VLBI Delay Reduced from S/C Observation and its Calibration in Chang'E Mission

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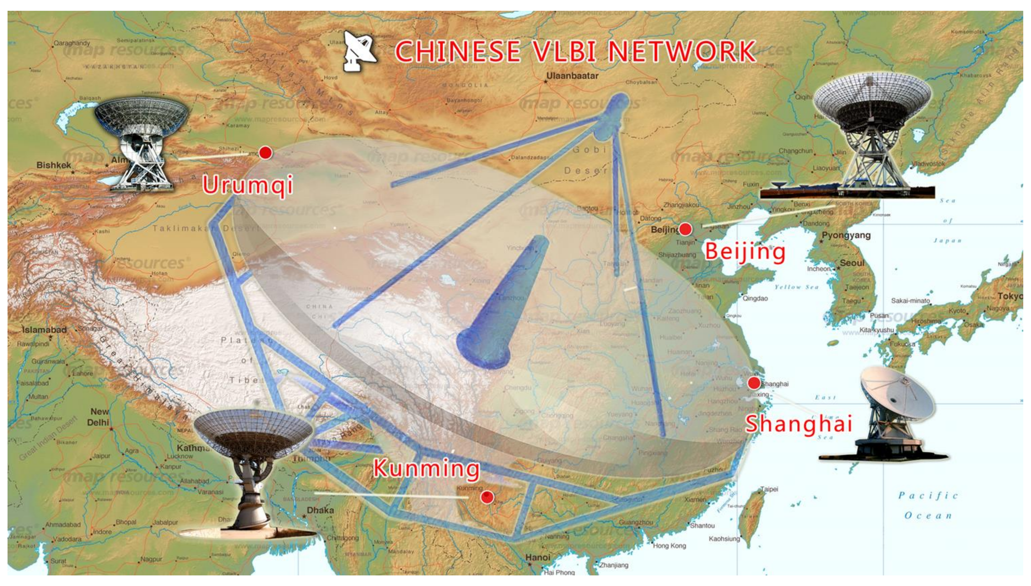
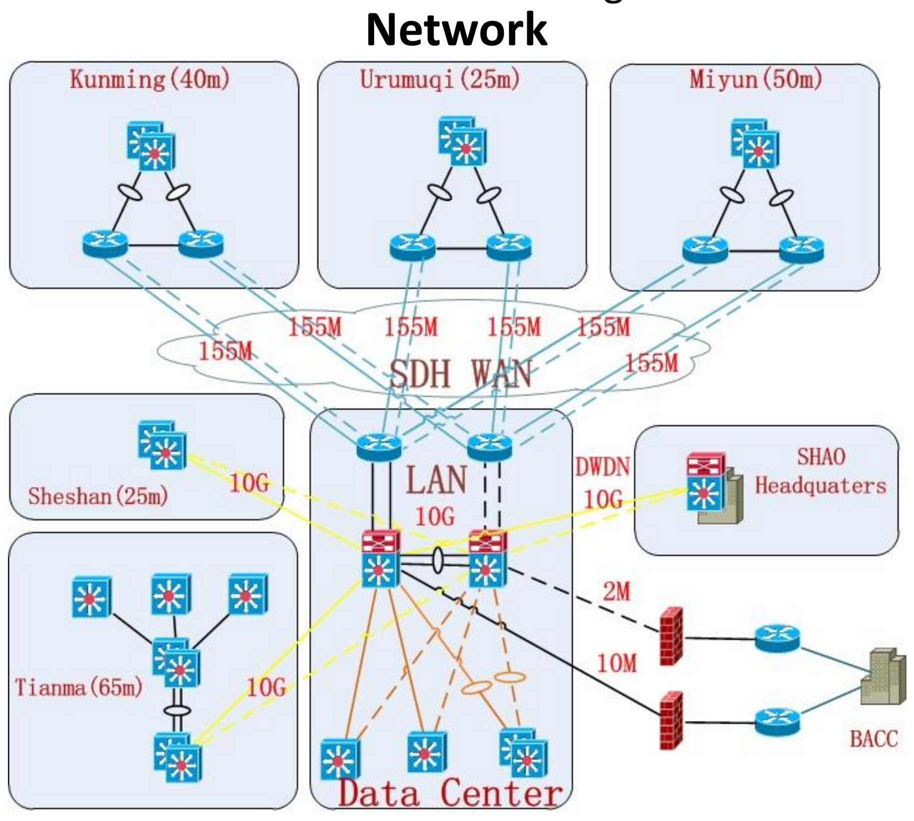
1. Background: VLBI Applied in China's Lunar Exploration Project



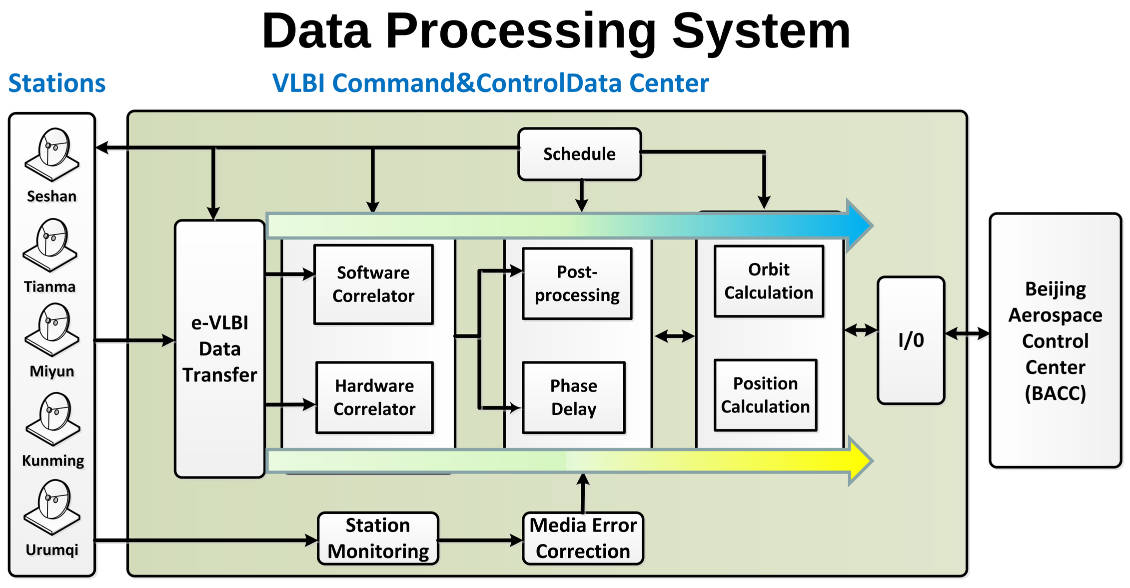
VLBI technique was used in China's Lunar Exploration Project Since the Chang'E-1 launched in the year of 2007, after then VLBI was played an important role in the series of Chang'E missions, CE-2, CE-3 and CE-5T1, and will be continued in the future space mission. The observation network consists of Shanghai 25m&65m, Beijing 50m, Kunming 40m and Urumqi 25m radio telescopes. Up to now it still works in the traditional astronomy-compatible S/X station systems , both quasar and S/C are observed in the same Frequency setup. In CE-1 & CE-2 the quasar and S/C switching rules are 15min quasar and 45min S/C, in CE-3 and thereafter are 5min switching.

Network



Five stations and a VLBI processing center operate together. During the mission, the whole system can work in real mode.

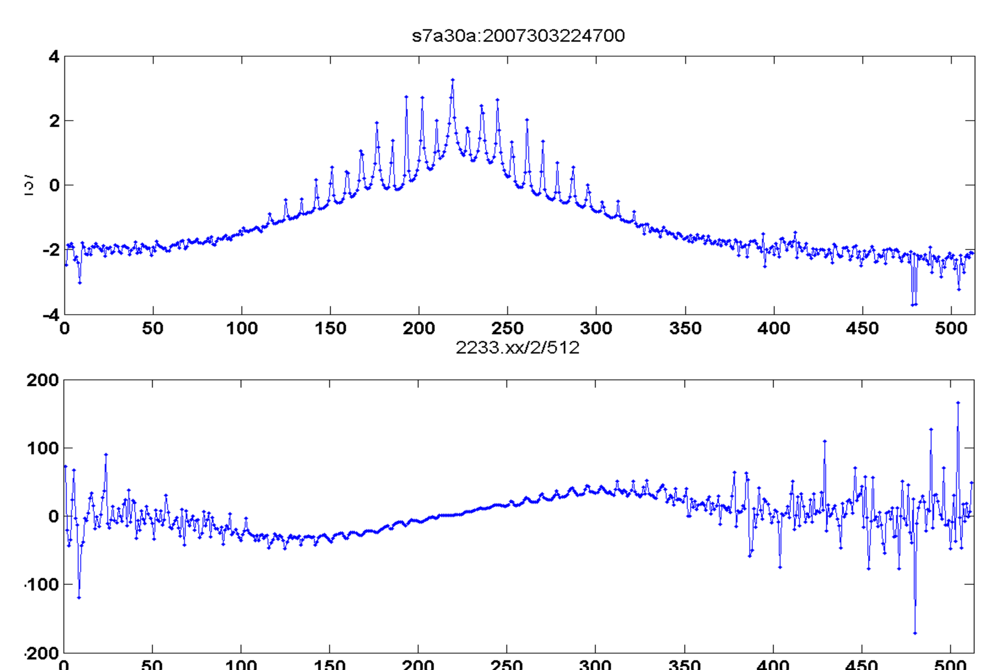
Data Processing System



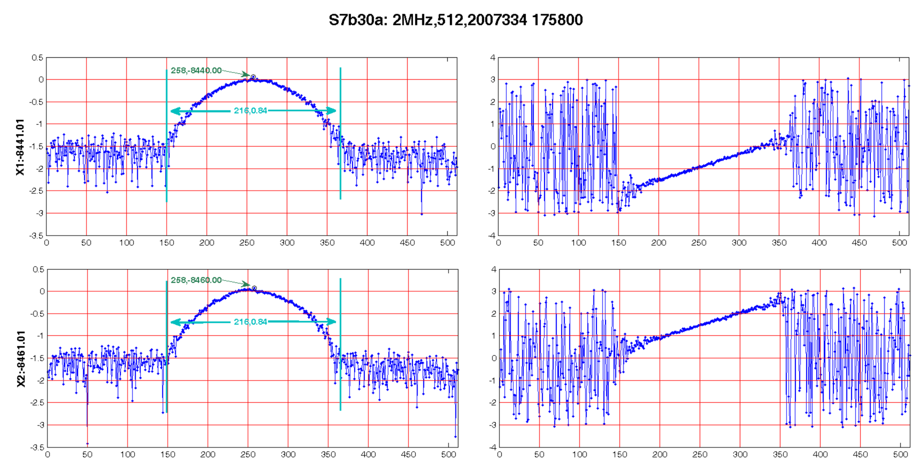
There are two parallel pipelines working in hot backup to improve the reliabilities. The VLBI system produces quasar-calibrated S/C delay and rate observations for orbit determination and positioning.

2. Delay reductions

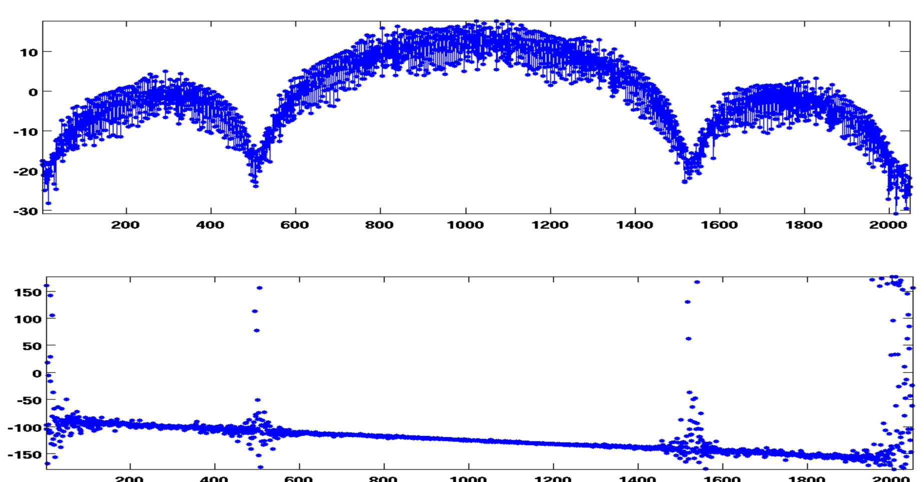
- Quasar delay is reduced in astronomical processing style.
- Different S/C signals are observed, and processing is different as well.



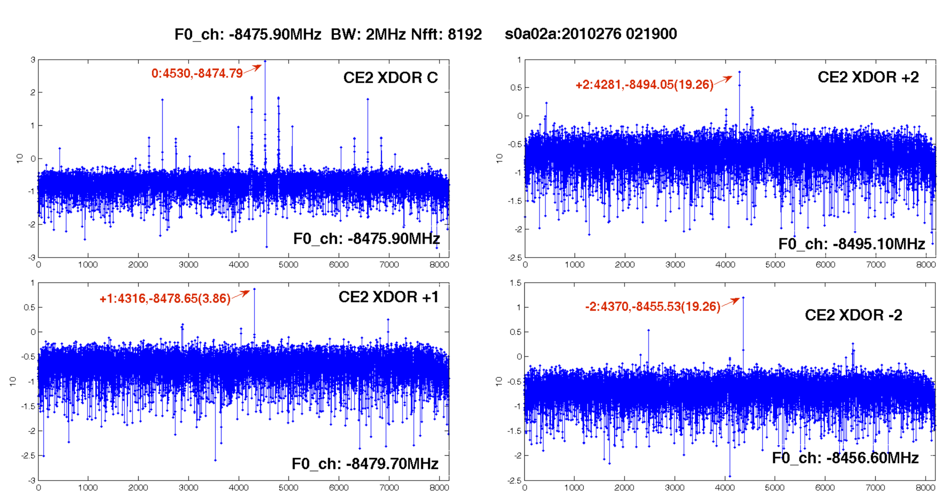
S/C TT&C signal@S Band. Upper:Freq vs Amplitude, Lower:Freq vs Phase. In CE-1&CE-2 VLBI delay reduced from this kind of signals in real mode. It looks phase varies non-linear with frequency, and practice shows the non-linear effect has relationship with apriori orbit error in some degree. SNR-Weighted LSQ fitting was used to obtain S/C delay, which could restrain this effect. Delay Error from this signal is more than 5ns some times, and it works with USB ranging, can satisfy the low demand in orbit determination.



VLBI signal which designed in CE-1&CE-2 for more precise delay. There are two signals separated 20MHz with ~500kHz for each bandwidth. Two signals was synthesized and some times 1ns delay precision can be obtained. Left two for Freq. vs Amp, right Phase vs Frequency. LSQ fitting is used but no weight, data points lower than SNR limit are excluded. This mode was working in offline mode.



Data Transfer Signal. Its processing is similar as VLBI X signals.



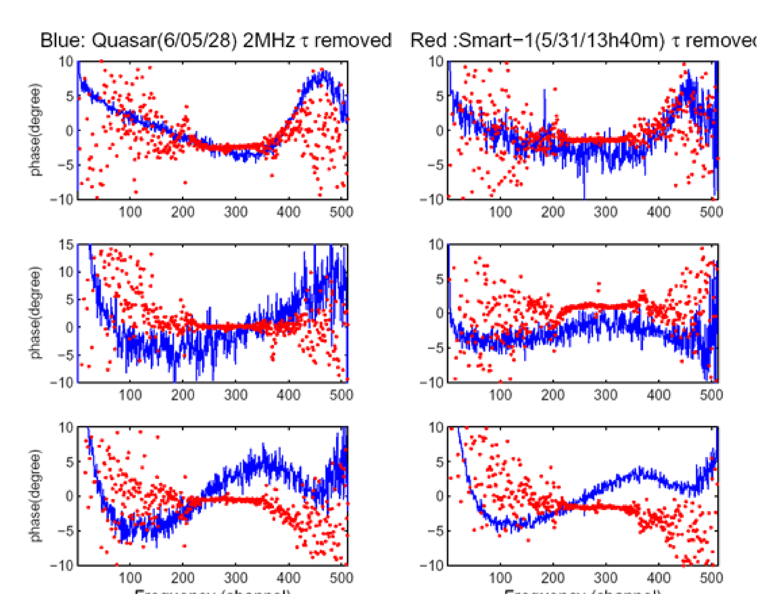
ΔDOR technique was first formally applied in CE-3, and it was carried a two-weeks long testing in CE-2 .

ΔDOR application in CE-3 mission, three breakthroughs:

- S/C phase-level calculation technique
- Auto-ambiguity resolution technique
- Long GPS-Timing applied to keeping accurate clock rate

3. S/C Delay Calibrations

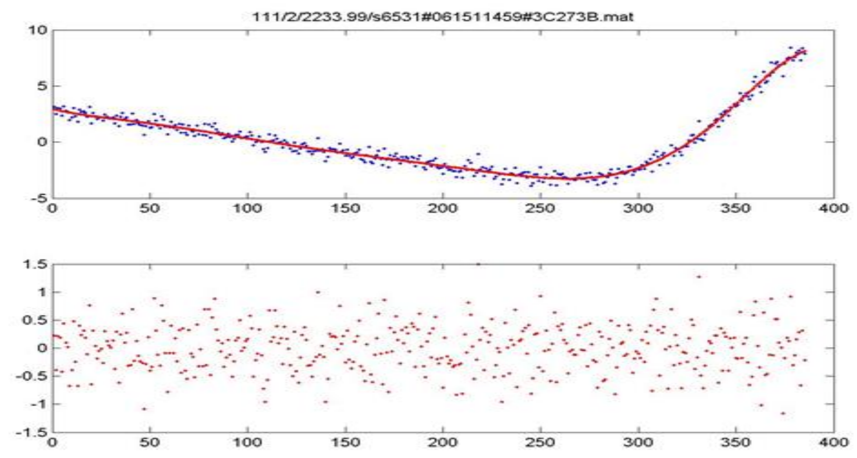
- Bandpass unfairness

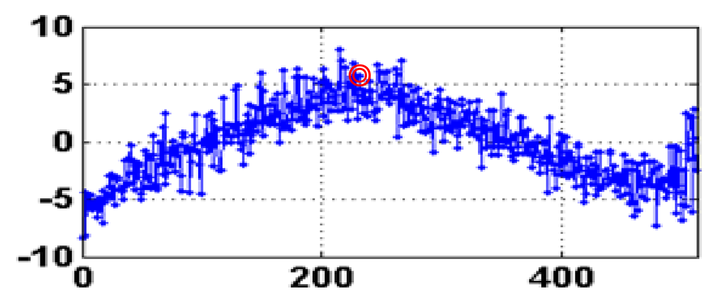


Baseline BBC's phase-freq. characteristics difference between QSR and S/C observation. Linear component were removed. Red is of S/C, blue is QSR. Due to the S/C signal does not uniformly cover the whole bandpass, it brings in extra delay calibration error, obviously at bottom row.

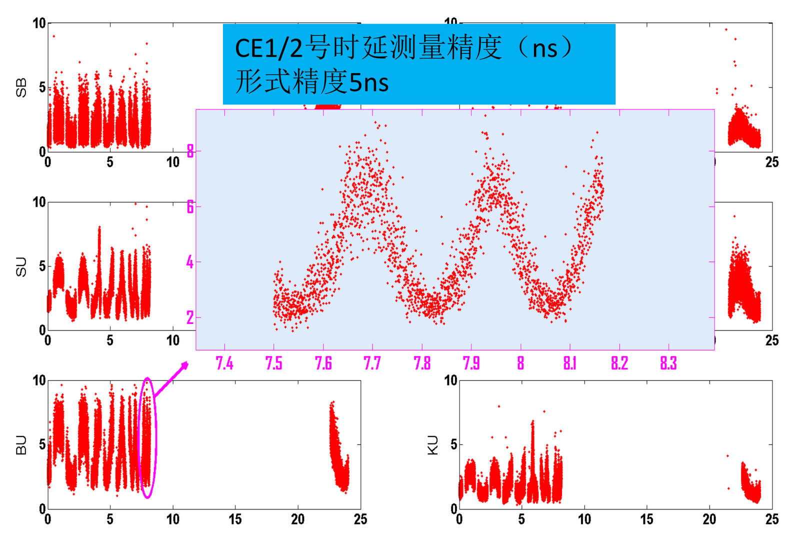
To account for this effect, strong QSR observed and integrated enough long time to obtain most precise bandpass profile expressed in high order polynomial.

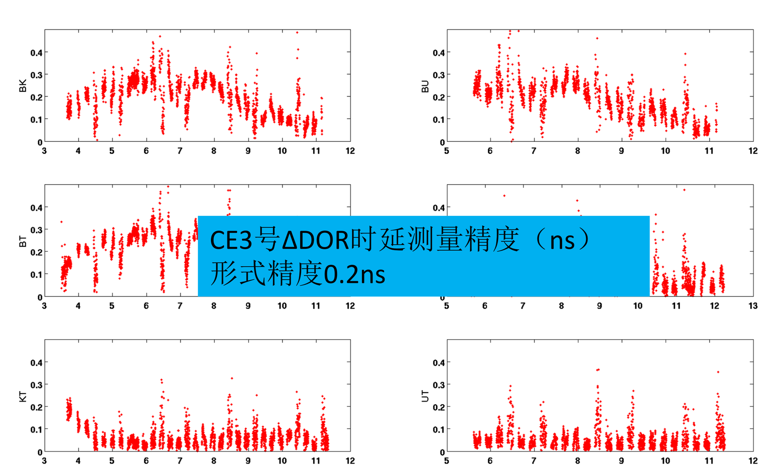
Right picture shows the bandpass effect. right bottom is the residuals after polynomial effect removed. This could improve the delay error about 2ns.





Phase error due to Nonlinear Bandpass Up to 5deg Causing 0.1ns ground error, Could be reduced by Bandpass profile Correction.





4. Summary

VLBI has played its roles in China's deep space projects almost 10 years. We've made great advance in both observation technique and data reduction this could be concluded from the below textbox.

CE series observation evolution	Delay Error		Realtime level	
	CE1	5-6ns	CE1	5-6m
	CE2	3-4ns	CE2	3-4m
	CE3	<1ns	CE3	<40s