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The Application of VLBI Positioning Technology in Chinese Lunar Project

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Mar,6rd,2012

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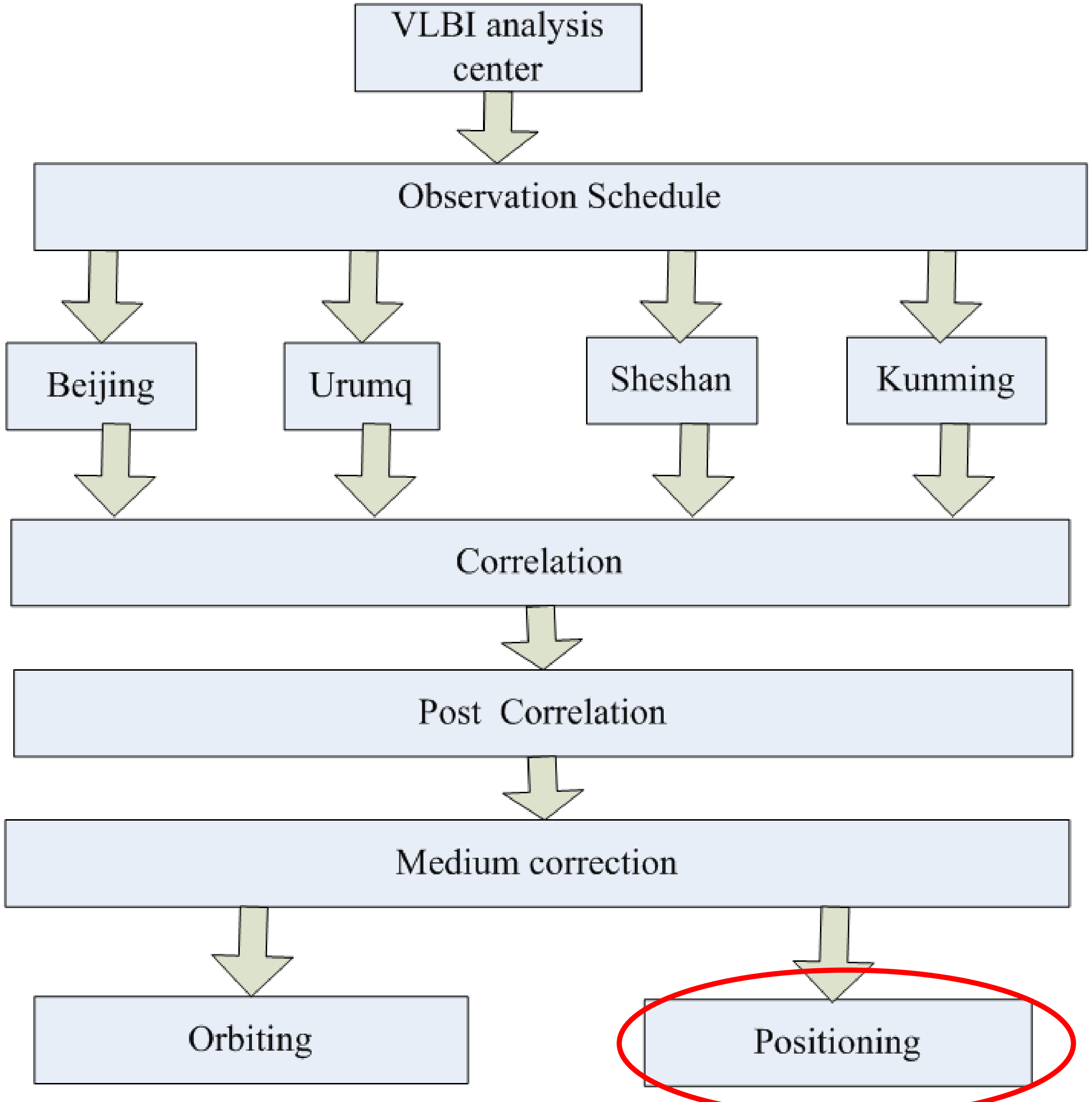
General Job Distribution in CE mission



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- Basic algorithm
- Comparison between positioning and orbiting strategies

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- in lunar capture arc
- controlling crash on the moon

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- Improvement on VLBI observations
- In orbit maneuver arc
- Experiments of orbital transfer
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- New challenge in CE-3
- Preliminary results in positioning simulation

1、The brief introduction of Positioning

- Basic algorithm
- Comparison between positioning and orbital strategies

Basic algorithm

Delay: $\tau = \frac{1}{c}\left(\left|r_2(t+tr+\tau) - r_s(t)\right| - \left|r_1(t+tr) - r_s(t)\right|\right)$ Rate: $\dot{\tau} = \Delta\tau/\Delta t$

USB range: $\rho = \left(\left|r_s(t) - r_1(t_1)\right| + \left|r_s(t) - r_2(t_2)\right|\right)/2$

Doppler: $\dot{\rho} = \left(\rho_2(t) - \rho_2(t-\Delta t)\right)/\Delta t$

✓Interpolation the observations of the same front wave，Cubic spline interpolation

✓Rapid trace measurement: instantaneous states vector

✓iteration for the theoretical value and light time, and VLBI delay

$$tr = \left(\left|r_1(t+tr0)\right| - \left|r_s(t)\right|\right)/c. \qquad \tau = \left(\left|r_2(t+tr0)\right| - \left|r_s(t)\right|\right)/c - tr1$$

✓Theoretical partials to unknowns, Taylor expansion of the corrections

$$\frac{\partial(c\tau)}{\partial x_s} = \left(\frac{x_1 - x_s}{R_1} - \frac{x_2 - x_s}{R_2}\right)$$

✓Constrain of geocentric distance and rate of a probe

$$\frac{x_s}{|r_{s0}|}\mathrm{d}x_s + \frac{y_s}{|r_{s0}|}\mathrm{d}y_s + \frac{z_s}{|r_{s0}|}\mathrm{d}z_s = 0$$

Comparison between positioning and orbiting strategies

Positioning analysis	Orbital analysis
Instantaneous state vector are obtained Rapidly	Sufficient long tracking pass
Real-time monitored	Observations are integrated to a ref epoch via state transfer matrix
Only concerning the geometrical figure	Force exerting on probes need to be precisely modeled
No limitation in the pivotal arcs such as orbital maneuver, soft-landing, lunar capture, surface walking	Avoid including the special arcs since the forces acting on the probes are hard to model accurately

2、Main contribution of Positioning in CE-1

- in lunar capture arc
- controlled impact on the moon

CE-1 mission

- Launched on October 24, 2007
- Continuously flied for 494 days
- Controlled landing on the moon on March 1, 2009
- accumulating technical and engineering experience for follow-on Chinese lunar exploration program

Trace monitoring of the CE-1 satellite during the lunar capture arc on November 5, 2007

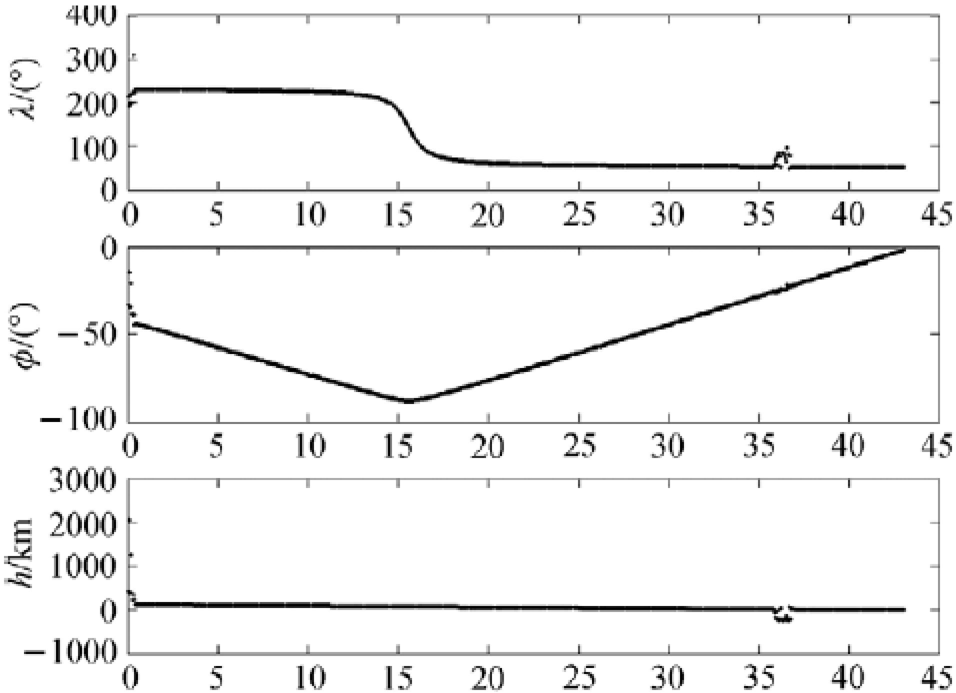
Epoch (UTC)	Semi-major axis (km)	Eccentricity
Hyperbola		
03:13:01	6618.708	1.29441
03:13:31	6641.511	1.29340
03:14:00	6664.319	1.29238
Very near to a parabola		
03:17:07	3406.991	1.08194
Ellipse		
03:20:53	2990.028	0.84911
03:20:58	3016.474	0.84918
03:42:01	6205.055	0.68567
03:42:30	6154.900	0.68305
03:43:00	6155.691	0.68311

Real-time monitoring of the orbital maneuver of the CE-1 satellite on November 6, 2007

Epoch (UTC)	Semi_major Axis(km)	Eccentricity	Inclination	Argument of the ascending node(deg)
03:21:14	6015.141	0.67682	87.524	265.446
03:21:39	5543.681	0.64883	87.522	265.431
03:22:08	4785.971	0.59599	87.496	265.293
03:22:23	4618.108	0.58076	87.500	265.293
03:22:43	4418.871	0.56143	87.503	265.290
03:26:29	3360.283	0.42134	87.555	265.223
03:26:49	3237.410	0.39931	87.559	265.221
03:27:33	3214.633	0.39420	87.561	265.277
03:28:37	3071.672	0.36547	87.573	265.279
03:28:46	3056.361	0.36189	87.581	265.279
03:29:11	2993.481	0.34900	87.578	265.278
03:29:26	2971.901	0.34367	87.583	265.281
03:31:43	2600.635	0.24986	87.607	265.299
03:31:58	2597.407	0.24883	87.605	265.310
03:32:18	2592.536	0.24780	87.603	265.326
03:32:33	2594.346	0.24800	87.602	265.339
03:32:57	2591.983	0.24783	87.594	265.357
03:33:02	2593.461	0.24816	87.593	265.361
03:33:17	2595.940	0.24898	87.589	265.373
03:33:46	2601.796	0.25105	87.578	265.396
03:35:34	2681.237	0.27258	87.535	265.481
03:36:43	2704.682	0.27867	87.531	265.484

Controlled impact on the moon

Reduced points



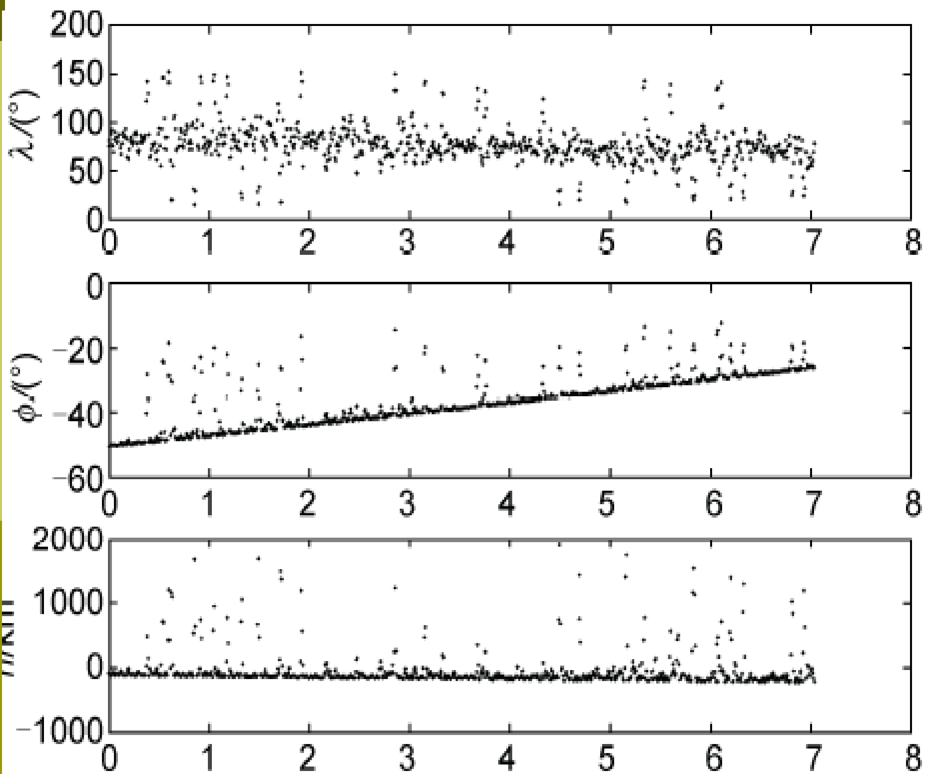
Minutes from 20090301 UTC 07h30m

LPAS coordinates of the landing point of CE-1 satllite on the moon

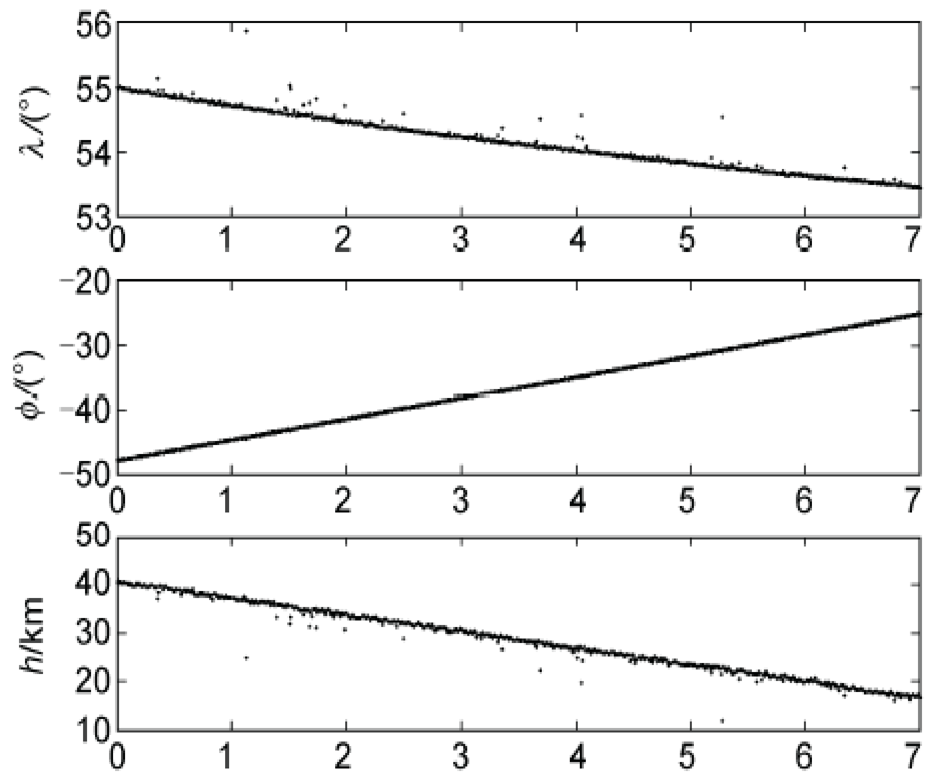
	solved	smoothed
Epoch	20090301 UTC8h13m06.514s	
E. long.	52.2760±0.0018	52.2732±0.0040
S. lat.	1.6407±0.0031	1.6440±0.0091
Surface H.	−3.30±0.06	−3.56±0.18

Figure 1 The landing trace of the CE-1 satellite on the Moon in the lunar primary axis system

Without constraint of geocentric distance



With constraint of geocentric distance



Minutes from UTC 20090301-7h59m

Statistics of the differences of overlapping arcs resultant from different data collections (unit: m)

Date	USB+VLBI			VLBI		
	R	T	N	R	T	N
24/25	12.09	36.7	14.38	14.76	149.16	223.49
25/26	3.45	-43.10	-116.50	50.04	-43.90	-63.48
26/27	1.39	-123.35	-19.20	3.9	-196.44	-121.72
27/28	10.83	-10.35	4.02	10.07	250.37	42.97
28/29	1.64	14.87	-0.87	1.28	-446.26	449.87
Mean	5.88	-25.05	-23.63	16.01	-57.41	106.23
STD	5.17	62.47	53.32	19.74	277.54	232.70

3、Role positioning plays in CE-2

- Improvement on VLBI observations
- In orbit maneuver arc
- Experiments of orbital transfer
- △DOR experiment analysis

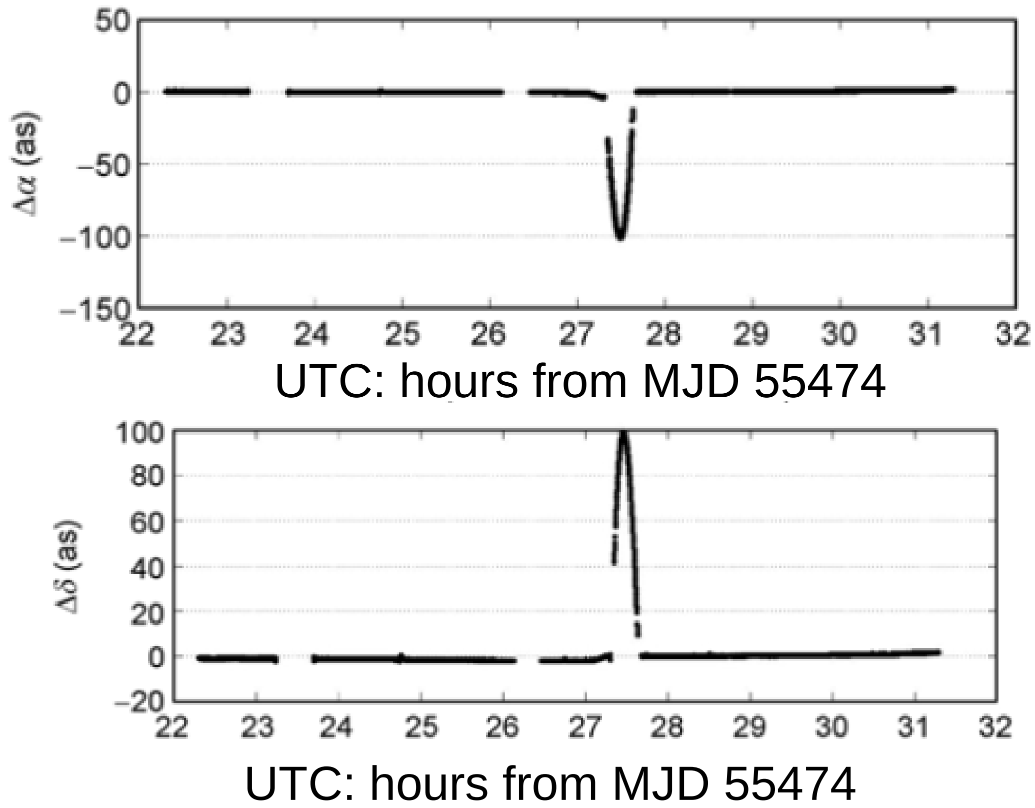
CE-2 mission

- Launched on Oct. 1^{th}, 2010
- Was captured by moon on Oct. 6^{th}, 2010
- 100*100km orbit Oct. 26^{th}
- Descend to 100*15km orbit to obtain the potograph of Sinus Iridum area
- Carry on the X-band system experiments
- Fly to Lagrangian point L2

Improvement on VLBI observations

- DBBC replace ABBC to overcome the non-linear phase frequency response
- More GPS and EGRS data were adopted to fit the clock drifts, and calibrate the instruments delay
- bandwidth synthesis of X-band signal with 40 MHZ bandwidth was introduced into the post-processing mode
- Delay data noise level reaches 0.2ns in the post-processing mode, comparing with 1-2ns level in real-time observation

In orbit maneuver arc



An example of monitoring the orbit maneuver by real-time positioning reduction

Table 3 Trajectory monitoring of the CE-2 satellite near the perilune on 6 October 2010

Epoch(h:m:s)	Semi-major Axis(km)	Eccentricity	selenocentric distance(km)
3: 5:54	5374.397	1.34349	2582.611
3: 6:59	5843.944	1.31506	2503.602
3: 7:54	6128.780	1.30082	2439.114
3: 8:54	6621.276	1.27838	2371.443
3: 9:54	7123.197	1.25882	2307.004
3:10:54	7738.643	1.23829	2245.893
3:11:54	8481.100	1.21744	2188.093
3:12:54	9340.710	1.19759	2134.084
3:13:54	10389.352	1.17780	2084.202
3:14:54	11756.060	1.15718	2038.740
3:15:54	13422.293	1.13780	1997.713
3:16:54	15838.508	1.11676	1961.058
3:17:24	17702.440	1.10445	1943.510
3:18:24	19894.449	1.09304	1915.783
3:22:24	89072.640	1.02072	1847.567
3:23:59	74142.196	0.97504	1851.707
3:24:59	39932.735	0.95364	1857.391
3:25:59	25277.891	0.92695	1863.579
3:26:54	24063.353	0.92307	1880.222
3:28:59	13686.220	0.86486	1921.803
3:29:54	11749.800	0.84276	1945.137
3:30:54	12144.902	0.84793	1972.760
3:31:44	9822.173	0.81138	2001.845
3:32:54	8367.467	0.77940	2041.582
3:33:54	7977.800	0.76772	2077.719
3:34:59	7385.144	0.74884	2118.986
3:35:54	7592.342	0.75576	2155.262
3:36:54	6522.559	0.71524	2196.170

Table 4 Trajectory monitoring of the CE-2 satellite in the experiment of lowering orbit on 26 October 2010

Epoch(h:m:s)	Semi-major Axis(km)	Eccentricity	selenocentric distance(km)
14:13:59	1812.520	0.03066	1771.544
14:14:59	1797.884	0.02342	1769.112
14:15:59	1803.847	0.02524	1767.333
14:16:59	1803.959	0.02542	1765.860
14:17:59	1798.746	0.02379	1764.366
14:18:59	1804.193	0.02546	1763.275
14:19:59	1804.250	0.02559	1762.111
14:20:54	1804.282	0.02555	1761.244
14:20:59	1811.456	0.02811	1762.019
14:21:59	1800.111	0.02376	1760.107
14:22:54	1804.019	0.02548	1759.596
14:23:59	1804.089	0.02551	1758.962
14:24:59	1803.858	0.02544	1758.453
14:25:59	1804.004	0.02550	1758.182
14:26:14	1806.188	0.02737	1756.924
14:27: 4	1798.321	0.02270	1757.637
14:28:59	1799.554	0.02336	1757.546
14:29:14	1806.525	0.02766	1756.784
14:29:24	1802.478	0.02598	1755.763
14:29:29	1804.695	0.02736	1755.520
14:29:44	1803.951	0.02683	1755.802
14:29:49	1805.988	0.02692	1757.804
14:29:59	1799.061	0.02282	1758.185
14:30:59	1804.222	0.02513	1759.744
14:31:59	1803.537	0.02524	1759.403
14:32:59	1805.750	0.02696	1759.586
14:33:49	1803.486	0.02523	1760.822
14:34:24	1803.343	0.02519	1761.299

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△DOR experiment analysis

ERS	SAT
Wide band	Narrow band
Post-processing	Real-time
For clock dif, atm	With the help of ERS obs

During CE-1、CE-2，VLBI observation noise reached 2-5ns level。

Hard to improve the precise, ΔDOR need to be introduced.

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ΔDOR technology

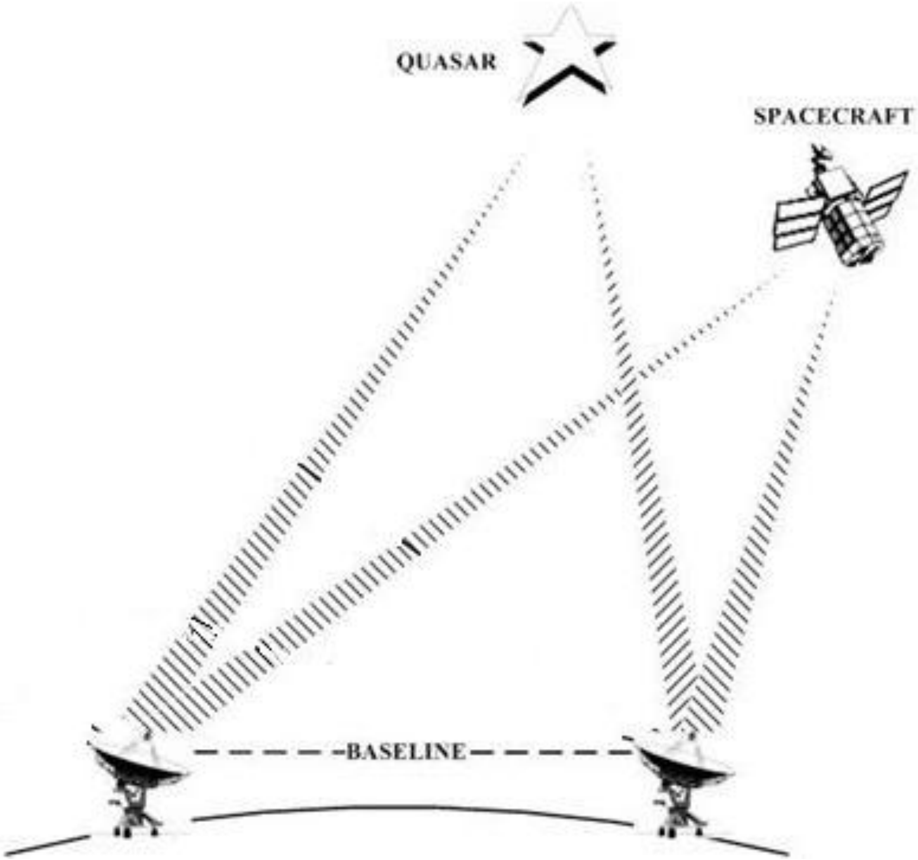
$$\tau_o = \tau_g + \tau_c + \tau_i + \tau_a + \cdots$$
$$= \tau_g + \tau_{err}$$

$$\tau_{o\_ers} = \tau_{g\_ers} + \tau_{err\_ers}$$

$$\tau_{o\_sat} = \tau_{g\_sat} + \tau_{err\_sat}$$

$$\tau_{err\_ers} \approx \tau_{err\_sat}$$

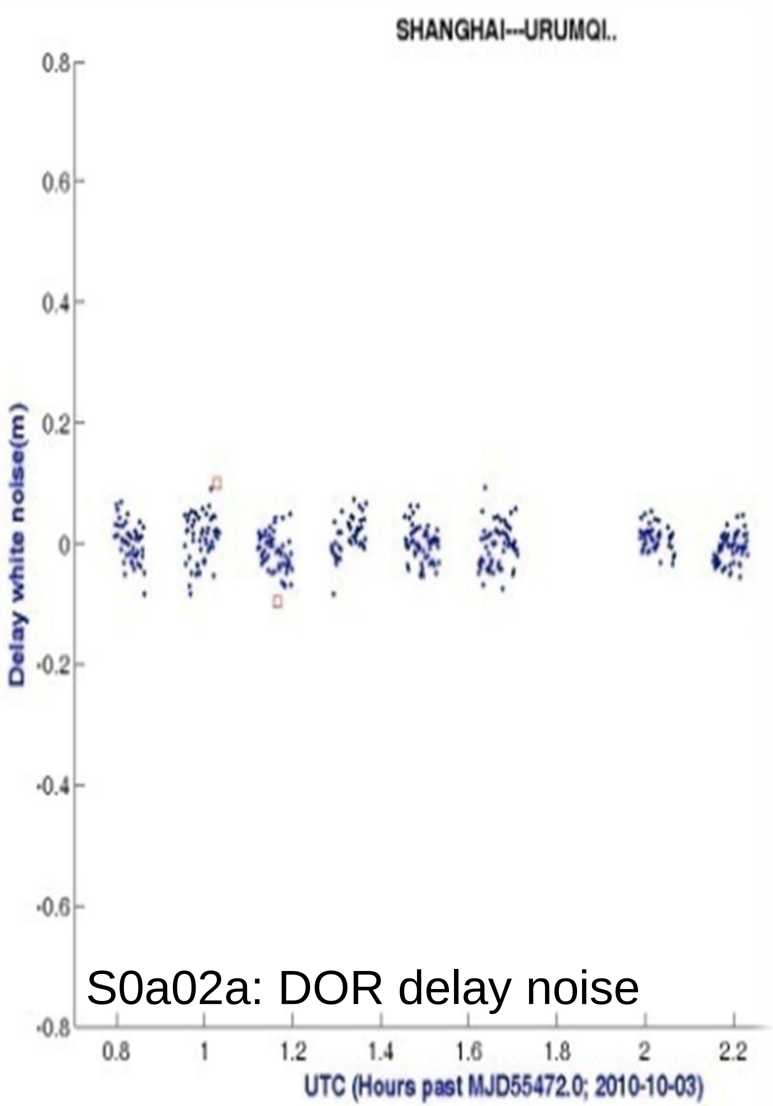
$$\tau_{g\_sat} = \tau_{o\_sat} - \left(\tau_{o\_ers} - \tau_{g\_ers}\right)$$

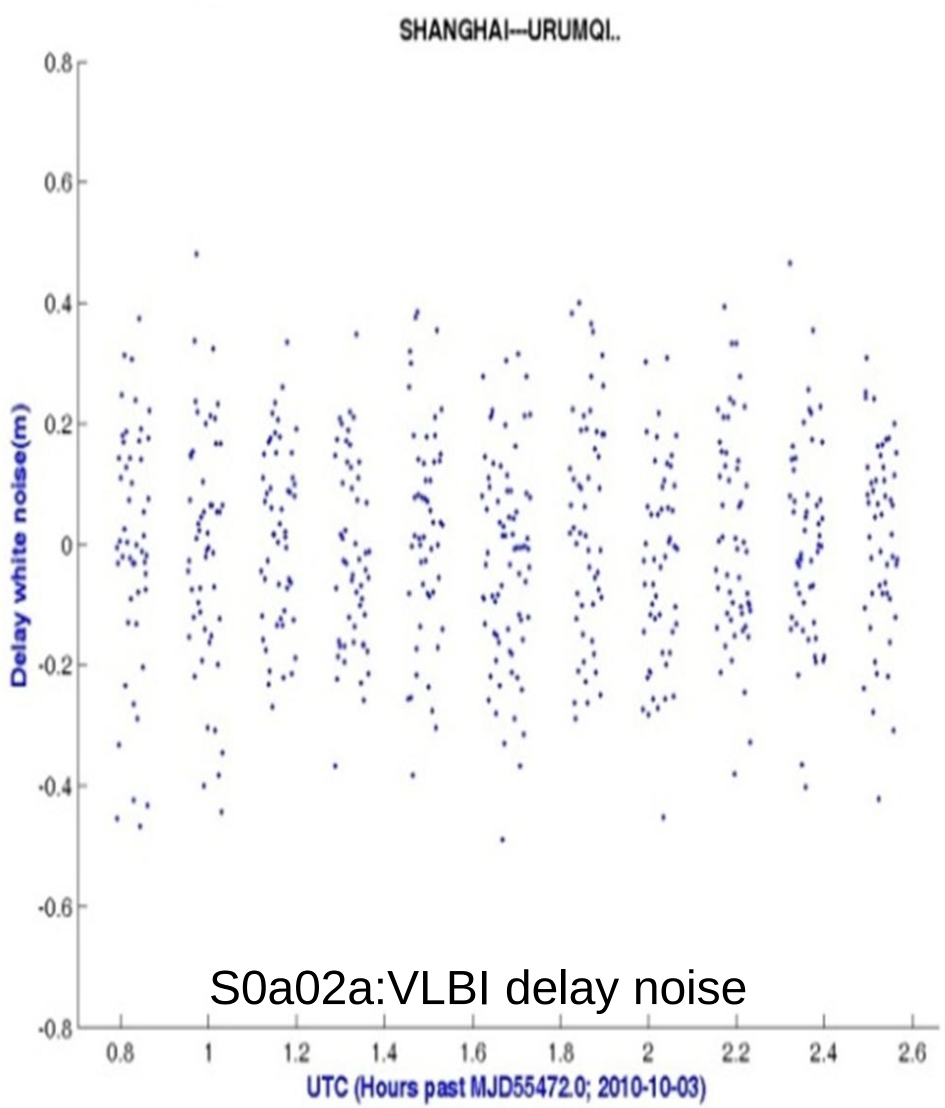


Positioning analysis with ΔDOR observations

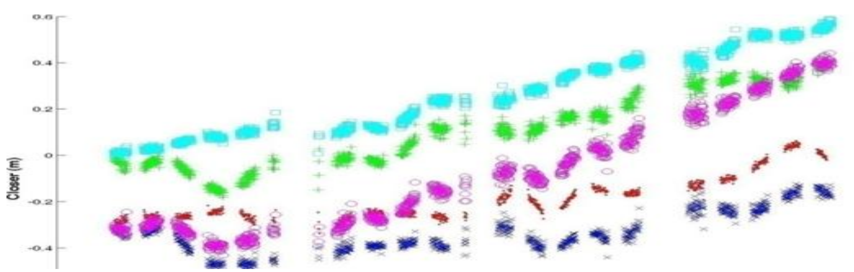
- ✓ Observation ability
- ✓ baseline closure error
- ✓ Positioning results

1、Observation ability

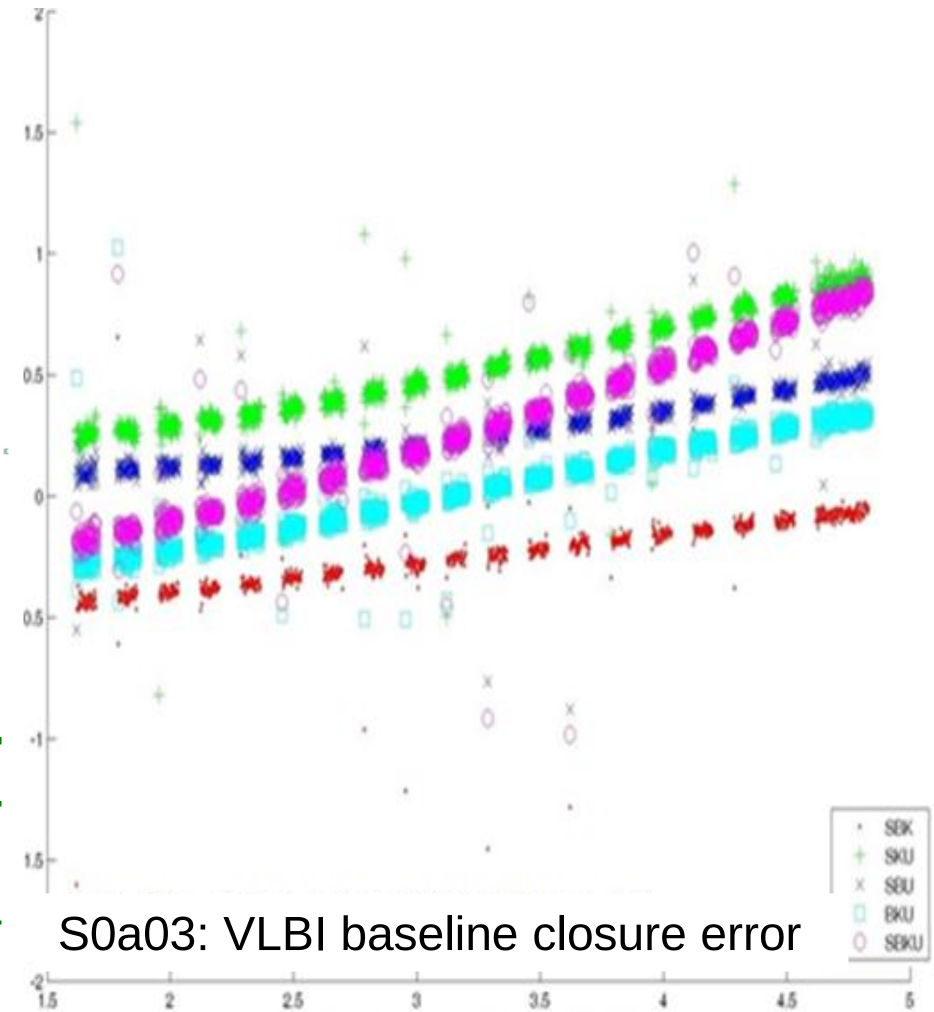




3、Baseline closure error



S0a03: DOR baseline closure error



S0a03: VLBI baseline closure error

Table baseline closure error

ID	s0a02a				s0a03a			
TP	DOR		VLBI		DOR		VLBI	
	c/m	sc/m	c/m	sc/m	c/m	sc/m	c/m	sc/m
SBK	-0.281	0.385	-0.447	0.358	-0.188	0.065	-0.244	0.162
SKU	0.017	0.407	0.087	0.378	0.109	0.116	0.548	0.166
SBU	-0.395	0.414	-0.909	0.398	-0.334	0.098	0.269	0.166
BKU	0.131	0.412	0.552	0.375	0.263	0.110	0.036	0.160
SBKU	-0.264	0.564	-0.359	0.381	-0.072	0.122	0.305	0.173

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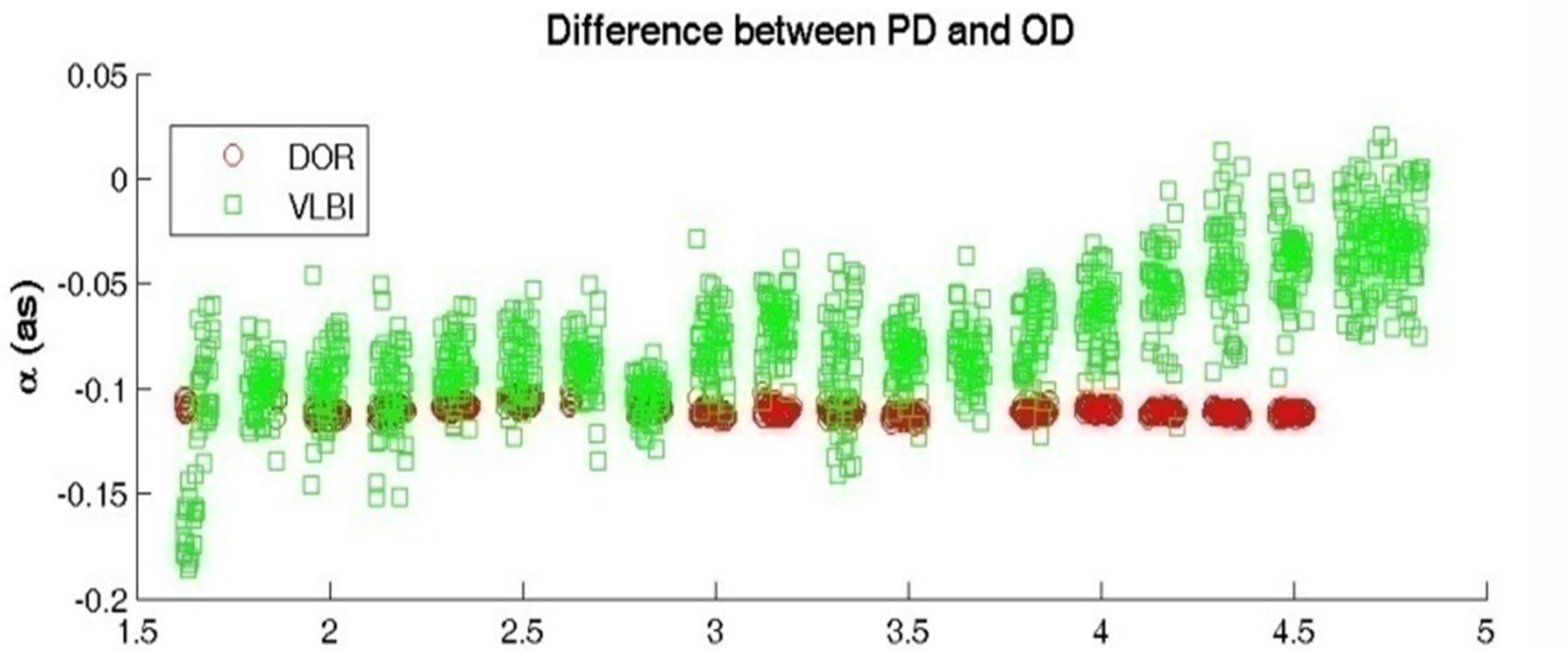
3、 Positioning results

Angular position fluctuation

ID	s0a02a		s0a03a	
ID	DOR	VLBI	DOR	VLBI
Ra/as	0. 005	0. 017	0. 003	0. 022
De/as	0. 010	0. 057	0. 007	0. 040



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ΔDOR experiment analysis

DOR is superior to VLBI through the test about the observation ability, delay baseline closure error and final results.

Whereas its not the true △DOR since the precise of ERS geometrical delay can only reach to ns level for requirements in project.

To make full use of △DOR advantages in accuracy， ERS geometrical delay should be precisely determined.

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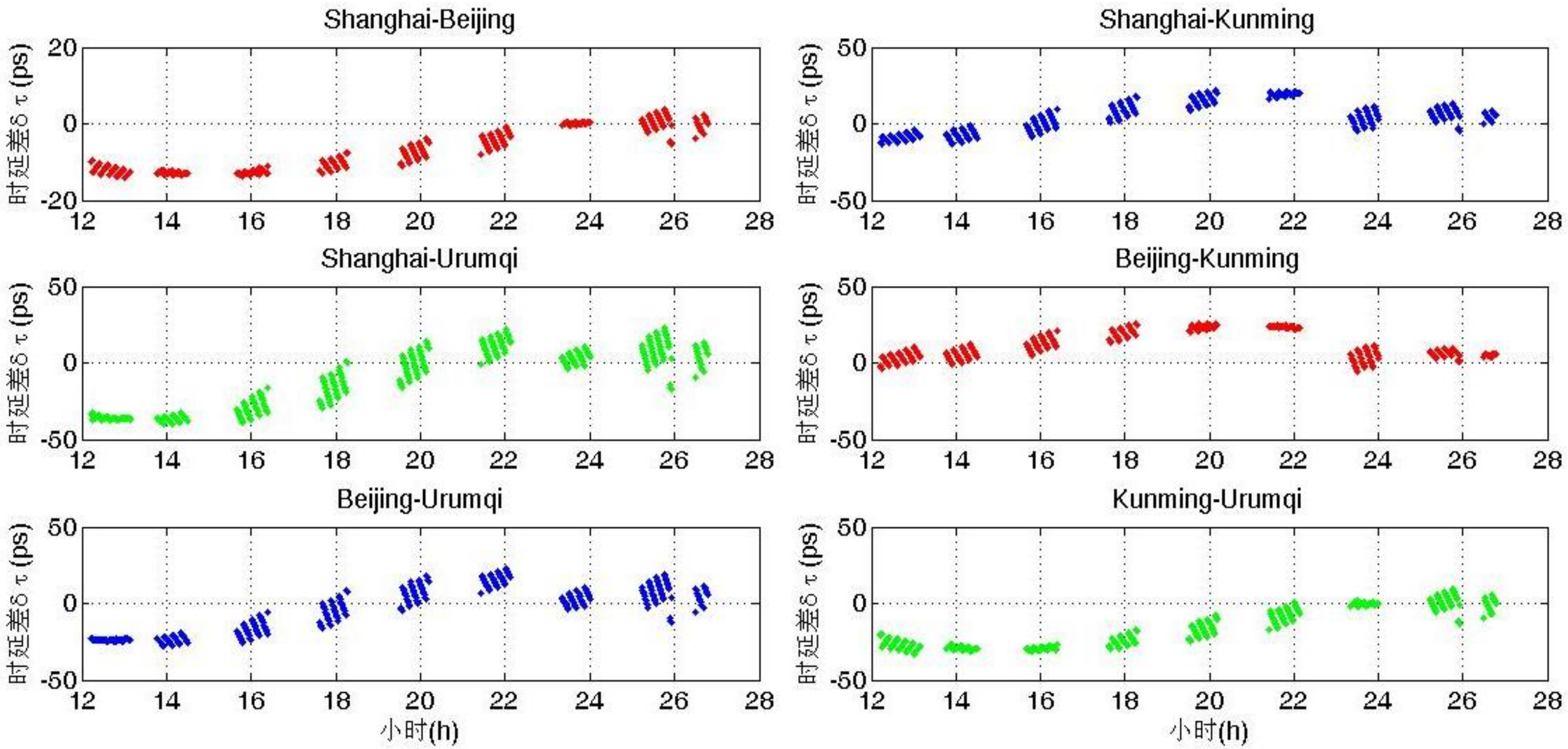
2、Develop ERS geometrical delay software

Comparison between Occam 6.3 and my program

	OCCAM6.3	My software
Planetary ephemeris	DE405	DE421
ERS catlog	ICRF(ICRF2000.cat)	ICRF2（IERS2010）
Solid earth tide	IERS2000	IERS2010
Celestial origin	Equinox	CIO
Precesion and nutation	IAU1976/80 或 IAU2000A	IAU2006
Free core nutation	None	Lambert IERS2010
Ocean tidal influence on UT1	IERS1992(Yorder,1981 Brosch1989)	More models in IERS2010
Variations in polar motion	IERS2003（no linear and zonal tides term）	IERS2010
Libration in earth rotation axis	None	UTLIBR
Diurnal and semi-diurnal terms of ocean tide influence on EOP	Choose between Ray and Eanes	Eanes
Earth rotation angle	GAST(Equinox)	ERA（CIO）
Relativity	3 degree term	No 3 degree term

2. Comparison and Evaluation



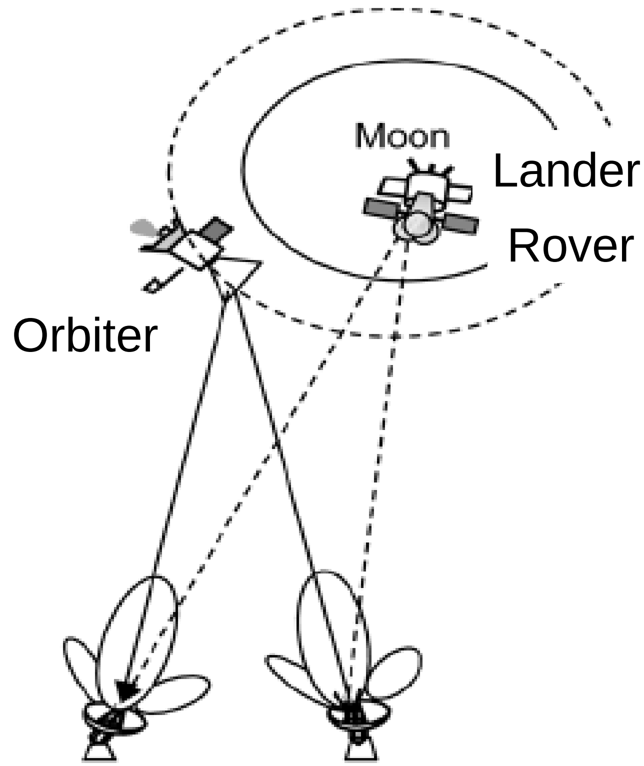
Difference With two mode is 10ps order of magnitude，possible explanations will
Take the differences on origin point, the frame bias and free core nutation, ERS catlog
And Ephemeries into account.

4、Possible application of positioning in CE-3

- New challenge in CE-3
- Strategy in positioning simulation

CE-3 satellite

- Lander will soft-land on the lunar surface for automatic exploration
- Rover will walk on the moon



New challenge in CE-3

- the ΔDOR and SBI methods are adopted, the old models should be updated synchronously
- when lander land, observation will accumulated on the moon as time variation

—multi-wave front, mult-stations solution,

—constrained by geometry and lunar topography

- the rover will move and stop in different sessions

—static relative positioning and trajectory monitoring

positioning simulation

- Strategies

Initial value: (30,40) in LFF

Simulation for the observation time series on Oct. 8th 2012

EOP prediction for the whole year was adopted

Model established for relative positioning

Observation ability

VLBI delay observation

Phase delay $\tau_{phase} = \dfrac{\phi}{2\pi f}$, $\sigma_{phase} = \sigma_{\phi} / 2\pi f \approx 0.2\sigma_{\phi} / f$

Group delay $\tau_{group} = \dfrac{\partial\phi}{\partial(2\pi f)}$ $\sigma_{group} = \sigma_{\phi} / 2\pi\sigma_{f} \approx 0.3\sigma_{\phi} / \Delta f$

Phase uncertainty $\sigma_{\phi} = \dfrac{1}{R_{SN}}$

Signal to noise ratio

$$R_{SN} = \sqrt{\frac{A_m\eta_m A_n\eta_n}{T_{sm}T_{sn}}}\sqrt{\frac{\Delta\nu\tau_{acc}}{2}}$$

For the SH-Ur baseline with length of 3000km, X-band, 40MHZ bandwidth, accuracy of group delay is 0.1ns level, phase delay: 1ps.

Model established for relative positioning

ERS-S/C relative positioning model

$$\Delta\tau = \tau_{sat} - \tau_{egrs} = \frac{\left|\vec{R}_2(t_2) - \vec{R}_s(t_1 - t_r)\right| - \left|\vec{R}_1(t_1) - \vec{R}_s(t_1 - t_r)\right|}{c} - \frac{-\vec{B}\cdot\hat{S}}{c} + \Delta\tau_e$$

Lander-Rover relative positioning mode

$$\vec{\rho} = \vec{S}_m - \vec{\vec{C}}^T \cdot \vec{r}_i + \vec{\vec{R}} \cdot \vec{r}_t$$

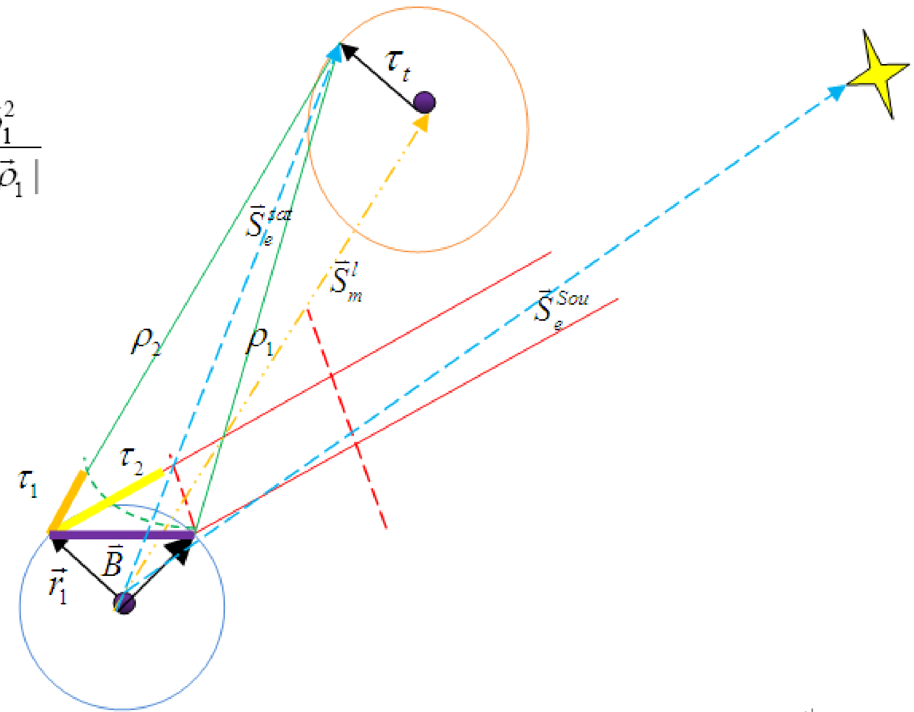
$$\vec{\vec{R}} = \vec{\vec{R}}_3(-\Lambda)\vec{\vec{R}}_1(-i_s)\vec{\vec{R}}_2(-\Omega')$$

$$c(\tau_r - \tau_l) = (|\vec{\rho}_4| - |\vec{\rho}_3|) - (|\vec{\rho}_2 - \vec{\rho}_1|) = \frac{\vec{\rho}_4^2 - \vec{\rho}_3^2}{|\vec{\rho}_4| + |\vec{\rho}_3|} - \frac{\vec{\rho}_2^2 - \vec{\rho}_1^2}{|\vec{\rho}_2| + |\vec{\rho}_1|}$$

$$= \frac{-2\vec{S}_e \cdot \vec{\vec{C}}^T(\vec{r}_2 - \vec{r}_1) - 2(R\cdot\vec{r}_r)[\vec{\vec{C}}^T \cdot (\vec{r}_2 - \vec{r}_1)]}{|\vec{\rho}_4| + |\vec{\rho}_3|}$$

$$- \frac{-2\vec{S}_e \cdot \vec{\vec{C}}^T(\vec{r}_2 - \vec{r}_1) - 2(R\cdot\vec{r}_l)[\vec{\vec{C}}^T \cdot (\vec{r}_2 - \vec{r}_1)]}{|\vec{\rho}_2| + |\vec{\rho}_1|}$$

$$cd(\tau_r - \tau_l) = \frac{-2[\vec{\vec{C}}^T \cdot (\vec{r}_2 - \vec{r}_1)]R \cdot d(\vec{r}_r - \vec{r}_l)}{|\vec{\rho}_2| + |\vec{\rho}_1|}$$



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Conclusion

- Positioning plays an irreplaceable role on the judgement and monitor of pivator arcs like lunar capture, orbit manoevor, orbit transfer, land in CE-1 and CE-2.
- DOR experiment showed the improvement on the observation ability，while the relative model should be updated and tested.
- CE-3 S/C will bring new challenge on the positioning. Data simulation and results analysis need to be done. High-precision positioning model will be introduced into the solution.

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Outlook

- ERS geometrical delay calculating software should be tested and adjusted to meet the requirement of CE-3

- Simulation for testing the high-precision model for Lander and Rover should be done, especially when the Rover surf-walking process

- The prior CE mission adopt the coordinate of reference points ITRF2000, with precision of cm level. The coordinate in ITRF2008 should be obtained by design observation for strong ERS aiming at the calibration.

- Study the physic mechanism by analyzing the time series of collocation sites.

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Thank you !

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