The ESA Navigation Facility at the European Space Operations Centre provides Data and Services to Precise Positioning, Navigation and Timing Applications

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Abstract: *The Navigation Support Office is ESA's centre of expertise in high-precision applications of navigation satellite systems. The Navigation Support Office is based at the European Space Operations Centre (ESOC) in Darmstadt, where it operates the ESA Navigation Facility with the objective to advance the theory and operations of precision navigation and timing, including all related scientific areas. It contributes to ESA missions, third-party activities and EU space programmes including Galileo, EGNOS and Copernicus. Among others, the Navigation Support Office is leading the Galileo Geodetic Service Provider (GGSP), a consortium which is responsible for the realisation and maintenance of a Galileo Terrestrial Reference Frame (GTRF). The GTRF is one of the key components contributing to the system performance of Galileo. In addition to this, ESA has been contributing to the Coordinated Universal Time (UTC) with atomic clocks. This has improved the ESA/ESOC timing performance capabilities significantly and has allowed to establish an operational service that can now be used by all ESA space missions and timing applications. The paper provides an overview on data and services that the ESA Navigation Facility provides to positioning, navigation and timing applications. This is complemented by example results that showcase the achievable accuracy and availability of such data and services.*

1. Introduction

The Navigation Support Office is ESA's centre of expertise in high-precision applications of navigation satellite systems. It contributes to ESA missions, third-party activities, and EU space programmes including Galileo, EGNOS and Copernicus. The Navigation Support Office is based at the European Space Operations Centre (ESOC) in Darmstadt, where it is integrated in the Ground Systems Engineering and Innovation Department. It develops, maintains, and operates its own infrastructure, which includes the ESA Navigation Facility (Figure 1), ESOC’s own global, real-time Global Navigation Satellite System (GNSS) sensor station network called EGON, and all application and infrastructure software needed for high-precision GNSS data processing.

Beside the data from the EGON network, the Navigation Support Office retrieves GNSS data (non-real time and real-time) from stations that are part of the International GNSS Service (IGS) sensor station network. All data are ‘Multi-GNSS’, meaning that they include all four global GNSS constellations and in addition the Japanese regional QZSS data.

In the frame of its responsibility to provide the Geodetic reference for ESA missions, the Navigation Support Office is contributing to the realisation of the International Terrestrial Reference Frame (ITRF) and the combined Earth Orientation Parameters (EOPs) provided by the

International Earth Rotation and Reference Systems Service (IERS). The contribution is realised through individual contributions to the services of the International Association of Geodesy (IAG) such as the International GNSS Service (IGS), the International Laser Ranging Services (ILRS), the International DORIS Service (IDS), the International Earth Rotation and Reference Systems Service (IERS) and in the future also to the International VLBI Service (IVS). DORIS stands for Doppler Orbitography and Radiopositioning Integrated by Satellite, which is a French Doppler tracking system mainly used for tracking satellites in Low-Earth orbit, and VLBI stands for Very-Long-Baseline Interferometry. In this context, the availability of highly accurate, up to date EOPs is of major importance for all positioning and navigation applications on Earth, sea, air but especially in space. This is equally true for ESA missions, EU space programmes and also for any other European space missions.

In addition to the above, the Navigation Support Office is leading the Galileo Geodetic Service Provider (GGSP), a consortium which is responsible for the realisation and maintenance of the Galileo Terrestrial Reference Frame (GTRF). The GTRF is one of the key components contributing to the system performance of Galileo and is compatible with the latest ITRF with a precision of well within 3 cm. In addition to the GTRF, the GGSP is delivering a wide variety of monitoring products, including precise orbits, clocks, station coordinates, EOPs, atmosphere and bias estimates. Only with such a complete and consistent set of high precision products, the GGSP can provide a reference frame to the various Galileo user communities. In addition, these high precision products are extremely valuable for the validation of the operational products generated by the Galileo Ground Mission Segment (GMS).

Figure 1: The Navigation Facility at ESOC

Having access to a precise reference time is considered part of the critical infrastructure in many countries. Since 2012, ESA has been contributing to the Coordinated Universal Time (UTC) with atomic clocks. More recently, the clocks run by the Navigation Support Office at ESOC have officially been added to contribute their measurements. This has improved ESA/ESOC timing performance capabilities significantly and has allowed to establish an operational service that can now be used by space missions and timing applications.

The Navigation Support Office is also an expert in the Precise Orbit Determination of LEO satellites. In this context it is routinely generating precise orbits for the ESA missions, such as Swarm and Cryosat, as well as for all the Sentinel satellites of the European Earth Observation program named Copernicus.

2. GNSS Data: The EGON Network

GNSS ground receiver data is a required input for all high-precision GNSS applications. The existing IGS network is an important and well-known source for such data. Despite its demonstrated availability and quality, it is made available without guarantee of continuation, and the special distribution of the data is very inhomogeneous, with high concentrations of data in North America and Europe.

In order to have more control, and a more even spatial distribution of data, the Navigation Support Office has been deploying receivers at global sites. These are all state-of-the-art multi-system geodetic receivers, presently of the type Septentrio PolaRx 5. All data from this network is streamed to ESOC in real time and is used at ESOC both in real-time and batch applications. Figure 2 shows the present status of this network, where a number of sites are still under deployment.

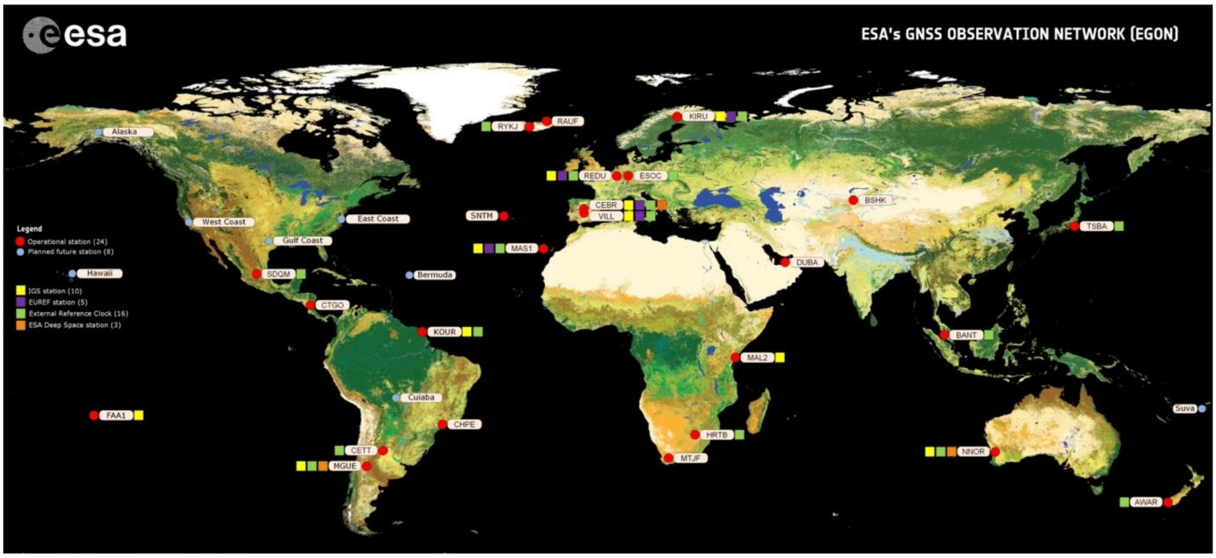

Figure 2: ESA's GNSS Observation Network (EGON) operated by the Navigation Support Office

3. International Collaboration

ESOC is one of the founding members of the International GNSS Service (then: International GPS Service for Geodynamics). This service has since then grown to become a global institution, which provides GNSS data and products for high-precision applications. ESOC is one of the analysis centres, which have been in a ‘competitive collaboration’ since the beginning, and which have been producing typical GNSS batch processing products like orbit and clock solutions, satellite biases, station coordinates and others. Individual solutions have been merged into combination products that have become the reference for internal comparisons. This approach has allowed ESOC’s products to be of ever-increasing accuracy, and they are now among the most accurate in IGS.

Beside these batch products, there is a similar IGS activity for real-time products, and here ESOC has been playing a key role as the coordinator of this effort. All batch and real-time products can be retrieved from the IGS web site [1].

Similar collaboration activities exist for the other space geodetic techniques. The ILRS is even older than IGS, but ESOC has become an Analysis Centre after joining IGS. For DORIS, the international service is IDS, as already mentioned above, and ESOC has been an analysis centre since its inception. Both in ILRS and IDS, ESOC ranks among the most accurate contributors. VLBI is the only geodetic technique that can be used to observe the celestial reference frame and create the link between the celestial and terrestrial reference frames, which is expressed through the Earth Orientation Parameters. ESOC has joined the related service (IVS) more recently as an associated Analysis Centre (AC) and is in the validation stage of VLBI data processing, estimating and predicting EOP data.

For batch processing of all data from the four geodetic techniques, the Navigation Support Office uses a single software infrastructure called NAPEOS (NAvigation Package for Earth Observation Satellites). This approach ensures a consistent processing of all data, using the same standards and models. This is a key aspect for reliable high-precision applications. The tool for real-time processing of GNSS data is called RETINA (REal TIme NAvigation). Strict configuration control ensures that both software infrastructures use the same standards and models. Both have been developed - and are being maintained - by the Navigation Support Office.

The Navigation Support Office is also deeply involved in the activities of the International Committee on GNSS (ICG), which is acting under the umbrella of the Unite Nations. In fact, ESA staff is co-chairing the so-called Space Use Subgroup (SUSG) together with representatives from US/NASA and China. The SUSG was responsible for the definition of the GNSS Space Service Volume (SSV) and the generation of a booklet that describes the SSV and also provides reference scenarios. This booklet is the GNSS SSV reference, because it is the only document related to this subject topic, which is endorsed by all GNSS service providers. The Navigation Support Office was together with NASA the main contributor to the booklets.

4. Reference Frame and Earth Orientation Parameters

The International Terrestrial Reference Frame (ITRF) is computed every few years, under coordination by the Institut National de l'Information Géographique et Forestière (IGN) in France. It uses data from all four geodetic techniques that were described above. Presently, ITRF-2020 is being finalised for publication in November 2022. The main parameters defining the ITRF are the positions and velocities of the contributing stations from all four techniques, but there are numerous additional models and parameters, like tectonic plate motion and Earth pole motion, that define the ITRF.

The input data that are used for each ITRF calculation are computed using dedicated re-processing campaigns in IGS, ILRS, IDS and IVS, using prescribed time intervals and models. ESOC is participating actively in these campaigns for the first three techniques and is well placed to continue this also for VLBI data processing.

When the Galileo project was defined, it was decided that for this constellation a dedicated reference frame would be computed based on Galileo infrastructure. For the computation of this reference frame, the Galileo Terrestrial Reference Frame (GTRF), a scientific consortium was selected, which consists of European experts in GNSS data processing and reference frame calculation. There is a requirement that the GTRF remains closely aligned with ITRF, within 3 cm at two sigma (95.4%) as shown in Figure 3.

The participating institutes to this consortium are:

- Astronomical Institute of the University of Bern, Switzerland (AIUB)
- Bundesamt für Kartografie und Geodäsie, Frankfurt, Germany (BKG)
- European Space Operations Centre, Darmstadt, Germany (ESOC)
- Deutsches GeoForschungsZentrum, Potsdam, Germany (GFZ)
- Institut National de l'Information Géographique et Forestière, France (IGN)

In this collaboration between five teams, ESOC has the coordinating role. The basis for the reference frame creation is the generation of independent orbit and clock solutions, station coordinates and all other relevant parameters. Three members of the team (AIUB, ESOC and GFZ) are also among the most accurate players in IGS, which ensures the high quality of these products. Combination products are generated just like in IGS. IGN is responsible for the generation of GTRF, based on solutions for all station coordinates. Quality control is ensured by monitoring the solutions against the combination, and by independent validation by BKG.

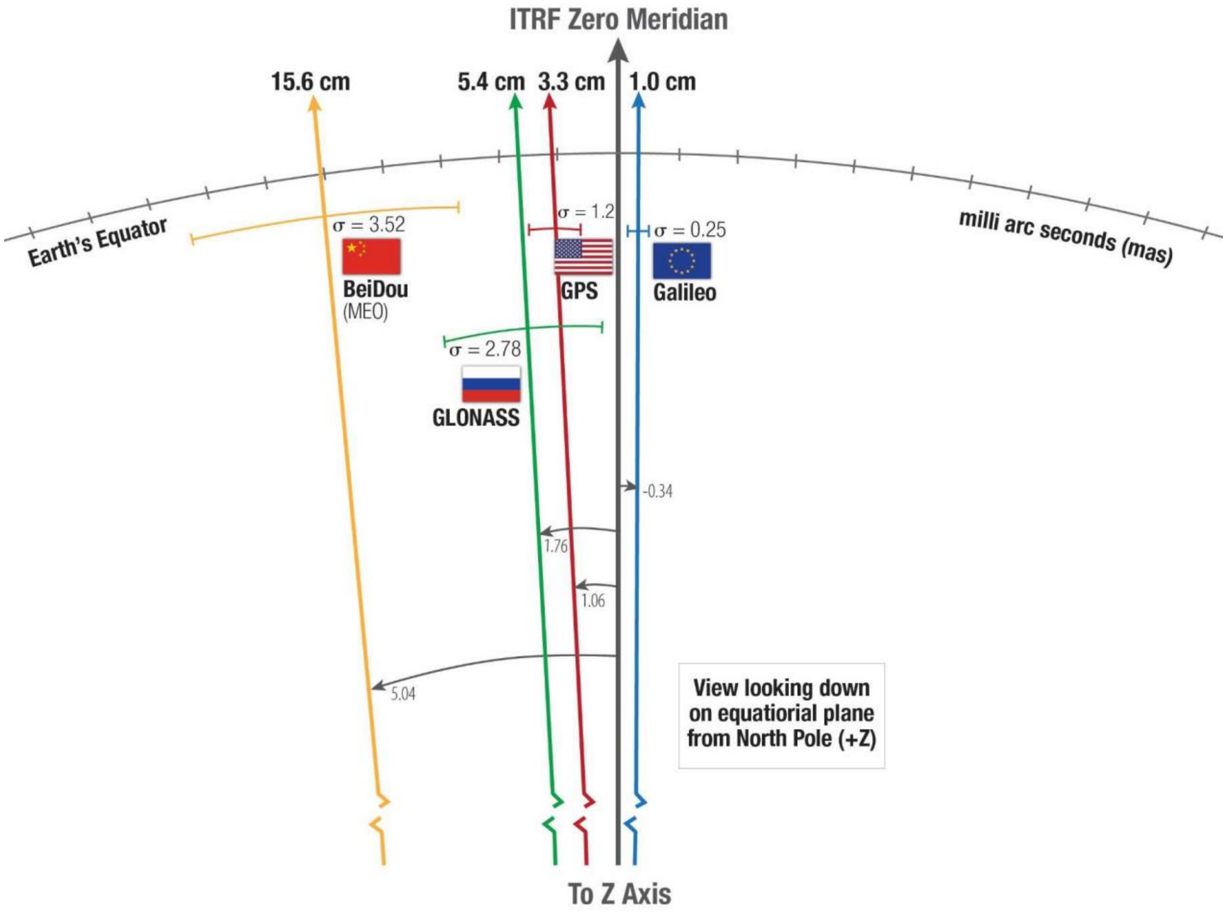

Figure 3: Comparison of Reference Frames for the 4 GNSS Systems in Terms of Accuracy of the Zero Meridian [2]

EOP data provides the link between the coordinate systems on Earth and in space. They represent a critical input for Precise Orbit Determination, and they are presently only available on US infrastructure. In order to provide more redundancy, ESOC is preparing for the generation of an independent product. This is presently at an experimental stage. The data production process consists of the following steps:

- Step 1: Observation and analysis of historical data, making use of all available geodetic techniques
- Step 2: Prediction by specially tailored extrapolation
- Step 3: Evaluation of the results

As part of an on-going comparison campaign, many teams are producing such experimental EOP prediction results, and these are evaluated by comparing with the actual EOP data post-facto. These comparisons demonstrate the excellent quality of the EOP predictions of ESOC's Navigation Support Office.

5. High-Precision Products

High-accuracy GNSS orbit and clock solutions are being computed in the frame of several projects, with different requirements on accuracy, timeliness and availability. For general use, a separate processing chain has been set up, in order to routinely provide solutions for all constellations. This set of solutions is based on EGON data combined with a selection of IGS sites of known reliability and quality, ensuring a satellite coverage that is as uniform as possible. They are generally referred to as MGNSS (for Multi-GNSS). These products are made available to the community free of charge, with a small delay. They are published at the web site of the Navigation Support Office, with a description of the properties of these products [3].

On the same web page, additional data and products are made available. These include ESOC's submissions to IGS, the EGON station data and links to ESOC's Real-Time product contributions to IGS.

6. Time Provision

Figure 4 provides an overview on the Timing Facility at ESOC. The local timescale generation is based on two active hydrogen masers operated in a thermally stable environment. Steering is performed via two independent phase and frequency offset generators and redundant processing on two parallel servers. Remote operations and performance monitoring are provided. A high availability is achieved thanks to full system redundancy.

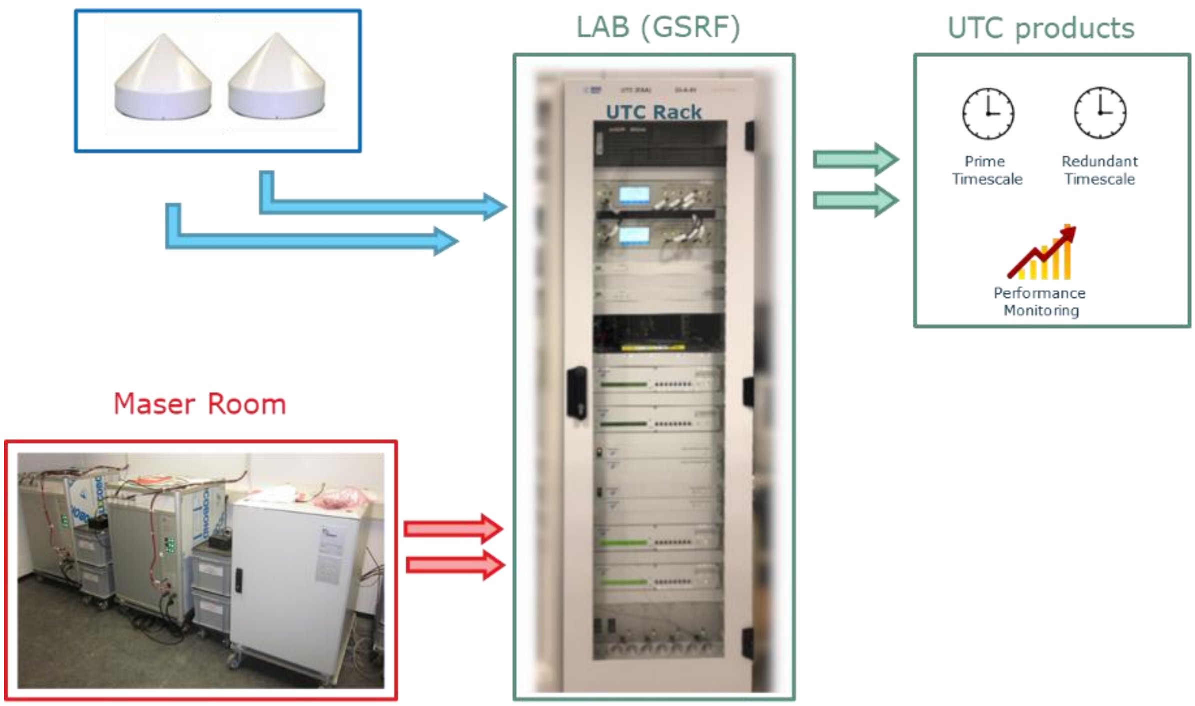

Figure 4: Timing Facility at ESOC [4]

A second timescale is generated at ESTEC, ESA's establishment in the Netherlands. The timescales operated at ESTEC and ESOC are independent, which provides additional redundancy. The ESTEC-ESOC Time Offset (EETO) is continuously monitored using a redundant calibrated multi-GNSS link (Figure 5).

The EETO is redundantly estimated at ESTEC using the so-called Common GPS GLONASS Time Transfer Standard (CGGTTS) and Precise Point Positioning (PPP). At ESOC this is achieved by CGGTTS and ESOC's above-mentioned MGNSS solution calculated with NAPEOS. The EETO value at 00:00 UTC is used to report the ESOC clocks in the ESA BIPM clock file, where BIPM stands for the International Bureau of Weights and Measures located in Sèvres, France.

The infrastructure shared between ESOC and ESTEC is used for the robust generation of the combined timescale, the so-called UTC(ESA), for:

- Distribution to local users and services
- Characterization of on-board equipment and clocks
- Monitoring of multi-GNSS time dissemination
- Ground stations and mission operations
- Assessment of new time and frequency transfer techniques

UTC(ESA) provides state-of-the-art timing performance, well within +/- 5ns as shown in Figure 6 over the year 2021.

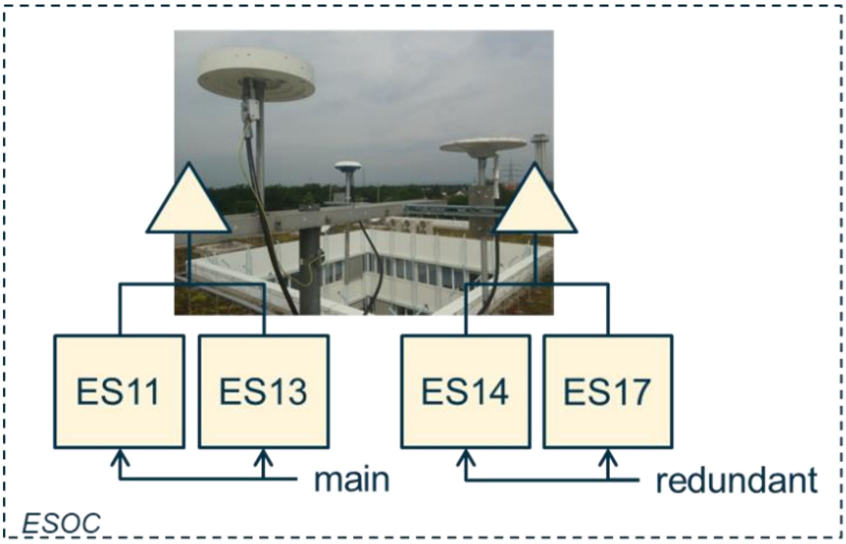

Figure 5: Redundant Calibrated multi-GNSS Link at ESOC [4]

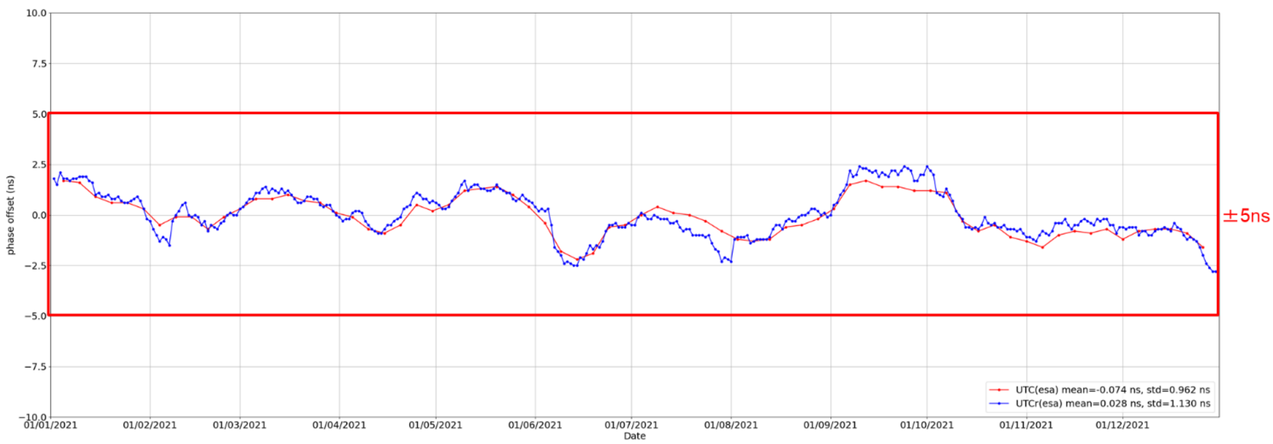

Figure 6: UTC(ESA) Performance in 2021 [4]

7. Summary and Conclusions

Both users and providers of GNSS data for systems and applications, require data of high accuracy, availability and reliability. Foremost are the GNSS transmitted data that allow precise positioning, and therefore must be of very high accuracy in real time. ESOC's Navigation Support Office has a demonstrated capability of providing such data for all global constellations through land communications, with an availability in the range of 99.5% - 99.9%. As this data is made available at best effort and without service guarantee, it is primarily useful for experimentation and validation both by service providers and users. Even more accurate post-processed data are available for the same purpose.

Having access to a stable and accurate time reference is of key importance primarily for service providers to space missions. Here, ESA's contribution to UTC is an important asset, and the ESA UTC time reference is available for use in specific GNSS products provided by the Navigation Support Office.

Providers also require reliable access to Earth Orientation Parameters. Until recently, these are only available from a single source outside Europe. On-going work at the Navigation Support Office is aiming at increasing the availability of these data and providing a redundant source within Europe.

For further information about ESA's Navigation Support Office and its products, please visit the web site http://navigation-office.esa.int/.

References

[1] See: https://igs.org/products/

[2] S. Malys, T, Johnson, T. Kawakami, Compatibility of Terrestrial Reference Frames used in GNSS Broadcast messages, Presented at the 24th National Space-Based PNT Advisory Board, Cocoa Beach, Florida, November 20 2019

[3] See: http://navigation-office.esa.int/GNSS_based_products.html

[4] P. Waller, C. Plantard, E. Schoenemann, F. Reckeweg, S. Mejri, A. Di Mira: Report on UTC Activities at the European Space Agency, International Technical Meeting (ITM/PTTI 2022), January 25 - 27, 2022, Long Beach, CA, USA,Session P5: Timescales, Algorithms, and Timing Services