodynamics” was no longer considered to accurately reflect all IGS activities, which by that time also included atmospheric studies. For more information concerning this early phase of the IGS see, e.g., [5, 3].

The IGS is based on the voluntary contributions of a large number of organizations. The current structure of the IGS consists of [4]: global network of tracking stations, operational centers, regional data centers, global data centers, analysis centers (AC), associate analysis centers (AAC), analysis center coordinator (ACC), central bureau (CB), governing board (GB), and working groups.

According to the Terms of Reference the accuracy of the IGS products should be sufficient to support current scientific objectives including: scientific satellite orbit determinations, monitoring Earth rotation, realization and easy global accessibility to the International Terrestrial Reference Frame (ITRF), monitoring deformations of the solid Earth, and variations in the liquid Earth, climatological research, eventually weather prediction, and ionosphere monitoring.

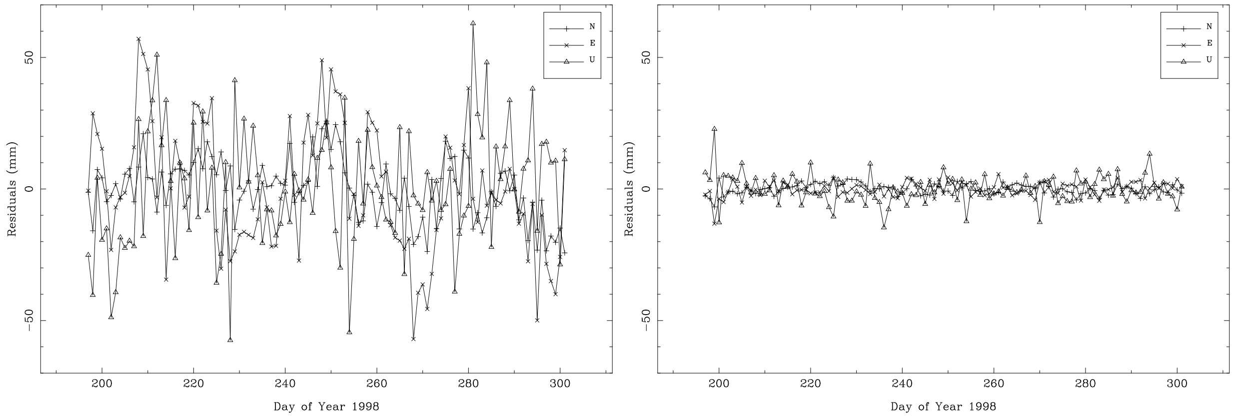
The primary objective of the IGS is to provide the reference system for a wide variety of scientific and practical applications involving GPS. To fulfill its role the IGS produces a number of “fundamental” products, which are: GPS data from a global network of about 200 stations, GPS satellite orbits, GPS satellite clocks, Earth rotation parameters, station coordinates and velocities, station specific tropospheric zenith path delays (ZPD), global ionosphere maps, and GPS receiver clocks. For more information about the IGS and all its components see, e.g., the IGS Annual Reports [12, 4, 6].

At the start of the IGS Test Campaign in 1992 the focus was mainly on the GPS satellite orbits. The goal was to provide orbits of an accuracy which would allow the “normal” geodetic GPS user to avoid orbit determination. The effect of an orbit error dR on an estimated baseline component is given by the following “rule of thumb”, see [2]:

$$dx \approx dR \cdot \frac{L}{R} \tag{1}$$

where L and dx are baseline length and baseline component error and R, dR are satellite distance and orbit error. From eqn. (1) we see that for a baseline with length $L = 400$ km, $dR = 2$ m (typical error for the GPS broadcast orbits), and $R = 20000$ km the baseline component error will be about 40 mm. Using IGS orbits, assuming an orbit error (dR) of about 100 mm, the baseline component error due to the orbit error will be at the 2 mm level. Figure 1 illustrates the effect of the orbit quality on baseline estimates quite nicely. A European baseline of approximately 400 km was processed once using broadcast orbits and once using precise IGS orbits; both solutions were performed over a period of 100 days. The coordinates of one station were kept fixed, whereas the coordinates of the second station were solved for. Figure 1 shows the variation of the daily position estimates of the second, free station, from both solutions. The RMS of the variations using broadcast orbits is 13, 24, and 23 mm in the north, east, and up directions, respectively. This corresponds quite well with the estimated orbit effect of 40 mm. In the case of the IGS orbits the RMS of the variations is 2, 3, and 6 mm in the north, east, and up directions, respectively.

Figure 2 shows the weighted orbit RMS (WRMS) of the individual Analysis Center solutions with respect to the combined IGS final orbit products. Figure 2 reflects the quality improvement of the IGS products as a function of time since 1994. The quality of the IGS orbit estimates has



(a) Using broadcast orbits

(b) Using IGS orbits

Figure 1. Residuals of daily position estimates on a 400 km baseline using orbits of different quality.

improved from the 200 mm to the 30 mm level in a time period of 5 to 6 years. The routine combinations of the products of the different IGS Analysis Centers have played a major role in the improvements of the IGS product quality. We are convinced that without the feedback coming from the IGS combinations the quality improvements would have been significantly smaller. Of course, Figure 2 only shows the internal consistency of the IGS products and not their accuracy. However, similar levels of accuracy are indicated by the IGS 7-day arc orbit analysis and by the comparisons with satellite laser ranging observations of the GPS satellites PRN 5 and 6. Notice also the quality of the IGS rapid orbit (IGR) in Figure 2. This orbit product is available with a delay of currently only 17 hours after the end of observation and its quality is comparable to that of the best individual Analysis Center final products.

2. Common Interests of the IGS and the IVS

In GPS and VLBI analysis there are a relatively large number of common parameters; station coordinates, Earth rotation parameters (X, Y, and LOD), tropospheric zenith delays and gradients, and the station clock offsets in those cases where the GPS and VLBI receivers are connected to the same external oscillator. The station coordinates, and their time evolution (velocity), and the Earth rotation parameters are of interest to all geodetic techniques and these will become (or already are) available in the SINEX (Software INdependent EXchange format) product files from the Analysis Centers of the different techniques. The tropospheric zenith delays and gradients, and the station clock offsets are common to GPS and VLBI.

The availability of the SINEX products from the different techniques will allow the routine comparison (or combination) of the reference frames of the individual techniques. The progress made within the IGS has shown how effective and useful the comparisons of different results are. The IGS has also defined exchange formats for tropospheric zenith delay and station clock estimates. It would be very valuable if the IVS would adopt the IGS formats, with enhancements where necessary, for these estimates because it would make comparisons of the results very easy.

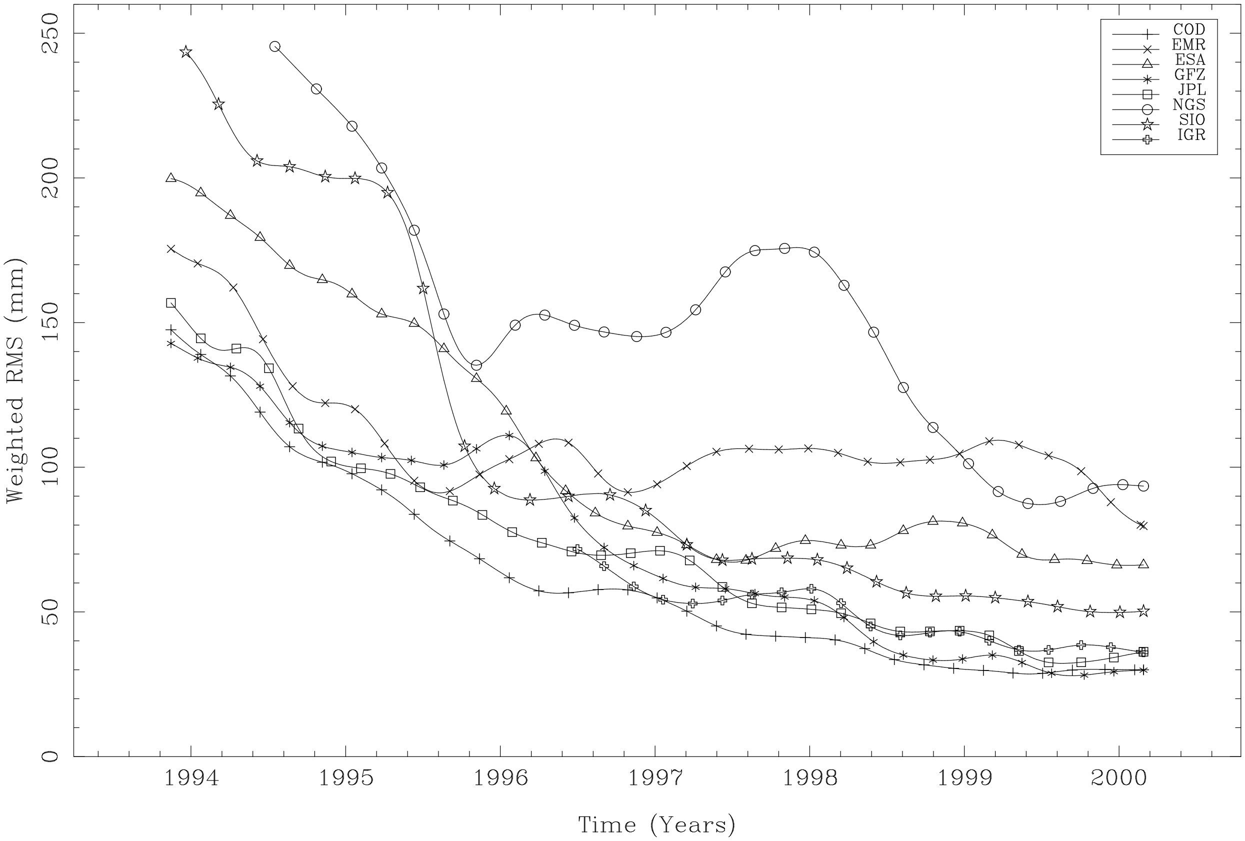


Figure 2. Weighted orbit RMS (cm) of the Analysis Center and IGS Rapid (IGR) orbit solutions with respect to the IGS final orbits. The weekly WRMS values from the IGS orbit combination summaries were smoothed, for plotting purposes, using a sliding 10 week window.

We are convinced that both techniques will greatly benefit from comparisons of all these products.

Furthermore, in the GPS (IGS) results there are currently two interesting problems which cannot be resolved by using GPS alone. For both problems the IGS needs the support of some other technique. The first problem, or at least interesting result, is that the time series of the coordinate estimates show similar signals for stations in the same geographical area. The question which has to be solved here is whether these signals represent real geophysical phenomena or whether they are some artificial signal caused by modeling problems in the GPS data analysis. One way to try to resolve this problem is by comparing the time series from different IGS Analysis Centers, which is routinely done within the IGS. However, it will be much more informative to compare time series from different Analysis Centers using different techniques. Here clearly the IVS may help the IGS.

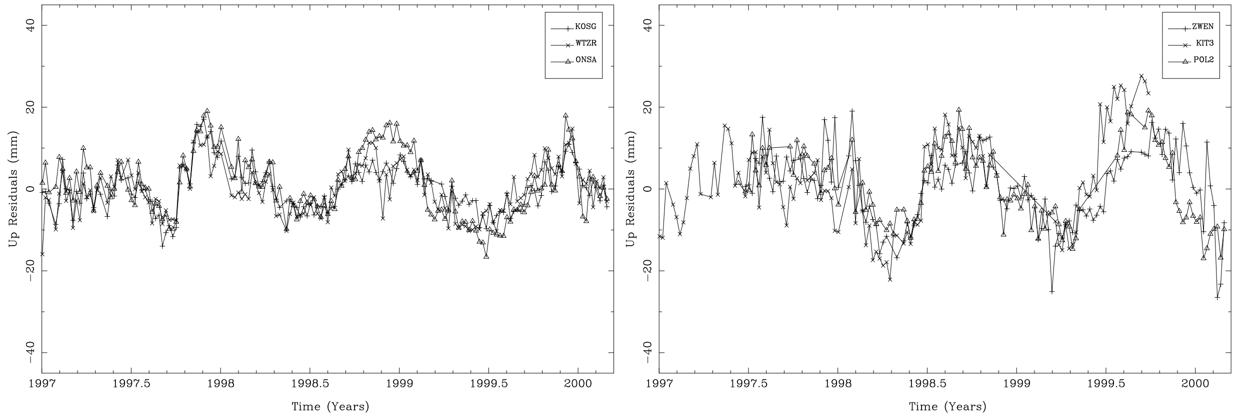
The second problem is the question of where the GPS satellite transmitter phase center is located. Recently it has become clear that there may be an error on the meter level in the location of the transmitter phase center. Because of correlations between the estimated parameters, especially with tropospheric zenith delays, the transmitter phase center location cannot be solved for using GPS data. For this purpose the IGS has requested the IVS to evaluate whether VLBI observations of the GPS satellites could help to solve this problem. Tom Herring proposed this at the IGS 1999 Analysis Center workshop held at the Scripps Institute for Oceanography, in La Jolla, California. Both problems will be discussed in more detail below.

2.1. Geographically Correlated Station Position Variations

It has become clear that the GPS time series of station coordinate estimates from the different IGS Analysis Centers show similar signals for stations in the same geographical area. The main question is whether these signals represent real geophysical phenomena or whether they are an artifact of the GPS data analysis. Figure 3 shows an example of these geographically correlated station position variations for two different areas, Eastern and Western Europe, over a time period of three years. These figures are based on the results of the CODE (Center for Orbit Determination in Europe) Analysis Center of the IGS [10].

Figure 3 shows that the height variations of the stations are as large as 20 mm with an approximately annual period. The coherence between the stations within a certain geographical area is very high. The difference between geographical areas, e.g., East and West Europe, are quite large. In Western Europe the height variation seems to have a maximum around the start of the year whereas in Eastern Europe a minimum is observed around this time. The size of these effects is such that they could easily be caused by geophysical processes like, e.g., atmospheric loading (which is in general not accounted for by the IGS analysis centers). However, there are several reasons why GPS results could show annual signals. First of all the solar radiation pressure, which is the dominant error source in the GPS orbit model, has an annual period. Secondly the 4 minute change per day of the station–satellite geometry, because the orbital revolution period of the GPS satellites is approximately half a sidereal day, also leads to an annual period in the station–satellite geometry. It is very likely that this annual period will show up in the results because of multipath effects which strongly depend on the station–satellite geometry.

The best way to resolve this problem is to compare the GPS based time series with time series from one or more of the other geodetic techniques. Of course also the (inter)comparison of GPS results from the different IGS Analysis Centers may give some idea. However, in most cases the



(a) Western Europe

(b) Eastern Europe

Figure 3. Residuals of daily height estimates from global GPS solutions for stations in the same geographical area.

GPS time series agree quite well which each other. The only exceptions are observed in some of the "remote" areas where only a few IGS stations are present. Clearly the comparisons of station coordinate time series from the IGS and the IVS will be most useful to resolve this issue.

2.2. GPS Satellite Transmitter Antenna Phase Center Offset

One of the major remaining problems in GPS data processing is the location of the satellite and receiver antenna phase centers. The recently observed bias (1 meter!) in the phase center location of the first block IIR satellite (PRN 13) has made it clear that the position of the satellite phase center offset is not well known [1]. Also, the elevation-dependent phase center variations of the receiver antennas are a major error source. A complicating factor is that the phase center offset estimates are highly correlated with the estimated tropospheric zenith delays and the terrestrial scale. To study the effects of the antenna phase center offsets we generated a series of test solutions using different processing strategies. The solutions should give a better understanding of the correlations between the antenna phase center offsets, the elevation dependent phase center variations, the tropospheric zenith delays, and the terrestrial scale. The following four processing options were modified in the test solutions:

- Constrained or free terrestrial scale. The "constrained" solutions are generated by constraining the coordinates of 37 reference stations to 1 mm. The free solution is generated by using minimal constraints (3 rotational constraints).
- The satellite transmitter phase center offset (Z-offset) is either fixed, artificially changed, or estimated. We call this a Z-offset because the direction of the satellite phase center offset corresponds with the Z-axis of the satellite-fixed reference frame. The Z-axis is the axis pointing from the center of mass of the satellite to the geocenter.
- Either relative receiver antenna phase center variations, relative to the Dorne Margolin antennas [8], or absolute variations using anechoic phase chamber values [7] are used.

	Differences w.r.t. Reference Solution			
Solution Description	Scale (ppb)	Tropos. (mm ZPD)	Z-off (m)	RMS (mm)
Scale Fixed	0.1	0	-	1.46
Scale Free, 15^o cut-off	-0.3	1	-	1.40
Scale Free, 20^o cut-off	-1.0	4	-	1.36
Scale Free, Z-off. +1 meter	-8.3	5	(+1.0)	1.46
Scale Fixed, Z-off Est.	1.5	-1	-0.2	1.44
Scale Free, Z-off Est.	13.2	-7	-1.6	1.44
Scale Free, Z-off Est. 15^o cut-off	17.0	-12	-2.0	1.39
Scale Free, Z-off Est. 20^o cut-off	22.8	-18	-2.5	1.34
Scale Fixed, Abs. P.C. Var.	8.5	-10	-	1.57
Scale Free, Abs. P.C. Var.	14.3	-18	-	1.53
Scale Fixed, Abs. P.C. Var., Z-off. Est.	-1.4	-9	2.1	1.49
Scale Free, Abs. P.C. Var., Z-off. Est.	-29.7	9	5.5	1.46

Table 1. Influence of small processing changes on the terrestrial scale, tropospheric zenith delay, and satellite antenna offset.

- Different elevation cut-off angles (10^o, 15^o, or 20^o) are used.

Combinations of these processing options were tested and the results are summarized in Table 1. The reference solution was a minimally constrained (3 rotational constraints) solution, which means in particular that the terrestrial scale was free. The other processing options of the reference solution were identical with those of our official IGS solution, i.e., 10^o cut-off angle with elevation-dependent weighting, relative phase center variations introduced, and no Z-offset estimated. The normalized RMS of the one-way L_1 phase observations of this reference solution was 1.46 mm. The first column of Table 1 identifies the processing option which was changed w.r.t. the reference solution. The next three columns show the mean difference between the test solution and the reference solution, in terrestrial scale, tropospheric zenith path delay, and estimated satellite antenna offsets. The last column gives the normalized RMS of the one-way L_1 phase observations.

We first wanted to know whether there were significant differences between the solutions with a fixed or free scale. No significant differences were found. Secondly, we tested the influence of the elevation cut-off angle by changing it from 10^o to 15^o and 20^o. Here a change of 1.0 ppb in the terrestrial scale was observed going from a 10^o to a 20^o cut-off angle. This change corresponds to a 6 mm height change of the station heights. The formal errors of the height estimates, however, were 3–5 mm and 3–6 mm for the 10^o and 20^o solutions, respectively. Thus a 1.0 ppb scale change is practically within the 1σ formal error, and therefore not significant. It is interesting to note that the noise of the normalized observation residuals (RMS) seems to decrease with increasing elevation despite the fact that we use elevation-dependent weighting for the observations.

Next we artificially changed the satellite phase center offsets of all satellites by one meter. In Table 1 we see that this change has a large impact on both the terrestrial scale and the tropospheric zenith delays. The scale changed by 8 ppb (50 mm in station height) and the zenith delays were changed by 5 mm (15 mm in station height). A comparison of the station coordinate estimates showed that they agreed at the few mm level after a 7 parameter transformation. Apart from the scale change of 8 ppb the coordinate transformation showed a small translation in the Z-direction of 5 mm. A comparison of the orbit estimates, without any parameter transformation, showed that they agreed on the mm level, which is remarkable considering the relatively large changes in the other parameters. These results underline the strong correlation between the satellite antenna phase center offset, the terrestrial scale, and the tropospheric zenith delays.

We then made the attempt to estimate the phase center offset of the satellites by estimating one offset for each individual satellite. It should be mentioned that the observability of this offset is rather poor due to the fact that the "observation angle" between the satellite–receiver and satellite–geocenter vectors is at maximum 14^o. This means that the major part of the Z-offset shows up as a range bias which may be absorbed by ambiguities and/or clock offsets and is strongly reduced in double difference observations. In this context the test where we changed the Z-offset by one meter is quite convincing. Only 70 mm (7%) of the 1 meter change showed up in the results.

The remaining effect of the Z-offset will have an elevation-dependent signature because the "observation angle" increases with decreasing satellite elevation. This elevation-dependent signature explains the correlation between the Z-offset and the estimated tropospheric delays. In addition, it is well known that the tropospheric delays correlate with the station heights and therefore with the terrestrial scale. The results of the four tests which were performed with Z-offset estimation are quite remarkable. If the scale of the terrestrial network is constrained the results look quite reasonable. However, as soon as the scale is left free to adjust the results differ quite significantly from the reference solutions with changes of 22 ppb in scale, 18 mm in zenith delay, and more than 2 m in satellite antenna phase center offset. Notice that the formal errors of the station heights (3–6 mm) and the tropospheric zenith delays (1–2 mm) barely change. The formal errors of the Z-offset estimates are a few centimeters only but increasing strongly with growing cut-off angle (from 40 to 70 mm going from 10^o to 20^o). Besides the scale change the coordinate transformation again showed small translations in the Z-direction of up to 15 mm. Also the orbits were now different but only by 20 mm in RMS without showing significant orientation differences. Quite disturbing is the pronounced elevation-dependency of the results.

In the last four tests we introduced the absolute receiver phase center offset and variations from anechoic chamber measurements. Earlier investigations had shown that the introduction of these absolute phase center measurements resulted in a 15 ppb terrestrial scale change of the GPS results [9]. In our earlier tests we noticed that the satellite antenna offsets also cause large scale effects in the terrestrial network. We therefore hoped to find a solution for the satellite antenna offset which would enable us to use the absolute phase center measurements without any residual effects on the terrestrial scale and the estimated tropospheric zenith delays.

The first two solutions, where we introduced the absolute phase center variations, confirm the fact that these give a 15 ppb terrestrial scale change and also large changes in the tropospheric delays. It is remarkable that, in the solution where the scale is constrained, the change of the scale is as large as 8 ppb! Notice also, that the RMS of these solutions is increased.

In the latter two solutions we solved for the satellite phase center offset in addition to introducing the chamber measurements. The solution with the constrained terrestrial scale looks quite acceptable although the Z-offset change of 2 meters is large. However, the minimal constrained solution shows a dramatic scale change of almost 30 ppb (180 mm station height). Also, the estimated Z-offset is very large (5 m). This solution is not acceptable which means that we are still not in a position to use the absolute phase center variations.

We conclude that it is not feasible to accurately solve for the satellite antenna offsets in an absolute sense due to the correlation with the terrestrial scale, the tropospheric delays, the receiver antenna phase center offsets, and elevation-dependent variations. However, we are able to solve for these offsets in a relative way, e.g., by adopting a specific value for a single satellite. The offsets of the other satellites may then be determined relative to this adopted value. Significant Z-offset differences were observed between the individual satellites. Two other IGS ACs, GFZ and JPL, which also estimated the satellite antenna offsets, observed very similar differences for individual satellites [1]. We furthermore conclude that biases observed in the terrestrial scale and tropospheric delays, based on GPS microwave measurements, are very likely the result of inaccurately known phase center positions (and their elevation dependency) of both the satellite and the receiver antennas. We hope that the IVS will be capable of tracking the GPS satellites and that this will allow us to determine the phase center offset and the elevation dependency of the GPS transmitter antenna. It is clear that this problem can not be resolved using GPS alone.

3. Outlook

The availability of service type of organizations for the three major space geodetic techniques will greatly improve the exchange of information and consequently the cooperation between the different techniques. At the same time this should help the scientists to get a better insight in the strengths *and* weaknesses of the individual techniques.

The combination of the reference frame products from the different techniques on the SINEX level should enable us to get the best out of all three techniques and truly unify the reference frames of the different techniques. It is quite clear that at present systematic differences at the few centimeter level exist between the techniques. The scientific community may therefore look forward to some very interesting results coming from the inter-technique comparisons based on the reference frame products which will be, or already are, routinely provided in the software independent exchange (SINEX) format.

Each of the three techniques has its own specialism and none of the techniques can provide all the answers. It is therefore clear the all three techniques are needed, also because they all depend on each other. In the previous section we have given two examples where GPS needs the help of one or more other techniques. From this perspective the establishment of the combined IVS, IGS, and ILRS working group during the IVS 2000 General Meeting which was held in Kötzting, Germany, is an excellent development. In this working group analysis experts from the three different techniques will work together and try to resolve problems and inconsistencies between the techniques. The first item on the list of this working group is the determination of the location of the GPS transmitter phase center offset. Secondly, the working group will study the observed SLR–microwave bias.

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