First International Workshop on VLBI observations of near-field targets

Delta-DOR in CE-3, MEX solar conjunction

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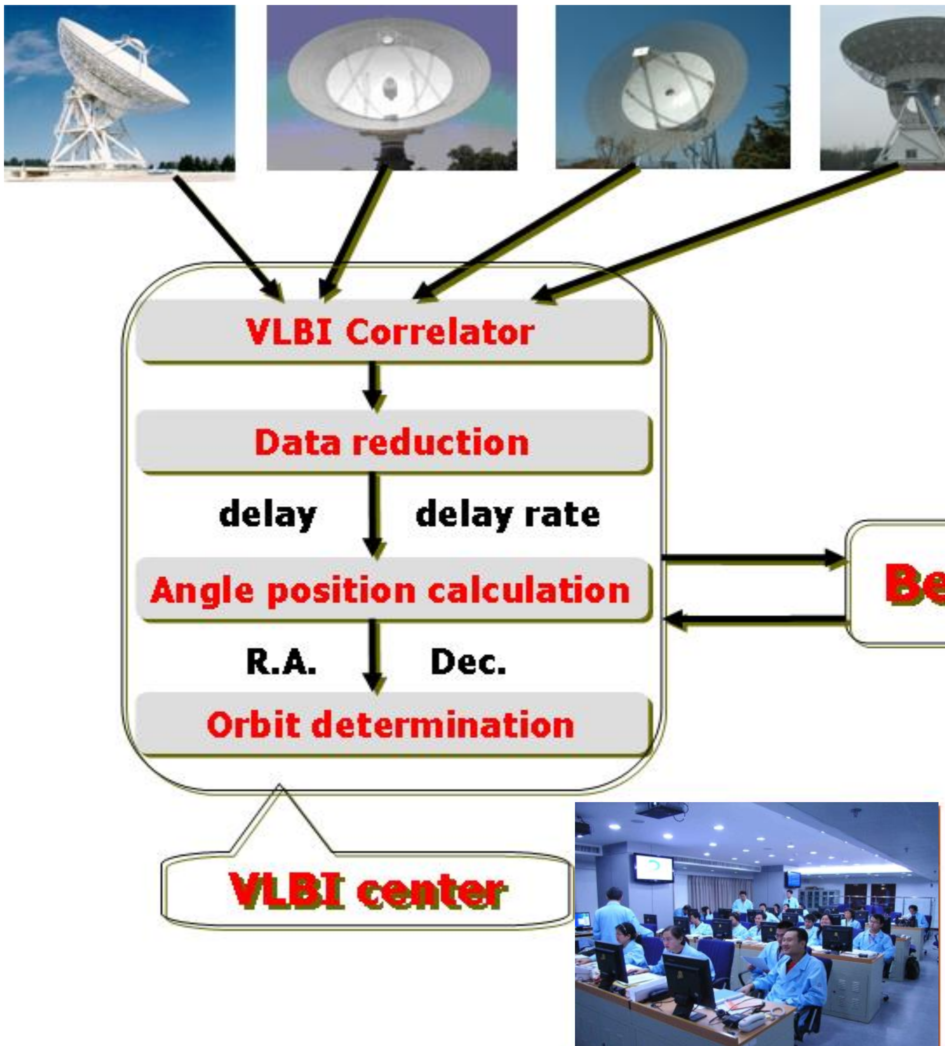
Outline

1. CVN in Chang'E-3 mission

2. CE-3 X-band Delta-DOR

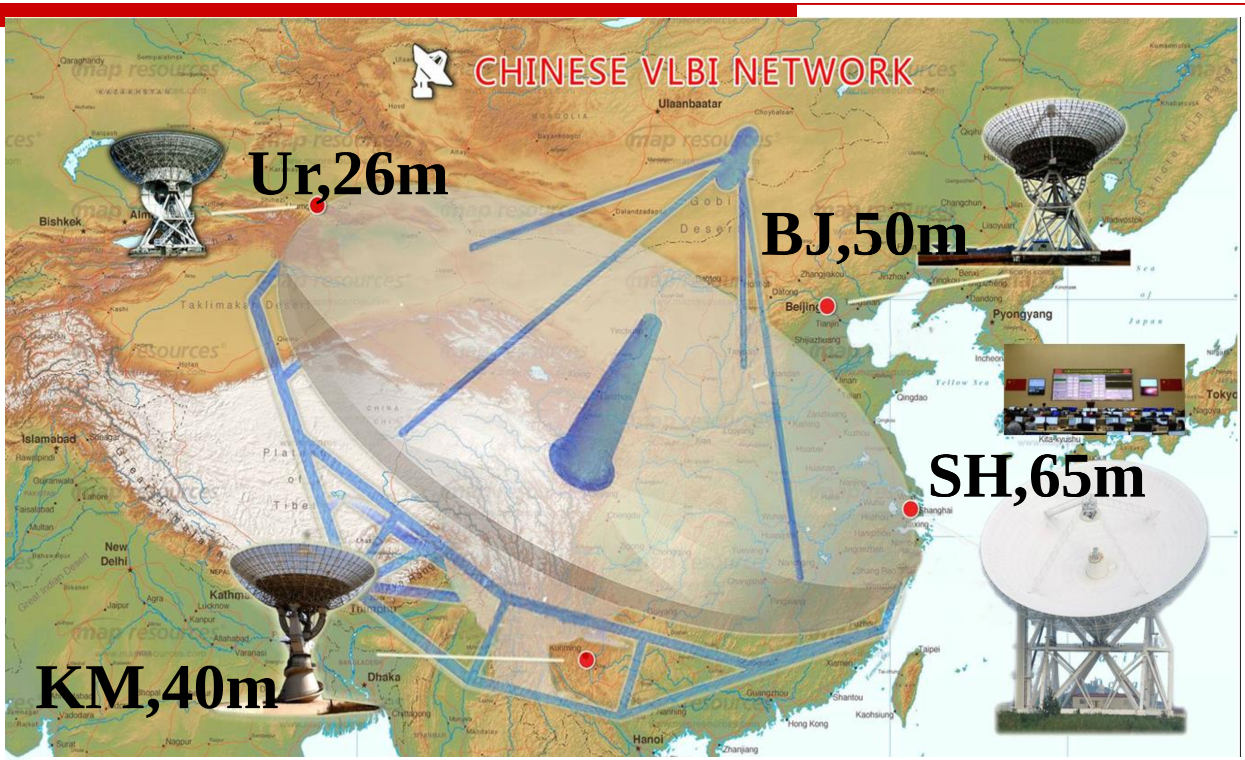
3. MEX Interplanetary scintillation observation

1. CVN



CVN, providing VLBI delay, delay rate, orbit, and angle data to Beijing Center. CE-1, CE-2, CE-3, CE5T1.

CVN upgrade in CE3



1. New VLBI data center
2. Shanghai Tianma 65m radio telescope
3. New X-band receiver & digital terminal

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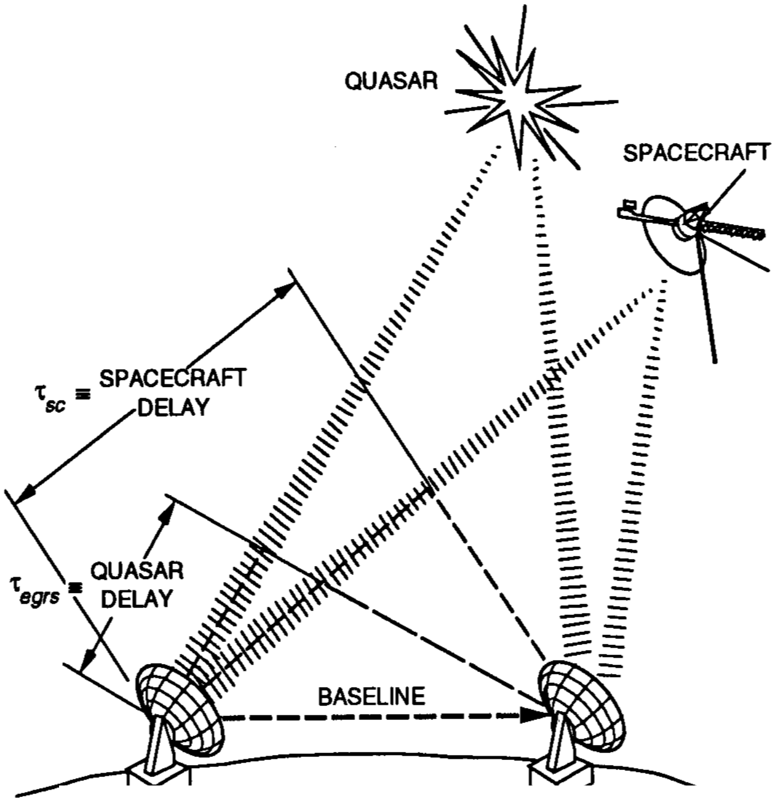
上海天文台
Shanghai Astronomical Observatory

2. CE-3 X-band Delta-DOR



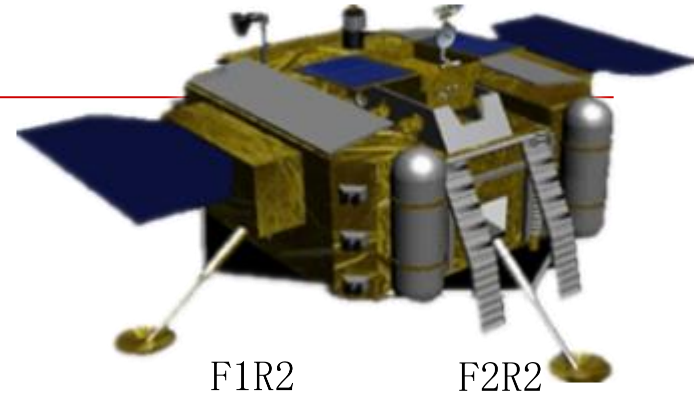
Peter Kroger: ΔDOR spacecraft tracking

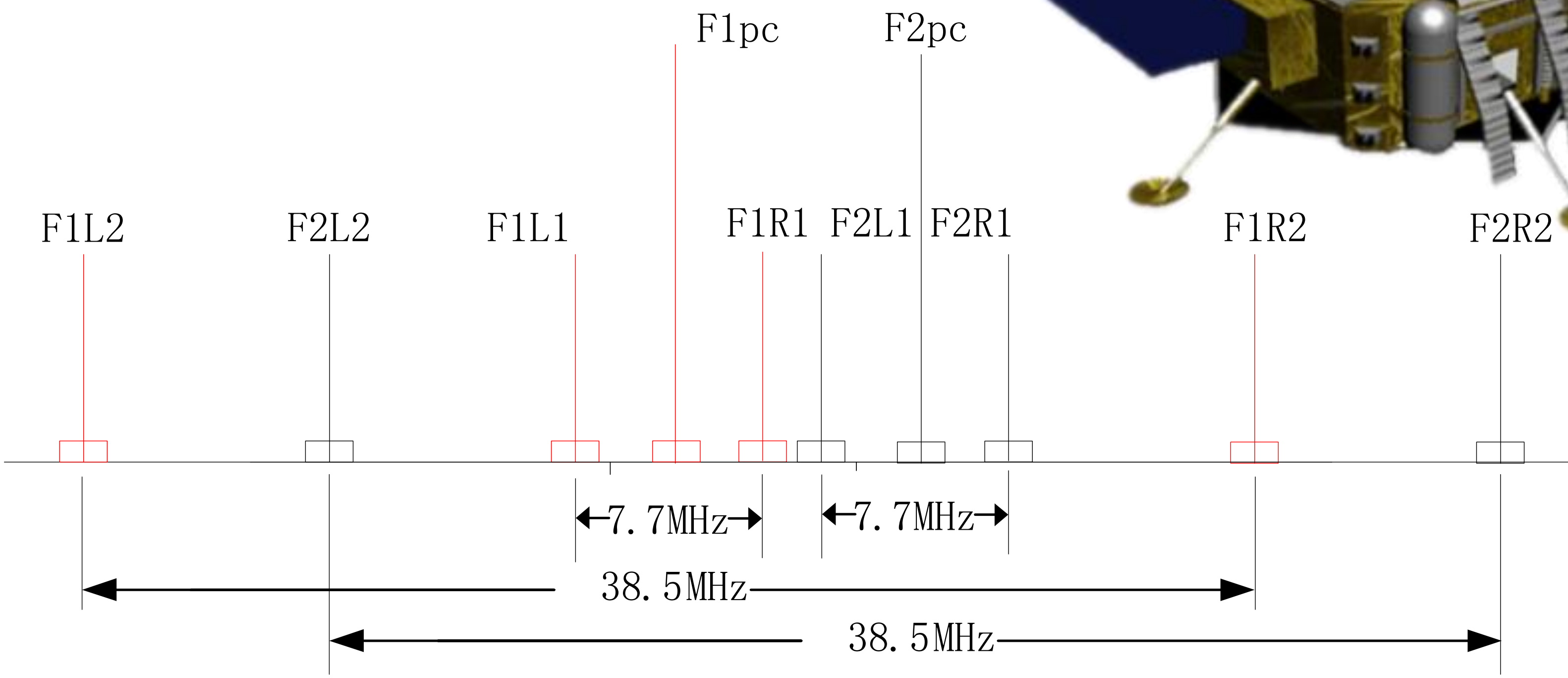
Fig. 1. Geometry of a typical ΔDOR observation.

Five-minute scan sequence: Quasar-CE3-Quasar-CE3

Angular distance between CE-3 and Quasar < 10°

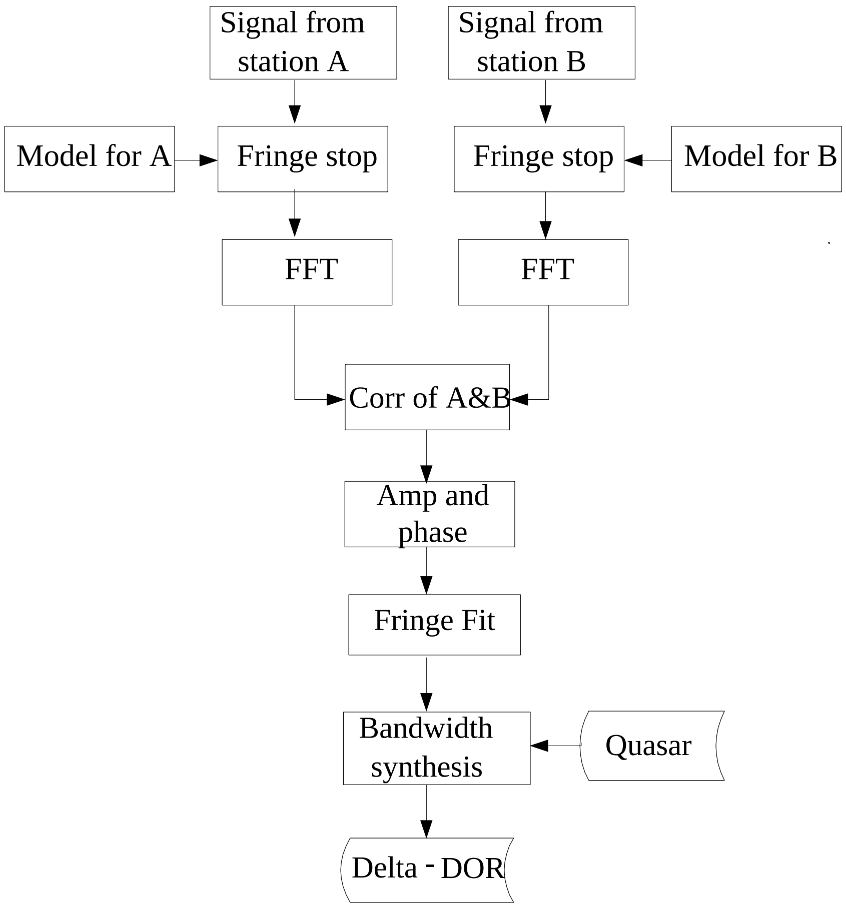
Remove media & system errors

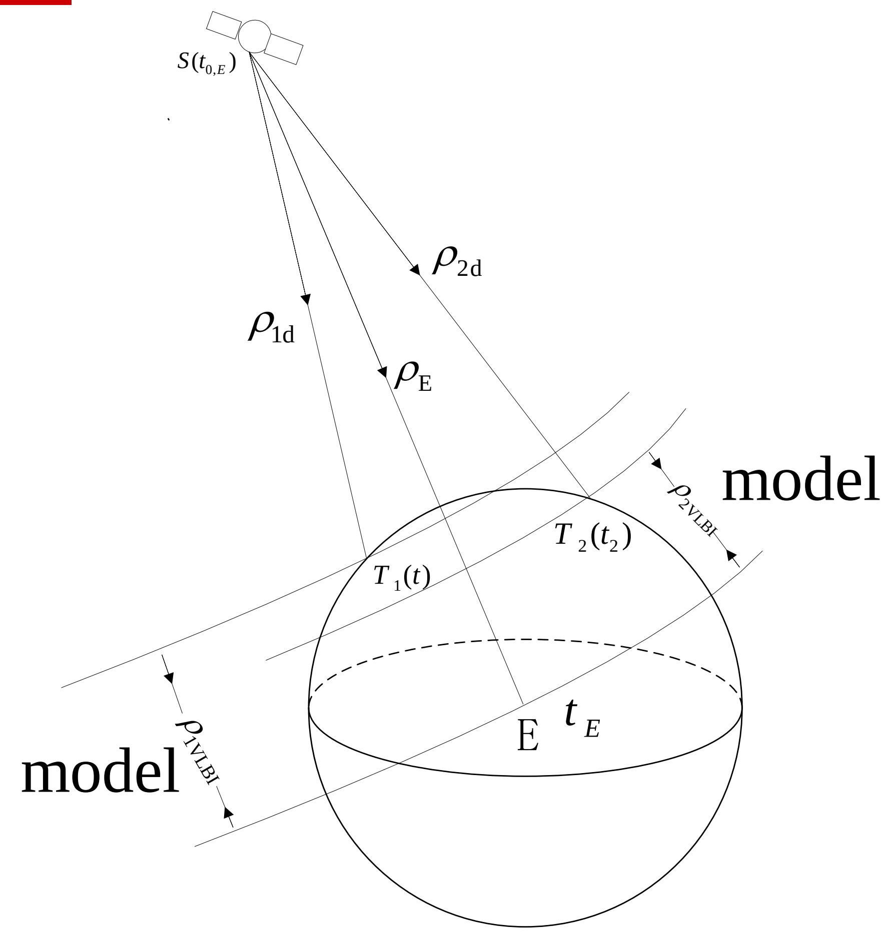




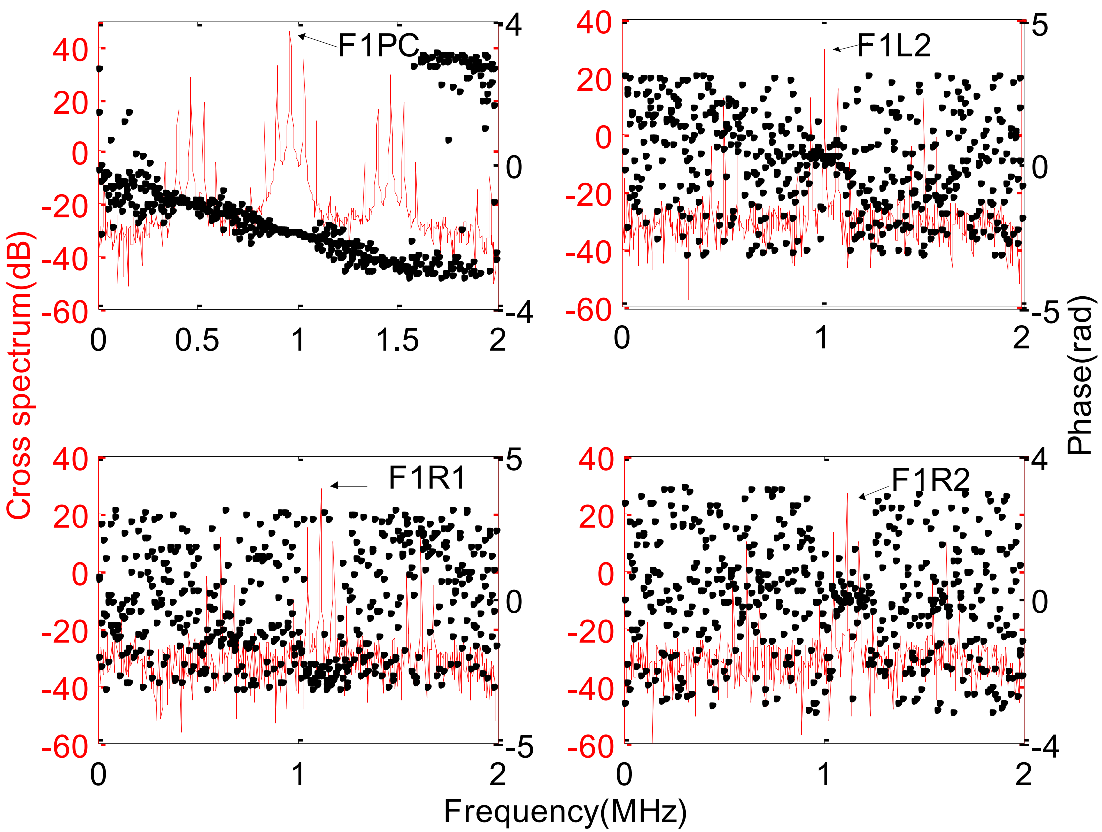
Two series of DOR signals, F1 and F2, located at both sides of the detector. One is coherent($10^{-13} \sim 10^{-14}$), the other is non-coherent($10^{-9} \sim 10^{-10}$).

FX correlator in CVN





FX correlator on DOR



Samplerate 4MHz
Bandwidth 2MHz
FFT point 1024

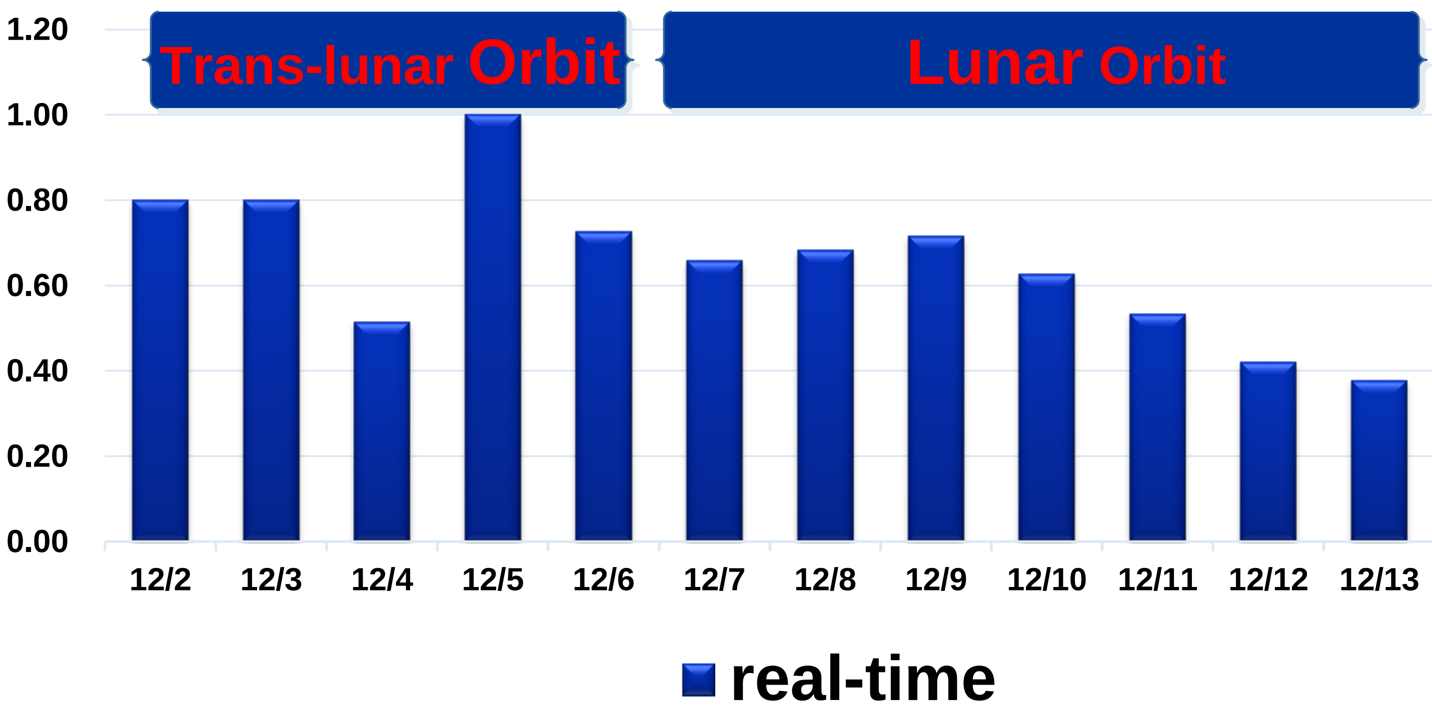
CNR loss due to
Spectral resolution:

$$10\log_{10}\sqrt{\frac{4000000}{1024}} \approx 18\text{dB}$$

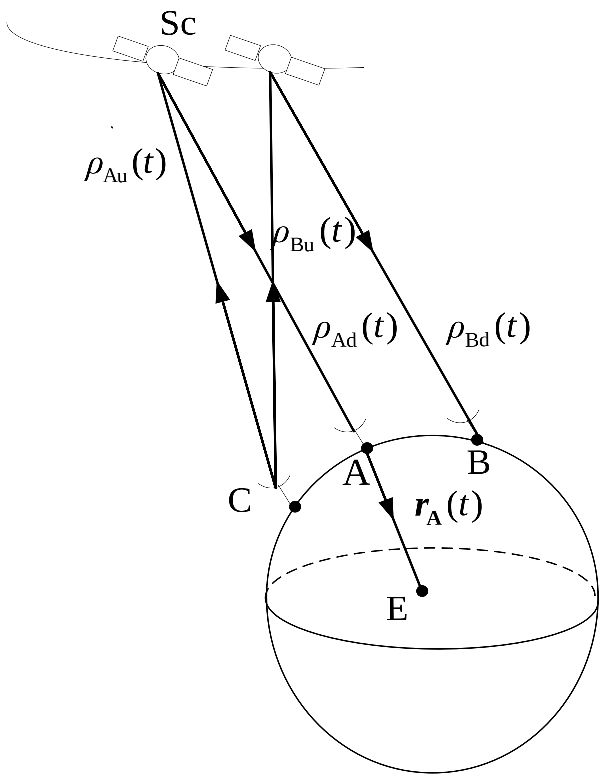
Residual statistics

- VLBI group delay residuals(X-band Delta-DOR):
  - ~ 1ns in trans-lunar orbit
  - ~ 0.5ns in lunar orbit.

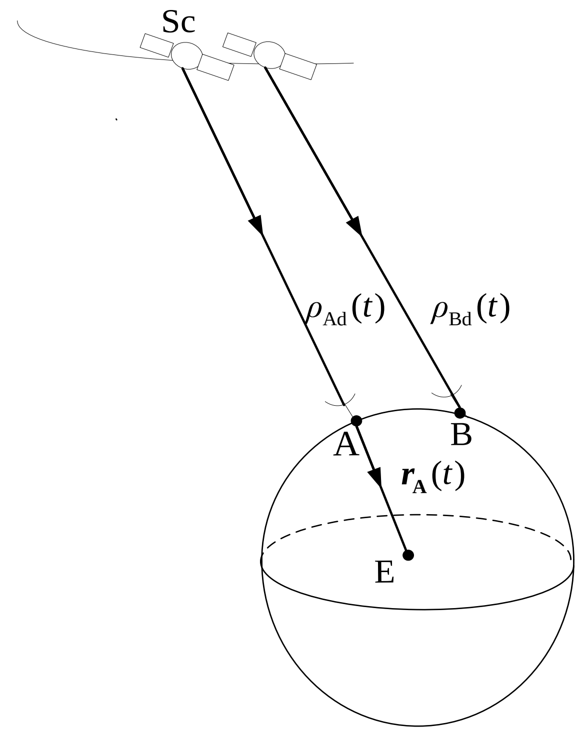
VLBI Delay Data Fit（unit: ns）



A different correlator from FX correlator



coherent



non-coherent

$$\tau_{\mathrm{DOR}}(t_0)=\boxed{\frac{\rho_{\mathrm{Bd}}(t_0)+\rho_{\mathrm{Bu}}(t_0)}{c}}-\boxed{\frac{\rho_{\mathrm{Ad}}(t_0)+\rho_{\mathrm{Au}}(t_0)}{c}}=t_2-t_2^{'}$$

$$\tau_{\mathrm{DOR}}(t_0)=\boxed{\frac{\rho_{\mathrm{Bd}}(t_0)}{c}}-\boxed{\frac{\rho_{\mathrm{Ad}}(t_0)}{c}}=t_1-t_1^{'}$$

Rogstad, Stephen P., et al.2009； Luciano Iess, Ricard Abellò Puyuelo, Alessandro Ardito, et al. The European ΔDOR Correlator.

Correlator

- Input: transmit frequency f_0
- Model: $\begin{cases} \rho_{\mathrm{Ad}}(t) = \left|\boldsymbol{r}_{\mathrm{Sc}}(t_1) - \boldsymbol{r}_{\mathrm{A}}(t)\right| \\ \rho_{\mathrm{Au}}(t) = \left|\boldsymbol{r}_{\mathrm{C}}(t_2) - \boldsymbol{r}_{\mathrm{Sc}}(t_1)\right| \end{cases}$ let $\tau_{\mathrm{geoA}}(t) = \dfrac{\rho_{\mathrm{Ad}}(t) + \rho_{\mathrm{Au}}(t)}{c}$

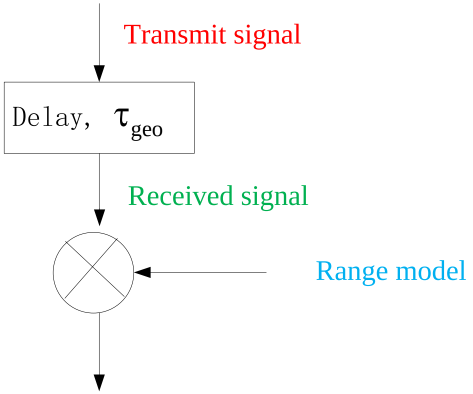
$$\boxed{s_t(t) = \mathrm{Re}\left[a \exp i\left(2\pi M f_0 t + \phi_0\right)\right]}$$

$$s_{\mathrm{A}}(t) = \mathrm{Re}\left[a_{\mathrm{A}} \exp i\left(2\pi M f_0\left(t - \tau_{\mathrm{geoA}}(t)\right) + \phi_0\right)\right]$$

$$s_{\mathrm{B}}(t) = \mathrm{Re}\left[a_{\mathrm{B}} \exp i\left(2\pi M f_0\left(t - \tau_{\mathrm{geoB}}(t)\right) + \phi_0\right)\right]$$

$$\boxed{s_{\mathrm{A,m}}(t) = \exp i\left(2\pi M f_0\left(t - \tau_{\mathrm{geoA,m}}(t)\right) + \phi_0\right)}$$

$$s_{\mathrm{A}}^{*}(t) = \frac{a_{\mathrm{A}}}{2} \exp i[2\pi M f_0(\tau_{\mathrm{geoA,m}}(t) - \tau_{\mathrm{geoA}}(t)) + \phi_0]$$



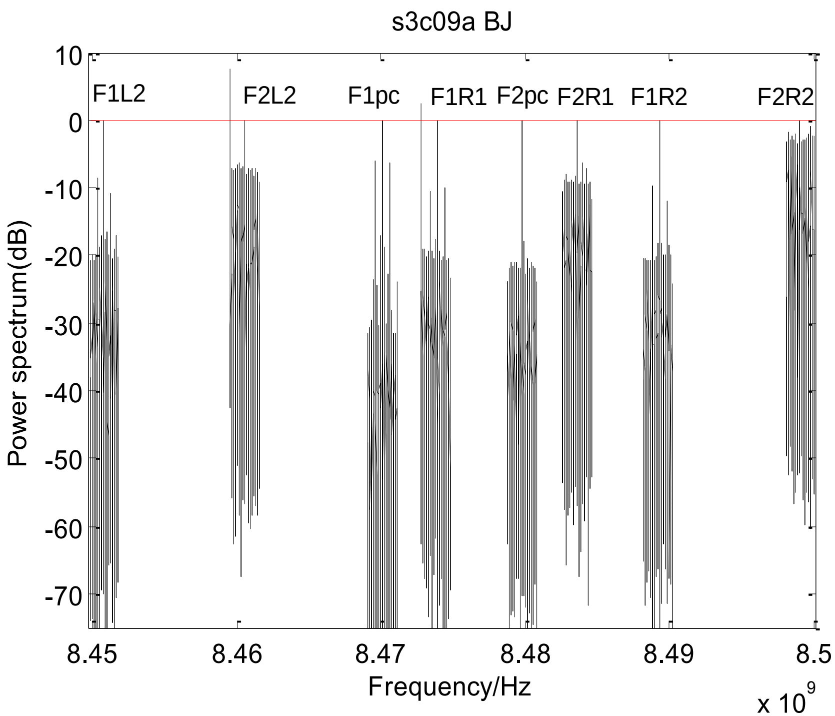
$s_{\mathrm{A}}^{*}(t)$ is a slow varying signal with low frequency.

Data process

CE-3, s3c07a, s3c08a, s3c09a,
100*100km lunar orbit
Samplerate:4MHz
Bandwidth:2MHz
Quantification:2bit

0001	3C273B	2013-12-07 02:43:00	2013-12-07 03:11:00	BjKmUrTm
0002	1334-127	2013-12-07 03:13:00	2013-12-07 03:42:00	BjKmUrTm
0003	SAT-CE03	2013-12-07 03:46:00	2013-12-07 03:53:00	BjTm
0004	1741-038	2013-12-07 03:56:00	2013-12-07 04:01:00	BjKmUrTm
…….				
0038	2128-123	2013-12-07 08:21:00	2013-12-07 08:26:00	BjKmUrTm
0039	SAT-CE03	2013-12-07 08:27:00	2013-12-07 08:35:00	BjKmUrTm
0040	2128-123	2013-12-07 08:36:00	2013-12-07 08:41:00	BjKmUrTm
0041	SAT-CE03	2013-12-07 08:42:00	2013-12-07 08:50:00	BjKmUrTm
0042	2128-123	2013-12-07 08:51:00	2013-12-07 08:56:00	BjKmUrTm
0043	SAT-CE03	2013-12-07 08:57:00	2013-12-07 09:05:00	BjKmUrTm
0044	2128-123	2013-12-07 09:06:00	2013-12-07 09:11:00	BjKmUrTm
0045	SAT-CE03	2013-12-07 09:12:00	2013-12-07 09:20:00	BjKmUrTm
0046	2128-123	2013-12-07 09:21:00	2013-12-07 09:26:00	BjKmUrTm
0047	SAT-CE03	2013-12-07 09:27:00	2013-12-07 09:35:00	BjKmUrTm
0048	2128-123	2013-12-07 09:36:00	2013-12-07 09:41:00	BjKmUrTm
………				
0070	2128-123	2013-12-07 12:21:00	2013-12-07 12:26:00	BjKmUrTm
0071	SAT-CE03	2013-12-07 12:27:00	2013-12-07 12:35:00	BjKmUrTm
0072	2134+00	2013-12-07 12:36:00	2013-12-07 12:41:00	BjKmUrTm
0073	SAT-CE03	2013-12-07 12:42:00	2013-12-07 12:46:00	BjKmUrTm
0074	SAT-CE03	2013-12-07 12:46:00	2013-12-07 12:55:00	KmUr
0075	2134+00	2013-12-07 12:56:00	2013-12-07 13:01:00	BjKmUrTm
0076	SAT-CE03	2013-12-07 13:02:00	2013-12-07 13:12:00	KmUr

Received signal by VLBI station



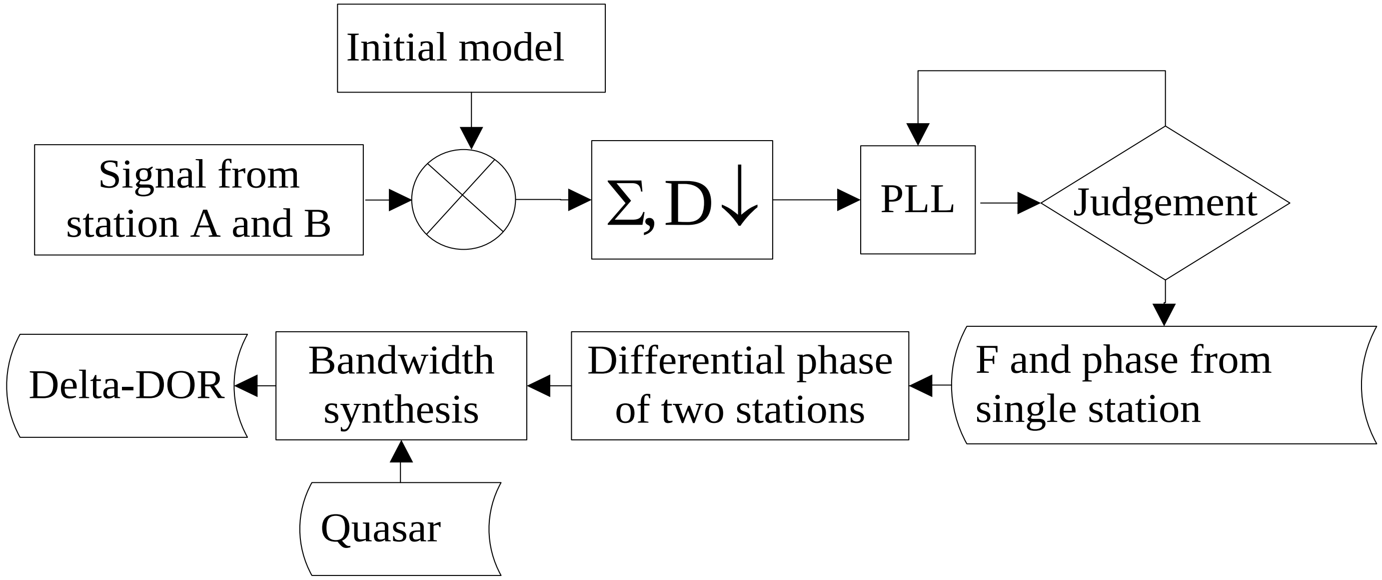
CNR of s3c09a BJ(dBHz)

	L2	pc	R1	R2
F1, coherent	40	50	40	40
F2,non-coherent	28	40	30	25

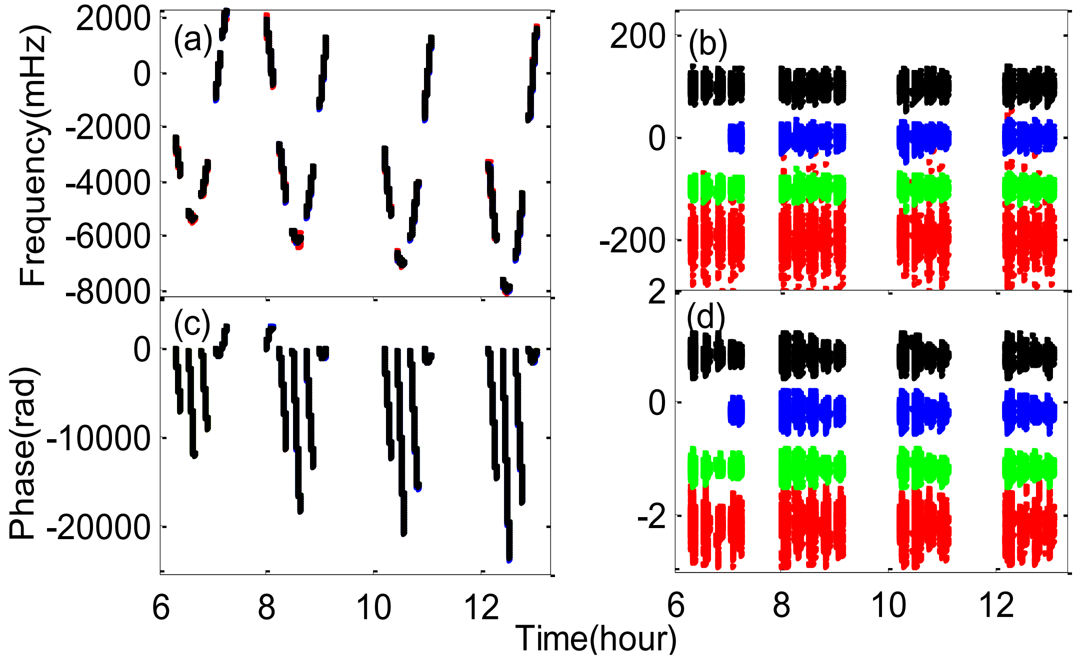
CNR：10*log(power of signal/noise)

Coherent

In the coherent situation, the transmitted frequency f_0 from uplink station is exactly known.



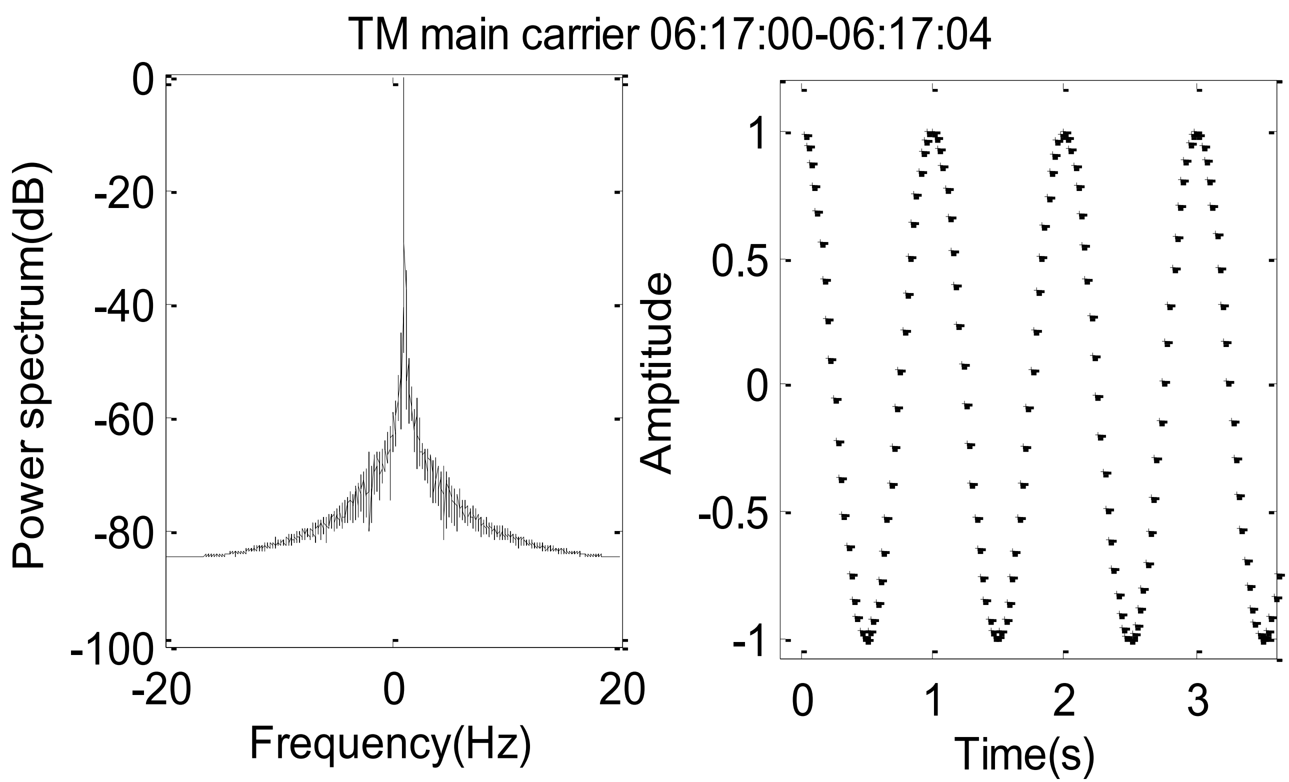
Take s3c09a as example



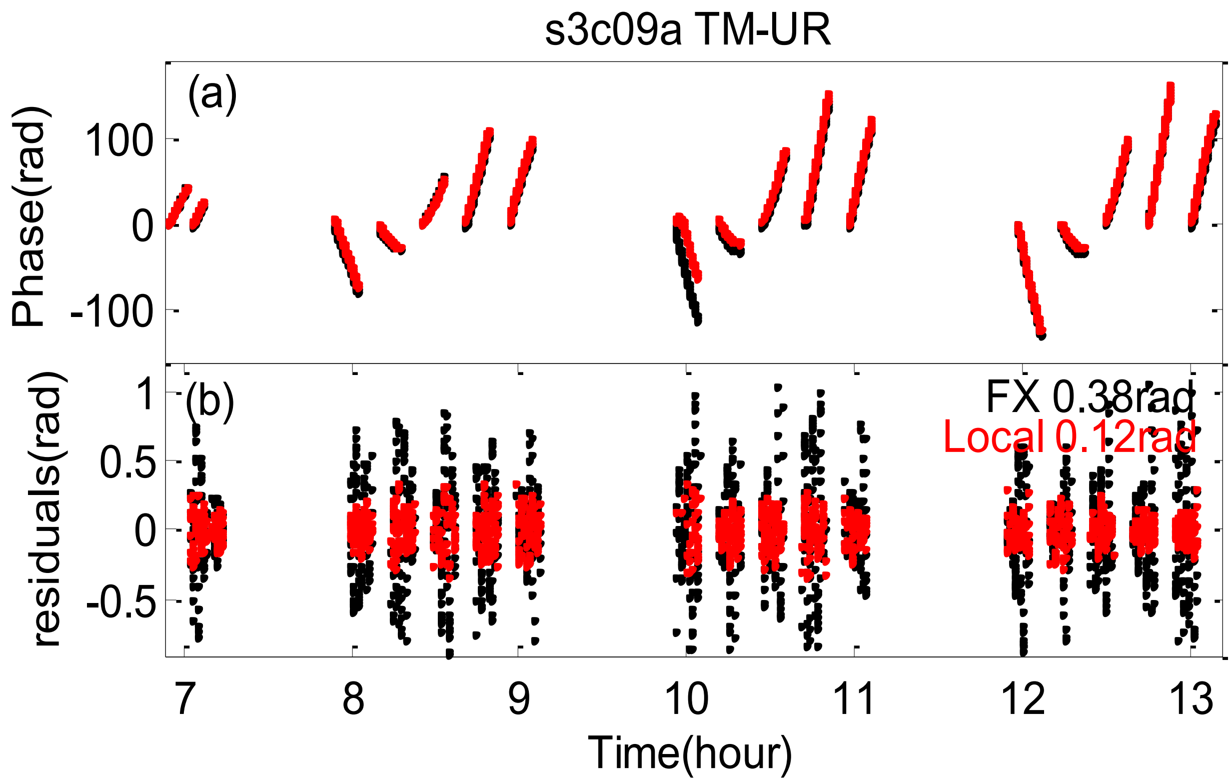
After integral filter　　　After PLL

	BJ	KM	UR	TM
Frequency(mHz)	8.23	52.9	9.4	11.3
Phase(rad)	0.11	0.26	0.13	0.13

TM F1pc after PLL



Phase compared with FX correlator

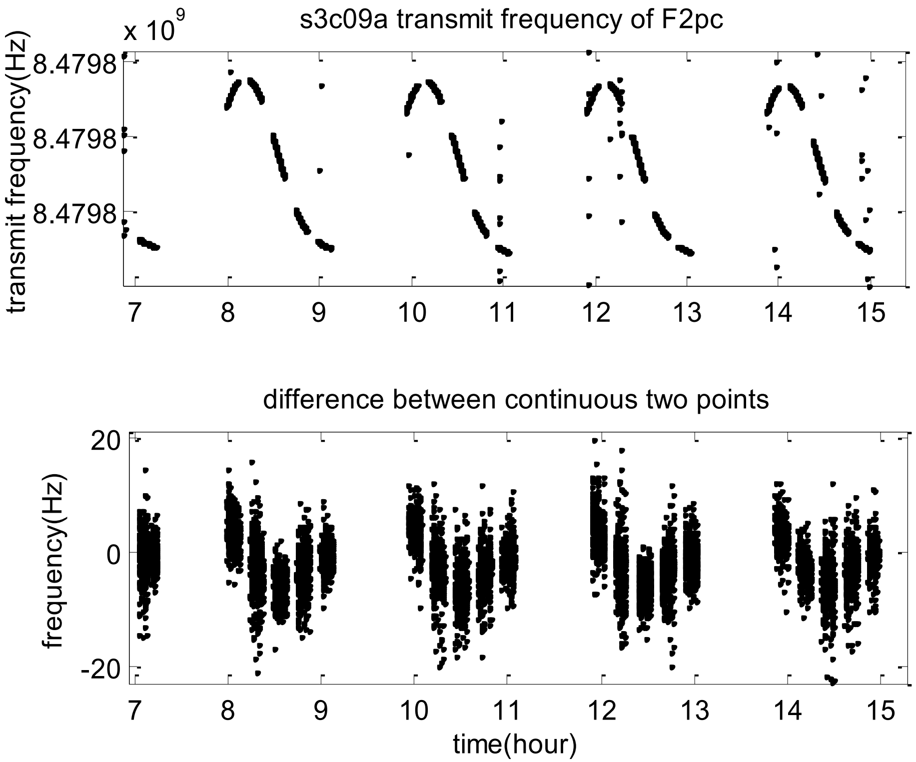


Phase compared with FX correlator

Baseline	s3c07a		s3c08a		s3c09a	
	New	FX	New	FX	New	FX
BJ-KM	0.29	0.35	0.28	0.38	0.25	0.38
BJ-UR	0.13	0.35	0.20	0.35	0.11	0.37
BJ-TM	0.13	0.20	0.15	0.22	0.14	0.27
KM-UR	0.27	0.40	0.29	0.40	0.28	0.38
KM-TM	0.29	0.39	0.30	0.40	0.28	0.40
UR-TM	0.17	0.39	0.15	0.38	0.12	0.39

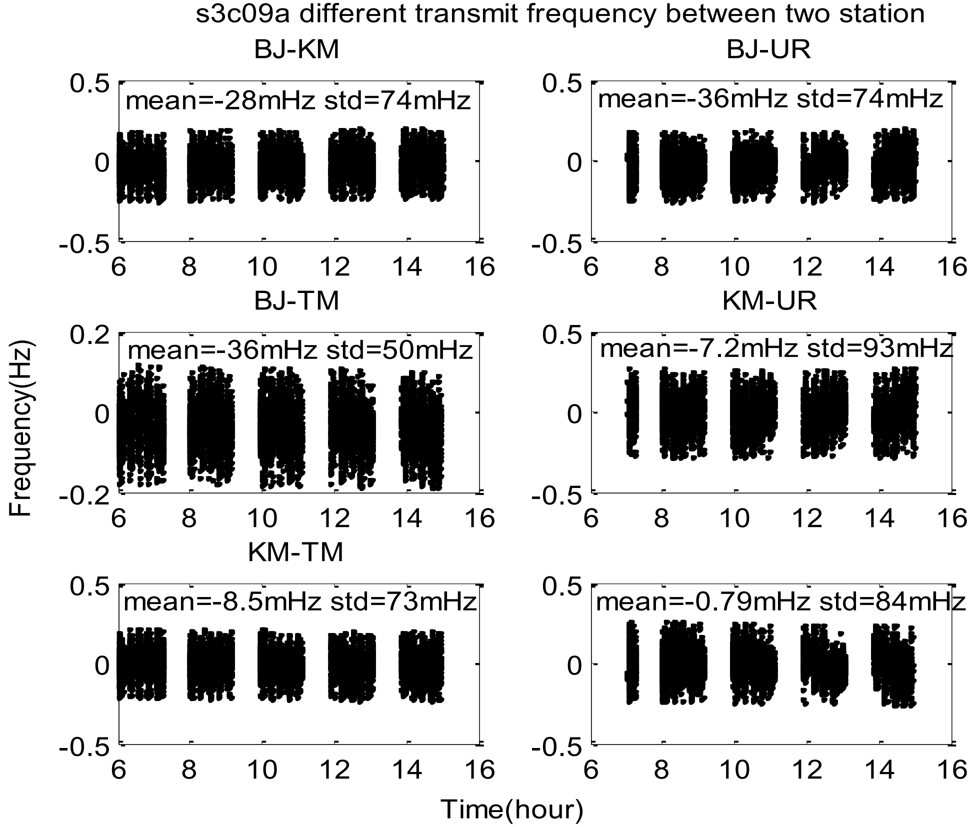
Phase precision from new method is better than the FX correlator.

Non-coherent: Estimate f_0 at first



Frequency difference between adjacent points is in the range of -10~10Hz

Difference transmit frequency between two stations



Frequency std is about 100mHz

Orbit determination results

Orbit determination between two correlator, F1

code	Delta-DOR+range(RMS)		Delta-VLBI+range(RMS)		Difference with 61+62	
	71	51(m)	61(ns)	51(m)	distance(m)	velocity(mm/s)
s3c07a	0.3	2.96	0.3	1.68	26.3	20.0
s3c08a	0.4	1.28	0.3	1.65	24.6	20.3
s3c09a	0.4	0.40	0.5	0.42	8.9	9.3

Orbit determination between two correlator, F2

code	Delta-DOR+range(RMS)		Difference with 61+62	
	73	51(m)	distance(m)	velocity(mm/s)
s3c07a	0.67	4.3	29.3	22.4
s3c08a	0.67	1.27	15.3	13.4
s3c09a	0.67	0.42	7.0	7.0

Error analysis

Table 1 ΔDOR error budget

<table>
<tr><th rowspan="2">Terms</th><th colspan="2">Error (ns)</th></tr>
<tr><th>5°*</th><th>10°*</th></tr>
<tr><td>Noise floor</td><td colspan="2">0.3~0.5</td></tr>
<tr><td>Troposphere**</td><td>0.10</td><td>0.20</td></tr>
<tr><td>Instrumental phase ripple</td><td colspan="2">0.10</td></tr>
<tr><td>Ionosphere</td><td>0.06</td><td>0.09</td></tr>
<tr><td>Clock instability</td><td colspan="2">0.06</td></tr>
<tr><td>Earth orientation</td><td>0.05</td><td>0.10</td></tr>
<tr><td>Station location</td><td>0.04</td><td>0.08</td></tr>
<tr><td>Quasar position and structure</td><td colspan="2">0.05</td></tr>
<tr><td>RSS</td><td>0.50</td><td>0.60</td></tr>
</table>

*: Angular seperation between satellite and quasar

**: Assuming elevation angle 45°

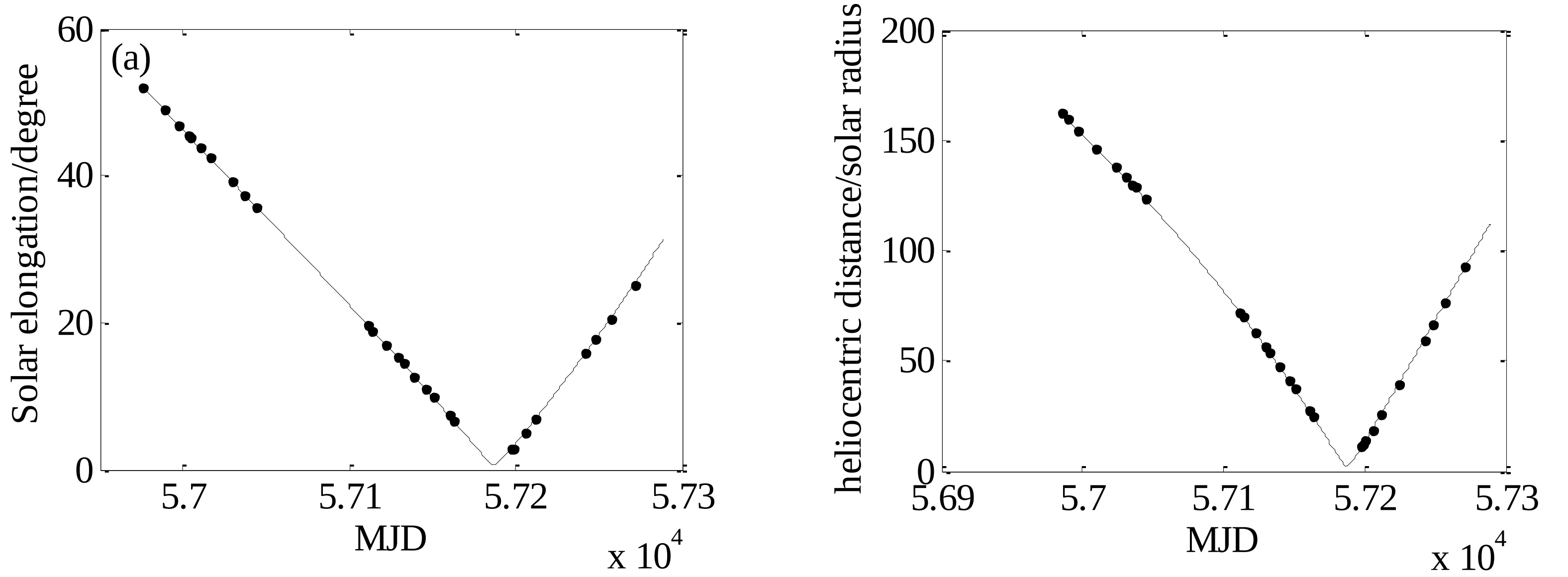
Wu Wei-ren, Wang Guangli, et al. 2013

Conclusion

1. The delay residuals after orbit determination are 0.5ns and 0.7ns respectively. The CNR of F2 is 10dB weaker than F1.
2. The phase from the result is better than FX correlator, while no improvement in orbit determination, system errors from CVN should be estimated.
3. The method reported here is more suitable for weak signal process compared with FX correlator.

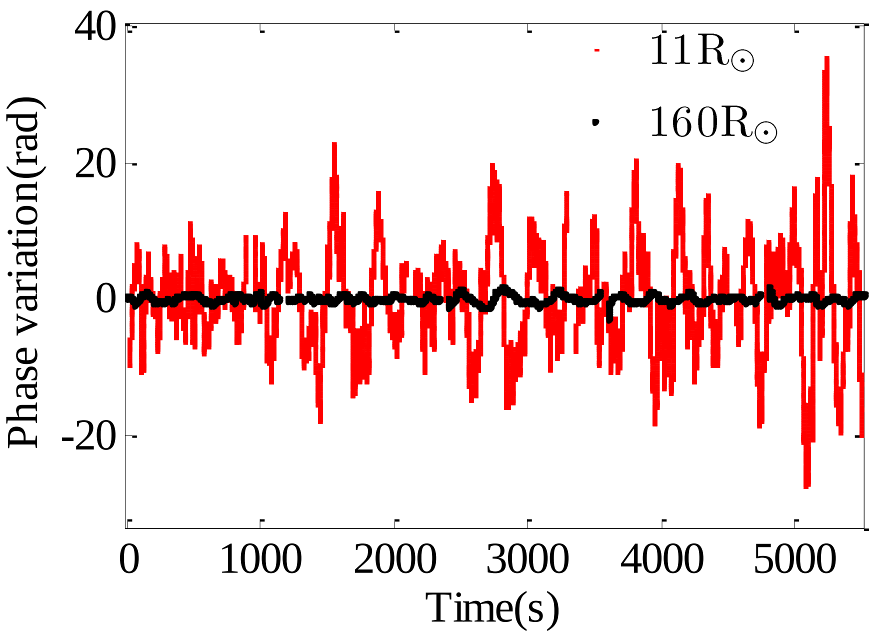
3.MEX Interplanetary scintillation observation

MEX is flying around Mars. Sheshan 25m radio telescope have observed MEX from 2014.11~2015.9. The observations are conducted by JIVE.

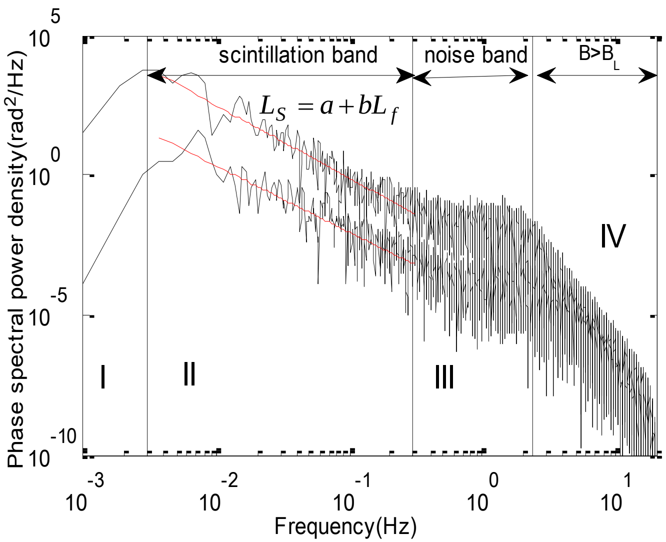


Solar elongation and minimum heliocentric distance vary from 2014.11~2015.09

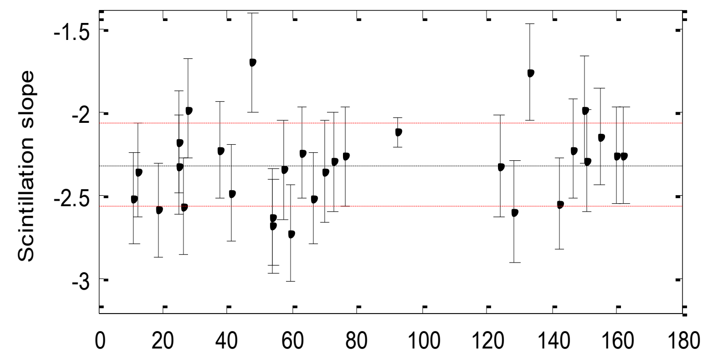
Orbit of MEX is got from ESA/ESOC. G. Molera Calves, et al. 2014.



	Phase	Frequency
11R⊙	21.2rad	16mHz
160R⊙	0.1rad	3mHz



Phase spectral power density at R=11R⊙ and 160 R⊙

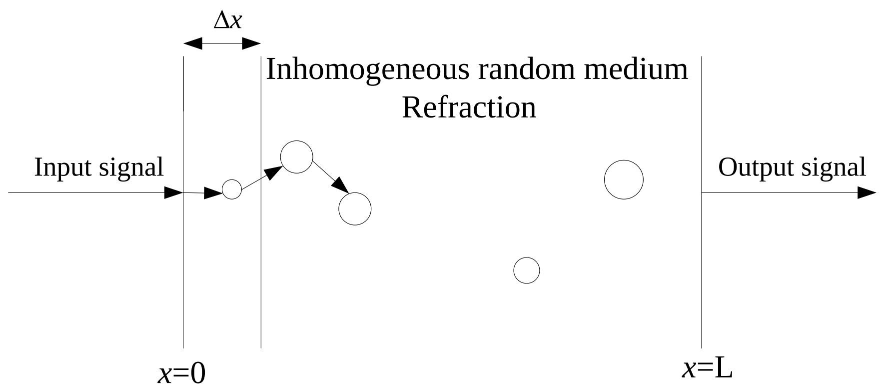


Slope of phase spectral power density

Close to Komlogorov index 8/3

Komlogorov Turbulence, 3mHz~0.3Hz, 1300km~130000km

Theory to explain phase scintillation



Refraction index $n(x,t)$, Taylor frozen-in hypothesis.
Structure function

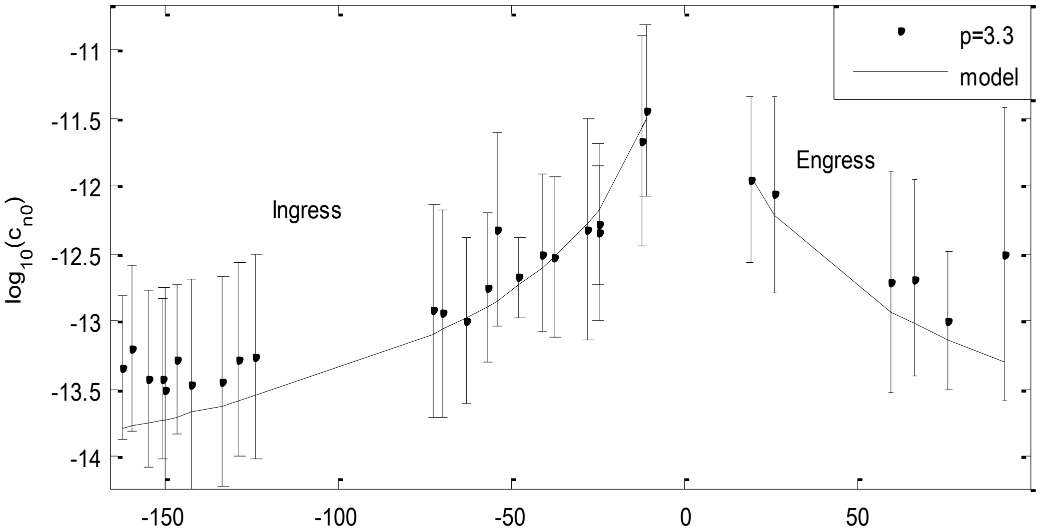
$$C_n(x) = c_{n0} \exp\left[-\left(\frac{x-L_2}{a_1 R}\right)\right]$$

$$W_S(f) = 0.033 c_{n0}{}^2 k^2 \frac{8\pi^3 a_1 R}{\upsilon}\left(\frac{2\pi f}{\upsilon}\right)^{1-p} \frac{\Gamma[(p-1)/2]}{\Gamma(p/2)}$$ [1]

Woo R, Yang F C. et al.1976

$$\sigma_S{}^2 = \int_{f_1}^{f_2} W_S(f)\,df$$

refraction structure constant



$$c_{n0} = c\left(\frac{R}{R_\odot}\right)^d \qquad c = (3.8 \pm 2.7) \times 10^{-10} \qquad d = -1.98 \pm 0.27$$

In Woo's paper(1976), d is close to 2.1

Conclusions with IPS

1.We use a single VLBI station to observe MEX. Doppler is used for IPS research. The method can be used in future Chinese Mars solar conjunction.

2.Solar wind and IPS theory are proposed in the 80s in last century. The research work reported here just confirmed earlier theory. Where is the break through point in solar wind and IPS research?

Thanks for attention!