Amateur VLBI with DSLWP-B

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Joint work with Wei Mingchuan (HIT) and CAMRAS Dwingeloo Radiotelescope

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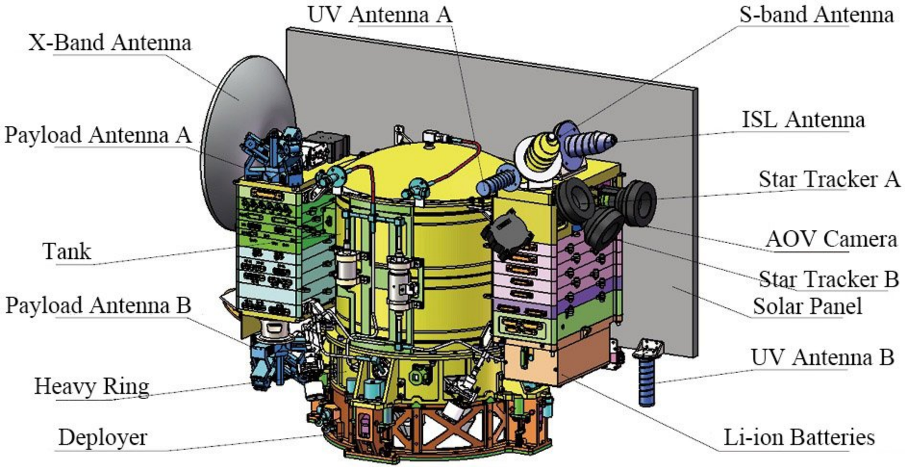
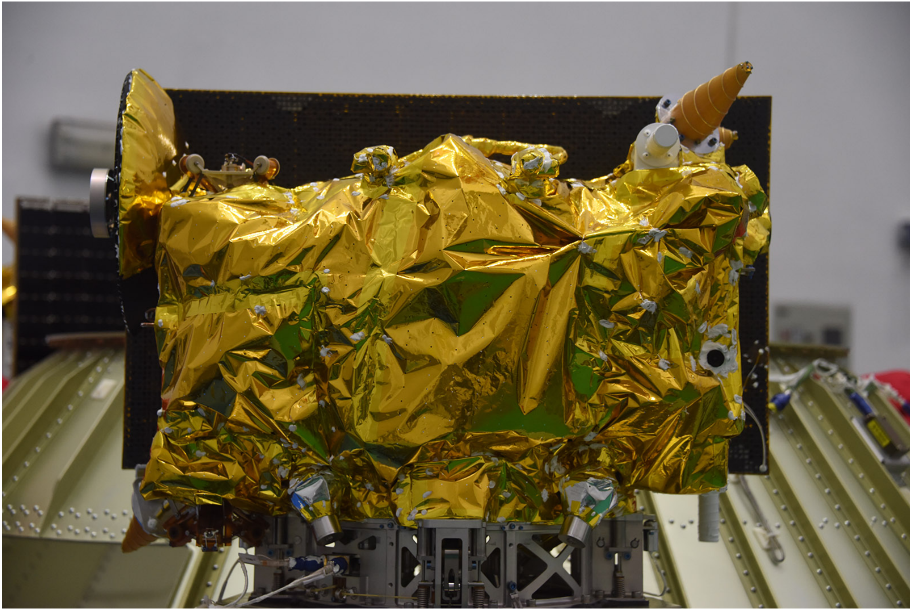
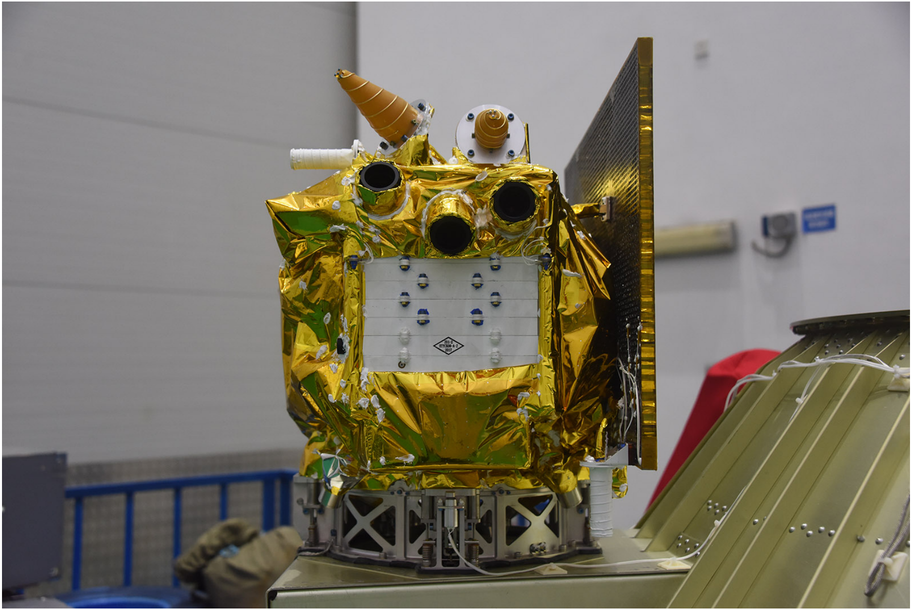
DSLWP-B

- Also known as Longjiang 2
- Lunar-orbiting microsatellite built by Harbin Institute of Technology
- 50x50x40cm, 45kg
- Launched to the Moon on 25 May 2018 with Queqiao and DSLWP-A (lost)
- Main mission: HF interferometry for radioastronomy
- Amateur payload: radio transceiver and camera
- End of mission on 31 July 2019 (deliberate collision with Moon)


UV Antenna A
S-band Antenna
X-Band Antenna
Payload Antenna A
ISL Antenna
Star Tracker A
Tank
AOV Camera
Star Tracker B
Payload Antenna B
Solar Panel
UV Antenna B
Heavy Ring
Deployer
Li-ion Batteries



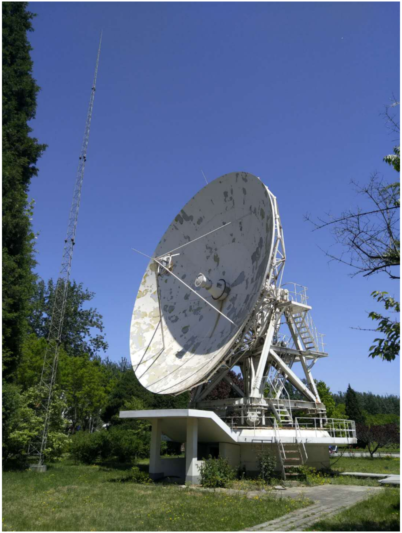


DSLWP-B Amateur payload

- Project led by Wei Mingchuan BG2BHC
- Participation around the world during the mission: Dwingeloo radiotelescope (The Netherlands), Wakayama University (Japan)...
- TX: 435MHz, RX: 145MHz.
- Camera (Inory Eye). SSDV used for image transmission.
- Main groundstations for RX: Dwingeloo PI9CAM (The Netherlands), 25m dish. Shahe (Beijing), 12m dish, Harbin BY2HIT, 8x 15-element yagi.
- Main groundstation for TX: Reinhard Kuehn DK5LA (Germany), 8x 32-element yagi.
- Modulations:
  - GMSK at 250 or 500 baud with $r = 1/2$ or $r = 1/4$ Turbo code. Telemetry and SSDV.
  - JT4G. Short telemetry and message repeater
- Telecommand by Amateurs: Message retransmission through JT4G repeater & Camera control

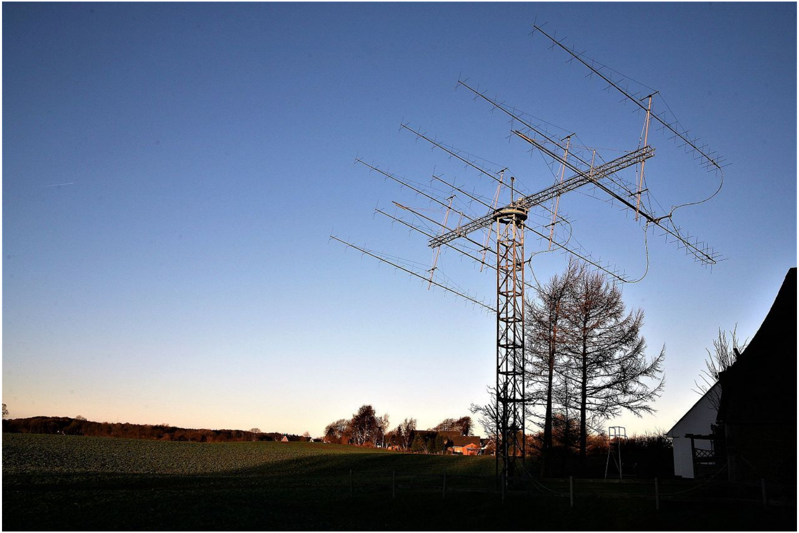
Dwingeloo

Shahe



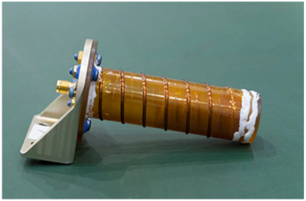
Harbin

Reinhard Kuehn



Amateur payload antennas

- Short bi-band double helix
- Linear polarization
- Peak gain: 0dBi at UHF, -9dBi at VHF



VLBI

- VLBI $=$ Very Long Baseline Interferometry
- *Interferometry:* comparison of the signals received by several stations (often adding or multiplying them, so they interfere)
- *Baseline:* the distance between stations
- *Very Long:* thousands of kilometres. Stations in different parts of the planet.

Introduction to VLBI

- Goal: Measuring the time difference of arrival of a signal to two (or more) stations
- As the speed of light in free space is c, this gives us the difference of distances between the transmitter and each station
- We also measure the difference of frequencies (or phases) of the signals observed by each station
- Due to the Doppler effect, this gives the difference of line-of-sight speeds between the transmitter and each station

VLBI in radioastronomy

- We can assume that astronomical objects are at infinity (very far), so their rays arrive to Earth parallel
- Since the rays are parallel, the time difference of arrival depends only on the angle between the rays and the line joining both stations
- In this way it is possible to enhance the angular resolution of observations
- Angular resolution of a radiotelescope: 10^{-1} deg
- Angular resolution of VLBI: 10^{-9} deg

VLBI for lunar satellites

- The Moon is far (380000km), but not far enough
- The rays do not arrive to Earth parallel
- Interpreting the observations is not as easy as in radioastronomy (angle of arrival)
- Using measurements from 4 or more stations it is possible to determine the position and velocity of the satellite
- VLBI measurements can be used for orbit determination, even using only 2 stations

Amateur VLBI in practice

- To compare observations made at different stations it is necessary to use synchronized receivers
- For DSLWP-B we have used USRP SDR receivers synchronized to GPS (using 1PPS and 10MHz).
- The Amateur payload signals are observed simultaneously with several stations and the data is stored as IQ sample files for later processing
- The signals from DSLWP-B are weak. To have good SNR, large antennas are needed.

Group and phase measurements

- Time difference of arrival measurements use the modulation of the signal (group delay)
- The precision of these measurements depends on the symbol rate
- GPS 1.023Msym/s, symbol length 293 metres. Measurement precision around 1 metre.
- DSLWP-B 250 or 500 sym/s, symbol length 1199km or 600km. Precision 2000 times worse than GPS.

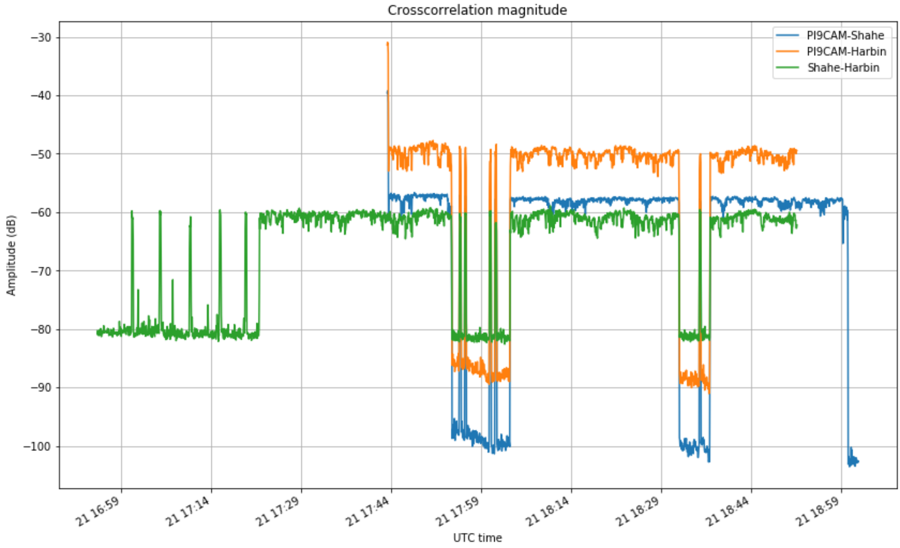
- Frequency or phase difference measurements use the carrier of the signal (phase delay)
- The precision of these measurements depends on the carrier frequency
- GPS 1575.42MHz. Wavelength 19cm. Sub-cm precision.
- DSLWP-B 436.4MHz. Wavelength 69cm. Only 3.6 times worse than GPS.
- Phase measurements are ambiguous (unknown integer number of cycles) and often require frequency stability of the transmitter
- However, Doppler can be used for very precise velocity measurements
- *Conclusion:* For DSLWP-B, velocity measurements are much more precise than distance measurments

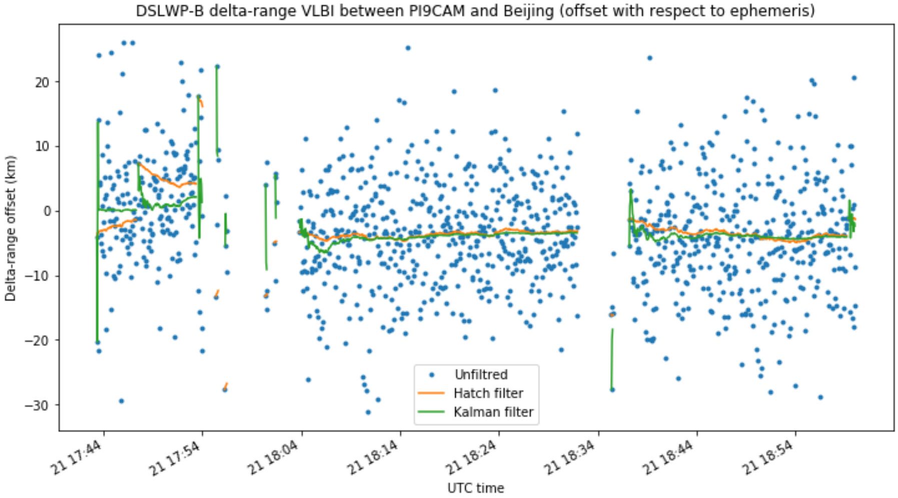
November 2018 VLBI experiment

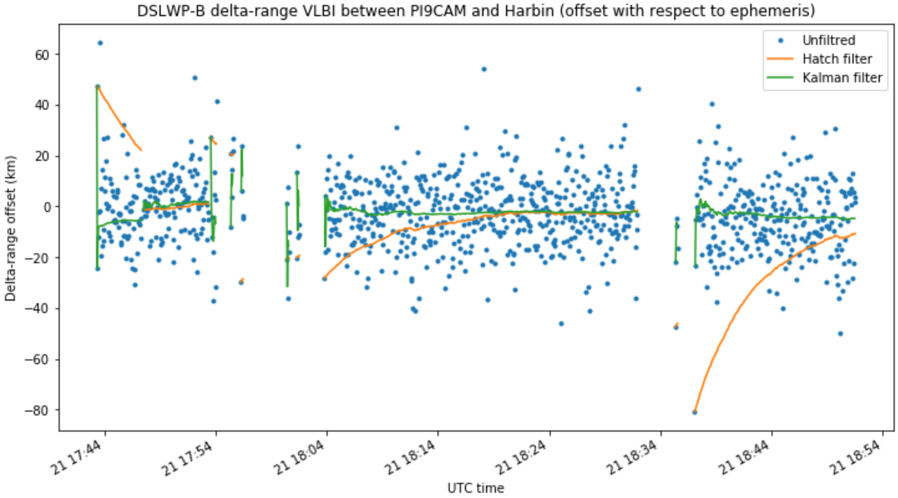
- 21 November 2018
- Receiving stations: Dwingeloo (PI9CAM), Shahe and Harbin
- Signals: 500baud GMSK at 436.4MHz with SSDV (also some short beacons at 435.4MHz)
- Three SSDV transmissions available, each lasting around 30 minutes

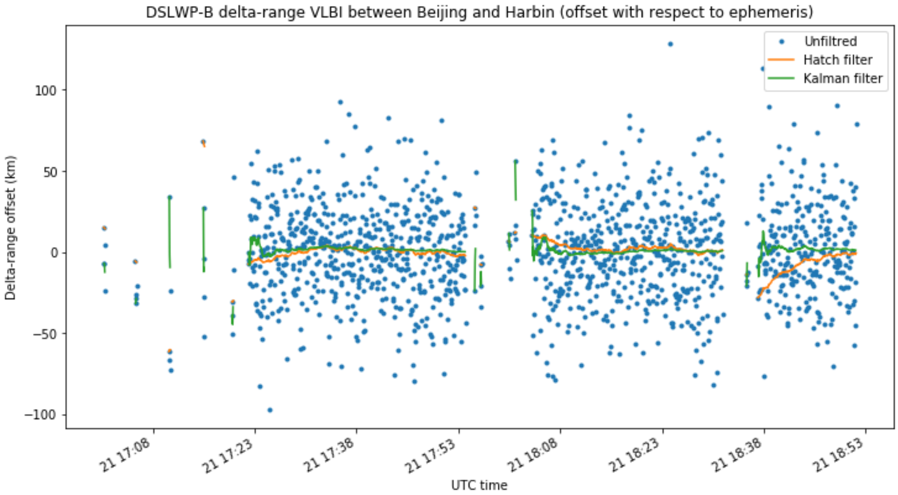
Signal processing

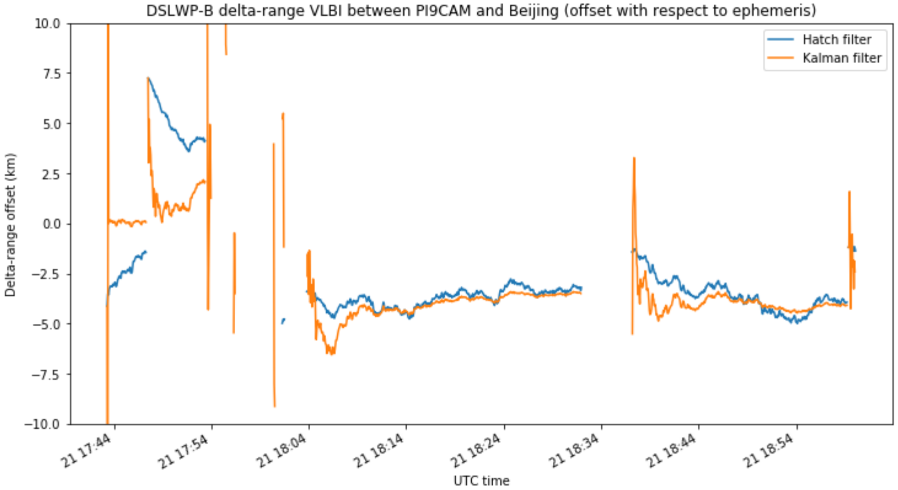
- Each long SSDV transmission is used to obtain “continuous” measurements (important for phase measurements)
- Coherent integration time of 3 seconds
- Measurments of delta-range using code (group delay) and phase.
- Delta-velocity is computed derivating the phase measurements.
- Filtering of the code measurements using the delta-velocity measurments:
  - Hatch filter (simple “1 pole IIR”-like filter well known in the GNSS literature)
  - Kalman filter
- Comparison of the results with a GMAT orbit simulation using Chinese DSN ephemeris

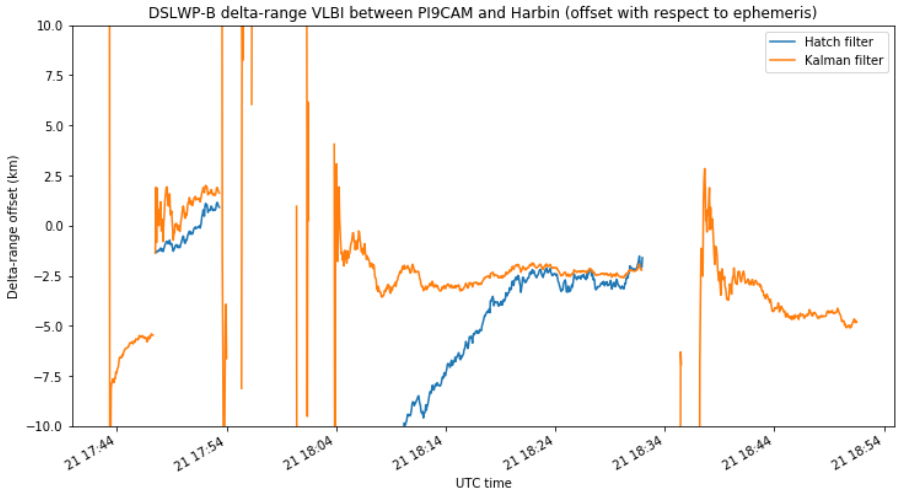

Crosscorrelation magnitude
PI9CAM-Shahe
PI9CAM-Harbin
Shahe-Harbin
Amplitude (dB)
−30
−40
−50
−60
−70
−80
−90
−100
21 16:59
21 17:14
21 17:29
21 17:44
21 17:59
21 18:14
21 18:29
21 18:44
21 18:59
UTC time

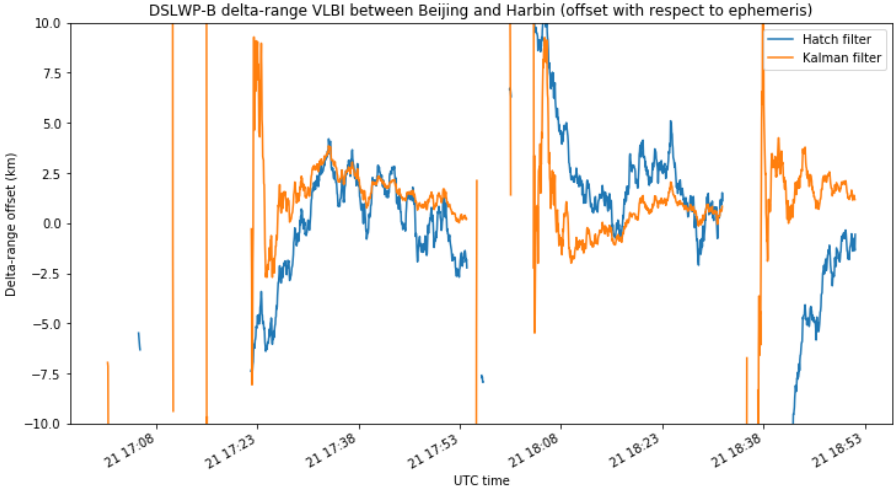

DSLWP-B delta-range VLBI between PI9CAM and Beijing (offset with respect to ephemeris)
Delta-range offset (km)
20
10
0
−10
−20
−30
Unfiltred
Hatch filter
Kalman filter
21 17:44
21 17:54
21 18:04
21 18:14
21 18:24
21 18:34
21 18:44
21 18:54
UTC time


DSLWP-B delta-range VLBI between PI9CAM and Harbin (offset with respect to ephemeris)
Unfiltred
Hatch filter
Kalman filter
Delta-range offset (km)
60
40
20
0
−20
−40
−60
−80
21 17:44
21 17:54
21 18:04
21 18:14
21 18:24
21 18:34
21 18:44
21 18:54
UTC time


DSLWP-B delta-range VLBI between Beijing and Harbin (offset with respect to ephemeris)
Unfiltred
Hatch filter
Kalman filter
100
50
0
−50
−100
Delta-range offset (km)
21 17:08
21 17:23
21 17:38
21 17:53
21 18:08
21 18:23
21 18:38
21 18:53
UTC time

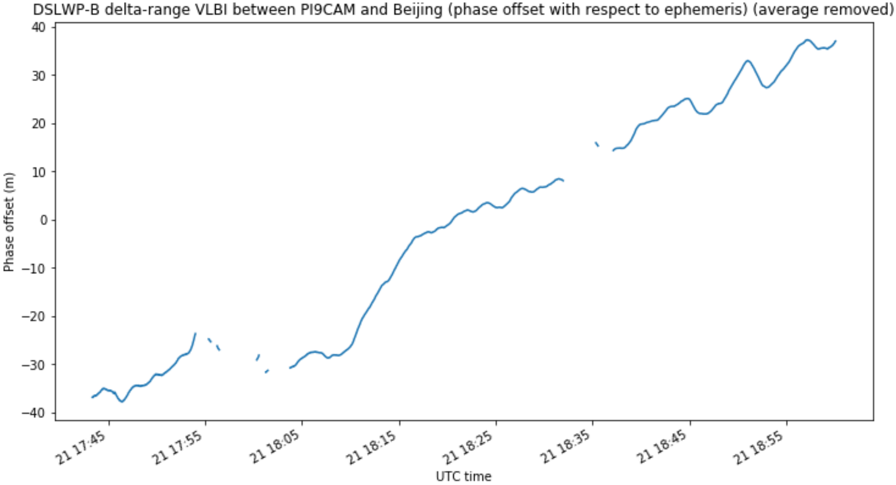

DSLWP-B delta-range VLBI between PI9CAM and Beijing (offset with respect to ephemeris)
Hatch filter
Kalman filter
Delta-range offset (km)
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
21 17:44
21 17:54
21 18:04
21 18:14
21 18:24
21 18:34
21 18:44
21 18:54
UTC time

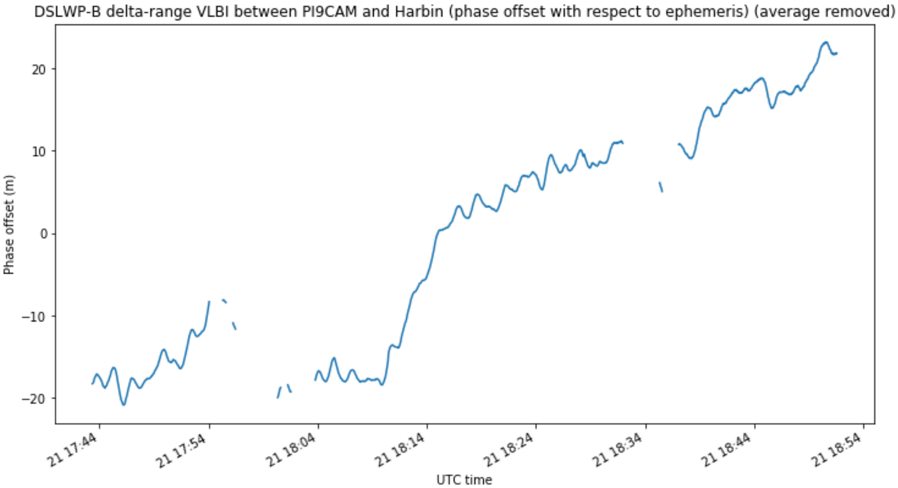

DSLWP-B delta-range VLBI between PI9CAM and Harbin (offset with respect to ephemeris)
Hatch filter
Kalman filter
Delta-range offset (km)
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
21 17:44
21 17:54
21 18:04
21 18:14
21 18:24
21 18:34
21 18:44
21 18:54
UTC time

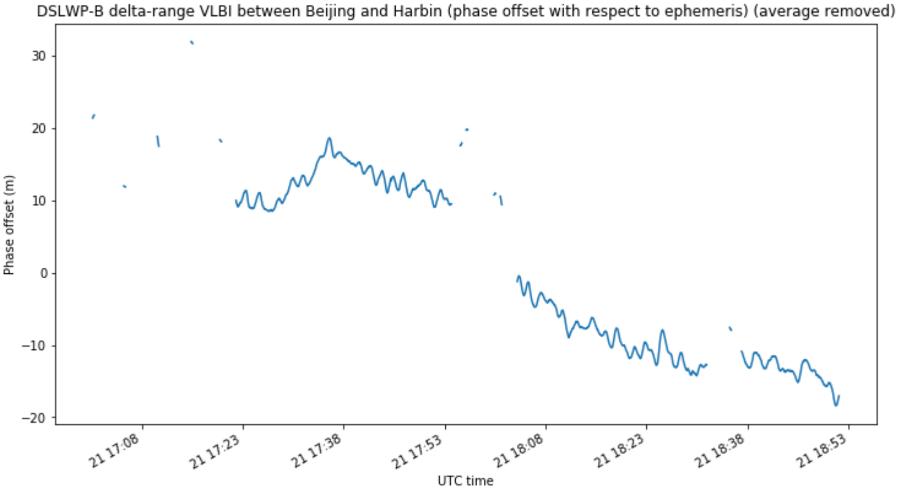

DSLWP-B delta-range VLBI between Beijing and Harbin (offset with respect to ephemeris)
Hatch filter
Kalman filter
Delta-range offset (km)
UTC time
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
21 17:08
21 17:23
21 17:38
21 17:53
21 18:08
21 18:23
21 18:38
21 18:53

Phase measurements

- Ambiguous: unknown integer number of cycles
- Can be used in two ways:
  - Accumulated phase: measures the delta-range (plus an unknown integer number of wavelengths)
  - Derivating: delta-velocity (Doppler) is obtained
- In accumulated phase measurements every error accumulates and the measurement diverges from the true value
- The transmitter needs to be stable in frequency. A small frequency error accumulates
- If the transmitter is stable enough and the group delay measurements are precise enough it is possible to determine and remove the ambiguity. For DSLWP-B it is very difficult to do this.


DSLWP-B delta-range VLBI between PI9CAM and Beijing (phase offset with respect to ephemeris) (average removed)
Phase offset (m)
40
30
20
10
0
−10
−20
−30
−40
21 17:45
21 17:55
21 18:05
21 18:15
21 18:25
21 18:35
21 18:45
21 18:55
UTC time


DSLWP-B delta-range VLBI between PI9CAM and Harbin (phase offset with respect to ephemeris) (average removed)
Phase offset (m)
20
10
0
−10
−20
21 17:44
21 17:54
21 18:04
21 18:14
21 18:24
21 18:34
21 18:44
21 18:54
UTC time


DSLWP-B delta-range VLBI between Beijing and Harbin (phase offset with respect to ephemeris) (average removed)
Phase offset (m)
30
20
10
0
−10
−20
21 17:08
21 17:23
21 17:38
21 17:53
21 18:08
21 18:23
21 18:38
21 18:53
UTC time

Transmitter frequency instability

- The error in delta-velocity is

$$\delta v = v\frac{\delta f}{f},$$

where v is the delta-velocity, δf is the error in frequency of the transmitter, and f is the nominal transmit frequency

- In a time interval $[0, T]$, we get an accumulated error in delta-range of

$$\delta r = (r(T) - r(0))\frac{\delta f}{f},$$

where $r(t)$ is the delta-range at time t.

- In the case of DSLWP-B VLBI observations, $r(T) - r(0) \approx 10^6$m, so a 1ppm frequency error produces a 1m accumulated error.

Outlook

- Still many observations to process (especially from the last month of the mission)
- Combination of phase observations at 435.4MHz and 436.4MHz to obtain a 300 metre wavelength (helps solving phase ambiguities)
- Using observation products for orbit determination
- VLBI observations of the signal reflected on the lunar surface?

References

- https://destevez.net/tag/dslwp/
- Wei Mingchuan https://twitter.com/bg2bhc
- People from CAMRAS Dwingeloo radiotelescope:
  - Cees Bassa https://twitter.com/cgbassa
  - Tammo Jan Dijkema https://twitter.com/tammojan/
- LilacSat and DSLWP webpage http://lilacsat.hit.edu.cn/