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SPECIAL ISSUE

Global GPS data analysis at the National Geodetic Survey

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Abstract NOAA's National Geodetic Survey (NGS) has been one of the Analysis Centers (ACs) of the International GNSS Service (IGS) since its inception in 1994. Solutions for daily GPS orbits and Earth orientation parameters are regularly contributed to the IGS Rapid and Final products, as well as solutions of weekly station positions. These solutions are combined with those of the other ACs and then the resultant IGS products are distributed to users. To perform these tasks, NGS has developed and refined the Program for the Adjustment of GPS EphemerideS (PAGES) software. Although PAGES has continuously evolved over the past 15 years, recent efforts have focused mostly on updating models and procedures to conform more closely to IGS and the International Earth Rotation Service (IERS) conventions. Details of our processing updates and demonstrations of the improvements will be provided.

Keywords Global Navigation Satellite Systems (GNSS) · Global Positioning System (GPS) · National Geodetic Survey (NGS) · International GNSS Service (IGS) · Analysis Centers (ACs)

1 Introduction

Today, the Global Positioning System (GPS), operated by the United States government, is one of two functioning Global Navigation Satellite Systems (GNSS); GLONASS, operated by the Russian Federation government, is the other system. A third system, GALILEO, to be operated by the European Union, is expected to be functional by 2013, and China is presently developing a fourth system called Compass.

Currently, there are about 29–32 usable GPS satellites broadcasting radio signals toward Earth. The signals contain approximate and precise information about the satellite's position in its orbit around Earth. A result of its design, this constellation of GPS satellites provides at least four satellites at any moment in time as viewed from any point on the Earth's surface (e.g., Hofmann-Wellenhof et al. 2001).

The National Geodetic Survey (NGS) uses the approximate and precise information contained in the GPS signals to estimate the position of each satellite at 15-min intervals. In addition to GPS satellite orbits, other products which are estimated include Earth Rotation Parameters (ERPs), weekly terrestrial reference frame coordinates and tropospheric zenith path delays.

Each day, NGS and seven other agencies (http://igscb.jpl.nasa.gov/organization/centers.html) distributed worldwide use the approximate and precise information collected at receivers in a global tracking network (e.g. Fig. 1) from the previous day to estimate the GPS satellite orbits during the previous day. These daily solutions are provided to

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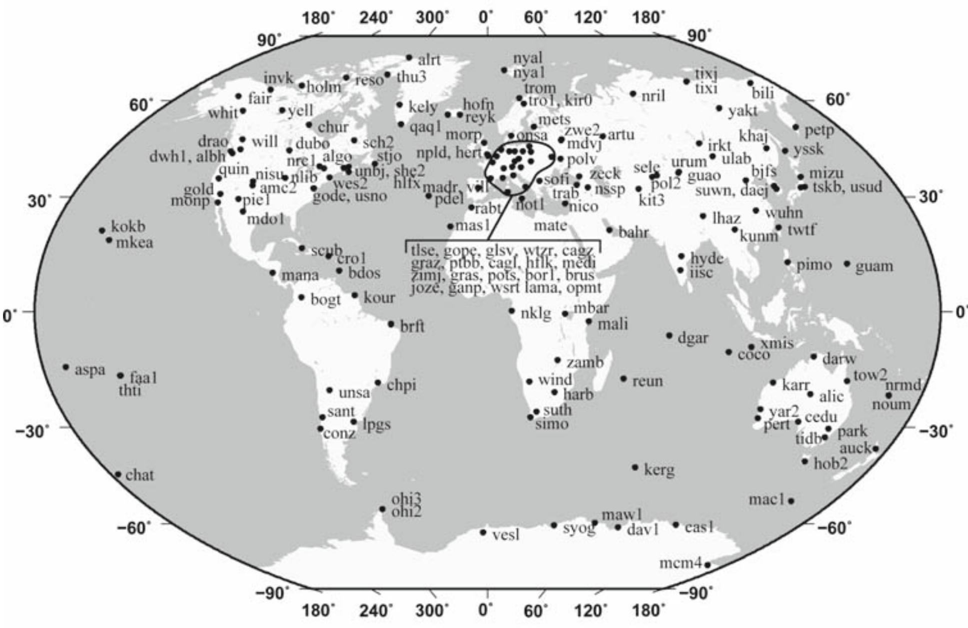

Fig. 1 The 165 GPS sites making up the NGS global GPS satellite-tracking network. About 130 of the sites are known independently by the IGS to have positions and velocities with relatively small uncertainty. Data collected at these 165 sites are available at ftp://cddis.gsfc.nasa.gov

the International GNSS Service (IGS), which combines them with other ACs solutions to generate the IGS Rapid combined orbit (with a 17-h latency).

Each week, (currently) eight agencies use the approximate and precise information collected over a 7-day period, but about two weeks earlier, to estimate more precisely the GPS satellite orbits during that 7-day period. These weekly solutions are also provided to the IGS, which combines them with other ACs solutions to generate the IGS Final combined orbit (10–14 day latency).

Because the IGS Rapid and Final orbits are a geometric and statistical weighted combination (e.g., Kouba et al. 1998) of the respective daily and weekly solutions from the eight IGS Analysis Centers, the precision of the IGS orbits depends on the combined precision of the individual solutions. The focus of this article is on summarizing the changes to the NGS GPS processing software and how the resulting NGS daily and weekly orbits compare to the IGS Rapid and Final orbits, respectively.

2 Overview of orbit estimation at NGS

Since 1984, NGS has been developing software designed specifically for estimating GPS orbits. The software in its current form mainly consists of three main FORTRAN programs: PAGES, which stands for “Precise Adjustment of GPS EphemeredeS”; GPSCOM, which stands for “GPS COMbination”; and ADJEPH, which stands for “ADJust EPHemeredes”. PAGES uses batch weighted least squares to estimate a variety of parameter types (e.g., satellite state vectors, polar motion parameters, station coordinates and tropospheric corrections). For efficiency, the processing of large networks is done by first processing sub-networks to reduce the size of normal equations within PAGES, and then combining those to determine global parameters using GPSCOM. Program ADJEPH adjusts an a priori (binary) ephemeris using either a PAGES or GPSCOM solution to output an ephemeris in the (ASCII) Standard Product (SP3) format (Spofford and Remondi 1994; Hilla 2007). The models and procedures in the GPS orbit estimation software have evolved continuously since 1984. The majority of the algorithms used in the software are unique to NGS. While a technical summary of the NGS models and procedures can be found at http://igscb.jpl.nasa.gov/igscb/center/analysis, the following sections will serve to highlight the underlying approach in GPS orbit estimation at NGS.

2.1 Observables

The GPS satellites broadcast two carrier radio signals (L1 and L2), at the central frequencies $f_{L1} = 1575.42$ MHz and $f_{L2} = 1227.60$ MHz. Superposed on the carrier signal are binary coded signals. NGS uses these phase and code data collected at 30-second intervals at each site in the tracking network with observations down to 10° above the horizon. Observations of GPS signals between 10° and 30° are important for the accurate estimation of the tropospheric delay. Because these low-elevation observations are subject to significant atmospheric interference and multipath noise, NGS began down-weighting observations as a function of the elevation angle beginning in January 2007 (GPS week 1412).

The phase and code observations used by NGS are contained in RINEX (Receiver INdependent EXchange) files generated at each site in the tracking network. After collecting RINEX files from the receivers in the tracking network, NGS pre-processes (or "cleans") the phase observations in each file in three relatively standard ways:

- using the "quality check" option in the TEQC software, developed by Estey and Meertens (1999), for the "Translation, Editing and Quality Checking" of phase and pseudorange observations in RINEX files;
- using the MERGEDB module, developed at NGS, to synchronize the phase and pseudorange observations in a set of RINEX files; and
- using the EDITDB module, also developed at NGS, for detecting and correcting systematic errors introduced by a GPS receiver losing track of a GPS satellite (i.e., a "cycle slip") by analyzing different linear combinations of L1 and L2.

The basic observables for the NGS orbit determination are the double-difference carrier phases obtained from daily networks of baselines chosen using an optimal Delaunay triangulation algorithm. The code signal is only used for receiver clock synchronization and to aid in fixing phase ambiguities using the Melbourne–Wuebbena widelane method (Melbourne 1985; Wübbena 1985).

2.2 Antenna calibrations

Calibration of GPS antennas (satellite and station) is critical to any orbit estimation if centimeter level precision is desired. Calibration allows for a correction to be applied when the instantaneous position of the direction-dependent antenna's phase center is different from the mean electrical phase center. These deviations between the actual phase center and the mean electrical phase center are called Phase Center Variations, or PCVs.

Relative PCVs are determined at the NGS field station in Corbin, Virginia by measuring the phase center pattern of one uncalibrated antenna compared to the phase center of a standard antenna (i.e. the AOA DORNE MARGOLIN T). It was observed, however, that relative antenna calibrations were inadequate based on baselines that had been established for long periods of time. The problems were evident in the vertical component of the position of a GPS site, resulting in an incorrect value for the Earth's volume. In addition, relative calibrations were measured only using observations from satellites at elevation angles greater than 10°.

"Absolute" PCVs are determined by a robotic system developed by the University of Hannover and the Geo++ company (Menge et al. 1998; Wübbena et al. 1996). The robot makes 3-D calibrations using observations from satellites at positions down to the local horizon of the antenna.

All absolute phase center variations and the related corrections are contained in the IGS ANTEX file "igs05_wwww.atx" (where wwww is the GPS week of the calibration), which is currently being maintained by Ralf Schmid at the Technical University of Munich (ftp://igscb.jpl.nasa.gov/igscb/station/general/).

Satellite center of mass offsets are satellite specific (Z-offsets) and satellite-block specific (X, Y-offsets). Satellite antenna phase center corrections are satellite-block specific and nadir angle dependent. The igs05_wwww.atx file also contains absolute station antenna PCVs and offsets which are elevation and azimuth dependent. With future satellite launches and technological upgrades by manufacturers, the igs05_wwww.atx file will be continually updated. NGS began using the IGS ANTEX file coincident with the switch to the IGS05 reference frame detailed in Sect. 2.4.

2.3 Troposphere, ionosphere and tidal displacements

The troposphere delay is estimated using models derived from global historical meteorological records (Bar-Sever et al. 1998; Boehm et al. 2006; Saastamoinen 1972). For the a priori tropospheric model, relative humidity is set to 50% for all sites and pressures and temperatures are derived from a season-dependent GPT (Global Pressure and Temperature) model. The zenith hydrostatic and wet delays are computed a priori using the formula of Saastamoinen. The Saastamoinen zenith delay models ("wet" and "dry") and the Boehm (GMF) Global Mapping Functions (dry and wet) are used to remove most of the neutral atmosphere (tropospheric) effects. The Boehm mapping functions are based on mean values of weather model data which reduce systematic effects (especially in the Southern hemisphere). No horizontal a priori gradient is used. Residual tropospheric errors are modeled by the parameter estimation described in Sect. 2.6.

The ionosphere delay is not estimated. Instead, the first order effect of the ionosphere is eliminated by using dual-frequency observations in linear combination. Second order and other effects are currently ignored.

The tidal displacements are derived from the International Earth Rotation Service (IERS) Conventions 2003. The IERS Conventions 2003 (McCarthy and Petit 2004) enable one to model the instantaneous position of a terrestrial point as a function of time. This is performed by initial "regularized" coordinates and velocities at a reference epoch and the summation of various "high-frequency" motions affecting that site position. The summation of tidal displacements applied by NGS are solid Earth tide (subroutine dehanttideinel.f), permanent tide (zero-frequency contribution left in tide model, not in site coordinates), ocean tide loading (FES2004 model using site-dependent amplitudes and phases for 11 main tides) and the ocean tide geocenter (site-dependent coefficients corrected for center of mass motion of whole

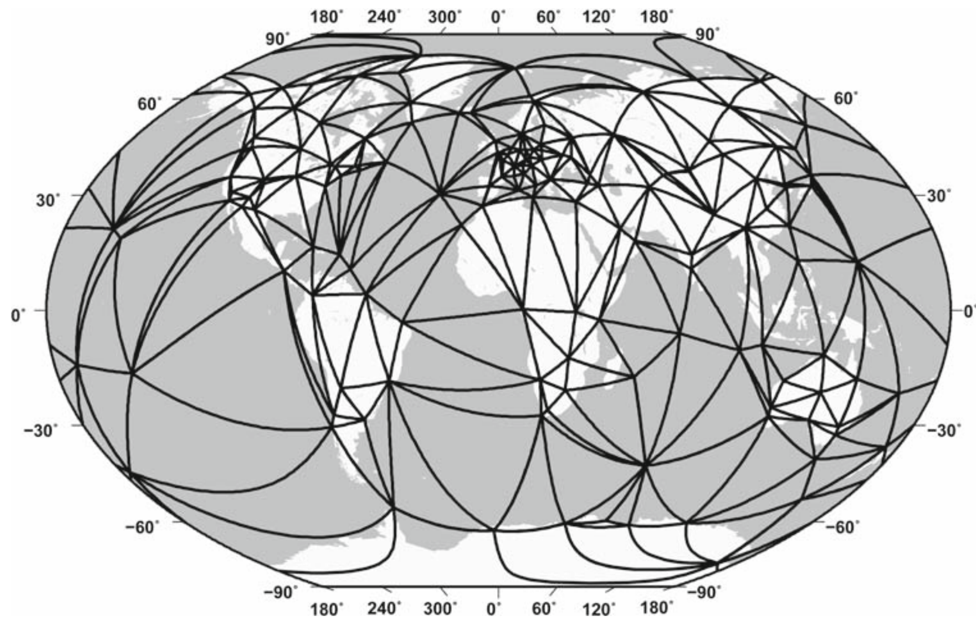

Fig. 2 A set of baselines chosen from the NGS global GPS satellite-tracking network (Fig. 1) using a Delaunay triangulation algorithm for points on a sphere (Renka 1997), which selects triangles of baselines by minimizing the size of each triangle and the differences in the internal angles of each triangle; there are 654 baselines

Earth; center of mass corrections are also applied to satellite orbits).

2.4 Terrestrial reference frame

Starting on 5 November 2006 (GPS week 1400), the Analysis Centers of the IGS switched from the IGS realization (IGb00) of the 2000 International Terrestrial Reference Frame (ITRF2000) to the IGS realization (IGS05) of the ITRF2005 (Altamimi et al. 2007). The primary difference between IGb00 and IGS05 is that the effect of switching from relative GPS antenna calibrations to absolute calibrations was accounted for by applying empirical corrections to the ITRF2005 coordinates. Another difference is the number of stations used to realize the frame, 90 in the case of IGb00 and 132 for IGS05. To be consistent with ITRF2005, the IGS05 is transformed using a seven-parameter similarity-transformation aligning IGS05 with ITRF2005. It is important to note, however, that polar motions were assumed to be approximately unchanged in switching from relative to absolute PCVs.

It is also important to note that the reference frame is defined by the tracking network. NGS uses all available stations of the 132 IGS05 set, plus others for improved distribution and geometry (approximately 165 sites per day). Data are processed in double-difference subnets and combined at the normal equation level. On 14 January 2007 (GPS week 1410), NGS switched from a network design consisting primarily of independent baselines to a completely connected network. These connected baseline networks are defined using an optimal Delaunay triangulation algorithm (Renka 1997) on a sphere. The Delaunay (Fig. 2) algorithm works by minimizing the differences in the internal angles of triangles in the triangulation while finding the nearest neighbor triangles. This same approach is used in finite element modeling.

2.5 Orbit models

Our numerical integration uses a variable (high) order Adams-Moulton predictor-corrector with direct integration of the second-order equations of motion. The Earth's gravitational/geopotential (static) field is defined by the Goddard Earth Model GEM-T3, which has been developed from a combination of conventional satellite tracking, satellite altimeter, and surface gravimetric data. GEM-T3 is truncated to the 8th degree and order. The geocentric gravitational constant (GM) is 398,600.4415 km^3/s^2 and the Earth's equatorial radius (AE) is 6,378,136.3 m.

NGS recently has changed its Solar Radiation Pressure (SRP) model to the modified CODE operational version of their SRP model, discussed in Sect. 3.3.

2.6 Estimated parameters

Because NGS uses double-differenced carrier-phase observations, satellite and receiver clocks are not estimated, but eliminated. The clock values given in NGS orbit files are extracted from the GPS Broadcast navigational message (not computed by NGS).

Station coordinates are adjusted, relative to the a priori values from the IGS05.snx file, a product published by the Reference Frame Working Group (RFWG), one of several IGS Working Groups. A no-net-rotation condition is applied with respect to the IGS05 frame using up to 132 reference frame stations. The a priori sigmas for non-reference frame stations are 1 m for each component.

The estimated orbital parameters are the geocentric positions and velocities, the solar radiation pressure scaling terms in 3 orthogonal directions (3 constant offset and 2 once-per-rev terms), and the midday 3D constrained velocity discontinuities. The final orbits are adjusted from a priori values and have a no-net-rotation condition imposed, with respect to the IGS05, using up to 132 IGS fiducial stations. The rapid orbits are rigidly constrained to the IGS05 frame by fixing the IGS "sanctioned" fiducial stations.

The tropospheric delay, consisting of the zenith hydrostatic delay, the zenith "wet" delay and a horizontal delay gradient, is adjusted for each station assuming the delays are mostly dominated by the wet component. Before 25 February 2007, the zenith delay was parameterized by a piecewise linear, continuous model with 1-h intervals. Since then, the delay is parameterized by a piecewise-constant, discontinuous model.

Real-valued double-differenced phase cycle ambiguities are adjusted except when they can be resolved confidently (<4.5 cm uncertainty), in which case they are fixed (approximately 95% are fixed).

The estimated Earth Rotation Parameters (ERP) are daily X & Y pole offsets, pole-rates, and length of day (LOD) estimated at day boundaries. The X & Y pole are estimated as piece-wise, linear offsets from IERS Bulletin A and IGS ERP (combined) a prioris over each 1-day segment. These estimates are then transformed to equivalent offsets and rates at noon epochs to be consistent with the IGS. No constraints are applied to the EOP estimates between days.

3 Other recent NGS changes

3.1 Ocean-loading tide model

In March 2006, the IGS Analysis Centers agreed to use a standard model for the correction of displacements due to ocean tide loading. The model was originally derived for satellite altimetry applications (Le Provost et al. 1994, 1998), but was shown to be effective for GPS applications, too. Access to the latest version of the model, FES2004, is available at http://www.oso.chalmers.se/~loading

3.2 De-weighting observations

Starting with GPS Week 1412 (1/28/2007–2/3/2007) NGS began de-weighting observations between a receiver and a satellite according to elevation angle, θ. Observations made using a satellite at elevation angles between 10° and 30° above the horizon are important for accurate estimates of the troposphere delay. Because a signal travels through so much atmosphere at lower elevation angles and the multipath effects increase dramatically, the observations made at the receiver are relatively noisy.

NGS assigns a priori standard deviations to receiver–satellite observations according to the following relation:

$$\sigma_{\text{a priori}} = A_0 + \frac{A_1}{\sin(\theta)} \tag{1}$$

Prior to GPS Week 1412, $A_0 = 0.05$ m and $A_1 = 0.00$ m, so that observations at all elevation angles were treated equally in the weighted least-squares solution.

By testing solutions at different A_1 values (i.e., $A_1 = 0.01, 0.02, 0.03, 0.04, 0.05$ and 0.10), a value of $A_1 = 0.02$ was found to be optimal. Thus, given that NGS ignores observations from satellites below 10°, observations at the lowest elevation angle would have the following a priori standard deviations:

$$\sigma_{\text{a priori}} = 0.05 + \frac{0.02}{\sin(10^\circ)} = 0.165\,\text{m} \tag{2a}$$

and observations at the highest elevation angle (zenith) would have the following a priori standard deviations:

$$\sigma_{\text{a priori}} = 0.05 + \frac{0.02}{\sin(90^\circ)} = 0.07\,\text{m} \tag{2b}$$

The a priori standard deviation at 10° is 2.36 times larger than at zenith. Thus, according to equations (2), satellite-receiver observations at an elevation angle of 90° are weighted, in the least-squares solution, 5.57 (i.e., $(2.36)^2$) times stronger than observations at an elevation angle of 10°.

Note that the formal errors for the final parameter adjustments are rescaled to give an overall reduced chi-square value of unity.

3.3 Solar radiation pressure model

On 17 June 2007, NGS switched to the Modified Center for Orbit Determination in Europe (CODE) Model, also known as the modified BERNE (6+5) solar radiation pressure model. Before 17 June 2007, NGS used the BERNE (6+9) model with constraints applied to all 9 radiation pressure terms:

$$\begin{aligned} D(u) &= D_0 + D_1\cos(u) + D_2\sin(u) \\ Y(u) &= Y_0 + Y_1\cos(u) + Y_2\sin(u) \\ B(u) &= B_0 + B_1\cos(u) + B_2\sin(u) \end{aligned} \tag{3a}$$

where D points to the sun, Y is the spin axis for the panels, B completes the right-handed system and (u) is the argument of latitude of the satellite. Velocity discontinuities are introduced at midday with moderate constraints on the three velocity component jumps for each satellite.

Upon realizing that these constraints reproduced the existing a priori orbit too closely, NGS switched to the BERNE

(6+5) model with no constraints applied to the 5 radiation pressure terms:

$$
\begin{aligned}
D(u) &= D_0 \\
Y(u) &= Y_0 \qquad \text{(3b)} \\
B(u) &= B_0 + B_1 \cos(u) + B_2 \sin(u)
\end{aligned}
$$

3.4 Deletion of RINEX observations for eclipsing satellites

Starting in GPS Week 1454, rather than model the yaw bias caused by a pre Block-IIR satellite searching for the sun during eclipse, NGS began deleting the observations from the RINEX files for the eclipse interval, including the 30 min recovery period following the eclipse.

4 Conclusions

For over 20 years, NGS has dedicated time and resources to fully encompass the importance of GNSS technology in order to reach the NGS strategic goals. Figures 3 and 4 reflect the efforts and improvements made by NGS since November 2006. And still, NGS will continue to pursue improved models, better approaches, in order to maintain and improve its products and vision. As a further example of its commitment,

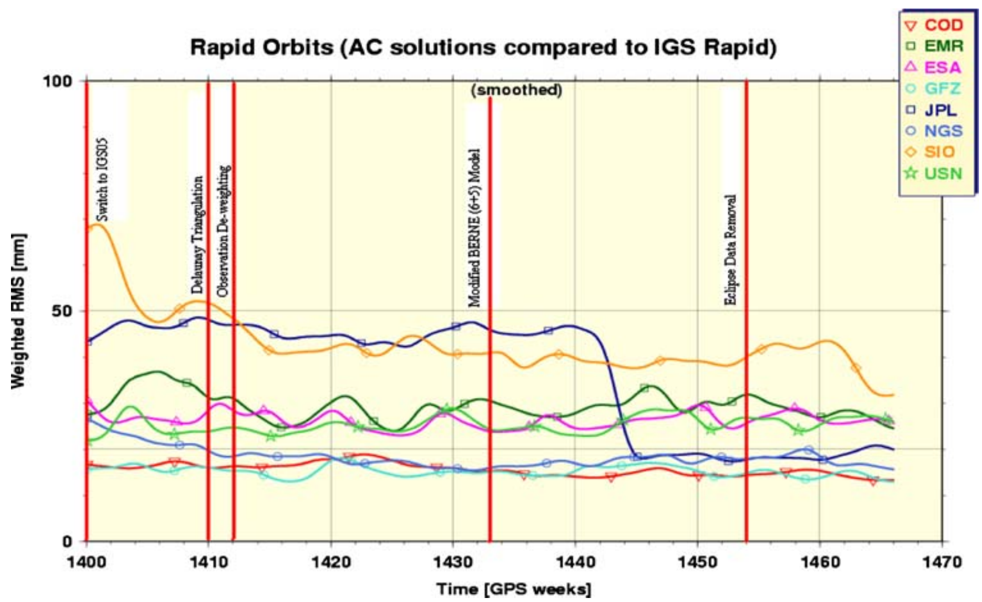

Fig. 3 Time series of Weighted RMS taken from the IGS Rapid orbit combination for each contributing IGS Analysis Center. A *red, vertical line* marks the epoch at which a change in processing strategy was applied. NGS is shown with a *medium blue line* and *medium blue circles*. Plot adapted from http://www.gfz-potsdam.de

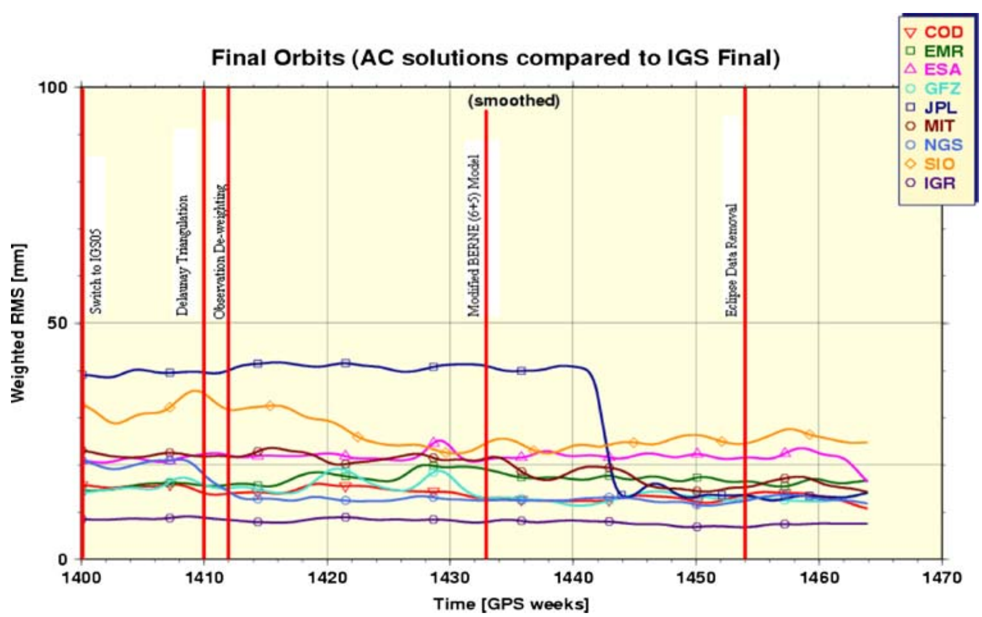

Fig. 4 Time series of Weighted RMS taken from the IGS Final orbit combination for each contributing IGS Analysis Center. A *red, vertical line* marks the epoch at which a change in processing strategy was applied. NGS is shown with a *medium blue line line* and *medium blue circles*. Plot adapted from http://www.gfz-potsdam.de

NGS has recently (January 2008) volunteered to host the IGS Coordination Center's activities for the next four calendar years.

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