VLBI Processing at ESOC

Claudia Flohrer, Erik Schönemann, Tim Springer, René Zandbergen, Werner Enderle

Abstract ESOC's Navigation Support Office (NavSO) is currently extending its expertise to VLBI processing and analysis by enhancing the processing capabilities of its software package NAPEOS, used for all activities requiring the highest accuracy. The processing of VLBI data will extend ESOC's capabilities of determining the absolute orientation of the Earth and therewith enables NavSO to provide a fully independent set of Earth orientation parameters for ESA missions. Hence, it will allow enhancement of the contribution to the IERS (International Earth Rotation and Reference Systems Service) whilst at the same time reducing the dependency on this service. In addition, NAPEOS is capable of combining all four space-geodetic techniques at the observation level and thus supporting GGOS, the Global Geodetic Observing System, to get a better understanding of our living planet. This paper gives an overview of the current status of the VLBI processing capability at ESOC and provides an outlook on future plans.

Keywords ESOC, NAPEOS, UT1–UTC, VLBI analysis, combination at observation level

1 Introduction

ESOC's Navigation Support Office (NavSO) is providing the geodetic reference for ESA missions and is the coordinator of a European Consortium that provides the Galileo Geodetic Reference Frame. NavSO has demonstrated its expertise in the processing of various space-geodetic techniques, such as GNSS, SLR, and DORIS, and their combination on the observation level. Nevertheless, the last piece missing for the generation of independent Earth Orientation Parameters (EOPs), required for the definition of the Earth's orientation, is VLBI.

In the following, NavSO is introduced, and its interest in VLBI data analysis is explained. An overview is provided of the current status of the VLBI implementation done so far in NAPEOS and of the next intended steps.

2 ESOC's Navigation Support Office - NavSO

ESA's European Space Operations Centre ESOC, located in Darmstadt, Germany, tracks and controls European spacecraft, and develops and manages ground systems. NavSO is an integral part of the Ground Systems Engineering Department of ESOC, under the directorate of operations.

The main objectives of NavSO are the provision of expertise for high-accuracy navigation, satellite geodesy, and the generation of related products and services for all ESA missions and for third-party customers, as well as supporting the European GNSS programs: Galileo and EGNOS. NavSO's main areas of expertise are:

- NavSO is providing the geodetic reference for ESA missions.
- NavSO is the coordinator of the Galileo Geodetic Service Provider (GGSP) consortium.
- NavSO is operating ESA's global GNSS sensor station network, currently consisting of 16 sites as

ESOC - Navigation Support Office (OPS-GN)

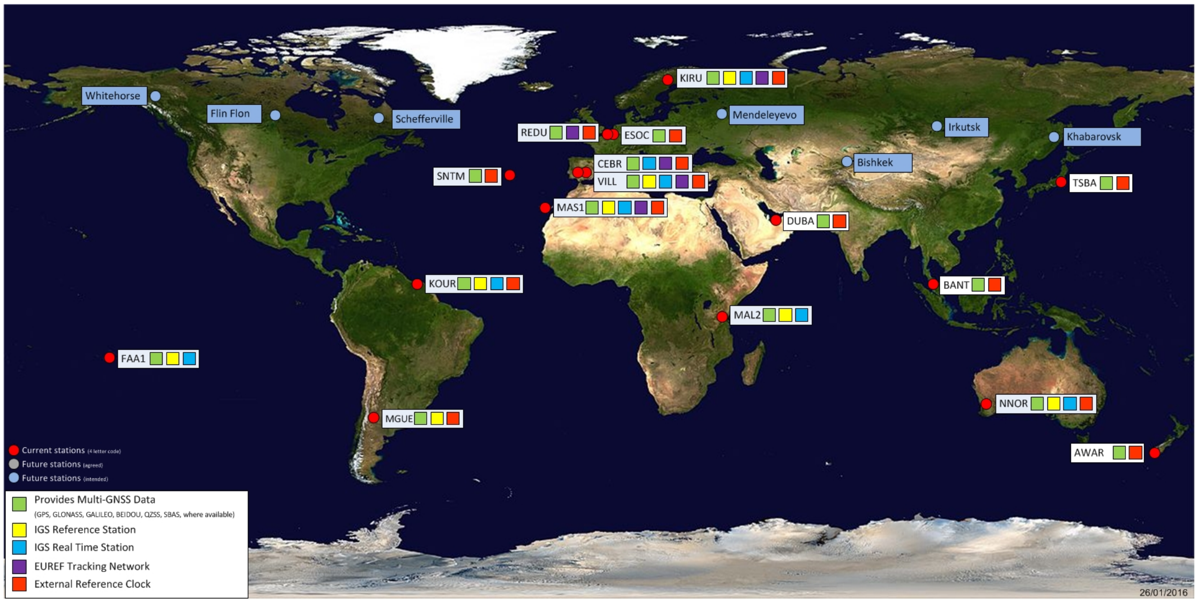

Fig. 1 ESA's GNSS Sensor Station Network operated by the Navigation Support Office.

shown in Figure 1. Several new sites are currently under implementation.

- NavSO is an IGS, ILRS, and IDS Analysis Center and thus contributes to the geodetic reference frame realization ITRF.
- NavSO does precise orbit and clock determination for GNSS and LEO satellites using its own software package NAPEOS (NAvigation Package for Earth Orbiting Satellites) [1]. It is capable of processing data from the various satellite-geodetic techniques, such as GNSS, SLR, DORIS, and altimetry, individually but also combined at the observation level. State-of-the-art models and algorithms are used and developed further to ensure high-precision products.
- NavSO has developed and is operating a UTC realization at ESOC, which can be used as time reference for ESA missions. The start of the official contribution to UTC is foreseen within 2016.

Currently NavSO is extending its expertise to be able to process and analyze VLBI observations. The processing of VLBI tracking data will complete ESOC's capabilities in generating EOPs to ensure the operational capability of ESOC. It will enable NavSO to enhance its contribution to the IERS service and to contribute to the IVS service as an analysis center. Finally, it will enable NAPEOS to combine all space-geodetic techniques at the observation level, bringing together the strengths of the individual techniques.

Table 1 shows the contribution of the individual techniques to the celestial and terrestrial reference frame (CRF and TRF) parameters and the EOPs, allowing conversion between the CRF and the TRF. While GNSS, SLR, and DORIS are contributing to polar motion and length-of-day (LOD), VLBI is the only technique able to determine the celestial pole offsets w.r.t. the IAU precession and nutation model (labeled as nutation parameter) and UT1–UTC.

Table 1 Contribution of the individual space-geodetic techniques to reference frames and EOPs.

	Parameter	GNSS	SLR	DORIS	VLBI
CRF	Quasar positions				x
	Satellite orbits	x	x	x	
EOP	Nutation				x
	UT1-UTC				x
	LOD	x	x	x	x
	Polar motion	x	x	x	x
TRF	Station positions	x	x	x	x
	Geocenter	x	x	x	

3 VLBI Implementation in NAPEOS

This section presents the implementation steps to enable the VLBI data processing in NAPEOS. The following list summarizes the different steps. The current status of each implementation step is given in brackets.

- Read observations (implemented)
  - Observations are read from the NGS card format. In the future the format can be replaced by vgosDB format based on netCDF files.
- Set up database (partially implemented)
  - Station and source coordinates are converted to the NAPEOS database format.
  - Site eccentricities, axis offsets, and mounting types have still to be incorporated.
- Set up new observation type (implemented)
  - A new observation type "VLBI group delay" is introduced.
- Set up observation equation (implemented)
  - The observation equation for the VLBI group delay is set up. The formulation from Schuh [2], which is consistent with the *Consensus model* of the IERS conventions [3], is used.
- Apply observation corrections (partially implemented)
  - Relativistic corrections: So far only terms larger than a maximum order of magnitude of $2 \cdot 10^{-10}$ s are considered; smaller terms still have to be added.
  - Clock synchronization: Clock offsets w.r.t. a reference clock are estimated, but clock breaks are not yet handled.
  - Tropospheric delay: Is taken into account using the meteorological data of each station.
  - Ionospheric delay: Is taken into account using the value provided in the NGS data files.
  - Instrumental delays: Axis offsets and cable delays still have to be implemented.
- Compute partial derivatives to enable parameter estimation (partially implemented)
  - The partial derivatives of the parameters to be estimated (e.g., tropospheric wet delay and gradients, station coordinates and clocks, EOPs) have to be set up w.r.t. the VLBI observation equation. This implementation step is still ongoing. The estimation of source coordinates will not be part of the current implementation but will still be possible at a later stage.
- Enable combination at observation level (partially implemented)
  - The combination of EOPs from different observation types is already possible with NAPEOS. Some implementation effort is still needed to combine troposphere parameters, station coordinates, and clocks, as local ties and biases have to be taken into account between VLBI and the other geodetic techniques.
- Apply observation weighting (implemented)
  - An elevation-dependent observation weighting can already be applied in NAPEOS.
  - When combining different observation types proper technique-specific weighting factors reflecting the different observation accuracies of each technique have to be applied.

4 Initial Results and Next Steps

The implementation of the presented steps into NAPEOS started in the end of 2015. The VieVS software [4] was used to validate the observation model and to compare the results. The current state of implementation allows the generation of O–C residuals at the 0.5 m level. An example is given in Figure 2, showing a screenshot of the NAPEOS graphical user interface with O–C residuals of one VLBI session with three baselines. The current order of magnitude is fully in line with the expectations, as antenna axis offsets are not yet taken into account and troposphere parameters are not yet estimated.

It is planned to finalize the parameter estimation part for VLBI observations within 2016, which will allow a proper VLBI data analysis and the comparison of results with other VLBI analysis groups. NavSO will take part in the *VLBI Analysis Software Comparison Campaign 2015* (VASCC 2015) performed by the Chalmers University of Technology, in order to validate the implementation of the observation model.

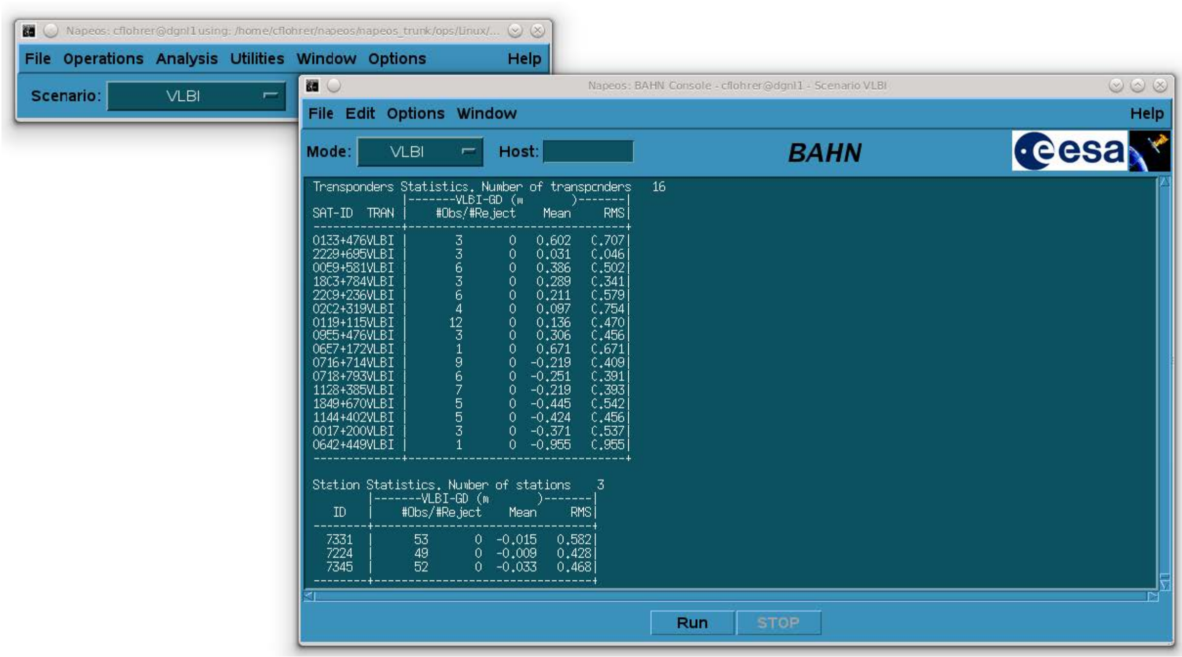

Fig. 2 Screenshot of the NAPEOS graphical user interface showing O–C residuals in meters for one session with three baselines.

In the long term NavSO plans to combine VLBI data with GNSS, SLR, and DORIS data on the observation level and to actively participate in the IVS.

References

1. ESA/ESOC, DOPS-SYS-TN-0100-OPS-GN, NAPEOS Mathematical Models and Algorithms, 2009.
2. Harald Schuh, Die Radiointerferometrie auf langen Basen zur Bestimmung von Punktverschiebungen und Erdrotationsparametern, C: Dt. Geodät. Komm. bei d. Bayer. Akad. d. Wiss, 1987.
3. Gérard Petit and Brian Luzum (eds.), IERS Conventions (2010), IERS Technical Note 36, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2010.
4. Johannes Böhm, Sigrid Böhm, Tobias Nilsson, Andrea Pany, Lucia Plank, Hana Spicakova, Kamil Teke, Harald Schuh, The New Vienna VLBI Software VieVS, in Proceedings of IAG Scientific Assembly 2009, International Association of Geodesy Symposia Series Vol. 136, edited by S. Kenyon, M. C. Pacino, and U. Marti, pp. 1007–1011, 2012.