ITRF, GPS Permanent Stations and the AFREF Project

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SUMMARY

The current status of the International Terrestrial Reference Frame (ITRF) is presented as well as expected improvements and enhancements of its future realization. The use of GPS permanent stations is discussed, through IGS and EUREF activities, with an emphasis of their use for ITRF densification as well as geophysical applications. IAG efforts for regional GPS permanent networks development are outlined, aiming at unifying and modernizing the national geodetic systems and their compatibility with the global ITRF. The present situation and objectives of the AFREF project with its sub-regional activities (NAFREF, SAFREF, etc.) are addressed, with some future goals and guidelines towards progress for its implementation.

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1. INTRODUCTION

The International Terrestrial Reference Frame is the worldwide adopted standard frame used as basis for all geodetic and geophysical applications. The use of GPS permanent stations for a variety of applications allows in particular the densification and dissemination of ITRF worldwide thanks to IGS high quality products, being reported to ITRF global frame. Point positioning using IGS clock corrections and orbits already expressed in the ITRF permits disseminating the ITRF at the cm-level, without reference to any other point on the Earth surface. The high level of accuracy and consistency of IGS products could not be reached without the revolutionary potential of GPS permanent stations.

Thanks to GPS permanent stations development and IGS products, modernisation, improvement and accurate long-term maintenance of continental and national geodetic systems are now possible. The International Association of Geodesy (IAG), through its first Commission (Reference Frames) and its sub-commission 1.3 (Regional Reference Frames) stimulate and encourage redefinition of continental and national geodetic systems, unifying them through their compatibility with the global ITRF frame. Due to the complexity of the African countries and their poor economical situations, some international effort and contribution are needed to develop the African Reference Frame (AFREF) project.

2. THE INTERNATIONAL TERRESTRIAL REFRENCE SYSTEM (ITRS)

Since the creation of the International Earth Rotation and Reference Systems Service (IERS) in 1988, the realization of the International Terrestrial Reference System (ITRS) has sustained continuous improvement and enhancement (Boucher and Altamimi, 1996, Altamimi et al. 2002). Its realization, called ITRF consists on combining station positions and velocities provided by IERS Analysis Centers, derived from the observations of space geodesy techniques (VLBI, LLR, SLR, GPS and DORIS).

1.1 ITRF Implementation

The initial model implemented in CATREF software (used for ITRF combination) allows simultaneous combination of station positions and velocities. A large description could be found in (Altamimi et al. 2002). Assuming that for each individual solution $\boldsymbol{s}$, and each point $\boldsymbol{i}$, we have position $\mathbf{X}^{\mathbf{i}}_{\mathbf{s}}$ at epoch $\mathbf{t}^{\mathbf{i}}_{\mathbf{s}}$ and velocity $\dot{X}^i_c$, expressed in a given TRF $\mathbf{k}$.

The combination consists in estimating:

- Positions X^i_c at a given epoch $\mathbf{t_0}$ and velocities $\dot{X}^i_c$, expressed in the combined TRF $\boldsymbol{c}$,

- Transformation parameters $\mathbf{T_k}$ at an epoch $\mathbf{t_k}$ and their rates $\mathbf{T_k}$, from the combined TRF ***c*** to each individual frame **k**.

The general combination model is given by the following equation:

$$
\begin{cases}
X_s^i = X_c^i + (t_s^i - t_0) + T_k + D_k X_c^i + R_k X_c^i \\
\quad + (t_s^i - t_k)[\, \dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i \,] \\
\dot{X}_s^i = \dot{X}_c^i + \dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i
\end{cases}
$$

More recently CATREF software was upgraded to allow the inclusion of Earth Orientation Parameters in the combination. Using pole coordinates $\mathbf{x^p}_s$, $\mathbf{y^p}_s$ and universal time UT_s as well as their daily time derivatives $\dot{x}_s^p, \dot{y}_s^p$ and LOD_s, the corresponding equations are :

$$
\begin{cases}
x_s^p = x^p + R2_k \\
y_s^p = y^p + R1_k \\
UT_s = UT - \frac{1}{f} R3_k \\
\dot{x}_s^p = \dot{x}^p + \dot{R}2_k \\
\dot{y}_s^p = \dot{y}^p + \dot{R}1_k \\
LOD_s = LOD + \frac{\Lambda}{f} \dot{R}3_k
\end{cases}
$$

where f = 1.002737909350795 is the conversion factor of UT into sideral time. Considering LOD = $\Lambda_0 \frac{dUT}{dt}$, □ is homogenous to time difference, so that □ = 1 day in time unit.
Note that the link between EOP and TRF is ensured upon the 3 rotation angles R1, R2, R3, and their time derivatives.

In order to precisely define the datum of the combined frame minimum constraints equations were implemented in CATREF software, allowing to express the combined solution in any external frame. For more details concerning equations of minimum constraints and their practical use, see for instance Altamimi et al., (2003).

Up to now, 10 ITRF versions are available, namely ITRF88, 89, 90, 91, 92, 93, 94, 96, 97 and the latest release, the ITRF2000. For more details about the analysis and results of the ITRF2000, see (Altamimi et al. 2002). Figure 1 shows the coverage of the ITRF2000 sites underlying the collocated techniques. All the ITRF2000 products are available http://lareg.ensg.ign.fr/ITRF/ITRF2000.

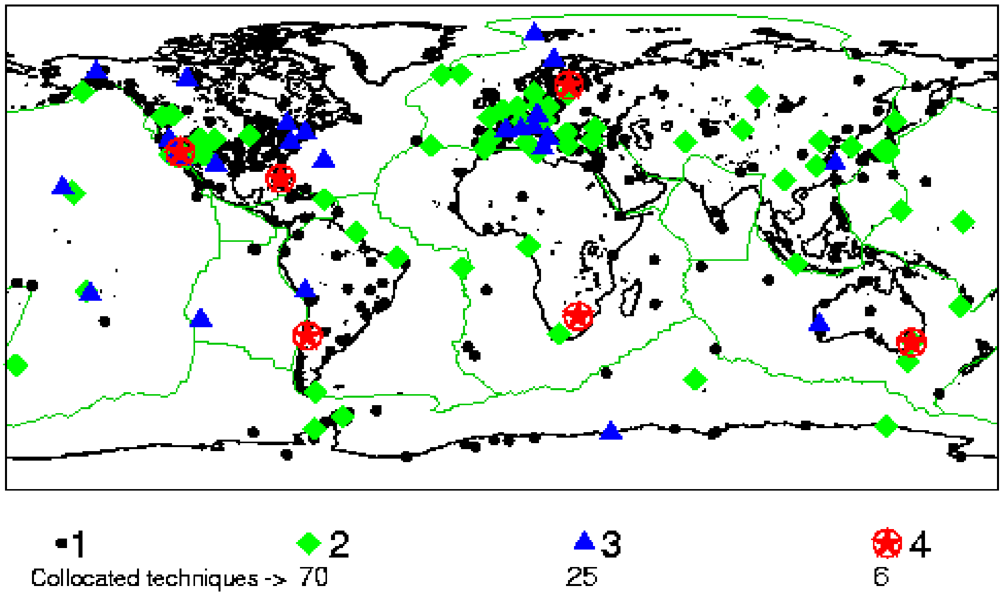

Figure 1: ITRF2000 and collocated sites

As overall quality indicators of the individual solutions included in ITRF2000 combination, the computed WRMS values indicate that a level of 2-5 mm in positions and 1-2 mm/y in velocities is currently reached by some of these solutions (Altamimi et al. 2002). Moreover, about 50% of ITRF2000 station positions have an error of less than 1 cm, and about 100 sites with velocities determined at better 1 mm/y level.
The accuracy of the stability over a decade of the ITRF2000 geocentric origin (defined by SLR) is estimated to be at a few millimeter level and its absolute scale (defined by SLR and VLBI) is around 0.5 ppb (equivalent to a shift of approximately 3 mm in station heights).

2.2 Current Status of Collocation Sites of Space Geodetic Techniques

The sites where stations of the 4 major techniques (VLBI, SLR, GPS, DORIS) are currently operating are illustrated in Figure 2. VLBI and SLR networks each include less than 50 sites. DORIS network is more homogeneous and includes 56 sites. Finally IGS GPS network is containing more than 300 permanent sites. Note on the other hand that there are more than 1000 continuously and permanently observing GPS stations all around the world due to regional denser networks whereas the IGS maintains a global focus. This huge number of GPS permanent stations deployed is due primarily to the low cost and easy installation of this type of equipment, compared to the other techniques.

Figure 3 depicts the number of collocation sites (approximately 72 sites) where stations of the 4 major techniques (VLBI, SLR, GPS and DORIS) are recently operating. While 58 sites are hosting 2 observing techniques, only 12 sites are having 3 techniques (with inhomogeneous distribution over the globe) and, more dramatically, only 2 sites with the 4 techniques.

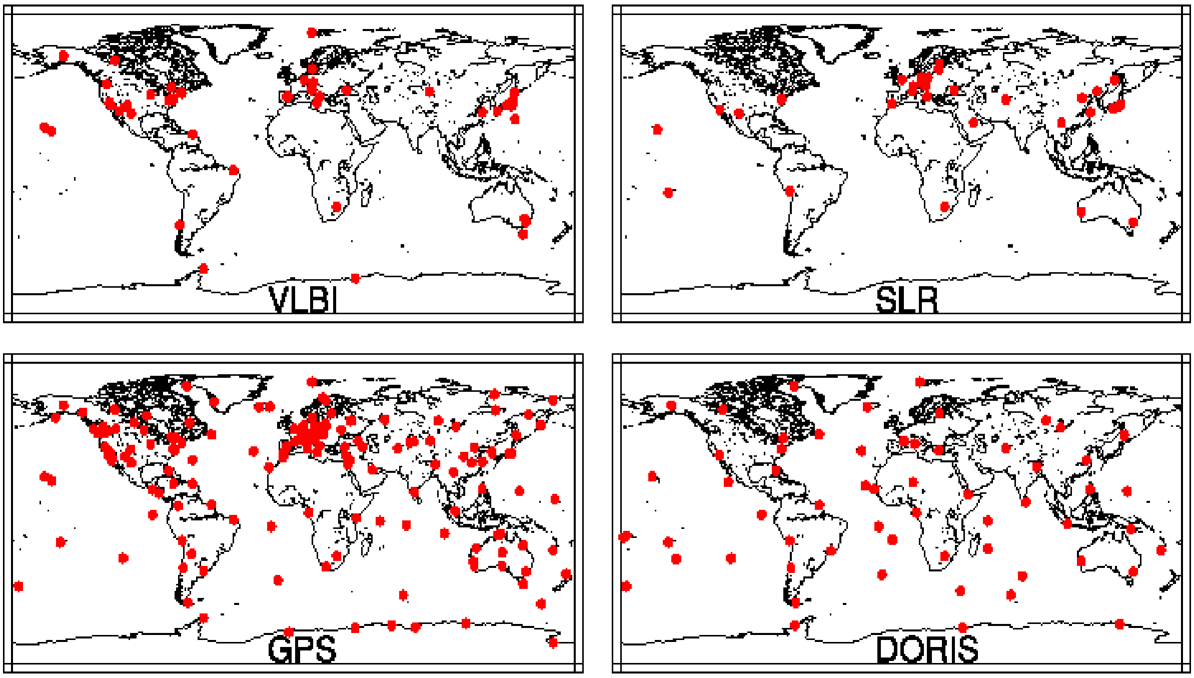

Figure 2: Current operating sites per technique

3. USE OF GPS PERMANENT STATIONS

The tremendous increase of the number of GPS permanent stations over the globe allows a variety of scientific applications. Continuous observations allow geophysical monitoring of tectonic plate motion, deformation, post-glacial rebound and seasonal variations over the Earth surface. From the geodetic point of view, the IGS high quality products based on observations of a permanent network of more than 300 stations allow the use of GPS data for any location to be analysed, holding the satellite orbits and clocks fixed to values published by the IGS. The high level of accuracy and consistency of the IGS products permits autonomous point positioning at the cm-level (Zumberge et al., 1997), thereby disseminating the ITRF without reference to any other specific point on the Earth's surface. This method represents a revolutionary change in the technical means of maintaining and disseminating a high-accuracy reference frame to a global community of users.

One of the main usages of GPS permanent stations is the densification of the ITRF via dense continental networks such as in Europe (EUREF), North America (NAREF), South America (SIRGAS), Antarctica, Asia and Pacific and AFREF being under development. These regional networks, through efforts of the International Association of Geodesy (IAG), and in particular within Sub-commission 1.3, Regional Reference Frames, are the basis of the redefinition, modernization and long-term maintenance of continental and national geodetic systems.

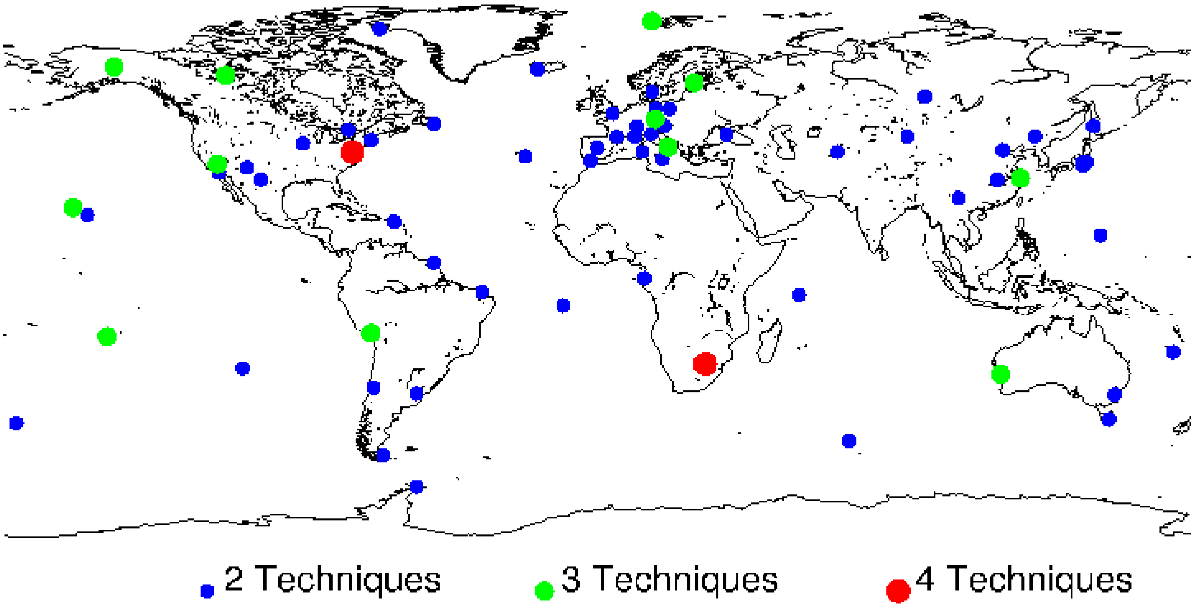

Figure 3: Current collocations of space geodetic techniques (Since 1999)

To illustrate the potential of GPS permanent networks at regional levels, we select here the EUREF Permanent Network (EPN) comprising more than 150 GPS permanent stations (Figure 4), http://www.epncb.oma.be/.

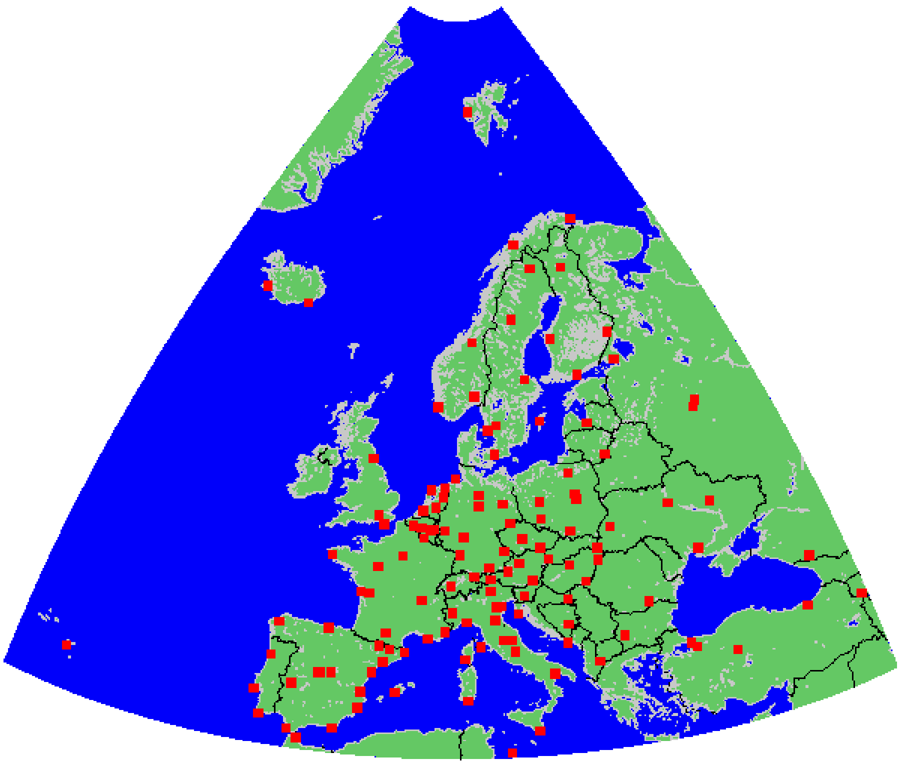

Figure 4: EUREF Permanent Network (EPN)

The EPN is the basis of the long-term maintenance of the European Terrestrial Reference System 1989 (ETRS89). Most of the European countries have or are in the process of adopting the ETRS89 as the basis for their national geo-referencing systems. The ETRS89 is defined in such a way that its realisation should be fixed to (or co-moving with) the stable part of the tectonic Eurasian plate (Boucher and Altamimi, 1992). This definition leads to minimize station velocities expressed in the ETRS89 so that for mapping applications, station coordinates have no significant time variations. However, for geophysical applications such as crust deformation, station velocities should be retained. In that respect, EUREF has set up a project called EUREF Dense Velocity Field for the ETRS89 long-term maintenance allowing to go from somehow static to kinematic realisation. To illustrate this discussion, a global combination of the weekly EPN station positions was performed. The weekly solutions span about 7 years for the most pioneering GPS permanent stations. The output of this time series combination consists of mean station positions at the central epoch of the used observations as well as a European velocity field expressed in ETRS89. Figure 5 illustrates ETRS89 station velocities where the magnitude of some stations may reach 5 mm/y.

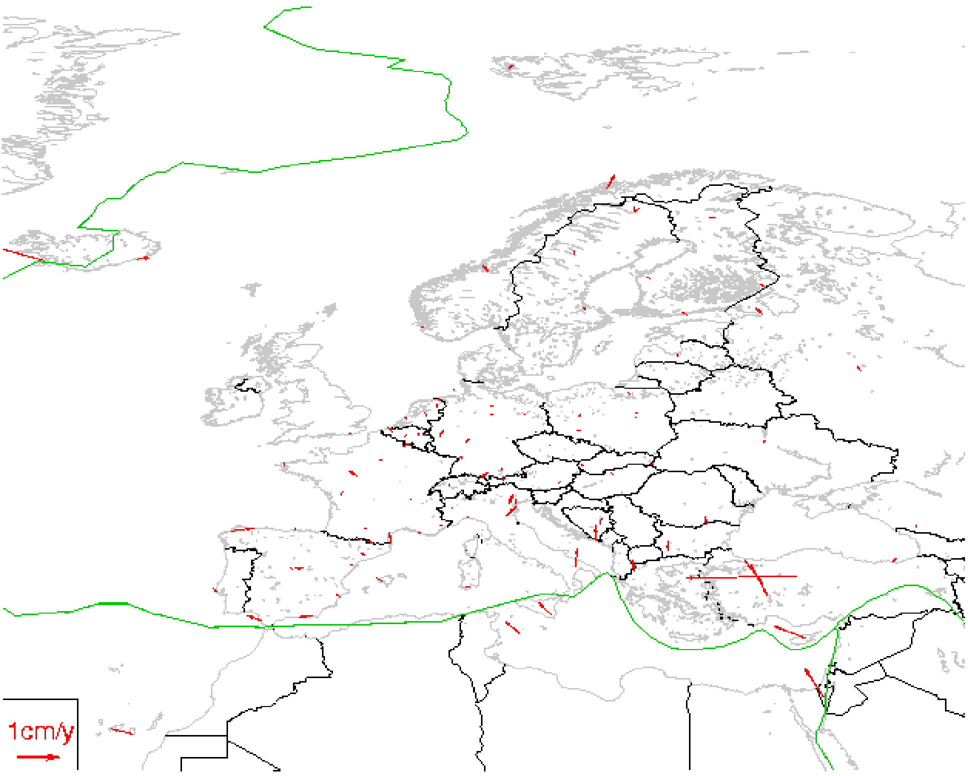

Figure 5: EPN station velocities expressed in the ETRS89

4. FUTURE ITRF SOLUTIONS

Unlike the previous ITRF versions, the future ITRF solutions will be based on time series of station positions and EOPs. Weekly or daily (VLBI) solutions will allow better monitoring of station non-linear motions and other kind of discontinuities in the time series. It in fact frequently happens that some discontinuities in station positions occur after GPS equipment change as shown in Figure 6 where a jump in the vertical component is observed in station Euskirchen, Germany. Some seasonal variations could also occur for some stations as the one illustrated in Figure 7 for station Roquetes in Spain. The discontinuity is usually corrected by estimating two different station positions; one before and one after the event as shown in Figure 6. The seasonal variations are generally modelled and removed by estimating annual amplitude and phase as seen in Figure 7.

The EOP parameters resulting from the future ITRF combinations will be used to recalibrate the current IERS EOP series, so that ITRF and EOP consistency will be ensured.

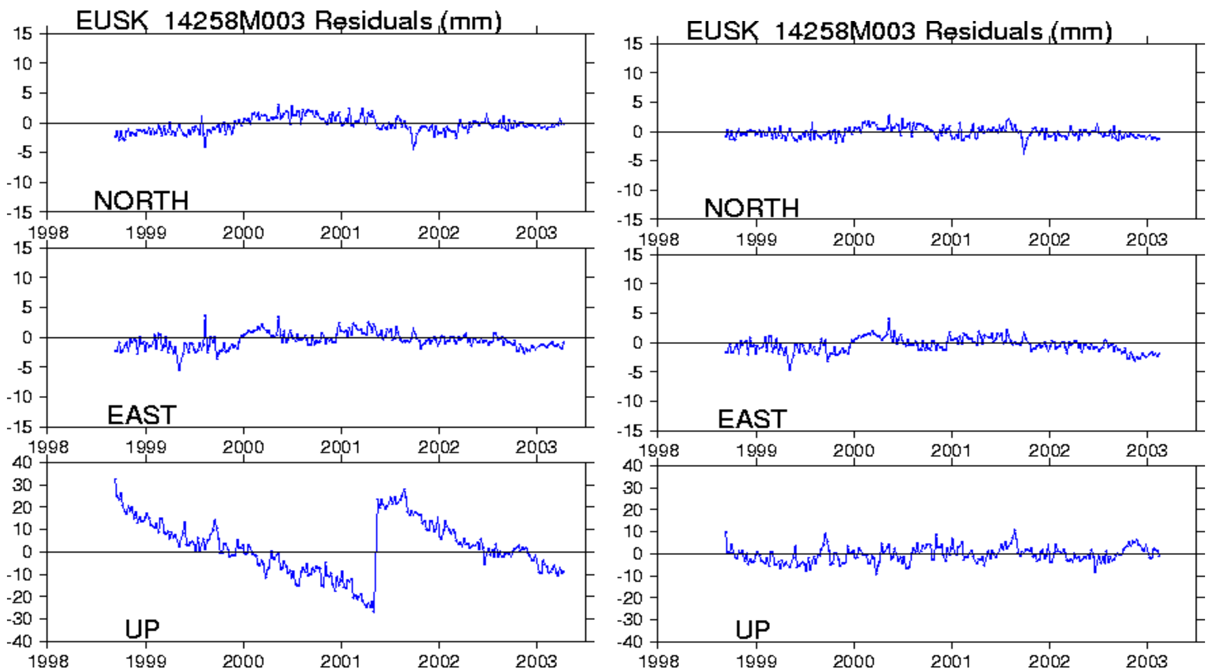

Figure 6: Example of jump in station vertical component (left), corrected (right) by estimating two positions, before and after the event

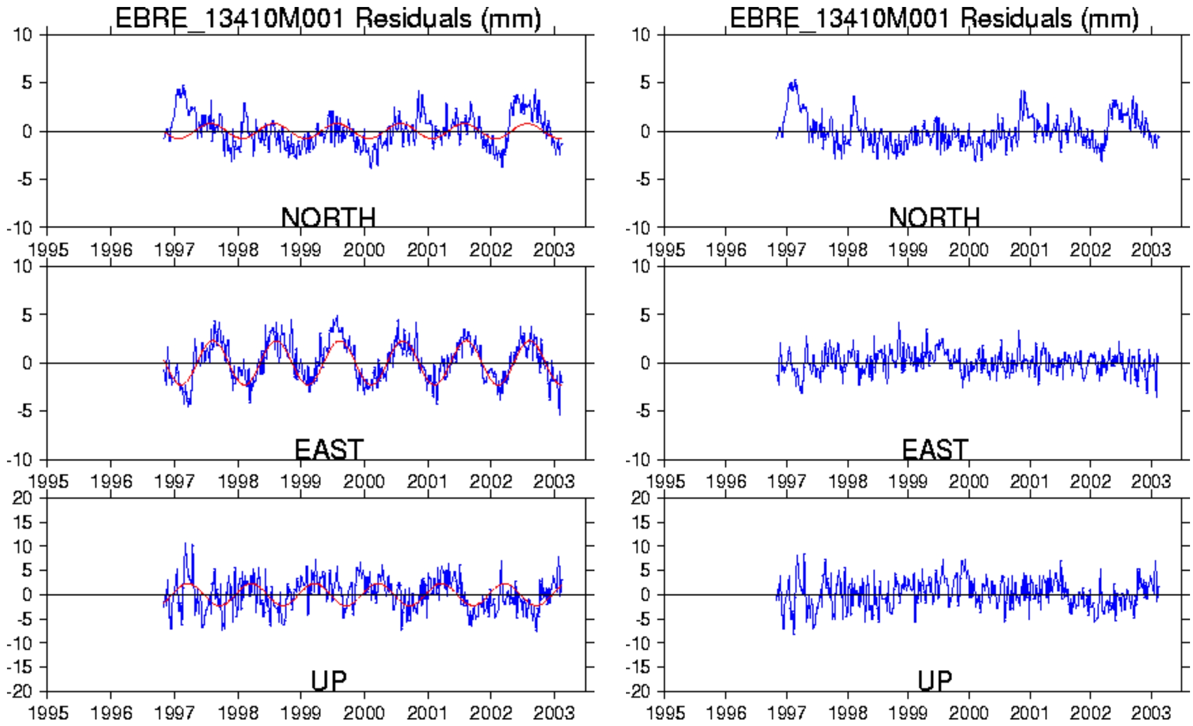

Figure 7: Example of seasonal variations (left), corrected (right) by estimating annual amplitude and phase

To illustrate the outcome of the future ITRF multi-technique combination of station positions and EOPs, we performed a test combination using available time series from VLBI, SLR, GPS and DORIS techniques, using the following data:

- VLBI: 24h-session sinex files over 1990-2003, provided by Goddard Space Flight Center (GSFC) VLBI Group, using the terrestrial reference frame of gsfd001 (IVS, 2003),
- SLR: weekly solutions over 1999-2002, provide by Italian Space Agency (ASI) , (Luceri, 2003),
- GPS: Official IGS weekly combined solutions over 1999-2003 (Ferland, 2003), and JPL weekly solutions over 1996-2002 available at IGS, (Heflin et al., 2003),
- DORIS: IGN-JPL weekly solutions over 1993-2003, by IGN-JPL, (Willis, 2003).

As results of this combination test, Figure 8 shows the polar motion post-fit residuals.

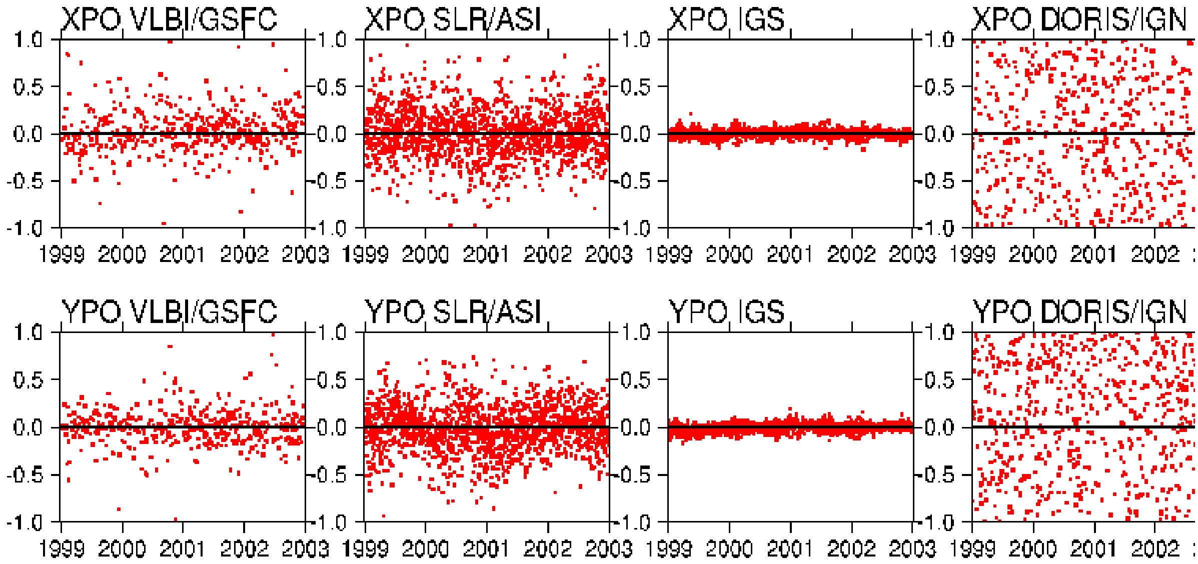

Figure 8: Post fit residual of Polar motion per technique (mas)

The EOP IGS results appear to dominate the other technique results. This is mainly due to the fact that the IGS solution is already a combination of 7 analysis centers, whereas the others are provided from one analysis center per technique. In addition, the IGS EOP estimates are based on continuous observations from more than 300 IGS sites homogenously distributed.

5. AFREF PROJECT

The new IAG structure, approved and adopted at the IUGG/IAG General Assembly held in Sapporo, July 2003, comprises 4 Commissions (replacing the old "Sections"). Commission 1 is called "Reference Frames" and includes 4 Sub-Commissions. The Sub-Commission of interest for AFREF is "1.3 Regional Reference Frames", which takes over the activities of the old "Commission X", and gathers 6 regional sub-commissions, including AFREF. One of the objective of Sub-commission 1.3 is to encourage and stimulate the emerging development of the AFREF project with close cooperation with IGS. Sub-commission 1.3d (Africa) is concerned with definition and realization of a unified continental reference frame (AFREF) for Africa which will be consistent and homogeneous with the global International Terrestrial Reference Frame (ITRF).

In collaboration with the IAG community and its services organisations and the National and Regional Mapping Organisations of Africa, the aims and objectives of Sub-commission 1.3d (Africa) are:

- To define the continental reference system of Africa. Establish and maintain a unified geodetic reference network as the fundamental basis for the national 3-d reference networks fully consistent and homogeneous with the global reference frame of the ITRF;
- To realize a unified vertical datum and support efforts to establish a precise African geoid, in concert with the African Geoid project activities;
- To establish continuous, permanent GPS stations such that each nation or each user has free access to, and is at most 500km from, such stations;

- To provide a sustainable development environment for technology transfer, so that these activities will enhance the national networks, and numerous applications, with readily available technology;
- To understand the necessary geodetic requirements of participating national and international agencies and;
- To assist in establishing in-country expertise for implementation, operations, processing and analyses of modern geodetic techniques, primarily GPS.

For practical effectiveness of AFREF implementation, sub-regional structure is envisaged so that sub-regional reference frames are defined: NAFREF (for North Africa), SAFREF (for Southern Africa), CAFREF (for Central Africa), EAFREF (for East Africa) and WAFREF (for West Africa), all still conforming and compatible with IGS/ITRF specifications. At an ultimate level a combination of these sub-regional reference frame will form the continental AFREF.

6. CONCLUSION

The ITRF, as a global Frame, is the standard reference for all geodetic and Earth science applications. The access to and dissemination of the ITRF for all surveyors is easily achievable through the high quality of IGS products. The use of GPS permanent stations for a variety of geodetic applications allows in particular the densification of the ITRF. They represent the basis of modernisation and long-term stability of continental and national geo-referencing systems. International effort and contribution are needed for the implementation of the African Reference Frame (AFREF) to rise its status to a level comparable to other regional reference frames.

REFERENCES

Altamimi, Z., P. Sillard, and C. Boucher, 2002, ITRF2000: A New Release of the International Terrestrial Reference Frame for Earth Science Applications, *J. Geophys. Res*., 107(B10), 2214,doi:10.1029/2001JB000561.

Altamimi, Z., P. Sillard, and C. Boucher, 2003, ITRF2000: From Theory to Implementation, Proceedings of IAG V Hotine Marussi symposium, In press.

Boucher, C. and Z. Altamimi, 1992, The EUREF Terrestrial Reference System and its first realizations, EUREF Meeting, Bern, Switzerland.

Ferland, R., 2003, Reference Frame Working Group Technical Report, International GPS Service, 2001-2002 Technical Reports.

Heflin,M.B., Y.E. Bar-Sever, D.C. Jefferson, R.F. Meyer, B.J. Newport and Y. Vigue-Rodi, 2003, JPL IGS Analysis center report, International GPS Service, 2001-2002 Technical Reports.

Luceri, 2003, SLR weekly solutions over 1999-2002 from the Italian Space Agency, personal communication.

Willis, P., Bar-Sever, Y.E., Tavernier, G., 2003. DORIS as a potential part of a Global Geodetic Observing System, IAG Symposium G07, Sapporo, Japan.

Zumberge, J.F., M.B. Heflin, D.C. Jefferson, M.M. Watkins, and F.H. Webb, 1997, Precise point positioning for the efficient and robust analysis of GPS data from large networks, J. Geophys. Res., 102, 5005-5017.

BIOGRAPHICAL NOTES

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