Progress on the VLBI Ecliptic Plane Survey

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Abstract We launched the VLBI Ecliptic Plane Survey program in 2015. The goal of this program is to find all compact sources within 7.5° of the ecliptic plane which are suitable as phase calibrators for anticipated phase referencing observations of spacecrafts. We planned to observe a complete sample of the sources brighter than 50 mJy at 5 GHz listed in the PMN and GB6 catalogs that have not yet been observed with VLBI. By April 2016, eight 24-hour sessions had been performed and processed. Among 2,227 observed sources, 435 sources were detected in three or more observations. We also ran three eight-hour segments with the VLBA for improving the positions of 71 ecliptic sources.

Keywords Radio astrometry, catalogs, ecliptic plane, high sensitivity observations

1 Introduction

This paper presents the status report of the ongoing VLBI Ecliptic Plane Survey (VEPS) program. The first goal of the program is to search for more ecliptic calibrators using a minimum network of three stations. We consider a source that is brighter than 30 mJy at a baseline projection length of 5,000 km as a calibrator. We have selected all objects within 7.5° of the ecliptic plane, with single dish flux densities brighter than 50 mJy at 5 GHz from the PMN (Parkes-MIT-NRAO) and GB6 (Green Bank 6 cm) catalogs except for those:

- that have been detected with VLBI before or
- that were observed with VLBI in a high sensitivity mode (detection limit better than 20mJy), but have not been detected.

As the number of target sources is more than 7,000, we planned to observe in two phases:

- Phase-A — Observations of 2,216 sources that have total flux densities at 5 GHz > 100 mJy
- Phase-B — Observations of 4,802 sources that have total flux densities at 5 GHz in the range [50, 100] mJy

More details about the observations of this large sample of target sources are given in Sections 2–4.

The second goal of the VEPS program is to improve the position accuracy to better than 1.5 nrad for those ecliptic calibrators detected in various VLBI experiments, but with large position uncertainties. This type of observation should be performed at S/X dual band and use a large network such as the VLBA, EVN, or IVS in a high-sensitivity mode. We will address this issue in Section 5.

2 Observations

The Phase-A observations began in February 2015. The participating stations include the three core Chinese VLBI stations: Seshan25, Kunming, and Urumqi. However, sometimes they are not available at the same time, or occasionally one or two of them have a risk of

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failure. In that case, one or two international stations are required.

Figure 1 shows the geographical distribution of all participating stations. Kashima34, Sejong, and Hobart26 have contributed to the past VEPS observations. They have middle-sized antennas and good common visibility for the ecliptic zone. Before joining in the VEPS survey, we made fringe tests to Sejong, Hobart26, and Kashim34 in December 2014, July 2015, and January 2016 respectively.

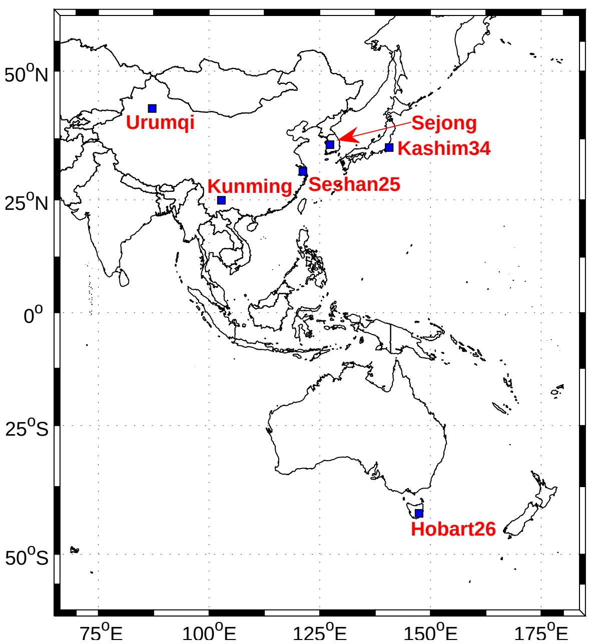

Fig. 1 Distribution of participating stations.

So far eight sessions have been observed, as summarized in Table 1. Each target source was observed in two scans of 90 seconds. Four calibrators were observed every hour for the reduction of atmospheric effects and amplitude calibration.

Figure 2 shows the frequency sequence used in the Phase-A observations. Eight USB channels and eight LSB channels spread over about an 800-MHz frequency range at X-band result in 16 IF channels, and the bandwidth for each IF channel is 32 MHz, so the total data rate is 2048 Mbps with two-bit sampling. The data volume is close to 16 TB for each station in one 24-hour session.

For the Sejong station, the maximum rate is 1024 Mbps, so the data sampling was changed to one bit. For

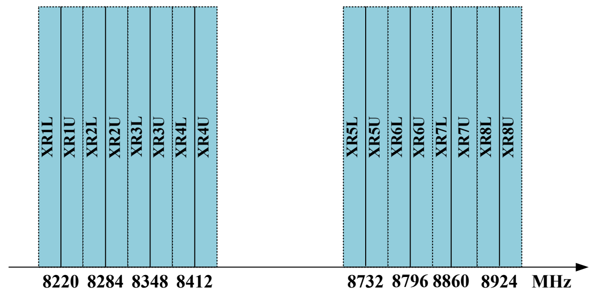

Fig. 2 Frequency sequence used in the VEPS observations.

Hobart26, its 32 MHz bandwidth had not been tested at that time, so we observed the first 16-MHz bandwidth for each IF channel instead. In the case of a 1024-Mbps data rate, the data volume is close to 8 TB for each station in one session.

3 Data Processing

The data from the Chinese domestic stations were recorded on 16-TB diskpacks and then shipped to Shanghai, while the data from international stations were transferred to Shanghai via high-speed network. The data volume for each session is much bigger than that of regular geodetic sessions, so the data processing is very time-consuming. Another technical issue is the correlation of mixed observing modes with different bandwidths or sampling bits. This could be supported by the DiFX correlator installed at Shanghai, which also serves as one of the IVS correlators.

For the correlation of one-bit sampled data from Sejong against two-bit sampled data from the other stations, a different treatment was implemented in the station-based processing module, and it turned out to have the same results after the data were transformed to the frequency domain.

For the correlation of 16-MHz bandwidth data from Hobart26 against 32-MHz bandwidth from the other stations, the zoom mode was selected to pick up the overlapped frequency band. Moreover, it was optional to correlate only on the 16-MHz bandwidth on the baselines to Hobart26, while the other stations with 32-MHz bandwidth went through an independent correlation pass, the same as the usual correlation procedures.

Table 1 Summary of the VEPS observations.

Date (yyyy-mm-dd)	Time UT	Dur hrs	Code	Stations	Frequency	Data rate (Mbps)	Channels	Sampling (bits)	Data volume (TB)	# Targets
2015-02-13	05h00m	24	VEPS01	ShKmUr	X	2048	16	2	48	293
2015-02-14	06h00m	24	VEPS02	ShKmUr	X	2048	16	2	48	338
2015-04-23	05h00m	24	VEPS03	ShKmUrKv	X	2048	16	2	56	300
2015-04-24	06h00m	24	VEPS04	ShKmUrKv	X	2048	16	2	56	400
2015-08-10	05h00m	25	VEPS05	ShKmKvHo	X	2048	16	2	42	252
2015-08-19	05h00m	25	VEPS06	ShKmKvHo	X	2048	16	2	42	277
2016-03-02	08h30m	24	VEPS07	ShKmUrKb	X	2048	16	2	52	333
2016-03-11	05h00m	24	VEPS08	ShKmUrKb	X	2048	16	2	60	477

Note 1. — Sh: Seshan25; Km: Kunming; Ur: Urumqi; Kv: Sejong; Kb: Kashim34; Ho: Hobart26.
Note 2. — The mode 1024 (data rate) — 16 (channels) — 1 (bit) was used at Sejong.
Note 3. — The mode 1024 (data rate) — 16 (channels) — 2 (bit) was used at Hobart26.

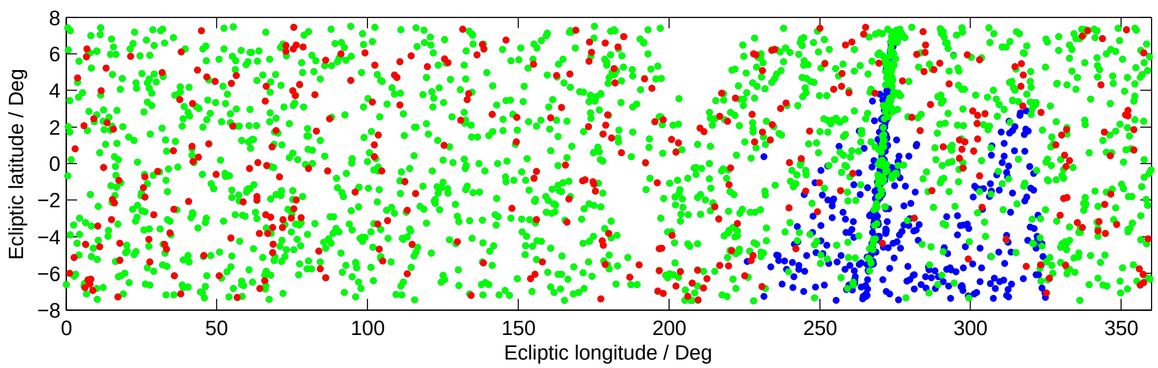

Fig. 3 Distribution of Phase-A sources. Among 2,216 target sources (blue, darkest), 1,903 sources (green, lightest) have been observed, and 363 sources (red, intermediate) were detected in three or more observations.

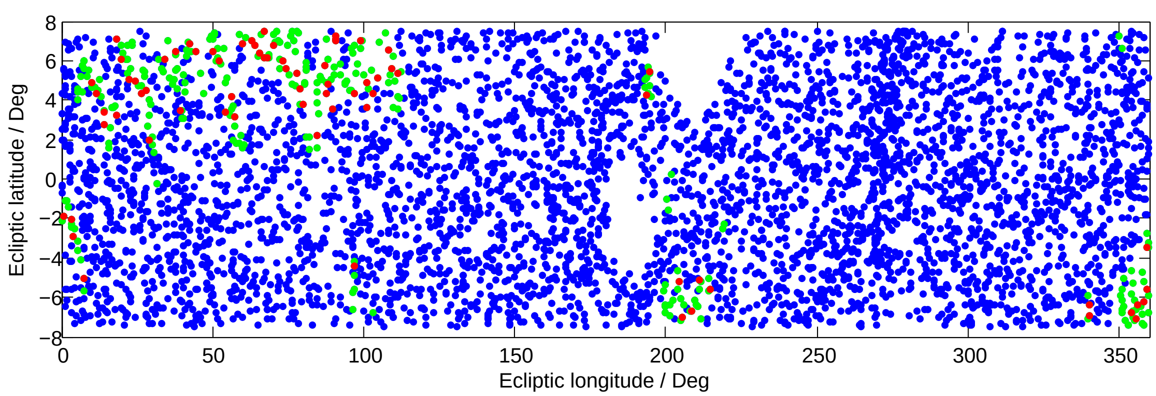

Fig. 4 Distribution of Phase-B sources. Among 4,802 target sources (blue, darkest), 324 sources (green, lightest) have been observed, and 72 sources (red, intermediate) were detected in three or more observations.

4 Preliminary Results

In general, the VEPS observing sessions were successful, although Urumqi had no fringes in the first half of the VEPS01 session due to a receiver problem, and Seshan25 and Kunming had no fringes in VEPS03 due to an incorrect use of B1950 source positions.

We have processed all of the observed sessions. Based on the data analysis, there are 435 target sources that were detected in three or more observations among 2,227 observed. The detection rate is about 20%. Their median position precision is about 18 nrad. The estimation of the correlated flux densities is better than 15%.

Except for the baselines to Sejong, the other baselines have detection limits better than 30 mJy. Deduced from the four VEPS sessions, the SEFD of Sejong varied from 3000 to 5000, which can also be confirmed by the IVS sessions in which it participated. The causes are under investigation and may be related to the antenna pointing model, aperture efficiency as a function of frequency, or the receiver system.

Figure 3 and Figure 4 show the distribution of Phase-A sources and Phase-B sources, respectively. Most Phase-A sources have now been observed. We can see there are two holes in the plots beside 200 degrees of ecliptic longitude. In the PMN surveys, these small regions were severely affected by solar contamination when the sidelobes of the antenna were encountering the Sun, so those data have been expunged from the survey [1]. In the next VEPS sessions, we will try to fill the two holes with sources from other radio catalogs.

In order to finish the survey of the remaining sources, an additional 400 hours of observing time will be required. We expect that Sejong will have a better performance with improved SEFDs and that Hobart26 will use the DBBC2 2-Gbps mode.

5 High-Sensitivity Astrometry

As of April 2016, we have observed 73 ecliptic sources with the VLBA in three eight-hour segments at 2.3 and 8.6 GHz at 2 Gbps (project code: BS250). The targets are the weakest calibrators with a correlated flux density at baseline project lengths of 5,000 km in the range [30, 50] mJy. A priori positions of one half the targets were derived from single-band VLBI observations at 4 or 8 GHz. We scheduled each target in three scans that were 180 seconds long. Two targets have not been detected at S-band. Position uncertainties of 71 remaining targets before our VLBA observations were in the range of [0.8, 294] nrad with a median of 6.2 nrad. After our VLBA observations, the position uncertainties dropped to [0.7, 5.6] nrad, with a median of 1.8 nrad (see Figure 5).

Statistics of VLBI-detected sources within $\pm 7.5^\circ$ of the ecliptic plane are shown in Table 2. The number of known calibrators in the ecliptic plane is growing rapidly and reached 1,167 recently. Positions of only 23% have been determined with accuracy better than 1.5 nrad using S/X dual-band VLBI. Changes on 2016-04-01 with respect to 2016-02-01 are contributed by some VEPS, VCS9, and VCS-II experiments [2]. Changes on 2016-05-01 with respect to 2016-04-01 are contributed by the project BS250.

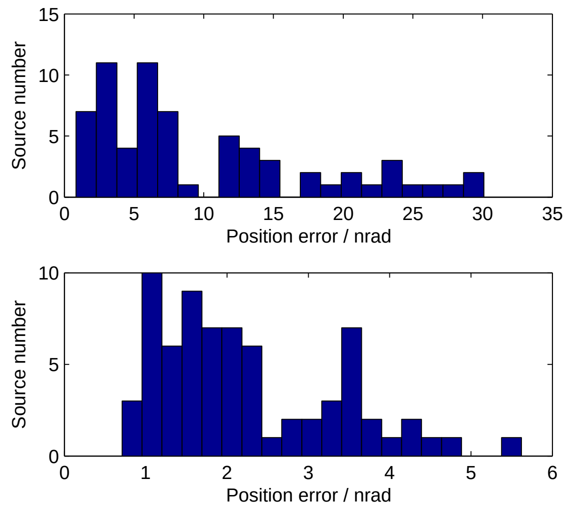

Fig. 5 Top: histogram of position errors of 71 sources before the VLBA observations. Please note that four sources with position errors larger than 35 nrad are not included in the statistics. Bottom: histogram of position errors of 71 sources after the VLBA observations.

In order to improve the positions of known calibrators, we plan to observe them with the VLBA, EVN, or IVS. In a more practical sense, it might be a good idea to form a high-sensitivity network with Asian and Oceanian antennas. In such a network, a compatible observing mode using S/X band at 2 Gbps needs to be defined and tested. With the inclusion of Tianma or Parkes, even the baselines to the small antennas of AuScope will have a sensitivity comparable to the VLBA.

6 Conclusions

The VEPS observations for detecting more ecliptic calibrators are running smoothly and have become routine work now. More than 400 sources have been detected on VLBI baselines for the first time.

Table 2 Statistics of sources detected with VLBI within $\pm 7.5^{\circ}$ of the ecliptic plane.

	2015-01-01	2016-02-01	2016-04-01	2016-05-01
# Calibrators with errors $<$ 1.0 nrad	130	133	143	155
# Calibrators with errors $<$ 1.5 nrad	187	191	261	293
# Calibrators with errors $<$ 2.0 nrad	279	283	405	449
# Calibrators with errors $<$ 2.5 nrad	336	349	479	533
# Calibrators with errors $<$ 3.0 nrad	402	423	518	574
# Calibrators with errors $<$ 5.0 nrad	521	549	625	681
Total # calibrators	772	969	1167	1167
Total # sources including non-calibrators	1154	1450	1710	1732

The VEPS observations for improving positions of known calibrators will benefit from a proposed high sensitive network with Asian and Oceanian antennas.

Acknowledgements

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