CODE IGS Analysis Center Technical Report 1999

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Introduction

CODE, the Center for Orbit Determination in Europe, is a joint venture of the following four institutions:

- the Federal Office of Topography (L+T), Wabern, Switzerland,
- the Federal Agency of Cartography and Geodesy (BKG), Frankfurt, Germany,
- the Institut Géographique National (IGN), Paris, France, and
- the Astronomical Institute of the University of Berne (AIUB), Berne, Switzerland.

CODE is located at the AIUB. Special emphasis lays on Europe, as reflected by the following facts:

- About one third of the sites included in the global CODE solutions are European sites. This should guarantee that the CODE orbits are of best possible quality over Europe.
- Separately a network of about 40 European sites is processed on a daily basis since day 204 (July 23), 1995, using different processing options. CODE is significantly contributing to the establishment and maintenance of the European Reference Frame (EUREF).

This report covers the time period from January to December 1999. It focuses on the major changes in the routine processing during this period and shows the new developments and products generated at CODE. The processing strategies used till December 1998 are described in the CODE annual reports of previous years [Rothacher et al., 1995, 1996, 1997, 1998, 1999].

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Solutions Generated at CODE

All solutions and results are produced with the latest version of the Bernese GPS Software [Rothacher and Mervart, 1996] (currently version 4.3). Three mayor processing procedures are running every day: (1) the normal IGS processing to generate the CODE final products, (2) the rapid orbit solution, and (3) the computation of an European solution [Springer, 1999]. The procedures are running on the VMS alpha cluster of the computing services of the University of Bern.

The routine processing for the final products at CODE is performed as follows:

- In a first step the observations are downloaded from the global data center at IGN and the regional data center at BKG. If necessary, additional data files are transformed from CDDIS or SIO. For the solutions (except the ionosphere solution) the number of stations is limited to 100. If more stations are available, those with the maximum number of observations are selected.

- The data files are checked for outliers. Code single point positioning is performed for each station in order to synchronize the station clocks to GPS time. If available, the rapid orbits are used as a priori information for the final processing. For the rapid processing broadcast orbits are used.

- A first 1-day ambiguity-free solution (called G1) is generated. The solution is used to clean the double difference phase data.

- The procedure for the 3-day solutions starts with the computation of the global ionosphere models which are used for fixing the ambiguities in the subsequent step. Ambiguities are fixed on baselines shorter than 2000 km using the QIF strategy [Mervart, 1995]. On the average about 70% of the ambiguities can be fixed to integer values. This relatively low percentage is caused by the low elevation cut-off angle of 10 deg.

- After ambiguity fixing a new 1-day solution (called Q1) is generated. The global network is split up into three regions (clusters). Within each cluster the mathematical correlations of all simultaneous double difference observations are treated correctly. The results for the three regions are combined to the global solution. The normal equation systems (NEQs) from this Q1-solution are saved for later use in the 3-day solution. The NEQs contain orbit parameters, station coordinates, 2-hourly ERPs, nutation drifts, geocenter offsets, tropospheric zenith delays, and satellite antenna offsets.

- Two additional 1-day solutions are generated, S1 to get the “best possible” 1-day orbits that will be compared to the 3-day orbits, and S1N for the study of coordinate time series.

- Five 3-day solutions are generated based on the NEQs from three successive days [Beutler et al., 1996]. They are labeled S3, R3, X3, Y3, Z3. S3 is used to generate station coordinate time series, the other four series differ by the set of estimated orbit model parameters.

- In the final clock solution satellite and station clock corrections are computed based on undifferenced smoothed code. All relevant parameters (orbits, ERPs, station coordinates, tropospheric zenith delays) are taken from the 3-day solution which ensures the compatibility of the clock estimates with the other products.

The official final product generated at CODE stems from the middle day of the 3-day solution. It is based on the extended radiation pressure model [Springer et al., 1999a] with five estimated parameters and stochastic terms. The elevation cut-off angle is set to 10 deg and the Niell mapping function [Niell, 1996] is used for mapping the dry atmosphere. No troposphere gradients are estimated. The observations are weighted using $\cos^2 z$, z being the zenith angle. The ocean loading coefficients from [Scherneck, 1991] are used.

The rapid solution is computed within 17 hours after the observations. It is generated along the same lines as the final products, but only one 1-day and one 3-day solution are generated. Minor differences in the processing allow to speed up the processing in order to guarantee a rapid submission of results. The same elevation cut-off angle and mapping function are used as in the final solution.

Special emphasis is put on the computation of solutions for an European network which is used to test and study different processing strategies. Currently eight solutions are generated each day:

- EG_: Full network solution without ambiguity fixing. An elevation cut-off angle of 15 deg is used and 12 tropospheric zenith delays are estimated per day and station. The Saastamoinen model [Saastamoinen, 1972] is used as a priori model. The mapping function $\cos^{-1} z$ is used to estimate the tropospheric zenith delay corrections to the a priori model.

- EQB: Same as EG_ but with ambiguities fixed to their integer values. 24 instead of 12 tropospheric delays are estimated per station. On the average 80-90% of all ambiguities are resolved using the QIF strategy.

- NMF: Same as EQB but using the Niell mapping function to estimate the total tropospheric zenith delays. No a priori correction is applied. With an elevation cut-off angle of 15 deg no significant differences to EQB are expected for the coordinate repeatability. The different mapping function, however, causes the scale to change by about 2 ppm [Rothacher, 1997].

- NMW: Same as NMF but using elevation dependent weighting. The function $\cos^2 z$ is used as weight for the undifferenced observations at zenith angle z.

- EQ_: Same as NMW but using an elevation cut-off angle of 10 deg. Lower elevation cut-off should give better decorrelation of station heights and tropospheric delays. On the other hand the observations show more cycle slips and multipath effects.

- ET_: Same as EQ_ but using tropospheric delay estimates from the CODE global solution for stations which are common to both, the global and the European networks. This approach should reduce the effects from the fact that absolute tropospheric delays are correlated for regional networks.

- NM5: Same as EQ_ but using an elevation cut-off angle of 5 deg.

- NMG: Same as NM5 but solving in addition for one set of tropospheric gradients for each station and day.

CODE is acting as an Analysis Center for the EUREF (European Reference Frame). The solution EQB described above is submitted to the EUREF ACC located at BKG.

Changes in the Routine Processing

The major changes implemented in the CODE routine analysis for the year 1999 are listed in Table 1. During the time period covered by the report the models used remained essentially unchanged. A number of new stations were included into the processing, the new IGS receiver and antenna names were implemented, and the terrestrial reference system was switched to the ITRF97.

Table 1: Modification of the processing scheme at the CODE Analysis Center from January 1999 to December 1999.

Date	Doy/Year	Description of Change, Impact
20-Mar-99	079/99	Zero-difference GIMs addressed as official CODE TEC product. New TEC product submitted to CDDIS.
05-Apr-99	095/99	Rapid ionosphere product (including DCB estimates) is derived from zero differences. Station-specific TEC models based on double differences are generated to improve QIF ambiguity resolution.
11-Apr-99	101/99	All available stations are used to derive the final ionosphere product (Z1 solution). For the station-specific TEC maps and DCBs (Z1N solution), up to 100 station are used. For this reason, the maximum degree of the spherical harmonics expansion was reduced from 4 to 3.
04-Jul-99	185/99	New receiver and antenna names used.
01-Aug-99	213/99	Switch to ITRF97. The new set of reference stations consists of about 50 stations. The complete ERP time series, going back to day 200 of 1993, was recomputed using ITRF97 coordinates and velocities (see IGS mail 2422).

24-Aug-99	236/99	Download also GZ RINEX observation files from JPL data archive if necessary.
26-Sep-99	269/99	12 new sites added: ARTU, BAKO, CORD, DAEJ, KUNM, PIMO, RIOG, RIOP, SYOG, URUM, YKRO, YSSK.
09-Oct-99	282/99	New site added: BILI.
04-Nov-99	308/99	The DCB solution from the final ionosphere run (Z1 solution) is now included in official CODE IONEX files. Validation studies showed that the quality of the estimates is comparable to those from the previously included separate solution (Z1N).
24-Dec-99	358/99	Upper limit of the number of stations to be processed in final solution (temporarily) reduced from 100 to 98 in order to be able to successfully analyze the 28th satellite, PRN 11, which is active since doy 355.

Product Quality and Results

Ionosphere

CODE is generating global ionosphere maps (GIMs) for each day [Schaer, 1999]. The long-time series of global TEC parameters available at CODE covers more than 4.5 years by now. Daily updated ionosphere maps as well as 1-day and 2-day predictions may be found on the WWW page http://www.aiub.unibe.ch/ionosphere.html.

GLONASS Processing

In the context of the International GLONASS Experiment (IGEX) CODE is computing precise orbits for all active GLONASS satellites since October 19, 1998. The orbits delivered are stemming from the middle day of a 5-day arc computed with the Bernese extended orbit model (Beutler et al., 1994) without setting stochastic pulses. Nine radiation pressure coefficients are estimated for each satellite and arc: A constant as well as two once-per-revolution terms in the direction of the direct radiation pressure (D-direction, Sun-satellite direction), in the direction of the solar panel axis (Y-direction, 'Y-bias'), and in the direction orthogonal to the previous two directions (X-direction).

To evaluate an improved orbit model for the GLONASS satellites a number of solutions were generated for which different sets of the total of nine radiation pressure coefficients were estimated [Ineichen et al., 2000]. The observations from 25 sites equipped with dual-frequency GPS/GLONASS receivers were processed together with the data from 135 IGS sites for a time span of three weeks (GPS weeks 998-1000). For comparison purposes GPS-only solutions were computed in order to evaluate the impact of a combined processing. Finally the solutions were compared to CODE's official IGEX solution.

To evaluate the quality of the various solution types orbit overlaps at the arc boundaries, the accuracy of the estimated ERP and the coordinate repeatabilities were studied. The tests showed that in order to get good results at least periodic terms in the X-direction have to be estimated in addition to the constant terms in all three directions.

The orbit overlap results are degraded by at least one order of magnitude for the GLONASS as well as for the GPS orbits, if no periodic radiation pressure coefficients or periodic terms only in the D-direction are estimated. On the other hand, the RMS of the orbit overlaps improves if not all nine radiation pressure coefficients are estimated.

Further studies showed that the RMS values of the ERP are increased for all solutions where the periodic radiation pressure coefficient in the D-direction are estimated. The RMS values are lower for the solutions based on 3-day arcs than for the solutions based on 5-day arcs.

The results of the study urge CODE to switch the parameterization of its GLONASS IGEX orbits from estimating all nine parameters to a solution which uses the same parameterization as used for CODE's official IGS GPS orbit products, i.e., constant radiation pressure coefficients in the D-, Y-, and X-direction, once-per-revolution periodic terms in X-direction, and stochastic pulses. The results show furthermore that a combined processing of the IGS and IGEX network to estimate all parameters in one step significantly improves the GLONASS results and does not compromise the quality of the products generated for IGS. A full GLONASS constellation *would* significantly contribute to the stability of the IGS products.

Earth Rotation Parameters

The combination of GPS and GLONASS data may help to improve the Earth Rotation Parameters (ERPs) because the revolution period of the GLONASS satellites is not in deep 2:1-resonance with the Earth's rotation as it is the case for the GPS satellites. Furthermore the different inclinations of the two satellite systems should lead to a better decorrelation of orbit and ERP estimates. The GLONASS, with a revolution period of 11h15m, could contribute significantly to the determination of tidal terms near one sidereal day (e.g., K_1, S_1, Psi_1) [Rothacher et al., 2000].

Tests were carried out using two weeks of simultaneous observations from 110 IGS and 30 IGEX sites in March 1999. The amount of GLONASS data is, however, below 10% of the total number of GPS and GLONASS observations. The reference frame was realized by fixing 43 sites to their ITRF96 coordinates in the combined solution.

Table 2 gives the RMS difference between the 2-hour ERP estimates of different solution types and the Rapid ERP Series from IERS Bulletin A. For the comparison the ERP subdaily terms according to the Ray model were added to the Bulletin A series. The LOD values show a significant improvement from solutions E3 to C3 (in view of and despite the small amount of GLONASS data involved). The formal a posteriori LOD error decreased by about 25% from E3 to C3 whereas those of polar motion remain almost identical. This result is caused by the different orbit inclinations of the two satellite systems [Rothacher et al., 1999].

Table 2: RMS differences between the 2-hour ERP estimates of different solution types and the IERS Bulletin A Series (with subdaily terms from the Ray model added).

Solution	X-Pole [mas]	Y-Pole [mas]	LOD [ms]
R3: Glonass only	0.490	0.538	0.250
E3: GPS only	0.241	0.239	0.158
C3: GPS and GLONASS fully combined	0.230	0.228	0.148

Antenna Phase Center Offsets and GPS Scale

The locations and the elevation dependence of the satellite and receiver antenna phase centers are a problem in GPS data processing. The major part of the satellite antenna offset in the Earth-pointing direction is absorbed by clock correction parameters or removed by forming single differences. The remaining effect has an elevation dependent signature. An elevation dependent variation of the satellite and receiver antenna offset correlates through the estimated tropospheric delays with the station heights and, as a result, with the terrestrial scale. A number of test solutions were generated [Springer, 1999] to study the dependence between antenna phase center offsets, phase center variations, the tropospheric zenith delay, and the terrestrial scale based on a dataset of one week in 1998. The following processing options were modified:

- Terrestrial scale is defined by constraining the coordinates of 37 reference stations to 1 mm or let free by only applying three rotational constraints.
- The satellite phase center offset (Z-offset) is either fixed, artificially changed by 1 m, or estimated for each satellite.
- Either relative receiver antenna phase center variations relative to the Dorne Margolin antennas [Rothacher et al., 1996] or absolute variations from the anechoic phase chamber calibrations [Rocken et al., 1996] are used.
- Different elevation cut-off angles (10, 15, 20 deg) with elevation dependent weighting are used.

Table 3 lists the differences of the generated solutions with respect to the reference solution which was computed with the terrestrial scale left free, an elevation cut-off angle of 10 deg with elevation dependent weighting, relative phase center variations introduced, and no satellite Z-offset estimated.

No significant scale change is observed for the solutions with fixed and free scales and varying cut-off angle whereas the scale changes by more than 8 ppb if the satellite antenna offset is artificially changed by 1 m. Estimating the antenna phase center offsets leads to a scale change of up to 23 ppb if the scale is left free. The formal errors of the station heights (3-6 mm) and for the tropospheric zenith delays (1-2 mm), on the other hand, barely change. This behaviour underlines the correlation between satellite antenna offset, troposphere delays, and station heights. It is, therefore, not possible to solve for the satellite antenna offsets in an absolute sense. The estimation of relative offsets between satellites of different blocks is, however, possible [Bar-Sever, 1998].

The introduction of absolute antenna phase center variations for the receivers change the terrestrial scale by about 14 ppb and a significant difference in the tropospheric zenith delay is observed. Even for the solution with the scale constrained the change of the scale is as large as 8 ppb! If the satellite antenna offsets are estimated, the free solution shows a scale change of 30 ppb. The results show that we are not yet in a position to use the absolute phase center variations.

Table 3: Influence of processing changes on the terrestrial scale, tropospheric delay, and satellite antenna offsets. Differences w.r.t. the reference solution and RMS of the one-way L1 phase observations.

Solution Description	Scale [ppb]	Tropos. [mm ZPD]	Z-off [m]	RMS [mm]
Scale fixed	0.1	0	–	1.46
Scale free, 15 deg cut-off	–0.3	1	–	1.40
Scale free, 20 deg cut-off	–1.0	4	–	1.36
Scale free, Z-offset + 1 meter	–8.3	5	(+1.0)	1.46
Scale fixed, Z-offset estimated	1.5	–1	–0.2	1.44
Scale free, Z-offset estimated	13.2	–7	–1.6	1.44
Scale free, Z-offset est., 15° cut-off	17.0	–12	–2.0	1.39
Scale free, Z-offset est., 20° cut-off	22.8	–18	–2.5	1.34
Scale fixed, abs. phase center var.	8.5	–10	–	1.57
Scale free, abs. phase center var.	14.3	–18	–	1.53
Scale fix., abs. p. c. var., Z-off. est.	–1.4	–9	2.1	1.49
Scale free, abs. p. c. var., Z-off. est.	–29.7	9	5.5	1.46

Summary and Outlook

During the year 1999 several important events occurred at CODE, the most important being the loss of Markus Rothacher who became a Professor at the Technical University of Munich, Germany, in September 1999. He was succeeded by Urs Hugentobler. The two other mayor events were the preparation and release of a new version of the Bernese GPS Software, and the start of the migration of the entire IGS routine processing from the VMS cluster to a Unix cluster which was installed at the university's computing department.

A number of problems remain to be studied and model improvements need to be implemented. The GPS scale problem and the shift of the geocenter which seems to be caused by orbit parametrization need to be addressed in more detail. A more appropriate

GLONASS radiation pressure model has been identified and will be implemented into the CODE IGEX processing. The advantages of the combination of GPS and GLONASS processing could be demonstrated. The implementation of a combined GPS/GLONASS routine processing will be the next step. The introduction of satellite specific weights may further stabilize the processing results.

Potential for improvements was identified in our modeling of the troposphere. Estimation of troposphere gradients, setting up of continuous troposhere zenith delay parameters, introduction of the dry Niell mapping function and estimation of the wet component of the Niell mapping are planned for the near future.

References

Bar-Sever, Y. E. (1998), Estimation of the GPS Transmit Antenna Phase Center Offset, EOS Transactions, 79(45), 183.

Beutler, G., E. Brockmann, W. Gurtner, U. Hugentobler, L. Mervart, M. Rothacher, A. Vernun (1994), Extended orbit modeling techniques at the CODE processing center of the international GPS service for geodynamics (IGS): theory and initial results, Manuscripta Geodetica, 19, 367-386.

Beutler, G., E. Brockmann, U. Hugentobler, L. Mervart, M. Rothacher, R. Weber (1996), Combining Consecutive Short Arcs into Long Arcs for Precise and Efficient GPS Orbit Determination, Journal of Geodesy, 70, 287-299.

Habrich, H. (1999), Geodetic Applications of the Global Navigation Satellite System (GLONASS) and of GLONASS/GPS Combinations, Ph.D. Thesis, Universität Bern.

Ineichen D., M. Rothacher, T. Springer, G. Beutler (1999), Computation of Precise GLONASS Orbits for IGEX-98, in Geodesy Beyond 2000, the Challenges of the First Decade, IAG Symposia Vol 121, edited by K.-P. Schwarz, IAG General Assembly, Birmingham, July 19-30, 1999, pp. 26-31.

Ineichen, D., T. Springer, G. Beutler (2000), Combined Processing of the IGS- and the IGEX-Network, submitted to Journal of Geodesy.

Mervart, L (1995), Ambiguity Resolution Techniques in Geodetic and Geodynamic Applications of the Global Positioning System, Geodäisch-geophysikalische Arbeiten in der Schweiz, Vol. 53, Schweizerische Geodäische Kommission, Institut für Geodäsie und Photogrammetrie, Eidg. Technische Hochschule Zürich, Zürich.

Niell, A. E. (1996), Global Mapping Functions for the Atmosphere Delay at Radio-Wavelengths, JGR, 101(B2), pp. 3227-3246.

Rocken, C., C. Meertens, B. Stephens, J. Braun, T. VanHove, S. Perry, O. Ruud, M. McCallum, J. Richardson (1996), Receiver and Antenna Test Report, UNAVCO Academic Research Infrastructure (ARI).

Rothacher, M., G. Beutler, E. Brockmann, L. Mervart, R. Weber, U. Wild, A. Wiget, H. Seeger, S. Botton, C. Boucher (1995), Annual Report 1994 of the CODE Processing Center of the IGS, in IGS 1994 Annual Report, edited by J. F. Zumberge et al., pp. 139-162, IGS Central Bureau, JPL, Pasadena, CA.

Rothacher, M., G. Beutler, E. Brockmann, L. Mervart, S. Schaer, T. A. Springer, U. Wild, A. Wiget, H. Seeger, C. Boucher (1996), Annual Report 1995 of the CODE Processing Center of the IGS, in IGS 1995 Annual Report, edited by J. F. Zumberge et al., pp. 151-174, IGS Central Bureau, JPL, Pasadena, CA.

Rothacher, M., L. Mervart (Eds.) (1996), The Bernese GPS Software Version 4.0, Astronomical Institute, University of Berne, September, 1996.

Rothacher, M., W, Gurtner, S. Schaer, R. Weber, H. O. Hase (1996), Azimuth- and Elevation-Dependent Phase Center Corrections for Geodetic GPS Antennas Estimated from GPS Calibration Campaigns, in IAG Symposium No. 115, edited by W. Torge, pp. 335-339, Springer-Verlag.

Rothacher, M., T. A. Springer, S. Schaer, G. Beutler, E. Brockmann, U. Wild, A. Wiget, C. Boucher, S. Botton, H. Seeger, (1997), Annual Report 1996 of the CODE Processing Center of the IGS, in IGS 1996 Annual Report, edited by J. F. Zumberge et al., pp. 201-219, IGS Central Bureau, JPL, Pasadena, CA.

Rothacher, M., T. A. Springer, S. Schaer, G. Beutler, D. Ineichen, U. Wild, A. Wiget, C. Boucher, S. Botton, H. Seeger, (1998), Annual Report 1997 of the CODE Processing Center of the IGS, in IGS 1997 Technical Reports, edited by I. Mueller et al., pp. 73-87, IGS Central Bureau, JPL, Pasadena, CA.

Rothacher, M., T. A. Springer, G. Beutler, R. Dach, U. Hugentobler, D. Ineichen, S. Schaer, U. Wild, A. Wiget, E. Brockmann, C. Boucher, E. Reinhart, H. Habrich (1999), Annual Report 1998 of the CODE Processing Center of the IGS, in IGS 1998 Technical Reports, edited by K. Gowey et al., pp. 61-73, IGS Central Bureau, JPL, Pasadena, CA.

Rothacher, M, T. Springer, S. Schaer, G. Beutler (1997), Processing Strategies for Regional GPS Networks, Proceedings of the IAG General Assembly, Rio, Brasil, September 3–9, 1997.

Rothacher, M., R. Weber (1999), Benefits from a Combined GPS/GLONASS Analysis for Earth Rotation Studies, in Proceedings of the ION GPS-99, Nashville, Tennessee, September 14-17, 1999.

Rothacher, M, G. Beutler, R. Weber, J. Hefty (2000), High-Frequency Earth Rotation Variations from Three Years of Global Positioning System Data, submitted to JGR.

Saastamoinen, J. (1972), Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites, in The Use of Artificial Satellites for Geodesy, Geophysical Monograph Series.

Schaer, S. (1999), Mapping and Predicting the Earth's Ionosphere using the Global Positioning System, Geodätische-geophysikalische Arbeiten in der Schweiz, Schweizerische Geodätische Kommission, Vol. 59, Institut für Geodäsie und Photogrammetrie, Eidg. Technische Hochschule Zürich, Zürich.

Scherneck, H.-G. (1991), A parametrized solid earth tide model and ocean tide loading effects for global geodetic baseline measurements, Geophys. J. Int., 106, pp. 677-694.

Springer, T. (1999), Modeling and Validating Orbits and Clocks Using the GPS, Ph.D. Thesis, Druckerei der Universität Bern, Bern.

Springer, T., G. Beutler, M. Rothacher (1999a), Improving the Orbit Estimates of GPS Satellites, Journal of Geodesy, 73, pp. 147-157.

Springer, T., G. Beutler, M. Rothacher (1999b), A new Solar Radiation Pressure Model for GPS, Adv. Space Res., 23, No. 4, pp 673-679.