IGS

ANALYSIS CENTER REPORTS

2000 Analysis Coordinator Report

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Introduction

Similar to the year before this report complements the Analysis Activities Report given in the IGS Annual Report 2000 (Weber, Springer, 2001). A summary of the most important changes and topics of the IGS Analysis Activities in 2000 will be presented, complemented by a huge number of figures focusing on the combination statistics of orbits, clocks and ERPs. Most of this figures are freely accessible and can be retrieved from the IGS ACC web-page at http://www.aiub.unibe.ch/acc.html.

Current IGS and AC product quality

The primary objective of the IGS is to provide a Reference System for a wide variety of GPS applications. To fulfil this role the IGS produces a large number of different combined products which constitute the practical realization of the IGS Reference System. Table 1 gives a brief overview of the estimated quality of these different IGS Reference Frame products at the beginning of the year 2001.

Table 1: Quality of the IGS Reference Frame products as of March 2001 (for details see http://igscb.jpl.nasa.gov/components/prods.html)

Products Delay	Predicted Real Time	Ultra-Rapid Real Time	Rapid 17 hours	Final 13 days	Units
Orbit	50.0	25.0	5.0	< 5.0	cm
Clock	150.0	5.0	0.2	0.1	ns
Polar Motion	(note: delivery		0.2	0.1	mas
LOD	of IGP–products		30.0	20.0	μs/d
Stations h/v	terminated in			3.0/6.0	mm
Troposphere	March 2001)			4.0	mm ZPD

The quality improvement of the IGS products since 1994 has been demonstrated in the IGS Annual Report 2000. Figure 1 shows the weighted orbit RMS (WRMS) of the Final Analysis Centre solutions with respect to the combined IGS final orbit products in 2000. Most Analysis Centres and also the IGS rapid orbit products have reached the 3-6 centimeter orbit precision level (Table 2). Similar levels of accuracy are indicated by the IGS 7-day arc orbit analysis and by comparisons with satellite laser ranging observations of the GPS satellites PRN 5 and 6. Figure 3 is related to the IGS rapid orbit combination.

The orbit consistency is about 5-8 cm, which is a quite small number having in mind the latency of only 17 hours and subsequently the lower amount of available tracking data. The yearly averages of weighted orbit RMS values of the Rapid Analysis Centre submissions with respect to the IGS Rapid combination (IGR) are also shown in Table 2.

Table 2: Yearly average weighted orbit RMS (cm) of the Final Analysis Center orbit submissions and the IGS Rapid (IGR) orbit solution with respect to the IGS final orbits + Yearly average weighted orbit RMS (cm) of the Rapid Analysis Center submissions with respect to the IGS Rapid orbit combination.

Year	COD	EMR	ESA	GFZ	JPL	NGS	SIO	IGR
Fin 2000	3	7	6	3	3	9	5	3
Rap2000	5	14	9	6	9	12	7	--

Figures 6-20 illustrate the time series of Helmert Transformation Parameters between the individual center submissions and the combined orbits, both for the Final and the Rapid IGS orbit.

Reference Frame

The most striking change in the implementation of the reference frame was the alignment of the IGS final orbit products to the IGS reference frame realization (based on a set of about 50 stations), starting with GPS week 1051. IGS reference frame products are available in SINEX format and issued by the IGS Reference Frame Coordinator on a weekly basis. The alignment ensures product consistency but delays the calculation and distribution of the combined orbits for an additional day (13 days after end of GPS-week). Detailed information may be inferred from (Kouba, Ray and Watkins, 1998), (Ferland, 2001) or from the weekly IGS Sinex Combination Reports (e.g. Ferland, Hutchison, 2001). The IGS realization of the ITRF97 has been labelled IGS97. An update of the ITRF (ITRF2000) and subsequently for the accompanying IGS realization (IGS00) is planned for end of December 2001.

Ultra Rapid Products

In September 2000 the IGS Analysis Center workshop was held at the U.S. Naval Observatory in Washington D.C. Current progress in carrier phase time transfer and the realization of an internal IGS time scale had been identified as major goals in this meeting. Furthermore, as proposed in a position paper by G.Gendt et al. the year before, IGS products have to move towards real-time availability. Thus this workshop discussed the quality of the recently implemented Ultra-Rapid products as well as their applications, e.g. for the derivation of ground-based GPS meteorological parameters used in numerical weather prediction.

In October 1999 the first Analysis Centre (GFZ) provided the new ultra rapid products. These products, delivered every 12 hours (two times per day), will contain a 48 hour orbit arc from which 24 hours are real orbit estimates and 24 hours are orbit predictions. The latency of this product is 3 hours. The generation of a combined ‘ultra-rapid’ product (IGU) has started in March 2000 based on contributions from up-to five different Analysis Centres. This product has been made available for real-time usage, like the IGS predicted orbits (IGP), but the quality is significantly better because the average age of the predictions was reduced from 36 to 9 hours. The next months the quality and the reliability of the IGS Ultra rapid (IGU) orbits were assessed against the IGS Predicted (IGP) and the IGS Rapid (IGR) products. Figure 5 shows a consistency of the individual orbit submissions at the 25 cm level during the year 2000 and figures 21-27 deliver the related series of Helmert Transformation Parameters with respect to the IGS Rapid orbits. Currently seven different Analysis Centres deliver contributions to the ultra-rapid products.

In November 2000 the IGU products became an official IGS product and subsequently the submission of predicted orbits (IGP) could be terminated in March 2001 (Wk 1105). Figures 28a,b show the year-2000 time series of Helmert Transformation Parameters of the IGS Predicted Orbits with respect to the IGS Rapid orbits.

Clock Combination

A new station and satellite clock combination, which is based on the RINEX clock format, has been implemented in November 2000 (about Wk 1088). This combination provides the regularly combined satellite clocks in the orbit (SP3) format and it also provides both satellite and station clocks in the RINEX clock format. These clock products have a sampling rate of 5 minutes, compared to the 15 minutes in SP3. Some Analysis Centres even provide higher sampled clock products, e.g., JPL provides clocks with a sampling rate of 30 sec. The new clock combination is distinguished by the high quality of the provided clocks and it has improved the robustness of the combination process tremendously by handling clock jumps. Figures 2 (IGS final) and 4 (IGS Rapid) illustrate impressively the considerable improved consistency of the submitted AC clock solutions at the 0.1 nsec level after implementation of the new clock combination in week 1088.

Summary and Outlook

Contrary to widely expressed concerns, the increasing ionospheric activity did not really harm IGS operations in 2000. Nevertheless, the policy of phasing out an old generation of GPS-receivers at the IGS sites and their replacement by updated technology has to be pursued continuously.

Logically the goal of IGS analysis groups is to further improve accuracy and consistency of IGS products. Besides these ongoing efforts there are a few special challenges like the clarification of remaining radial orbital biases with respect to orbit determination of GPS satellites based on SLR tracking data. Another challenge is of course the complete integration of GLONASS tracking data into IGS operations and analysis.

On July 15, 2000 the 'Challenging Minisatellite Payload for Geophysical Research and Application (CHAMP)' has been launched. CHAMP and the number of upcoming LEO missions have the potential to fundamentally increase the demands on IGS-products as we know it today. In this context the generation of more frequent IGS products for near real-time use is an urgent need. Near real time products as well as orbit predictions are also a topic in view of the increasing number of RT surveying applications. Therefore the next IGS Analysis workshop in Ottawa is dedicated to real-time requirements and IGS real-time products.

Last but not least its my pleasure to acknowledge my predecessor Tim A.Springer, who left the position of an IGS AC Coordinator in December 2000 for his efforts and his continuous support. He was heavily involved in most of the activities described above, especially in establishing the new clock combination and in launching smoothly the Ultra Rapid Products.

References

Ferland, R. (2001). IGS Reference Frame Coordination and Working Group Activities, in IGS Annual Report 2000,pp. 24-27.

Ferland, R., D. Hutchison (2001). *IGSREPORT-8898, Wk 1144 IGS SINEX Combination.*

Kouba, J., J.R. Ray and M. Watkins (1998). *IGS Reference Frame Realisation,* in *Proceedings of the 1998 IGS Analysis Center workshop,* pp. 139-172.

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Weber, R., T.A. Springer (2001). *Analysis Activities,* in *IGS Annual Report 2000,* pp. 14-17.

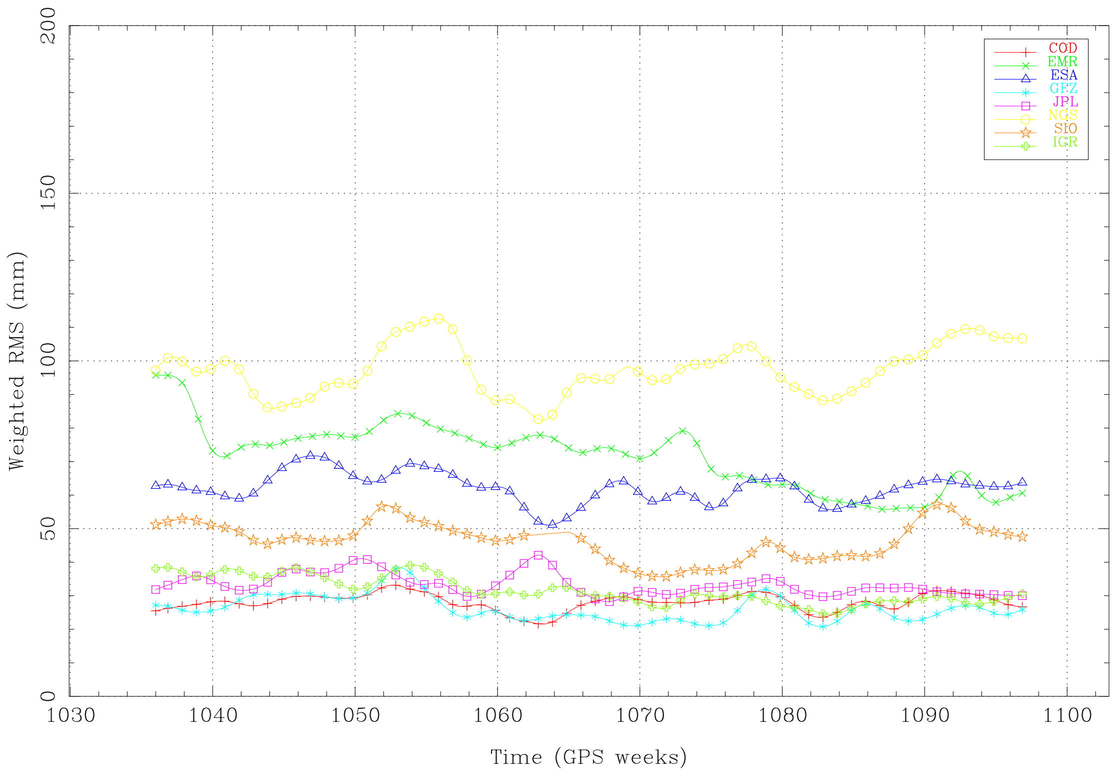


Figure 1: Weighted orbit RMS(mm) of the Final AC submission w.r.t the IGS Final combination.

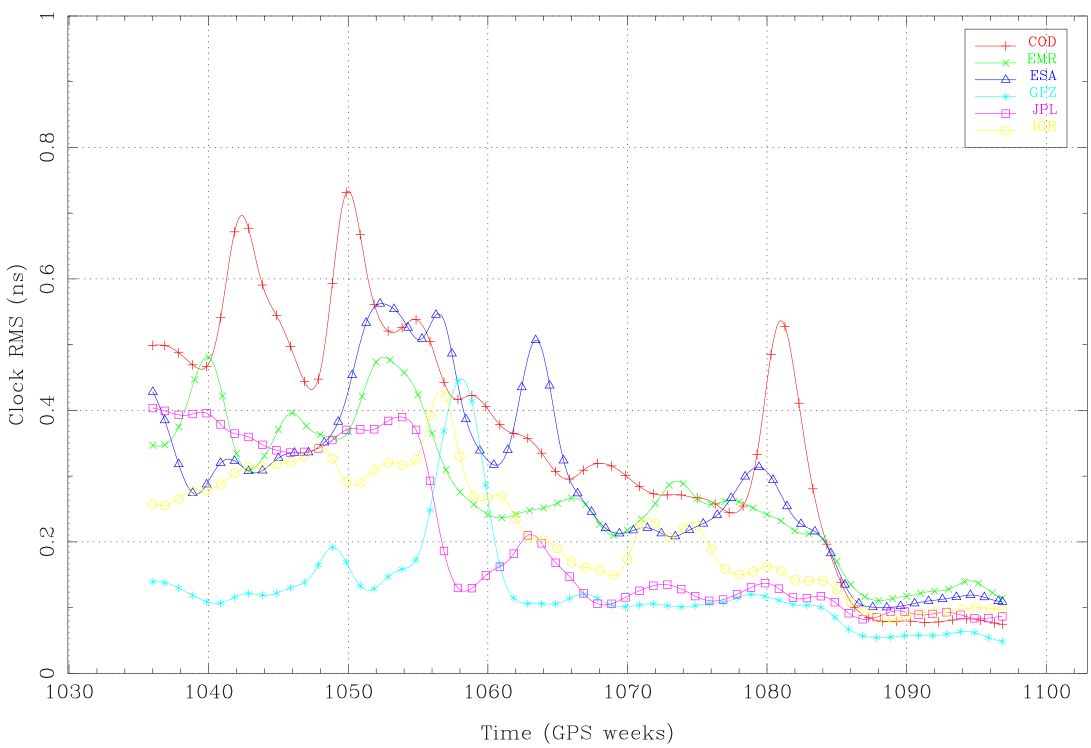


Figure 2: Weighted clock RMS(ns) of the Final AC submission w.r.t the IGS Final combination.

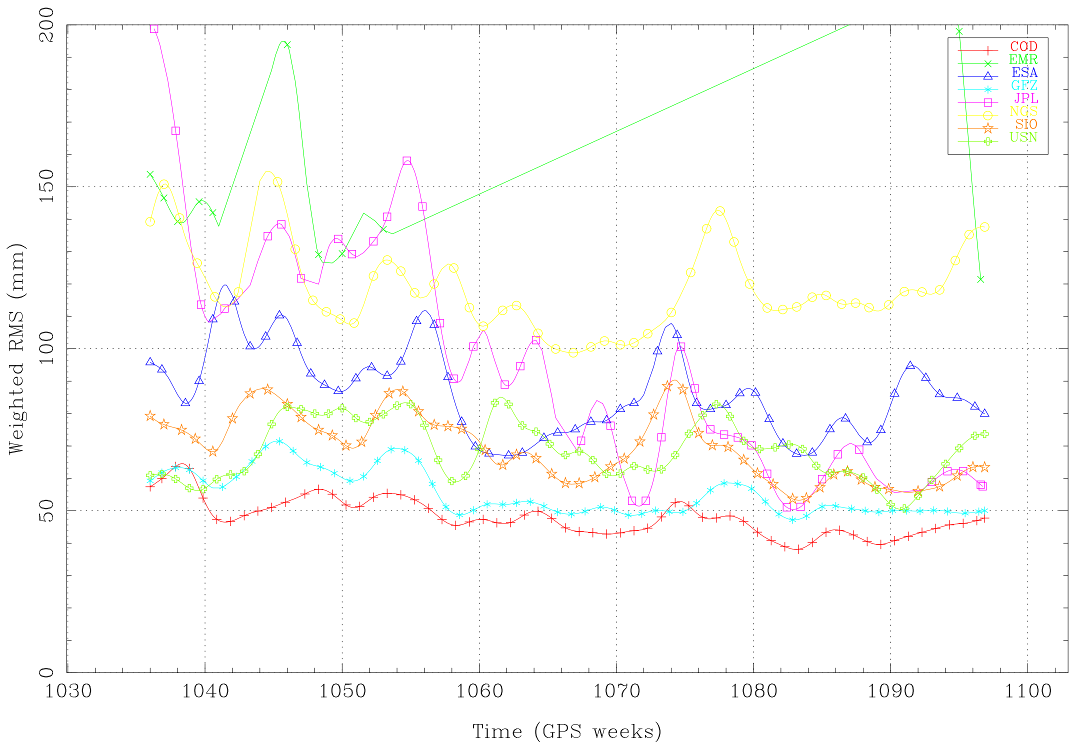


Figure 3: Weighted orbit RMS(mm) of the Rapid AC submission w.r.t the IGS Rapid combination The daily RMS values of the combination summaries were smoothed for plotting purposes, using a sliding 7 day window.

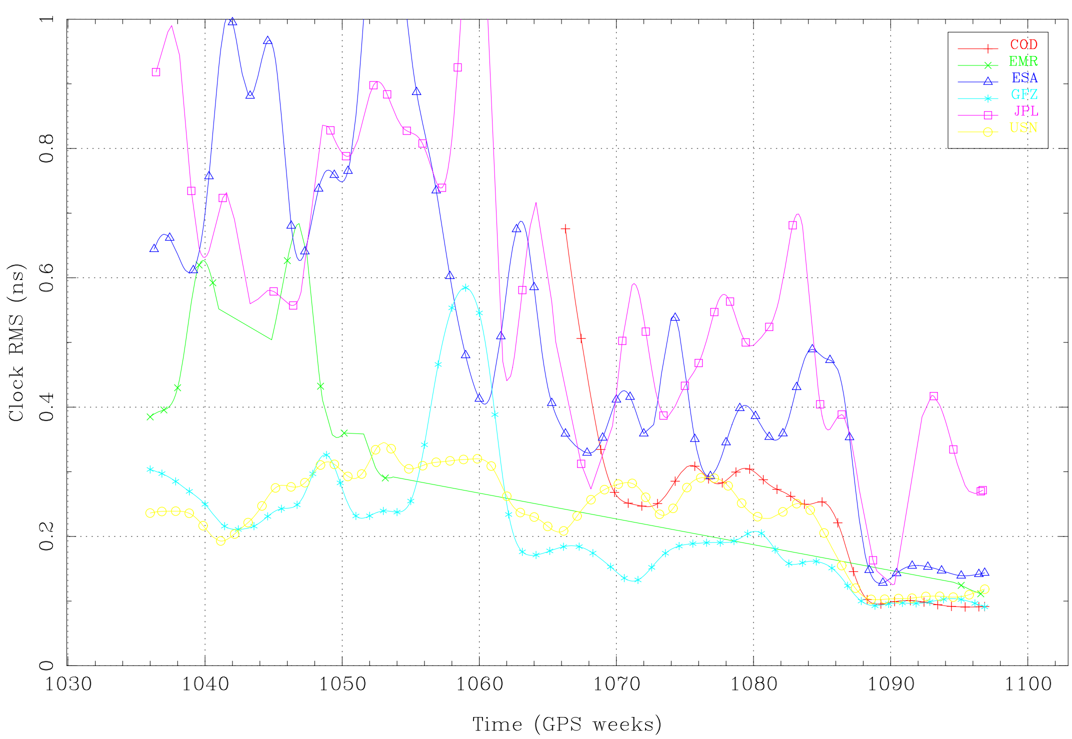


Figure 4: Weighted clock RMS(ns) of the Rapid AC submission w.r.t the IGS Rapid combination. The daily RMS values of the combination summaries were smoothed for plotting purposes, using a sliding 7 day window.

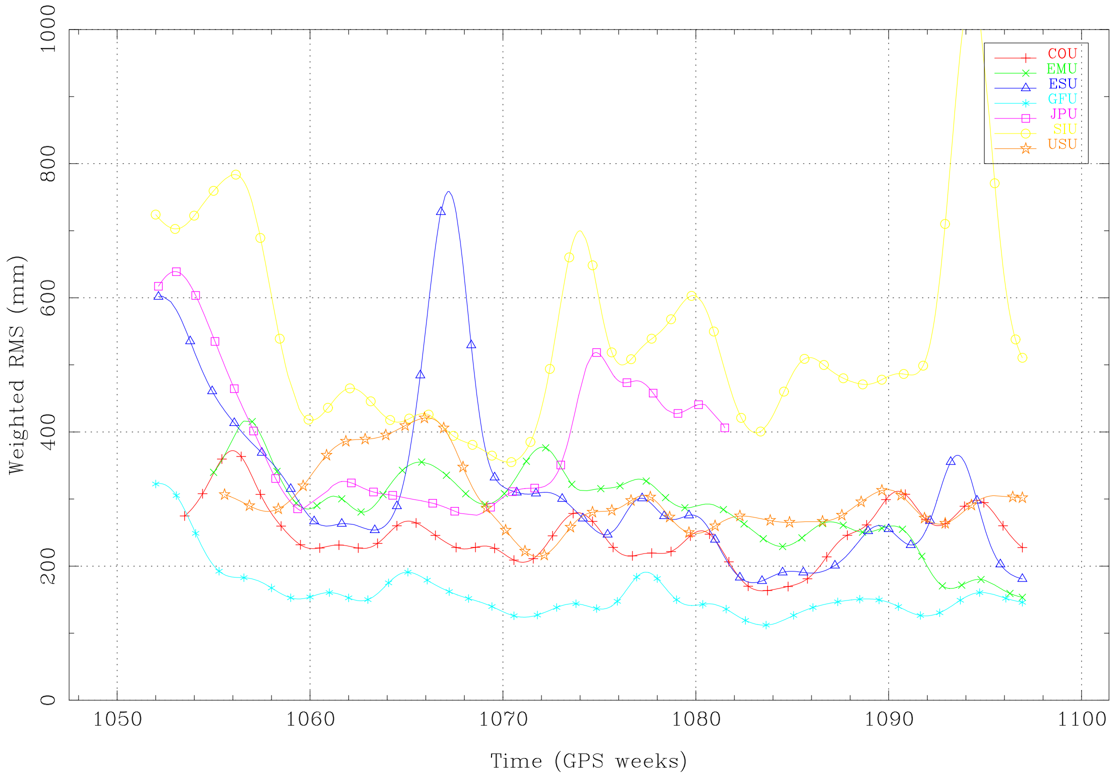
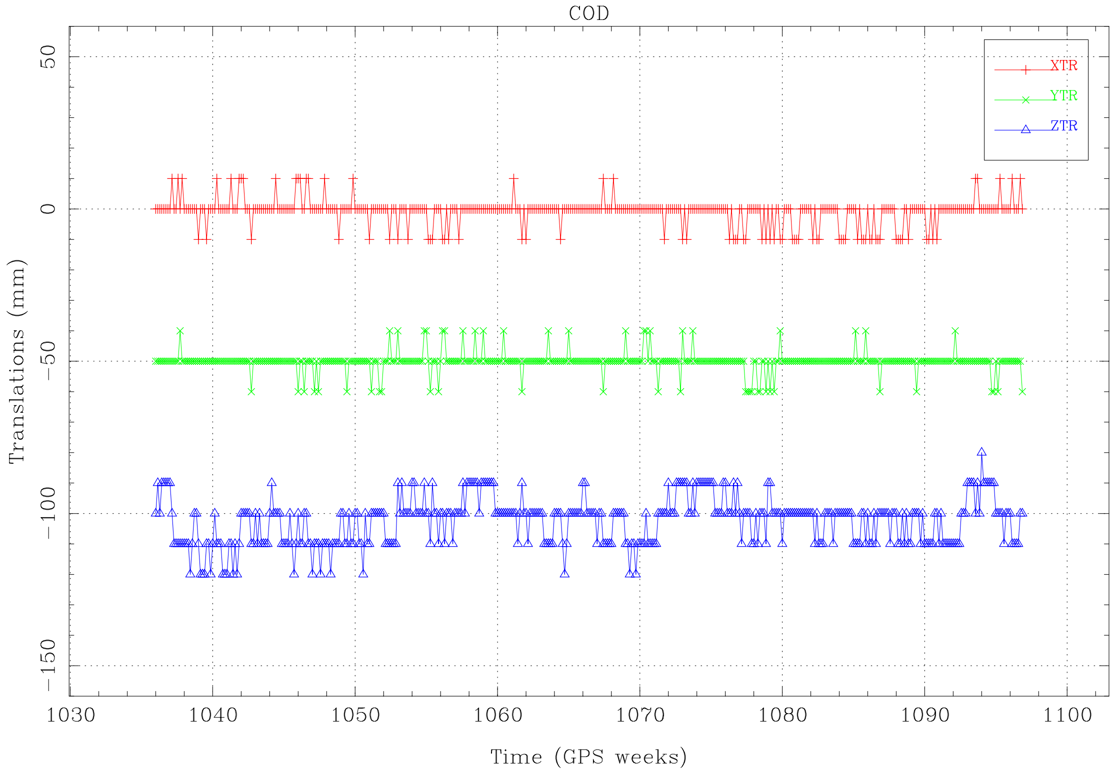
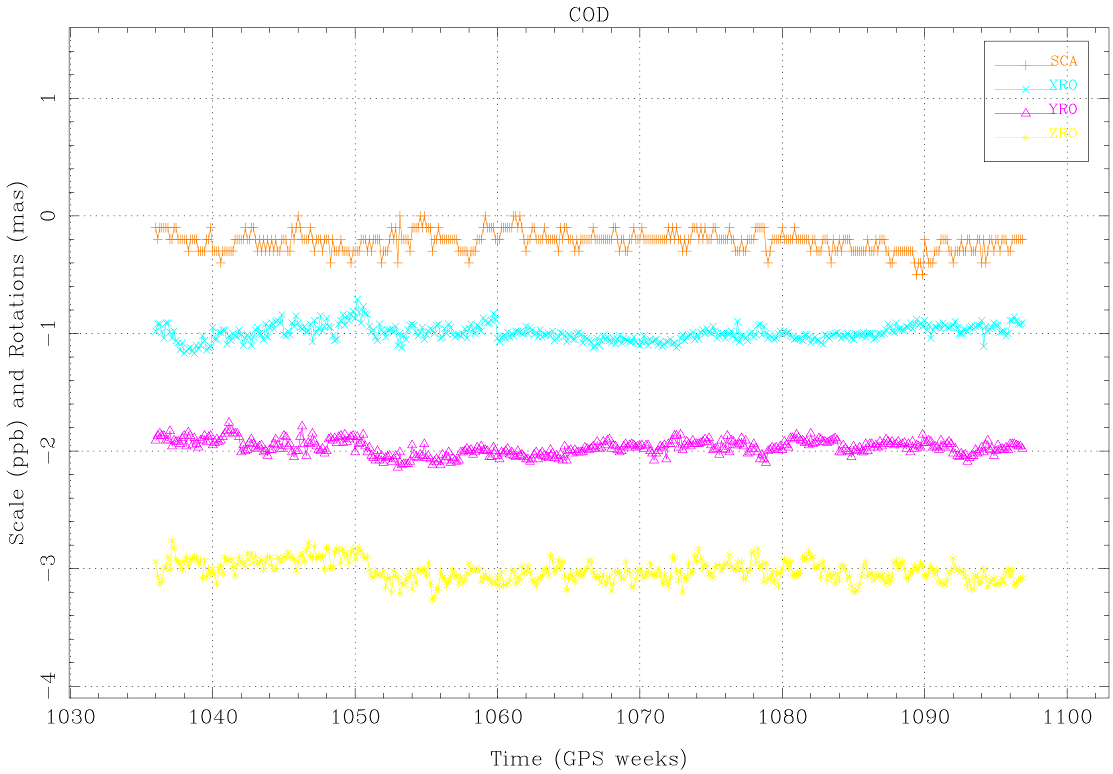
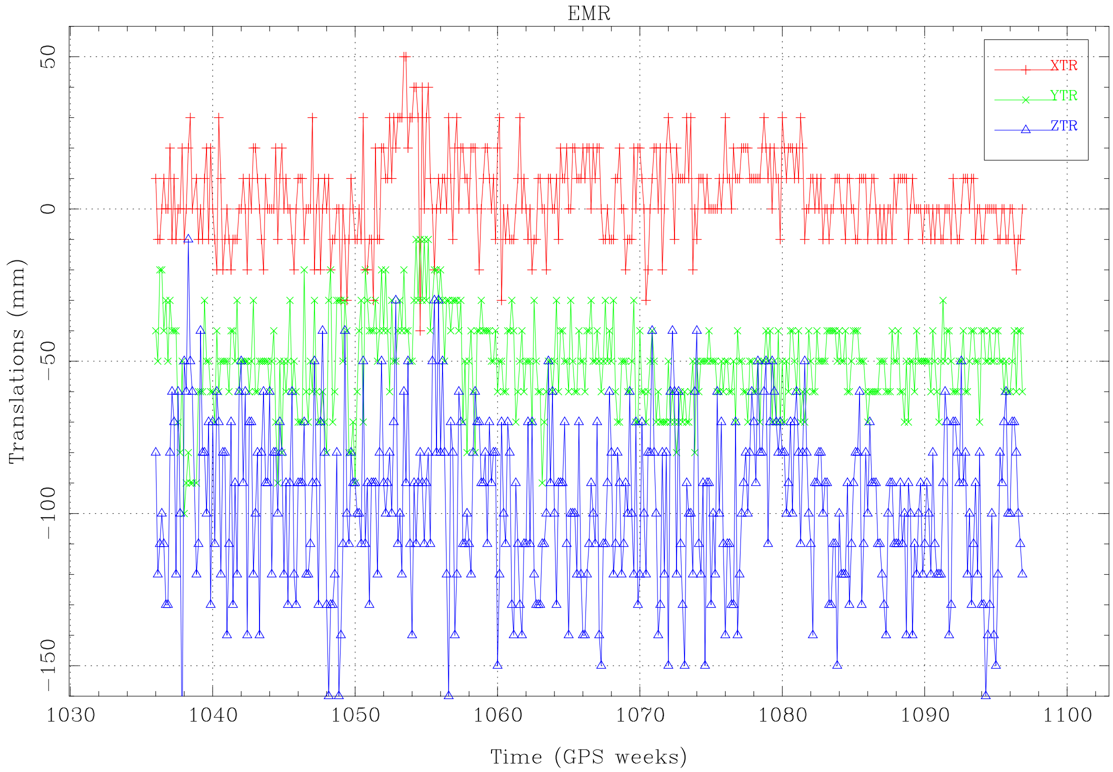


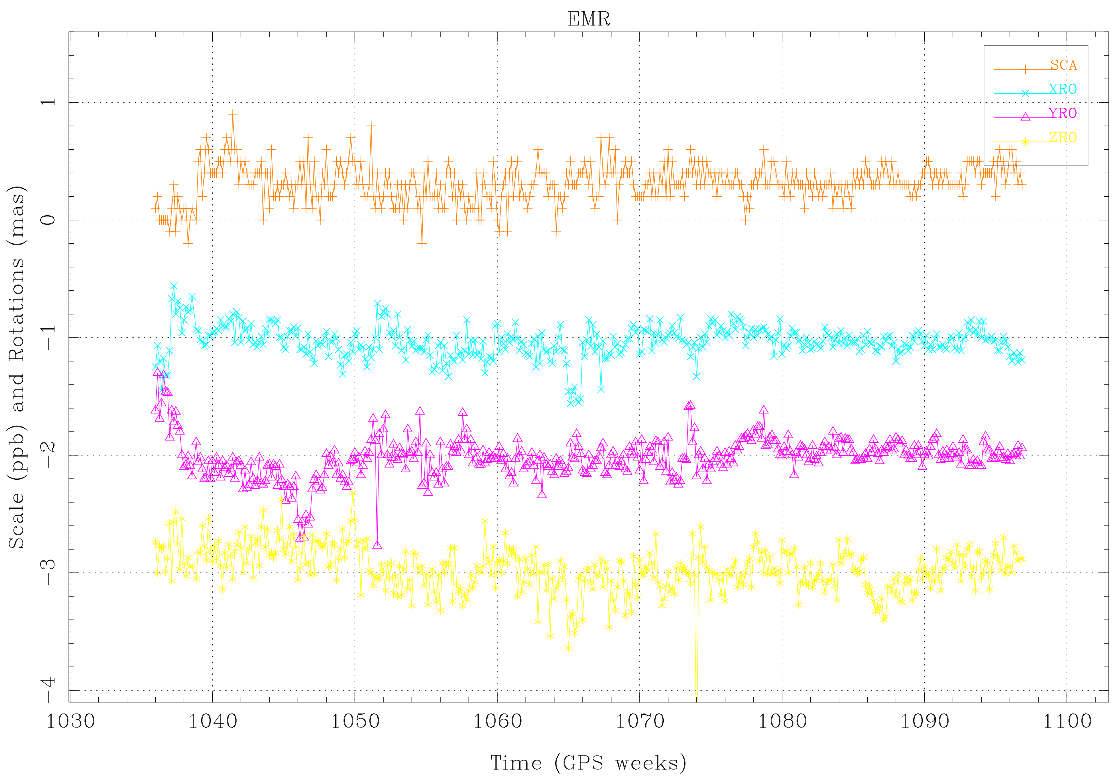
Figure 5: Weighted orbit RMS(mm) of the Ultra Rapid AC submission w.r.t the IGS Ultra-Rapid combination The RMS values of the combination summaries (twice per day) were smoothed for plotting purposes, using a sliding 7 day window.



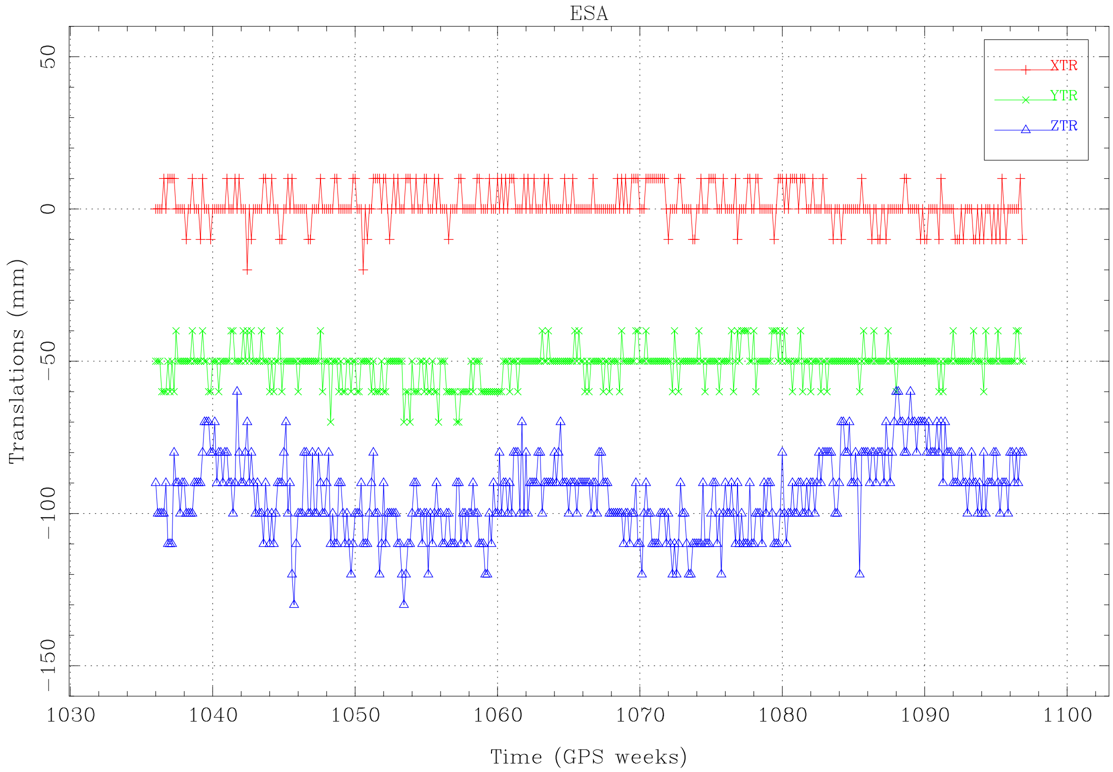


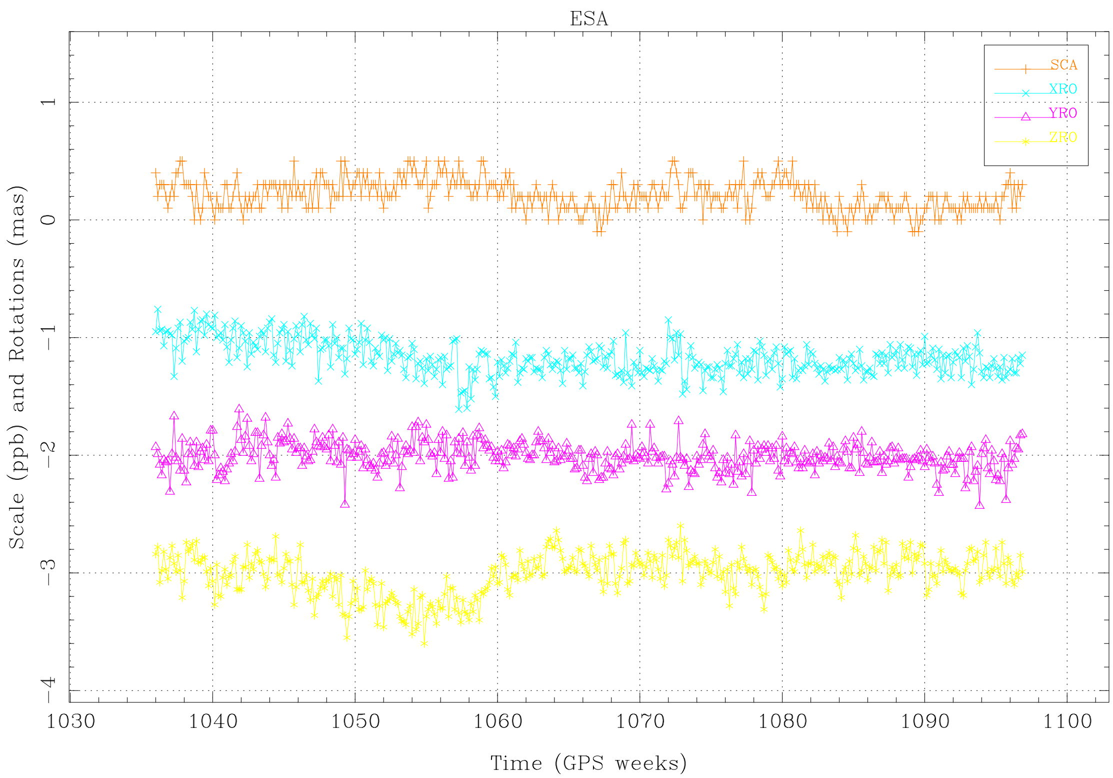
Figures 6a,b: Daily Transformation parameters of the COD Final orbits w.r.t. the IGS Final orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



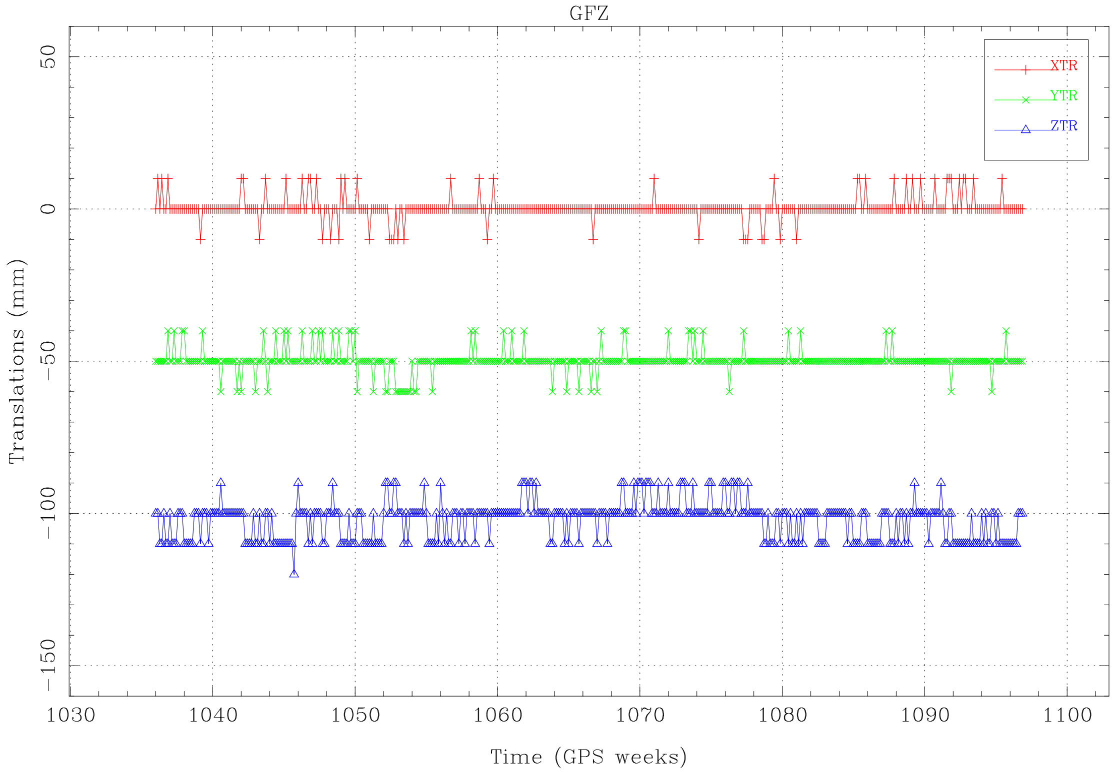


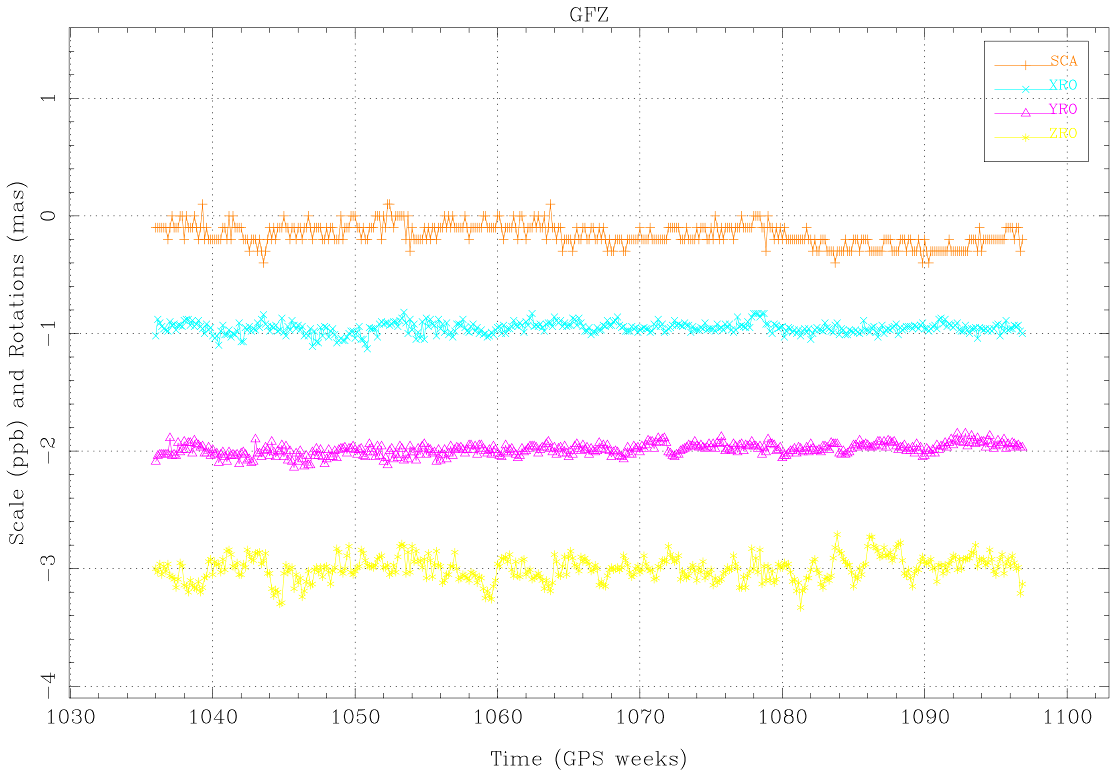
Figures 7a,b: Daily Transformation parameters of the EMR Final orbits w.r.t. the IGS Final orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



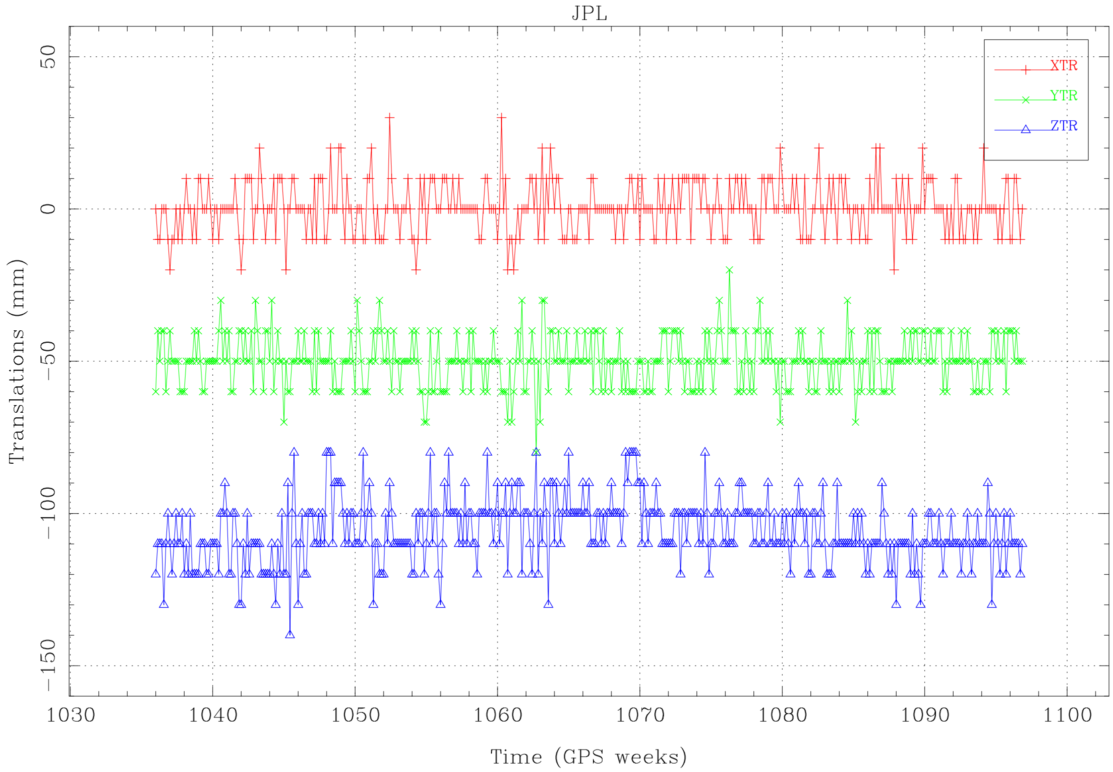


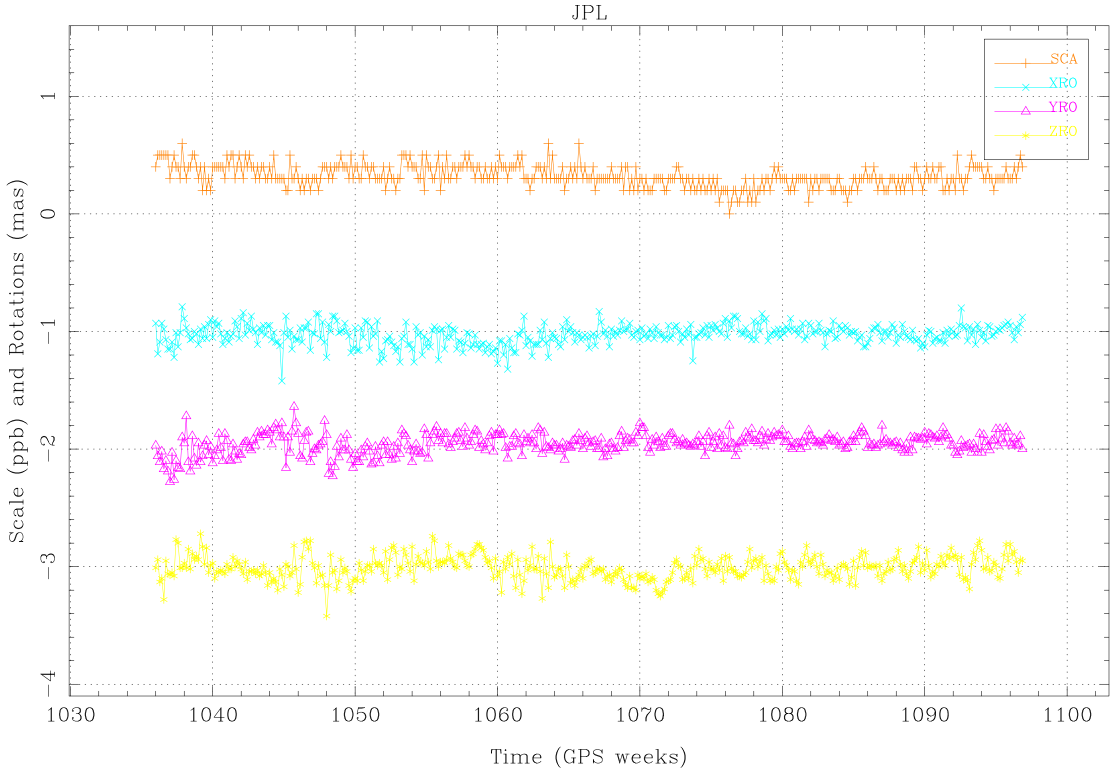
Figures 8a,b: Daily Transformation parameters of the ESA Final orbits w.r.t. the IGS Final orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



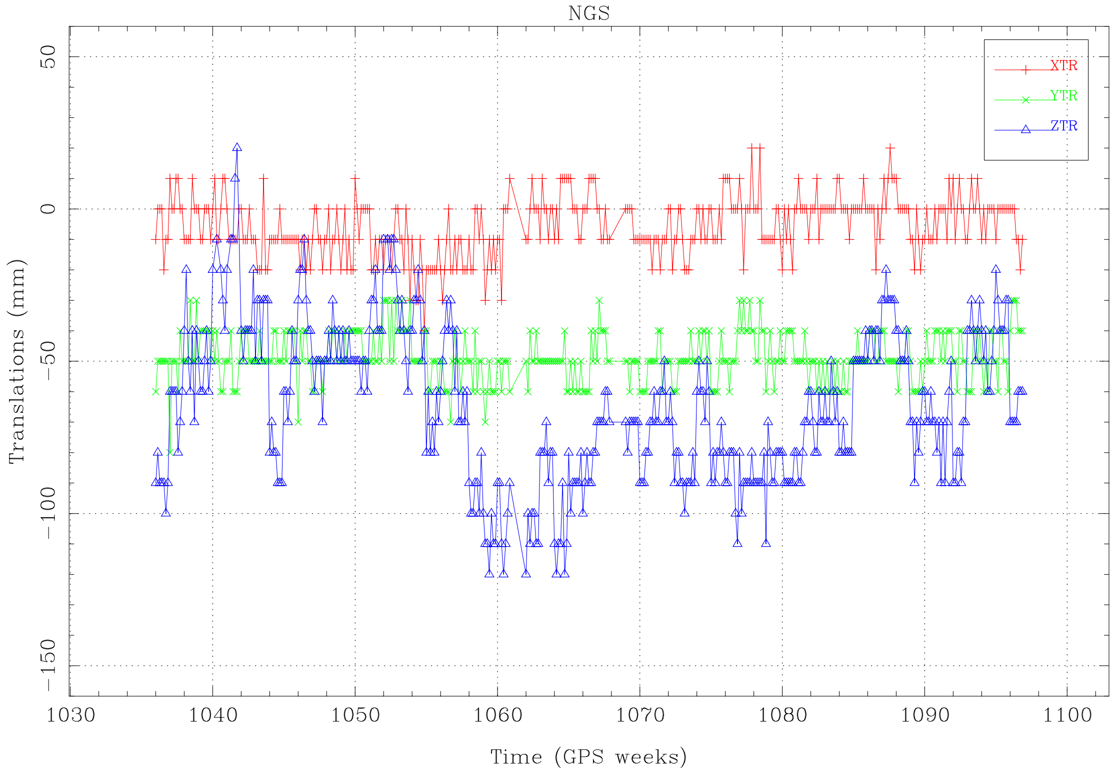


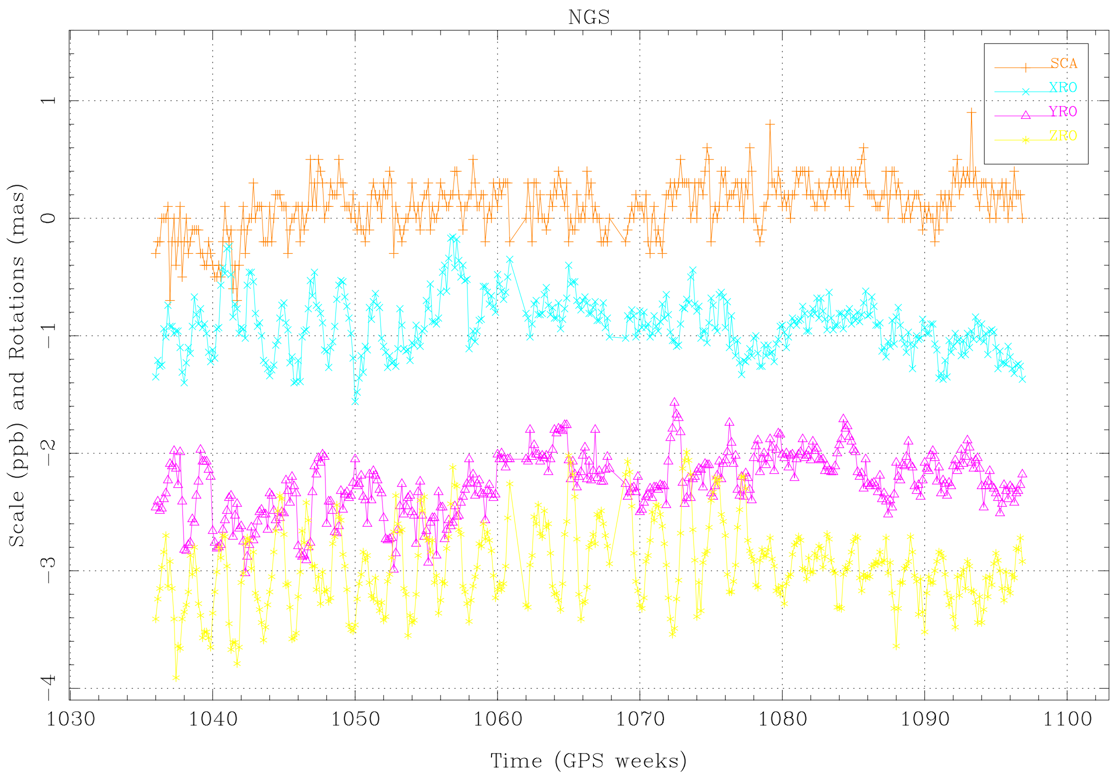
Figures 9a,b: Daily Transformation parameters of the GFZ Final orbits w.r.t. the IGS Final orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



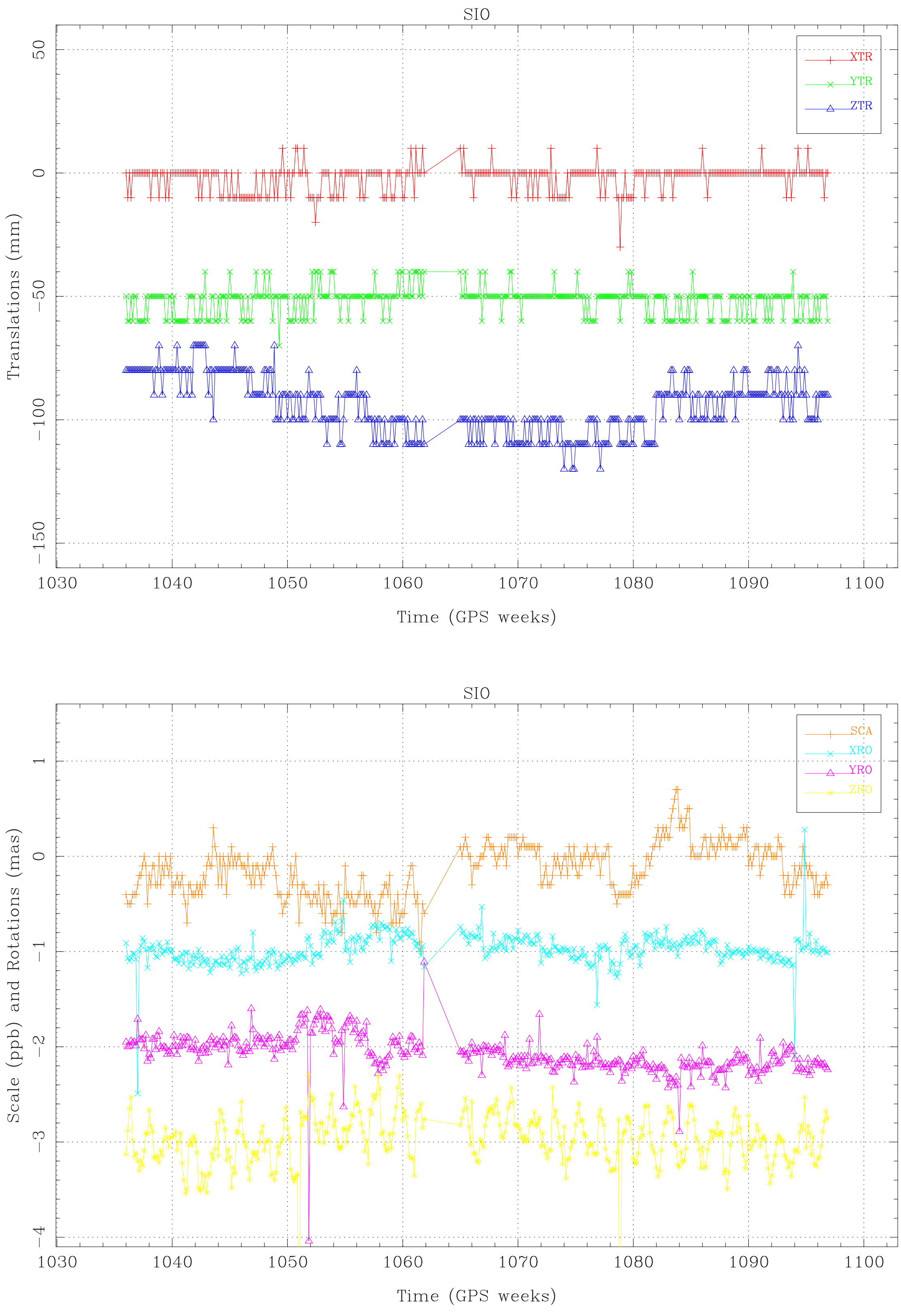


Figures 10a,b: Daily Transformation parameters of the JPL Final orbits w.r.t. the IGS Final orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.

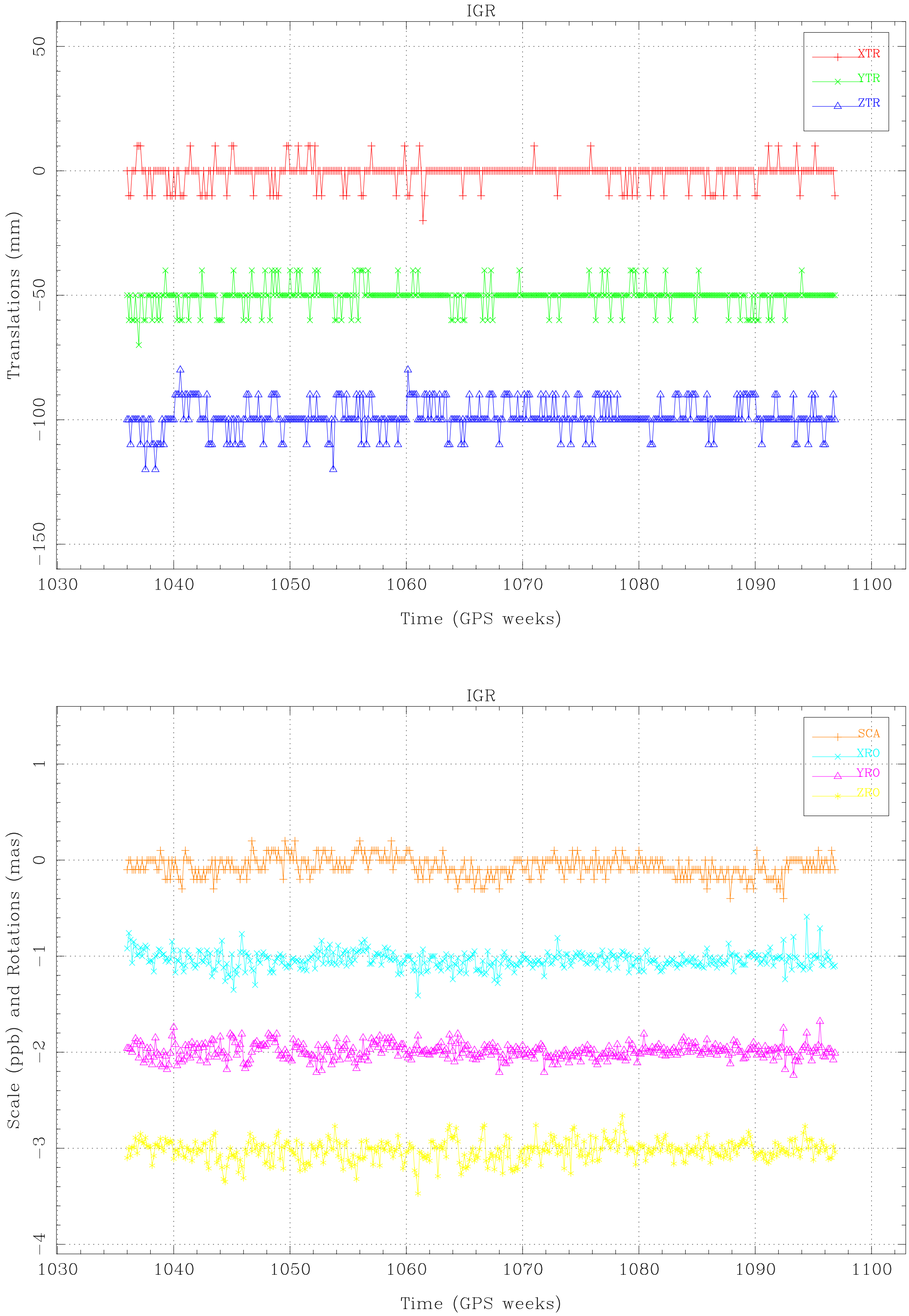




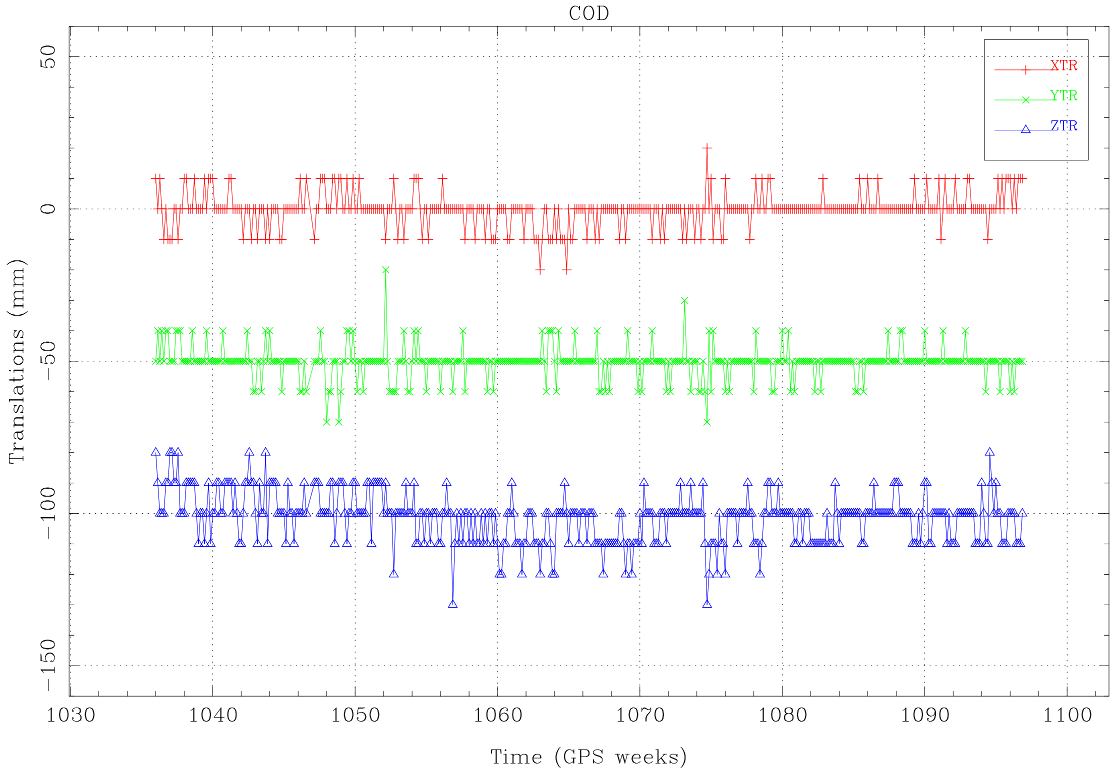
Figures 11a,b: Daily Transformation parameters of the NGS Final orbits w.r.t. the IGS Final orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.

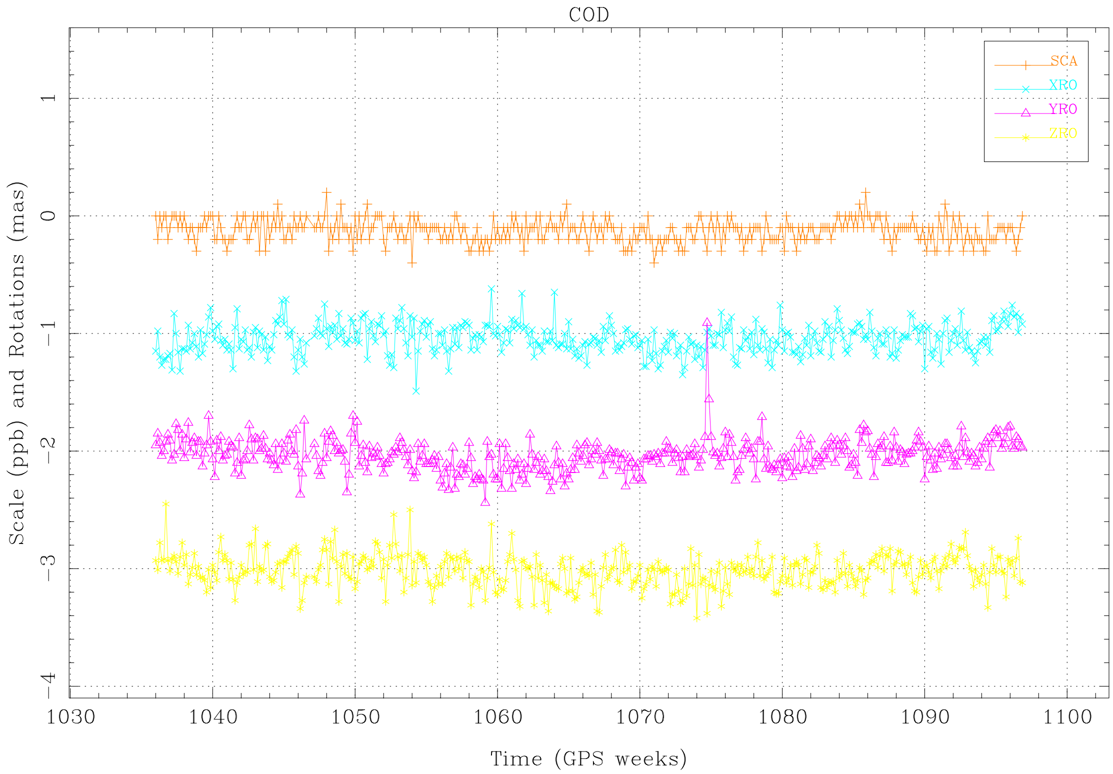


Figures 12a,b: Daily Transformation parameters of the SIO Final orbits w.r.t. the IGS Final orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.

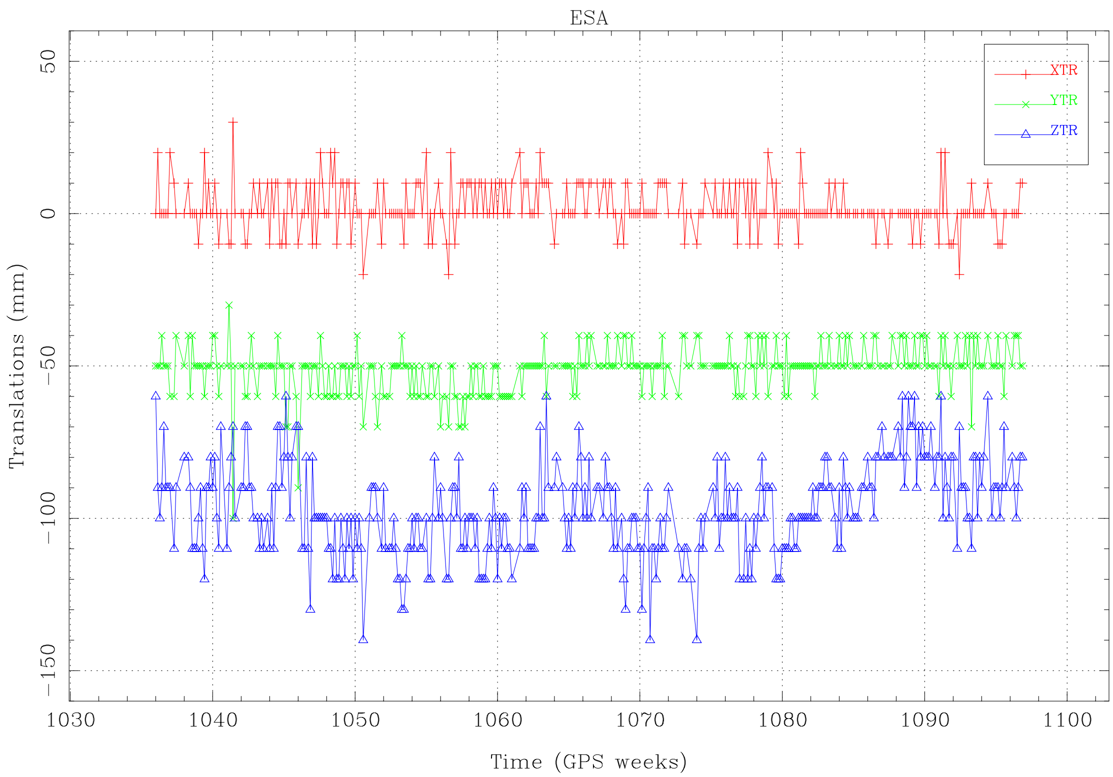


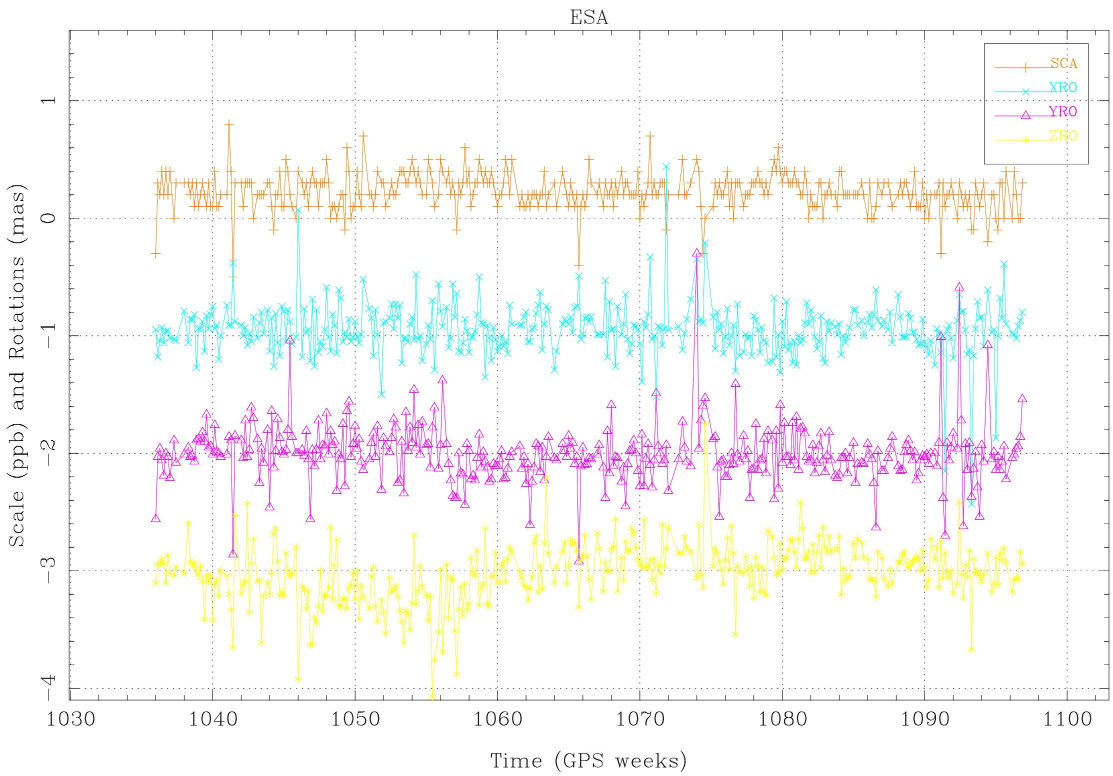
Figures 13a,b: Daily Transformation parameters of the IGS Rapid orbits w.r.t. the IGS Final orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



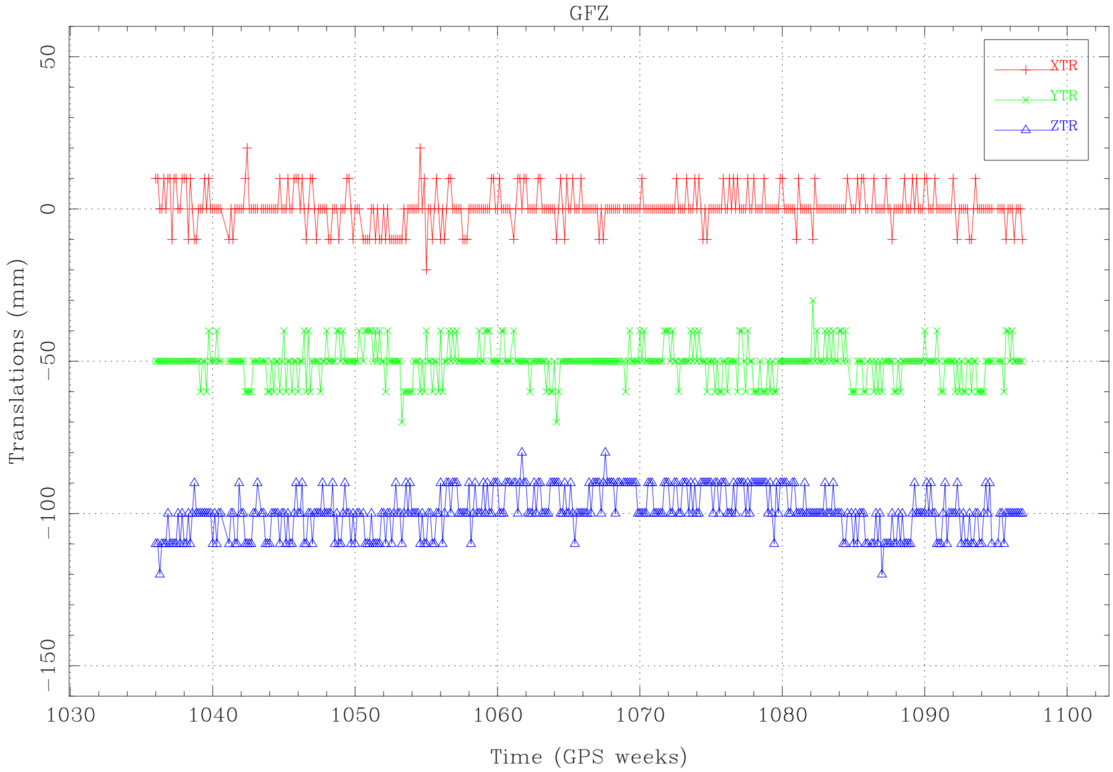


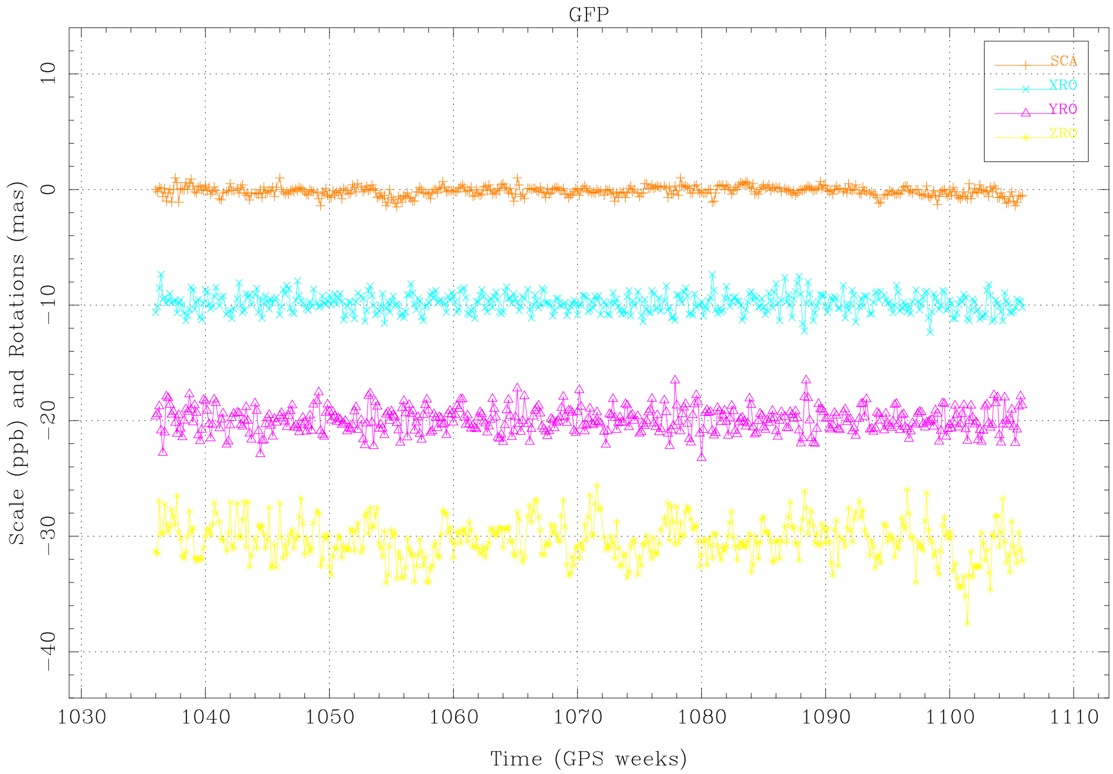
Figures 14a,b: Daily Transformation parameters of the COD Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



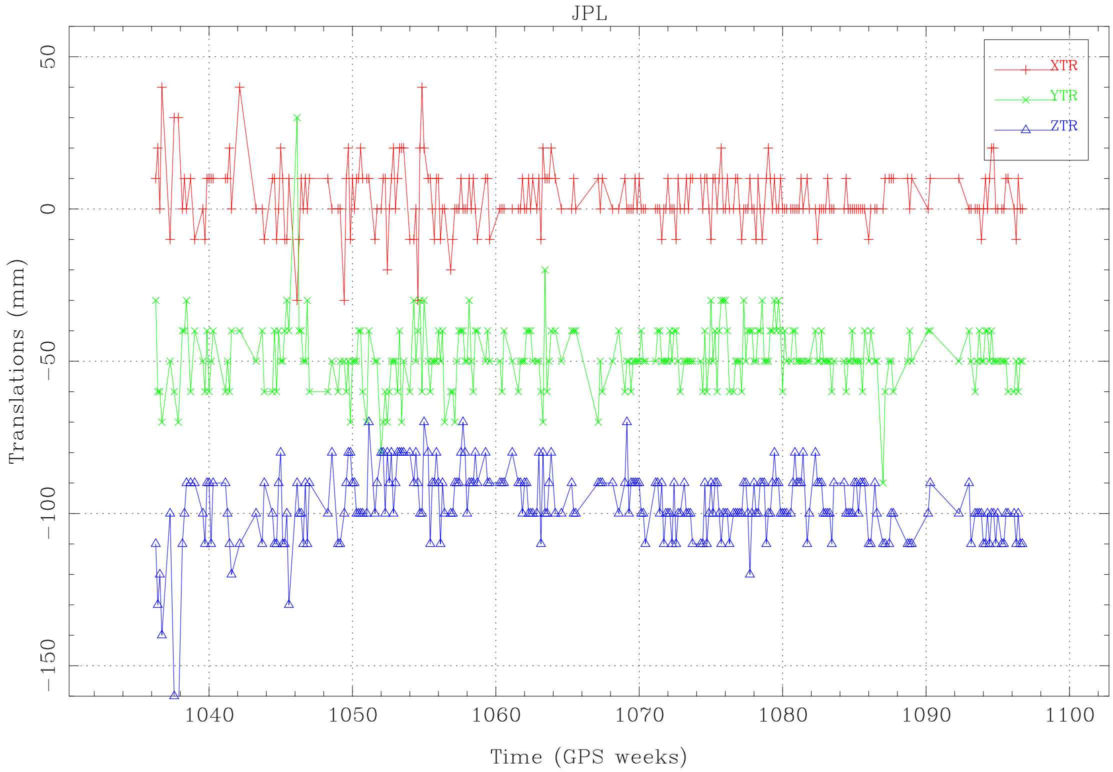


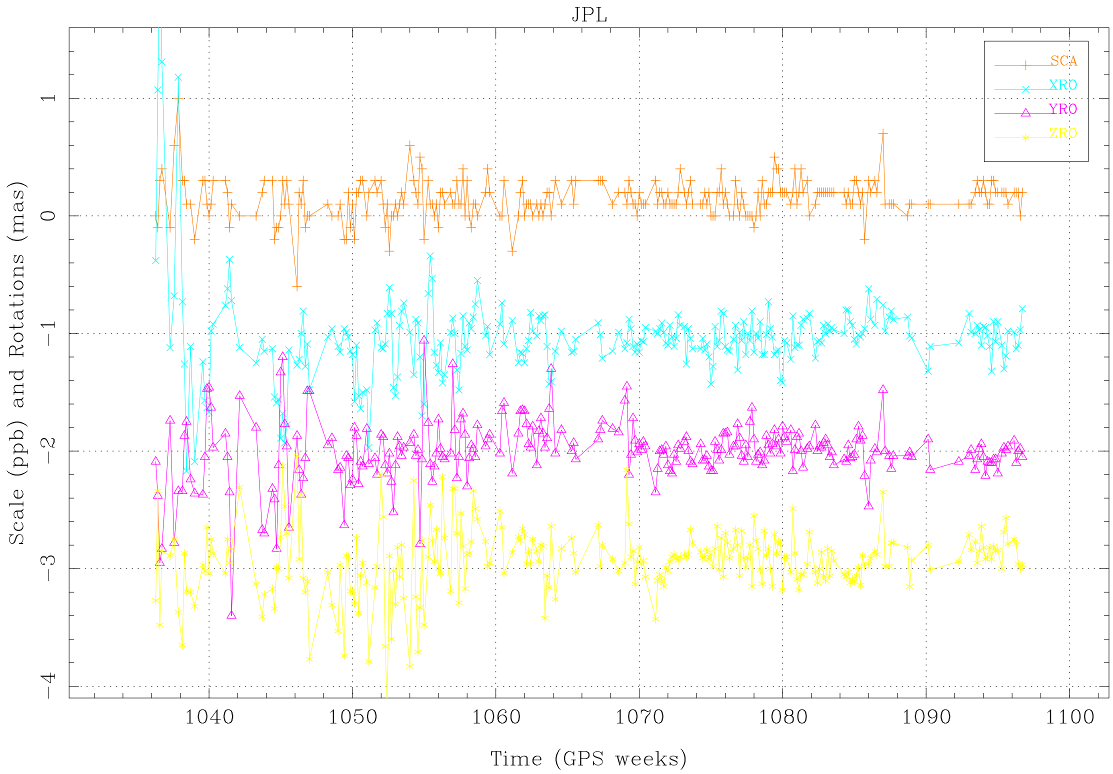
Figures 15a,b: Daily Transformation parameters of the ESA Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



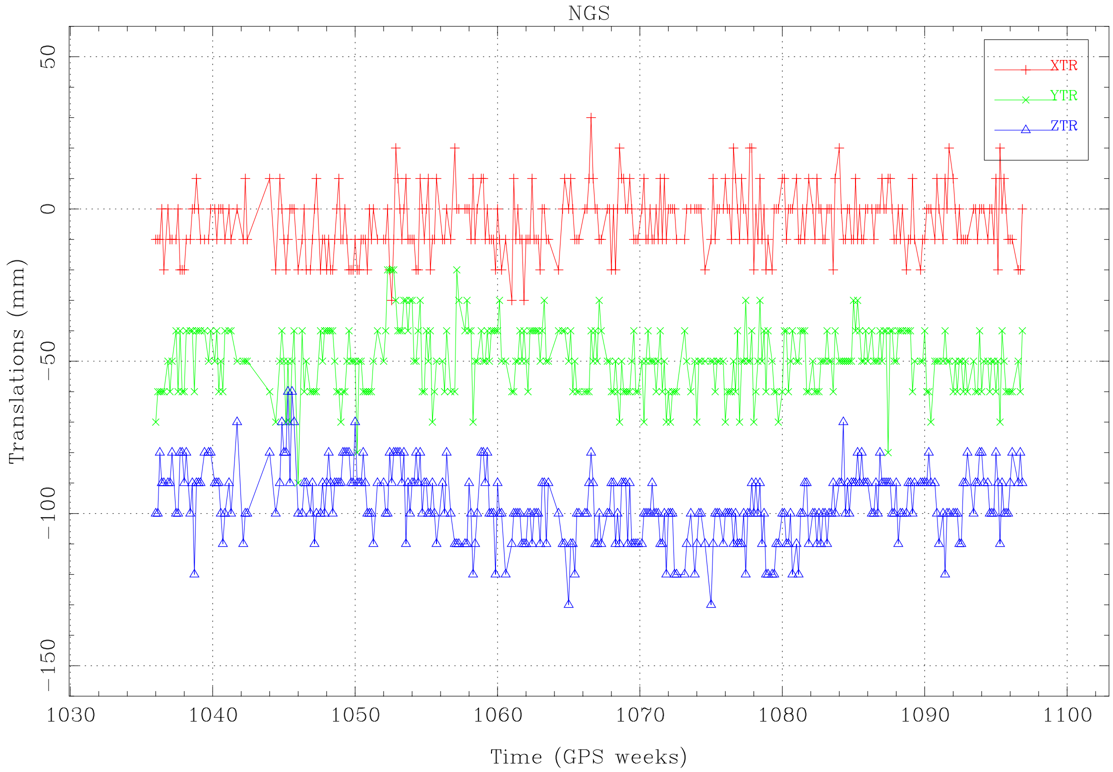


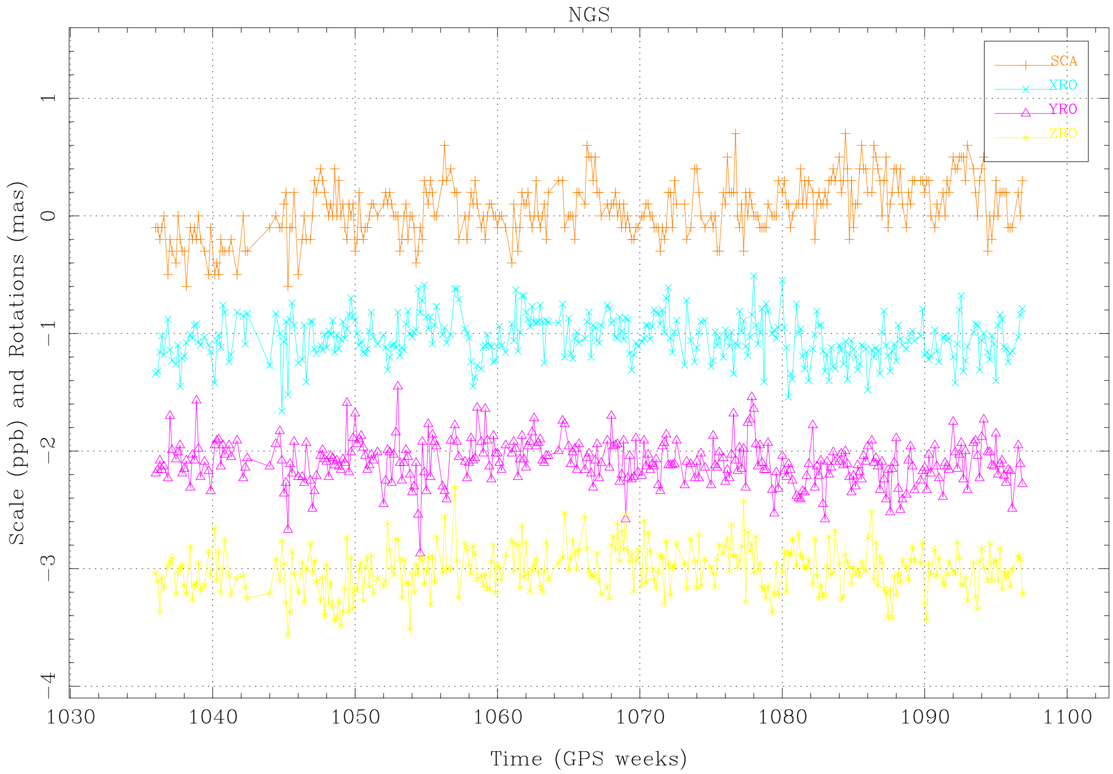
Figures 16a,b: Daily Transformation parameters of the GFZ Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



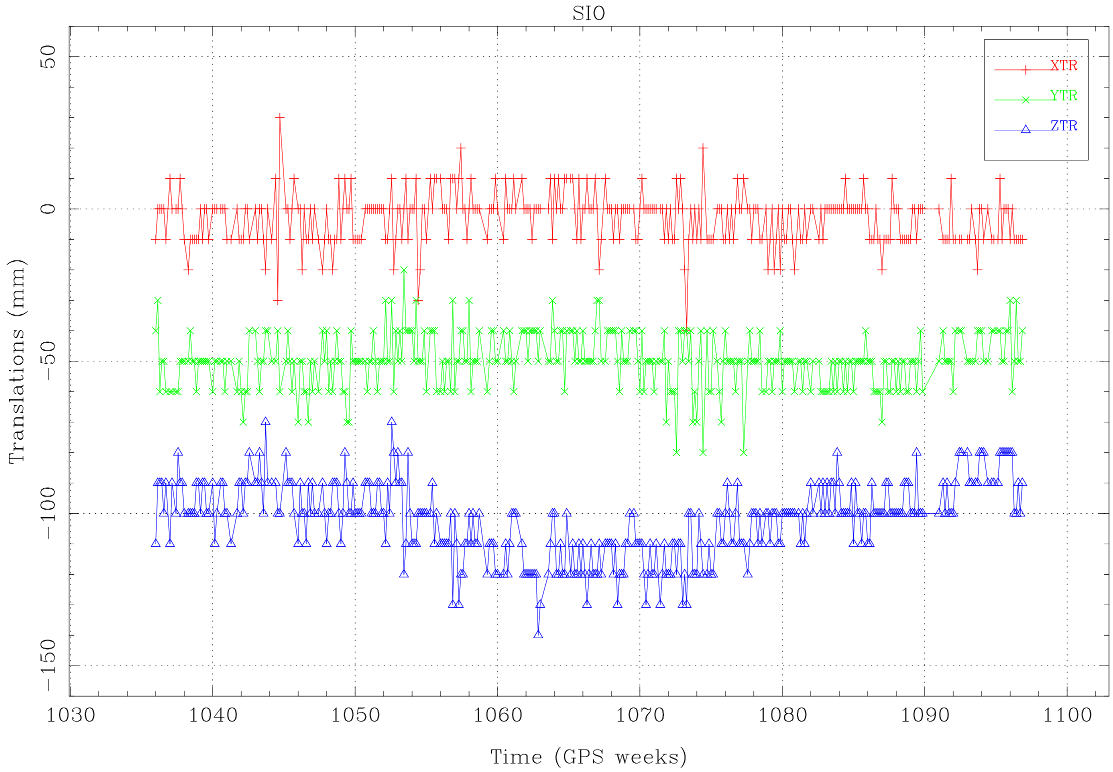


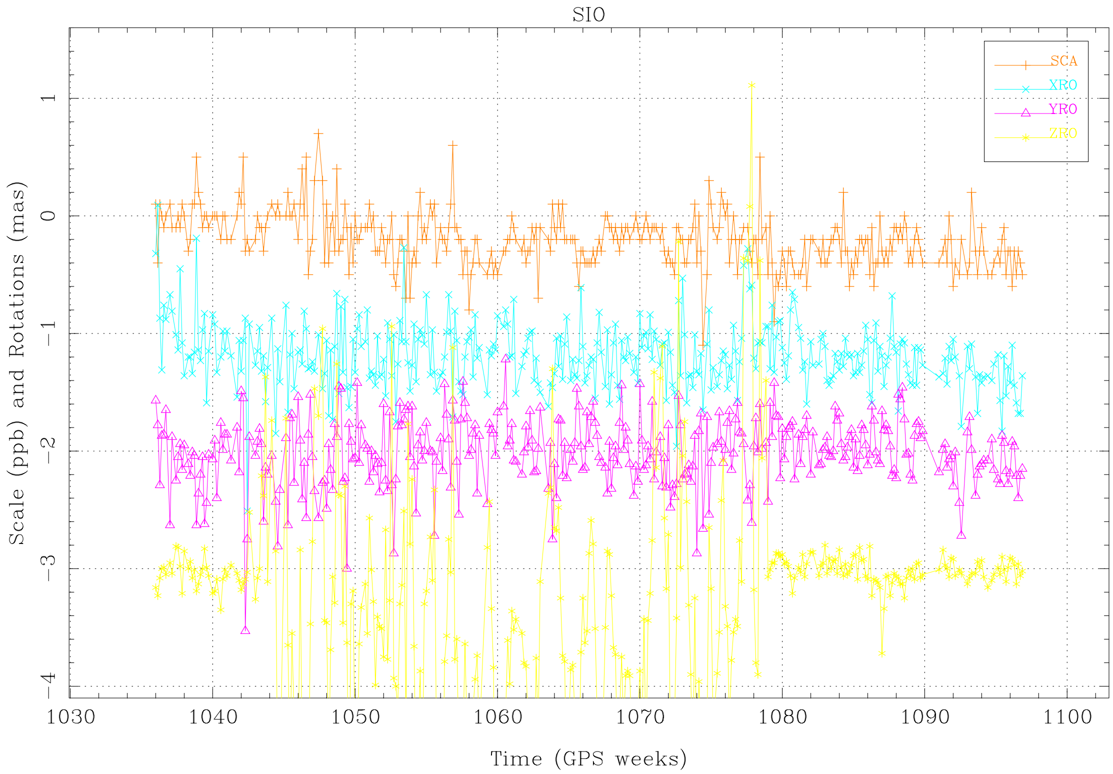
Figures 17a,b: Daily Transformation parameters of the JPL Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



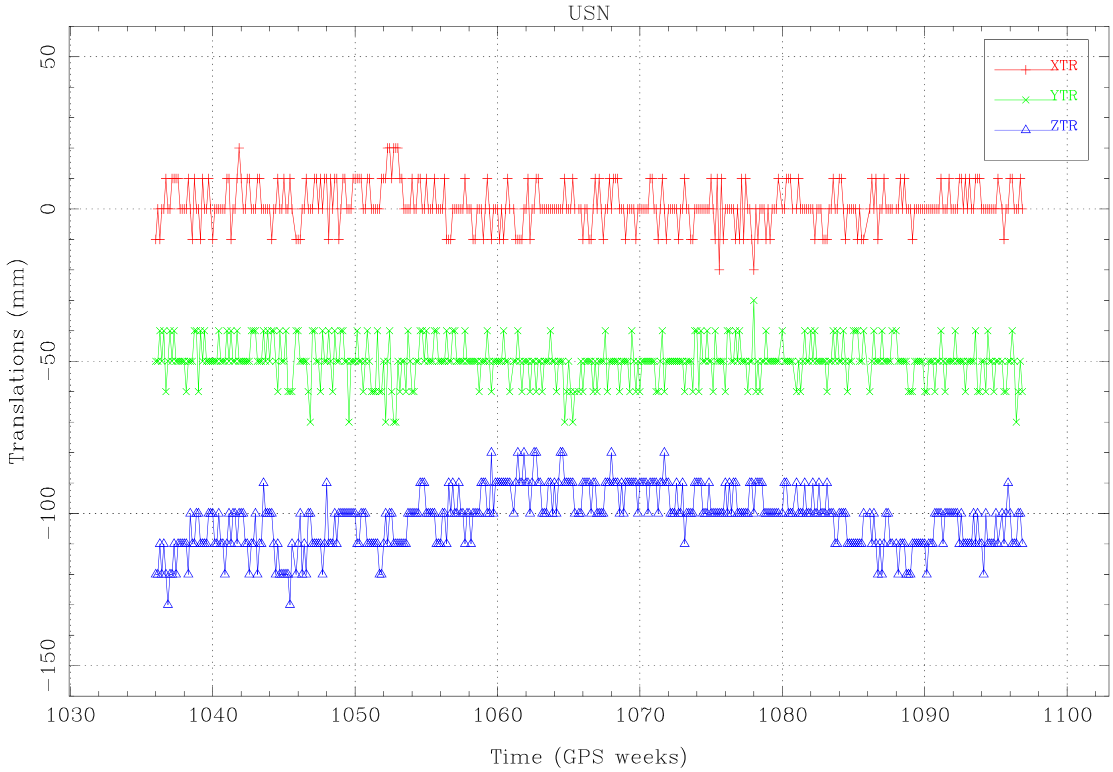


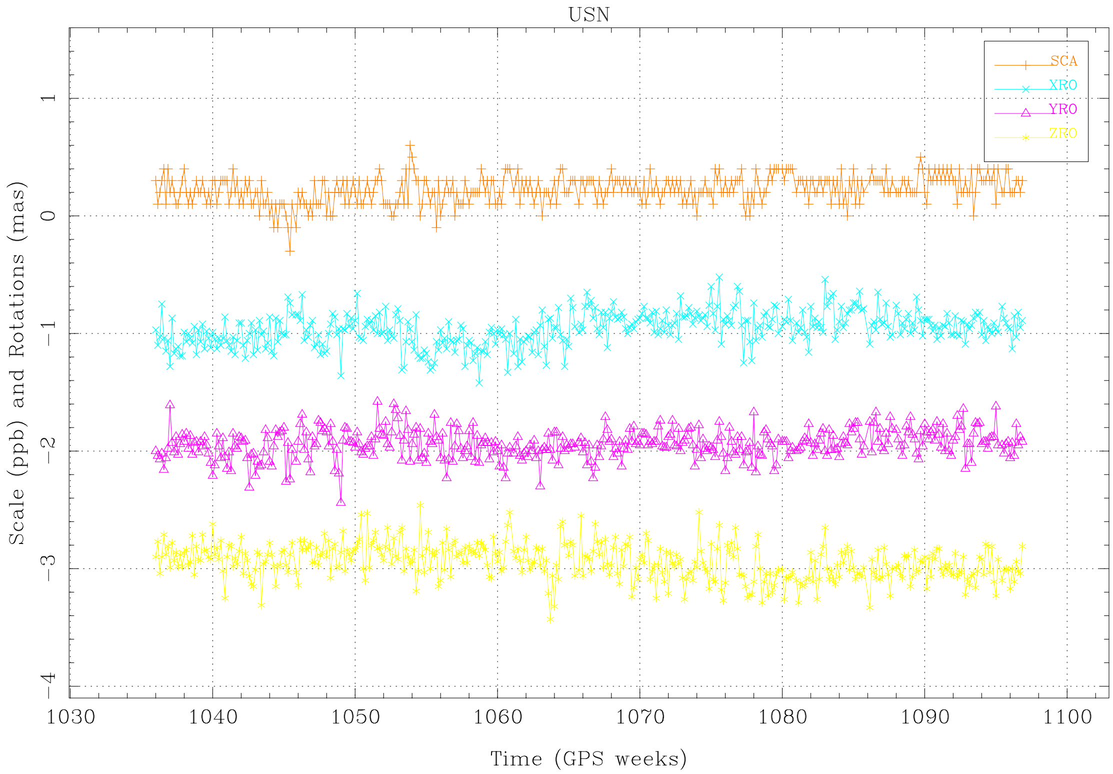
Figures 18a,b: Daily Transformation parameters of the NGS Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



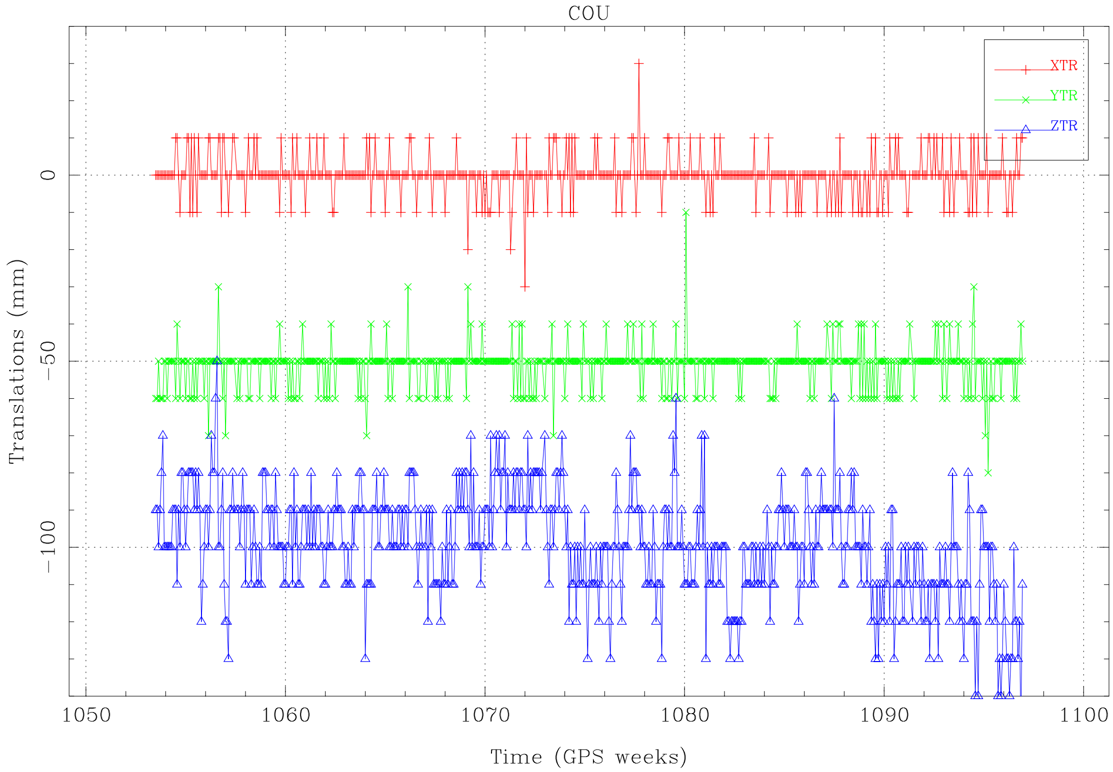


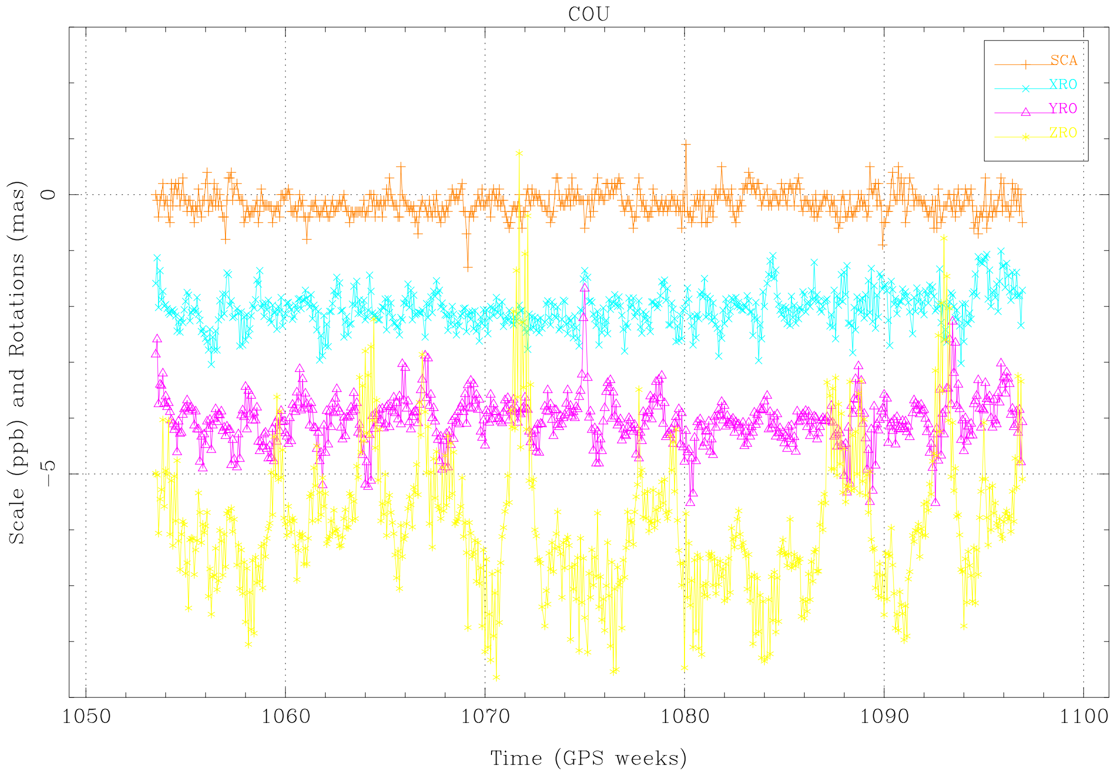
Figures 19a,b: Daily Transformation parameters of the SIO Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



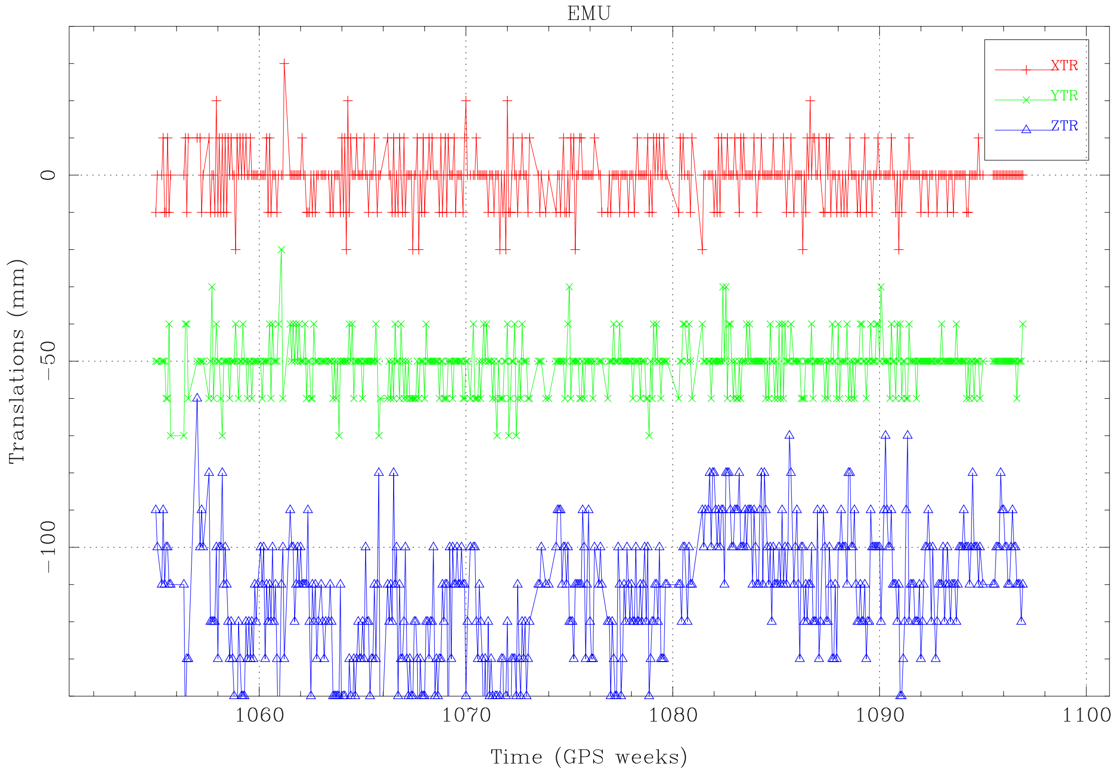


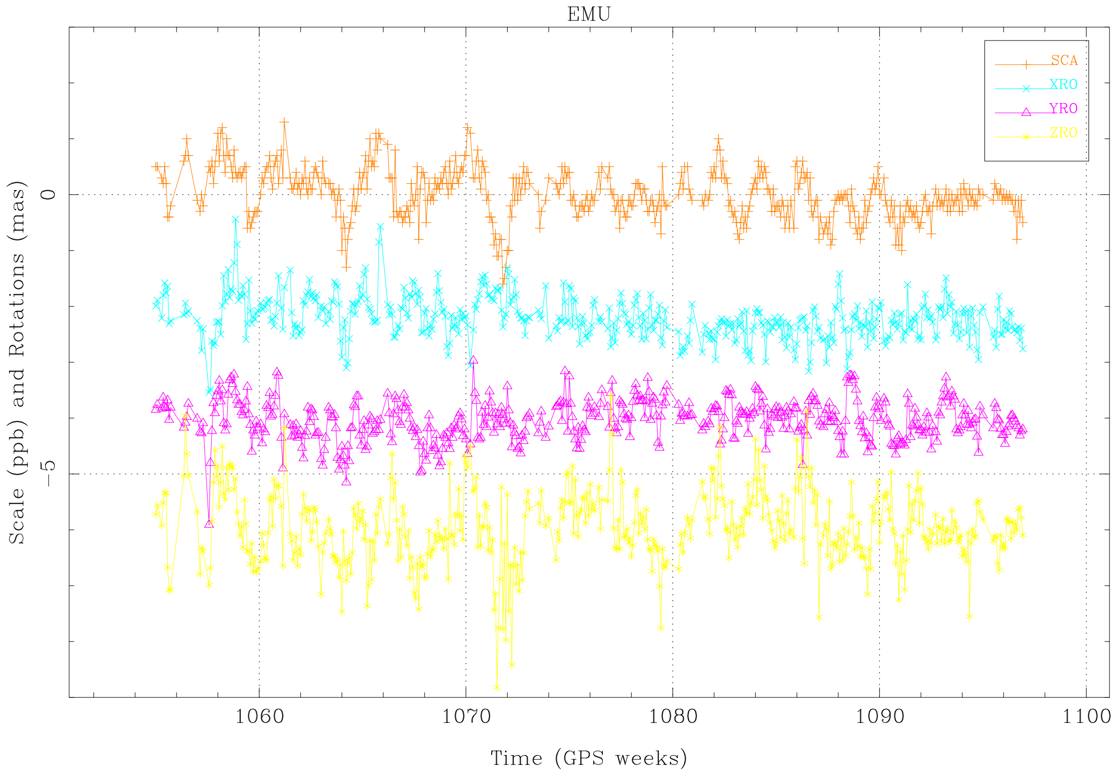
Figures 20a,b: Daily Transformation parameters of the USN Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 1 mas.



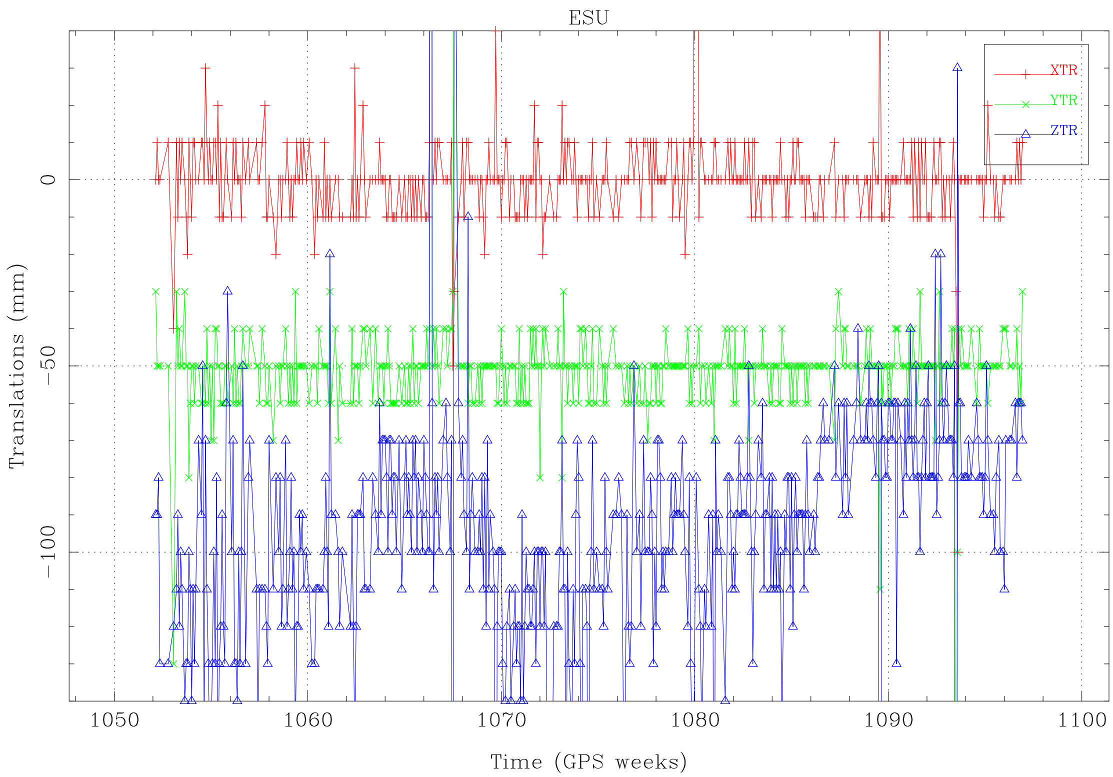


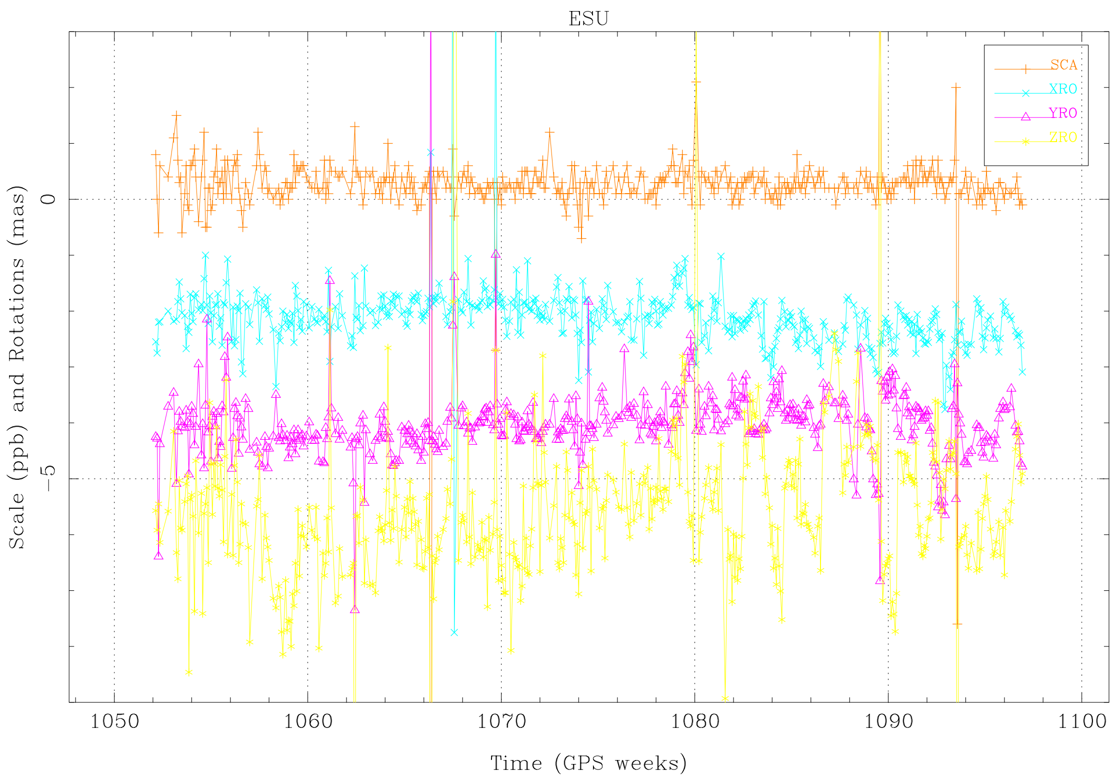
Figures 21a,b: Daily Transformation parameters of the COD Ultra Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 2 mas.



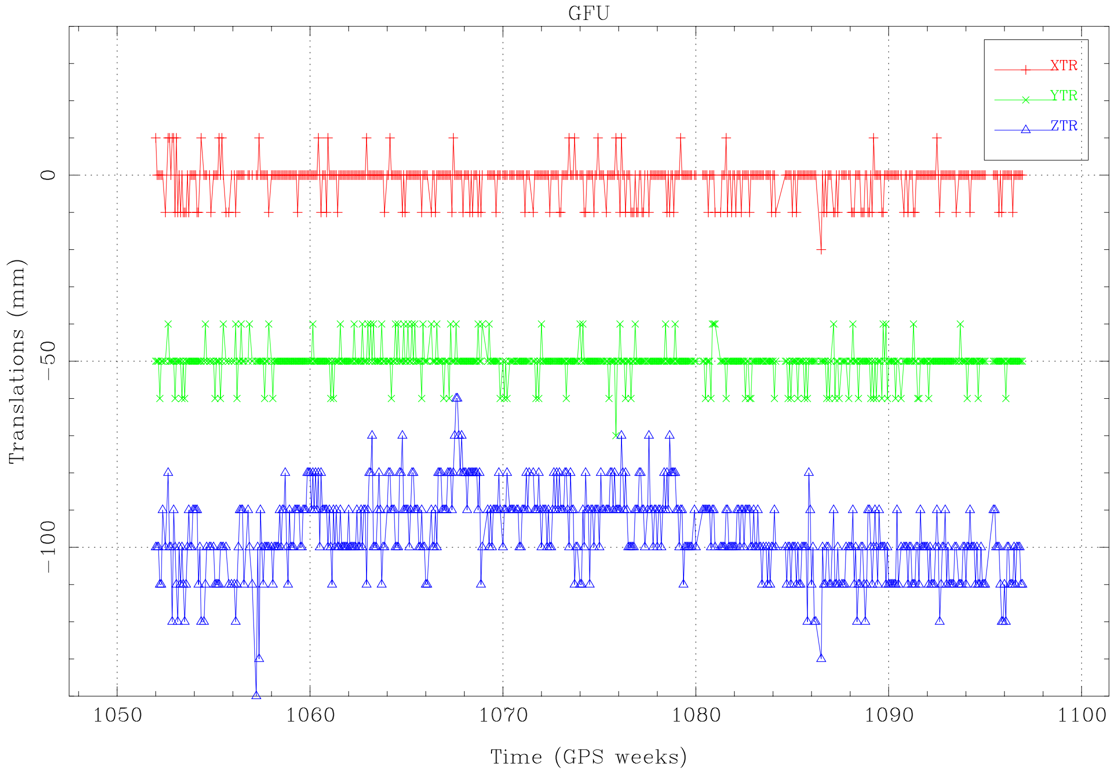


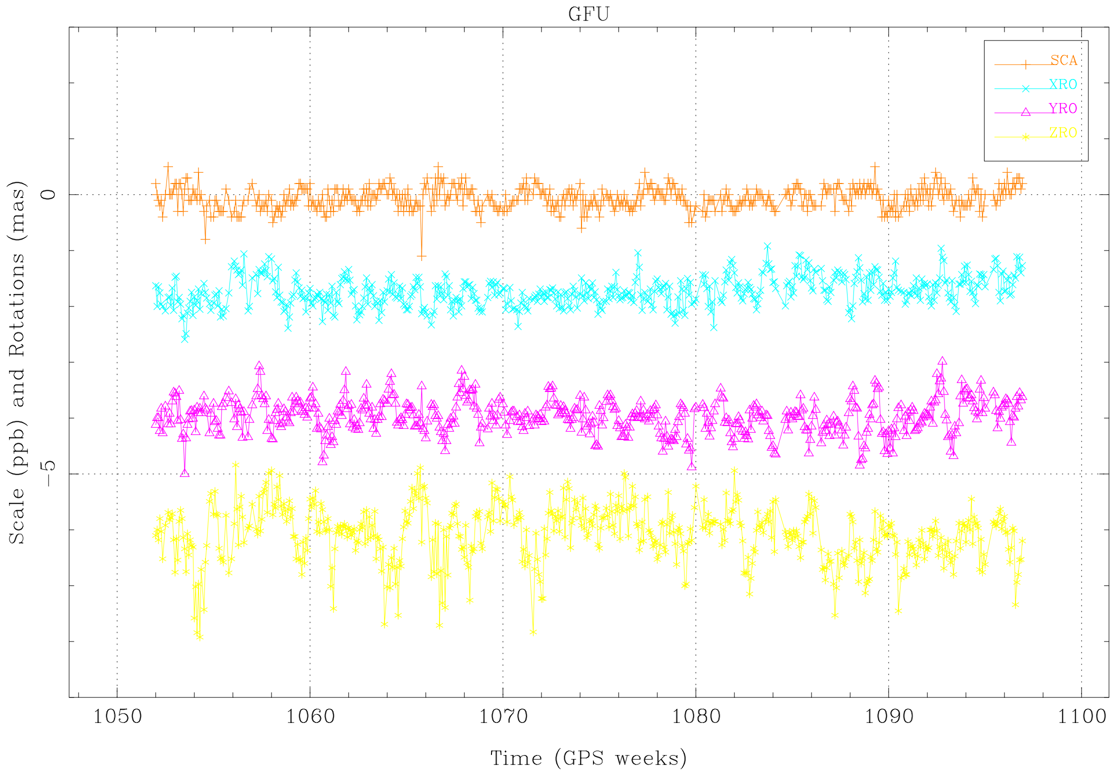
Figures 22a,b: Daily Transformation parameters of the EMR Ultra Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 2 mas.



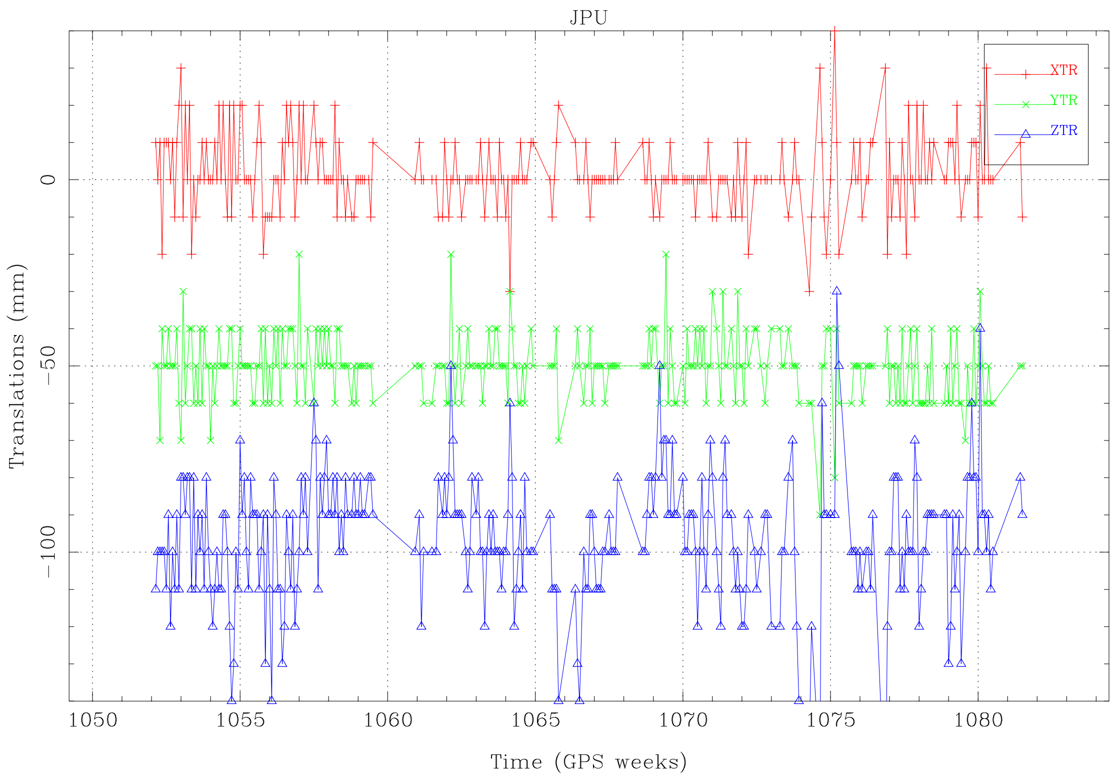


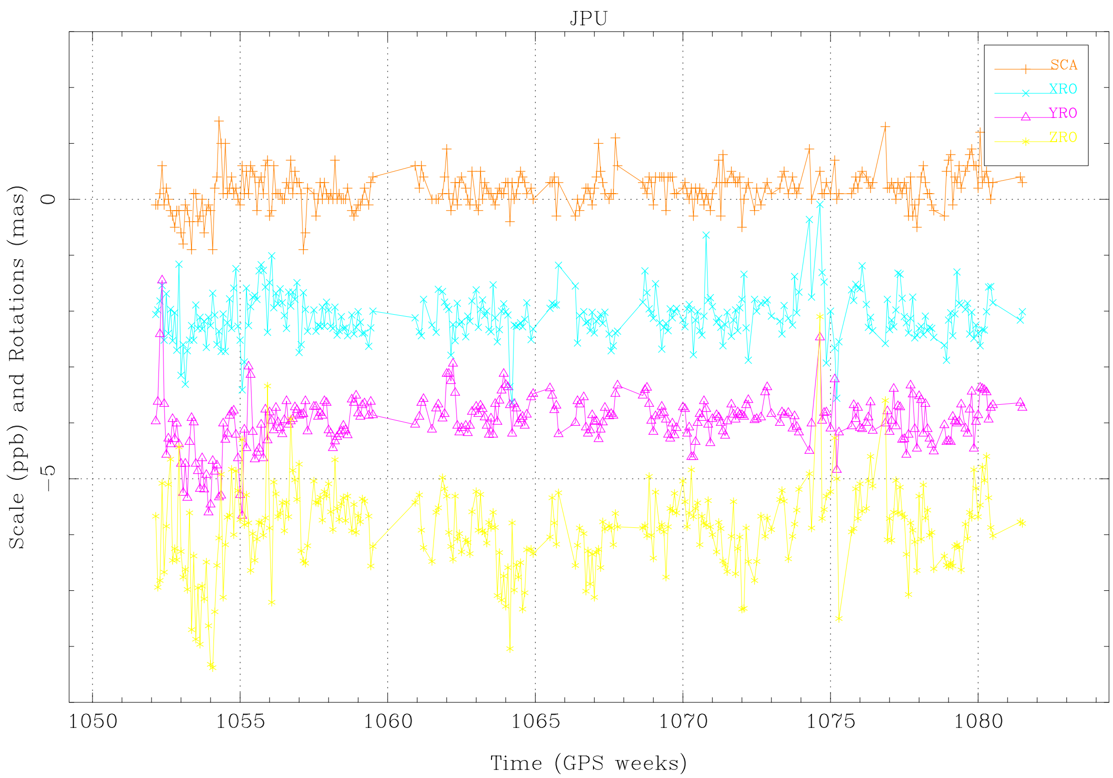
Figures 23a,b: Daily Transformation parameters of the ESA Ultra Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 2 mas.



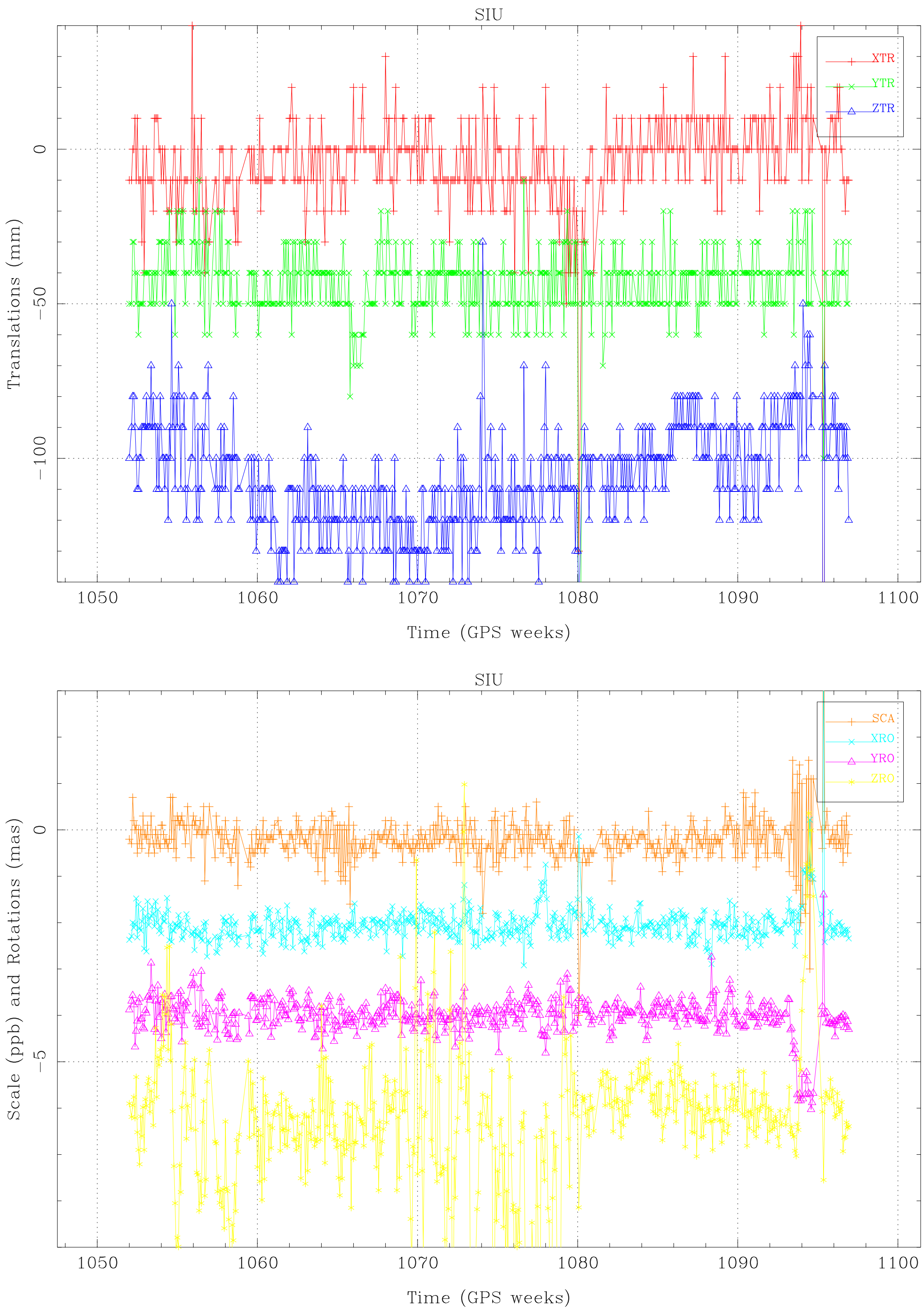


Figures 24a,b: Daily Transformation parameters of the GFZ Ultra Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 2 mas.

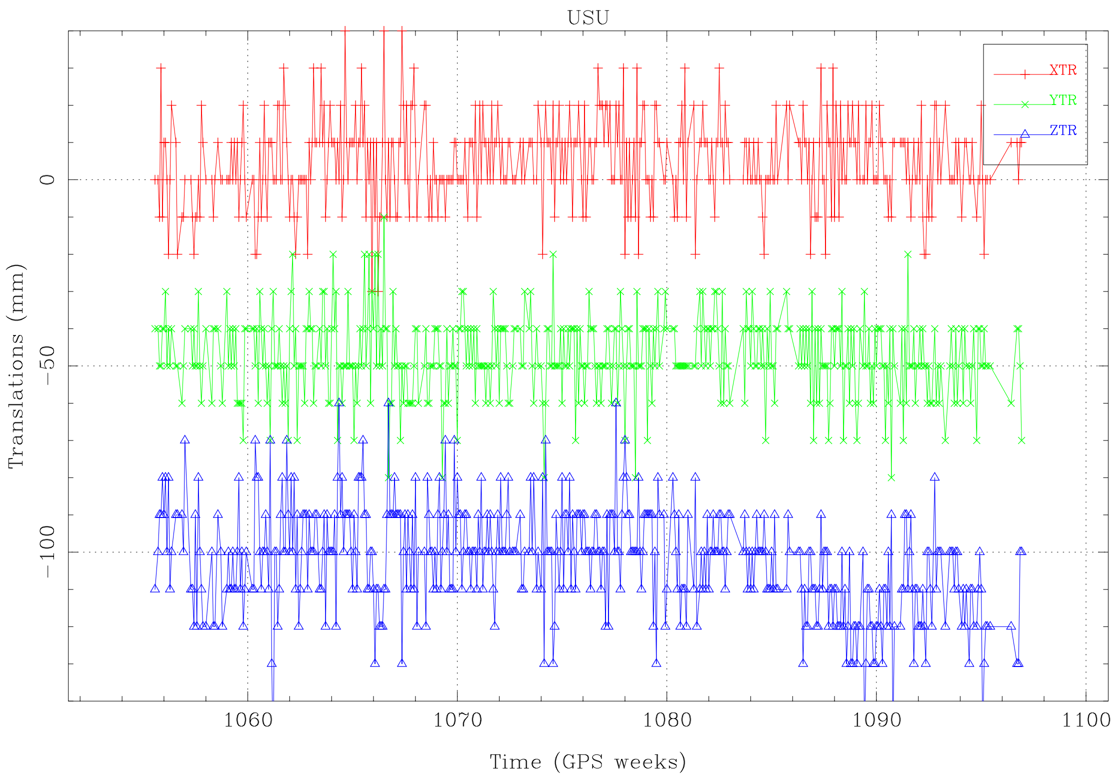


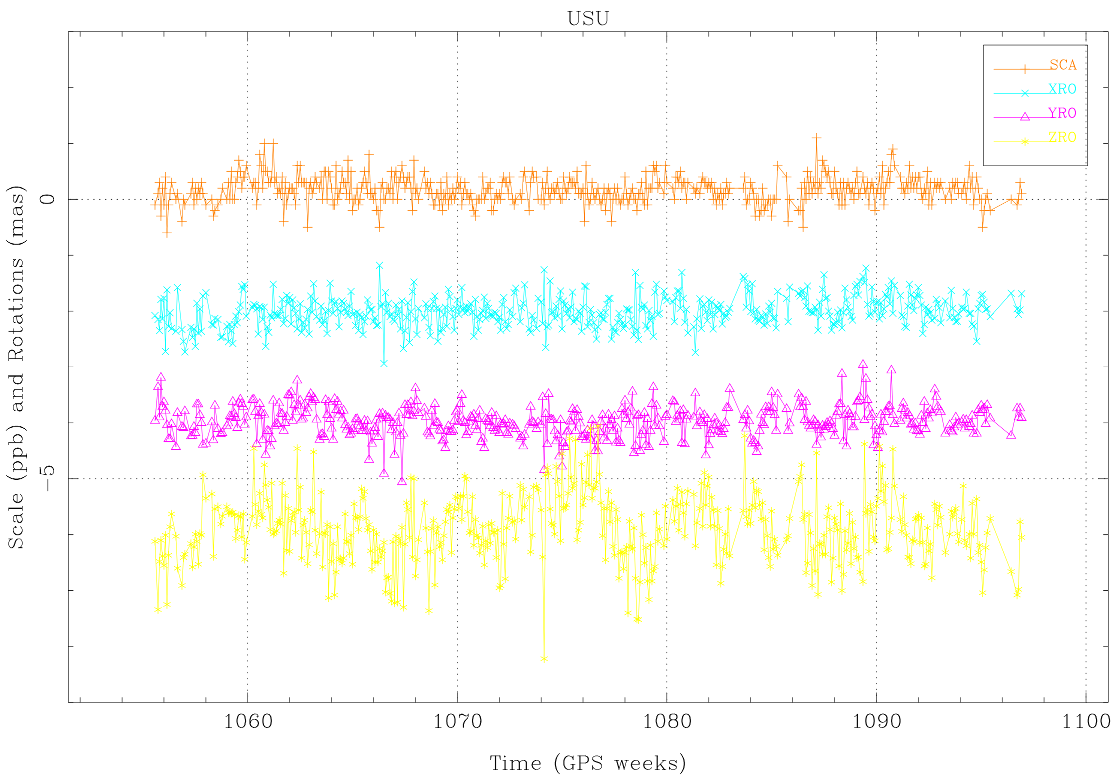


Figures 25a,b: Daily Transformation parameters of the JPL Ultra Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 2 mas.

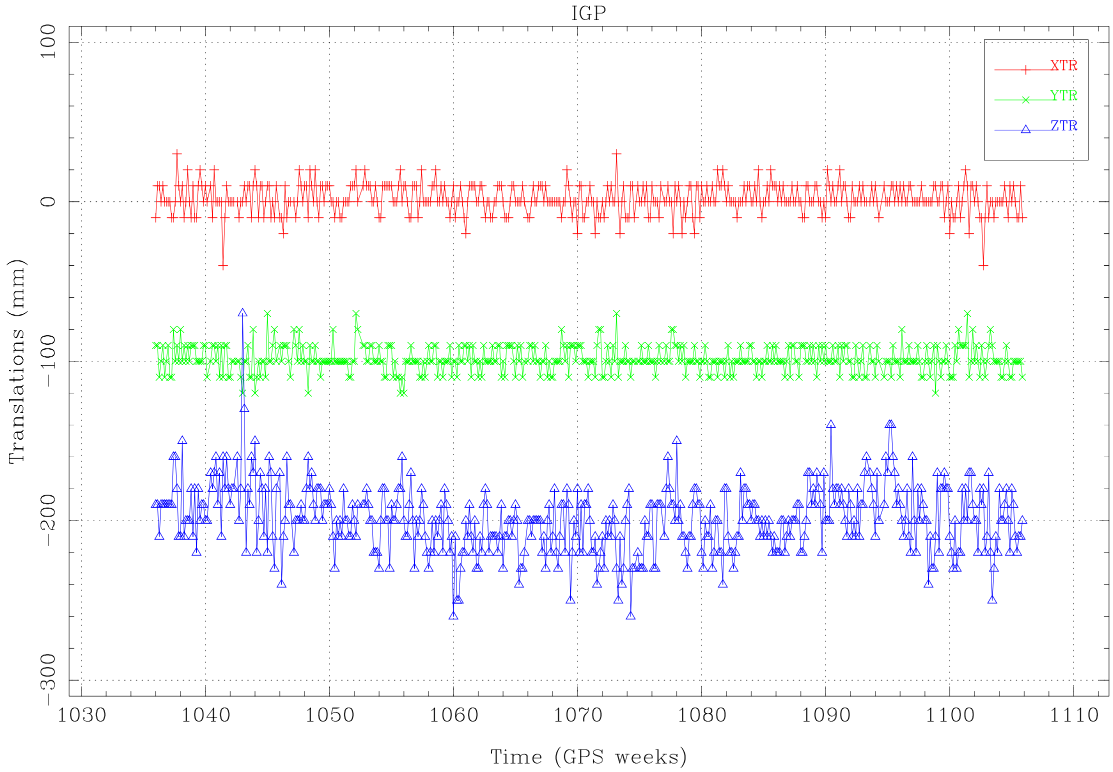


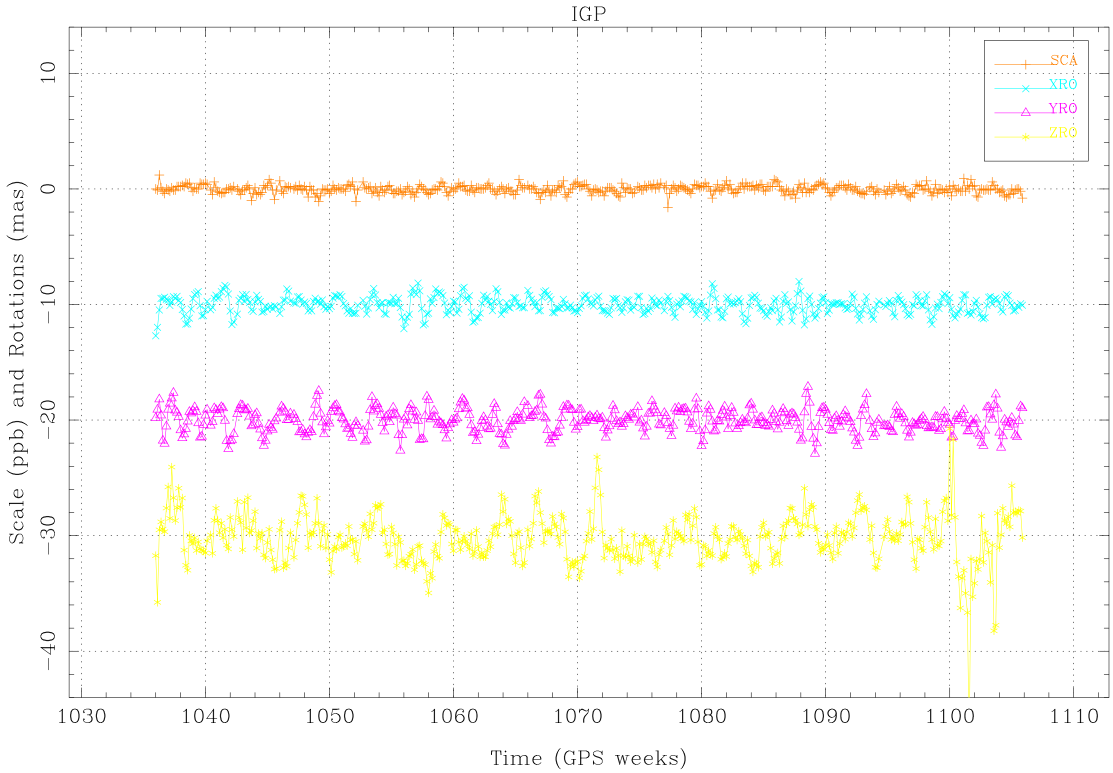
Figures 26a,b: Daily Transformation parameters of the SIO Ultra Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 2 mas.





Figures 27a,b: Daily Transformation parameters of the USN Ultra Rapid orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 50 mm, Rotations are shifted by 2 mas.





Figures 28a,b: Daily Transformation parameters of the IGS Predicted orbits w.r.t. the IGS Rapid orbits. Translations are shifted by 100 mm, Rotations are shifted by 10 mas.

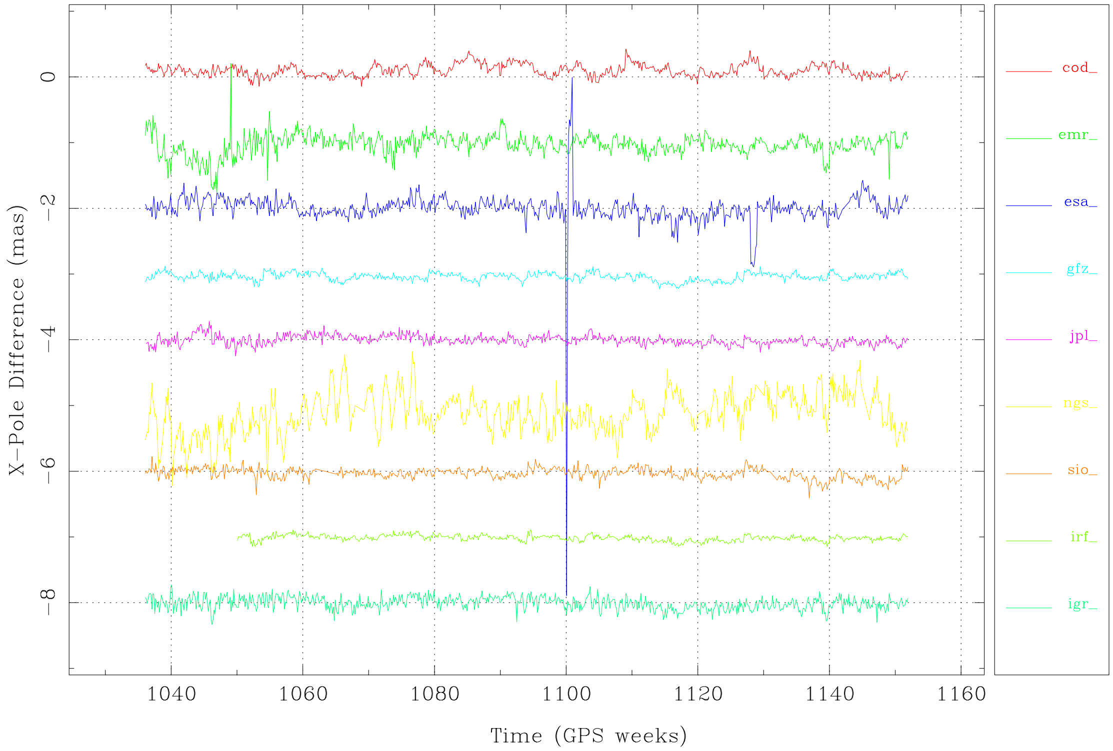


Figure 29: Daily AC Final x-Pole Differences w.r.t. the IGS Final x-Pole. ACs are shifted by 1 mas.

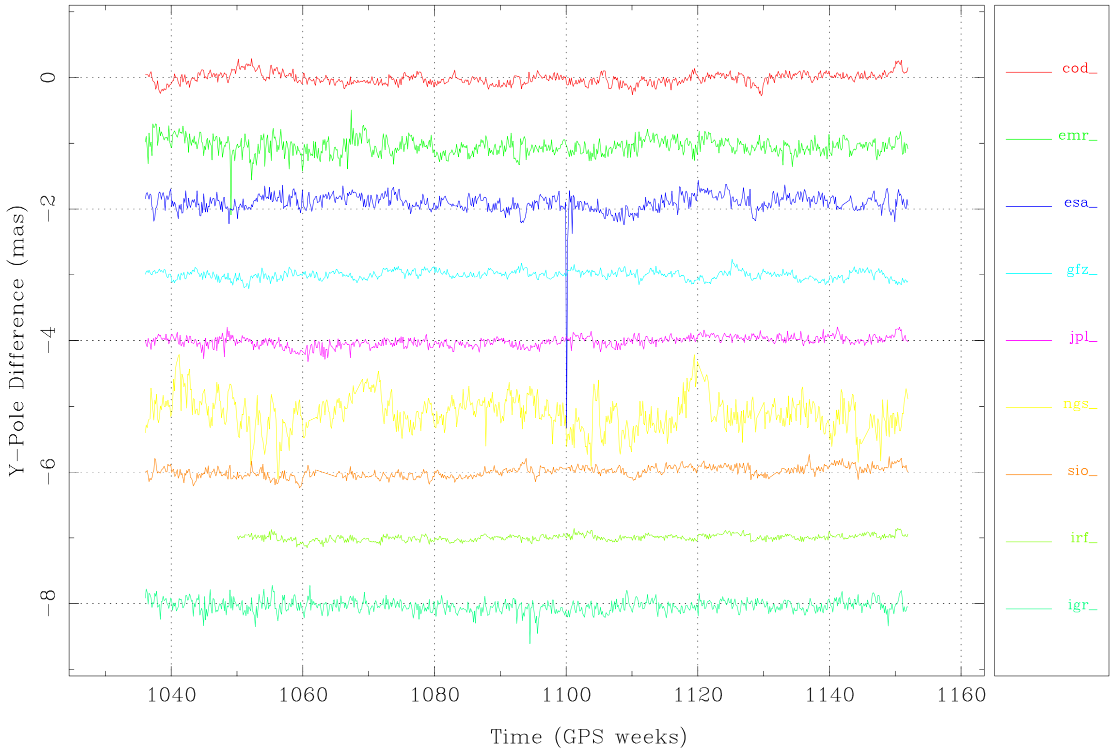


Figure 30: Daily AC Final y-Pole Differences w.r.t. the IGS Final y-Pole. ACs are shifted by 1 mas.

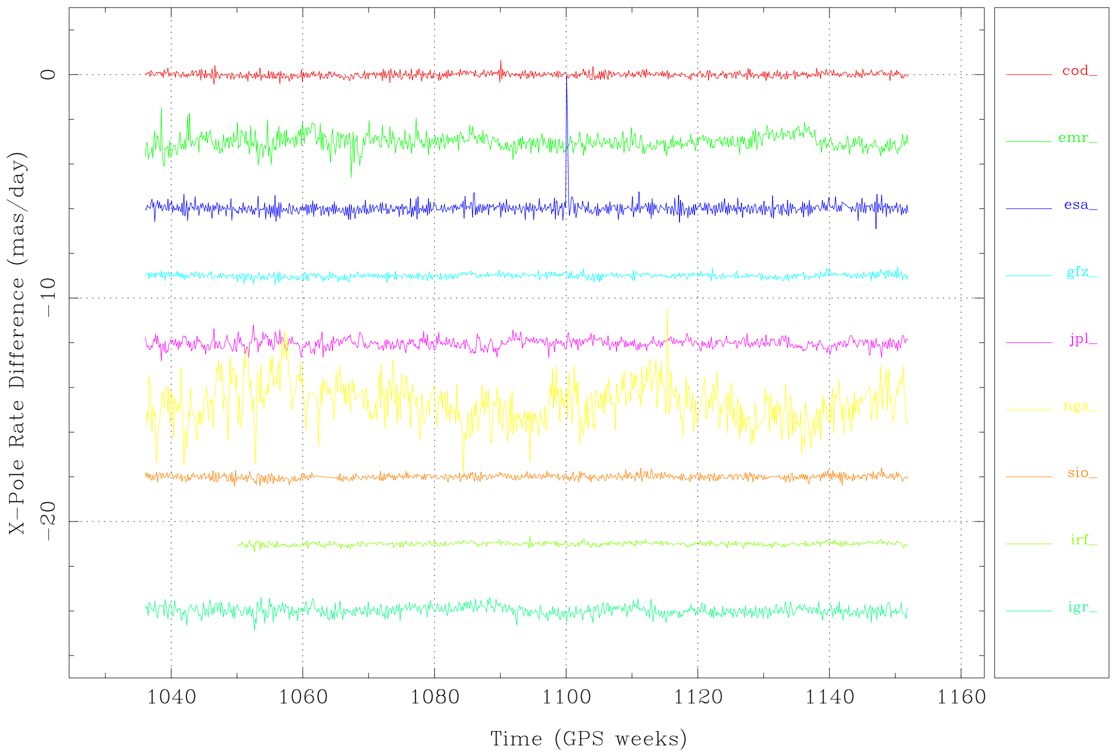


Figure 31: Daily AC Final x-Pole-rate Differences w.r.t. the IGS Final x-Pole-rates. ACs are shifted by 3 mas/day.

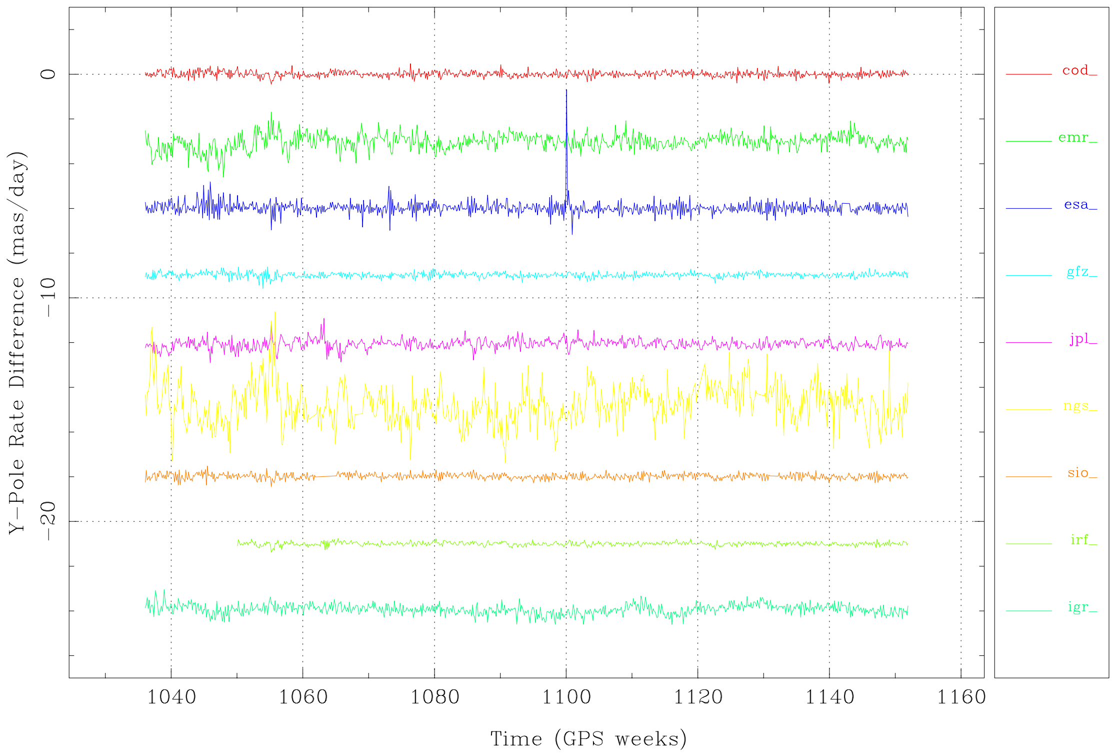


Figure 32: Daily AC Final y-Pole-rate Differences w.r.t. the IGS Final y-Pole-rates. ACs are shifted by 3 mas/day.

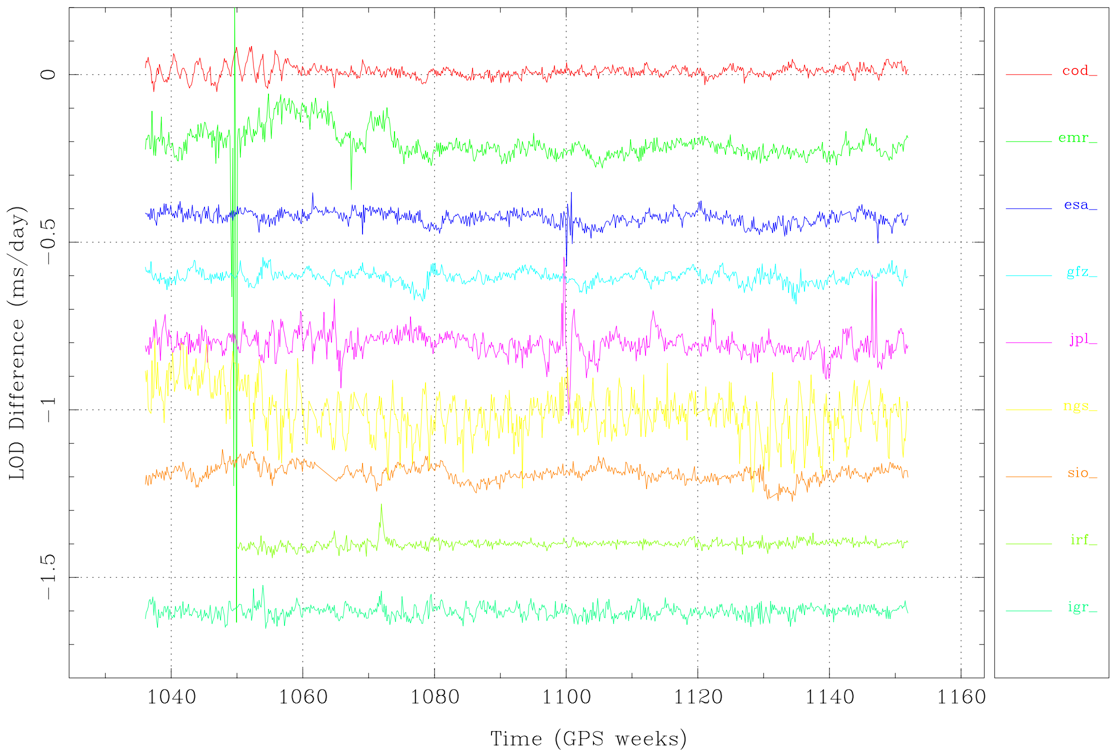


Figure 33: Daily AC Final LOD Differences w.r.t. the IGS Final Pole.
ACs are shifted by 0.2 ms/day.

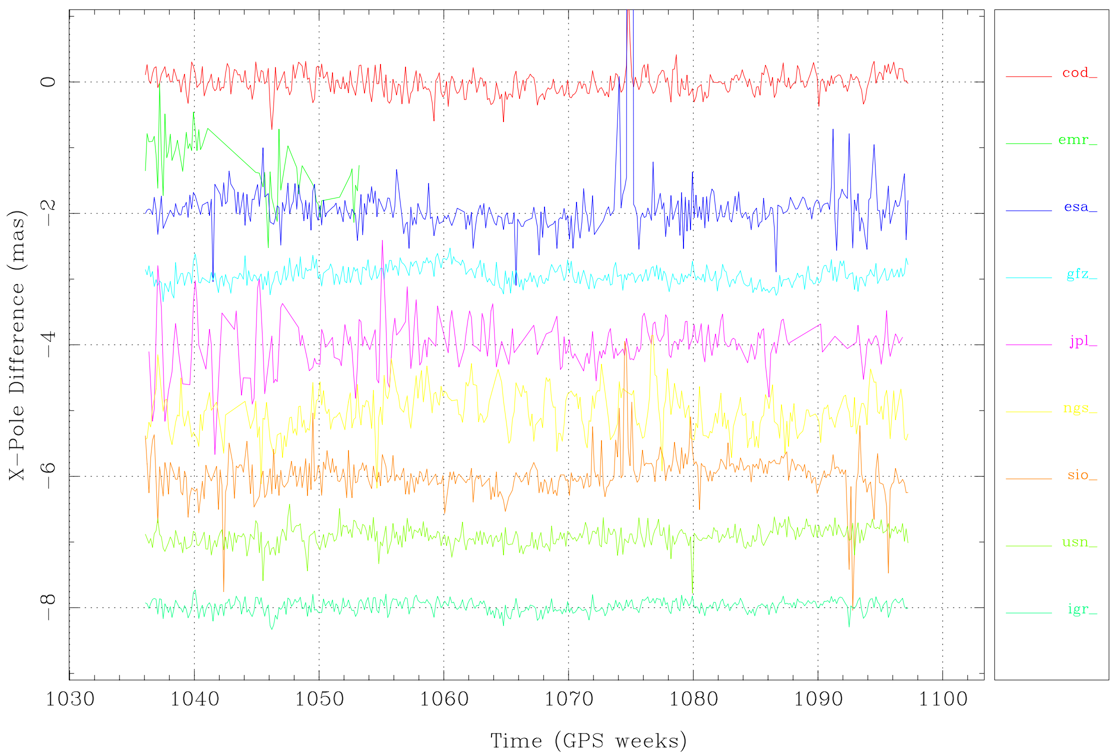


Figure 34: Daily AC Rapid x-Pole Differences w.r.t. the IGS Final x-Pole.
ACs are shifted by 1 mas.

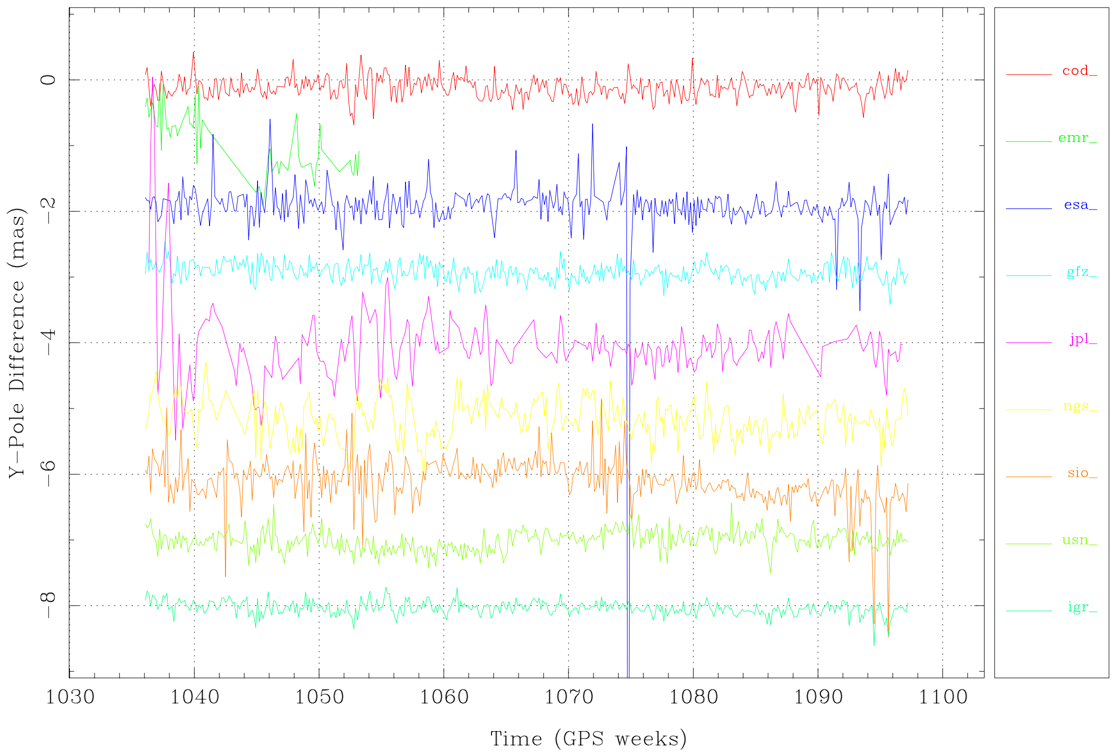


Figure 35: Daily AC Rapid y-Pole Differences w.r.t. the IGS Final y-Pole. ACs are shifted by 1 mas.

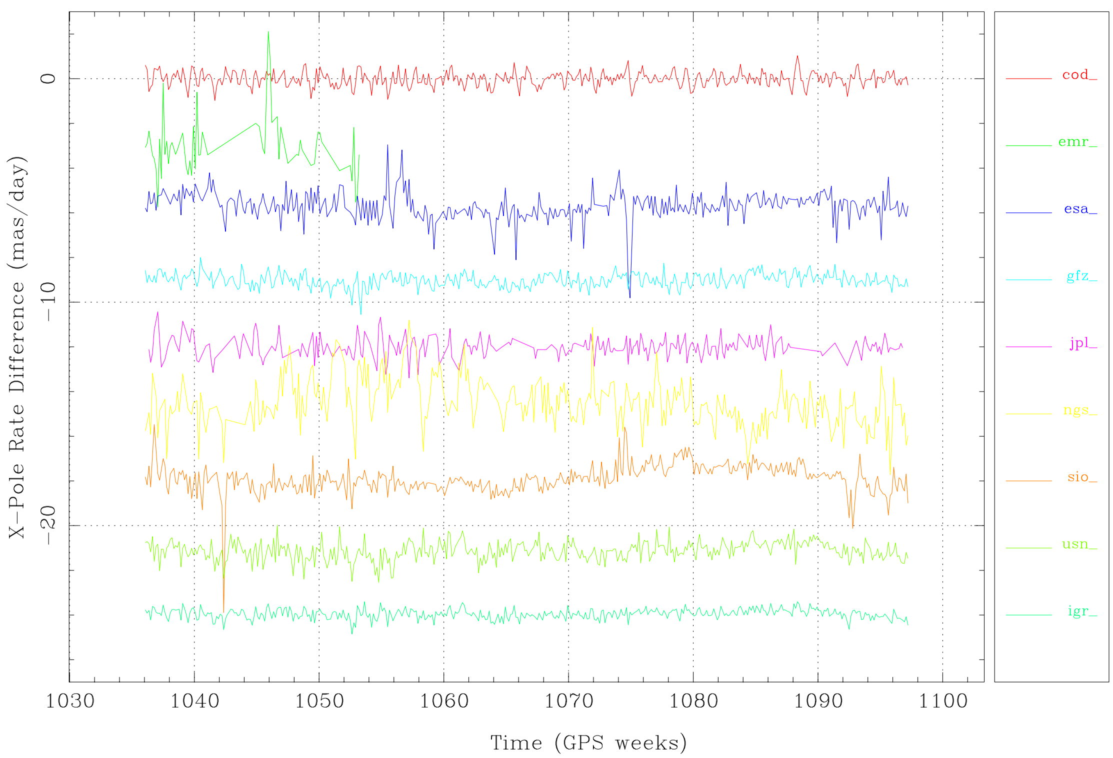


Figure 36: Daily AC Rapid x-Pole-rate Differences w.r.t. the IGS Final x-Pole-rates. ACs are shifted by 3 mas/day.

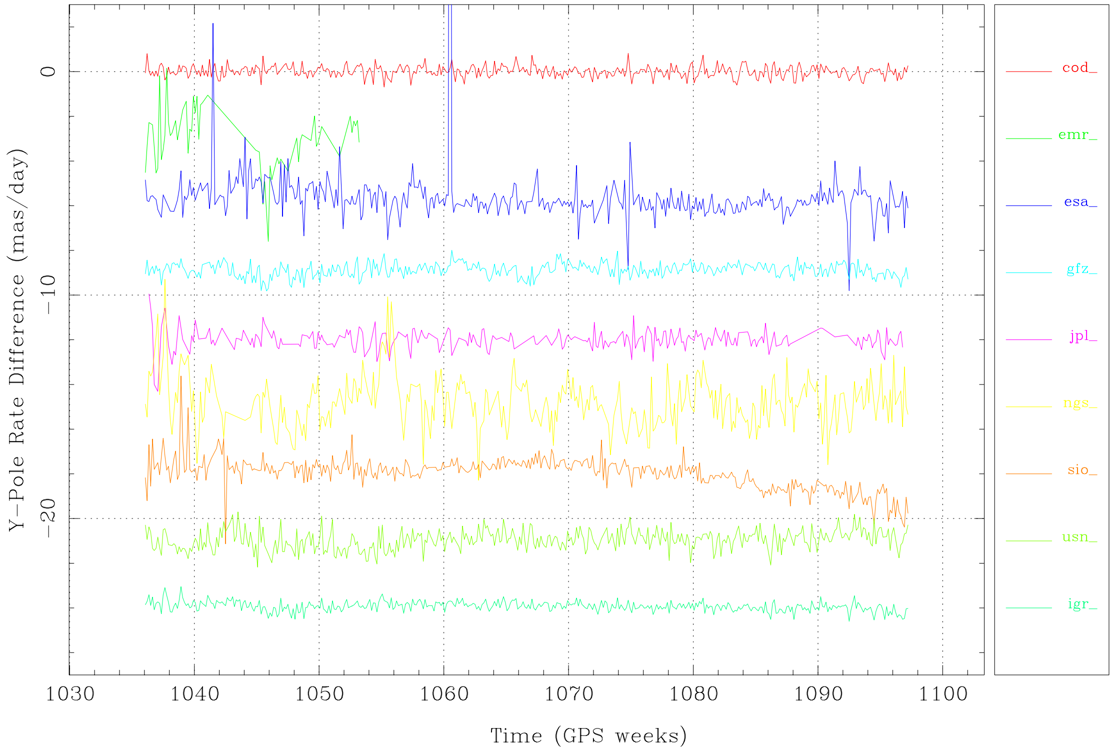


Figure 37: Daily AC Rapid y-Pole-rate Differences w.r.t. the IGS Final y-Pole-rates. ACs are shifted by 3 mas/day.

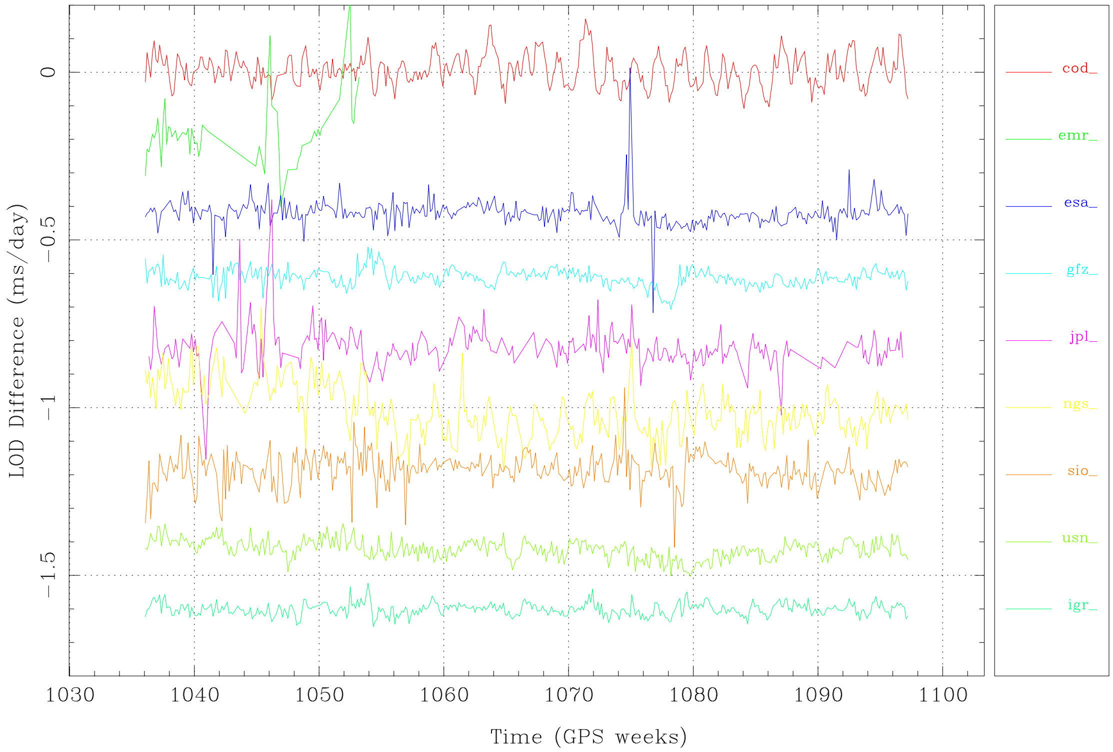


Figure 38: Daily AC Rapid LOD Differences w.r.t. the IGS Final Pole. ACs are shifted by 0.2 ms/day.

Current State of IGS Analysis: Quality Assessment

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Abstract

In this paper we examine the current state of the IGS analysis of GPS data and the needs of users. Since the initial sessions of the meeting examine near real-time analysis issues, we will examine the conventional IGS products. We will examine the needs of users for knowing the quality of both IGS products, and more fundamentally the quality of individual satellites and stations in the IGS network. There already exists a number of methods that can be used to assess IGS quality and we will review the contents of these existing mail, ftp, and web sites. We will consider how best to report marginal satellites and sites to users particularly in the form of interactive web based tools that could be developed, and how to integrate the existing information into a coherent assessment tool for users.

Introduction

The International GPS Service generates products from the analysis of GPS data that are made available through international data centers. The primary IGS data center is located at the Goddard Space Flight Center in Greenbelt, Maryland (cddisa.gsfc.nasa.gov). The products are stored in directories, accessible with anonymous ftp, with names of the form gps/products/[WWWW] where [WWWW] is the GPS week number. The current IGS products are (a) orbits for the GPS satellites that are available in three forms: final orbits; rapid orbits; and predicted orbits, (b) Earth orientation parameters, (c) tropospheric delay estimates, and (d) combined terrestrial reference frame SINEX files, one for the week and the other an accumulation to the week. In addition to the products themselves there are many summary and log files that contain a wealth of information about the products if the correct files are examined. In addition to these official products, there are other products in development that are available but are not deposited in the standard IGS product areas. These include satellite and ground receiver clock estimates, ionospheric delay maps, and combined GPS/GLONASS analyses. In this paper, we will discuss mainly the quality of the official products.

Within the area of quality we will consider timeliness and accuracy. For accuracy, we need to consider not only the accuracy of the products but also the quality of the data input to the analyses. In the latter area, we consider not only the GPS stations and receivers but also the satellites. In addressing these issues we also consider the needs of the users. We start the discussion, with user needs and then consider timeliness and accuracy.

User Needs

There has not been a recent widespread survey of the users of the IGS products but based the activities of the research community the main uses of the IGS products are reasonably clear. Probably the most used IGS products are the orbit files, although for volume of data transferred, the RINEX files from the IGS stations are the largest. The Earth orientation parameter (EOP) files are also widely used by the International Earth Rotation Service (IERS) but because the IGS orbits are distributed in an Earth fixed frame, the EOP parameters are not necessarily needed for processing GPS data. As users become more aware of the availability of the new IGS combined SINEX files, their use should increase for tectonic studies. The ways the tropospheric delay files are used is not clear at the moment although most likely these are used to evaluate the utility of these types of data in meteorological forecasts. Since these files are currently only available about 4-weeks behind real-time, their latency is too large to be of use in forecasting. The clock estimates are being studied by the international timing community as a means of transferring time globally with sub-nanosecond accuracy. We will concentrate here on the needs of users for precise positioning using IGS products and data. We will also emphasize that the IGS supports the research community and because all of the major GPS analysis programs are used by the IGS analysis centers, the IGS provides a natural framework for making significant improvements to accuracy of GPS results. Such improvements are very evident when the evolution of quality of GPS results is examined over the last decade.

Timeliness

For many users, the timeliness of products is important. For groups working near real-time this is particular important. But also many geophysical researchers who operate continuous GPS networks want results to be available at known times so that they can be sure that their processing can be done in autonomous fashion. To evaluate the timeliness of the IGS orbit products we examined the difference between the product date and the time-stamp on the file at the cddisa.gsfc.nasa.gov data center. We did this for files from late 1998 to the current date. (We can't use this technique to go back too far in time because the file time stamps may have been reset when files are moved between storage areas). The results are shown in Figure 1 for the IGS final, rapid and predicted orbits. The two large excursions in the results starting in late July 1999 and the beginning of 2000 corresponds to a large disk failure and a particularly difficult Y2K transition, respectively. Excluding these intervals, the delivery of the IGS final orbit has been very reliable and generally within 3-weeks of real-time. The rapid and predicted results are more erratic and some of the excursions here may be due to re-posting of results rather than date of original transmission. However, if results are re-posted then users working with these products, in near real-time, would not have the best product at the time.

Probably the most worrisome feature of Figure 1, is the “single-point” failure mode of the results. The loss of the cddisa data center caused large delays until the use of alternative data centers was implemented by the IGS analysis center. The IGS should develop more formal contingency plans for the loss of a data center, and encourage the organizations that fund the data centers to allocate greater resources to ensure redundancy within the data centers themselves.

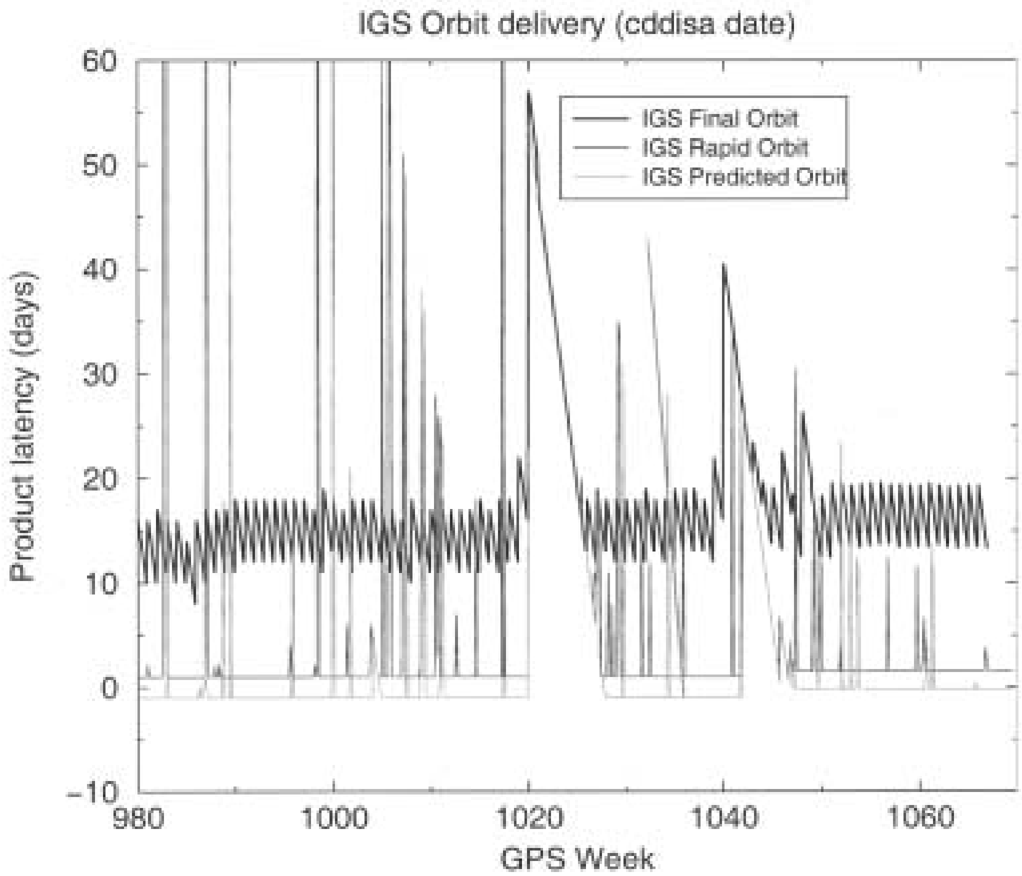

Figure 1: Difference between product date and file stamp for the interval between Oct 18, 1998 and July 2, 2000 shown as a function of GPS week number. The IGS final orbit (black line) is posted once per week, which explains the saw-toothed structure of the results. The rapid (red curve) and predicted (green curve) are posted daily. For results prior to Week 1042, the time difference has 1-day resolution of due to the nature of the time stamps.

Product Quality

There are a number of methods available for assessing the quality of the IGS products and the contributions of the individual analysis centers. The longest running product of the IGS is the final orbit of each satellite given in the SP3 format and these files have accuracy assessments each satellite. In addition, there are summary files that report the quality of each analysis center. Users can assess the accuracy of the products, if they know to look in the correct places in the files. However, what is not clear from these summaries is why a particular satellite is bad on a given day, and which parts of the orbits may be good to use for satellites that have thruster firings during the day. It is also not clear from these summaries, how individual analysis centers can improve their results for poorly behaved satellites. In particular, there are a group of satellites whose momentum wheels have either partially or fully failed, and while the list of these satellites is given in some IGS reports, conveniently finding this information is not easy. Efforts to improve the overall quality of the IGS analysis centers should concentrate on sharing this type of information and making available likely causes of problems rather than simply reporting (through RMS scatters of results) that a problem exists. These types of studies are carried out and disseminated in IGS reports by individual centers but what seems to be needed in more directed access to these results.

The other major effect on the quality of the IGS products is the operation of the GPS receivers in the network. Problems with receivers and/or the configuration of the stations are probably one of the greatest issues facing the IGS. In this category there are many facets that effect both the IGS analysis centers and the users of IGS data. The overall quality of the IGS data set and position results is impressive. Shown in Figure 2 are histograms of the RMS scatters of the position estimates from the 67 weeks of the combined IGS SINEX files after linear trends are removed from the results. The median RMS scatter for the horizontal components is about 2 mm and for the vertical 6 mm.

The average statistics of the IGS position determinations does not reveal the important fact that there are failures of some stations that can dramatically effect users if they are using these stations as the primary link to the IGS reference frame. Also not revealed in the statistics are the temporal and spatial correlations with the results. Within the IGS community there are some well-known receiver failures such as the MADR/MAD2 where for almost 3-years the station returned data regularly but the position estimates showed multi-centimeter scatters. Similarly, near the end of 1996 the WETT site started to show anomalous position estimates although the RINEX data from the site was not obviously corrupt. As far as we know, the data from these sites can still be obtained during these intervals by anyone doing "historical data" processing, nor do the IGS log files make any mention of the problems with these data during these times.

There are web sites that can be accessed to see the time series either from the IGS analyses or individual analysis centers. The Jet Propulsion Laboratory site http://sideshow.jpl.nasa.gov/mbh/series.html shows results from the JPL analysis. The Scripps Institution of Oceanography (SIO) site http://lox.ucsd.edu shows results from the SIO analysis. Both of these analyses show daily position estimates. MIT maintains a site http://www-gpsg.mit.edu/~fresh/MIT_IGS_AAC.html that shows results from different IGS analysis centers and recently from the IGS combined SINEX file. The IGS combined results are now updated weekly. This latter site allows results from the combination and from thee different analysis centers to be overlaid pair-wise. In all these sites, a possible problem with assessing the quality of data from site is that times when results from are poor, the data is likely not be included in the time series plots. This is particularly the case when sites are trying to present geophysical results (such as velocity fields) in addition to the time series. For a user of IGS data, the problem arises that it is not always clear when results from a site are missing whether this is due to poor quality data or if, due to communication problems, the data were simply not available in a sufficiently timely fashion to be included in the IGS analyses. Currently, there is no easy way for a user to access this information.

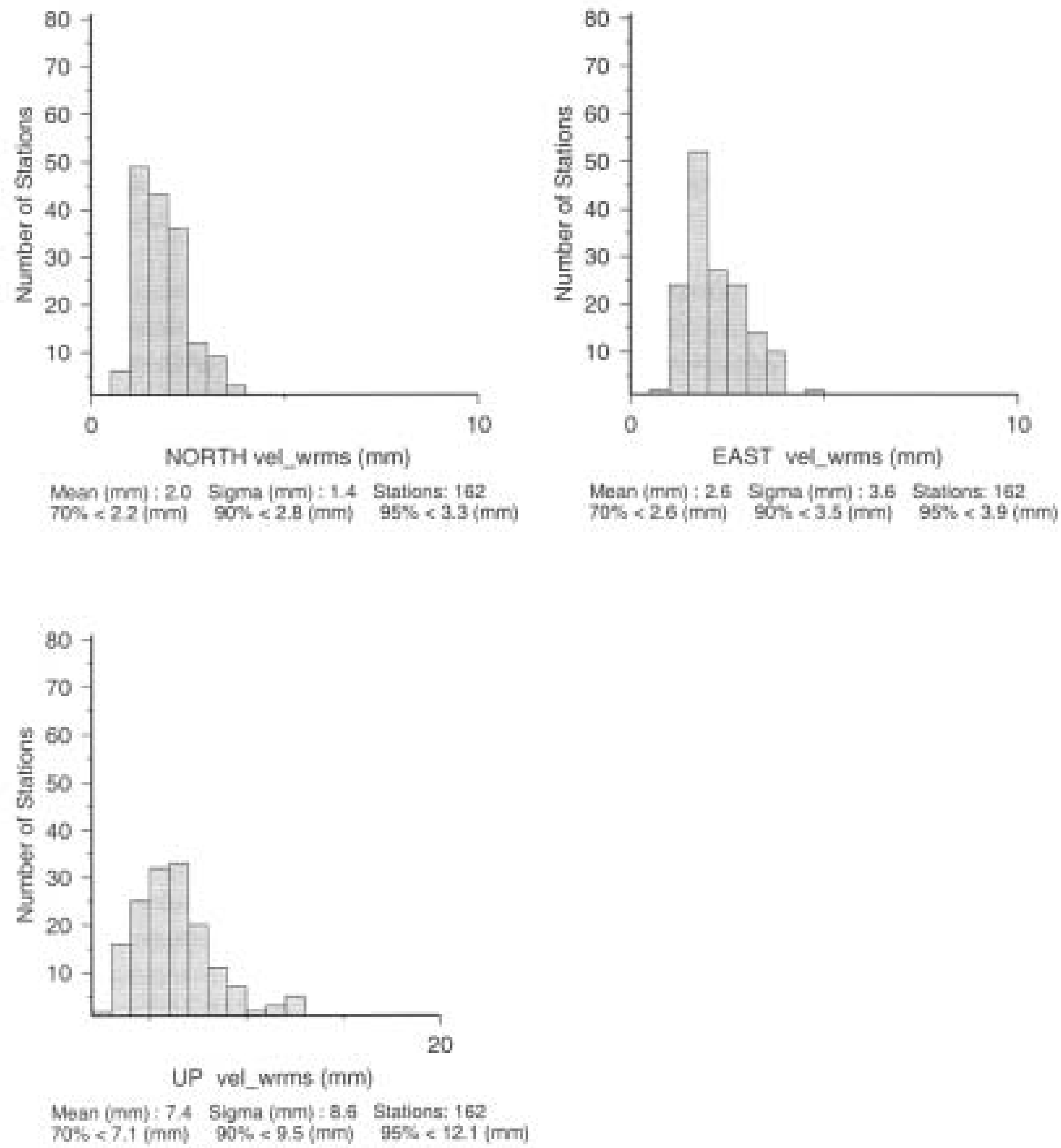

Figure 2. Histograms of the RMS scatter of the site position estimates (about a linear regression) from the weekly IGS combined SINEX files. In North, East and Up the median RMS scatters are 1.8, 2.0, and 6.2 mm, respectively.

In Figure 3, we show a recent example of the subtle failure of an IGS station and the way that this can effect IGS analysis (these results can be viewed and obtained from the MIT IGS web site). (On both the JPL and SIO web sites, the time series end near the beginning of 2000 although SIO continues to include the site their IGS submissions.) What has precisely happened at this site is not clear although all three components of the site position are affected. It is also that the data from the site is not obviously corrupt especially in early 2000 with the first northward motion where the error bars do not appreciably change size. (The most recent results have larger error bars suggesting that large portions of the data from the site are either not in the RINEX files or are being deleted during data analysis.) It is also clear that the COD analysis center stopped processing data from this site although the reason is not clear. Currently there is no formal forum for analysis centers to exchange information about the problematic sites. A user of data from this site would also find it difficult to know that data from this site was problematic.

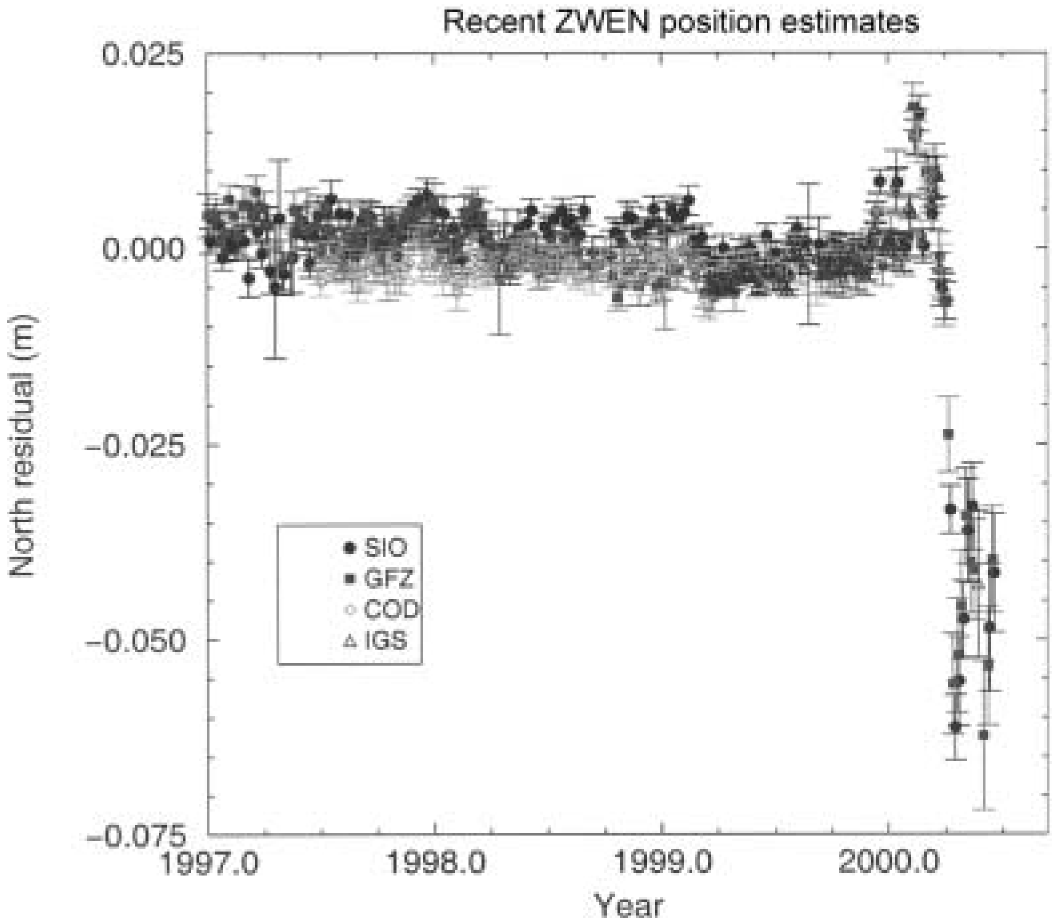

Figure 3: Recent time series for the North component of the IGS site ZWEN. There clearly is some failure of the site although it continues to generate results that are sufficiently high quality to be included in some IGS analysis center submissions.

Examination of all the results from the IGS analyses and other regional analyses such as the SCIGN array in California show a variety of failure modes of GPS receivers whose precise origins are rarely clear. In some cases, the reason is known. A specific case is the IGS SELE in Central Asia. In early 1999, the horizontal coordinates of the site show erratic daily deviations with amplitudes of 10-20 mm although the quality of the phase data seemed largely unaffected. The reason for the problem was traced to a loose antenna mounting (the antenna was literally being blown around by the wind). Although many IGS analysis centers include this station, there was never any report to the station operator that there was a problem. For many IGS stations, it is not clear that the operators of the stations process their own data because one of the advantages of being an IGS station is that your data is processed by the IGS. Currently, there is no formal feedback mechanism to station operators from the IGS analysis centers. Various sites in the Southern California Integrated Geodetic Network (SCIGN) have shown failure modes which appear to be related to water entering antennas and cables. Again, these failure modes do not necessarily produce obviously corrupt phase data; just the position estimates can be erratic.

One other class of failure mode is weather related. A number of IGS stations are located in regions where snow can accumulate during the winter. Depending in the raydome configuration, the present of snow near, in and on the antenna can have a dramatic effect on the position estimates. One of the extreme cases in the Antarctic site CAS1 where the height changed nearly 100 mm over a six-month interval. A visit to the site showed that the raydome on the antenna had been damaged and it was replaced. However, careful examination of date the raydome was replaced shows that the height of the site had returned to its nominal value about 1-month before the replacement. The implication is that the anomalous height changes were not due to damage to the raydome but rather due to snow entering the area through the hole in the raydome. This is a very remote site and so there were no direct observations of the sites at the time the height was anomalous. The effects of the presence of snow and other corrupting signals can be quantified using the signal-to-noise ratio (SNR) from the GPS receivers. Standalone software is available (http://www-gpsg.mit.edu/~tah/snrprog) that will read RINEX files with SNR included (e.g., by using the S1 and S2 observable types in the teqc program) and generates estimates of phase residuals to be expected from interfering signals. This analysis technique has been very successful at detecting the corrupting effects of the presence of snow. It can also show whether an anomalous change in station position is due to the receiver or to motion of the monument.

Some IGS sites show non-secular position variations whose origin is not clear. One very clear example is the permafrost site at Yakutsk. This site shows annual deviations in it north position with peak-to-peak variations of nearly 20 mm. The height shows even larger variations. Local measurements to a nearby site on a building have shown that these motions are due to the movement (most likely tilting) of the monument in the permafrost. Again, there is no easy way for a general user of IGS data to know that this site is problematic. Nearly all IGS sites show annual height variations whose cause is not directly known. In some cases, a portion of the movement could be due to atmospheric pressure loading and in other cases they could be due to ground water effects, either through loading and/or soil expansion and contraction. In many of the IGS log files, the precise configuration of geologic setting of a site is not given (in other cases, the descriptions can be quite expansive). As interest in interpreting non-secular motions of sites increases, there will need to be greater emphasis placed on the configurations of stations.

Enhancement of IGS Quality

Fundamentally, the quality of IGS products is controlled by the quality of station and satellite data used in the analyses. Currently a number of IGS stations yield problematic data and the characteristics of a number of satellites is less than desirable. Correction of these problems or increased dissemination of information about the causes of problems would increase the quality if IGS analysis and aid users of both the products and data.

A subtler problem is the overall accuracy of the GPS results being currently obtained. This is a more difficult problem because of the uniqueness of GPS in its temporal resolution and the overall number of stations. The IGS is at the forefront of developing standards that allow combination of initially results from different IGS analysis centers but now also includes results from different techniques. These rigorous combination procedures are now being investigated by the IERS and possibly in the future the IERS will the lead operational entity that makes the combinations. Such studies are now in their infancy but in long run will hopefully provide improvements to all techniques in the same way that IGS analysis centers have all improved over the last few years. Some recent combination results of merging VLBI and GPS with internally consistent earth orientation parameters have suggested that the VLBI results may be degraded by the combination. In examining time series from both systems the indication is that some part of the annual signals seen in GPS results may be artifacts (possibly induced by orbit modeling errors that have an annual modulation due to the orbital period of the GPS satellites). However, the assessment is difficult due to the sparse temporal and spatial coverage of VLBI measurements. Satellite Laser Ranging (SLR) results are starting to become available and these data may help clarify the situation.

Conclusions and Recommendations

While the overall quality and timeliness of IGS products is very high, we have some recommendations that should enhance these characteristics even more.

Timeliness

The IGS is very dependent on its data centers and we recommend that

- Formal contingency plans be developed and tested that allow transition between data centers in the event of a failure of one the centers; and
- The funding agencies for the data centers be made aware of their importance and be encouraged to provide sufficient funds to make the data centers more robust.

Quality

Since the IGS depends so much on the quality of the data from the IGS stations and the users of the products depend on these same data, we recommend that

- The IGS develop plans to have a more positive feedback between the site operators, the IGS analysis centers, and the IGS product and data users. Such plans, we imagine would include autonomous system to monitor station quality through both phase and position quality. When a station appears to be failing the IGS should be proactive in contacting the site operator to ascertain the problem and in informing users of the problems. A web site, maintained by the central bureau, could have a ranked list of sites that would be updated at frequent intervals. A historical ranked list should also be maintained for users that are processing older data.
- The IGS data centers should be encouraged to move data files for stations that were known to be corrupt from the main data areas to other areas where users will be aware that they use the data at their own risk.
- Station operators should be encouraged to make measurements to local reference sites at sites that are suspected of being unstable and that these local data be made available to the IGS data centers for anyone to process.
- The IGS encourage regional data centers to include the SNR in RINEX files. The impact on the size of the files is about a 10% increase in compressed files. These RINEX files can then be used as part of the monitoring system and provide a means of assessing quickly whether the degradation of site positions is receiver or monument related.

Reference Frame Working Group Technical Report

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Abstract

Natural Resources Canada's (NRCan) Geodetic Survey Division (GSD), on behalf of the International GPS Service (IGS) and its Reference Frame Working Group, combines a consistent set of station coordinates, velocities, Earth Rotation Parameters (ERP) and apparent geocenter to produce the IGS official station position/ERP solutions in the Software Independent Exchange (SINEX) format. The weekly combination includes solutions from the Analysis Centers (AC), while the Global Networks Associates Analysis Centers (GNAAC) provides quality control.

The weekly AC solutions include estimates of weekly station coordinates, apparent geocenter positions and daily ERPs. The ACs also provide separately, satellite orbit and clock estimates as part of their daily products, which are independently but consistently combined by the IGS AC Coordinator to produce the IGS orbit/clock products. All the AC products are required to be in a consistent reference frame. The combination of station coordinates originating from different ACs involves removing all available constraints and re-scaling the covariance information. The weekly combined station coordinates are accumulated in a cumulative solution containing estimated station coordinates and velocities at a reference epoch.

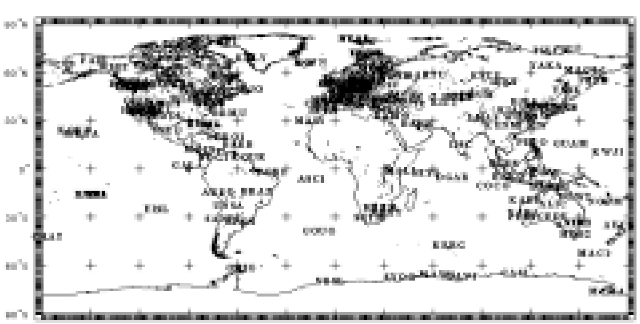


Figure 1. Stations in the Cumulative Solution

The weekly combination generally includes estimates of coordinates for 120 to 140 globally distributed stations. While the cumulative solution currently includes approximately 250 stations, about 180 (Figure 1) of them have complete information and reliable velocity estimates. The IGS combined products are required to be consistent with the most recent realization of ITRF (currently ITRF97 (Boucher et al., 1997)). This is done by transforming the weekly and cumulative solutions, respectively using 7 and 14 Helmert transformation parameters (3 translations, 3 rotations, 1 scale and their respective rates). The transformation parameters are determined from a subset of 51 high quality, globally distributed and collocated (with other space techniques) stations, also known as Reference Frame (RF) stations.

Since the beginning of 1996, weekly comparisons with ITRF97 show an accuracy of 3-4 mm horizontally and 10-12 mm vertically. Gradual improvements are apparent. Various non-random effects are present in the station coordinates time series residuals, such as periodicities and discontinuities. Equipment, local environment and processing changes are the causes for a number of discontinuities.

Introduction

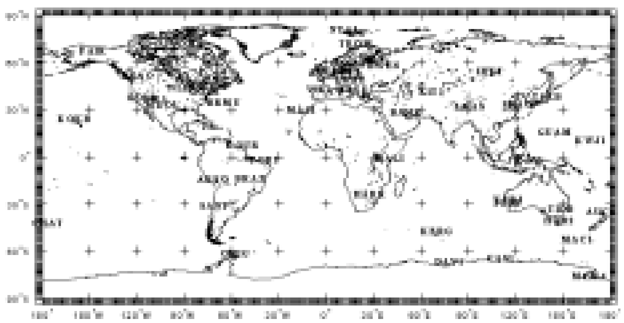


Figure 2. IGS stations used to realize ITRF97

The IGS contribution to ITRF can be subdivided into two main initiatives. First, the participation of ACs and IGS in the ITRF solutions and second, the realization and dissemination of ITRF. The IGS contribution to ITRF2000 consisted essentially in a cumulative solution that included data between GPS weeks 0837 and 1088 (96/01/21 – 00/11/18). The solution involved 167 stations distributed as shown above in Figure 1. The ITRF realization is accomplished with a station subset of the IGS network. For the realization of ITRF97, 51 high quality stations were selected (Figure 2) (Kouba et al., 1998). The accessibility to the reference frame is facilitated through the combined "IGS core products" of station coordinates, the Earth Rotation Parameters and/or the precise orbits, and the satellites/stations clock solutions. The IGS Reference frame realization of ITRF can be accessed, by GPS users, with the precise code and phase observations. The IGS participation (IGS stations) and the IGS realization aspects are very closely related. Data used to realize an IGS ITRF will also be subsequently contributed to the IERS combination process to generate ITRF at future epochs.

IGS Participation to ITRF2000

The ITRF2000 combines solutions from a number of space techniques including Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Doppler Orbitography by Radio-positioning Integrated on Satellite (DORIS) and GPS. The IGS solution was part of a group of about 20 global solutions used for the realization of ITRF2000. Five other GPS (AC) global solutions were also submitted as well as six densification solutions.

Between GPS weeks 0837 (96/01/21) and 0977 (98/10/03), the weekly combined solutions from JPL, MIT and NCL Global Associates Analysis Centers (GNAAC) were used in the cumulative solution. Since GPS week 0978 (98/10/04), the seven Analysis Centers (AC) (CODE, ESA, GFZ, JPL, NGS NRCan and SIO) are used in the combination, while the GNAAC are used to quality control the weekly combination (Table 1).

The AC solutions are combined using the least-squares technique. All the available covariance information between the station coordinates within each AC solution is used. Since GPS week 1013 (99/06/06) the weekly combination also includes daily ERP (pole position and rate, calibrated length of day (Mireault et al. 1999)) and since GPS week 0978 (98/10/04) weekly apparent geocenter estimates. The cumulative combination is updated every week with the latest weekly combination. This cumulative solution includes station coordinates and velocities for about 250 sites. Of those, about 180 have reliable velocity estimate. The cumulative solution is currently aligned to ITRF97 by applying a 14-parameter transformation estimated using the set of 51 RF stations. Inner constraints in origin, orientation and scale (and their rates) are applied to the solution. Due to the large number of input solutions used and the variety of sources, there are some concerns for potential numerical instabilities; but, at this time, they appear to be that under control.

Table 1

IGS Analysis Centers (AC)	
CODE	Center for Orbit Determination in Europe, AIUB, Switzerland
ESOC	European Space Operations Center, ESA, Germany
GFZ	GeoForschungsZentrum, Germany
JPL	Jet Propulsion Laboratory, USA
NOAA	National Oceanic and Atmospheric Administration / NGS, USA
NRCan	Natural Resources Canada, Canada
SIO	Scripps Institution of Oceanography, USA
IGS Global Network Associate Analysis Centers (GNAAC)	
NCL	University of Newcastle-upon-Tyne
MIT	Massachusetts Institute of Technology
JPL	FLINN Analysis Center Jet Propulsion Laboratory

IGS Analysis and Associate Analysis Centers

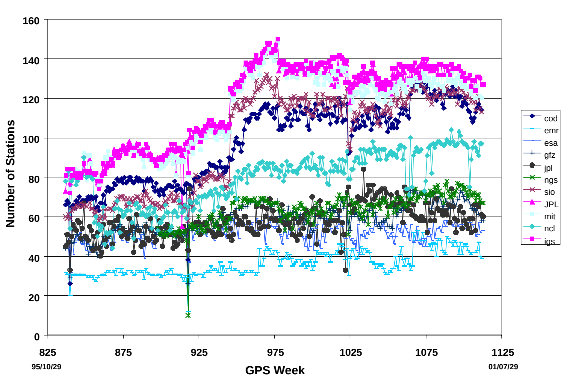


Figure 3. Number of AC/GNAAC/IGS stations in the weekly solutions

The number of stations contributing to weekly SINEX solutions has increased steadily since the beginning of IGS. The number of stations has gone from 25 to 60 stations in 1996 to between 40 and 130 stations currently (Figure 3). There is a significant overlap between the stations used by each AC. Out of the 130 stations actively used in the IGS network, about 95 are used weekly by 3 or more ACs. Human and computer resource limitations are the main factors constraining the number of stations used by each AC. The ACs have continuously upgraded their software and approaches, which has resulted in gradual improvements of their solution results. Ideally, all the processed data should be done in a consistent manner. But, due to the large quantity of data and processing load involved, none of the ACs has yet to complete the reprocessing. On the hardware side, receiver/antenna, communication and computer technologies have also progressed, resulting in higher quality data, faster access and processing.

The standard deviations of residuals between the ITRF2000 and the IGS solution are summarized in Table 2. They show a horizontal position precision approaching the 1mm level and the vertical component approaching 3mm. The velocity precision is approaching 2mm/y horizontal while the vertical component is about 5mm/y. These are probably somewhat optimistic, since the GPS solutions in the ITRF2000 combination used, to a large extent a common set of IGS stations. As mentioned above, the common station coordinates are to a large extent derived from a common set of code and phase measurements.

Table 2.

	Position (mm)	Velocity (mm/y)
Latitude	1.1	1.8
Longitude	0.9	2.3
Height	3.1	5.1

IGS standard deviations (STD) with respect to ITRF2000

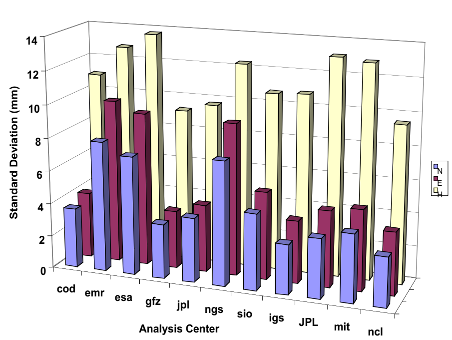


Figure 5. AC/GNAAC Station Coordinates Residuals STD with respect to the Cumulative Solution

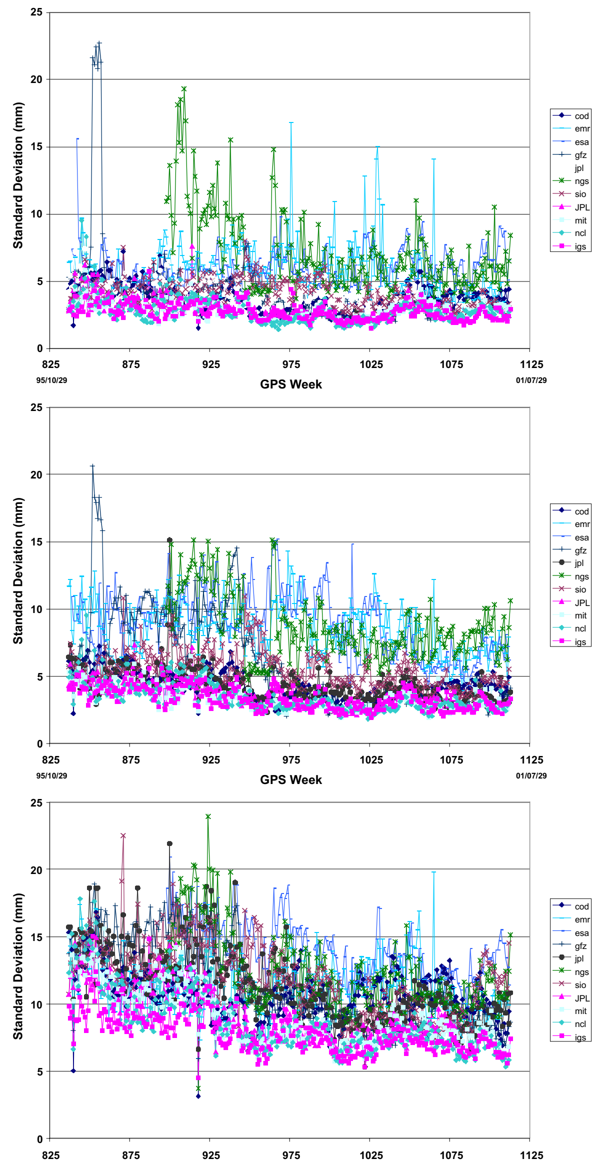
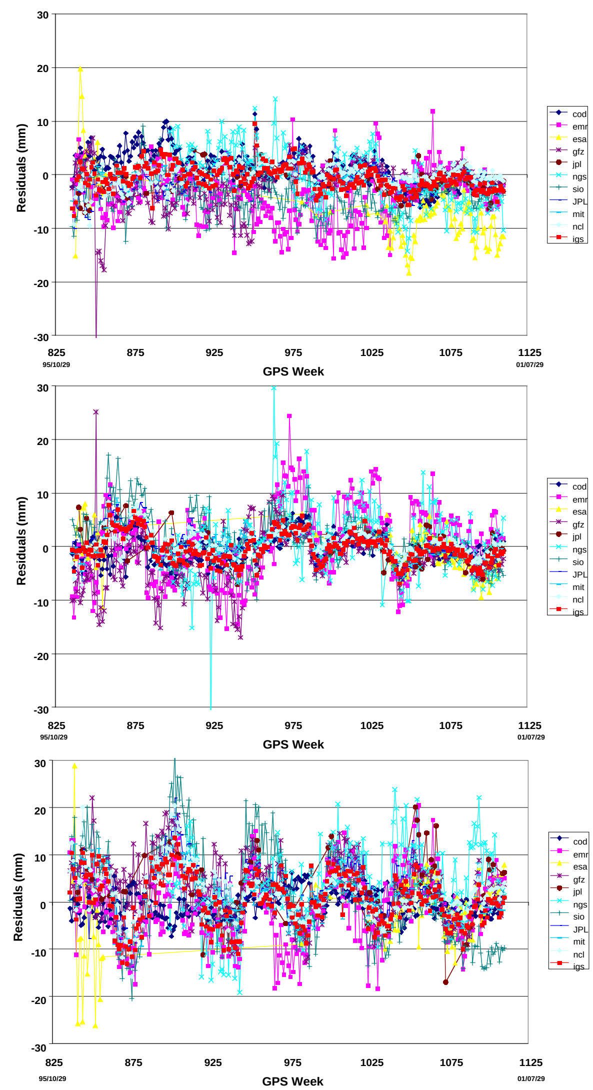


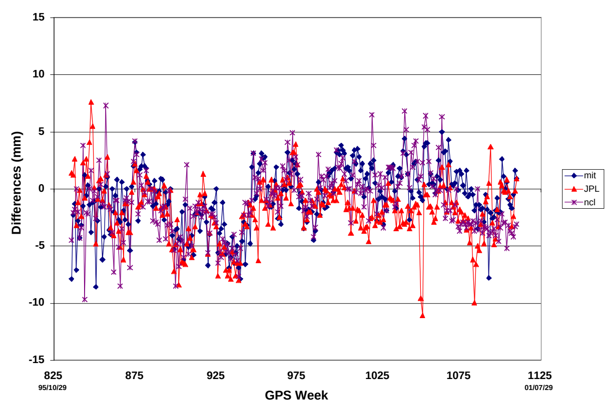
Figure 4 a-b-c
Latitude, Longitude and Height weekly STD with respect to Cumulative Combination

The standard deviations of the residuals between the weekly and the cumulative solutions for all stations have been estimated for each center (AC/GNAAC/IGS). Figure 4 a-b-c shows the time series of the standard deviations for the latitude, longitude and height components. The IGS and GNAAC standard deviations are 3-4mm horizontal and 7-10mm vertical (Figure 5). The ACs are also generally close to that level. Also noticeable is the gradual improvement of the statistics, especially in the height component (Figure 4c). The bandwidth of the standard deviations is also decreasing, indicating a better level of agreement between the various solutions. Similar improvements have been reported for the precise orbit/clock combinations also done weekly by the IGS AC Coordinator (http://www.aiub.unibe.ch.acc.html).

At the station level, a detailed look at the residual position time series shows the longer-term systematic effects present at some stations. For example, Figure 6 a-b-c shows residuals of the weekly AC/GNAAC/IGS solutions with respect to the cumulative solution for the latitude, longitude and height components at station Penticton (DRAO). An annual period with amplitude of about 7mm is noticeable in the height component. Some periodic effects can also be seen in the longitude residuals. The level of agreement among the AC's also improves with time. The RMS of the residuals for the AC/GNAAC/IGS are respectively (Lat:5.4/2.4/2.4, Lon: 5.3/2.7/2.7, Hgt: 8.2/5.7/5.4). This station shows a rather large periodic signal (although not the largest). Most stations have little or no significant periodic signal. This periodic effect is possibly caused by variations in seasonal atmospheric pressure loading, which are not currently modeled in AC solutions. A detailed analysis of the periodic effects will be possible once the reprocessing is completed. Occasionally, biases do exist between the solutions, usually in the height component. Those biases are sometimes caused by incorrect antenna height used in the processing. The redundant time series are very useful to separate isolated outliers from ongoing biases. As part of the reprocessing of the AC solutions, a number of stations



Figures 6 a-b-c. Latitude, Longitude and Height residuals between the weekly and cumulative solutions at station Penticton (DRAO) coordinate residuals time series discontinuities problems have been explained and corrected. Comparisons done in the past between the weekly and the cumulative solutions statistics have indicated that 60-70% of the noise is caused by short-term effects, while the rest has a longer-term signature. Those long-term signatures often take the form of discontinuities, which tend to affect mainly the height. They are generally caused by either blunders, equipment or processing changes.



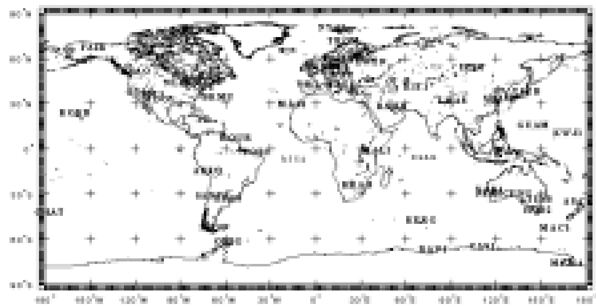
Penticton (DRAO) Height differences (IGS-GNAAC)
Figure 7

Figure 7 shows height differences between the IGS and the GNAAC solutions at station Penticton. The standard deviation is 3 mm over a period of about 5 years. Differences of this magnitude are expected, due to differences in the processing strategies of the GNAACs. A small bias is apparent in the early weeks, a more refined analysis is expected to explain and potentially correct this artifact.

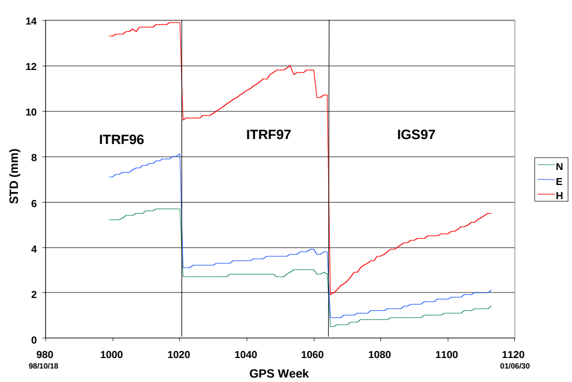
The reprocessing of the AC SINEX solutions between GPS weeks 0837 (96/01/21) and 0977 (98/10/03) is currently underway. Two iterations have at this time been completed. During the first iteration, the most obvious inconsistencies were removed. Nearly 9000 outliers were flagged. Explanations for many outliers could be found, thus allowing for corrective measures to be applied. A second iteration was run. This allowed to test the validity of the corrective measures applied to a number of weekly solutions, and to uncover new outliers. The exact number of iterations required is yet unknown. Once complete, the reprocessing will improve the quality of the weekly and cumulative solutions as well as its consistency and traceability by using a consistent strategy (Ferland et al. 2000). This reprocessing is using all the available information provided by the ACs and GNAACs. Each solution (AC/GNAAC) is unconstrained, its covariance information is rescaled with an estimated variance factor (chi squared per degree of freedom). AC/GNAAC station coordinates estimates are compared and rejected if they exceed the thresholds of 5 sigmas or 50mm (8 sigmas and 80mm for the first iteration). The residuals in the in the variance factor estimation are determined by taking the difference between each AC and the cumulative solution. The AC and GNAAC solutions are considered independent during the processing. In reality there is a significant level of correlation between the AC solutions mainly because they use the same code and phase observations for all the common stations. The differences between the AC solutions are mainly caused by variations in the processing strategies and the network distribution. A variance factor is also estimated and applied to the weekly IGS combination, again by using the cumulative solution as a reference. This should partially compensate for the neglected correlation between the AC solutions during the weekly solution combination. Similar correlations also exist between the IGS and the GNAAC weekly solutions. This is somewhat less of a concern, because the GNAAC are used mainly for quality control. The cumulative solution also needs to be rescaled, because the parameters covariance information gradually becomes unrealistically small as weekly solutions are added. More investigation is required to properly rescale the cumulative solution.

IGS Realization and Dissemination Of ITRF2000

The current IGS realization of ITRF97 has been shown in Figure 2. It includes 51 globally distributed RF stations. The proposed set of stations to realize the ITRF2000 is shown in Figure 8. It currently includes 55 stations. All the proposed additions/changes are in the Southern Hemisphere with the objective to improve the station distribution. Two new stations are proposed in South America while one would be removed. Three other stations are proposed, one on Ascension Island in the Atlantic Ocean and one on Diego Garcia Island in the Indian Ocean as well as one in Australia.



Proposed IGS Stations for the Realization of ITRF2000
Figure 8



Weekly Reference Frame Station Coordinates Residuals STD between each Reference Frame Realization and the IGS Cumulative solutions
Figure 9

Figure 9, shows the quality of the fit between the successive IGS/ITRF realizations and the weekly updated cumulative solutions in ITRF96, starting with GPS week 0999 (99/02/28). There were already some improvements between the realization of ITRF96 and the original realization of ITRF97, and further improvements were made with the implementation of the IGS97. For ITRF96, ITRF97 and IGS97, the horizontal standard deviations went down from 5-8mm, to 3-4mm and to 1-2mm. In the vertical component they decreased from 13-14mm, to 10-12mm and to 2-6mm, respectively. The gradual degradation is caused mainly by propagated errors in the station coordinates and velocity of the reference frame realizations, as the extrapolation time increases. Preliminary tests done with the proposed IGS realization of ITRF2000 would result in sub-mm standard deviations for GPS week 1110-1114 (May 2001). The use of ITRF2000 directly would

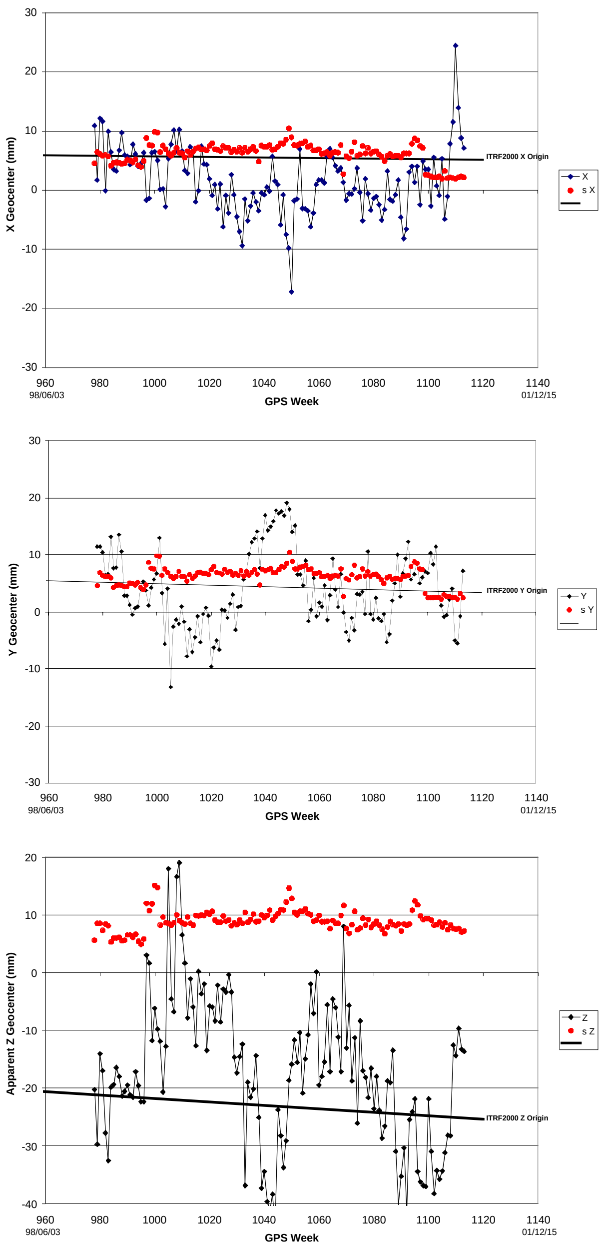


Figure 10 a-b-c . Apparent Geocenter Weekly estimates and formal sigmas as well as proposed IGS realization of ITRF2000 origin with respect to current IGS realization of ITRF97.

results in standard deviations of about 3mm horizontally and 6mm vertically for the same epoch.

The weekly estimated IGS geocenter is also affected by the proposed realization. Figure 10 a-b-c shows the X, Y and Z estimated geocenter with respect to the realization of ITRF97. The estimated weekly geocenter positions currently rely on COD, ESA and JPL SINEX solutions. The Figure 10 a-b-c also shows the position of the origin of the proposed IGS realization of ITRF2000 with respect to ITRF97. The time series show an average offset 1.6mm, 4.0mm and –17.4mm for the X, Y, and Z components in ITRF97.

The average offsets of the ITRF2000 geocenter for the same period are 5.5mm, 4.0mm and –22.7mm. This leaves a difference of 3.9mm, 0.0mm and 5.3mm for each component. This shows an improvement for each axis, specially the Z component.
The ERPs are combined in the weekly SINEX solution along with the station coordinates by making use of all covariance information. The best AC pole (and rates) are consistent at the 0.05-0.10mas (0.10–0.20mas/d), while the calibrated LOD are consistent at 20-30us. Figure 11 show the daily time series residuals for the X and Y pole (Top) and their rates (Middle) between the combined solution "igs00p02" and the AC/GNAAC. The bottom portion shows the daily difference between the combined solution and Bulletin A. The IGS combined solution and the Bulletin A are not independent, since the AC solutions

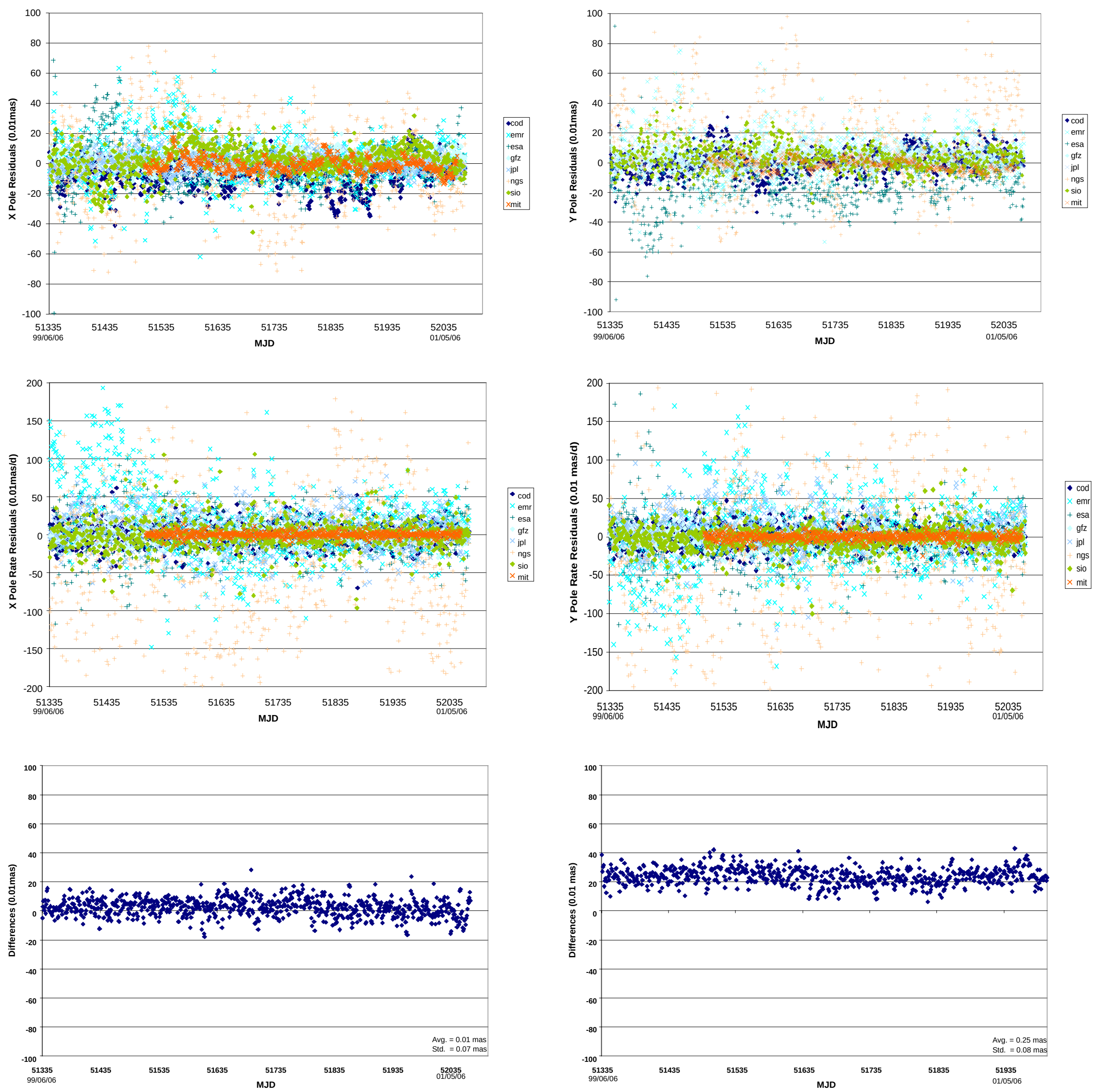


Figure 11 a-b (top) c-d (middle) e-f (bottom).
Daily X Pole, Y Pole, (top) X Pole Rate, Y Pole Rate (middle) differences between the combined solution “igs00P02” and the AC/GNAAC estimates.
Daily X Pole, Y Pole, (bottom) differences between the combined solution “igs00P02” and the Bulletin A.

contribute significantly to Bulletin A. The Bulletin A daily estimates were linearly interpolated to match the IGS combined values epochs. Small differences between the AC combined pole and pole rates are due to differences in processing strategy (e.g.: different weighting and rejection criterion). Similar daily ERPs are also estimated as part of the final GPS orbit combination process “igs95p02”. Comparison between the igs00p02 and igs95p02 show no significant average difference between them, and a noise level of about 0.07mas which is similar to the differences with respect to Bulletin A (bias removed). The combined ERPs are consistent with those combinations at about 0.05mas (0.10-0.20mas/d).

Summary

The IGS cumulative solution now contains about 270 stations among which 167 were submitted to ITRF for inclusion in ITRF2000. Analysis of the residuals of the ITRF2000 combination show horizontal/vertical position RMS of about 1mm / 3mm and horizontal/vertical velocity RMS of 2mm/y / 5mm/y. The IGS realizations of ITRF uses a subset of the IGS cumulative solution. This improves the internal stability and consistency of the weekly product alignment. The use of the 7 ACs and the 3 GNAACs provide significant redundancy and robustness to the analysis. The analysis has also shown that station statistics have a gradually improved over the years. The weekly apparent geocenter estimates show improved agreement with the proposed IGS realization of ITRF2000 origin compared to the IGS realization of ITRF97.

Acknowledgements

A large number of agencies contribute to IGS. Among them are the agencies responsible for the installation and maintenance of the tracking stations, the regional and global data centers in addition to the ACs and GNAACs already mentioned. A complete list of contributors can be found at the IGS web site (http://igscb.jpl.nasa.gov/).

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