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COPERNICUS MISSIONS - PRECISE ORBIT DETERMINATION

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ABSTRACT

The **Copernicus Precise Orbit Determination (CPOD) Service** is in charge of computing the precise orbits and auxiliary files of the Copernicus Sentinel-1, -2, -3 and -6 missions, using the GPS&GAL observations obtained on-board. The orbital products and auxiliary data files are provided to the corresponding Payload Data Ground Segments (PDGS) and to external users through the Copernicus Open Access Hub.
The CPOD Service is supported by the CPOD **Quality Working Group (QWG)**, a group of leading experts on GNSS and POD, which provides independent orbit solutions and techniques to support the quality control of the operational products.
The architecture of the CPOD Service, the processing scheme, and the quality control, including the latest results are described here.

1. INTRODUCTION

The **European Copernicus** programme [1] consists of several satellite missions dedicated to various remote sensing techniques of planet Earth.
The European Commission (EC) manages the Programme, which is implemented in partnership with the Member States, the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for Medium-Range Weather Forecasts (ECMWF), EU Agencies and Mercator Océan [2].
It provides added value **Copernicus services** in the following areas: Atmosphere, Marine, Land, Climate Change, Security and Emergency [3].

The provision of Copernicus services is based on the processing of environmental data collected from Earth observation satellites (Sentinels) and in situ sensors.

The Sentinel satellites are divided into missions. **Sentinel-1, -2, -3 and -6** are dedicated satellites, while Sentinel-4 and -5 are instruments onboard EUMETSAT´s weather satellites.

Sentinel-1 consists of two satellites with imaging C-band radars and continues the C-band SAR data gathered by ERS and Envisat missions. **Sentinel-2** consists of two satellites with a Multi-Spectral Instrument (MSI) optical and infrared sensors and continues the provision of the products delivered by former Landsat and SPOT missions. **Sentinel-3** consists of two satellites with several sensors and continues the generation of the products from Envisat and ERS missions. The list of products provided by Sentinel-3 includes surface colour products, surface temperature products, land vegetation products, surface topography products, derived from the combination of data produced by the Radar Altimeter, MWR and GNSS receiver. **Sentinel-6** mission will ensure continuity to the JASON series of operational missions providing high precision ocean altimetry measurements.

The **Copernicus Precise Orbit Determination** (CPOD) Service is in charge of computing the precise orbits and auxiliary files of the Copernicus Sentinel-1, -2, -3 and -6 missions. The orbital products and auxiliary data files are provided to the corresponding Payload Data Ground Segments (PDGS) / Payload Data and Acquisition Processing (PDAP) to support the generation of the Copernicus services. The service is a consortium led by **GMV**, Spain, being responsible for all operations and operational developments. The consortium includes the following members:

- PosiTim UG, Germany
- Astronomical Institute of the University of Bern (AIUB), Switzerland
- German Space Operations Centre, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany
- GeoForschungsZentrum (GFZ), Germany
- Faculty of Aerospace Engineering, Delft University of Technology (TUD), The Netherlands
- Institute for Physical and Astronomical Geodesy and German Geodetic Research Institute, Technical University of Munich (TUM), Germany

The CPOD Service generates different types of orbital products, with demanding timeliness and accuracy requirements (see Tab. 1 and Tab. 2)

The type of orbital products is linked to the timeliness:

- **Predicted (PRE)**: orbit predictions covering one to five orbits.
- **Near-Real Time (NRT)**: precise orbits computed in less than 10 / 30 min from the availability of data.
- **Short Time Critical (STC)**: precise orbits computed one day after sensing time.
- **Non Time Critical (NTC)**: precise orbits computed 20 – 25 days after sensing time.

Considering the current level of accuracy achieved at the CPOD Service (see section 4), more demanding accuracy requirements will be required from 2023 onwards.

Table 1. Mission Accuracy Requirements

Product type	Sen-1 [3D]	Sen-2 [3D]	Sen-3 [rad]	Sen-6 [rad]
PRE	1 m	3 m	n/a	n/a
NRT	10 cm	1 m	8 cm	5 cm
STC	n/a	n/a	3 cm	n/a
NTC	5 cm	n/a	2 cm	n/a

Table 2. Timeliness requirements

Product type	Sen-1	Sen-2	Sen-3	Sen-6
PRE	10 min	-90 min[1]	n/a	n/a
NRT	180 min	30 min	10 min	10 min
STC	n/a	n/a	1.5 days	n/a
NTC	20 days	n/a	25 days	n/a

2. PHYSICAL DESIGN

The CPOD Service is physically located in a **public Cloud** hosted by the company GIGAS. The physical design is composed of processing machines, FTPs, Firewalls, and archives. In figures, the current status is:

- 10 processing machines,
- 80 CPU cores,
- 120 GB of RAM,
- 1.2 TB of hard disk memory and,
- 10 TB of archive

There are two main processing machines, running in parallel for robustness in case of issues in one machine. There are two FTPs, mounted as a high-availability cluster, plus a HTTPS API Rest server as interfaces with operational users (the PDGS/PDAP). Then, there are several monitoring and reporting machines, which includes a secure server to exchange data and products with the CPOD Quality Working Group (section 3.5), and an online monitoring tool based on Grafana (section 3.6).

This design allows supporting the 4 Sentinel missions, with a total of 7 satellites. Overall, the CPOD Service generates approximately 100,000 orbital products per year, of different timeliness (PRE, NRT, STC, NTC).

3. LOGICAL DESIGN & OPERATIONS

The logical design and operations are presented along the following areas:

- **Interfaces**: the external data and products used to compute the precise orbits.
- **Storage and dissemination**: how the data and products are obtained, disseminated, and archived into the CPOD system.
- **Data & process management**: how the CPOD Service is orchestrated to generate the products.
- **POD computational core**: the software and processing scheme used.
- **Quality control**: the approach used to monitor the quality of the products
- **Reporting and monitoring**: the tools used to report the status of the CPOD Service and the quality of products.

3.1. Interfaces

The CPOD Service needs several inputs to carry out the POD:

- **GNSS & NAVATT L0**. The GNSS observations gathered by the GNSS receiver on-board the Sentinels. The NAVATT includes the satellite´s attitude as quaternions measured on-board, and the navigation solution computed by the GNSS receiver.
  This data is provided by the respective PDGS/PDAP in binary L0 packages as downloaded from the satellite, so at least there is new data per orbit.

- **Flight Dynamics products**. The respective Flight Operation Segment (FOS). It is ESOC for Sentinel-1 and -2, and EUMETSAT for Sentinel-3 and -6. They compute and provide manoeuvre information, the mass and centre of mass history files, and their own restituted and predicted orbit that contains the orbit number counter.

- **External orbital products**. Precise orbits computed by external centres, which are used for quality control. They are provided by the CPOD QWG, which includes more than 10 centres in Europe and USA (section 3.5)

- **GNSS products**. The GNSS POD process requires precise orbits, clocks, and biases of the GNSS constellations used. The **External GNSS Provider (EGP)** is in charge of delivering these inputs: for NRT and STC it is used the GMV´s ***magicGNSS***

[1] 90 minutes in advance

and DLR´s RETICLE services, while for NTC it is used the CODE final and rapid products.

The GMV´s ***magicGNSS*** service will make use of a global network of GNSS receivers owned by GMV, to enhance the performance and capabilities of the GNSS products. Additionally, it will provide biases to allow doing Integer Ambiguity Resolution in STC and NRT, as it is done in NTC with CODE products.

– **Geodynamic products**. This include the EOPs, Leap Seconds, Solar Activity indexes and Atmospheric Gravity data. This is provided by IERS, NOAA and GFZ. Additionally, AIUB is currently providing quarterly geopotentials from the COTS-G project (https://cost-g.org)

– **DORIS & SLR observations**. CNES provides DORIS RINEX data of Sentinel-3 and -6, while ILRS provides SLR observations from the stations tracking Sentinel-3 and -6.

The CPOD generates the following types of products:

- **Orbital products** for the respective PDGS/PDAP. Most of these products are also available to external users through the Copernicus Open Access Hub (COAH) [6]. Additionally, orbital predictions of Sentinel-3 are generated to support the SLR tracking done by ILRS, and orbits in SP3 format are generated for the CPOD QWG.

- **Platform data files** for the Sentinel-3 mission.

- **GNSS RINEX & Quaternions** for external users (through COAH), and for the CPOD QWG.

- **Others**: Manoeuvre information, mass and CoG history and Phase Centre Offset and Variations (PCO/PCV) are provided to the CPOD QWG and external users.

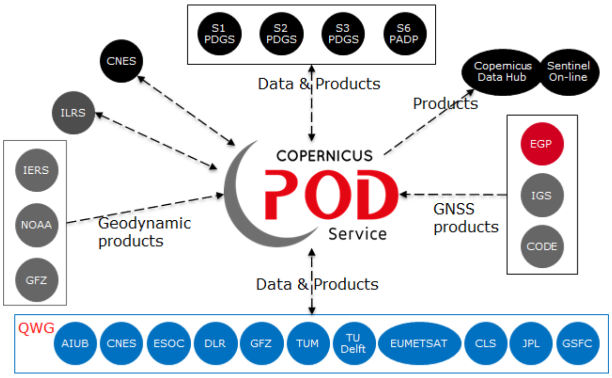


Figure 3.1-1. Overview of external interfaces

3.2. Storage & Dissemination

The CPOD Service has been storing all the inputs received and products generated since the beginning of the service in 2014. Additionally, all processing metrics and quality control metrics are also storage in a DB for monitoring and reporting.

The CPOD Service uses a high-availability secure server as an interface point with the PDGS/PDAP. It can be used with Secure FTP or HTTPS API REST protocols. In case of FTPS, the clients get products and put inputs into the server, which are retrieved by each processing machine. In case of HTTPS API REST, the secure server keeps a local archive and DB to support external clients´ needs.

The processing machines can also make use of different communication protocols to get inputs from external sources, including FTP, FTPS, SFTP, HTTP and HTTPS API REST.

All in all, the CPOD Service allow retrieval and dissemination using a wide range of secure protocols. The use of HTTPS API REST allows for some advance functionalities like:

- Perform advanced queries to get inputs
- Use subscription services to warn users about the availability of new inputs & products.
- Monitor the use of the interface.

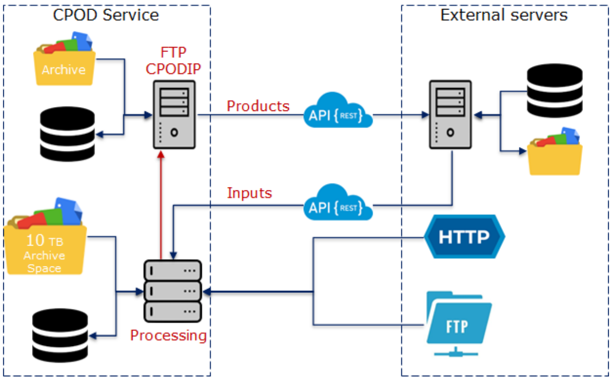


Figure 3.2-1. Storage & Dissemination

3.3. Data & Process Management

Currently, the orchestration of the multiple processes is done using the Linux **crontab** that launches processes that either:

- check the availability of new L0 inputs that trigger the generation of NRT products or,
- generate products at specific times for STC, NTC, QC, and other products.

This design is very robust, but it has several drawbacks:

- it does not make an optimum use of the HW. Multiple executions are launched every minute just to check if it is necessary to launch a process.

- it limits the timeliness of processes launched at specific times, while sometimes the generation can be anticipated if the inputs arrive earlier.
- It is prone to failure when some needed input arrives late (e.g., the quality control against an external reference)

To overcome these drawbacks, a new design is being developed. Instead of using the crontab, one or several services running on the machine will be developed. These services will be connected to the DBs, such that once new inputs or products are inserted, a decision process will be triggered to decide whether or not some actions can be performed. With this approach:
- The generation of NRT will be executed just after the arrival of the required inputs.
- The generation of STC, NTC and QC (comparisons), etc. will be performed once all the necessary inputs are available. This should allow reducing their timeliness and avoid failures.

3.4. POD Computational core

The POD Computational core is composed by the SW in charge of:
- To decode the input L0 GNSS & NAVATT packages.
- To perform the POD and generate the products.
- To perform different Quality Control processes (section 3.5).

Currently, these different tasks are carried out by several SW programs, which can be divided into:

- **L0 decoders**: this is written in C++ and it generates ASCII files with the GNSS observations (RINEX), navigation solution (SP3) and quaternions.

- **NAPEOS**: This is an ESA/ESOC, state-of-the art SW package, written in Fortran 90/95 and TCL/TK. It is composed by numerous programs, each of them in charge of specific tasks like input preparation, measurements pre-processing, POD, product formatting, comparisons, etc.

GMV is developing a new POD SW called ***focusPOD***, which will substitute the L0 decoders and NAPEOS from 2023 onwards. Written in C++ and python from scratch, it has been designed as a multi-purpose library, from which it is possible to build ad-hoc or generic programs.

The generation of precise orbits is split into the following steps:

- **Retrieval of inputs**: All inputs are retrieved from external sources and archived into the CPOD Service by independent chains. Therefore, this step just consists in selecting the best inputs (L0 GNSS & NAVATT, GNSS products, geodynamic inputs, FOS inputs, etc.) querying to the CPOD DB.
- **L0 decoding**: The GNSS & NAVATT L0 packages need to be decoded to obtain the GNSS observations, the on-board navigation solution, and quaternions.
- **GNSS products handling**: The EGP provides GNSS products with different coverages and timeliness. This task generates a consolidated coverage that fit the determination interval which is used. Typically, this requires merging the content of several input files.
- **GNSS Pre-processing**: The raw GNSS observations are combined to generate ionosphere-free linear combinations. Then, several checks are performed to identify and reject outliers. Afterwards, passes are identified, and an initial ambiguity is computed. Finally, using the ionosphere-free pseudo-range observables with the Bancroft algorithm, an initial Position, Velocity & Time (PVT) of the LEO satellite is computed as a rough initial solution.
- **Least Square**: The POD problem is parametrized as a Least Square problem, on which several parameters are estimated per determination arc: initial state-vector, drag (CD) and solar radiation (RP) coefficients, Constant-per-revolution (CPR) empirical accelerations, manoeuvre calibrations, clock biases and float ambiguities per pass.
- **Integer Ambiguity Resolution (IAR)**: In this step, the float ambiguities are fixed. This step is done currently only for the NTC products, as it requires the code and phase GNSS biases. In the future, this will be also done for the STC and NRT, once the ***magicGNSS*** start delivering biases as well. After fixing the ambiguities, the POD Least Square adjustment is done once more to compute the final precise orbit.
- **Product generation**: The final product is formatted accordingly.
- **Archive**: The final product is archived into the CPOD Service prior to its dissemination. Additionally, processing metrics are dumped into the DB.
- **Dissemination**: New products are disseminated to their final user, which can be the PDGS/PDAP or the Copernicus Open Access Hub (COAH).

With the legacy system, the steps between GNSS *product handling* and *product generation* are done with multiple programs of NAPEOS, which are exchanging data using local files. With ***focusPOD***, it is intended that all steps are done with a single binary, which also perform the L0 decoding. This should allow an improvement in processing time and resources needed.

Besides POD, the SW also carried out the following processes:

- Compute the ground-track deviation, and Sentinel-1 tube control, for monitoring.
- Compute the Sentinel-3 & -6 GNSS USO frequency drift, for monitoring.
- Perform orbit and attitude comparisons against external sources.
- Perform SLR residuals analysis.
- Perform an orbit combination as a weighted mean of different, independent solutions.

3.5. Quality control

Quality control is needed to identify degraded products. Currently, using the processing metrics of each POD, a simple algorithm identifies anomalies and flag each state-vector, and the product. The metrics used includes the number of observations used and rejected, the RMS of the code and phase residuals and the presence of manoeuvres and data gaps. In the case of number of observations and residuals, a simple threshold is used to decide whether the product is degraded or not. In the case of manoeuvre and data gaps, those state-vectors impacted are flagged accordingly.

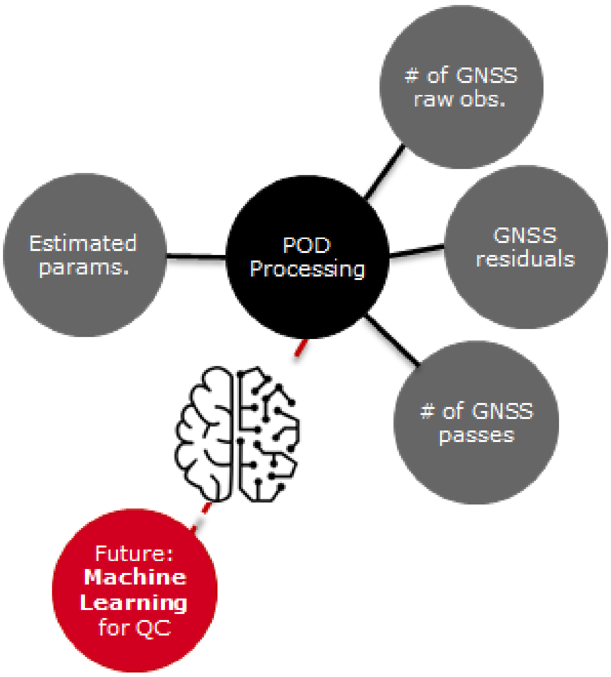


Figure 3.5-1. POD based QC

A new scheme is being developed to use Machine Learning (ML) to decide whether a product is degraded. In this case, it is possible to use more metrics, including the estimated dynamical parameters (i.e., the CD, RP and CPRs). With this approach, it is expected to reduce the number of false positives (good products erroneously flagged as degraded) and false negatives (bad products erroneously flagged as nominal).

Every three / four months, a thorough review of the CPOD Service is done, to report about the quality of the service. They are called **Regular Service Reviews (RSR)** and include the following tasks:

- To report the availability and timeliness statistics of inputs received and products generated.
- To perform an independent generation of precise orbits by the Copernicus POD QWG (Figure 3.5-3).
- To generate an orbital **combined solution** which is used as reference for orbit comparison. The combined solution is generated as a weighted mean of the independent solutions provided by the QWG.
- To perform the orbit comparison of all operational products generated against the combined solution.
- To assess the accuracy of the GNSS Products generated by the External GNSS Provider (EGP) ***magicGNSS*** / RETICLE, using CODE rapid products as reference (to compare GALILEO as well).
- To assess the GNSS sensor performance, including the GNSS USO drift.
- To perform SLR residual analysis
- Altimetry cross-over analysis (only once per year)

These analyses are documented and published on the Sentinel Online [5] under Technical guides – Sentinel-[123] – POD instruments and Products – Documentation library.

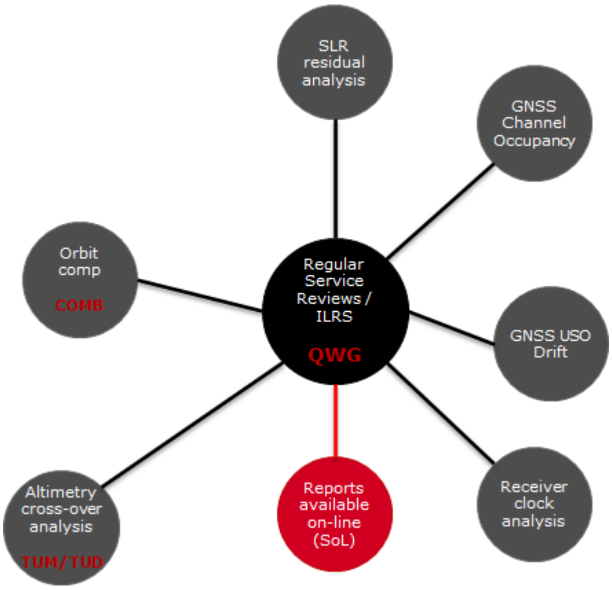


Figure 3.5-2. Regular Service Review

Figure 3.5-3. Members of CPOD QWG

3.6. Reporting & Monitoring

The following two tools support the monitoring of the CPOD System:

- **NAGIOS** is used to monitor the machines, networks, availability of inputs and products, and the nominal functioning of the system. A team of IT engineers, available 24x7, identify issues with the machines and networks, and directly contact the cloud provider in case of problems. They also contact the POD Experts in case of issues with the processing chains, in particular if there is lack of inputs or products.

- **Grafana** is used for the Online monitoring tool. The POD Experts use this tool to monitor not only the availability of inputs and products, but also the timeliness, and quality control metrics which are generated routinely. The POD Experts are available on Normal Working Hours (NWH), and they are on-call during the weekends and public holidays.

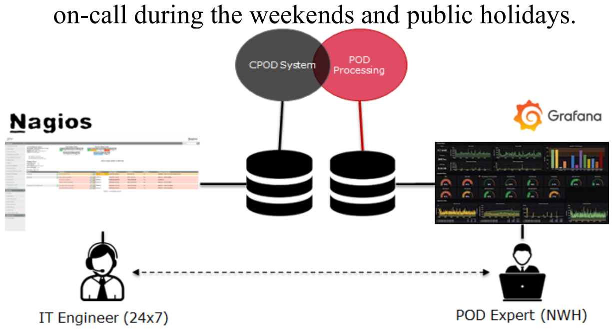


Figure 3.6-1. Monitoring tools

In terms of reporting, the online monitoring tool is also accessible to ESA & EUMETSAT.
The CPOD Service provides data, products, and documents to final users, through two mechanisms:

Sentinel online [5]. There are dedicated webpages to the POD under the Technical guides. External users can find:

- Documentation: The File Format Specification of the POD products, the POD technical information, the RSR reports and ILRS reports.
- Manoeuvre and mass history files, as computed by the respective Flight Operations Segments.
- Phase Centre Offset and Variations (PCO/PCV) of the antennas on-board the Sentinels.

Copernicus Open Access Hub [6]. A web portal that allows external users to download the following products:

- Orbital products computed by the CPOD Service
- GNSS RINEX observation files
- Quaternions files.

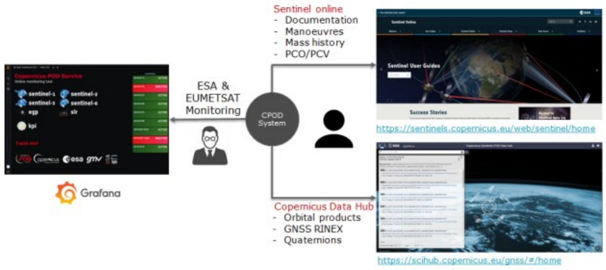


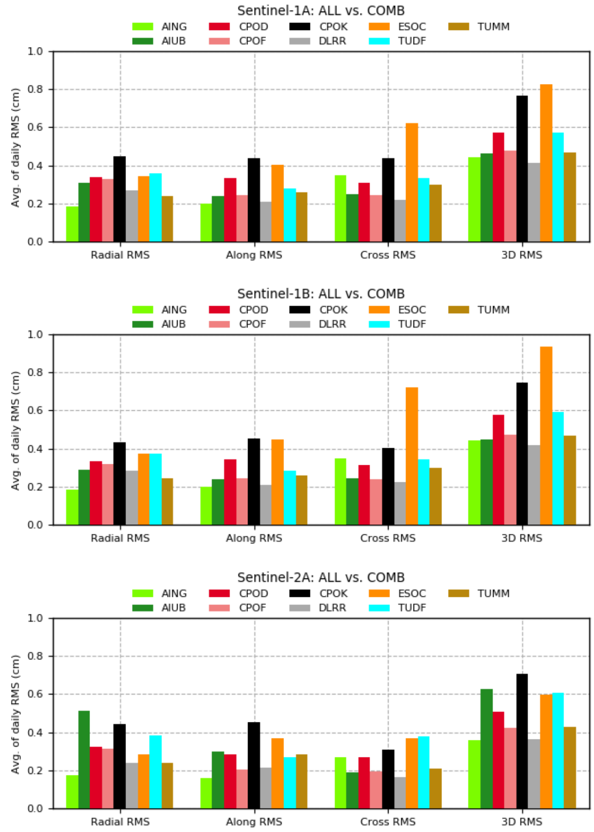
Figure 3.6-2: Reporting

4. PERFORMANCE

This section shows examples of the current performance obtained by the CPOD Service.

The following figures show the mean differences over the first quarter of 2022, between different orbital solutions provided by the CPOD QWG, and the combined solution computed as a weighted mean of them. The CPOD solution is the operational NTC solution, while the CPOF solution is a reprocessed solution using the latest COST-G geopotential model.

The number of centres participating in this analysis is 6 for Sentinel-1 & -2, 11 for Sentinel-3 and 12 for Sentinel-6. Some centres like AIUB, CNES and GMV generate several solutions.



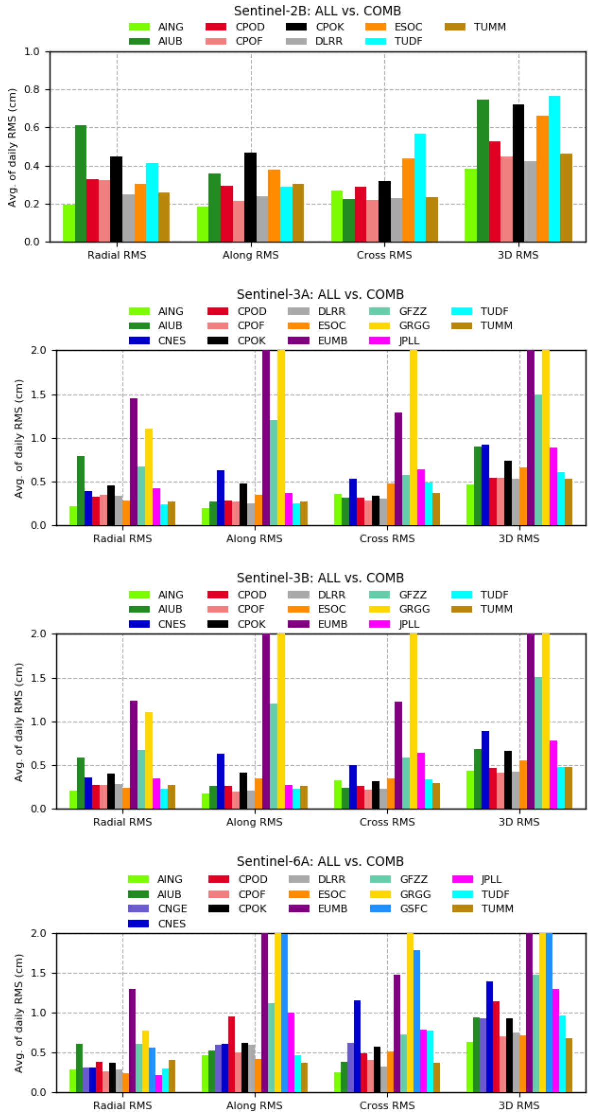
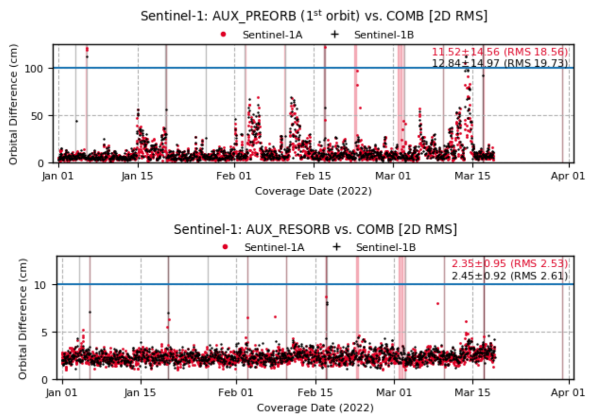


Figure 4-1: Average of daily RMS; Q1 2022; QWG orbital solutions vs. Combined solution (COMB)

The following figures show the differences of each operational orbital product generated by CPOD, against the combined solution.



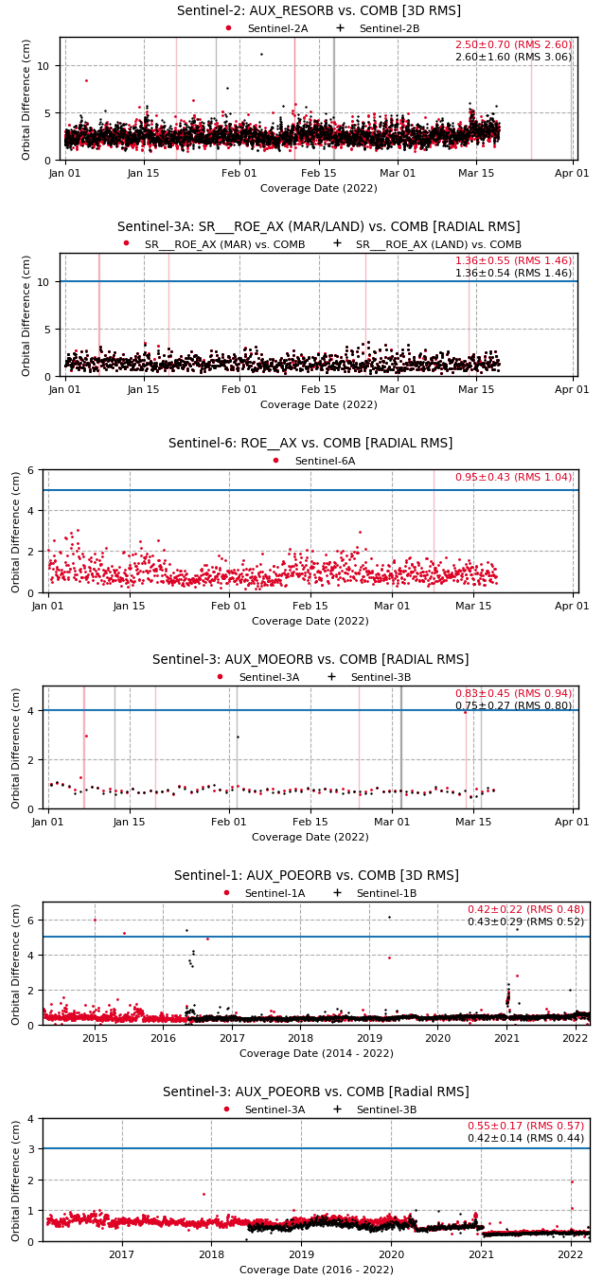


Figure 4-2: Orbital differences of CPOD operational products vs. COMB

Sentinel-1, -2 and -3 have currently two satellites labelled A&B. These satellites have two GPS dual-frequency receivers. Sentinel-6A is the first scientific satellite that carries GPS+GAL dual-frequency receivers. Future Sentinel-1, -2 and -3 satellite will also carry GPS+GAL receivers. At CPOD Service, the NRT orbital processing is done with GPS only, but additionally, a validation chain is using GALILEO only. Therefore, it is possible to compare the performance using GPS only, or Galileo only. Figure 4-3 shows the percentiles of accuracy using one or the other GNSS constellation. The statistics are based on the products generated from February to August 2022. And it can be seen that Galileo outperforms GPS in terms of accuracy. This is a good indication to support a future change to use Galileo only on the Sentinel-6A NRT processing.

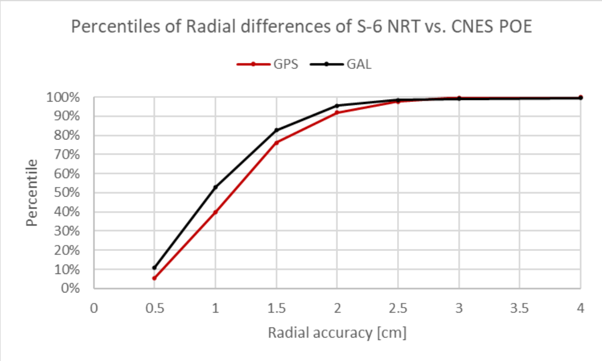


Figure 4-3: Percentiles of radial differences of S-6 NRT vs. CNES POE with GPS or GAL only

5. CONCLUSIONS

The CPOD Service provides state-of-the art, operational, Precise Orbits of the Sentinels-1, -2, -3 and -6 satellites.

It is built on a flexible and powerful design that allows fulfilling all requirements.

The CPOD Service will implement major changes in the near future to change the POD computational layer (from NAPEOS to ***FocusPOD***), and its orchestration layer.

The CPOD Service manages the CPOD Quality Working Group (QWG), to support the quality control, and advances in algorithms.

The CPOD Service provides products, documentation, and data to final users, to support scientific research and other applications.

6. REFERENCES

1. Aschbacher, J. & Milagro-Pérez, M. (2012). The European Earth monitoring GMES programme: Status and perspectives. *Remote Sens. Environ.*, Vol. 120, pp. 3-8. https://doi.org/10.1016/j.rse.2011.08.028

2. Copernicus Overview. https://www.copernicus.eu/en/about-copernicus

3. Copernicus Services. https://www.copernicus.eu/en/copernicus-services

4. Copernicus infrastructure overview. https://www.copernicus.eu/en/about-copernicus/infrastructure-overview

5. Sentinel Online. https://sentinels.copernicus.eu/web/sentinel/home

6. Copernicus Sentinels POD Data Hub. https://scihub.copernicus.eu/gnss/#/home