Identification and Mitigation of GNSS Errors

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Abstract

The session "Identification and Mitigation of GNSS Errors" covers a broad spectrum of effects that potentially induce undesirable contributions in GNSS analysis results. They involve near-field and far-field multipath effects, but also orbit modeling deficiencies. Of particular importance are correlations between geodetic results and observation errors as it is likely that significant technique-related errors are sometimes being misinterpreted as geophysical effects. Given the increasing popularity of precise point positioning for a large variety of applications it is mandatory to identify, understand, and solve inconsistencies between AC products and to minimize inconsistencies of IGS orbit and clock products.

The heterogeneous list presented in this paper aims at recording questions and problems that deserve attention and further investigations in the near future. It is recommended that the IGS stimulates research activities in the different fields, studying the effects of suspected error sources and mitigation thereof in order to decorrelate technique problems from geophysical signals and to improve the stability of the reference frame. All aspects of GNSS geodesy are potentially involved, from field observations through data analysis and interpretation.

In the field...

Far-field and site multipath

Far-field and site multipath includes local environmental effects, such as trees, snow, rain water, etc. Generally these errors are expected to average down for 24-hr observing sessions, but can be very important for high time-resolved studies (e.g., for GPS seismology). Different techniques are used for identification and mitigation, e.g., sidereal filtering, local site phase maps, stacked residuals. See (Larson 2006; van der Marel 2006).

Figure 1 shows, as an example, the effect of strong snowfall for the AGNES (Automatic GPS Network Switzerland) station Hohtenn. Residuals from near real-time hourly coordinate estimates reach 4 cm in horizontal and 35 cm in vertical direction. With already rather high temperatures in mid February 2006 the snow melted quickly and estimated coordinates returned to their original value.

Near-field and internal multipath

Near-field and internal multipath includes effects of antenna mounting, monumentation, cable connections, etc. This could be one of the most important sources of systematic positioning errors, but very little study has been done, partly due to the difficulty of detecting such errors.

A possible solution could be to include the interface to the monument (tribach, extender, etc.) in the antenna calibration. Using two robot calibrations for an antenna used by the Dutch Cadaster (no chokering) with and without mounting construction included, resulted in systematic height differences of about 3 cm in a RTK solution.

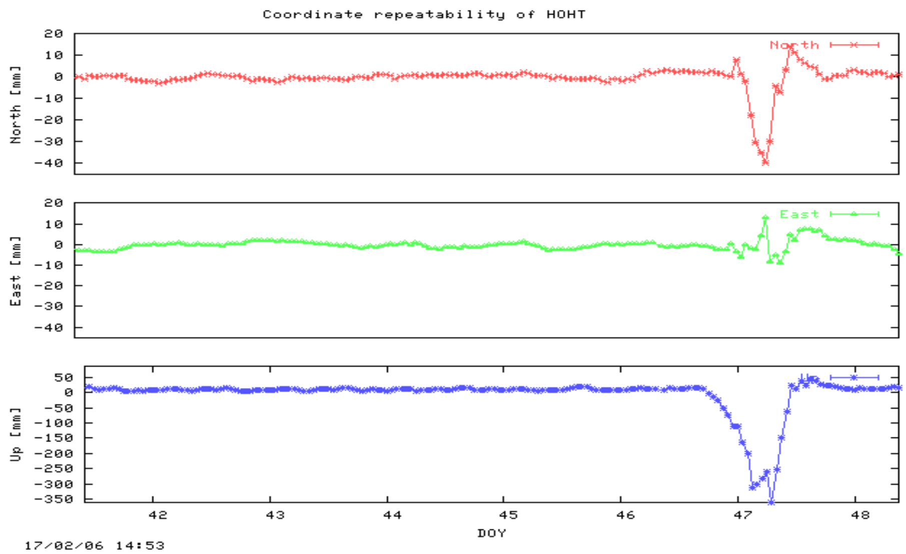

Figure 1: Effect of snow on the antenna on near-realtime hourly site coordinate estimates (courtesy E. Brockmann, swisstopo).

Radio frequency interference

Radio frequency interference, if not inhibiting tracking at all, may cause perturbations of measured signals. E.g., the SCIGN installation KYVW shows a significant signal with a period of 12 sec that is not multipath because it persists at all elevations. Radio frequency interference is a probable cause (Larson and Bilich 2006).

Radome effects and antenna calibrations

Radomes are known to cause antenna phase center variations up to about one centimeter. To what extent can repeatable calibrations be made accurately? How can the use of radomes be further discouraged within the IGS, or is there a radome design that is widely usable? That radomes are problematic is shown, e.g., by (Schmid et al. 2006).

Figure 2 shows the RMS of the phase residuals for seven daily global solutions based on about 150 IGS stations using relative or absolute antenna phase patterns. The improvement is of the order of 10%. A small, though insignificant improvement can be seen if existing absolute calibrations for antenna-radome combinations are used.

Correlations between geodetic results and observation errors

It is likely that significant technique-related errors are sometimes being misinterpreted as geophysical effects. This may, e.g., be the case for orbit and troposphere modeling deficiencies or near-field multipath. How well do we understand technique GNSS errors and their role in apparent non-linear site motion such as, e.g., seasonal height variations?

Tracking data amount and quality

Across the IGS network, variations of tracking data amount and quality are still quite large. Consistent tracking of "unhealthy" satellites is still not standard throughout the IGS network. Tracking problems are particularly pronounced with respect to GLONASS satellites where the number of tracking stations is already low.

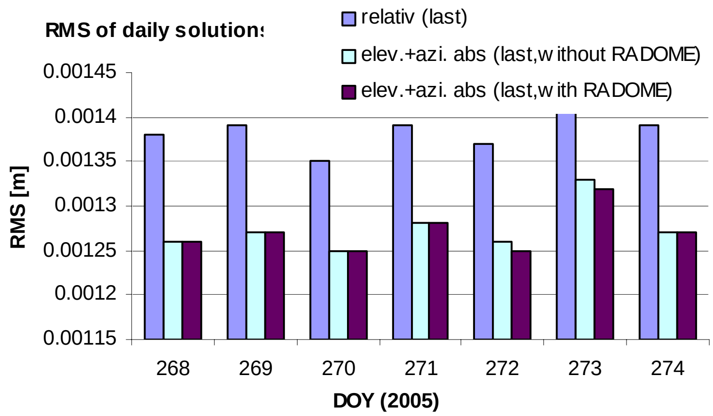

Figure 2: RMS values of phase residuals from seven one-day global solutions with relative and absolute antenna phase patterns.

In the signal propagation ...

Troposphere modeling

How do new troposphere mapping functions improve geodetic results and reference frame stability? Is the GMF mapping function good enough for GNSS? See (Boehm et al. 2006).

The ACs use different strategies to remove the hydrostatic delay from the signal, which affects both the estimation of the zenith total delay as well as other parameters, This results in systematic differences between the ACs. What is the effect? Should the ACs agree on a common strategy?

Higher order ionosphere corrections

The effect of higher order ionosphere corrections on reference frame stability should be studied further. See (Komjathy et al. 2006).

Relativistic correction for propagation

Are analysis groups implementing propagation models in the IERS Conventions fully and consistently? Can some be neglected as pure scale changes?

In the satellites ...

Inter-modulation biases

Procedures have to be included within the IGS for handling inter-modulation biases (also known more specifically as differential code biases). The problem is soon to become much more complicated with new GPS, Galileo, and GLONASS signals. Inter-modulation biases mainly affect clock estimation, but also some ambiguity resolution techniques and thus may have an impact on other geodetic parameters. What should the IGS conventions be for handling these biases and how to develop such conventions?

New signals and carrier phase biases

Time varying biases in the carrier phases have always been absorbed by the satellite and receiver clock estimates, or have been eliminated by double differencing between likewise signals. Now, with the introduction of new signals, different ionosphere free linear combinations may be formed and used in the processing. Should we solve for more than one satellite clock (one for each type of ionosphere free linear combination), or alternatively, form single/double differences only between similar types of linear combinations? Or can we mix different signals? In fact, this situation already exists to some degree with receivers tracking either P-code or C/A-code phase, but it will become more complicated with the new L2C signal, future L5, and Galileo signals. Does this mean that for PPP applications more than one clock product has to be generated? Should there be IGS conventions for tracking which signals?

In the receivers ...

Inter-modulation biases, new signals

Many of the problems with the new signals and inter-modulations biases referred to in the previous section also persist in the receiver. This may be further complicated by different implementations of the signal processing in the receivers, e.g., for multipath reduction, leading to receiver and signal dependent delays.

Relative performance of different signal observables

How do, e.g., C1 and P1 compare in terms of performance?

In the orbits ...

Orbit modeling defects

Orbit modeling parameters, in particular radiation pressure parameters, may correlate with geodetic parameters. Such correlations do, e.g., affect the observability of geocenter motions. Is GNSS capable of reliably measuring geocenter motions? What will it take to reduce technique-related errors?

Geocenter variations obtained from GNSS analysis show a pattern in particular in the z-direction that is sensitive to the a priori radiation pressure model used to model the orbits for the GNSS satellites (see Figure 3). Distinct periods of about 350 days can be found in the time series that correspond to the repeat period of the Sun with respect to the satellite constellation. This is an indication that a significant part of the variations is not caused by geophysical effects but induced by orbit modeling deficiencies.

Should the ACs, in view of the modest sensitivity of GNSS for the geocenter position, apply not only a no-net rotation constraint to the reference sites when solving for site coordinates and satellite orbits but in addition a no-net translation constraint? The geocenter coordinates would then be constrained to zero and orbits, clocks, and site coordinates would be consistent with ITRF by construction. It would make sense to constrain the frame origin to a geocenter model, e.g., by constraining to reference site coordinates that include the geocenter tidal motion in the ocean tidal loading model. The translation constraints could in any case be removed at SINEX level allowing to study geocenter motions.

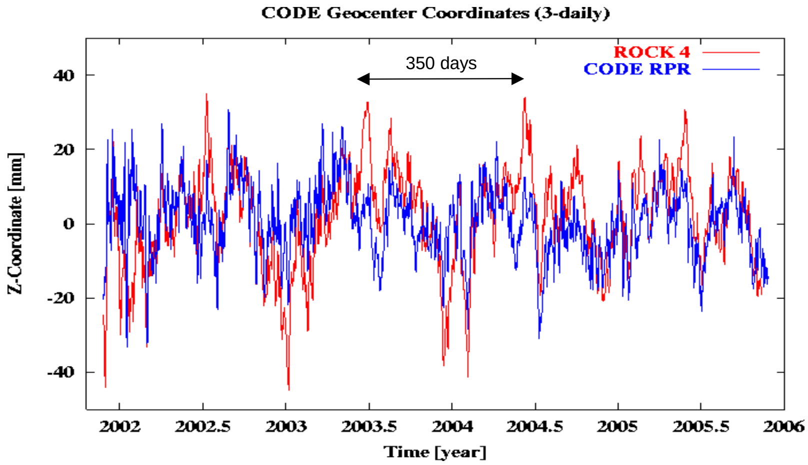

Figure 3: CODE 3-daily geocenter offsets in z-direction for two different GPS a priori radiation pressure models. Distinct periods of about 350 days can be found in the time series, corresponding to the repeat period of the Sun with respect to the satellite constellation.

Figure 4 shows the SLR residuals for GNSS orbits obtained in global solutions with different constraints applied to reference sites. The time interval covers 41 days that include the CONT'05 campaign. The first solution is computed using a no-net rotation constraint, i.e., minimum constraints only. The second and the third solution are based on an additional no-net translation constraints on IGS00b reference site coordinates without and with inclusion of the motion of the geocenter induced by the ocean tidal model FES2004. As for station position repeatabilities (not shown) the effect of the additional constraint is minimal. A slight improvement of the SLR residuals is, however, indicated by the analysis results.

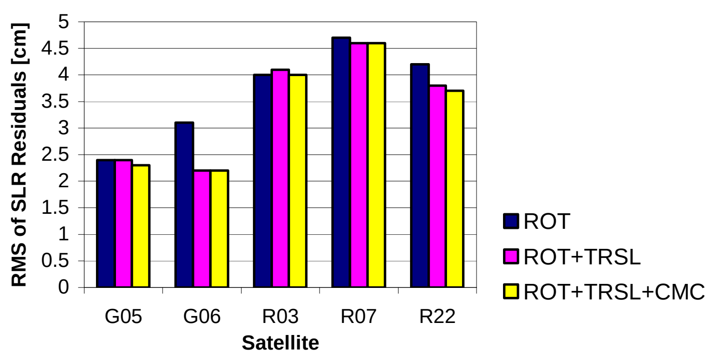

Figure 4: SLR residuals of GNSS satellites obtained from global solutions with a no-net rotation condition applied to reference site coordinates (ROT) and with an additional no-net translation constraint to IGS00b positions without (ROT+TRSL) and with inclusion of the geocenter motion induced by the ocean tidal model FES2004 (ROT+TRSL+CMC).

Satellite attitude

Satellite attitude concerns orbit modeling (radiation pressure) on one hand, and geometric effects (rotation of Block II/IIA antenna) on the other hand. A particular question is whether attitude should be included in the phase windup or not. This question is only relevant for the clocks. Considering only the component of the phase windup that originates from the changing relative geometry of satellites and stations would be easier to handle. A special problem is handling attitude control problems in some older satellites.

Shift of orbits in Earth-fixed frame

Shifts of the orbits, in particular in the Earth-fixed y-direction, were described by (Springer, 1999). Are such shifts still present and what is their cause? Orbit modeling problems, e.g., due to radiation pressure modeling deficiencies may cause orbit shifts in the inertial frame but not in the Earth-fixed frame.

As a test, let us adjust satellite orbit positions with a simple orbit model that includes only two radiation pressure parameters, namely the direct solar radiation parameter and the y-bias. When comparing the new with the original orbit through a Helmert transformation in the Earth-fixed frame, systematic translations are observed. Figure 5 shows Helmert translation parameters in the Earth fixed frame between original and fitted CODE final orbits and indicates a systematic offset between the two orbits of nearly 1 cm in the y-direction that persists over several years. Similar offsets can be observed in the Earth-fixed y-direction when IGS orbits are used.

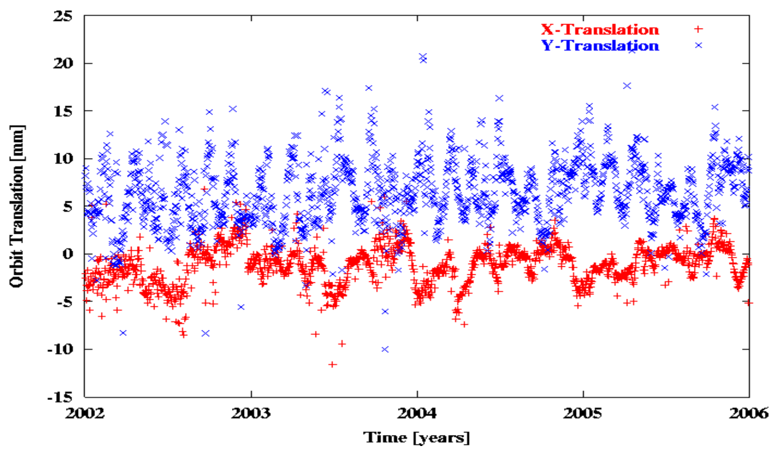

Figure 5: Daily mean offsets in the Earth-fixed frame of orbit positions from CODE precise files and of positions derived from an orbit fit of these positions with a simple orbit parameterisation.

Update on SLR validation

What is the source or the sources of the persistent radial bias that is still observed in the SLR measurements with respect to microwave-derived GPS orbits? What can be done to improve the understanding? Patterns in the residuals observed for IGS orbits as well as for different AC deliveries indicate problems with orbit modeling. See (Urschl et al. 2006).

In the frame ...

Distribution and quality of reference frame sites

The overall quality of the IGS reference network continues to decline due to equipment changes or other problems at reference sites. The number of reference sites that can be used for attachment is steadily decreasing. What can be done to reverse this trend and to rebuild an adequate core reference network? Or, how can the impact of inevitable changes at reference sites be minimized?

Effect of antenna change

In the foreseeable future antennas will be replaced by antennas capable to track Galileo signals. How antenna changes should be performed in order to guarantee minimum effect on the estimation of station position and velocity and on reference frame stability?

Co-location

How should multiple receivers, antennas and receivers with antenna-sharing at reference sites be handled? Or, should more than one receiver/antenna operated at core sites be included in the solution, e.g., by combination with local baseline analysis results?

In combined multi-GNSS solutions ...

Improvements with GPS + Galileo + GLONASS

Using multi-GNSS results in a threefold increase in the number of satellites, but will this also result in a corresponding improvement of the results? For example, will GPS + Galileo really give improved results over Galileo alone? Are the GPS systematic errors (e.g., related to orbital resonance) significant enough that multi-GNSS combinations will give degraded results (for high-accuracy geodesy) compared to Galileo alone? Can differential weighting schemes overcome this type of problem?

Figure 6 shows the repeatability of the baseline length between Onsala and Wettzell for four different solutions including a GNSS combined analysis, a GPS-only and a GLONASS-only analysis as well as a GPS analysis based on the same number of satellites as available for the GLONASS-only solution. The scatter in baseline length for the GLONASS-only solution is larger than that for the 14-satellite GPS solution, a direct consequence of the lower GLONASS orbit quality (5-6cm instead of 2-3cm) that has its origin in the sub-optimal tracking network of combined receivers. All solutions that include GPS observations provide the same mean baseline length while the GLONASS-only analysis results in a scale that is 5 ppb larger. This inconsistency should disappear when absolute antenna phase patterns are used.

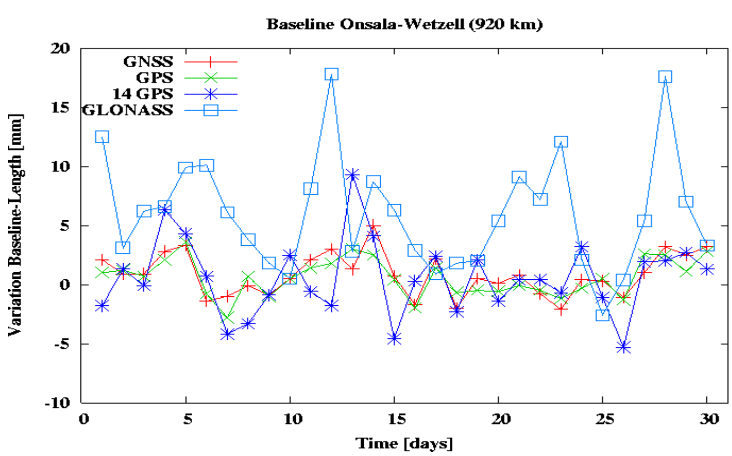

Figure 6: Length variations of the baseline Onsala-Wettzell for four different solutions including GNSS combined, GPS-only, and GLONASS-only analysis.

In the geodetic results ...

New models

How do new models for solid Earth, ocean, atmospheric tidal variations, for subdaily EOP variations, and for nutation improve geodetic results? Figure 7 shows, as an example, the RMS difference of two ocean tide loading time series for some 250 IGS sites. The two time series are both based the GOT00.2 ocean tide model but one of them considers the 11 major tidal constituents only while the other considers 141 constituents provided by the hardisp routine by Duncan Agnew that is available from IERS (Ray 2006). Mean vertical RMS differences are 2 mm and tend to increase towards high latitudes.

Loading

Can non-tidal loading continue to be neglected at the observation level and retained in the geodetic results? Is there evidence of aliasing of tidal loading signals into longer-period signals, as, e.g., described by (Penna and Stewart 2003; Watson et al. 2006)?

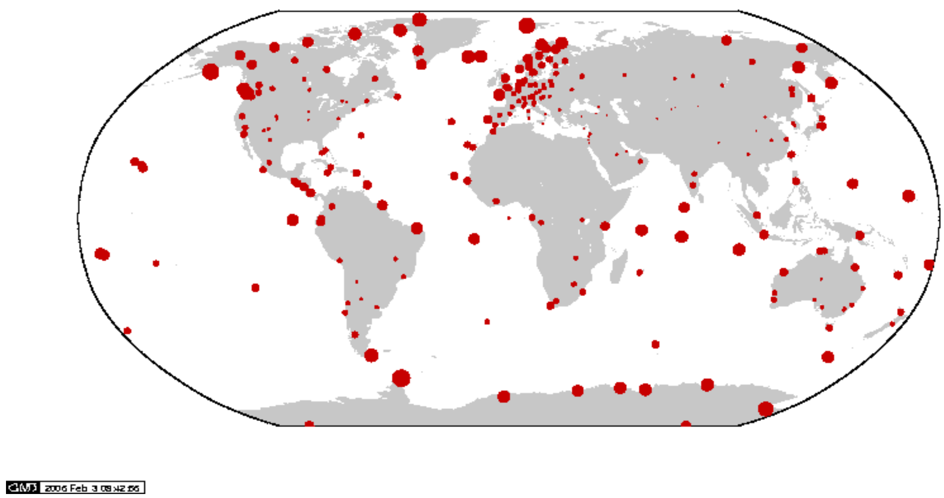

Figure 7: Comparison of two ocean tide loading time series, one based on 11 tidal constituents only, the other on 141 tidal constituents as provided by the hardisp routine from Duncan Agnew (Ray 2006). The diameter of the dots for some 250 IGS sites is proportional to the RMS difference between the time series covering 14 days each. The largest value of 5 mm is observed for O'Higgins in Antarctica.

Seasonal height variations

Are seasonal height variations observed in station time series of geophysical origin, due to model deficiencies (e.g., troposphere or orbit modeling), to technique-specific measurement errors (e.g., near-field multipath), or to analysis strategies or software problems?

In the IGS products ...

Consistency, in particular for PPP

Inconsistencies between individual AC orbit and clock contributions still exist. This concerns analysis strategy and modeling differences, different levels of implementation of IERS conventions, and in particular also the fact that the Bern IGS Workshop recommendation concerning consistency of orbits and clocks with ITRF is not yet implemented by all ACs. As a consequence the consistency of the IGS combined products is degraded which in particular affects precise point positioning (PPP) applications. How the consistency between the ACs can be improved? How can the analysis noise be reduced? How to document and maintain IGS conventions? And finally, what is the consistency of user software with IERS & IGS conventions?

Figure 8 shows the repeatability RMS values for the height components for 41 EUREF sites based on 60 daily coordinate estimates obtained with a PPP relying on five different orbit and clock products. Since the PPP is performed using the Bernese GPS Software it is no surprise that the PPP results based on CODE products (produced with the same software) show the smallest RMS values for all stations. Higher repeatability RMS values for PPP results based on products from IGS or from other ACs indicate inconsistencies.

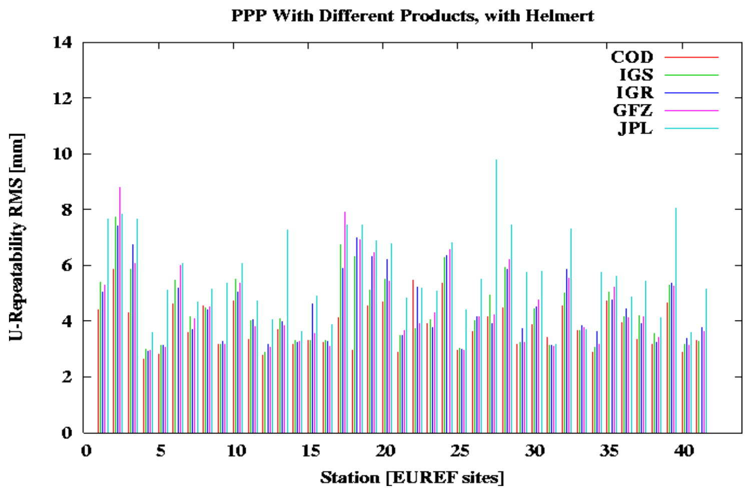

Figure 8: Height repeatability RMS for coordinates of 41 EUREF sites derived from 60 daily PPP solutions based on orbit and clock products from IGS Final, IGS Rapid, CODE, GFZ, and JPL. The differences between the solutions indicate inconsistencies.

Ambiguity resolution in PPP (single receiver) mode should be possible (at least in theory) if biases are properly taken into account and if models used for generating orbits and clocks and models in user software agree at the few centimeter level. Is it also possible in practice? What could be done to approach this situation?

Combination

Is the multi-AC combination approach still the best approach for IGS in view of the still considerable differences between the AC solutions, and in view of the increasing usage of precise point positioning?

Recommendations

The IGS should stimulate research leading to a better understanding of the different error sources and technique-related problems, in particular of not well understood effects such as near-field and internal multipath errors and their mitigation. This may be done by organizing dedicated workshops or sessions at assemblies such as AGU or EGU, inviting a wider community in participating.

The consistency between AC products and of combined IGS products should be further improved, in particular for supporting precise point positioning applications.

Acknowledgements

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