PMD Analysis Center Report

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Abstract This report summarizes the activities of the Politecnico di Milano (PMD) Analysis Center (AC) during the years 2021 and 2022. Different methods used by space-geodetic techniques to assess both tropospheric and ionospheric effects on radio signals have been of specific interest for the AC. Problems related to the defense of those parts of the spectrum used during experiments carried out by legacy VLBI and VGOS antennas have been tackled under scientific need and considering current international regulations. The AC has collaborated with the "Large-scale dimensional measurements for geodesy" GEOMETRE project on European Metrology Programme for Innovation and Research (EMPIR).

1 General Information

The PMD Analysis Center is hosted at the Department of Civil and Environmental Engineering (DICA) of the Politecnico di Milano, which brings together professors, researchers, PhD students, and technical and administrative staff. DICA takes care of several laboratory facilities. Following a renovation, people and offices belonging to the thematic division Geodesy and Geomatics have been moved from building number 3 of the Politecnico di Milano Campus "Leonardo" to the new building 3A (called Lerici). The PMD AC is also located in the new Lerici building now. The construction has two floors above ground and a final flat roof with floors set at different heights. The composition of the volumes has made it possible to create three levels of green roofs (see Figure 1). The architectural structure, even if in a smaller size, follows modern ambitious metropolitan reforestation projects through the vertical densification of greenery.

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Fig. 1 Politecnico di Milano Campus Leonardo, new building 3A with three green roofs, where the PMD AC is hosted.

Analyses of VLBI sessions have been carried out with VieVS-VLBI v3.2 software, a module of Vienna VLBI and Satellite Software [1]. Schedules and simulations have been tested using VieSched++ v1.1. Both modules run on a Matlab installation (R2016b). Another software developed and maintained by TU Wien is Ray-traced Delays in the Atmosphere (RADIATE) [2]. This software has also been used at PMD to calculate the Zenith Total Delay (ZTD), the Zenith Hydrostatic Delay (ZHD), and the Zenith Wet Delay (ZWD) at sites and epochs of interest. Three parameters—Geopotential height Z [m], specific humidity Q [g/kg], and absolute temperature T [K]—were used as input on 25 pressure levels and with a spatial resolution of 1×1 degrees. RADIATE computations are based on Numerical Weather Models (NWM) and can compute also other tropospheric ray-traced parameters useful for space or satellite geodetic techniques.

2 Current Status and Activities

2.1 Studies on Assessment of Tropospheric Parameters

Investigations into the assessment of the accuracy of precipitable water vapor (PW) retrieval by space and in-situ techniques, calculated by numerical models, have been carried out in Arctic and Antarctic regions. Data are still scarce and often not easy to collect in polar regions, but, anyway, long-time series of water vapor content (PW) have been estimated. The PW varies both in space and time, and its measurement is challenging. Water vapor content in the polar regions is a significant indicator for Earth's climate state and evolution on the whole. Water vapor is present in the list of the Essential Climate Variables (ECV), contributing to the characterization of Earth's climate according to the definition given by the Global Climate Observing System (GCOS).

Fig. 2 The nine-meter VLBI antenna of O'Higgins Antarctic Station. [Credit: DLR (CC BY-NC-ND 3.0)]

Precipitable water vapor estimated at GNSS sites has been compared with PW estimates by radio sondes (RS) when co-located with GNSS stations. These values have also been compared with PW obtained by the ERA-Interim reanalysis model provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) that recently has been superseded by the ERA5 reanalysis [3]. Studies have been made also on estimations of ZWD and PW using data from the O'Higgins VLBI station (see Figure 2) in the Antarctic Peninsula.

But these products are still under investigation because they look very noisy and epochs in common with GNSS values are very sparse. After validation of different methods to retrieve water vapor, long-term trends in the Arctic and Antarctic regions were estimated. More details on the work and on the results can be found in [4]. This work has been developed in collaboration with the Italian INAF IVS AC.

2.2 Estimation of Ionospheric Parameters at the Regional Level

Vertical Total Electron Content (VTEC) can be retrieved from the measurements of most space geodetic techniques; often different methods inside the same technique are used to estimate the same parameters. The International GNSS Service (IGS), for example, provides global ionospheric maps (GIMs) of global ionospheric vertical total electron content (VTEC) in a standard format known as IONosphere map EXchange (IONEX). These files provide global values of VTEC every two hours with the spatial resolution of 2.5° in latitude and 5° in longitude. To know the value of VTEC at a single point where a GNSS station is installed, GIMs need to be interpolated to the coordinates and epochs under consideration.

Another method, known as the Cirarolo method (see the description in [5]), uses receiver-independent exchange (RINEX) files containing GPS carrier phase observables at the L1 and L2 frequencies. The implemented algorithm calculates the VTEC values for each single GPS station. To evaluate possible discrepancies between the two methods at the regional level, we have compared VTEC values obtained from GIMs at three Italian stations belonging to the GPS permanent network "Rete Integrata Nazionale GPS (RING)" (see Figure 3) of the "Istituto Nazionale di Geofisica e Vulcanologia" (INGV).

The main steps of the analysis and results obtained in this work have been published in [6]; differences between the two methods have been found. These differ-

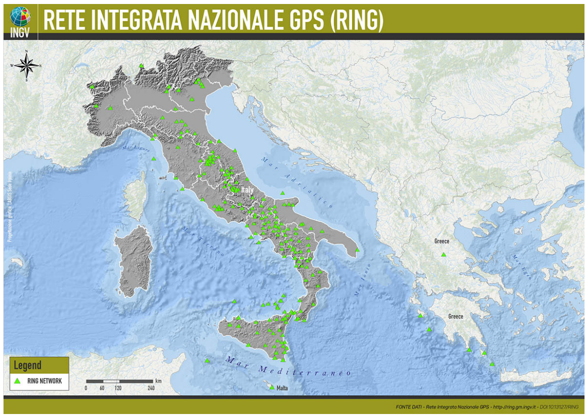

Fig. 3 GNSS stations of the INGV “Rete Integrata Nazionale GPS (RING).” [Credit: “Istituto Nazionale di Geofisica e Vulcanologia” (INGV)]

ences increase as the latitude decreases and as the solar activity intensifies. Possible developments of this study could be to use GPS stations co-located with VLBI radio telescopes in Italy, to compare VTEC estimates at these stations from GIMs and the Cirarolo method and with VTEC from VLBI observations.

2.3 Spectrum Management Activities for Protection of VGOS Systems

The PMD AC has been deeply involved in activities related to the protection of the frequencies observed during geodetic VLBI experiments with legacy antennas and new advanced VGOS radio telescopes. Due to the development of technology for wideband devices and space commercialization, active international telecommunication organizations are asking for and using increasing bandwidth both on the Earth (e.g., 5G) and in space (wide satellite constellations). Because geodetic VLBI has no allocated frequency bands at the International Telecommunication Union (ITU) level, it has become urgent at least to raise the awareness of the risks of the pollution and of the presence of detrimental signals in the 2–14 GHz band. Anyone involved in geodetic VLBI, or in Earth sciences, including researchers, engineers, and policymakers, needs to be informed about the ongoing importance of geodetic VLBI and VGOS technology for accurately measuring the Earth’s rotation and other geodetic parameters.

The action of spectrum management and protection of the Radio Astronomy Service (RAS) in Europe has been taken by the European Committee on Radio Astronomy Frequencies (CRAF) in the so-called ITU Region 1 since 1988. A VGOS Working Group has been formed in order to discuss strategies and actions to be taken at this aim. The group has met in several regular internal meetings; some group members also participate in meetings of interest at the level of the ITU or of the Electronic Communications Committee of European Conference of Postal and Telecommunications Administrations (CEPT/ECC) [7]. The group has also carried out simulations of the impact of signals from telecommunication services on geodetic VLBI observations and fundamentals for the redaction of official documents to defend VGOS observations.

One of the main achievements that has been reached is the approval and publication of the first ITU-R document on geodetic VLBI: the Report RA.2507 “Technical and operational characteristics of the existing and planned Geodetic Very Long Baseline Interferometry” [8]. The report summarizes recent advances in VLBI technology and techniques, including improvements in antenna design and signal processing. It presents also in the annex a list of threshold levels of interference detrimental to VLBI observations for VGOS radio telescopes. The report was approved during the meeting of the Study Group 7 (Scientific Services) of the ITU Radio Communication Section held in Geneva, Switzerland, in October 2022.

2.4 Large-Scale Dimensional Measurements for Geodesy

The AC has taken part in the Stakeholder advisory board of the GEOMETRE project, a joint research project within the European Metrology Research Programme (EMPIR) “Large-scale dimensional measurements for geodesy” (see [9] and the reference therein). The project’s aim was to develop a new generation of large-scale dimensional metrology instruments for geodesy. New algorithms and analysis procedures were developed and applied to improve the quality and reliability of global positioning.

During the project new distance meters with a range of up to 5 km were designed and produced. High-precision systems based on measuring principles based on simultaneous laser multilateration have been developed for large structure monitoring. A novel strategy for GNSS-based distance determination was also developed. New devices for acoustic thermometry and vertical temperature gradients in outdoor measurements have been realized, and also spectroscopic thermometry has been used in campaigns at Nummela (near the Metsähovi observatory) and Warsaw. To reduce the meteorological uncertainties in precise distance measurements, different methods for refractivity compensation were established and characterized; they were based on classical sensors, on dispersion, on spectroscopic thermometry, and on the speed of sound. Once these systems were validated they were used to study European standard baseline EURO5000 at the Pieniny Kippen Belt, Poland.

Among sensor-based baseline refractive index compensation we show a multi-wavelength interferometer TeleYAG-II that has been developed for measurements under outdoor conditions. After indoor calibration it has been also used to calibrate the baselines of the reference network of the space geodetic station in Metsähovi, Finland.

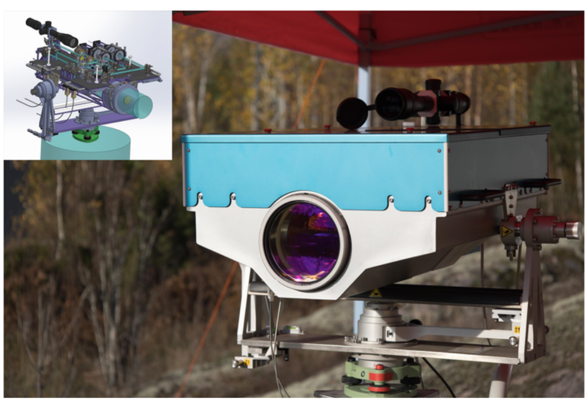

Fig. 4 Multi-wavelength interferometer TeleYAG-II. [Credit: National Metrology Institute of Germany (Physikalisch-Technische Bundesanstalt, PTB)]

The small schematic picture on the left in Figure 4 shows the optical interferometer setup within the system (light beams are indicated in green). Measurements were successfully carried out; in the process, the instrument was able to demonstrate the targeted resistance to external influences as well as its structural long-term stability.

Also, enhanced local tie metrology at GGOS space geodetic core stations was investigated and its benefit for the complex measurement analysis and for the final product critically assessed. Close-range photogrammetry for reference point determination of space geodetic telescopes has also been used. A local gravity field to consider the deviations of the vertical was used in the data processing to reduce the uncertainty of coordinate transformations.

Four progress meetings were organized in the period of project development. The PMD AC participated in two of them during 2020 and in the other two on June 29–30 and November 15–16, 2021. These meetings were online, while the final project meeting was both online and in person at the central office of measurements (GUM) Warsaw during November 21–22, 2022.

3 Future Plans

The PMD AC plans concern continuation of studies on tropospheric parameters in polar regions. Ionospheric parameter estimation in regional areas will also be deeply investigated. Comparisons with products of other space techniques are intended to be carried out, e.g., using satellite measurements or images. Activities to protect the VGOS spectrum from unwanted emissions will be one of the main points to be tackled. New investigations and experiments on time transfer using the VLBI technique are also intended to be carried out during the next biennial period.

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