Markus Rothacher: Combination of Space-Geodetic Techniques, IVS 2002 General Meeting Proceedings, p.33–43
http://ivscc.gsfc.nasa.gov/publications/gm2002/rothacher

Combination of Space-Geodetic Techniques

Markus Rothacher

Forschungseinrichtung Satellitengeodäsie, TU Munich
e-mail: `rothacher@bv.tum.de`

Abstract

The combination of all major space-geodetic techniques — Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Global Positioning System (GPS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) — into an "Integrated Global Geodetic Observing System" (IGGOS) must be a primary goal in geodesy in the next years. Such an integrated system should also include observation techniques such as satellite altimetry, Synthetic Aperture Radar (SAR) and the various measurements that become or will become available through the new satellite gravity missions CHAMP, GRACE, and GOCE. In this article we will mainly focus on the combination of the observation techniques VLBI, SLR, LLR, GPS, and DORIS, that form the basis for the realization of the International Terrestrial Reference Frame (ITRF), the International Celestial Reference Frame (ICRF), and the Earth orientation parameters (EOPs) that describe the transformation between the ICRF and ITRF. A combination of these techniques is beneficial in many ways, especially to distinguish genuine geodetic/geophysical signals from technique-specific systematic biases and to ensure the consistency of the resulting geodetic products. The integration effort should finally lead to a more detailed view and understanding of the complexity of the "System Earth" and its geophysical processes.

The variety of combination aspects resulting from a rigorous integration will be discussed and illustrated.

1. General Combination Aspects

The idea to compare and combine the results of the major space-geodetic techniques is not new. For a long time groups involved in the processing of data of one space-geodetic technique have compared their results with those of groups working on other observation techniques. But in most cases these comparisons were limited so far to one specific parameter type, e.g., the station coordinates of collocated sites, the troposphere zenith delays at collocated sites or the Earth Rotation Parameters determined by different techniques. The only product that is presently based on a rigorous combination of the results of the individual techniques is the ITRF, where the full variance-covariance information of the individual solutions is included in the combination algorithms to obtain site coordinates and velocities. The EOP series of the International Earth Rotation Service (IERS) are still generated with rather simple procedures (typically a weighted mean of the individual series) and independent of the ICRF and ITRF. It is clear, however, that there are considerable benefits to be expected from a rigorous combination and integration of the space-geodetic observation techniques. The most important aspects are:

- It helps to distinguish technique-specific systematic biases from real geodetic or geophysical signals, a crucial aspect in view of the fact that the results of the individual techniques are primarily limited by systematic biases today.
- The complementarity, strengths and weaknesses of the individual techniques may be used to obtain an optimum solution for the geodetic and geophysical parameters concerning not

only the precision and accuracy, but also time resolution and availability of the results.

- We can benefit from the collocation of different observing instruments at the same site. The data of these instruments have to yield identical results for site-specific parameters common to more than one technique.
- There is only one orientation of the Earth's rotation axis for all techniques, only one rotation velocity of the Earth, only one tropospheric and ionospheric refraction for VLBI, GPS, and other microwave techniques, and only one set of coordinates and velocities should result for collocated sites.
- Observing satellites with different techniques (e.g. GPS, SLR, and DORIS) should yield identical orbits, independent of the technique used.
- The rigorous combination is a prerequisite to ensure the consistency of the geodetic results obtained, in particular the consistency of the ITRF, ICRF, and EOP products of the International Earth Rotation Service (IERS).

The final goal of such an integration process would be the combination of all observing techniques into an "Integrated Global Geodetic Observing System" (IGGOS). This should also include observation techniques like satellite altimetry, Synthetic Aperture Radar (SAR), and the measurements of the new gravity satellite missions CHAMP, GRACE, and GOCE, and thus embrace all the three pillars of geodesy: the site positions (displacement fields), Earth orientation and the gravity field.

1.1. Links Between the Space-Geodetic Techniques

Let us now consider the two principal types of links that exist between the individual observation techniques: (1) links at individual stations or satellites and (2) links through common parameters. The first type of link concerns the connection between the techniques that can be established on the Earth's surface (stations) and in space (satellites):

- *Stations as link*: Different observation techniques present at the same location — typically at sites called fundamental stations (e.g. Wettzell, Onsala, Fairbanks, ...) — may be linked using accurate information about the local ties between the reference points of the individual techniques.
- *Satellites as link*: Tracking of a satellite with several observation techniques (e.g. SLR, GPS, DORIS, altimetry) allows for a link at the satellite, if the offsets between the various instruments on the satellite (GPS antenna phase center, SLR reflector, ...) are accurately known.

These two types of links will be discussed in more detail in Sections 2 and 3.

The second type of link is realized by all parameters that are common to more than one space-geodetic technique. This link based on common parameters can be performed on two different levels, namely, the combination of the common parameters on the normal equation level (stacking of normal equation matrices) or on the observation level.

The second approach is certainly more demanding and only one or two software packages are available today capable of treating all the major techniques in a consistent way. In principle, both methods (normal equation and observation level) are mathematically equivalent and give identical results. In practice, however, it is much more difficult to ensure the consistency of all the models involved in the processing of the space-geodetic data, if independent computer programs are used to generate the normal equations (or variance-covariance matrices) and the parameterization might not be identical, which inevitably leads to problems in the combination. In addition, the combination on the observation level has the advantage that parameters that have to be estimated with a high temporal resolution can easily be treated (e.g. using pre-elimination schemes or filter algorithms) without having to deal with extremely large and bulky normal equation systems.

It should be pointed out that — independent of the method chosen to combine the results — consistent standards (IERS Conventions and more) and parameterizations are a necessity for a correct and rigorous combination procedure.

Let us have a closer look now at the observation equations of the individual techniques to get more insight into the various parameter types involved.

1.2. Basic Observation Equations and Parameter Space

It is not our intention and goal here to come up with an elaborate and complex observation model including, e.g., a fully relativistic formulation and going into the subtleties of the individual techniques. Detailed observation equations may be found in [7] (GPS), [1] (SLR), [6] (VLBI), and many text books on space geodesy (see e.g. [5]). The simplified observation equations for GPS, SLR, and VLBI given here — similar equations exist for GLONASS, DORIS, altimetry — should primarily demonstrate the similarities between the techniques and show where the various parameter types turn up in the individual observation equations:

$$c\,\Delta\tau_R^{S,GPS} = |\boldsymbol{r}_i^S - \boldsymbol{R}\cdot\boldsymbol{r}_{e,R}| - c\,\delta t^S + c\,\delta t_R + \delta\rho^S_{trp,R} + \delta\rho^S_{ion,R} + \delta\rho^S_{rel,R} + \ldots + \epsilon \qquad (1)$$

$$\frac{1}{2}\,c\,\Delta\tau_R^{S,SLR} = |\boldsymbol{r}_i^S - \boldsymbol{R}\cdot\boldsymbol{r}_{e,R}| + \delta\rho^S_{trp,R} + \delta\rho^S_{rel,R} + \ldots + \epsilon \qquad (2)$$

$$\begin{aligned} c\;\Delta\tau_{R_1,R_2}^{S,VLBI} = {} & -\boldsymbol{R}\cdot\boldsymbol{r}_{e,R_1}\cdot\boldsymbol{e}_i^S - c\cdot\delta t_{R_1} - \delta\rho^S_{trp,R_1} - \delta\rho^S_{ion,R_1} - \delta\rho^S_{rel,R_1} \\ & +\boldsymbol{R}\cdot\boldsymbol{r}_{e,R_2}\cdot\boldsymbol{e}_i^S + c\cdot\delta t_{R_2} + \delta\rho^S_{trp,R_2} + \delta\rho^S_{ion,R_2} + \delta\rho^S_{rel,R_2} + \ldots + \epsilon \qquad (3) \end{aligned}$$

with the following quantities and parameters (parameter types are given in italics):

$\Delta\tau_R^{S,GPS}$	Code or phase observation between satellite S and station R (pseudo light travel time)
$\Delta\tau_R^{S,SLR}$	Light travel time (station $R \rightarrow$ satellite $S \rightarrow$ station R)
$\Delta\tau_{R_1,R_2}^{S,VLBI}$	Light travel time difference between stations R_1 and R_2 for radio source S
c	Speed of light in vacuum
$\boldsymbol{r}_i^S$	Position of satellite S in inertial frame: *orbit parameters, coefficients of the gravity field*
$\boldsymbol{e}_i^S$	Direction of radio source S in inertial frame: *radio source coordinates*
$\boldsymbol{r}_{e,R}$	Position of station R in the Earth-fixed frame: *station coordinates*
$\boldsymbol{R}$	Rotation matrix of Earth rotation: *Earth orientation parameters* (x,y,*UT1*,$\Delta\epsilon$,$\Delta\psi$)
δt^S	Clock error of satellite S: *satellite clock parameters*
δt_R	Clock error of station R: *station clock parameters*
$\delta\rho^S_{trp,R}$	Tropospheric delay: *troposphere parameters*
$\delta\rho^S_{ion,R}$	Ionospheric delay: *ionosphere parameters*

$\delta\rho^S_{rel,R}$	Relativistic corrections: *parameters of relativity theories*
ϵ	Measurement error

Let us briefly mention some essential shortcomings present in these three equations:

- The satellite as well as the station positions ($\boldsymbol{r}^S_i$ and $\boldsymbol{r}_{e,R}$, respectively) differ from observation technique to observation technique by the local ties or sensor eccentricities. The local ties (at the ground) and the eccentricities between the center of mass of the satellite and the individual sensors are therefore extremely important elements to connect the techniques.
- The tropospheric and ionospheric delays are not identical for all techniques. They depend on the frequency of the signals used.
- Different time arguments (e.g. for signal emission and reception; for the two rotation matrices $\boldsymbol{R}$ included in (3); ...) have to be used for the various quantities.
- The "..." in (1), (2) and (3) indicate that additional, technique-specific correction terms and parameters (initial phase ambiguities and phase center variations in GPS, range biases and system delays in SLR, telescope deformation and radio source variability in VLBI, to name just a few) have to be taken into account.

From the observation equations (1), (2) and (3) we immediately see that only VLBI is capable of realizing the ICRF (radio source positions), that all techniques including the satellite position $\boldsymbol{r}^S_i$ may in principle be used for gravity field determination, and that all the three equations contain station coordinates $\boldsymbol{r}_{e,R}$ and Earth orientation parameters (rotation matrix $\boldsymbol{R}$) and can thus contribute to the realization of the ITRF and to the EOP series. The terms $\delta\rho^S_{trp,R}$ and $\delta\rho^S_{ion,R}$ indicate that information about the atmosphere also may be derived from the various observation techniques, although with varying precision.

We conclude this section with Table 1, which gives a summary of the connections between the techniques in the parameter space. It has to be the goal to rigorously combine all the parameters common to more than one technique in order to obtain the most consistent and accurate geodetic products (ITRF, ICRF, EOPs, gravity field, atmosphere, ...).

2. Stations as Link Between Techniques

Stations may only serve as link between techniques if they are so-called fundamental sites i.e., sites where more than one observation technique is collocated. For collocated sites two different types of links may be established:

- Link between site coordinates ($\boldsymbol{r}_{e,R}$) of the individual techniques through local ties.
- Link between parameters describing the atmospheric delays ($\delta\rho^S_{trp,R}$, $\delta\rho^S_{ion,R}$) of the individual techniques.

Let us have a closer look at these two types of links (Sections 2.1 and 2.2).

2.1. Site Coordinates and Velocities

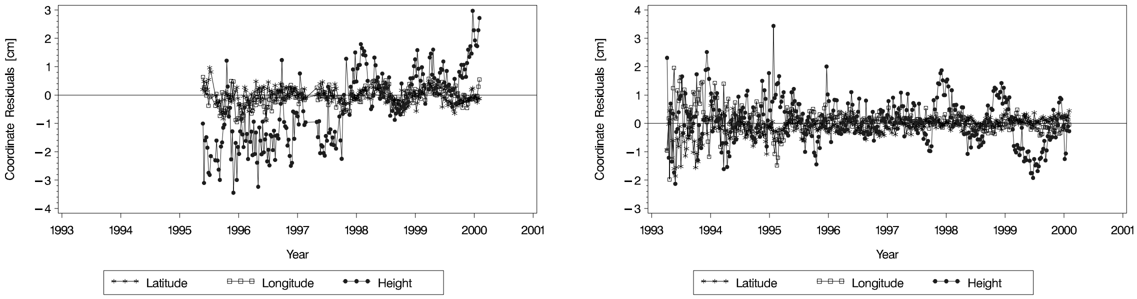
The links established through fundamental stations with accurate local ties are the most important connections between the individual techniques and are, at present, the only links between the terrestrial reference frame realizations of the individual technique. Without these links, the

Table 1. Parameter space for the combination of space-geodetic techniques.

Parameter Type	**VLBI**	**GPS/GLO.**	**DORIS**	**SLR**	**LLR**	**Altimetry**
Quasar Coord. (ICRF)	X					
Nutation $\Delta\epsilon$,$\Delta\psi$	X	(X)			X	
Pole x, y	X	X	X	X	X	
UT1	X					
Length of Day		X	X	X	X	
Sub-daily ERPs	X	X				
ERP-Ampl. (Ocean tides)	X	X		X		X
Coord.+Veloc.(ITRF)	X	X	X	X	X	(X)
Geocenter		X	X	X		X
Gravity Field		X	X	X	(X)	X
Orbits		X	X	X	X	X
LEO-POD		X	X	X		X
Troposphere	X	X	X	(X)		X
Ionosphere	X	X	X			X
Clocks (time transfer)	X	X		(X)		

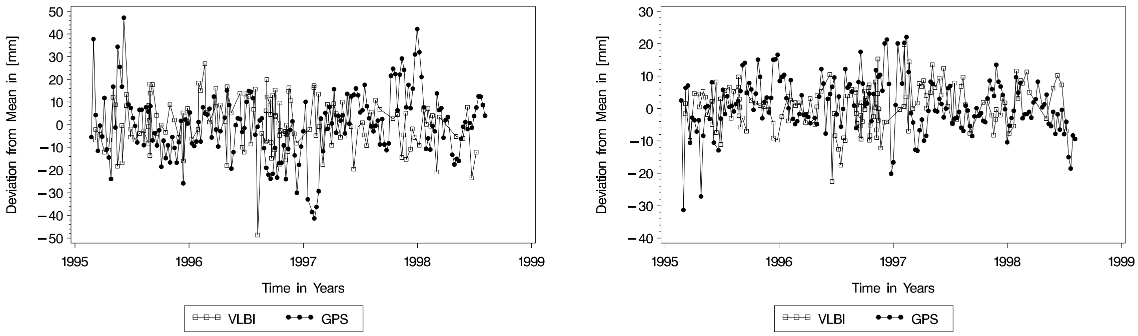
reference frames of the individual techniques would be arbitrarily translated and rotated with respect to each other. It has to be emphasized that today fundamental stations will only contribute significantly to the global link budget — given by a weighted mean of all known local ties — if the local ties between the reference points of the observing instruments are accurately known. In view of the precision achieved nowadays by each of the individual techniques, the local ties have to be known with an accuracy of 1-2 mm or better. Local ties are one of the major if not the major error source in the realization of a common terrestrial reference frame.

For quite some time multi-year solutions of the individual techniques have been combined by the ITRF Product Center including all local ties and the full variance-covariance matrices of the individual solutions to obtain a consistent terrestrial reference frame: ITRF station coordinates and velocities. Time series of coordinates from fundamental stations, however, have not been routinely compared between techniques and combined into consistent time series so far. Such comparisons are crucial for the separation of technique-specific effects and real signals (geodynamics, geophysics). The two GPS coordinate time series from the CODE analysis center of the IGS shown in Figures 1(a) and (b) may illustrate this point. It is not really clear whether the annual signal seen in the Onsala time series (Figure 1(a)) after mid 1997 is genuine or a systematic bias produced by the processing strategy or the modeling (e.g., the troposphere mapping function). Especially the circumstance that the annual period only starts to be visible around mid of 1997 should make us suspicious and hold us back from geophysical interpretation, unless a similar signal is also visible in the VLBI time series. (Even then it might still be an artifact coming from a modeling error common to both the VLBI and GPS processing strategy.)



(a) Onsala (Sweden) (b) Thule (Greenland)

Figure 1. GPS site coordinate time series from the CODE analysis center.



(a) Comparison of height difference (b) Comparison of baseline length

Figure 2. Baseline length and height difference between Fairbanks (Alaska) and Wettzell (Germany) from GPS and VLBI time series.

Similarly, we should be cautious to interpret the height change in Thule, which looks very much like a post-glacial rebound signal (Figure 1(b)), without having an additional independent check.

That a lot of work still has to be done in this area can be seen in Figure 2, where the height difference and the baseline length of a GPS (CODE: Center for Orbit Determination in Europe) and a VLBI (GSFC: Goddard Space Flight Center) time series are compared. Common signals cannot be detected so far and the series seem to be dominated by noise. Conclusive comparisons of this kind are made difficult by the fact that only very few fundamental stations exist with long and accurate coordinate time series of more than one technique. Activities initiated by the IERS Analysis Coordinator (see `http://alpha.fesg.tu-muenchen.de/iers/`, e.g., the SINEX Campaign to combine weekly/monthly SINEX files from all major techniques) will hopefully lead to deeper insights into the behavior of coordinate time series.

The local ties at fundamental sites also have an impact on the consistency of the EOP series from different techniques. An analysis campaign of the IERS is presently studying remaining systematic biases (offsets, rates) between EOP series from different techniques after careful alignment of the series to the ITRF2000 reference frame. The IERS is now starting to look into the rigorous combination of ITRF, EOPs and ICRF using the time series of these parameters (SINEX files) from all contributing space-geodetic techniques. A lot of problems will still have to be overcome

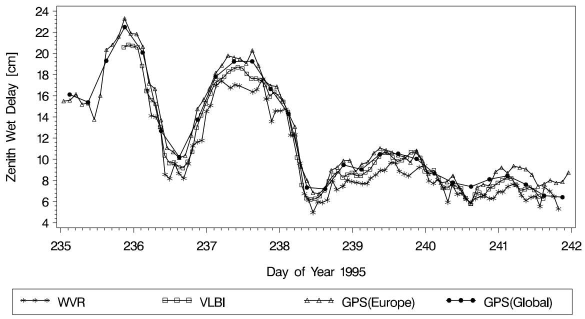


Figure 3. Comparison of troposphere zenith wet delays from VLBI, GPS (global and European solutions) and from the water vapor radiometer (WVR) at the Onsala site in Sweden during the CONT95 campaign.

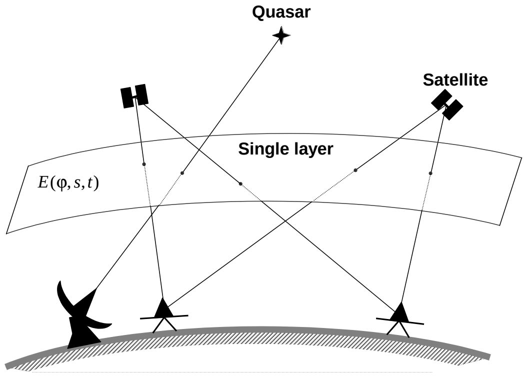


Figure 4. Validation of global GPS ionosphere models by VLBI.

on the way to such a consistent set of IERS products (e.g. the combination of UT1 from VLBI and LOD from satellite techniques).

2.2. Troposphere and Ionosphere

So far the fact that the tropospheric zenith delays have to be identical for GPS and VLBI observations made at a collocation site has not been used in any combination of solutions. It is clear from comparison studies, however, that especially the height component should benefit from such a combination. At some of the fundamental stations a lot of different information on the atmosphere is available and should be exploited:

- GPS and VLBI estimates of tropospheric zenith delays
- Water vapor radiometer (WVR) measurements
- 2-color SLR measurements
- Meteorological data (pressure, temperature, humidity)

Because of the complementarity of some of these measurements (optical pulses of SLR are much less affected by water vapor than the radiowaves of VLBI and GPS; meteorological data and WVR data can be used to compute the dry and wet zenith delay, respectively), we may expect to obtain better height estimates from a combination of all these data. A comparison of the wet zenith delays computed from VLBI, GPS (global and European) and water vapor radiometer (WVR) data is depicted in Figure 3 and shows the good and encouraging agreement between the estimates of the independent techniques.

The VLBI station network will probably never be dense enough to compute global ionosphere models similar to those obtained from the global IGS network. But VLBI observations could very well be used to validate the GPS-derived global ionosphere models (see Figure 4). Interesting results on how VLBI might be used to obtain information about the ionosphere have recently been presented by [2] (this volume).

3. Satellites as Link Between Techniques

Apart from the obvious links at fundamental stations we may also make use of the links that exist at a satellite if the satellite is tracked by more than one technique. A typical example is the TOPEX/Poseidon mission, where four different techniques, namely, SLR, DORIS, GPS, and altimetry, could be used for precise orbit determination (POD). The possibility to inter-compare all these different orbit types led to a considerable improvement in POD strategies and insight into the suitability of different tracking systems for POD.

Another example are the GPS (SVN35 and SVN36) and GLONASS satellites that carry SLR retro-reflectors. Using SLR data to these satellites the accuracy of the GPS and GLONASS microwave orbits could be confirmed with an independent technique and a systematic bias between the SLR observations and the orbit determined using the GPS/GLONASS microwave data could be detected. The origin of this bias of about 5 cm — SLR ranges are too short compared to the microwave orbits — is not yet clear and needs further investigation.

In the future an additional interesting link might be established at the satellite level: the observation of GPS or GLONASS L-band signals with VLBI. Differential VLBI observations between quasars and GPS/GLONASS satellites could tie the satellite orbits directly into the inertial reference frame of the quasars and give interesting information on UT1–UTC and on the non-conservative forces acting on GPS/GLONASS satellites (e.g. systematic orbit errors).

4. Earth Orientation Parameters

According to observation equations (1), (2), and (3) Earth orientation parameters may be estimated from the data of all the major space-geodetic techniques. Due to the one-to-one correspondence between orbital elements on one side and UT1–UTC and nutation offsets on the other side, satellite techniques may only determine polar motion (PM), the rate of change of UT1–UTC, i.e., the length of day (LOD), and nutation rates (see [3] for details). With these limitations, the EOP series of all techniques should agree on the level of precision of the individual techniques. There are still considerable systematic biases that are not yet properly understood, however, between the polar motion series of the individual techniques. Much work is still required in this field to come up with a combined consistent EOP product from all techniques.

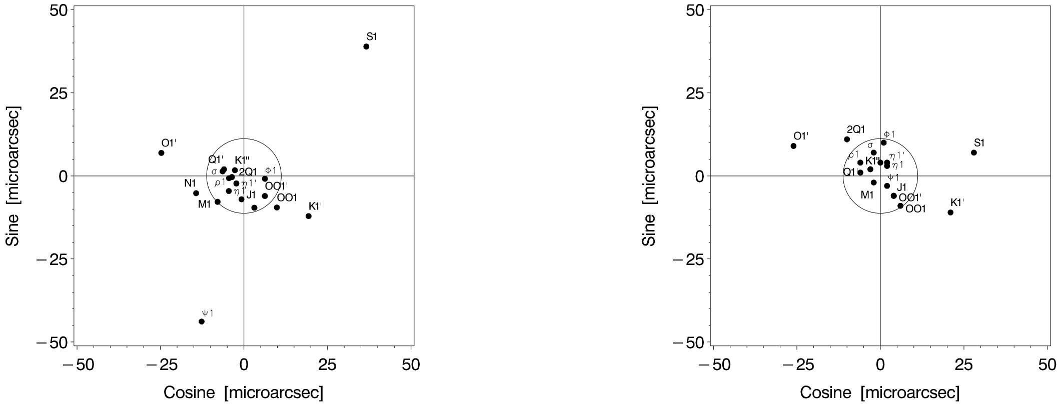
In this paper we will focus on two examples to illustrate the benefits of a combination of the techniques: sub-daily Earth rotation parameters (Section 4.1) and nutation amplitudes derived from nutation offsets and rates (Section 4.2).

4.1. Sub-daily Earth Rotation Parameters

Sub-daily Earth Rotation Parameters (ERPs) are available nowadays from both GPS and VLBI solutions. The GPS series analyzed here were computed by the CODE analysis center in Berne, the VLBI series by the group at GSFC. The GPS and VLBI series cover a period of 6.5 and 20 years and have a time resolution of 2 hours and 1 hour, respectively. These two series were used to estimate the amplitudes of all the major diurnal and semi-diurnal terms due to ocean tides (57 tides in PM, 41 in UT1; see also [4] for details). Apart from the estimation of amplitudes based on the individual series a combined estimation from the GPS and VLBI series was also performed. The amplitude differences (RMS difference) over all these diurnal and semi-diurnal terms between different solutions are given in Table 2. In addition, the GPS and VLBI results were compared to

Table 2. Comparison of ocean tide amplitudes in Earth rotation parameters obtained from different space-geodetic techniques (RMS difference between amplitudes).

	UT1 Amplitudes in μs				**PM Amplitudes in μas**			
Technique	VLBI	GPS+VLBI	SLR	Altim.	VLBI	GPS+VLBI	SLR	Altim.
GPS	0.71	0.40	1.20	0.95	6.73	3.31	10.61	8.40
VLBI		0.41	1.20	1.04		3.77	9.25	7.09
GPS+VLBI			1.12	0.66			9.01	5.79
SLR				1.21				9.04



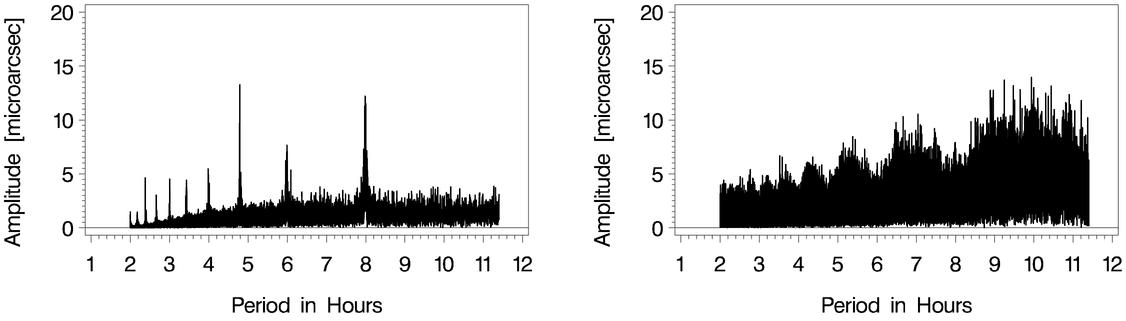
(a) GPS (b) VLBI

Figure 5. Comparison of small ocean tide amplitudes in prograde polar motion estimated from GPS and VLBI data, respectively. The circle indicates the 3-σ RMS of the GPS estimates.

the amplitudes derived from SLR data and from altimetry data of the TOPEX/Poseidon mission.

We see that the results of all the different techniques show a very good agreement on the 1 μs and the several μas level for UT1 and PM, respectively. In the context here, it is interesting to note that the combined GPS/VLBI amplitudes are in better agreement with the altimetry results than those of the individual solutions. This shows that a considerable improvement can be obtained by the combination of the two techniques.

In Figure 5 we present the sine and cosine amplitudes of very small ocean tide terms in a so-called phasor diagram. If we compare the GPS and VLBI amplitudes, we immediately see that two terms exhibit major discrepancies between the techniques, namely, the terms S_1 and ψ_1. The periods of both terms are very near to one solar day, and we may conclude therefore, that the GPS amplitudes of these terms are significantly biased by remaining errors in the modeling of solar radiation pressure acting on the GPS satellites, having a period of 12 solar hours. The comparison of the two techniques thus allows a crucial validation of the individual results.



(a) GPS (b) VLBI

Figure 6. Comparison of the prograde polar motion spectrum below periods of 11 hours derived from sub-daily GPS and VLBI ERP estimates, respectively.

A similar situation may be seen when comparing the high-frequency prograde polar motion spectrum obtained from GPS and VLBI, as depicted in Figure 6. Whereas significant amplitudes are visible in the GPS spectrum at frequencies of 2, 3, 4, ... cycles per day, no such signals can be detected in the corresponding VLBI spectrum. There is even a decrease in the VLBI amplitudes at these frequencies. A closer inspection of the GPS ERP time series suggests that a very small systematic bias in the daily polar motion rate of only a few tens of microarcseconds is sufficient to produce such a spectrum. Due to the fact that the GPS results can be compared to those of VLBI, we are able to conclude that most (if not all) of the signals seen at periods below 11 hours should be considered as artifacts resulting from the GPS processing strategies (e.g. small systematic biases in the orbit modeling over each daily solution).

4.2. Nutation Offsets and Rates

Complementary information is available from VLBI and GPS for the estimation of nutation amplitudes. Whereas nutation offsets ($\Delta\epsilon$ in obliquity and $\Delta\psi$ in longitude) are routinely estimated once per day from the VLBI data, only nutation rates $\Delta\dot{\epsilon}$, $\Delta\dot{\psi}$ may be derived from GPS measurements (typically estimated over 1–3 days). The VLBI nutation estimates are free of orbit errors and allow the long-term monitoring of the Earth's rotation axis in space (nutation and precession). The GPS nutation rate estimates in contrast are very sensitive to orbit modeling errors but may provide dense information on the short-term variations (periods smaller than about 20–30 days).

In view of these strengths and weaknesses, a comparison and combination of the techniques will help to check the results obtained by an individual technique and to gain more confidence in the results in general. The sine and cosine amplitudes of the 13.66-day period of nutation derived from different techniques are shown in Figure 7 as an example. The nutation amplitudes at this period are essential to test different non-rigid Earth models and the elasticity of the Earth. The agreement between VLBI and GPS amplitudes establishes a solid basis for the geophysical interpretation of the results.

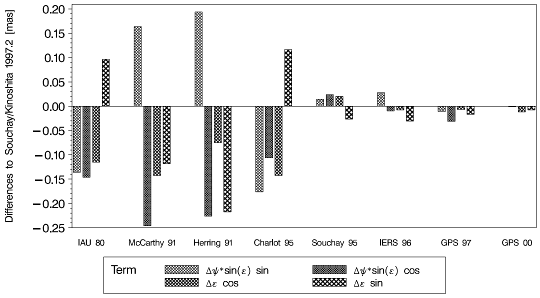


Figure 7. Comparison of the amplitudes of the 13.66-day nutation period derived from different techniques with the Souchay/Kinoshita model 1997.2 .

5. Conclusions

We have seen that the integration and combination of the space-geodetic techniques is essential to improve the consistency of the results, to realize optimum reference frames (ITRF, ICRF, and EOPs) for future missions and challenges (e.g. global change), and to distinguish between technique-specific biases and geophysical signals.

All links between the techniques — be it on the station or satellite level — should be determined as accurately as possible (local ties, satellite antenna offsets, ...) to allow for an optimum integration of the techniques.

All parameter types common to more than one technique should be compared in detail and combined as rigorously as possible. This will eventually lead to a set of consistent combined products for all major geodetic parameter types, an important step towards an "Integrated Global Geodetic Observing Systems" (IGGOS). Such an IGGOS is crucial to get a more detailed view and understanding of the complexity of the "System Earth" and its geophysical processes.

References

[1] Degnan, J.J., Millimeter Accuracy Satellite Laser Ranging: A Review, In: Contributions of Space Geodesy to Geodynamics: Earth Dynamics, Geodyn. Ser., vol. 25, edited by D.E. Smith and D. L. Turcott, pp. 133–162, AGU, Washington, D.C., 1993.

[2] Hobiger, T., J. Boehm, and H. Schuh, Determination of Ionospheric Parameters by Geodetic VLBI, this volume, 2002.

[3] Rothacher, M., G. Beutler, T.A. Herring, and R. Weber, Estimation of nutation using the Global Positioning System, J. Geophys. Res., 104, 4835–4859, 1999.

[4] Rothacher, M., G. Beutler, R. Weber, and J. Hefty, High-Frequency Variation of Earth Rotation from Global Positioning System Data, J. Geophys. Res., 106(B7), 13,711–13,738, 2001.

[5] Seeber, G., Satellite Geodesy, Walter de Gruyter, Berlin, New York, ISBN 3-11-012753-9, 1993.

[6] Sovers, O.J., J.L. Fanselow, and C.S. Jacobs, Astrometry and geodesy with radio interferometry: experiments, models, results, Reviews of Modern Physics, 70(4), 1393–1454, 1998.

[7] Teunissen, P. J. G., and A. Kleusberg (Eds.), GPS for Geodesy, Lecture Notes in Earth Sciences, Springer Verlag, 2nd edition, 1998.