Analysis of VGOS Sessions: Evaluation of Performance with Different Software

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Abstract VGOS (VLBI Global Observing System) is the new generation of the VLBI system. It has been developed since 2005, and it is based on the so-called broadband delay that uses four or more frequency bands. High data rate observations are taken by fast-slewing antennas, smaller than those used in the current legacy S/X infrastructure. These improvements in instrumentation are aimed at obtaining more accurate geodetic products. In order to test the analysis of these new data, the historical VGOS sessions have been analyzed with different software. Difficulties in the current processing and similarities with the S/X generation processing are studied. Results in terms of the accuracy in EOP (Earth Orientation Parameter) estimation and coordinate repeatability are also discussed in this contribution.

Keywords Analysis, Geodesy, GGOS, VGOS, VLBI

1 Introduction

The Global Geodetic Observing System (GGOS) is the contribution of Geodesy to the scientific and non-scientific community providing geodetic observations, data, and products for monitoring the Earth system and global change research. Among these products are the reference frames required for all location-dependent observations. These frames are defined using several Space-Geodetic techniques, among them VLBI, GNSS, SLR, and DORIS.

With modern instrumentation and analytical techniques, Geodesy is now capable of detecting time variations ranging from large and secular scales to very small and transient deformations with increasing spatial and temporal resolution, high accuracy, and decreasing latency. An example of this modernization is the new generation VLBI system VGOS (VLBI Global Observing System, [8]). It has been developed since 2005, and it is based on the so-called broadband delay that uses four or more frequency bands. High data rate observations are taken by fast-slewing antennas, smaller than those used in the current legacy S/X infrastructure.

In order to test the analysis of these new data, the historical VGOS sessions were analyzed with different software. Difficulties in the current processing and similarities with the S/X generation processing are studied. Results in terms of the accuracy in EOP (Earth Orientation Parameter) estimation and coordinate repeatability are also discussed in this contribution.

2 The RAEGE Project

The co-location of the different space geodetic techniques is key in the definition of reference systems, as they allow the integration of the individual networks of each technique into a single system. Additionally, they provide an idea of the quality and precision of the systems themselves, thanks to the validation of the results between techniques. This is realized by worldwide dis-

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tributed Fundamental Space Geodetic Stations, some of which are GGOS Core Sites.

RAEGE (Atlantic Network of Geodynamic and Space Stations) is a project resulting from the cooperation between the National Geographic Institute of Spain (IGN) and the Government of Azores. It is a unique project at a geodetic and geodynamic level. It is devoted to the combination of geodetic techniques in four stations: two in Spain (Yebes and Gran Canaria) and two in Azores (Flores and Santa Maria). They will be Fundamental Space Geodetic Stations, being classified as GGOS core sites.

The RAEGE project focuses not only on the instrumentation and on operating the observing and the stations but also on developing analysis capabilities that allow RAEGE observatories to explode the geodetic observations. A VLBI analysis group, in the frame of RAEGE, was established. The group consists of collaborators from the IGN and the observatories of Yebes and Santa Maria. Among the objectives of this group are the promotion of the VLBI analysis activities in the RAEGE project, expansion of its research activities, obtaining opportunities to participate in other international projects and/or interact with other groups, and testing and improving the capacity of processing VGOS data. Several research activities are currently being developed by the RAEGE Data Analysis Group; among them are multi-technique analysis with special focus on VGOS data processing and GNSS, station performance and statistics, and the study of the gravitational deformation of the antennas.

3 Analysis of VGOS Sessions and Test Cases

Two software sets are used in the analysis group for VLBI analysis: VieVS software, [5], from the Technical University of Vienna and Where, [10], from the Norwegian Mapping Authority. The use of different software strengthens the group skills and allows the comparison and validation of results. Beyond the routine processing of the IGN as an IVS Analysis Center (AC) and works carried out in the processing of R1/R4 sessions, CONT campaigns and Intensive sessions, [2] [14], the group is starting into the processing of VGOS data. The goal is testing the capabilities for this new type of data and identifying the differences and best setting for its optimal processing.

The main differences found between VGOS and legacy analysis are the selection of the reference coordinates and velocities and the outlier removal criterion. The selection of the reference coordinates and velocities is important because some of these stations have not enough history for defining reliable velocities. In some sessions very few stations participate, and datum definition is limited. Each software avoids this difficulty in different ways: VieVS uses its self coordinates and velocities, VieTRF, and Where fixes the coordinates due to the lack of reference stations for imposing the datum. Moreover in VGOS sessions there are more observations, and maybe more outliers can be removed due to quality parameters than in legacy sessions. For testing this, an additional test case, being strict with the removal of outliers, in processing with VieVS is considered. Hence different test cases are distinguished to evaluate the influence of these assumptions on the final estimated parameters. Test cases are shown in Table 1.

Table 1 Test case configuration.

Solution	Software	CRD ref	Vel ref	Outlier removal
RAEG #1	VieVS	VieTRF	VieTRF	Standard
RAEG #2	VieVS	VieTRF	VieTRF	Strict
RAEG #3	VieVS	VieTRF	GNSS ITRF14	Standard
RAEG #4	Where	Fixed to a priori values		Strict
RAEG #5	Where	VieTRF	VieTRF	Strict
RAEG #6	Where	VieTRF	GNSS ITRF14	Strict

The use of nearby GNSS stations' velocities is considered in test cases 3 and 6 to test if there are significant differences with the use of these velocities. There are some differences between GNSS velocities (using the ITRF2014 as reference, [1]) and the ones used in VLBI analysis that can reach the mm level per year (Table 2). All VGOS stations analyzed are co-located with a GNSS station that has a long data history (at least more than the VGOS antenna). Moreover most of these GNSS stations have participated in the ITRF2014, except for the ISHI GNSS station close to the ISHIOKA VGOS antenna, and reliable velocities are known. Due to proximity, if the GNSS station is stable and there is no deformation due to monument use, its velocity represents also the VLBI antenna velocity.

The performance of each software for processing VGOS sessions has been evaluated. Seventy-six VGOS sessions published from January 2019 to December

Table 2 VGOS antenna list and co-located GNSS antennas with GNSS vel (ITRF14) – VLBI vel (VieTRF) differences in X, Y, and Z coordinates in mm/yr.

VLBI antenna	GNSS antenna	X diff	Y diff	Z diff
WESTFORD	WES2	0.1	−0.2	0.0
WETTZ13S	WTZR	0.5	−0.1	0.3
GGAO12M	GODZ	−0.5	1.1	−0.7
KOKEE12M	KOKB	0.2	0.2	0.1
MACGO12M	MDO1	0.2	−0.2	−1.7
ONSA13NE	ONSA	0.1	−0.1	0.0
ONSA13SW	ONSA	0.1	−0.1	0.0
RAEGYEB	YEBE	−0.4	0.0	−0.5
ISHIOKA	ISHI	–	–	–

2021 were analyzed. Three were not processed by any software. Some problems in the Where software for processing sessions with an extremely small number of stations were observed. The number of observations processed in the VGOS sessions is notably larger than in R1/R4 sessions during the time span. A different criterion for removing outliers was tested, being less or more lax removing observations.

As the volume of the network correlates with the expected EOP accuracy, the theoretical volume of each network was computed for R1/R4 sessions and VGOS. The volume was computed as the volume of tetrahedrons defined by a Delaunay triangulation, following [11], for VGOS networks and also for R1/R4 session networks. The mean values of network volumes are 230.62 Mm^3 for R1/R4 sessions and 13.38 Mm^3 for VGOS sessions. There is an important difference in the order of magnitude between both networks that would be fixed with the addition of more VGOS stations and a better geographical distribution.

4 Results

4.1 Earth Orientation Parameters

EOPs from different test cases with respect to the EOP 14 C04 series (IAU2000, [3]) are analyzed in terms of Weighted Mean (WM) and Weighted Root Mean Square (WRMS) errors. The solutions from additional Analysis Centers that processed VGOS sessions have been included to compare the results. These Analysis Centers are BKG, GFZ, and OPA. These solutions rely on the standard VLBI analysis configuration; in particular, the IERS Conventions 2010 [9], the VMF1 mapping function [4] and ITRF2014 [1] and ICRF3. The only point to be highlighted is that VieVS does not estimate derivatives of the EOP because it uses a parametrization based on continuous piecewise linear offsets. The software used and the number of sessions processed are shown in Table 3.

Table 3 Processing compared and software used.

Solution	Software	# sessions
RAEG #1	VieVS	73
RAEG #2	VieVS	73
RAEG #3	VieVS	73
RAEG #4	Where	69
RAEG #5	Where	69
RAEG #6	Where	69
BKG	Calc/Solve	76
GFZ	Port	76
OPA	Calc/Solve	76

Results are shown in Table 6. Differences in the WM of RAEGE processing were detected with respect to other Analysis Centers. In the polar motion components, the WM is significantly smaller than the results of the other ACs, except for the test case RAEG #4 (fixing the station coordinates and not estimating them). Adopting a relaxed or strict criterion for removing outliers has not significantly affected the results. The use of GNSS velocities produces variations in EOPs (most notably in pole coordinates with tens of micro arc seconds in some cases).

4.2 Site Coordinate Repeatabilities

Site coordinate repeatabilities in mm were computed. Results are shown in Table 4. As expected, the solution fixing coordinates (grey in the table) have almost zero repeatabilities, where the non zero values of WESTFORD, RAEGYEB, and ISHIOKA are due to taking those stations' coordinates and velocities from vtrf2017d, while the rest of the stations are fixed to their static a priori coordinates. A similar order of magnitude with both software sets was obtained. Comparing the three VieVS tests, there are no significant variations in the results. Comparing the Where processing, slight differences in the GNSS solution are appreciated.

Table 4 Mean site coordinate repeatabilities in mm. N, E, U components.

Solution	# coord estimated	Global repeatabilities in mm		
		N	E	U
RAEG #1	469	13.63	21.3	5.03
RAEG #2	471	13.53	21.31	4.9
RAEG #3	471	13.7	22.25	4.74
RAEG #4	453	4.22	6.5	1.11
RAEG #5	453	14.83	23.23	6.96
RAEG #6	453	15.84	24.04	8.16

Table 5 VLBI vs. GNSS troposphere ZTD.

VLBI	GNSS	Δ(G−V) height (m)	Δ(G−V) trop. tie (mm)	ZTD diff (m)	
				Mean	STD
WESTFORD	WES2	−1.8	−0.6	+3.2	70.1
WETT13S	471	−6.5	−1.9	+1.7	10.0
GGAO12M	471	−4.0	−1.3	−1.9	17.7
KOKEE12M	453	−1.1	−0.3	−3.3	13.2
MACGO12M	453	114.5	+28.1	−1.7	14.4
ONSA13NE	453	−6.6	−2.1	+0.9	11.6

4.3 Troposphere Parameters

VLBI estimation of the troposphere zenith total delay with respect to a reference GNSS solution in co-located antennas was analyzed. VLBI ZTD were extracted from the VieVS standard processing, which were estimated using a sampling interval of 30 minutes. The GNSS solution was retrieved from the Center for Orbit Determination in Europe (CODE) products, [6]. In this solution, troposphere delays are estimated every two hours using double differences in a globally distributed network. For the correction of the troposphere tie due to the height difference between the co-located antennas, meteorological data derived from the GPT3 model [7] over the period 2019–2022 were used, and then a mean value of the troposphere tie for this period was computed. For the computation of the height difference, the eccentricity of the GNSS antenna was also considered. The list of stations analyzed is shown in Table 5, together with the height difference between the VLBI and the GNSS antennas and the troposphere tie. The ZTD differences in terms of mean and standard deviation are also shown in Table 5. Values of a few millimeters for the mean of the differences and values larger than 10 mm for the standard deviation were obtained. These values are significantly larger than those obtained in other studies for R1/R4 sessions, [14], with values around 7 mm in the standard deviation. Large outliers in the VLBI solution at Westford, degrading significantly the standard deviation of the differences, were also found.

5 Conclusions

We have seen that the main differences between R1/R4 and VGOS analysis are the selection of reference coordinates and velocities and the possibility of being more strict or lax in the outlier removal. Evaluating the performance of the software in VGOS processing, we have been able to process 96% of the published sessions successfully with VieVS and 90% with the Where software, finding some problems in sessions with very few stations. Moreover a much smaller volume of the VGOS network than the R1/R4 network was noted. In the future, more VGOS stations and a better geographical distribution could fix this difference.

The EOP analysis shows that in comparison with other AC solutions of VGOS processing published in the IVS, significantly smaller differences with respect to IERS C04 EOP have been achieved in the RAEGE processing, with the exception of the test case without site coordinate estimation. To adopt a lax or strict outlier removal criterion has not affected significantly the solution (the X component of the polar motion (PM) is the most sensitive). The use of GNSS velocities, as a priori data, produces significant variations in the WM of the EOP: larger variations in the X component of the PM were observed. Differences with respect to IERS seem to be minimized in the X component of the PM and enlarged in the Y component, but the results are not conclusive enough.

The coordinate repeatability analysis shows that in VieVS, the use of different a priori coordinates plus velocities or a different outlier removal criterion does not affect significantly the coordinates' repeatabilities. In Where, the a priori coordinates and velocities define the estimation or non-estimation of the coordinates during the processing. The use of GNSS velocities affects the results (maximum differences of ~1.2 mm in the UP component and being the worst repeatabilities in all components). A similar order of magnitude with both software sets was obtained.

The troposphere analysis shows that the mean and the STD of the ZTD differences are significantly larger than in the R1/R4 sessions.

Table 6 Weighted Mean (WM) and Weighted Root Mean Square (WRMS) differences between solutions and the IERS long term EOP, EOP 14 C04 (IAU2000A).

Solution	XPO (μas)		YPO (μas)		UTC (μs)		NUTX (μas)		NUTY (μas)		XPOR (μas)		YPOR (μas)		LOD (μs)	
	WM	WRMS	WM	WRMS	WM	WRMS	WM	WRMS	WM	WRMS	WM	WRMS	WM	WRMS	WM	WRMS
RAEG #1	-102.78	599.46	57.82	579.26	-24.49	291.95	-11.30	321.24	-19.41	242.73						
RAEG #2	-128.10	607.96	54.27	575.63	-24.40	290.70	-1.65	253.66	-17.24	234.80						
RAEG #3	4.15	613.19	-267.62	554.07	-27.92	289.93	-18.82	319.21	-21.05	235.78						
RAEG #4	-4896.71	3173.60	-3399.11	1803.25	204.24	247.61	18.41	2318.72	-385.63	2017.64	168.35	2311.04	600.79	1738.84	13.58	101.40
RAEG #5	-92.39	584.73	-115.50	550.90	30.21	221.98	-15.50	358.38	-229.47	520.14	-227.07	1096.35	399.22	1270.89	-4.81	71.97
RAEG #6	-38.42	633.76	-128.46	536.93	36.35	224.04	-14.19	358.69	-229.37	520.31	-225.49	1095.43	399.08	1271.01	-4.81	71.98
BKG	1672.01	674.30	-1728.70	616.76	92.08	318.356	-13805.01	27290.20	-5973.76	19645.68	-233.03	1208.72	91.05	1286.22	-2.54	73.32
GFZ	-1568.96	2020.78	-803.26	545.27	-29.98	383.59	-8.49	328.92	-79.95	340.84	71.29	1290.35	-151.80	1030.35	-7.79	74.93
OPA	-461.98	7541.69	26392.77	28751.17	366.79	696.98	-8948.15	21523.83	-3527.34	15945.37	-221.17	1288.60	386.97	1399.537	5.2	63.47

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