Accurate spacecraft positioning by VLBI imaging

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Outline

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2. VLBI imaging principle
3. Spacecraft phase-reference VLBI positioning experiments
4. Next plan
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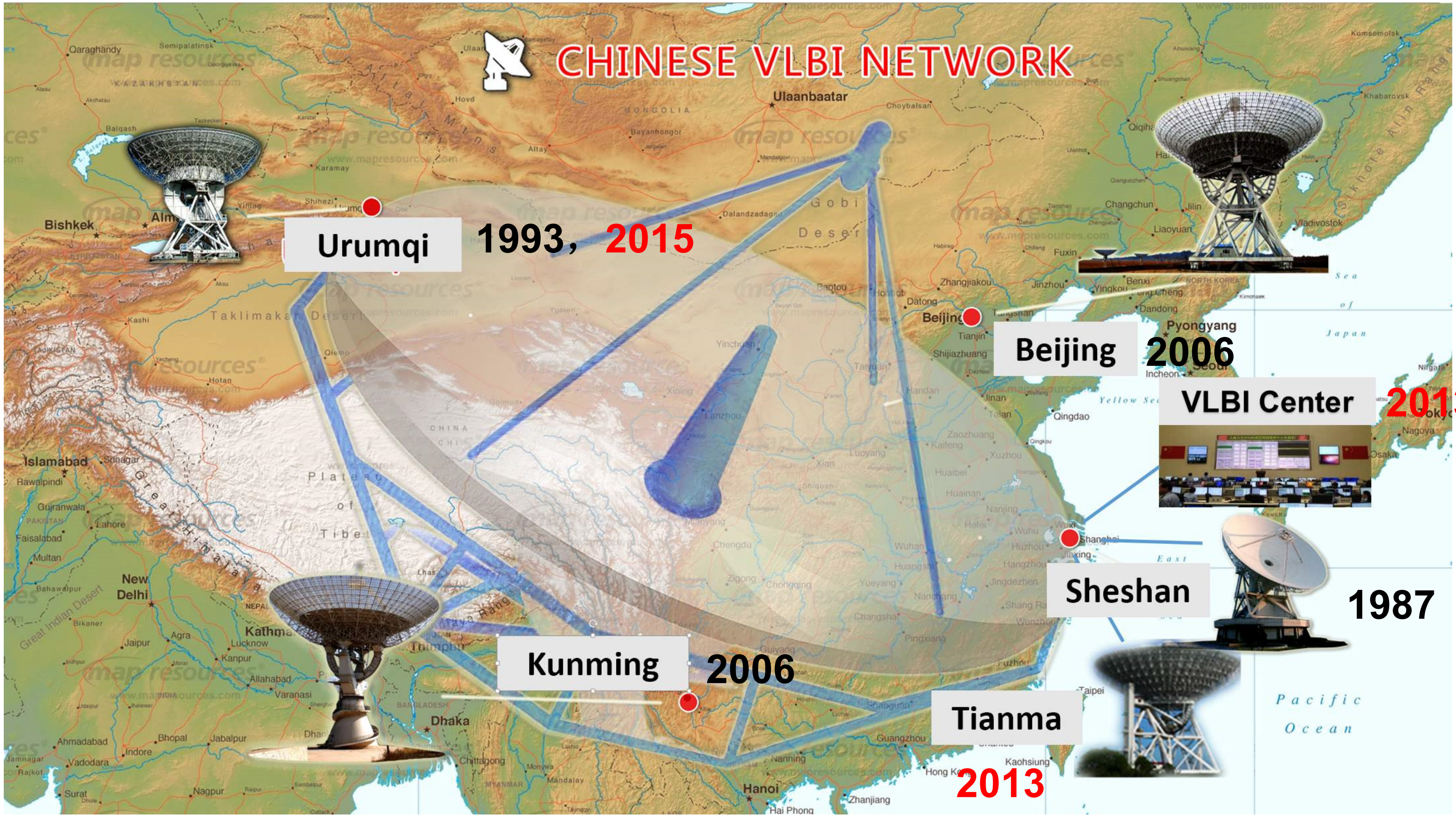
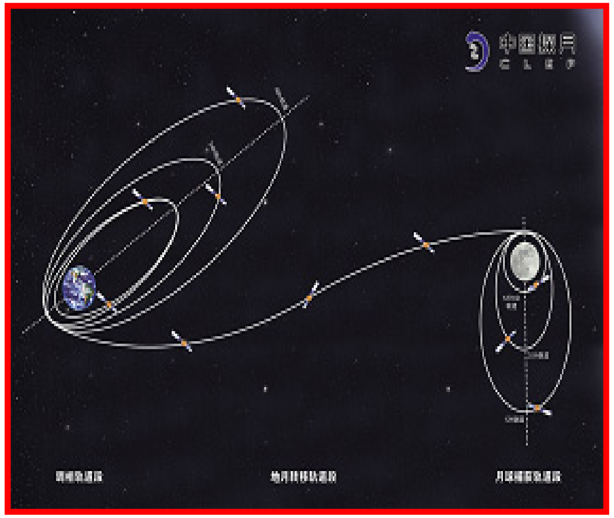
1. Background

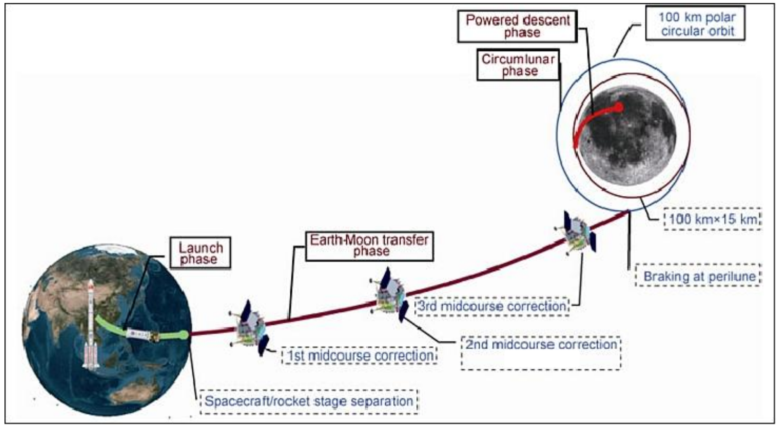


CVN supported CE lunar missions

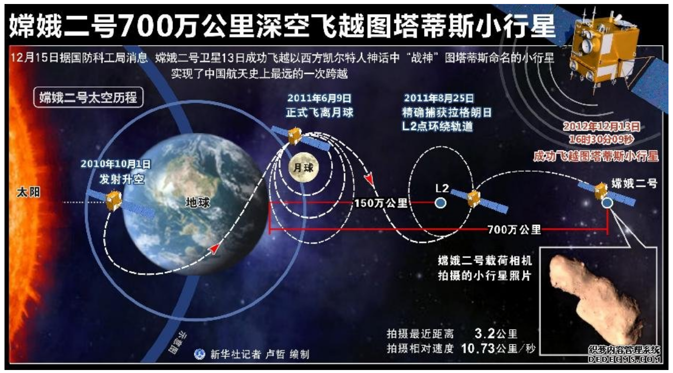
CE-1



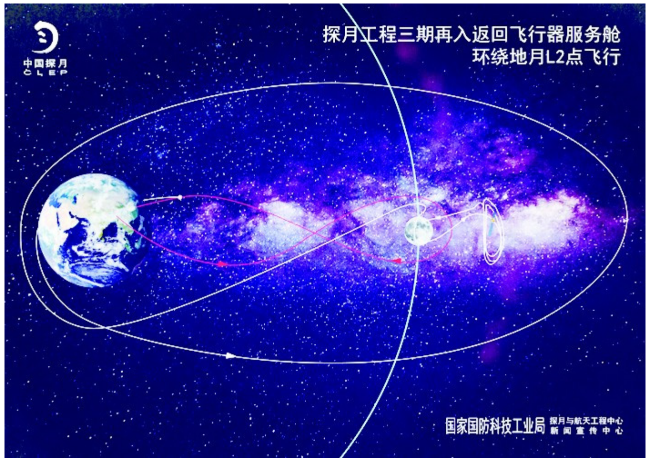
CE-3



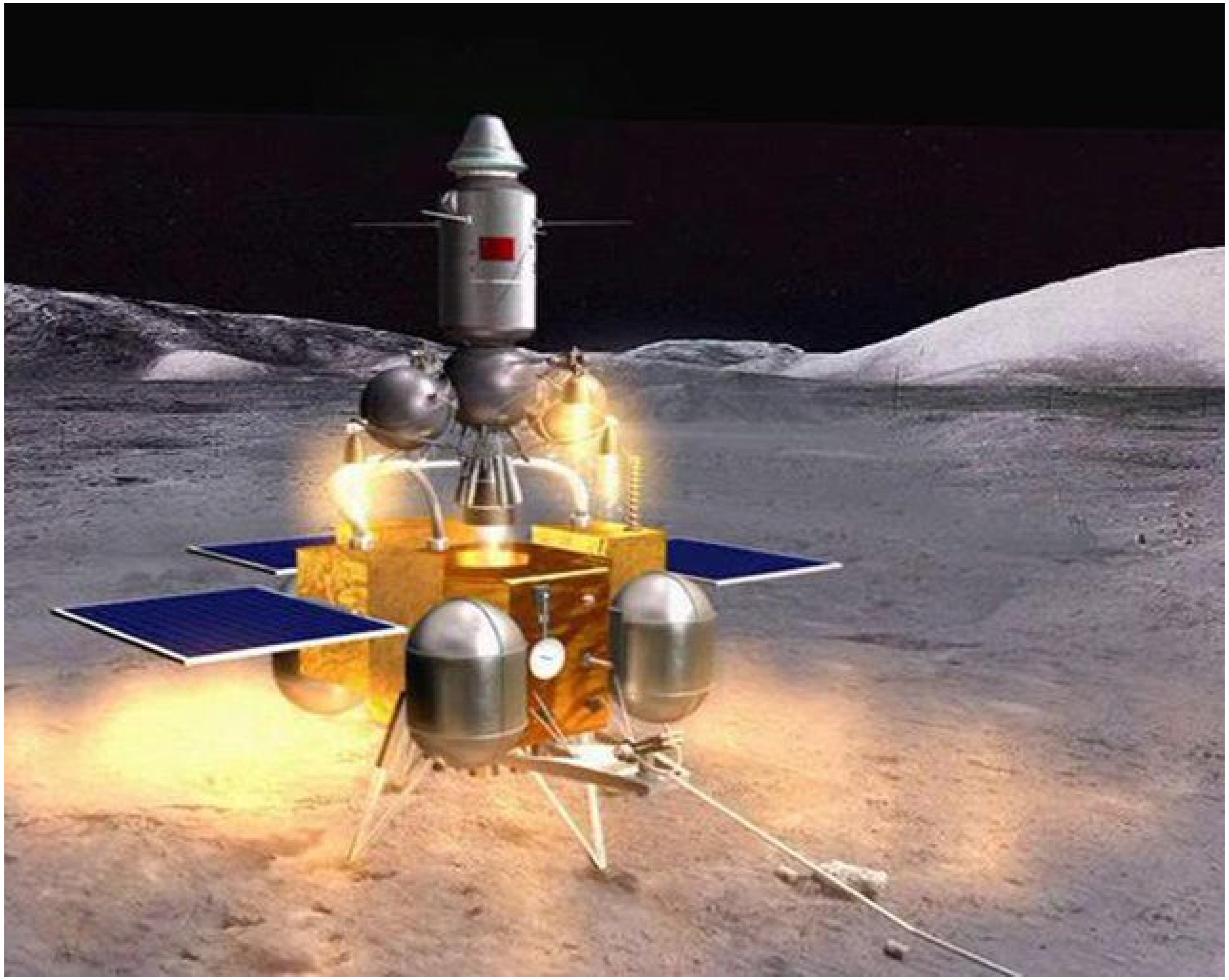
CE-2



CE-5T1



CE-5 landers need more accurate position



- **CE-3 lander moon surface absolute position accuracy <100m. （VLBI group delay + range）**

- **CE-5/Mars probe require more accurate position. (1mas~2m, Moon; 1mas~2km, Mars)**

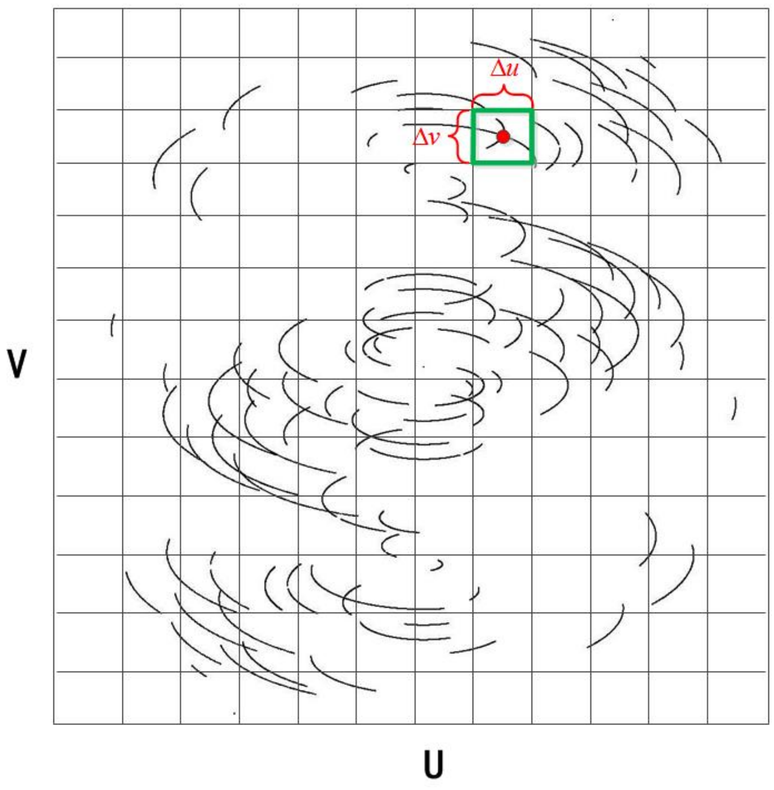
- **Phase reference VLBI imaging can reach <0.1mas-level accuracy in astronomy observations.**

- **mas-level spacecraft positioning by phase reference VLBI imaging is attractive.**

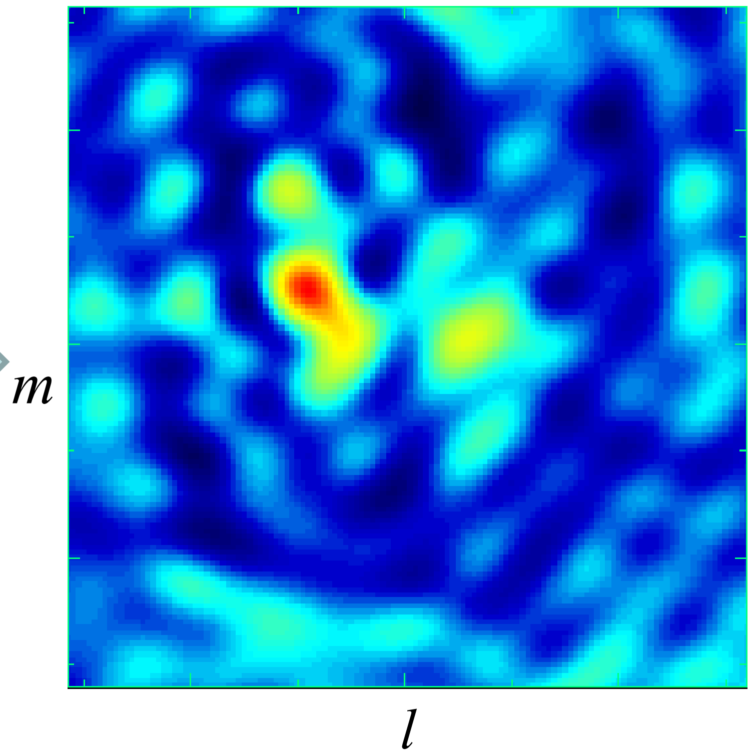
2. VLBI Imaging principle

$$V(u,v) = \iint I(l,m) \cdot e^{-2\pi i(ul+vm)}\,dxdy$$

$$\Rightarrow I(l,m) = \iint V(u,v) \cdot e^{2\pi i(ul+vm)}\,dudv$$



$$\begin{cases} \Delta u = (M \cdot \Delta l)^{-1} \\ \Delta v = (N \cdot \Delta m)^{-1} \\ \Delta l = (M \cdot \Delta u)^{-1} \\ \Delta m = (N \cdot \Delta v)^{-1} \end{cases}$$



uv sampling and imaging results

Phase-reference VLBI Imaging

- By phase reference VLBI method, target phase is calibrated by a reference source (calibrator).
- Nearby reference calibrator and fast switching.
- The calibrated target phase only contains phase caused by position offset.
- The center of the phase-reference image is the relative position of the probe to the calibrator with high accuracy.

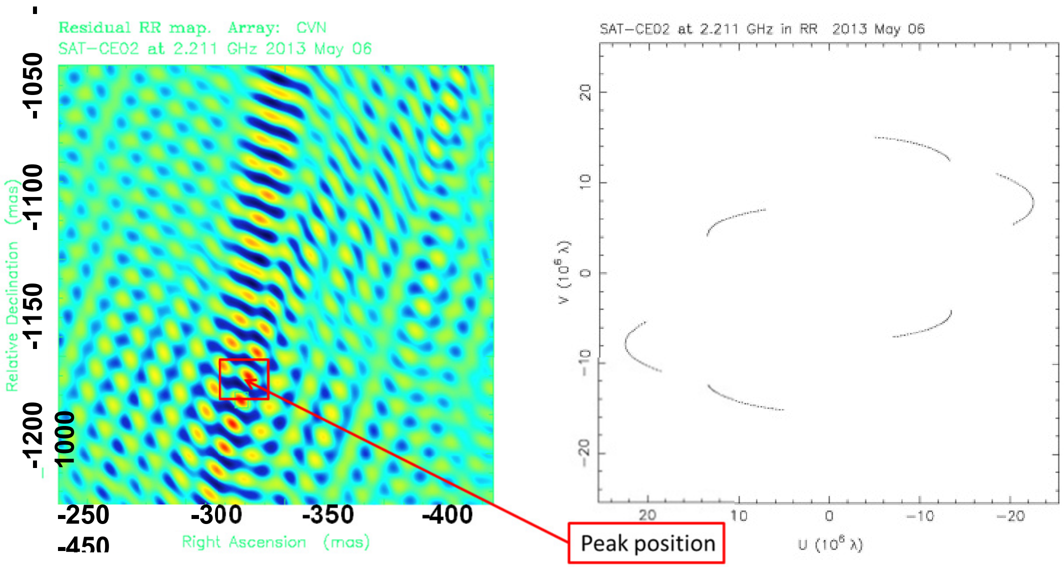
- **Spacecraft: switching cycle time ＜4min, and separation angle ＜5° for X-band.**
- **The accuracy of far/near field VLBI time delay value will affect the phase-reference VLBI results.**
- **CVN, hundreds of ps time delay error will cause tens of mas positioning error.**
- **Accurate far/near field time delay models of IERS(2010) and Sekido (2006).**
- **UVW is defined as W-axis point from the Geocenter to the observed target, U-axis point to the East, V-axis point to the North pole.**

3. Spacecraft phase-reference VLBI experiments

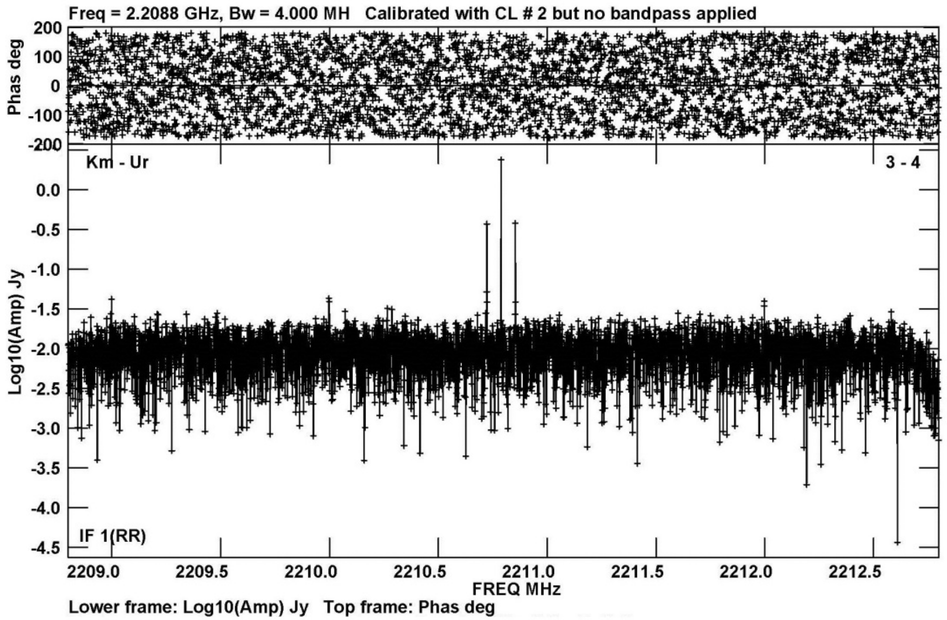
Spacecraft	Date	Session length	Distance from Earth	Frequency
CE-2	2013-05	~6h	~5x10^7 km	S band
CE-3	2013-12	~30h(5 positions)	~4x10^5 km	X band
CE-5T1	2014-12	~6h	~4x10^5 km	X band
MEX	2015-01	~2h	~1.9895AU	X band
Rosetta	2015-09	~10h	~1.7889AU	X band

$$1AU = 1.49597870699626200 \times 10^8 km$$

CE-2 vs. 0952+179



CE-2 phase-reference results and UV coverage



Received CE-2 signal

Distance from earth:

$\sim 5 \times 10^7 \, km$

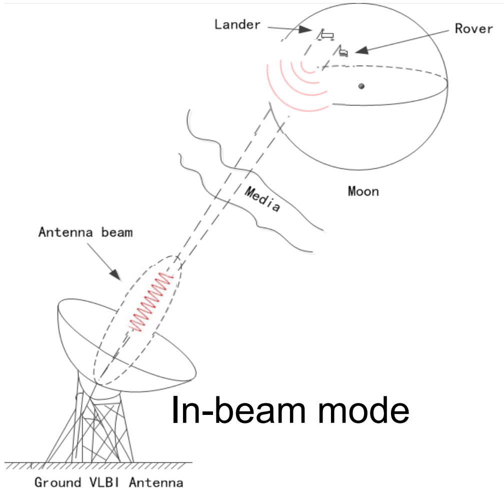
Separation angle: $< 7^\circ$

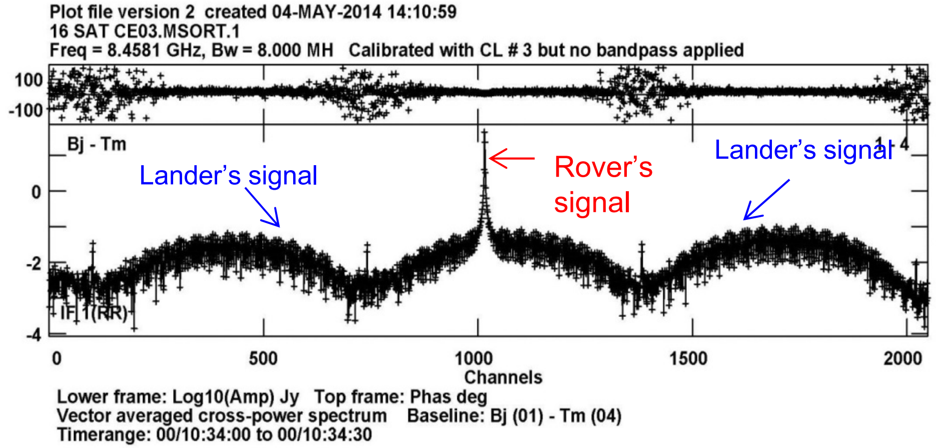
@ S-band

Station: SH、KM、UR

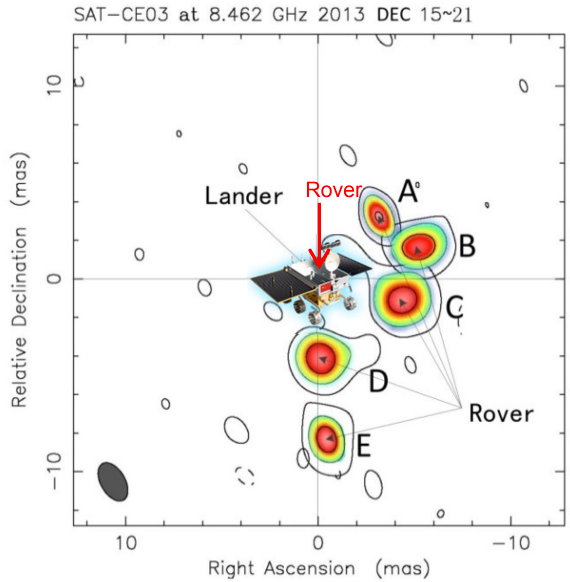
- ~4h observation data
- Results is consistent with CE-2 orbit determination (~10km)
- Correlator: SCORR
  -- CVN software correlator

CE-3 In-beam observation of Lander and Rover





Received signal of lander and Rover

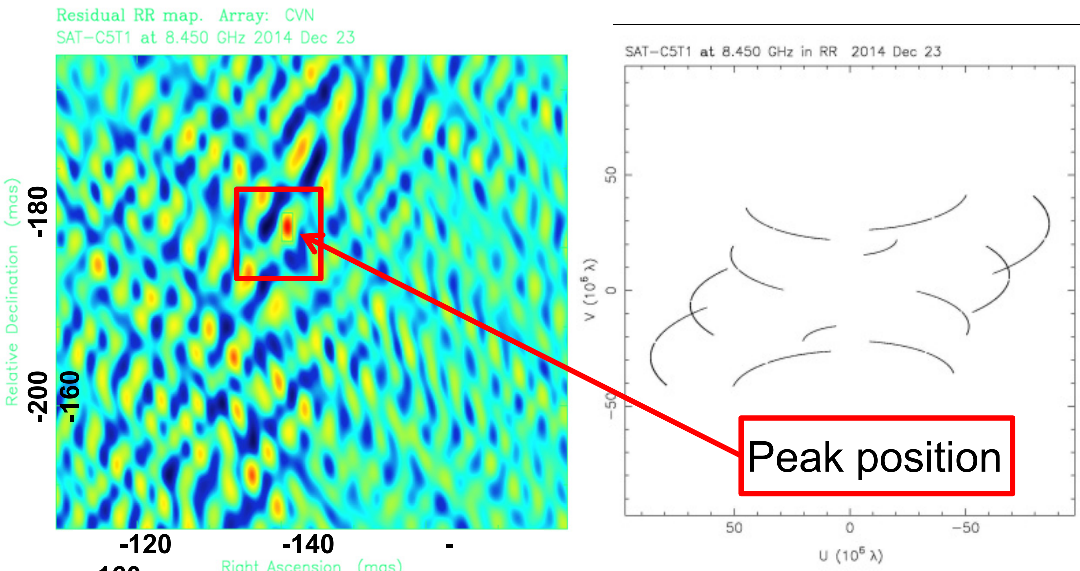


The accuracy of the relative position between Lander and Rover is ~1m (0.5mas).

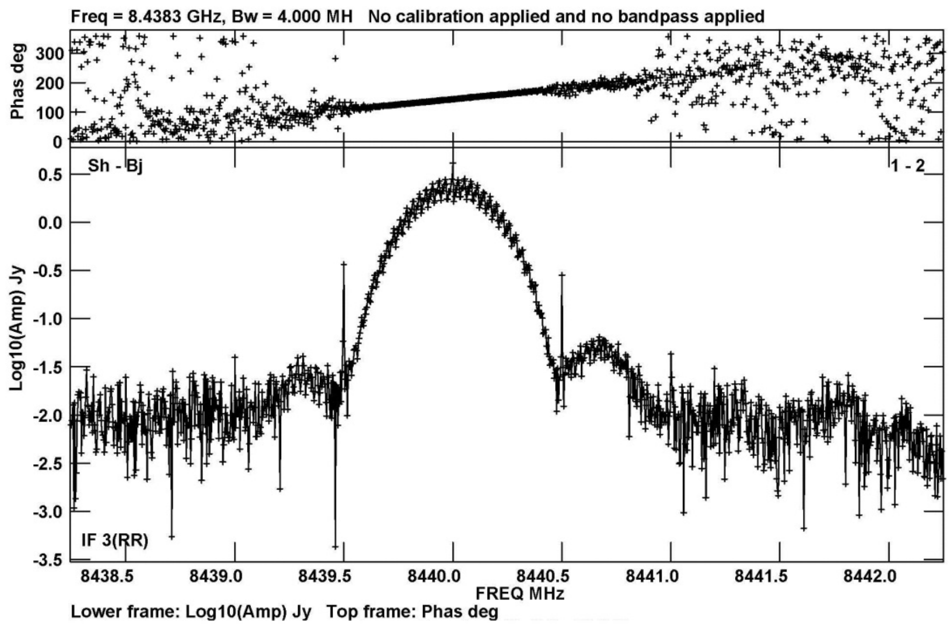
CE-3 phase-reference imaging results

3-D positioning method using imaging results

CE-5T1 vs. 1920-211



CE-5T1 phase-reference results and UV coverage



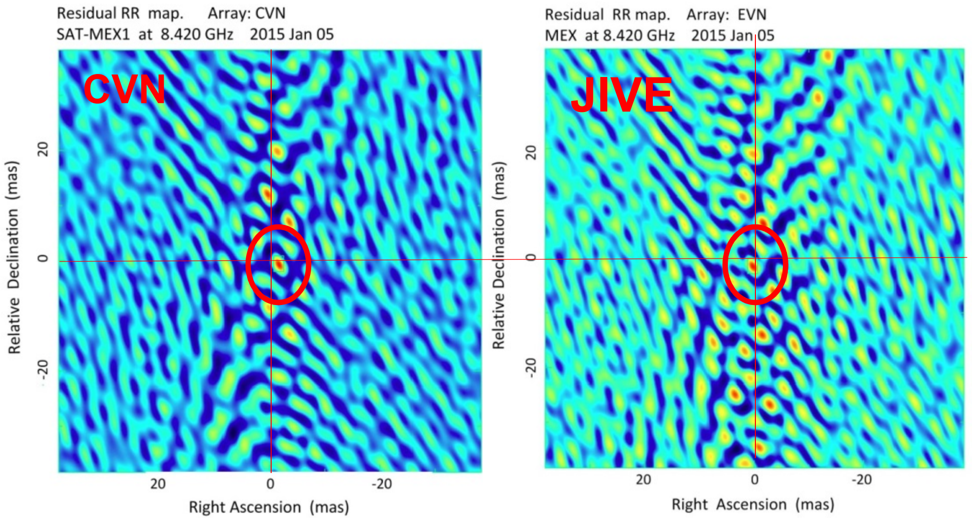
Received CE-5T1 signal

- Distance from earth: ~3.8×10⁵km

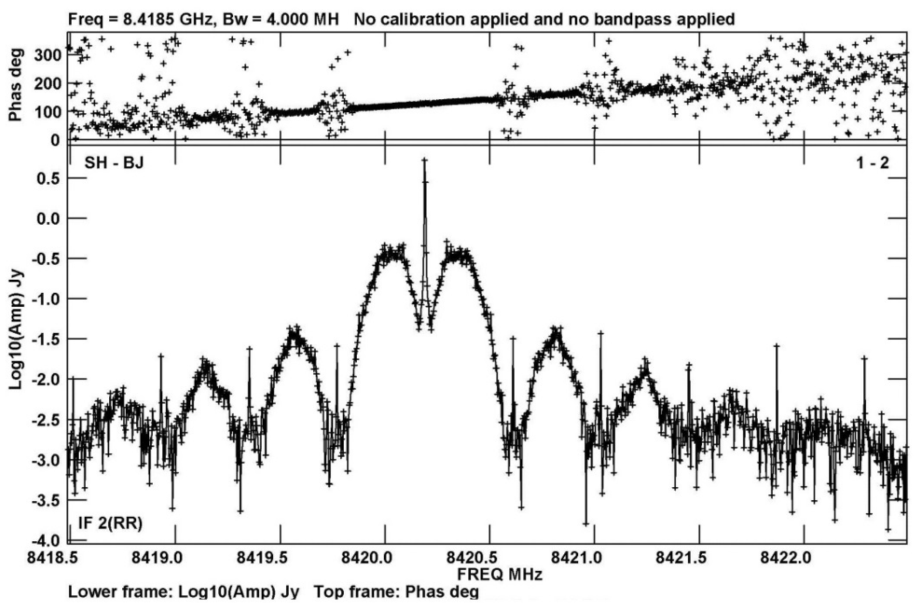
Separation angle:<1.3°
@X-band

- Station: SH, BJ, KM, UR
- ~2h observation data
- Results is consistent with CE-5T1 orbit determination (~100m)
- Correlator: SCORR

MEX and 2155-152



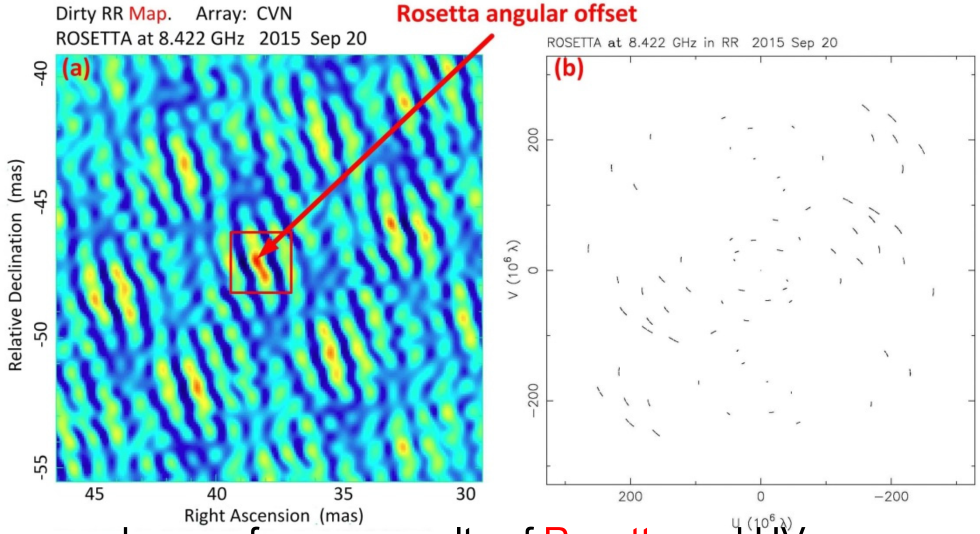
CVN and JIVE phase-reference results of MEX



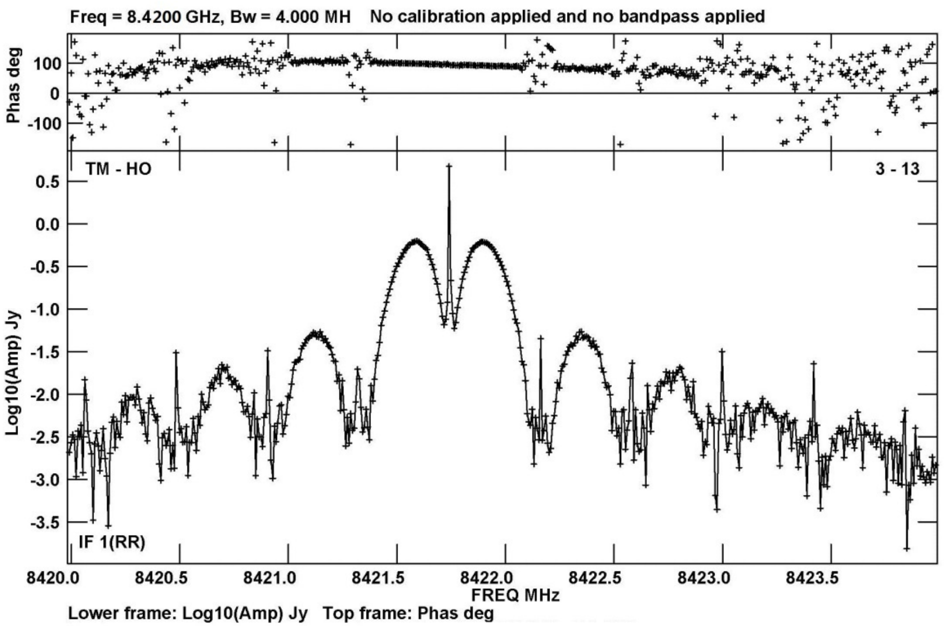
Received MEX signal

- Distance: ~1.9895AU
- Separation angle: ＜2.5° @ X-band
- SH, BJ, KM, UR, BD joined
- ~1.5h VLBI observation data
- Both CVN and JIVE results keep consistence with MEX precision orbit ~1mas
- Correlator: SCORR & SFXC

Rosetta vs. OJ287



phase-reference results of Rosetta and UV coverage

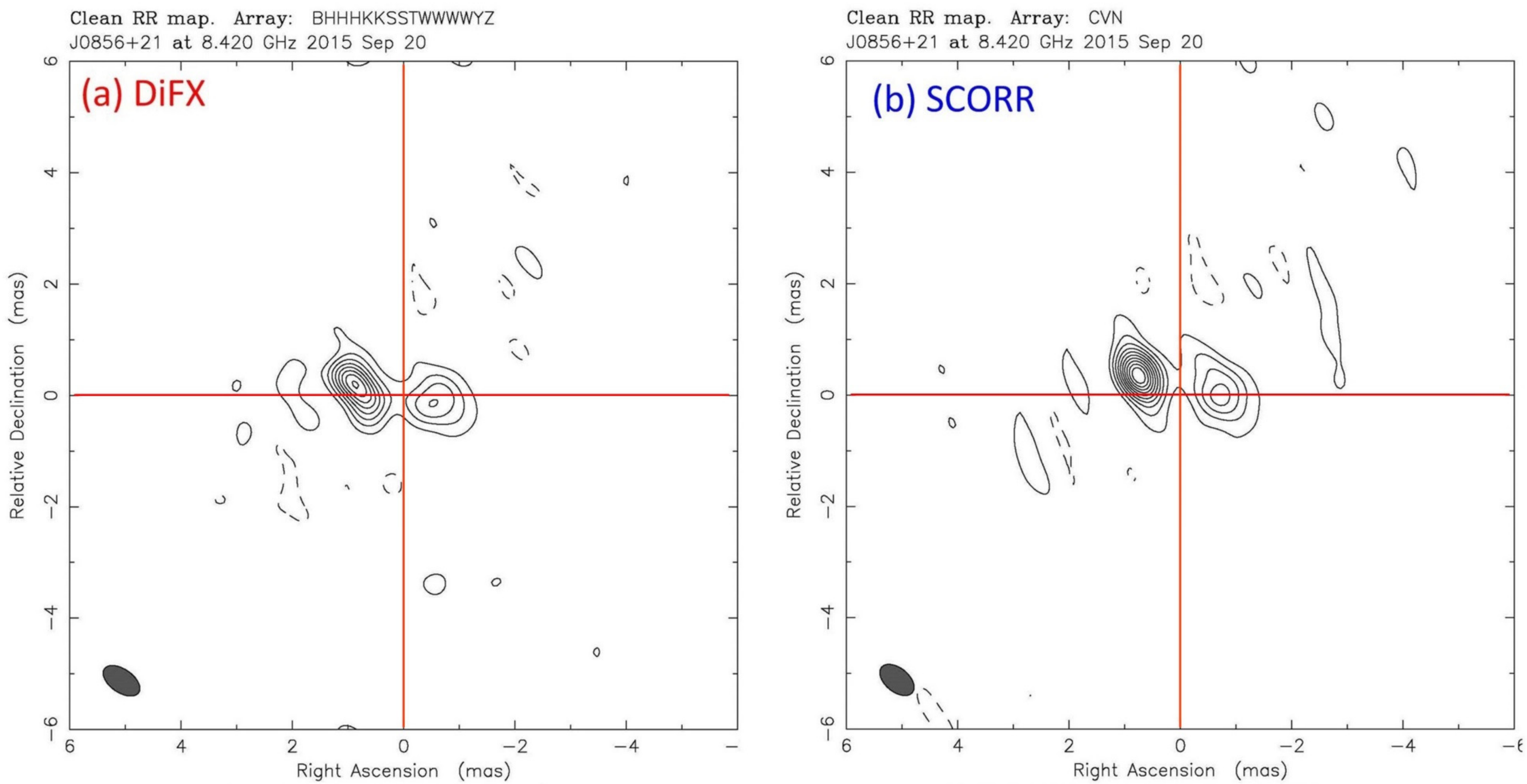


Received Rosetta signal

Distance: ~1.7889AU

- ✓ SH, KM, TM;SV, ZC, BD; WW, WA; HT, HH; KE, YG, HO; WZ, WN
- ✓ Separation angle: ＜1.3° @ X-band
- ✓ Total observation time is ~10h, left figure just use ~30min data
- ✓ The result is almost the same compared with Rosetta orbit accuracy
- ✓ Correlator: SCORR

Clean image J0856+2111 vs. OJ287 in Rosetta session



Discrepancy of SCORR and DiFX results ~0.1mas

SCORR far-field delay accuracy is the same level of DIFX

4. Next plan

- Chinese lunar probe lander CE-3 imaging experiment.
- IVS session?
- Lunar lander absolute position hopes to reach meter level or better.
- Long time observation perhaps can improve Lunar ephemeris?

5. Summary

- CVN spacecraft phase reference VLBI imaging can obtain mas-level positioning results.
- Phase-reference VLBI doesn’t need special designed radio beacon.
- Observation session is not very long.
- Phase reference VLBI imaging applies in lunar/Martian surface lander high accuracy positioning in the future .

Acknowledgment

- JIVE – result comparison
- HT, HH; SV, ZC, BD; KE, YG, HO; WZ, WN; WW, WA – observations
- Dr. Sergei Pogrebenko

Thanks for your attention!