IGS White Paper on Satellite and Operations Information for Generation of Precise GNSS Orbit and Clock Products

O. Montenbruck on behalf of the IGS Multi-GNSS Working Group

Abstract

The International GNSS Service (IGS) provides precise orbit and clock solutions for GNSS satellites that support a wide range of science and engineering applications with numerous benefits for society at large. All IGS data and products are made freely available to the scientific community and the general public. To best fulfill its mission, the IGS depends on information from the GNSS providers concerning the characteristics of individual types of satellites as well as their operations. This white paper describes the parameters needed to ensure the highest possible performance of IGS products for all constellations and motivates the need for provision of satellite and operations information by the GNSS providers. All information requested by the IGS is considered to be sufficiently abstract such as to neither interfere with the GNSS providers' safety and security interests nor with intellectual property rights.

1. The International GNSS Service

The International GNSS Service (IGS), formerly the International GPS Service, is a voluntary federation of more than 200 agencies worldwide that pool resources and permanent GNSS station data to generate high-precision GNSS products. According to its mission statement,

> "*the International GNSS Service provides, on an openly available basis, the highest quality GNSS data, products, and services in support of the terrestrial reference frame; Earth observation and research; Positioning, Navigation and Timing (PNT); and other applications that benefit the scientific community and society.*"

The backbone of the IGS is its global network of over 400 permanent, continuously operating, geodetic quality stations tracking GPS, GLONASS, Galileo, BeiDou, QZSS, and SBAS. The IGS collects, archives and distributes these GNSS observational data sets to meet the objectives of a wide range of applications and experimentation. Within the IGS these data sets are used to generate the following data products:

- High accuracy GNSS satellite ephemerides and related information
- Earth rotation parameters
- Coordinates and velocities of the IGS tracking stations
- GNSS satellite and tracking station clock information, timescale products
- Ionospheric information
- Tropospheric information

The accuracy of these products is sufficient to support diverse scientific objectives such as

- Realization of global accessibility to, and the improvement of, the International Terrestrial Reference Frame (ITRF)
- Monitoring deformation of the solid Earth
- Monitoring Earth rotation
- Monitoring variations in the hydrosphere (sea level, ice sheets, etc.)
- Scientific satellite orbit determination
- Ionosphere monitoring
- Climatological research, and eventually weather prediction models
- Time and frequency transfer

Apart from their scientific use, the IGS products play an important role in engineering applications (from timing to structural monitoring, to name just a few) and even support the works of GNSS system providers in the definition of temporal and spatial reference systems as well as a routine performance monitoring.

Currently, the IGS supports two GNSSs on a fully operational basis with highest reliability and performance, namely the US GPS and the Russian GLONASS. In view of the ongoing GPS modernization and the deployment of new navigation systems such as BeiDou, Galileo and QZSS, the IGS has established the Multi-GNSS Experiment (MGEX, [1]), which is now continued as an IGS pilot project. MGEX aims to extent the service portfolio to these new constellations and to achieve a consistent data and product quality for all constellations.

2. The Art and Science of GNSS Observation Modeling

The high-precision use of GPS and other GNSSs relies on the use of carrier phase observations. At a typical wavelength of about 20 cm, carrier phase measurements offer a noise level of about 1 mm. However, it is obvious that models of compatible performance will be required to exploit this level of precision in global precise point positioning (PPP) applications. These models are used to describe the total signal travel time from the transmitting satellite to the receiver and account for the motion of the satellite, the offsets between the center-of-mass and the phase center of the antenna, constant and direction-dependent phase delays, phase wind-up, free-space wave propagation (in a relativistic framework), atmospheric effects, etc. Through it's work, the IGS has contributed to a steady refinement of such models [2]-[3], the characterization of user equipment (antennas, receivers) as well as the GPS and GLONASS space segments. As a result of this work, an adequate level of understanding has been reached that presently enables the generation of orbit and clock products with a presumed accuracy of a few centimeters for these constellations and allows users to find their absolute position around the globe with mm to cm level accuracy. However, even after 20 years, continuous effort is required to ensure, to confirm and to improve this level of performance. At the same time deficiencies and simplifications of established models become apparent as more and new GNSSs become available. Last but not least, each new constellation requires a detailed characterization of its properties to enable a competitive contribution to a “global navigation system of systems”.

3. Spacecraft and Operations Information

To support the effort of the IGS and to meet the science objectives, GNSS providers are requested to disclose a limited set of technical information on the satellites as well as operational information related to irregular events in the mission timeline. Neither of this information is considered to be sensitive in terms of mission safety or property rights. However, availability of such information to the science community will greatly reduce tedious “reverse engineering” efforts, improve the employed models and ultimately result in more robust and accurate IGS products. Availability of such information is particularly important for the rapidly evolving new GNSS constellations, for which users expect precise products of comparable quality as those related to GPS and GLONASS, but cannot afford to wait for two decades of knowledge gain. The same, however, applies for the legacy systems whenever new types of spacecraft are brought into operation.

3.1 Mass and Center-of-Mass Coordinates

Knowledge of the mass of a GNSS satellite is required to compute the acceleration caused by non-gravitational forces (such as solar radiation pressure, radiation thrust, or Earth radiation pressure). In line with the quality of other model parameters, a 1% accuracy is typically deemed adequate for this purpose. Updates following the start of initial operations are only required after maneuvers and incremental mass changes of more than 1 kg.

Because dynamic orbit models describe the motion of a spacecraft's center of mass, knowledge of the (potentially time-varying) center-of-mass (CoM) location w.r.t. to the origin of the spacecraft reference frame is required to express the position of other reference points (antenna or laser retroreflector) relative to the CoM. To exploit the precision of GNSS carrier phase measurements and the technical capabilities of CoM measurements, knowledge of the CoM location is desired with a representative accuracy of 1-10 mm.

While it has long been common practice to use the CoM as origin for the specification of antenna and sensor offsets, this practice makes it difficult to handle CoM variations that may be caused by orbit maneuvers. Efforts are therefore underway within the IGS to switch to an invariant spacecraft frame when specifying antenna and sensor coordinates.

3.2 Antenna and Reflector Data

The modeling of GNSS measurements requires concise information on the location of the antenna phase center and potential line-of-sight dependent phase variations. While this information can, to a certain extent, be reconstructed from observations with a global ground network, such inflight calibrations [4]-[5] are presently limited to combinations of dual-frequency observations and therefore limit the establishment of a GNSS-only terrestrial reference frame.

The provision of preflight calibrations of the phase center (at 1 cm accuracy) and variations (with mm accuracy) for each individual signal band is therefore deemed a prerequisite for fully exploiting the accuracy of present GNSS observations.

Likewise, the reference point coordinates of laser retroreflectors should be provided by the manufacturer with a 1(-10) mm accuracy.

3.3 Panel Model

With a representative magnitude of 100 nm/s^2, solar radiation pressure (SRP) represents the dominating non-gravitational acceleration acting on a GNSS satellite. Over the past years, use of a box-wing model (optionally with supplementary empirical estimation parameters) has been demonstrated to be of great benefit for GPS and GLONASS [4] processing and is adopted by an increasing number of IGS analysis centers. Also, it has been found to be essential for the Galileo and QZS satellites, which exhibit a notably stretched satellite body [7][8]. Given the typical shape of current GNSS satellites, a box-wing model comprising a six-faced cuboid for the satellite body and additional solar panels represents a good initial approximation and can typically deliver a modeling accuracy of better than 5%. An even better approximation of the real forces is expected from raytracing based on CAD models, which are particularly desirable for s/c with complex shape [9]. Detailed knowledge of a CAD model helps to address shading that can have notable effects on the satellite orbit as shown in [10] and is also a major issue for BeiDou and QZS GEO satellites with large antenna structures. Overall a 1% (or 1 nm/s^2) modeling accuracy is targeted for a priori SRP models.

3.4 Radiated Power

The transmission of radio-frequency signals imposes a subtle force on the GNSS satellite. This force is mainly directed in radial direction and causes s small change of the mean orbital radius. At representative power levels of one to a few hundred Watts and the given orbital altitude, a 1-2 cm shift may be experienced [11] which becomes relevant for geodetic GNSS data analysis. Knowledge of the transmit power with a representative accuracy of 20W is therefore desired for each type of satellite.

3.5 Attitude

Knowledge of the GNSS satellite attitude is required to compute the position of the antenna phase center (the point where the GNSS signals merge) relative to the center-of-mass (that is described by the equation of motion and the coordinates of which are provided by the precise orbit products). At a lever arm of about 2 m, a 1° attitude error corresponds to a phase center position error of 4 cm (which translates into a modelled range error of 1 cm). Also, attitude information is needed to describe phase windup (with a magnitude of one wavelength for a full s/c rotation). Finally, attitude should be considered in solar radiation pressure modeling. So far, nominal attitude models (yaw-steering, orbit normal mode) are well documented [12] for all GNSS and adequate to describe the real s/c orientation outside the eclipse season. Only partial information is available, though, for noon and midnight turns at low elevations of the Sun w.r.t. to the orbital plane. Proper documentation of these special attitude phases is sought from the s/c manufacturer or GNSS provider to ensure a consistent and high-grade modeling of GNSS orbits at all times. For satellites performing mode transitions (e.g. between yaw-steering and orbit normal mode), the exact times of such transitions are therefore required to adapt the respective models in the precise orbit determination and data analysis. Infos on planned/executed transitions should therefore be posted by the system operators, e.g. as part of dedicated “Notice Advisory to Navigation Users (NANUs)“ bulletins.

3.6 Maneuvers

Maneuvers imply discontinuities of orbit solutions that must be modelled in the POD process. They presently come as a surprise and interrupt the regular processing flow of IGS analysis centers. In particular, the epoch and duration of a maneuver must be known for proper orbit modelling but can, so far, only be guessed or approximately reconstructed by labor-intensive trial-and error efforts. GPS and other MEO constellations perform moderate amount of maneuvers, but QZSS and BDS IGSO and (most critically) BDS/QZS GEOs perform maneuvers rather frequently. Information on planned/executed maneuvers should therefore be posted by the system operators, e.g. as part of dedicated “Notice Advisory to Navigation Users (NANUs)“ bulletins.

3. Summary and Conclusions

Satellite metadata and selected operational information relevant to the orbit and attitude modeling are essential for GNSS high-precision applications. All providers and operators of global/regional navigation satellite systems are requested to make such information available on a public and traceable basis. Initial examples include the satellite metadata websites of Galileo and QZSS, which provide encouraging examples for other system providers and are particularly appreciated by the IGS.

References

[1] Montenbruck O., Steigenberger P., Prange L., Deng Z., Zhao Q., Perosanz F., Romero I., Noll C., Stürze A., Weber G., Schmid R., MacLeod K., Schaer S.; *The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) -- Achievements, Prospects and Challenges*; Advances in Space Research 59(7) (2017) DOI 10.1016/j.asr.2017.01.011

[2] J. Kouba, P. Héroux: Precise point positioning using IGS orbit and clock products, GPS Solutions 5(2), 12–28 (2001)

[3] J. Kouba: A Guide to Using International GNSS Service (IGS) Products (IGS, Pasadena 2015), http://kb.igs.org/

[4] Steigenberger P., Dach R., Fritsche M., Schmid R., Montenbruck O., Prange L., Uhlemann M.; Estimation of Galileo Satellite Antenna Phase Center Offsets; Journal of Geodesy 90(8):773–785 (2016)

[5] Dilssner, F., Springer, T., Schönemann, E., Enderle, W.; Estimation of satellite antenna phase center corrections for BeiDou. In: IGS Workshop 2014, Pasadena. (2014)

[6] C. J. Rodriguez-Solano, U. Hugentobler, P. Steigenberger: Adjustable Box-Wing Model for Solar Radiation Pressure Impacting GPS Satellites, Advances in Space Research 49(7), 1113 – 1128 (2012)

[7] Montenbruck O., Steigenberger P., Hugentobler U.; Enhanced Solar Radiation Pressure Modeling for Galileo Satellites; Journal of Geodesy 89(3):283-297 (2015). DOI 10.1007/s00190-014-0774-0

[8] Montenbruck O., Steigenberger P., Darugna F. ; Semi-Analytical Solar Radiation Pressure Modeling for QZS-1 Orbit-Normal and Yaw-Steering Attitude; Advances in Space Research 59(8):2088-2100 (2017) DOI 10.1016/j.asr.2017.01.036

[9] Ziebart M.: Generalized analytical solar radiation pressure modeling algorithm for spacecraft of complex shape, J. Spacecraft Rockets 41(5), 840 – 848 (2004)

[10] Steigenberger P., Montenbruck O., Hugentobler U.; GIOVE-B Solar Radiation Pressure Modeling for Precise Orbit Determination; Advances in Space Research 55(5): 1422-1431 (2015) DOI 10.1016/j.asr.2014.12.009

[11] Steigenberger P., Thölert S., Montenbruck O.; Determination of GNSS satellite transmit power and its impact on orbit determination; in print: Journal of Geodesy (2017)

[12] Montenbruck O., Schmid R., Mercier F., Steigenberger P., Noll C., Fatkulin R., Kogure S., Ganeshan A.S.; GNSS Satellite Geometry and Attitude Models; Advances in Space Research 56(6):1015-1029: (2015) DOI 10.1016/j.asr.2015.06.019

4. Satellite Metadata Table

Item	**Type**	**Used for**	**Desired properties**	**Relevance**	**Availability of provider information**	**Refs**
Mass	S/C	Modeling of non-gravitational forces (radiation pressure, Earth radiation pressure, antenna thrust)	Accuracy 0.1-1.0% (1-10kg)	High	GAL,QZS	(1),(2)
	OPS		Variation over time	Low	GAL,(QZS)	(1),(2)
Center-of-mass (in s/c frame)	S/C	Modeling of antenna and laser reflector coordinates relative to the reference point of all orbit products	0.1-1.0 cm in all axes	High	GLO,GAL,QZS,(BDS)	(1),(2)
	OPS		Variation over time	Low	GAL,(QZS)	(1),(2)
Laser reflector position in (s/c frame)	S/C	Modeling of satellite laser ranging observations	0.1-1.0 cm	High	GLO,BDS,GAL,QZS,IRS	(1),(2)
GNSS antenna phase center location (in s/c frame)	S/C	Modeling of the effective point of signal emission	1 cm; to be supplied for each individual antenna and signal frequency	High	(GPS),(GLO),GAL,QZS	(3),(2),(4)
			Direction dependent phase center variations (1 mm)	Medium	(GPS),GAL,QZS	(2),(3),(4)
Panel model	S/C	Modeling of solar and Earth radiation pressure	Dimension of solar panels (1-10%) Dimensions of satellite body (six surfaces, 1-10%) Optical properties (absorption, specular and diffuse reflection; 1-5%) Distance of panels from body (for BeiDou and QZSS)	High	GAL,QZS	(2),(4)
			CAD model (coarse; for complex structures with relevant shading)	Low/ Medium	-	
Radiated antenna power	S/C	Modelling of antenna thrust	Accuracy 20W	Low	(QZS)	
	OPS		Variation over time	Low	-	
Attitude	S/C	Modelling of antenna offset, phase wind-up and radiation pressure	Nominal attitude law outside eclipses (1-2 deg)	High	GPS,GLO,BDS, GAL,QZS,IRS	
	S/C, OPS		Attitude during noon and midnight turns in the eclipse season	High	(GPS),(GLO),GAL	(4)
	OPS		Epochs of mode transition (yaw steering vs normal mode; for BeiDou and QZSS)	High	(QZS)	(2)
Orbit maneuvers	OPS	Modeling of orbit discontinuities	Time (5s) and Delta-V (0.1-1cm/s)	High (BDS) Medium (others)	(QZS)	(2)

Notes:

Brackets around constellation names in column 6 (“Availability of provider information”) indicate that the respective information is only available for a subset of satellites in this constellation, e.g. a single block

Abbreviations:

S/C=Spacecraft information, OPS=Operational information

References:

(1) ILRS List of Supported Missions. https://ilrs.cddis.eosdis.nasa.gov/missions/satellite_missions/
(2) QZSS Satellite Information website. URL http://qzss.go.jp/en/technical/qzssinfo/ (includes QZS-1/2; last updated 2017/10/06)
(3) The GPS Block IIR/IIR-M Antenna Panel Pattern. URL http://www.lockheedmartin.com/us/products/gps/gps-publications.html
(4) Galileo Satellite Metadata website. URL https://www.gsc-europa.eu/support-to-developers/galileo-iov-satellite-metadata (includes IOV-1 to -4 and FOC-1 to -14; last updated 2017/10/06)