The Second LBA Calibrator Survey of southern compact extragalactic radio sources — LCS2

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ABSTRACT

We present the second catalogue of accurate positions and correlated flux densities for 1100 compact extragalactic radio sources that were not observed before 2008 at high resolution. The catalogue spans the declination range $[-90°, -30°]$ and was constructed from nineteen 24-hour VLBI observing sessions with the Australian Long Baseline Array at 8.3 GHz. The catalogue presents the final part of the program that was started in the 2008. The goals of that campaign are 1) to extend the number of compact radio sources with precise coordinates and measured correlated flux densities, which can be used for phase referencing observations, geodetic VLBI, search for sources with significant offset with respect to *Gaia* positions, and space navigation; 2) to extend the complete flux-limited sample of compact extragalactic sources to the southern hemisphere; and 3) to investigate the parsec-scale properties of sources from the high-frequency AT20G survey. The median uncertainty of the source positions is 3.5 mas. As a result of this VLBI campaign, the number of compact radio sources south of declination $-40°$ which have measured VLBI correlated flux densities and positions known to milliarcsecond accuracy has increased by a factor of 6.4. The catalogue and supporting material is available at `http://astrogeo.org/lcs`.

Key words: astrometry – catalogues – instrumentation: interferometers – radio continuum – surveys

1 INTRODUCTION

Until recently, the method of very long baseline interferometry (VLBI) proposed by Matveenko et al. (1965) was the only way to measure positions of extragalactic radio sources that are almost exclusively active galactic nuclea (AGNs) with sub-nanoradian accuracy. Recently, it has been demonstrated (Lindegren et al. 2016) that *Gaia* is able to get the position accuracy in par with VLBI. However, comparison of VLBI and *Gaia* matching sources showed (Mignard et al. 2016; Petrov & Kovalev 2017a) that there is a population of sources with statistically significant position offsets. A more detailed analysis by Kovalev et al. (2017) revealed that VLBI/*Gaia* offsets have a preferred direction along the jet with the mean offset in a range of 1–2 mas that was interpreted as a manifestation of the contribution of optical jet to the centroid position. This allowed Petrov & Kovalev (2017b) to make a conclusion that VLBI/*Gaia* difference is due to the fact VLBI and *Gaia* see different part of a source and further improvement in accuracy beyond 1–2 mas level will not result in a reconciliation of VLBI and *Gaia* coordinates of active galaxies. Moreover, the VLBI/*Gaia* offsets brings an important signal that allows us to make an inference about milliarcsecond scale source structure of AGNs that currently cannot be observed directly. As a consequence, if we need achieve accuracy better 1–2 mas, we

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cannot borrow *Gaia* positions of a matching sources, but have to rely on VLBI determination of source coordinates for applications that needs high accuracy, such as space navigation, Earth orientation parameter monitoring, and comparison of positions of pulsars determined with VLBI and timing.

In this context, it becomes increasingly important to have an all-sky, deep, and precise catalogue of positions of extragalactic sources from radio observations. The most productive instrument for absolute radio astrometry is the Very Long Baseline Array. Using VLBA, one can easily determine positions of sources at declinations [-30°, +90°] (Beasley et al. 2002; Petrov et al. 2005, 2006; Kovalev et al. 2007; Petrov et al. 2008; Petrov 2011, 2013; Petrov & Taylor 2011; Petrov et al. 2011a; Immer et al. 2011; Condon et al. 2017; Gordon et al. 2016; Petrov 2016); with some difficulties positions of sources at declinations [-45°, -30°] (Fomalont et al. 2003); but with some exceptions one cannot observe sources below -45°. The sequence of VLBA Calibrator Surveys 1–9 (VCS) (e.g., Petrov et al. 2008, and references therein) provided a dense grid of calibrator sources.

The lack of a VLBA analogue in the southern hemisphere resulted in the past in a significant hemisphere disparity of the source distribution in absolute radioastrometry catalogues. To alleviate this problem, we launched a program for observing radio sources at declinations [-90°, -40°] with Long Baseline Array (LBA) in 2008. The main goal of the program was to increase the density of calibrator sources with positions known at milliarcsecond level in the southern hemisphere to make an analogue of VCS in the south. Unlike to the VCS surveys at the northern hemisphere, we used predominately AT20G at 20 GHz from Australia Telescope Compact Array (ATCA) observations for drawing the candidate list for LBA observations.

The results of the first part of this campaign for observing the brightest sources, the catalogue LCS–1 was published by (Petrov et al. 2011b). Here we present results of the second, final part of the campaign. In the following sections we describe observations, data analysis, analysis of errors, and investigate the relationship of the correlated flux density at milliarcsecond scales derived from our VLBI observations with flux densities of the parent AT20G catalogues at arcsecond scales.

2 OBSERVATIONS

2.1 Network

The network of observing station includes 11 stations listed in Table 1, although at any given experiment only a subset of stations participated. The list of VLBI experiments, observation dates, and the participating network is shown in Table 2. The network, except station Hh, is shown in Figure 1. Station As participated in three experiments, station Td observed only during 4–8 hours intervals. The 64 m station Pa was scheduled in every experiment, in every scan of target sources since it is the most sensitive station of the network and the baselines with Pa are the most sensitive.

Stations At, Mp and Cd were equipped with the LBA VLBI backend consisting of an Australia Telescope National Facility (ATNF) Data Acquisition System (DAS) with an

Table 1. The LBA network. The typical System Equivalent Flux Density (SEFD) at 8.3 GHz at elevation angles > 45° achieved in LCS experiments is shown in the last column.

| Code	Name	ϕ_{gc}	λ	Diam	SEFD
As	ASKAP	-26°.53	116°.63	12 m	8300 Jy
At	ATCA	-30°.15	149°.57	5 × 22 m	140 Jy
Cd	CEDUNA	-31°.70	133°.81	32 m	600 Jy
Ha	HARTRAO	-25°.74	27°.69	26 m	1200 Jy
Ho	HOBART26	-42°.62	147°.44	26 m	850 Jy
Ke	KATH12M	-14°.28	132°.15	12 m	3000 Jy
Mp	MOPRA	-31°.10	149°.10	22 m	400 Jy
Pa	PARKES	-32°.82	148°.26	64 m	50 Jy
Td	TIDBINBILLA	-35°.22	148°.98	34 m	120 Jy
Yg	YARRA12M	-28°.88	115°.35	12 m	3000 Jy
Ww	WARK12M	-36°.25	174°.66	12 m	3000 Jy
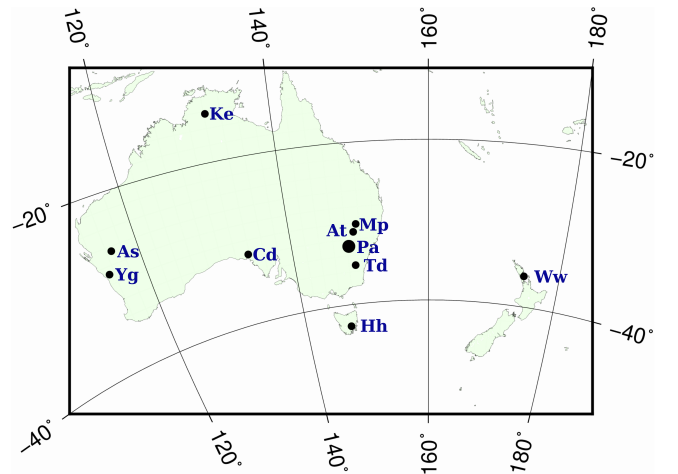
Figure 1. The LBA stations network. Station Hh (HARTRAO), 60 km north-west of Johannesburg, South Africa, is not shown.

LBADR recorder. The ATNF DAS only allows two simultaneous intermediate frequencies (IFs): either 2 frequencies or 2 polarizations. For each of these IFs the input 64 MHz analog IF is digitally filtered to 2 contiguous 16 MHz bands. Stations At and Mp were equipped with two LBDAR recorders, however additional recorders could not be used for expanding the bandwidth due to hardware limitations, but could be used for recording both polarizations. Thus, the stations equipped with the ATNF backend could record two bands 32 MHz wide. This imposed a limitation on the frequency setup: spreading the frequencies too narrow would result in degradation of group delay accuracy and spreading the frequencies two wide would results in group delay ambiguities with very narrow group delay ambiguities spacings. Our choice was to spread 32 MHz sub-bands at 256 MHz that allowed to determine group delay with uncertainly 123 ps when the signal to noise ratio is 10 and with ambiguity 3.9125 ns.

Other stations were equipped with Mark-4 data acquisition terminals that were replaced with Mark-5 during to the course of the campaign. Station Cd was upgraded from the ATNF backend to Mark-5 in 2015 and used Mark-5 in last three campaigns. Stations equipped with Mark-5 recorded

Table 2. List of the LBA Calibrator Survey experiments. The first column shows the campaign segment, the second and third show the observing session and experiment ID, and the last segment shows the network of participating stations.

|			
LCS–1	20080205_r	v254b	At-Cd-Ho-Mp-Pa
LCS–1	20080810_r	v271a	At-Cd-Ho-Mp-Pa-Td
LCS–1	20081128_r	v271b	At-Cd-Ho-Mp-Pa-Td
LCS–1	20090704_r	v271c	At-Cd-Ho-Mp-Pa
LCS–2	20091212_r	v271d	At-Cd-Ho-Mp-Pa
LCS–2	20100311_r	v271e	At-Cd-Ho-Mp-Pa
LCS–2	20100725_p	v271f	At-Cd-Ho-Mp-Pa
LCS–2	20101029_p	v271g	At-Cd-Mp-Pa
LCS–2	20110402_p	v271h	At-Cd-Ho-Hh-Ww-Td
LCS–2	20110723_p	v271i	As-At-Cd-Ho-Hh-Mp-Pa-Td-Ww
LCS–2	20111111_p	v271j	At-Cd-Ho-Hh-Mp-Td
LCS–2	20111112_p	v441a	At-Cd-Ho-Hh-Mp-Td
LCS–2	20120428_p	v271k	At-Cd-Ho-Hh-Mp-Pa-Ww-Yg
LCS–2	20130315_p	v271l	As-At-Cd-Ho-Hh-Mp-Pa-Ww-Td
LCS–2	20130615_p	v271m	At-Cd-Ho-Hh-Mp-Pa-Ww-Td
LCS–2	20140603_p	v493a	At-Cd-Ho-Hh-Mp-Pa-Td
LCS–2	20150407_p	v271n	At-Cd-Ho-Hh-Ke-Pa-Ww-Yg
LCS–2	20150929_q	v271o	As-At-Cd-Ho-Hh-Ke-Pa-Ww-Yg
LCS–2	20160628_q	v493c	As-At-Cd-Ke-Mp-Pa-Yg
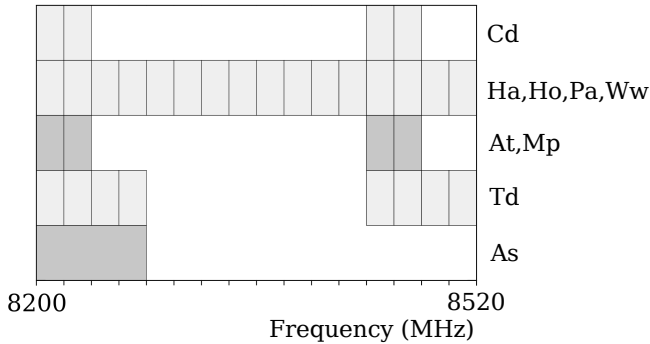
Figure 2. The frequency allocation in v271i experiment. The channel width is 16 MHz for all stations, except As, which has the channel width 64 MHz. Single polarization channels are shown with light-gray color and dual polarization channels are shown with dark-Gray color.

256 MHz bandwidth, except Td that prior 2016 was able to record only 128 MHz and station As that could record a single bandwidth 64 MHz, dual polarization. Stations equipped with Mark-4 or Mark-5 recorded more 16 MHz wide frequency channels with 320 MHz wide bandwidth that partly overlapped with the frequency channels recorded by the stations with the ATNF backend In every experiment network stations used from 2 to 5 different setups and these setups were changing from the experiment to experiment. Figure 2 shows as an example the frequency setup of v271i experiment. The versatility of the DiFX-2 correlator (Deller et al. 2011) allowed to cross-correlate the overlapping regions of such experiments. The heterogeneity of the the available VLBI hardware made correlation more difficult but, fortunately did not introduced noticeable systematic errors in group delay. The most profound effect of this frequency allocation is ambiguities in group delay at baselines with stations that record with the ATNF backend.
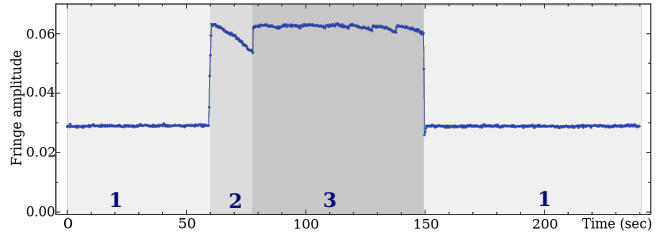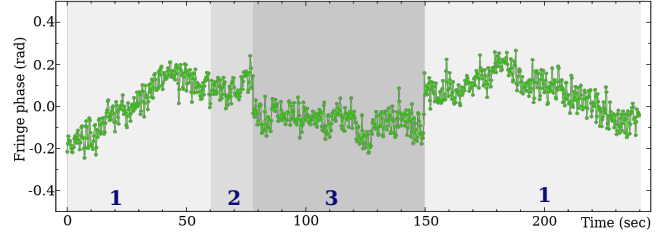
Figure 3. The fringe plot at ATCA/PARKES, source J2225-0457 during vt10k test experiment. The upper plot shows fringe phase, the lower plot shows fringe amplitude. Light-gray area "1" denotes the interval when single ATCA station records. The dark-gray area "3" denotes the interval when the phased-array records. The medium-gray area "2" denotes the intermediate interval.

The Australia Telescope Compact Array (ATCA) consists of six 22 m antennas. Five of them can be phased up and record signal as a single element of the VLBI network. The position of the ATCA phase center can be specified by the user. This feature became available in 2009 **Chris, correct?**. However, we exercised a caution in using phased ATCA since attempts to use phased Westerbork array for astrometry revealed significant phase fluctuations which rendered it highly problematic for precise astrometry (Pogrebenko, private communication, 2010). Therefore, we investigated performance of phase ATCA in a special 4 hour long test experiment that we ran on May 08, 2010. Stations ATCA, CEDUNA, HOBART26, MOPRA, and PARKES recorded the same frequency setup as in the LCS experiments. For the first 60 seconds of a 4 minute long scan ATCA recorded signal from the single antenna at pad with ID 104 (see LCS1 paper for the nomenclature of ATCA pads), then it switched to the phased array with the phase center at the same pad and recorded for 90 second. Finally, it ATCA switched back to recording the signal from a single station. In total, 232 scans of strong sources were recorded. The typical plots of the normalized uncalibrated fringe amplitude and fringe phase as a function of time within a scan are shown in figure 3.

We see that for 18 seconds after switching to the phased-up mode the fringe amplitude is steadily drops by 15% and then suddenly returns back and stays stable within 2%. We consider this as transitional interval. **Chris, we need to explain this behavior**. The fringe phase does not show change greater 0.01 rad just after switching back to the phased mode, but shows a sudden change in a range of 0.1–0.2 rad after the end of the transitional interval and immediately after switching from the phased to the single antenna record mode.

We computed average fringe phases, phase delay rates, group delays and group delay rates by running the fringe fit-

Corr 1

Corr 2

ting algorithm trough the same data three times. During the first processing run we masked out single antenna recording mode and the first 18 s of the phased recording mode keeping 72 s long data in each scan when ATCA recorded in the phased mode. During the second processing run we masked out the data when ATCA recorded in the phased mode. During the third run we processed first 60 s and last 90 s of each scan when ATCA recorded in the single antenna mode. We referred group delay and fringe phases to the same common epoch within a scan and formed their differences.

The differences in group delay between phased and single antenna recording mode at different baselines with ATCA is shown on Figure 4 with green color. The weighted root mean square (wrms) of the differences is 38 ps. For comparison, the differences in group delays computed using the first 60 seconds and last 90 seconds of a 4 minute long scan recorded at ATCA in the single antenna mode and referred to the same middle epoch are shown with blue color. The wrms of these differences is 59 ps. The differences in fringe phase between recording at ATCA with phased model and single antenna mode are shown in Figure 5. The wrms of phase differences is 0.12 rad.

We analyzed dependence if the differences versus elevation, azimuth and parallactic angle, but found no pattern. The uncalibrated averaged fringe amplitude at baselines with ATCA data recorded as a phased array is a factor of 2.27 greater than the uncalibrated fringe amplitude with ATCA data recorded as a single antenna, which is within 2% of $\sqrt{5}$.

We conclude that phasing ATCA up does not introduce noticeable systematic errors in group delay and fringe phases. The differences in group delays is a factor of 1.5 less than the difference in group delay computed from two subset of data separated by 90 s. The differences in phases is random noise with wrms is 0.12 rad, which corresponds to 0.6 mm. Therefore, we concluded that using of phased ATCA as an element of the VLBI network does not introduce systematic errors, but improves sensitivity of ATCA by a factor of 2.27. This was the first use of phased array as an element of VLBI network for absolute astrometry.

2.2 Source selection

We selected for observations the target sources that were previously detected with single dish observations or with connected interferometers at baseline 0.1–5 km. The input catalogues provided the estimates of flux density at resolutions 1–100″. The response of an interferometer to an extended source depends on its compactness and the size of the interferometer. The baseline projection lengths of the LCS network vary in a range of 5–300 Mλ. That means the interferometer will be sensitive for emission from the compact components of milliarcsecond size. The response to extended emission with a size more than 1 mas at the longest baselines and 50 mas at the shortest baselines will be attenuated, and the interferometer will not detect signal from emission with size a more than a factor 2–5 beyond that level.

In order to maximize the number of detected sources, we have to select the targets with the highest compactness: the ratio of the correlated flux density at 5–300 Mλ to the total flux density. As a marker of high compactness we initially used spectral index defined as $S \sim f^{\alpha}$, where f is
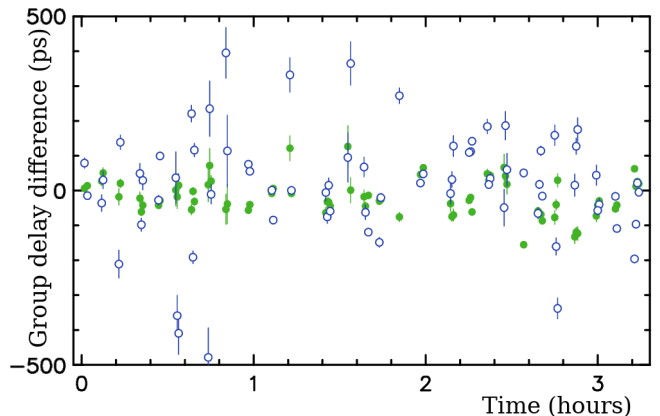

Figure 4. Differences in group delays from the same observations in test vt10k experiment. The solid green circles show the differences in group delay between ATCA phased-array and ATCA-single stations. The wrms of the differences is 38 ps. For comparison, the whole blue circles show the differences in group delay from first 60 sec and last 90 seconds of the integration interval.
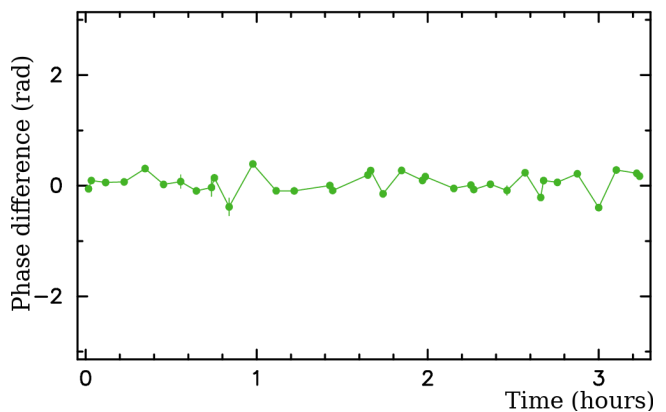

Figure 5. Differences in fringe phase delays between ATCA phased-array and ATCA-single recording from the same observations in test vt10k experiment. The wrms of the differences ins 0.12 rad.

the frequency. As a result of synchrotron self-absorption the emission from the optically thick jet based that is morphologically referred to as the core of an AGN, has flat ($\alpha \approx 0$) or inverted spectrum ($\alpha > 0$). The optically think emission from the extended jet and extended radio-lobes that are a result of interaction of the jet with surrounding interstellar medium usually has steep spectrum ($\alpha < 1$). Therefore, one can expect the sources with flat spectrum, on average, will have a higher compactness, which was confirmed with observations (e.g., Beasley et al. 2002).

For the coarse of the 8-year long campaign our sources selection strategy gradually evolved, but all the time it was focused on selecting the sources with brightest correlated flux density. In the first three experiments we selected the sources with spectral index > -0.50 from the quarter-Jansky survey (Jackson et al. 2002) brighter 200 mJy. In following experiments were used several criteria for selecting the targets. In experiments v271c–v271m we selected

the candidate sources brighter 150 mJy with spectral index > -0.55 from the AT20G catalogue (Murphy et al. 2010). In addition to that, we selected the sources brighter 180 mJy and spectral index > -0.55 from the PMN catalogue (Griffith & Wright 1993; Wright et al. 1994; Griffith et al. 1994; Condon et al. 1993; Tasker et al. 1994; Griffith et al. 1995; Wright et al. 1996). In v271k–v271m experiments we selected the sources brighter 170 mJy and spectral index > -0.55 from the ATPMN catalogue (McConnell et al. 2012).

However, an approach of selecting flat spectrum sources does not provide a good prediction for correlated flux density for the sources within 5–7° of the Galactic plane. First, the the Galactic plane is crowded and a chance to make an error in cross-matching the sources observed with instruments are different resolutions and poor positional accuracy rather high. This will result in a gross mistake in the estimate of the spectral indices. Second, the density of galactic sources with flat spectrum, such as supernova remnants and ultra-compact H II regions is much higher within the Galactic plane. An attempt to observe flat spectrum sources in the Galactic plane by cross-matching the MGPS-2 catalogue at 843 MHz Murphy et al. (2007) resulted in a detection rate of $\sim 10\%$. To overcome this problem, we used another approach to find candidate sources in the Galactic plane: we analyzed IR color-color diagram. Massaro et al. (2011) noticed that the blazars occupied a special zone in the color-color diagram 3.4–4.6 μm and 4.6–12 μm. We analyzed this dependence independently and delineated the zone that encompasses over 85% compact radio-loud AGNs from the cumulative VLBI catalogue RFC (Petrov & Kovalev, 2019, in preparation[1]). See section 4.2 in Schinzel et al. (2015) for detail. After the failure with cross matching MGPS-2 with higher frequency radio catalogues, we tried the second approach: we selected all the sources within 5° of the Galactic plane and declinations below $-40°$ and flux density > 50 mJy and left those that have cross-matches against IR WISE catalogue (Wright et al. 2010; Mainzer et al. 2011) within 30″. Then we throw away the sources that are away the zone of the 3.4–4.6 μm and 4.6–12 μm diagram that contains 85% radio loud AGNs. We observed the brightest sources from the remaining sample. The detection rate of this sample was 57%.

In addition to these selection methods, we observed in three experiments, v441a, v493a, and v493c the flat spectrum sources brighter 10 mJy that were detected at 5 and 9 GHz by the Australia Telescope Compact Array (ATCA) within its error ellipse, i.e. 2–5′ of unassociated sources γ-ray sources detected with *Fermi* mission (Abdo et al. 2010) that we found in a dedicated program (Petrov et al. 2013; Schinzel et al. 2015, 2017) focused in finding the most plausible radio counterparts of γ-ray source. Since radio-loud γ-ray AGNs tend to be very compact, the presence of a radio source detected with a connected interferometer within the error ellipse of a γ-ray raises the probability of being detected with VLBI. Observing such sources first, fits the primary goal of the LCS program, second, allows to find an association to *Fermi* objects that previously were considered unassociated.

2.3 Scheduling

The experiment scheduled was generated automatically with program sur_sked in a sequence that minimizes the slewing time and obey a number of constraints. Target sources was observed in three-four scans for 2 to 4 minutes long each, except weak targets of candidates to *Fermi* associations that were observe for 5–10 minutes. Observing session had nominal duration of 24 hours. During a session 80–100 target sources were observed. The minimum gap between consecutive observations of the same source was set to 2.5 hours. Station Parkes was required to participate in each scan, since it is the most sensitive antenna of the array. After 1.5 hours of observing targets sources, a block of so-called calibrator sources was inserted. These are the sources picked from the pool of known compact objects stronger 300 mJy. The block consists of 4 sources, with two of them observed at each station in the elevations in the range of 10–30° (30–40° for Parkes that have elevation limit 31°) and two observed at elevations 55–85°. The goal of these observations: 1) to improve the estimate of the atmosphere path delay in zenith direction; 2) to connect the LCS catalogue to the accumulative catalogue of compact radio sources; 3) to use these sources as bandpass calibrator; 4) to use these sources as amplitude calibrators for elevation gain corrections.

3 DATA ANALYSIS

The antenna recorded voltage sampled with 2-bits and the aggregate bit rate from 256 to 1024 millions of samples per second. The first step of data analysis is correlation that is performed at the dedicated facility followed by post-correlator analysis that computes group delays and phase delay rates using the spectrum of cross-correlated data, followed by astrometric analysis that computes source positions, followed by amplitude analysis that either produces source images or estimates of the correlated flux density at the specified range of the lengths of projected baselines.

3.1 Correlation and post-correlation analysis

The first four experiments were correlated with the Bonn Mark4 Correlator. The data from ATCA-104, CEDUNA, and MOPRA, originally recorded in LBADR format were transformed to the Mark5B format before correlation. Correlation of the data from LBADR data acquisition rack against the data from the Mark-4 data acquisition terminal was complicated since this is a non-standard operation. Post-correlation analysis of these data was was performed at the correlator using software program FOURFIT, the baseline-based fringe fit offered within the Haystack Observatory Package Software (HOPS) to estimate the residual group delay and phase delay rate. More detail about processing these experiments can be found in Petrov et al. (2011b).

Other experiments were correlated with the DiFX software correlator (Deller et al. 2011) at the International Centre for Radio Astronomy Research, the joint venture between Curtin University and the University of Western Australia. The output of DiFX correlator was converted to FITS-IDI format and further processed with PIMA VLBI data analysis software Petrov et al. (2011a). The correlator provided

the time series of cross- auto-correlated output spectral resolution 0.25 MHz and time resolution 0.25 s. Such a choice of correlation parameters allowed to detect a sources within several arcminutes of pointing direction, i.e., everywhere within the primary beam of PARKES radio telescope that has full with half maximum (FWHM) at 8.4 GHz is $\sim 2'$.

The post-correlator analysis chain includes the following steps:

• Coarse fringe fitting that is performed using an abridged grid of group delays and delay rates without further refinement. The goals of this step is to find at each baseline 10–15 observations with the highest signal to noise ratio (SNR) and detect failures at one or more IFs

• Computation of complex bandpass using the 12 observations with the highest SNR. The complex bandpass describes a distortion of the phase and amplitude of the recorded signal with respect to the signal that reached the antennas. We flagged at this step the IFs that either were not recorded or failed. We used 12 observations for redundancy in order to evaluate the statistics of residual deviation of the phase and amplitude as a function of frequency from the ideal after applying the bandpass computed over 12 observations using least squares. Large residuals triggered detailed investigation that in a case of serious hardware problem resulted in flagging affected spectral channels.

• Fine fringe fitting that is performed using the complex bandpass and the bandpass mask derived in the previous step. The preliminary value of the group delay and phase delay is found as the maximum element of the two-dimensional Fourier transform of the time series of cross-correlation spectrum sampled over time and frequency with a step 4 times finer over each dimension than the data. The fine value of the group delay and phase delay rate is adjusted from phases of the cross-correlation function (also known as fringe phases) as small corrections to the preliminary values using least squares. Phase residuals of the cross-correlation spectrum are analyzed and additive corrections to the a priori weights are computed on the basis of this analysis. The uncertainties of estimates of group delays are derived from uncertainties of fringe phases and additive weights corrections. The uncertainties of fringe phases depend on fringe amplitudes. The explicit expression can be found on page 233 of Thompson et al. (2017).

• Computation of total group delays and phase delay rates. The group delays and phase delay rates computed at the previous step are corrections to the a priori delays and phase delay rates used during correlation. The mathematical model of the a priori group delay and phase rate used by the correlator is presented as a set of coefficients of polynomials at intervals of time that cover the time range of a VLBI experiment. Using these coefficients, the a priori group delays and phase delay rates are computed to a common epoch within a scan for the event of arriving the wavefront at a reference station of a baseline. Using these a priori group delays and phase delay rates, the total group delays for that epoch are formed.

3.2 Astrometric analysis

Group delay is the main observable for astrometric analysis. The a priori model of group delay, more sophisticated that
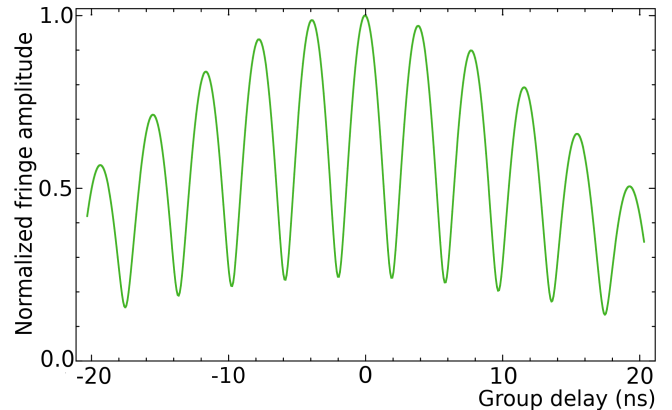

Figure 6. The nomalized fringe amplitude as a function of group delay between stations that had LBDAR recording system. The fringe amplitude is difived by the amplitude at the global maximum.

that used for correlation is computed and the differences between observed and theoretical path delays are formed. The partial derivatives of this model over source coordinates, station positions, the Earth ordination parameters, atmosphere path delay in zenith direction, and clock function are computed corrections to that parameters are computed using least squares.

The frequency setup used for this campaign selected due to hardware limitation, see as an example the setup for v271i segment in Figure 2, posed a challenge in data analysis. The Fourier transform over frequency over baselines with At, Cd, Mp in this example that uses LBDAR data aquisition system has strong secondary maxima (see Figure 6). The amplitude of the 2nd maximum is 0.98, the third maxiumum 0.93, the fourth maxium 0.83 wirt respect of the grobal maximum. Due to the noise in data and phase distortion, the fringe fitting process cannot reliably distinguish the primary and the secondary maxima, and as a result, group delay is determined with the ambiguity of $N \times 1/2.56 \cdot 10^8 \approx 3.9$ ns, where N is a random integer number, typically in a range [-2,2].

The first phase of astrometric data analysis is to clean for outliers in the so-called narrow-band group delays computed as an arithmetic average of group delays computed over each IF independently. The narrow-band delays do not have ambiguities, but are one order of magnitude less precise than group delays computed over the entire band. The estimated parameters at this stage are station positions and coordinates of target sources, as well as atmospheric path delays in zenith direction and clock function in a form of expansion over B-spline. The contribution of the adjusted parameters to path delay computed using the narrow-band delays is substituted to the group delay residuals and then used for initial resolving group delay ambiguities. The procedure for group delay ambiguity resolution is described in detail in Petrov et al. (2011b).

After the group delay ambiguities are resolved, the dataset is cleaned for outliers in group delay. If necessary, the parametric model of clock is refined for incorporating discontinuities at specified epochs. Initial data weights were chosen to be reciprocal to the group delay uncertainty σ_g.

Then the additive baseline-dependent wight corrections a were computed for each observing session to make the ratio of the weighted sum of residuals be close to their mathematical expectation. These weights wee used in the initial solution. The weights in the final solution were used in the form

$$w = \frac{1}{k \cdot \sqrt{\sigma_g^2 + a^2 + b^2}}, \quad (1)$$

where k is a multiplicative factor and b an additive weight correction for taking into account mismodeled ionosphere contribution to group delay (see below). Such clean dataset is used for further analysis.

The final LCS catalogue was derived using all dual-band X/S (8.4/2.3 GHz) observations since 1980 through July 2018 under geodesy and astrometry programs that are publicly available and 19 LCS X-band experiments in a single least square solution. The estimated parameters are split into three groups: global parameters that are estimated for the entire dataset, local parameters that are specific for a given experiment, and segmented parameters that are specific for a timer interval shorter than session duration. The global estimated parameters are coordinates of all observed sources, positions and velocities of all observing stations, harmonic variations of station positions at annual, semi-annual, diurnal, and semi-diurnal frequencies, B-spline coefficients that describe discontinuities and non-linear motion of station caused by seismic activity. The local parameters are pole coordinates UT1 and their first time derivative. The segmented parameters are clock function for all the station except the reference one, and residual atmosphere path delay in zenith direction.

For the course of LCS campaign, a number of target sources were observed in follow-up VLBI experiments. We excluded these sources from dual-band experiments in our LCS solution. The position of LCS target sources were derived using only LCS 8.4 GHz data. Observations of these sources were later used for evaluation of errors of the LCS catalogue and computation of the multiplicative weight correction k.

Since equations of electromagnetic wave propagation are invariant with respect to rotation of the celestial coordinate system, and translation and rotation of terrestrial coordinate system, the system of equations have a rank deficiency and determine only a family of solution. In order to define the solution from that family we applied no-net-rotation for source coordinates requiring the new catalogue of source position have no net-rotation for 212 so-called defining sources with respect to their positions in the ICRF1 catalogue (Ma et al. 1998). Similarly, we applied no-net-rotation and no-net-translation constraints on station positions.

3.3 Imaging analysis

Alet and Alessandra: here is the place for your song.

3.4 Determination of flux densities

Here I will describe results of non-imaging analysis for those experiments Alet and Alessandra still did not process.

4 ERROR ANALYSIS

Single-band group delays are affected by the contribution of the ionosphere Considering the ionosphere as a thin shell at a certain height above the Earth surface (typically 450 km), the group delay can be expressed as

$$\tau_{\rm iono} = \frac{\alpha}{f_{\rm eff}^2} \, {\rm TEC} \, \frac{1}{\cos \beta}, \quad (2)$$

where $f_{\rm eff}$ is the effective frequency, β is the zenith angle at the ionosphere piercing point, TEC is the total electron contents in the zenith direction at the ionosphere piercing point, and α is a constant (see Sovers et al. (1998) for detail). We have computed the a priori ionosphere contribution to group path delay using TEC maps from analysis if Global Navigation Satellite System (GNSS) observations. Specifically, we used CODE TEC time series (Schaer 1999)[2] with resolution $5° \times 2.5° \times 1^h$ ($5° \times 2.5° \times 2^h$ before December 19, 2013).

The TEC model from GNSS observation is an approximation and the accuracy of a priori $\tau_{\rm iono}$ from such a model is significantly lower than the accuracy of $\tau_{\rm iono}$ computed from the linear combination of group delays at X and S (or X and C) bands from dual-band observations. The errors of $\tau_{\rm iono}$ from latter observations is at level of several picoseconds according to Hawarey et al. (2005). We consider the contribution of mismodeled ionospheric path delay as dominating in the error budget and, therefore, we investigated it in detail.

We used the global dataset of VLBI observations after July 01, 1998 for investigation of the residual ionospheric contribution to group delay after applying the a priori path delay delay from CODE global TEC maps. For each dual-band observing sessions, we decompose the slant ionosperic path delay from X/S observatyions at the product of the path delay in zenith direction and the mapping function, the ratio of the ionospheric path delay in a given elevation to the the ionospheric path delay in zenith direction. Then we computed the rms of the total $\tau_{\rm iono}$ in zenith direction from CODE global TEC maps and the rms of the residual $\tau_{\rm iono}$ after subtracting the a priori ionospheric group delay in zenith direction computed from CODE global TEC maps from $\tau_{\rm iono}$ in zenith direction derived from dual-band X/S group delays. The ratio of these two statistics, $A = \frac{\sigma_r^2}{\sigma_t^2}$ is a measure of a goodness of the model. Assuming A is stable, we can predict unknown to us statistics of σ_r^2 for single-band observation using σ_t^2 that we can compute from TEC model. We computed the time series of parameter A.

Parameter A is not stable with time. Since A is computed as a ratio of variances, we sought an empirical regression models where A enters as a multiplicative factor. We

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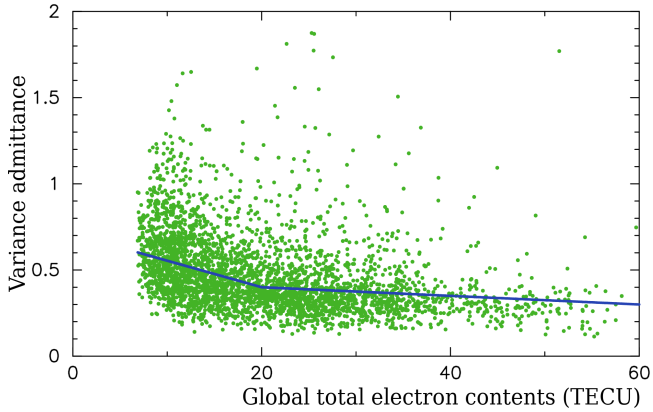[2] Available at ftp.aiub.unibe.ch/CODE/

Figure 7. The dependence of the variance admittance factor A on the global total electron contents. The so-called TEC units (10^{16} electrons over zenith direction) are used fgor GTEC.

Figure 8. The sky distribution of compact radio source at the southern hemisphere. Blue light color denotes 186 sources with declinations $< -40°$ with VLBI positions known prior the LCS program. Green dark color denotes 1100 sources detected in LCS program. Red line shows the Galactic plane.

computed the global total electron content (GTEC), by averaging the TEC over the sphere. As it was show by **?**, such a parameter characterizes the global state of the ionosphere. Figure refr:gtec shows the dependence of A on GTEC. We represent this dependence with a broken linear function with A=0.6 at GTEC=7.0, A=0.40 at GTEC=20.0 and A=0.30 at GTEC=60.0.

Using this dependence, for a given experiment we computed the GTEC, averaged it over the period of experiment duration, computed parameter A using the liner regression, computed for each station of a baseline the time series of the ionospheric contribution from the GTEC model, and then computed the variances for the first and second station of a baseline, Cov_{11} and Cov_{22}, as well as their covariances. Then for each observation we computed the predicted rms of mismodeled ionospheric contribution as

$$b = A\sqrt{\mathrm{Cov}_{11}^2\ M_1^2(e) - 2\,\mathrm{Cov}_{12}\ M_1(e)\ M_2(e) + \mathrm{Cov}_{22}^2\ M_2^2(e)},\quad (3$$

where $M_1(e)$ and $M_2(e)$ are mapping function of the ionospheric path delay. These parameters b were used for weight corrections in expression 1.

Parameter A varied from 0.35 to 0.59 with the mean 0.48 for the LCS2 campaign This means that applying the ionospheric contribution from the CODE TEC maps, we reduce the variance of the total contribution by a factor of 2, and the mismodeled part of the contribution is accounted in inflating uncertainty of group delay. The known deficiency of this approach is that first, the regression dependence of parameter on A on GTEC is rather coarse, and second, the correlations between residual ionospheric contributions are neglected.

For a check of the contribution of remaining systematic errors, we compared our source positions derived from X-band only LCS experiments with results of dial-band observations that included some LCS target sources. In 2017, a program of follow-up observations
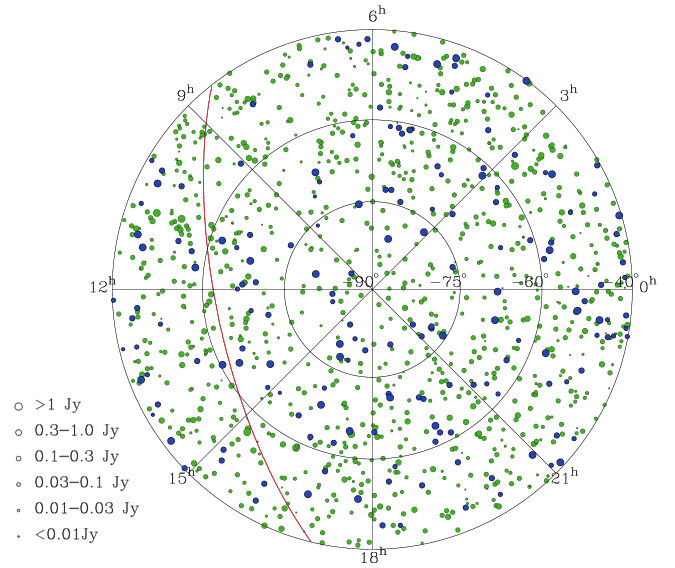

Density scale – number of sources in a circle with radius $2°.0$

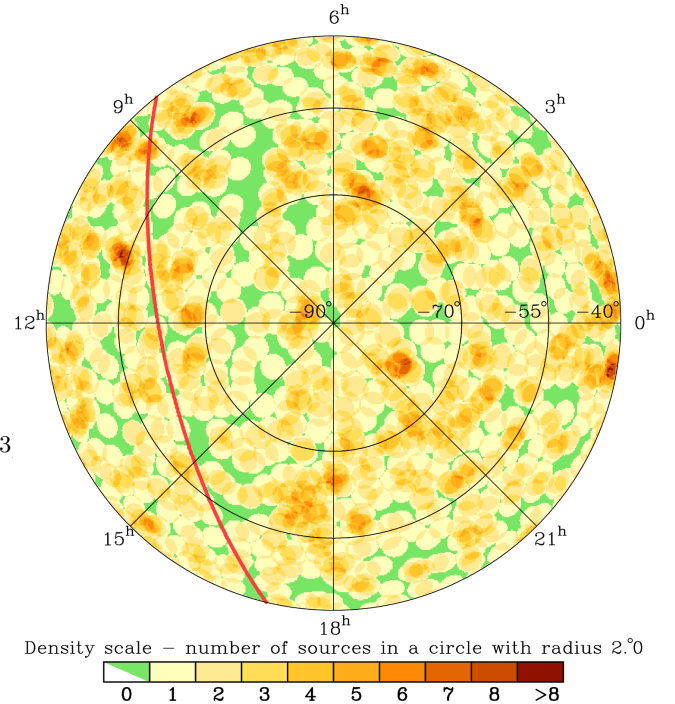**Figure 9.** The sky density of calibrator sources in the zone with declinations $< -40°$ defined as the number of compact sources with flux density > 30 mJy in a circle of $2°$ radius. TheGalactic plane is shown with the red line.
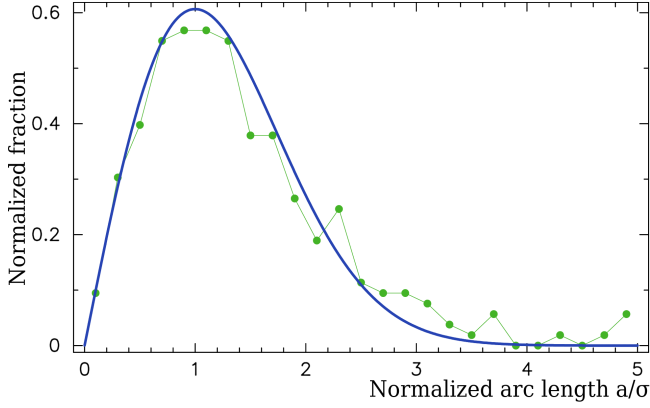
Figure 10. The distribution of the normalized arc lengths between LCS2 X-band only positions of 269 sources and their X/S positions from the follow-up campaigns (Green dots). For comparison, the Rayleigh distribution with $\sigma = 1$ parameter is shown with a blue line.
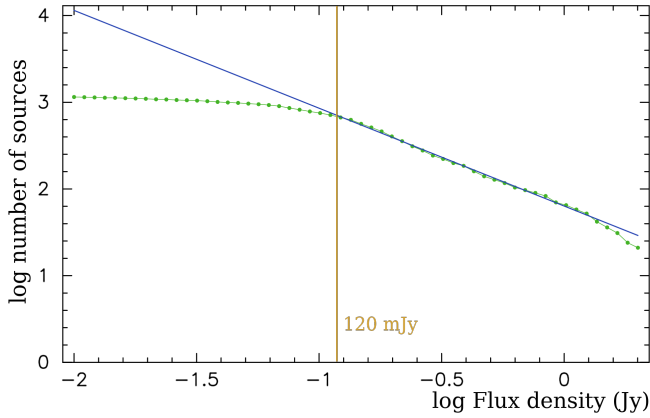

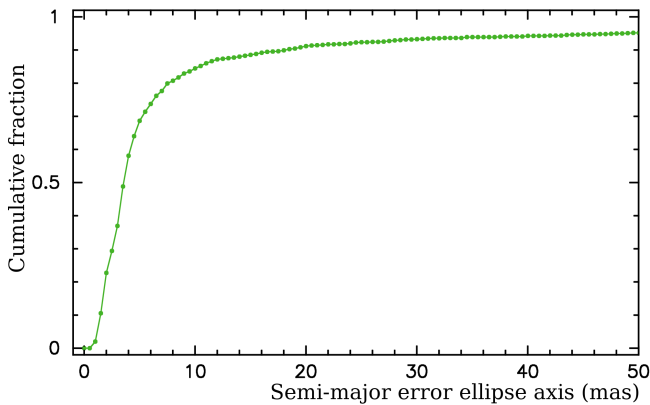**Figure 11.** The log N–log S dependence for the LCS2 catalogue.

Figure 12. The cumulative distribution of the LCS2 position errors.

5 THE CATALOGUE

6 POPULATION ANALYSIS

Elaine: this is the part where I anticipate your contribution. I suggest to take all the cross-matches between AT20G and VLBI, not limiting ourselves to LCS2 only. The majority of matches will be from LCS1,2 but I do not think we should exclude the sources from VLBI.

I bear in mind compactness analysis (ration of VLBI to AT20G flux density), correlation between compactness and spectral indices. Anything else?

7 CONCLUSION

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