Journal of Geodesy manuscript No.
(will be inserted by the editor)

Astronomy VLBA campaign MOJAVE used in geodesy

Hana Krásná · Leonid Petrov

Received: date / Accepted: date

Abstract Insert your abstract here.

Keywords First keyword · Second keyword · More

1 Introduction

MOJAVE (Monitoring Of Jets in Active galactic nuclei with VLBA (Very Long Baseline Array) Experiments) is a long-term program carried out by an astrophysics community, which focuses on monitoring of radio brightness and polarization variations in jets associated with active galaxies on parsec-scales visible in the northern sky (Lister et al., 2018). In September 2016 the observing series with the VLBA observation code BL229 has started. In this series, the observations are carried out at a wavelength of 2 cm (15 GHz, Ku-band) approximately every month within 2048 Mbps 24 hour-long experiments. In this publication, we show for the first time the capability of astrophysics VLBA measurements to provide estimates of the geodetic parameters, such as Earth orientation parameters or terrestrial reference frame on a comparable accuracy level as the dedicated geodetic VLBA sessions. The Earth orientation parameters, which built the link between the terrestrial and celestial reference frame, are regularly estimated by Very Long Baseline Interferometry. The unsubstitutable role of VLBI is in the measurement of UT1-UTC and nutation components. Until recently, the estimates of EOP were produced only from the observations in the traditional S/X bands (2.3/8.6 GHz, 13/3.6 cm). In Krásná et al. (2019) the first estimates of the EOP from the dedicated geodetic VLBA experiments in K-band (24 GHz, 1.2 cm) were published. In this paper, we present the first EOP estimates in Ku-band (15 GHz, 2 cm) from purely astrophysics VLBA sessions covering the last four years (2016.7 - 2020.5). In Krásná and Petrov (2021, in preparation) we further focus on the MOJAVE data from the astrometry point of view, dealing with the estimated radio source positions which built a celestial reference frame.

H. Krásná
1. TU Wien, Department of Geodesy and Geoinformation, Wien, Austria
2. Astronomical Institute of the Czech Academy of Sciences, Prague, Czech Republic
E-mail: hana.krasna@tuwien.ac.at

L. Petrov
NASA Goddard Space Flight Center, Code 61A, Greenbelt, USA

2 Data analysis

The VLBA network consists of ten 25-meters radio telescopes located on U.S. territory (eight in North America, one in the Pacific, and one in the Caribbean), see Fig. 1. The dataset BL229 from the VLBA correlator is publicly available through the National Radio Astronomy Observatory (NRAO) Science Data archive[1] in the FITS-IDI (Interferometry Data Interchange) format. This observing series started on September 26, 2016 and we include the first 33 experiments with the last one on July 02, 2020 in this publication. In the first 25 experiments (BL229aa-ay) the observed Ku-band is split into eight sub-bands with an individual bandwidth of 32 MHz including 64 channels each. Since July 2019 (experiment BL229az) the bandwidth of a sub-band has increased to 64 MHz, which built four sub-bands covering 128 channels (see Table 1). We processed the observations with the fringe-fitting software PIMA (Petrov

[1] https://archive.nrao.edu/archive

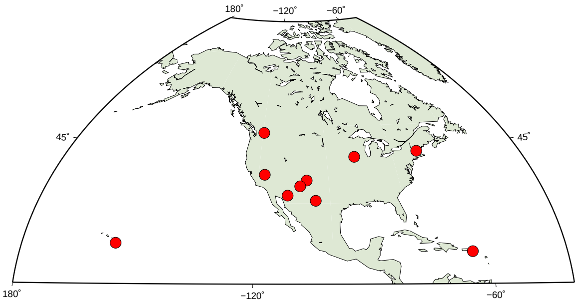

Fig. 1 Distribution of the ten VLBA radio telescopes.

Table 1 Lower edge frequency of the sub-bands in the BL229 experiments in GHz.

BL229aa-ay	BL229az-bg
15.22400	15.17575
15.25600	15.25575
15.28800	15.31975
15.32000	15.38375
15.35200	
15.38400	
15.41600	
15.44800	

et al., 2011) (coarse fringe fitting – bandpass calibration – fine fringe fitting) and produced databases including among others group delays and their uncertainties in a geo-VLBI format GVH and its plain ascii database counter-part VGOSDA, or for short VDA[2]. These databases serve as input for the data analysis software package pSolve[3] and as an alternative input for the analysis software package VieVS (Böhm et al., 2018).
(DO WE WANT TO GIVE MORE DETAILS FOR THE FRINGE FITTING, OR FLAGGING OF OUTLIERS?)

We process the MOJAVE group delays with these two independent analysis software packages and compare the estimated baseline lengths and Earth orientation parameters in terms of the weighted root mean square. Furthermore, we analyse the geodetic RDV and CN sessions observed in S/X band for the same time span (starting with RV119 on September 14, 2016 until RV141 on July 07, 2020) which are 22 RDV and 6 CN experiments in total. RDV sessions are astrometric/geodetic sessions scheduled for full ten stations VLBA network plus up to ten geodetic stations capable of recording VLBA modes. These sessions are scheduled to provide among others accurate EOP and a high accuracy TRF where the VLBA stations are incorporated into the VLBI reference frame through the inclusion of other geodetic stations with long history of observations. The CN experiments consist of the ten VLBA stations only and run concurrent with the Rapid turnaround Monday IVS sessions (IVS-R1). We show the comparison of the baseline length scatter between the VLBA telescopes and of the estimated EOP from the astrophysics VLBA measurements and from the dedicated geodetic experiments.
Besides the comparison of the estimated geodetic parameters from two diverse VLBA datasets, we take the opportunity to show the differences in the estimated parameters due to the use of different software packages. Therefore, we analyse the VLBA data in several ways. The first solution was produced using the software PIMA for the fringe-fitting and pSolve for the analysis. In the second solution we analysed the group delays produced with the PIMA software with the analysis software VieVS. For the RDV&CN experiments we run a third solution where we use the official vgosDB database maintained by the IVS Data Centers and analysed it with the software VieVS.

Table 2 summarizes the a priori models used in pSolve and VieVS during the group delay analysis. Tables 3 and 4 contain the parametrization of the estimated parameters in the solutions. The MOJAVE and RDV&CN experiments are processed in the same manner with the same parametrization to allow for an informative comparison. But there are several important differences between the datasets. One of them is the fact, that MOJAVE sessions are single-band experiments. This causes the impossibility to correct the measurements for the ionospheric delay by using the observations in two radio bands as it is done for the RDV&CN experiments. We concentrate on this issue in detail in Section 3. Another difference is the scheduling approach due to the different goals of the experiments. In Fig. 2 we show the sky coverage during a 24-hour observing session at three selected telescopes (BR-VLBA, FD-VLBA, SC-VLBA) where colors depict the time passed since the start of the session. As an example we show the sky coverage during the MOJAVE session BL229bc observed on December 22, 2019 in the upper plots and the CN1924 session observed with the same network on December 09, 2019 in the lower plots. Table 5 summarizes the mean number of scans in a 24-hour experiment at each of the ten VLBA telescopes computed over the investigated time period (September 2016 - July 2020). The numbers show, that during geodetic experiments there are twice as many scans at each telescope as during the MOJAVE sessions. The geodetic sessions focus on even distribution of the observations over all azimuth

[2] http://astrogeo.org/gvh/vda
[3] http://astrogeo.org/psolve

Table 2 A priori models used in the analysis

	pSolve	VieVS
CRF	gsf_2020c	ICRF3 (Charlot et al., 2020) including Galactic Aberration
TRF	gsf_2020c	ITRF2014 (Altamimi et al., 2016)
precession/nutation model	IAU2006/2000A (Mathews et al., 2002; Capitaine et al., 2003)	
EOP	gsf_2020c (heo_20200606.heo)	14C04
non-tidal atmosphere loading	merra2_geosfpit	Vienna APL

Table 3 Parametrization of estimated parameters of the single session solutions in pSolve

	pSolve
CRF	selected sources with constraint sigma 20 as
TRF	NNT/NNR condition on VLBA stations with 0.1 mm constraints
polar motion	offset and rate with constraint sigma 45 mas on offset
UT1	offset and rate with constraint sigma 3 ms on offset
celestial pole offsets	offset without constraints
zenith wet delay	B-spline with the time span 20 min and sigma of constraints 50.00 ps/h
tropo. gradients	8 hours with sigma of constr. 0.5 mm on offset and 2.00 mm/day on rate
clocks	B-spline with the time span 60 min and constraint sigma 5.e-14 s/s
baseline clock offsets	offset with constraint sigma 500 ns
weights	yes

Table 4 Parametrization of estimated parameters of the single session solutions in VieVS

	VieVS
CRF	selected sources without contraints
TRF	NNT/NNR condition on VLBA stations
polar motion	pwlo with the time span 24 hours with relative constraints 1 mas
EOP	offset
zenith wet delay	pwlo with time span 30 min with relative constraints 1.5 cm
tropo. gradients	pwlo with time span 180 min with relative constraints 0.5 cm
clocks	pwlo with time span 60 min with relative constraints 1.3 cm, one rate and one quadratic term per clock
baseline clock offsets	offset without constraints
weights	baseline-dependent weighting

and elevation angles in the common visibility sky area to ensure a good decorrelation of station dependent parameters such as station height, zenith wet delay, clock parameters or baseline clock offsets. On the other hand, the primary goal of the BL229 experiments is in monitoring of jets in active galactic nuclei, therefore the schedule is optimized to track a set of sources in a 24-hour session. The Fig. 3 depicts the total number of observed sources in each session (upper plot) and the median number of observations during a 24-hour session for each source computed over the respective four years period. The red crosses show the MOJAVE sessions, and blue x-signs depict the RDV&CN sessions. The median of observed sources lies at 30 radio sources during a MOJAVE session, and at 78 radio sources during a RDV&CN session. Comparison of the number of observations for each source during a whole session shows that 95% of the AGN observed in MOJAVE sessions have more than 150 observations whereas only 35% of the sources observed in RDV&CN sessions gets over this limit. This shows again the interest of MOJAVE sessions to obtain enough data for particular sources during an experiment to allow for imaging and astrophysics study. Sources with few observations in geodetic experiments served for a good sky coverage over the stations which allows an accurate estimation of geodetic relevant parameters.

Baseline length repeatability. We run several solutions which we compare in terms of baseline scatter. In Table 6 we compare the baseline length repeatabilities using a linear approximation. In Fig. 4 the wrms of the estimated baseline length is plotted for solutions estimated with pSolve (upper figure) and with VieVS (lower figure). In both figures the red crosses denote the baselines determined from the MOJAVE experiments and the blue x-signs depict the VLBA baselines estimated from RDV&CN sessions when the whole scheduled network (i.e., with the non-VLBA telescopes) was adjusted in the analysis. The green diamonds in the upper figure show the wrms for the VLBA baselines from

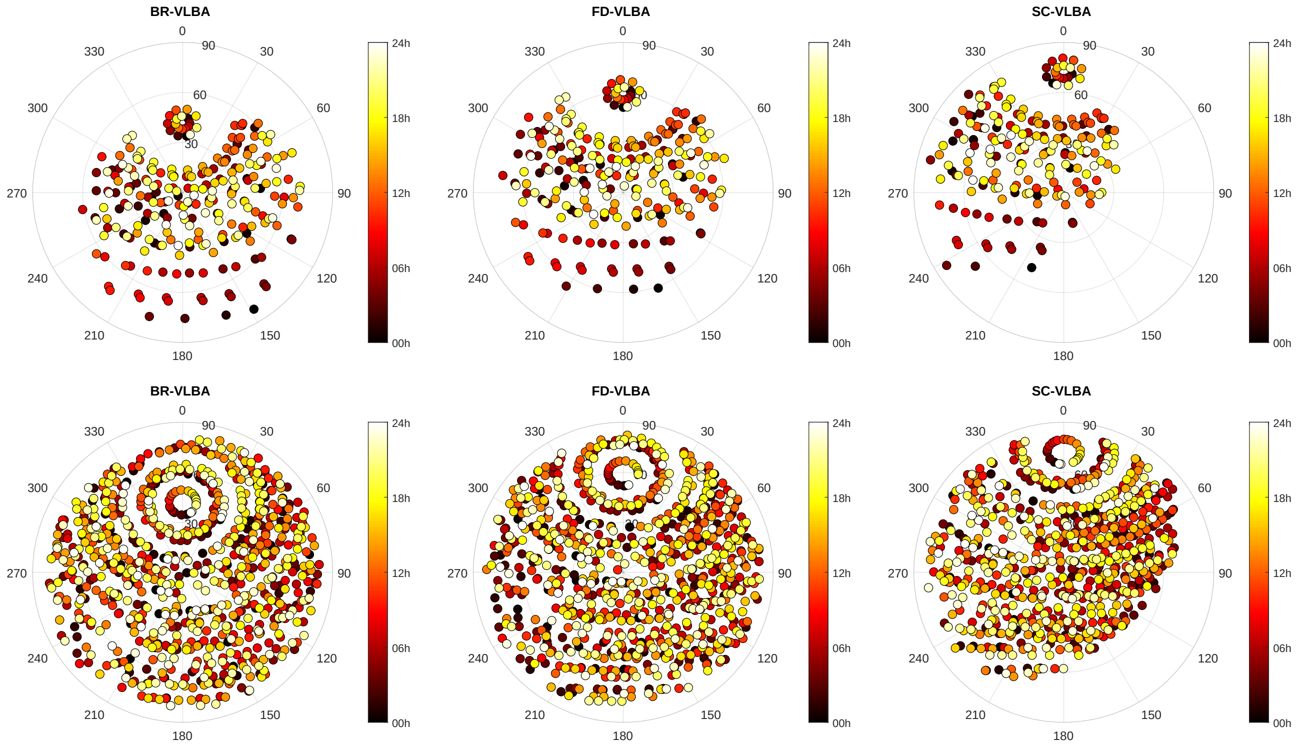

Fig. 2 Sky coverage

Table 5 Mean number of scans at VLBA telescopes in one session computed over the period of interest (September 2016 - July 2020).

	Br	Fd	Hn	Kp	La	Mk	Nl	Ov	Pt	Sc
MOJAVE BL229 series	245	245	241	248	251	204	251	252	235	219
geodetic RDV&CN experiments	451	485	445	493	483	357	467	487	451	423

Table 6 Baseline length scatter. Coefficients of a linear approximation: $a \cdot L + b$ where L is length of baseline in [mm].

	software	a	b
BL229	PIMA, pSolve	$9.12e^{-10}$	2.50
BL229	PIMA, VieVS	$9.79e^{-10}$	2.04
RDV&CN VLBA only	PIMA, pSolve	$6.41e^{-10}$	1.51
RDV&CN all stat	PIMA, pSolve	$6.14e^{-10}$	1.54
RDV&CN all stat	PIMA, VieVS	$8.13e^{-10}$	0.81
RDV&CN all stat	vgosDB, VieVS	$5.98e^{-10}$	1.17

RDV&CN sessions when measurement at non-VLBA stations was removed from the analysis. Brown circles in the lower figure show the baseline scatter at VLBA stations when the vgosDB for the RDV&CN sessions were taken as input in the VieVS software.

– comparable baseline scatter for MOJAVE sessions from pSolve and VieVS
– similar baseline scatter for VLBA telescopes with/witout non-VLBA stations
– lowest baseline scatter from the vgosDB ...

Earth orientation parameters The Earth orientation parameters are estimated in a so-called backward solution, i.e., a solution consistent with globally estimated terrestrial and celestial reference frame from the respective sessions. The orientation of the TRF is set with the NNT/NNR condition on all 10 VLBA stations and the CRF is oriented with the NNR condition on ICRF3 defining sources in VieVS and on selected (??? the listed sources in the .cnt are not the icrf2 defining sources...) sources in pSolve. Several solutions similar to that introduced in the afore-noted paragraph are computed and the EOP estimated in pSolve and VieVS are depicted in Figs. 5 and 6, respectively. Differences between the EOP MOJAVE and RDV&CN series are characterized in Table 7 in terms of the relative offset, relative drift and wrms for each of the five EOP, i.e., the two polar motion components (x-pole, y-pole), the rotation dUT1, and the two nutation offsets (dX, dY). Table 8 contains the median formal error for the respective EOP time series.

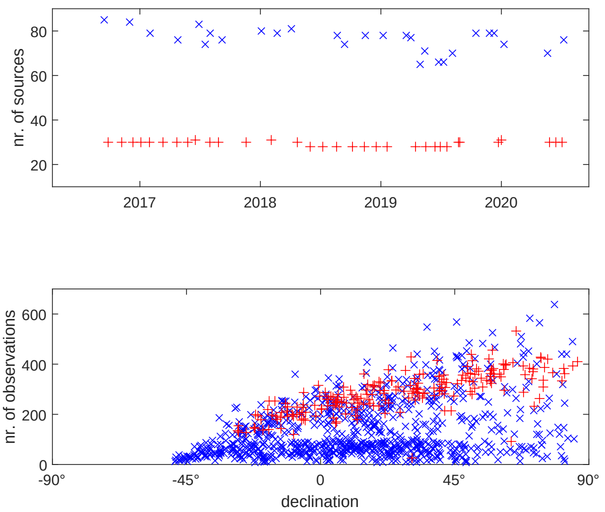

Fig. 3 The upper plot shows number of observed sources in each session. The lower plot depicts the median number of observations for each source. The red crosses stand for the BL229 experiments, blue x-signs for the RDV&CN experiments.

Table 7 EOP statistics of the differences between MOJAVE and RDV&CN series. Difference in wrms is computed w.r.t. the linear trends.

	x-pole	y-pole	dUT1	dX	dY
MOJAVE w.r.t. RDV&CN all stat (PIMA, pSolve)					
offset [μ(a)s]	-10.8	76.6	-11.1	-	-
drift [μ(a)s/y]	46.0	-93.8	3.5	-	-
wrms [μ(a)s]	180.9	191.8	10.1	97.1	40.4
MOJAVE w.r.t. RDV&CN VLBA only (PIMA, pSolve)					
offset [μ(a)s]	-11.2	-13.2	-9.4	-	-
drift [μ(a)s/y]	111.0	-151.4	0.1	-	-
wrms [μ(a)s]	144.1	62.7	7.0	80.3	-1.7
MOJAVE w.r.t. RDV&CN VLBA only (PIMA, VieVS)					
offset [μ(a)s]	-335.8	335.2	7.6	-	-
drift [μ(a)s/y]	119.4	-224.1	0.4	-	-
wrms [μ(a)s]	85.2	49.6	8.8	-1.3	62.1
MOJAVE w.r.t. RDV&CN VLBA only (vgosDB, VieVS)					
offset [μ(a)s]	-327.2	878.0	-2.7	-	-
drift [μ(a)s/y]	-5.9	299.7	-0.9	-	-
wrms [μ(a)s]	69.4	-8.7	1.2	-5.3	67.0

3 Ionosphere

Acknowledgements HK works within the Hertha Firnberg position T697-N29, funded by the Austrian Science Fund (FWF). This research has made use of data from the MOJAVE database that is maintained by the MOJAVE team (Lister et al., 2018). The VLBA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, and operated under cooperative agreement by Associated Universities, Inc.

References

Altamimi Z, Rebischung P, Métivier L, Collilieux X (2016) Itrf2014: A new release of the international terrestrial reference frame modeling nonlinear station motions. Journal of Geophysical Research: Solid Earth 121(8):6109–6131, DOI 10.1002/2016JB013098

Böhm J, Böhm S, Boisits J, Girdiuk A, Gruber J, Hellerschmied A, Krásná H, Landskron D, Madzak M, Mayer D, McCallum J, McCallum L, Schartner M, Teke K (2018) Vienna VLBI and Satellite Software (VieVS) for Geodesy and Astrometry. Publications of the Astronomical Society of the Pacific 130(986):044503, DOI 10.1088/1538-3873/aaa22b

Capitaine N, Wallace P, Chapront J (2003) Expressions for IAU 2000 precession quantities. Astron Astrophys 412, DOI 10.1051/0004-6361:20031539

Charlot P, Jacobs CS, Gordon D, Lambert S, de Witt A, Böhm J, Fey AL, Heinkelmann R, Skurikhina E, Titov O, Arias EF, Bolotin S, Bourda G, Ma C, Malkin Z, Nothnagel A, Mayer D, MacMillan DS, Nilsson T, Gaume R (2020) The third realization of the international celestial reference frame by very long baseline interferometry. A&A 644:A159, DOI 10.1051/0004-6361/202038368

Krásná H, Gordon D, de Witt A, Jacobs CS, Soja B (2019) Earth Orientation Parameters Estimated From K-band VLBA Measurements. In: Haas R, Garcia-Espada S, Lopez Fernandez J (eds) Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, Chalmers University of Technology, vol 24, DOI 10.7419/162.08.2019

Lister ML, Aller MF, Aller HD, Hodge MA, Homan DC, Kovalev YY, Pushkarev AB, Savolainen T (2018) MOJAVE. XV. VLBA 15 GHz Total Intensity and Polarization Maps of 437 Parsec-scale AGN Jets from 1996 to 2017. ApJS 234(1):12, DOI 10.3847/1538-4365/aa9c44

Mathews P, Herring T, Buffet B (2002) Modeling of nutation and precession: New nutation series for nonrigid Earth, and insights into the Earth's interior. J Geophys Res 107/B4(2068):26, DOI 10.1029/2001JB000390

Petrov L, Kovalev YY, Fomalont EB, Gordon D (2011) THE VERY LONG BASELINE ARRAY GALACTIC PLANE SURVEY—VGaPS. The Astronomical Journal 142(2):35, DOI 10.1088/0004-6256/142/2/35

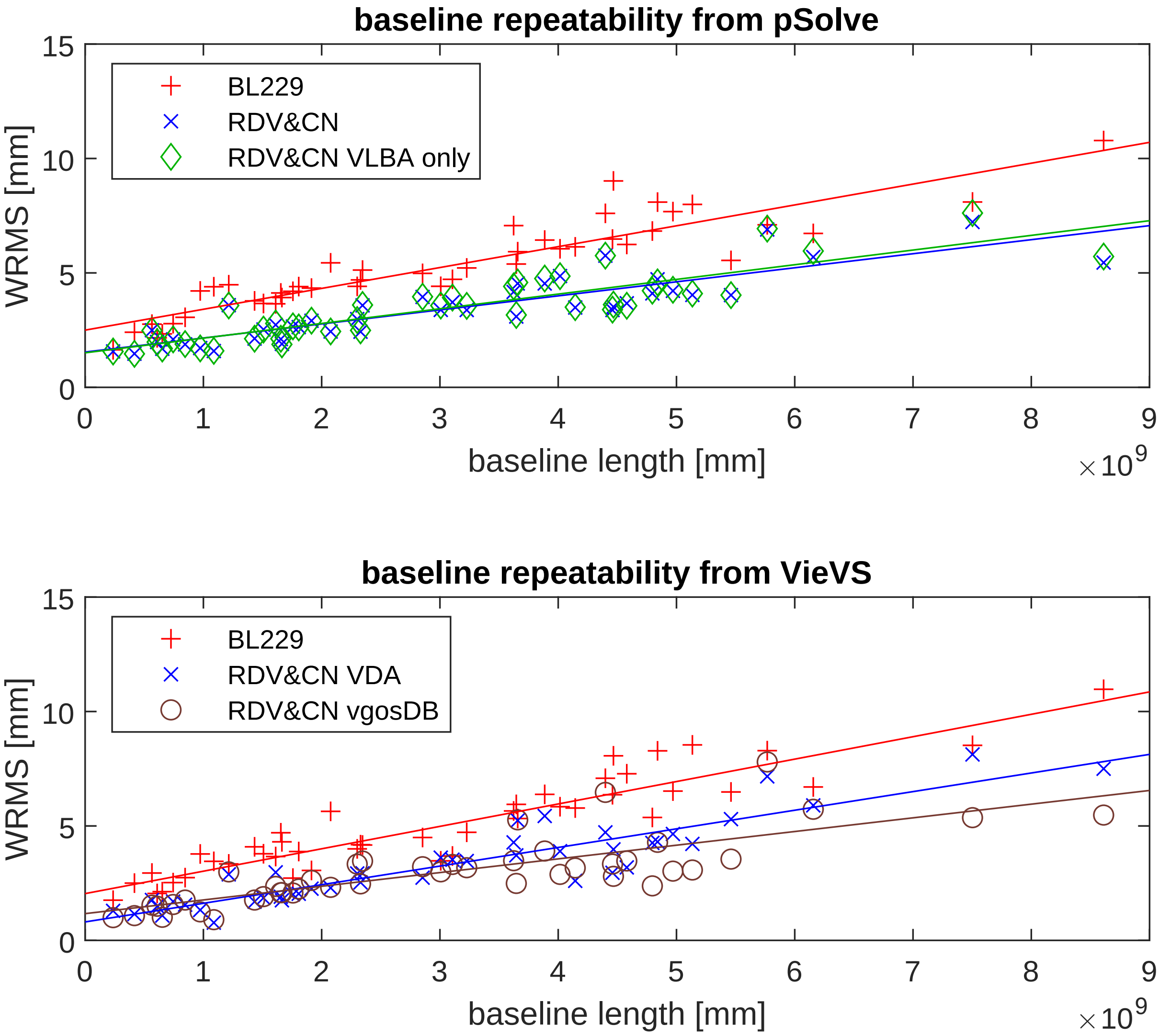

Fig. 4 Baseline length scatter. Without iono correction.

Table 8 Median formal errors for the EOP estimates from backward solution.

	x-pole [μas]	y-pole [μas]	dUT1 [μs]	dX [μas]	dY [μas]
MOJAVE (PIMA, pSolve)	108.6	153.3	8.6	59.1	56.1
RDV&CN all stat (PIMA, pSolve)	56.9	89.1	3.6	85.6	60.2
RDV&CN VLBA only (PIMA, pSolve)	79.7	119.6	5.7	91.7	69.1
MOJAVE VLBA only (PIMA, VieVS)	81.9	97.4	6.9	50.1	55.4
RDV&CN VLBA only (PIMA, VieVS)	50.9	62.1	4.2	39.0	36.6
RDV&CN VLBA only (vgosDB, VieVS)	72.1	92.2	6.1	76.8	65.6

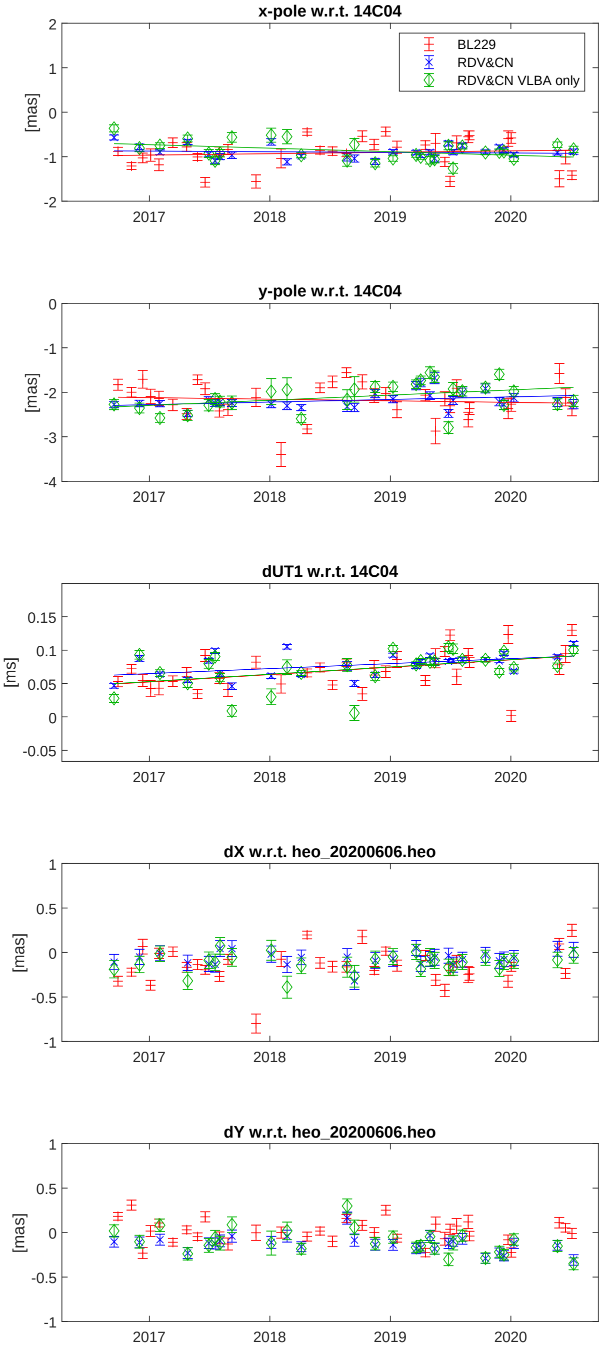

Fig. 5 EOP from pSolve

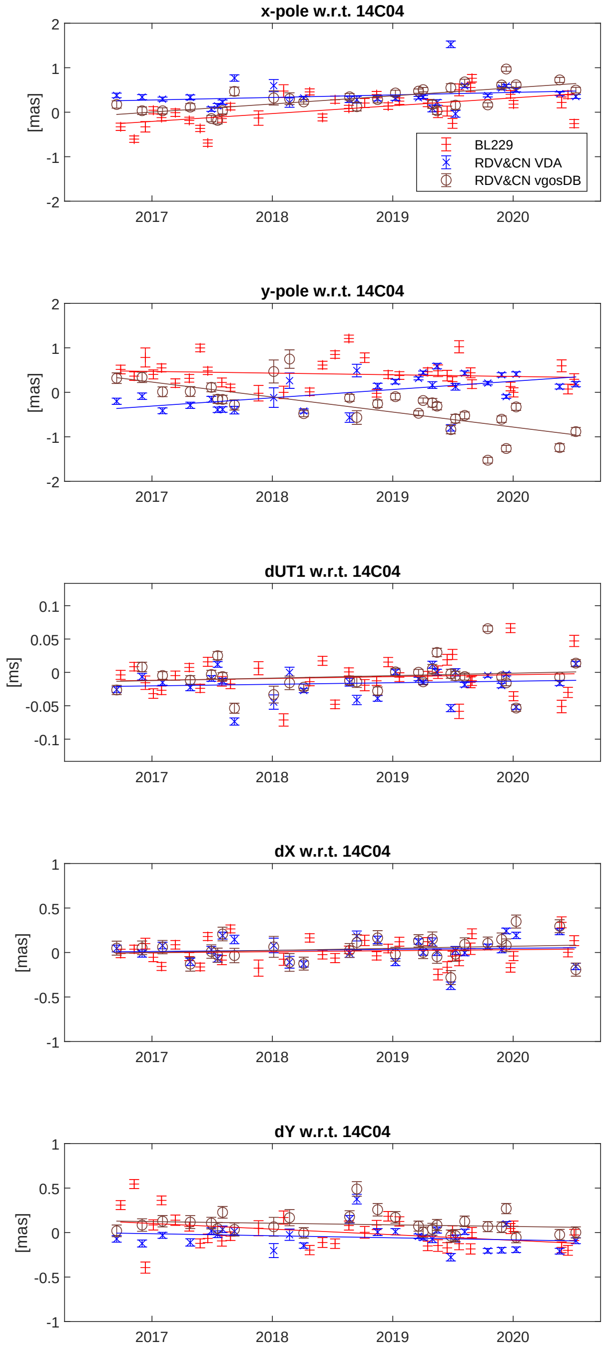

Fig. 6 EOP from VieVS