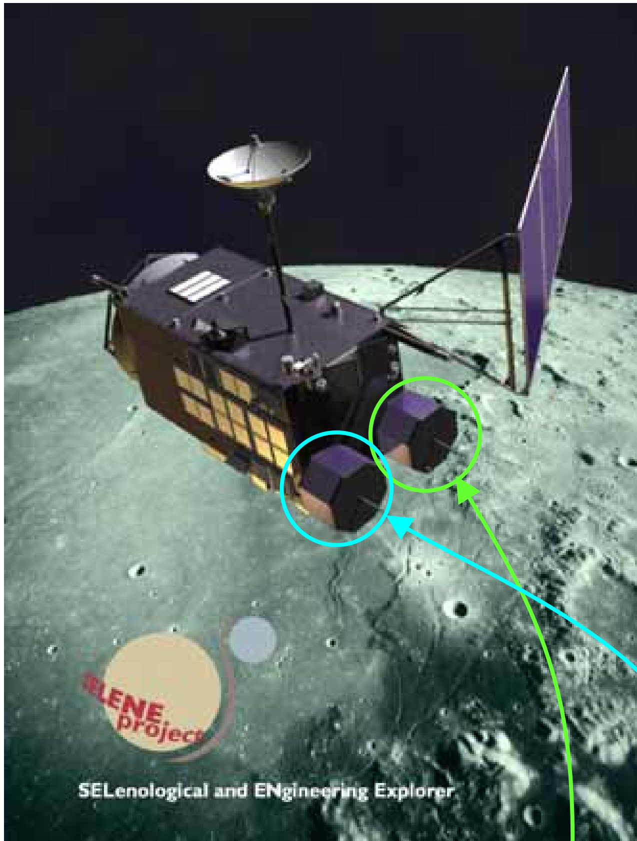
SELENEのVLBIとDoppler技術を用いた月重力場の計測

劉 慶会　菊池冬彦　花田英夫　Sander Goossens
松本晃治　河野宣之　浅利一善　鶴田誠逸　石川利昭
原田雄司　石原吉明　岩田隆浩[2]　並木則行[3]　野田寛大
佐々木晶　柴田克典　岩館健三朗　田村良明
寺家孝明　酒井俐　VERA team

National Astronomical Observatory of Japan (RISE+VERA);
[2]JAXA, Japan; [3]Kyushu University, Japan

第6回VERAユーザーズミーティング @三鷹

Kaguya(SELENE) Selenological and Engineering Explorer



● SELENE consists of ;

1) Main Orbiter
2) Relay Satellite (Rstar)
3) VLBI Radio Satellite (Vstar)

chemical elements	X-ray Spectrometer Gamma-ray Spectrometer
mineralogy	Spectral Profiler Multi-band Imager
surface structure	Terrain Camera Rader Sounder Laser Altimeter
surface environment	Magnetometer Plasma Imager Charged Particle Spectrometer Plasma Analyzer Radio Science Observation
imaging	High Definition Television Camera
gravity field	Relay Satellite Transponder Differential VLBI Radio Sources

Two techniques for lunar gravity field

Doppler technique **(Sensitivity in line-of-sight)**

Spin influence on Doppler measurement

Remove spin influence using LPF

Orbit determination

Global lunar gravity field

Phase characteristic of onboard antenna

Differential VLBI technique

(Sensitivity in direction perpendicular to LOS)

SELENE VLBI observation

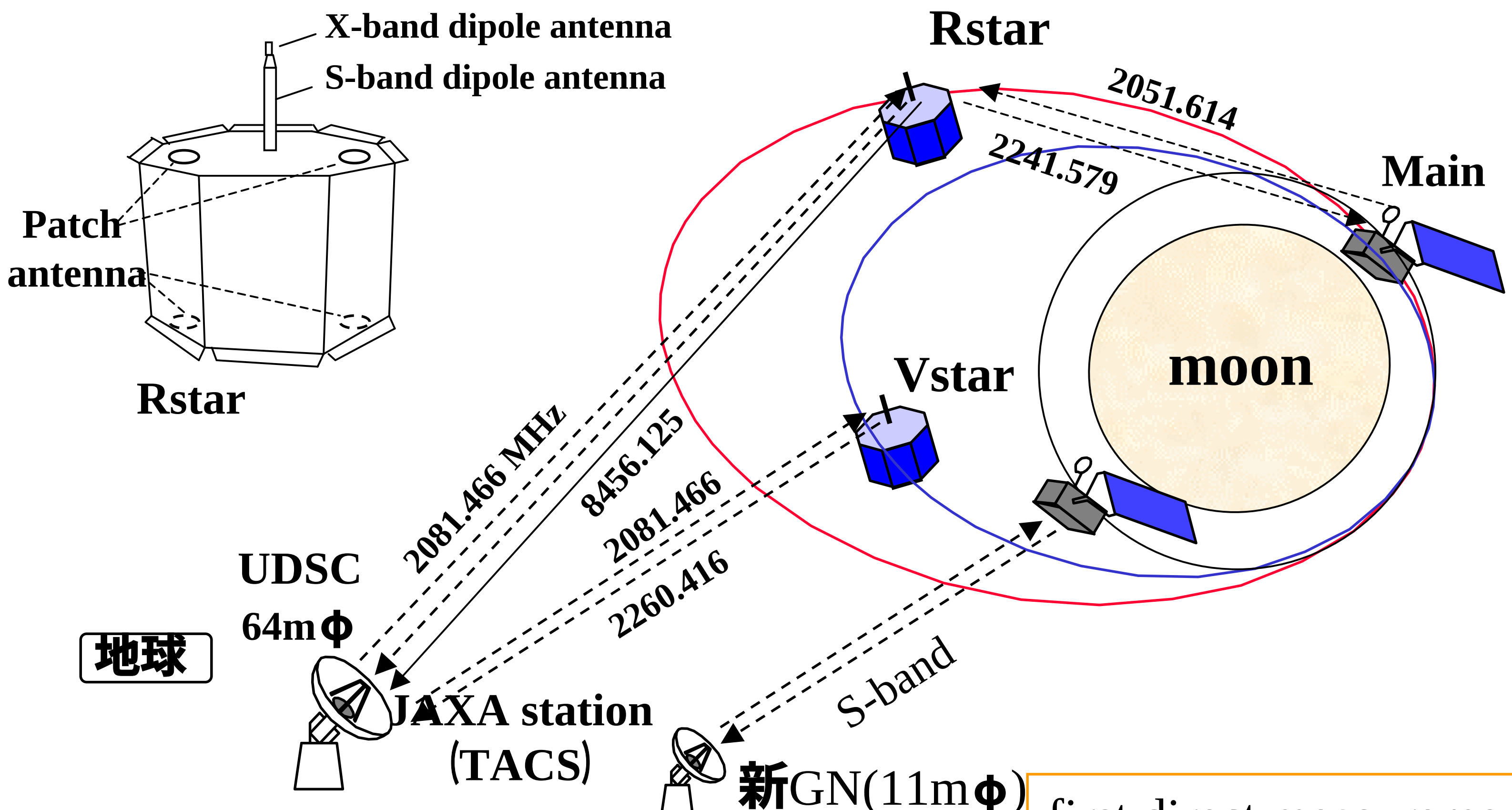
Differential phase delay

Orbit determination

Gravity experiment by 2- and 4-way Doppler in SELENE

Sensitivity in line-of-sight

(1) 4-way Doppler of main-satellite for far side (2) 2-way Doppler and range of Rstar and Vstar
(3) Doppler and range of satellites for near side



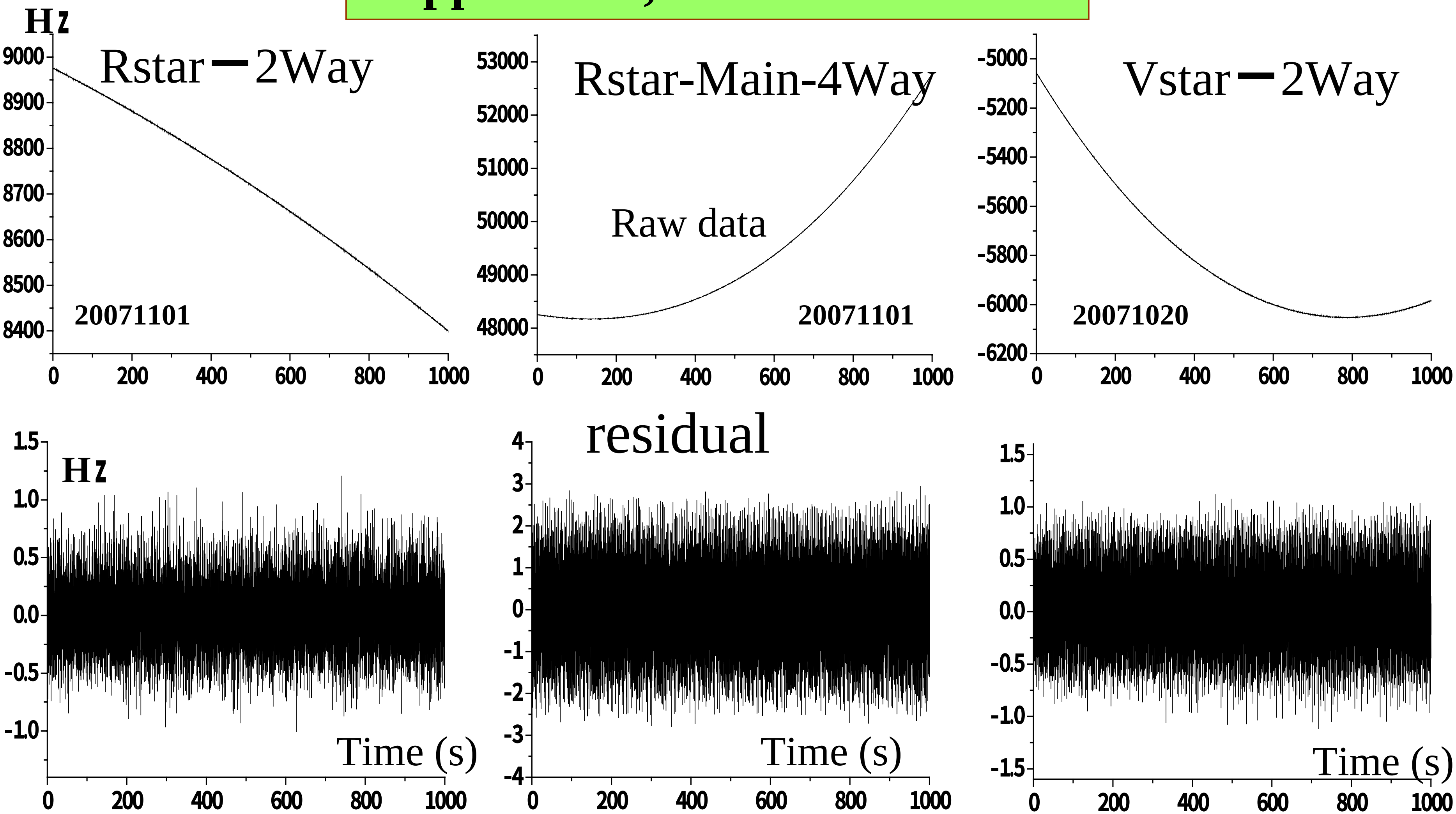
first direct measurement of the gravity field on the far side

2way: m/s = 0.5 * C /(k1* fup) *Hz

4way: m/s=(f4way-fbias)*C/(k5*k6*fup)

fbias=fref-(k2+k5*k6)*fup; fref=8456.125M (30kHz)

Doppler data, Time interval 0.1s

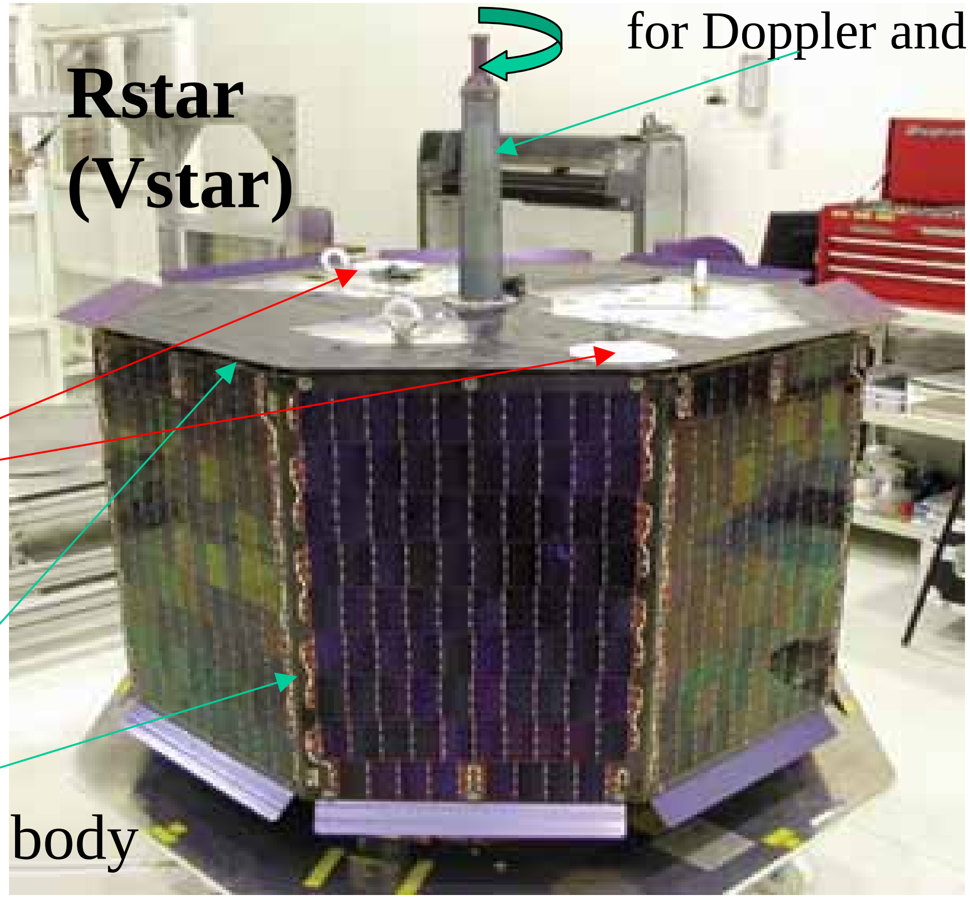


0.293 Hz RMS **1.028 Hz RMS** **0.355 Hz RMS**

RMS is larger than the desired accuracy 0.0033Hz (0.2mm/s) even if by using 10 s integration

Irregularities in the phase characteristics of antennas onboard spin satellites

S/X Dipole antenna
for Doppler and VLBI



Patch Antenna
link Rstar and Main

Octagonal prism body

Qinghui Liu et. al ``New method of measuring phase characteristics of antenna using Doppler frequency measurement technique", **IEEE Trans**., Antenna and Propa., 3312-3318, 2004.

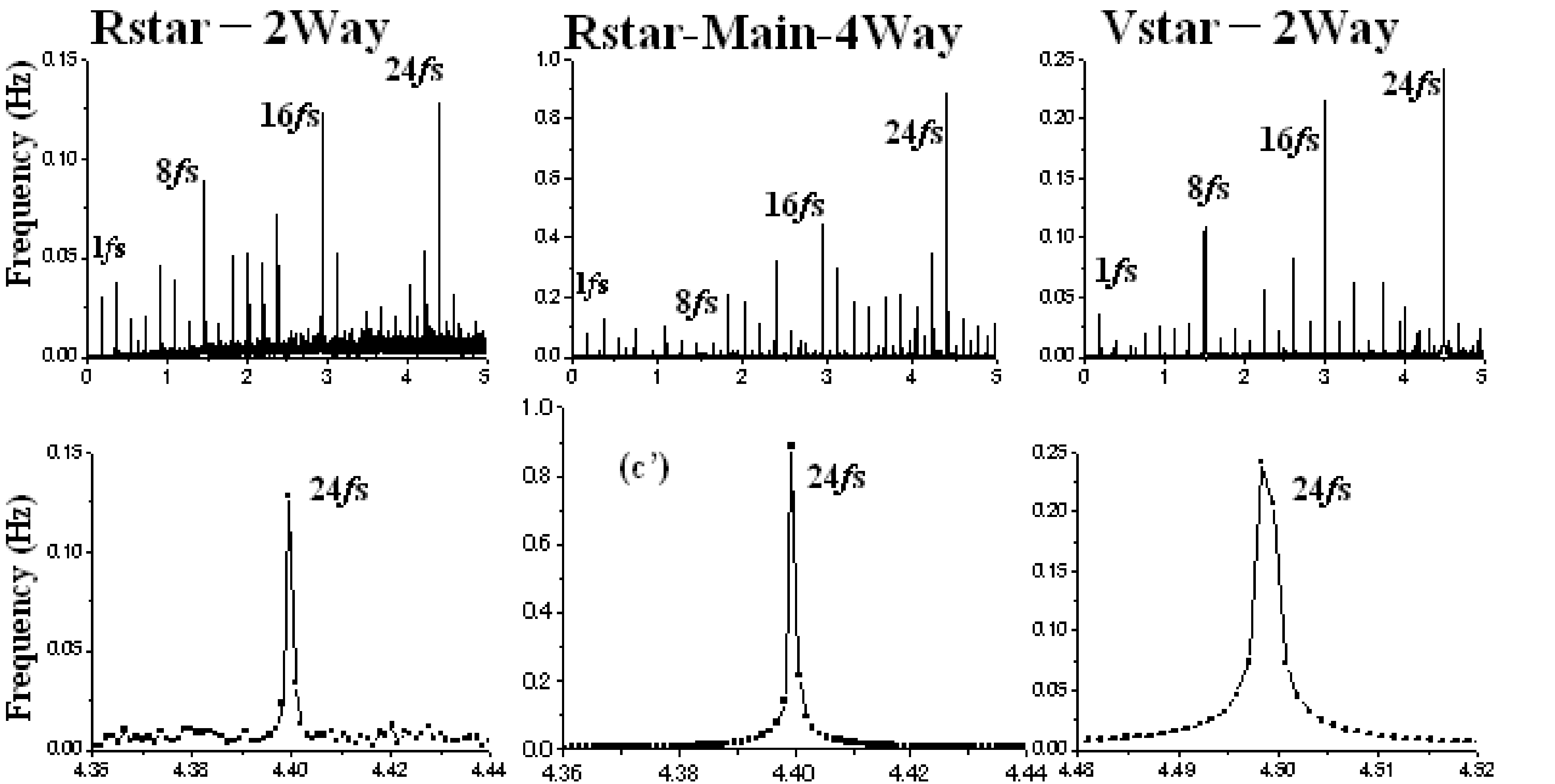
Qinghui Liu et. al ``Effect of In-situ Phase Characteristics of Antennas Onboard Spin Satellites on Doppler Measurements for lunar gravity field ", **IEEE Trans**., A&M, (submitted)

Influence on Doppler measurement:

2WAY: phase characteristics of S-band antenna + octagonal prism body

4WAY: phase characteristics of S- ,X-band and patch antennas + octagonal prism body + offset of patch antennas from the rotation axis

Doppler-Residual Spectrum (harmonic components of n*fs)



fs=4.39968/24=0.18332Hz
T=**5.4549s**

fs=4.39968/24=0.18332Hz
T=**5.4549s**

fs=4.4988/24=0.18745Hz
T=**5.3348s**

Estimate spin frequency *fs* with an accuracy 0.0001 Hz

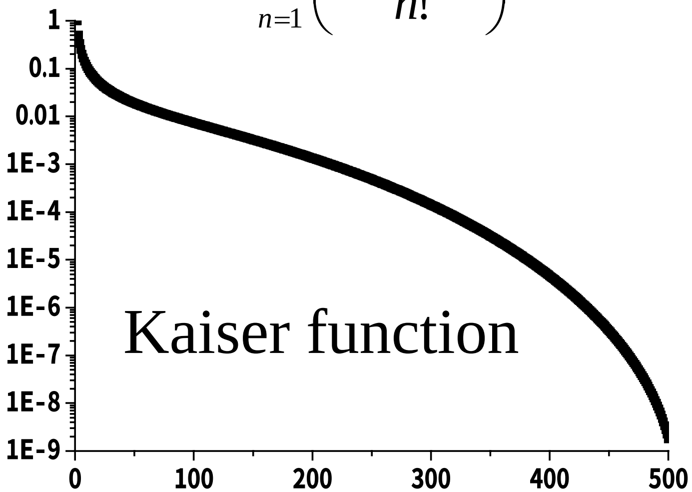
Remove spin influence using LPF

Linear phase LPF using Kaiser window function

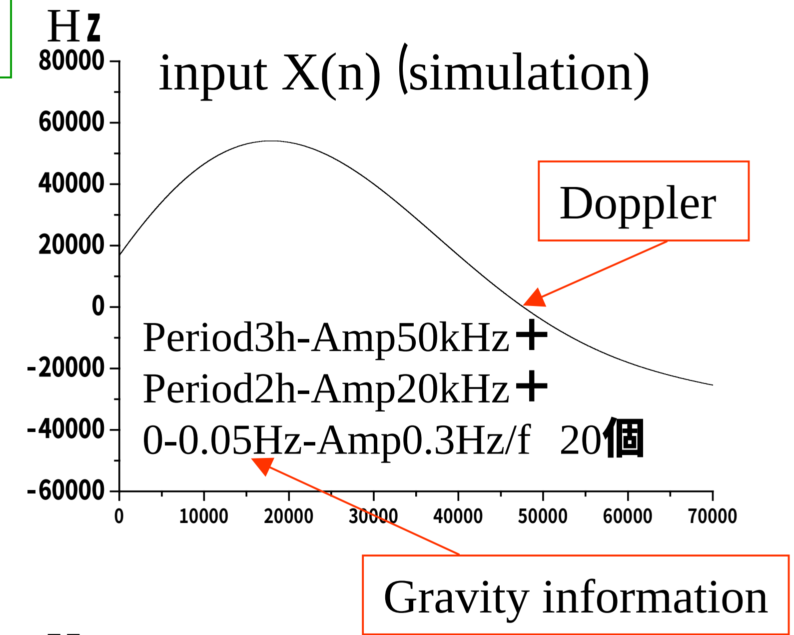
Kaiser function

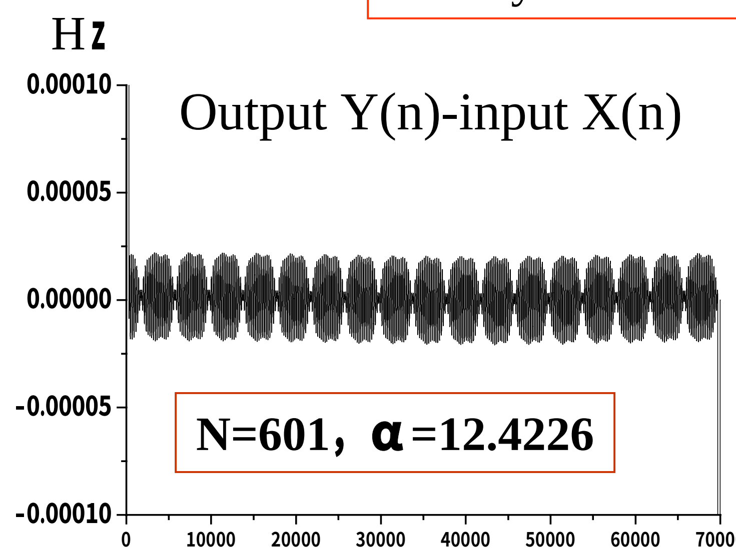
$$W_k = \begin{cases} \dfrac{I\left(\alpha\sqrt{1-(2k/(N-1))^2}\right)}{I_0(\alpha)} & k \le (N-1)/2 \\ 0, \quad k > (N-1)/2 \end{cases}$$

$$I_0(x) = 1 + \sum_{n=1}^{\infty}\left(\frac{(x/2)^n}{n!}\right)^2$$



Important to give a suitable value for α





Accuracy for conserving gravity information in 0-0.05Hz → **0.00002Hz**

Sorry!

10 pages (10-20) were deleted for Doppler

Summary on Doppler technique

(Sensitivity in line-of-sight)

1. 2way-Doppler: 0.1mm/s RMS @ 0.1s after LPF
2. 4way-Doppler can also be determined at a high accuracy after LPF, and the gravity signals on the far side were detected firstly.
3. SELENE lunar gravity field model: SGM90e

Differential VLBI technique

(Sensitivity in direction perpendicular to LOS)

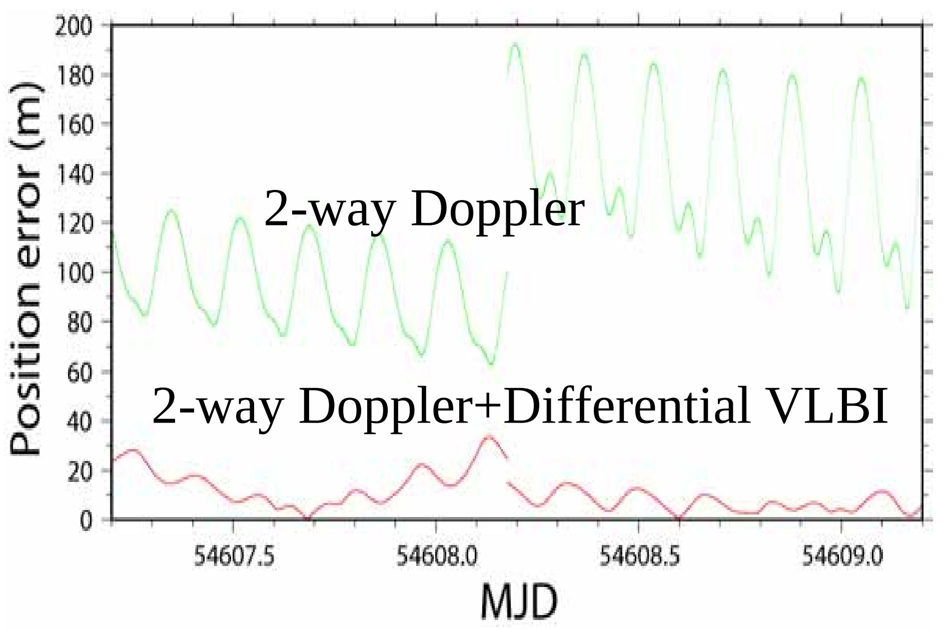
SELENE VLBI observation

Differential phase delay

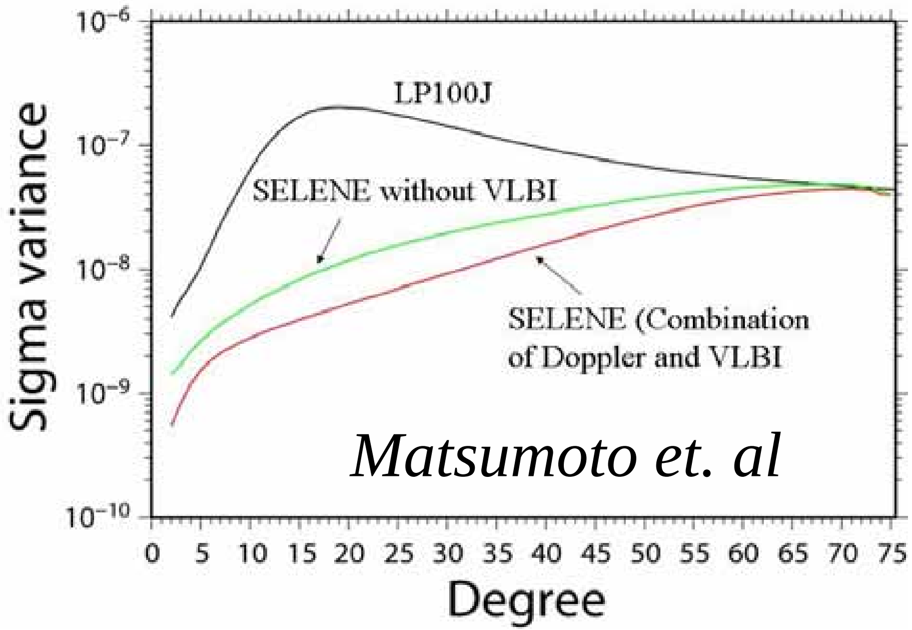
Orbit determination

Why do VLBI observations in SELENE?

Position error of Rstar



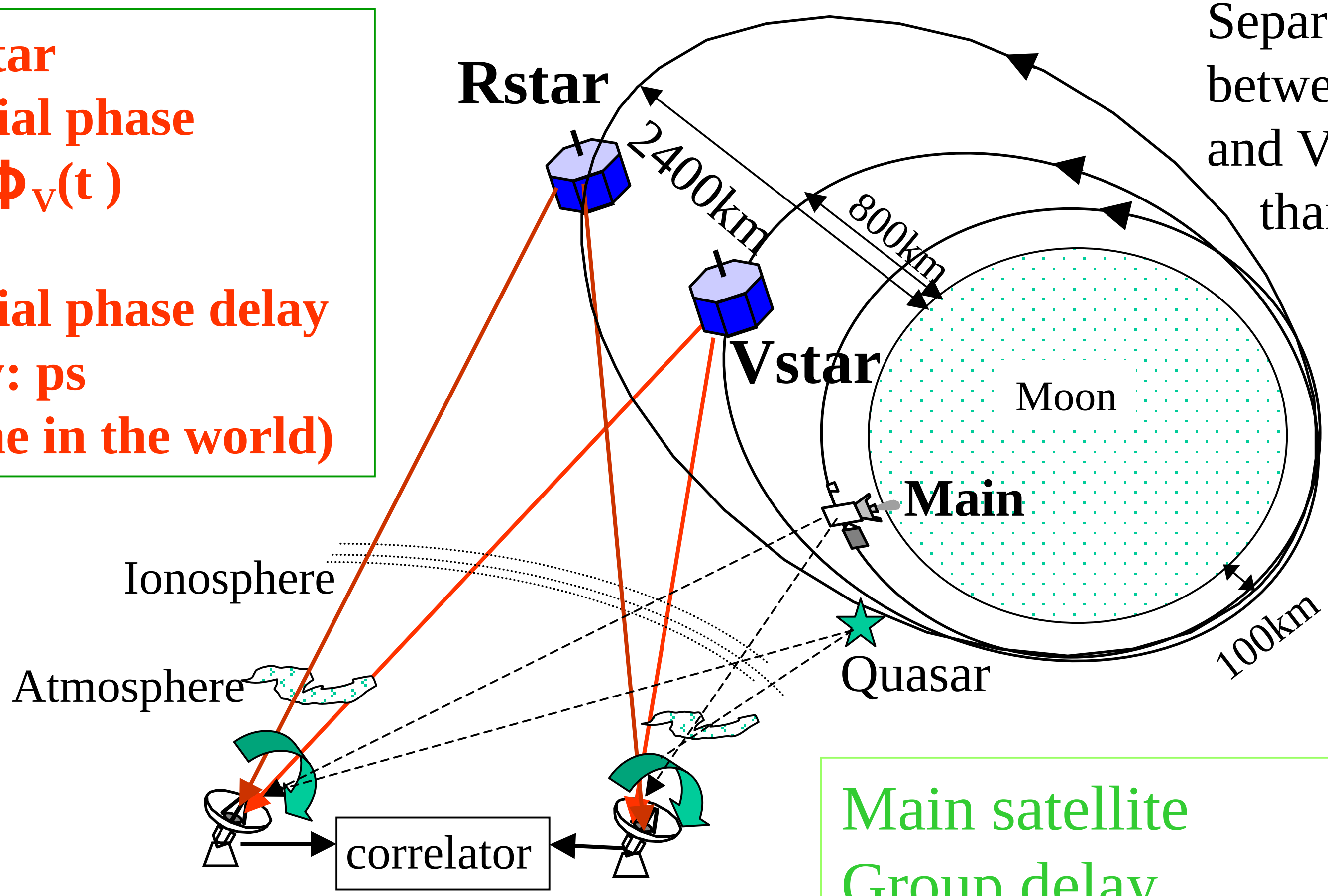
Anticipated coefficient sigma degree variances of spherical harmonic of lunar gravity field



Simulation results

VLBI observations in SELENE
(Sensitivity in direction perpendicular to LOS)

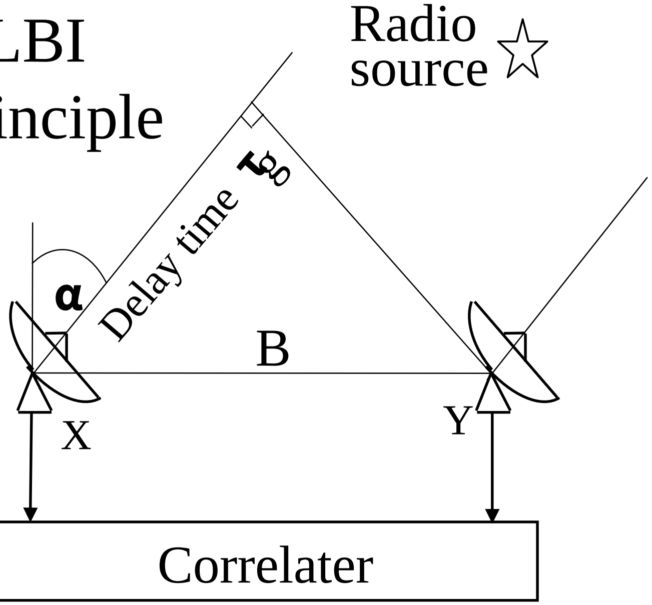
Rstar Vstar
Differential phase
$\Phi_R(t) - \Phi_V(t)$
↓
Differential phase delay
Accuracy: ps
(First time in the world)



Separate angle between Rstar and Vstar is less than **0.9deg**

Main satellite
Group delay
Accuracy: ns
(Conventional method)

VLBI principle



Time delay $\tau g = B\sin\alpha/c$

SELENE MAIN and other spacecrafts
Bandwidth 10MHz

Group delay $\tau g = \Delta phase/\Delta freq.$

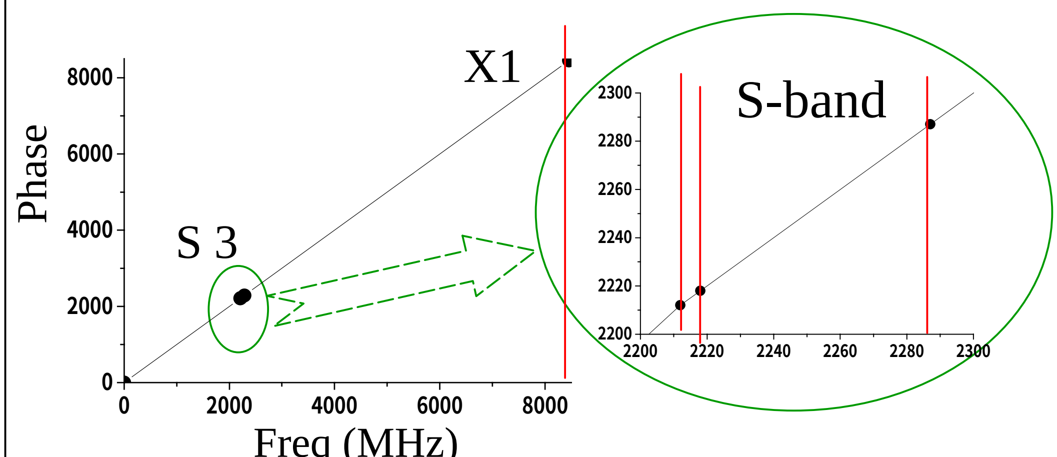
When error of phase is 3.6 deg,
Error of **group delay** 3.6/360/**10M=1ns**

τg=Phase/frequency

2π ambiguity

Error of phase in SELENE have to be less than
<4.3 deg in S-band
severe condition

Rstar&Vstar Differential phase delay

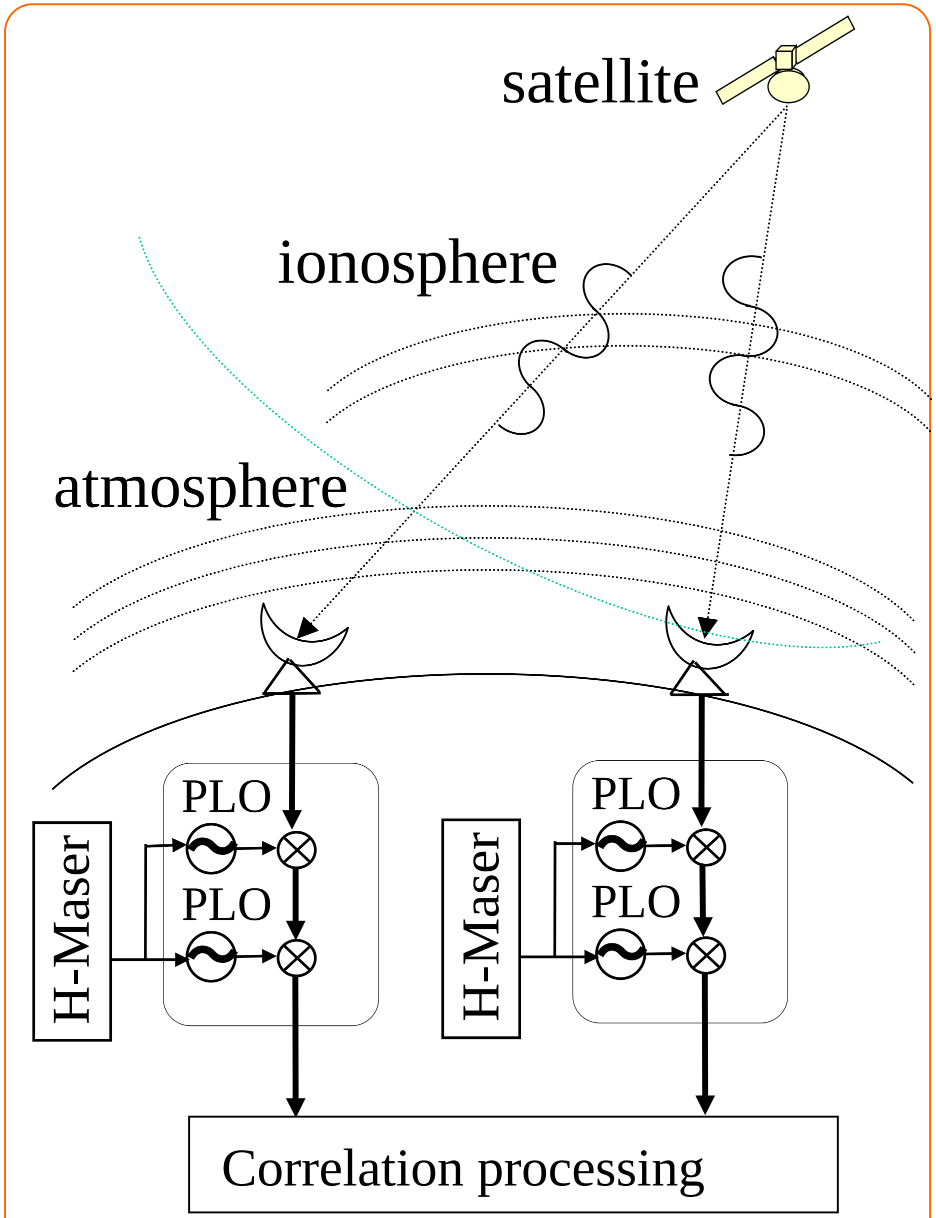


When error of phase is 10 deg
Error of **phase delay** 3.6/360/**8456M=1ps**

Origin of phase fluctuation

- frequency variation of radio wave (temporal、spatial)
- ionosphere
- atmosphere
- thermal noise
- phase variation in receiver

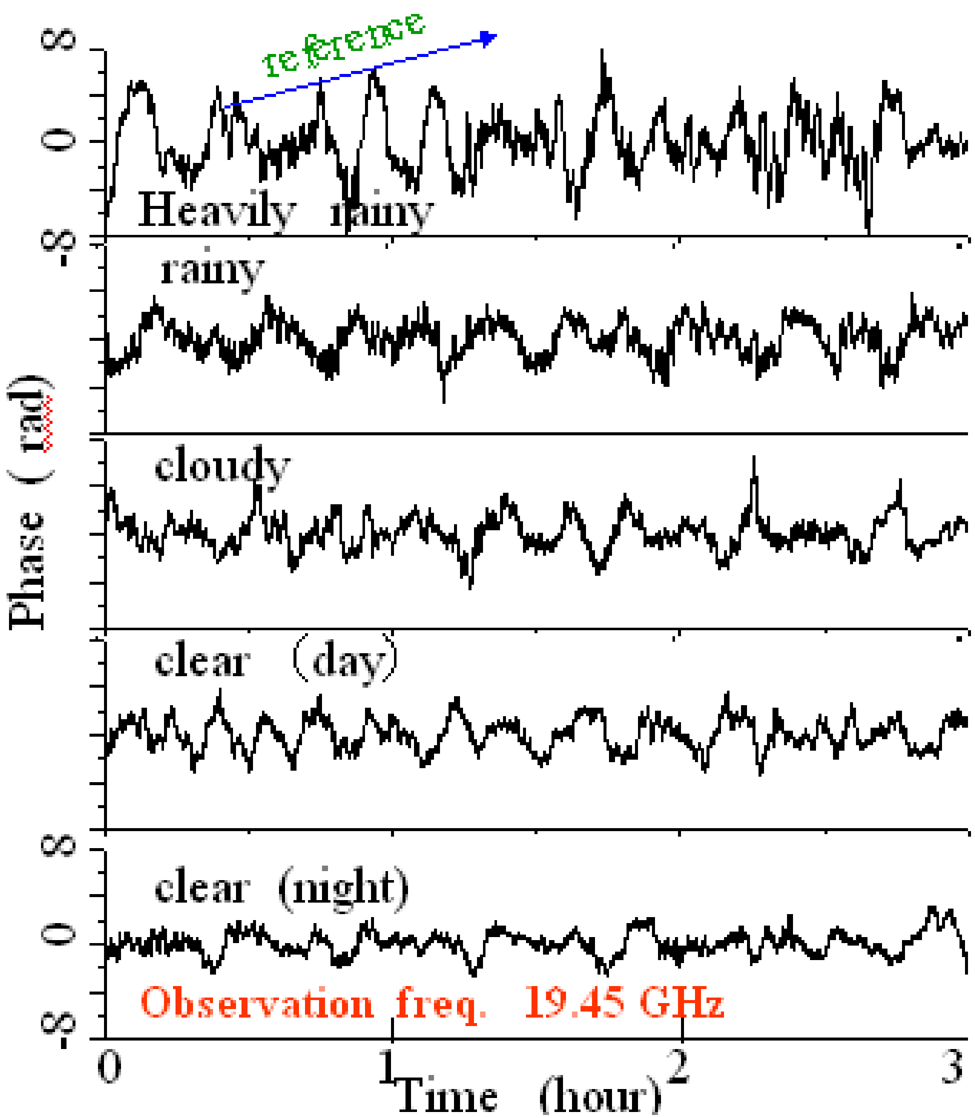
It is difficult to obtain the correlation phase with an accuracy of 4.3 deg

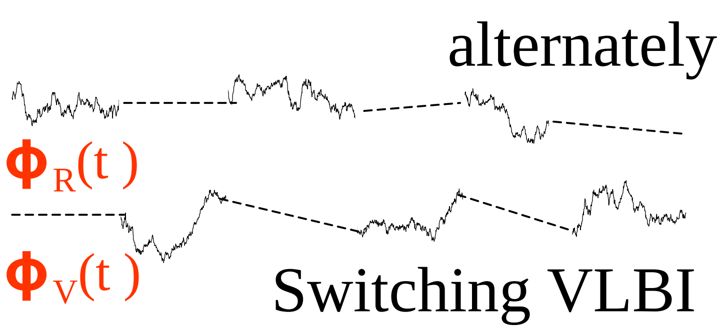


Atmospheric phase fluctuation

Qinghui Liu, et. al, **IEEE Trans**., Antenna and Propa., Apr. 2005.

Nishio Masanori, Qinghui Liu, et.al, **IEEE Trans**., Antenna and Propa., July 2007.

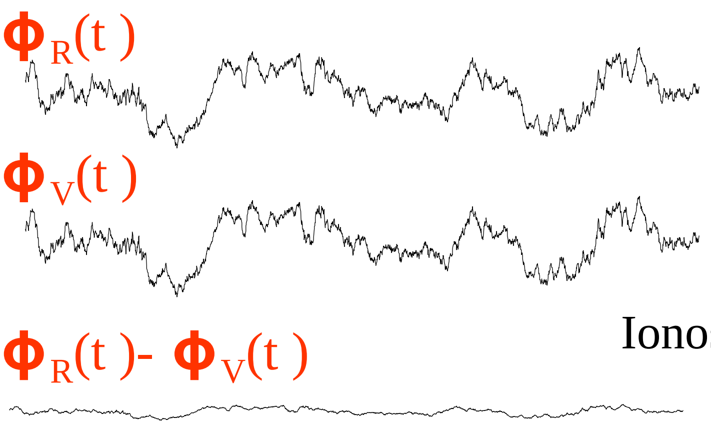


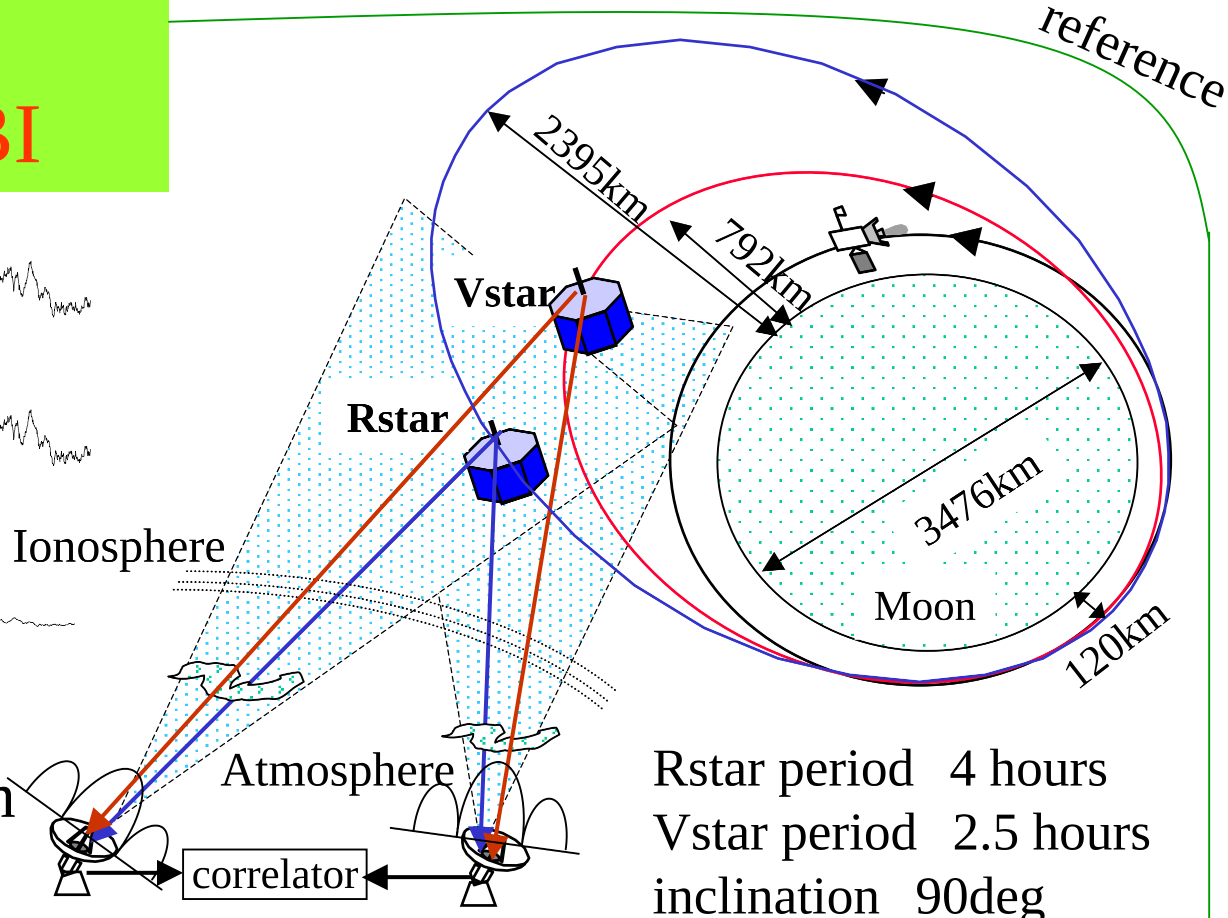


Using switching VLBI observation

Condition for determining $\Phi_R(t) - \Phi_V(t)$ with an error of **4.3 deg cannot be satisfied** when ionosphere and atmosphere fluctuation is strong.

Same-beam differential VLBI





Rstar period 4 hours
Vstar period 2.5 hours
inclination 90deg

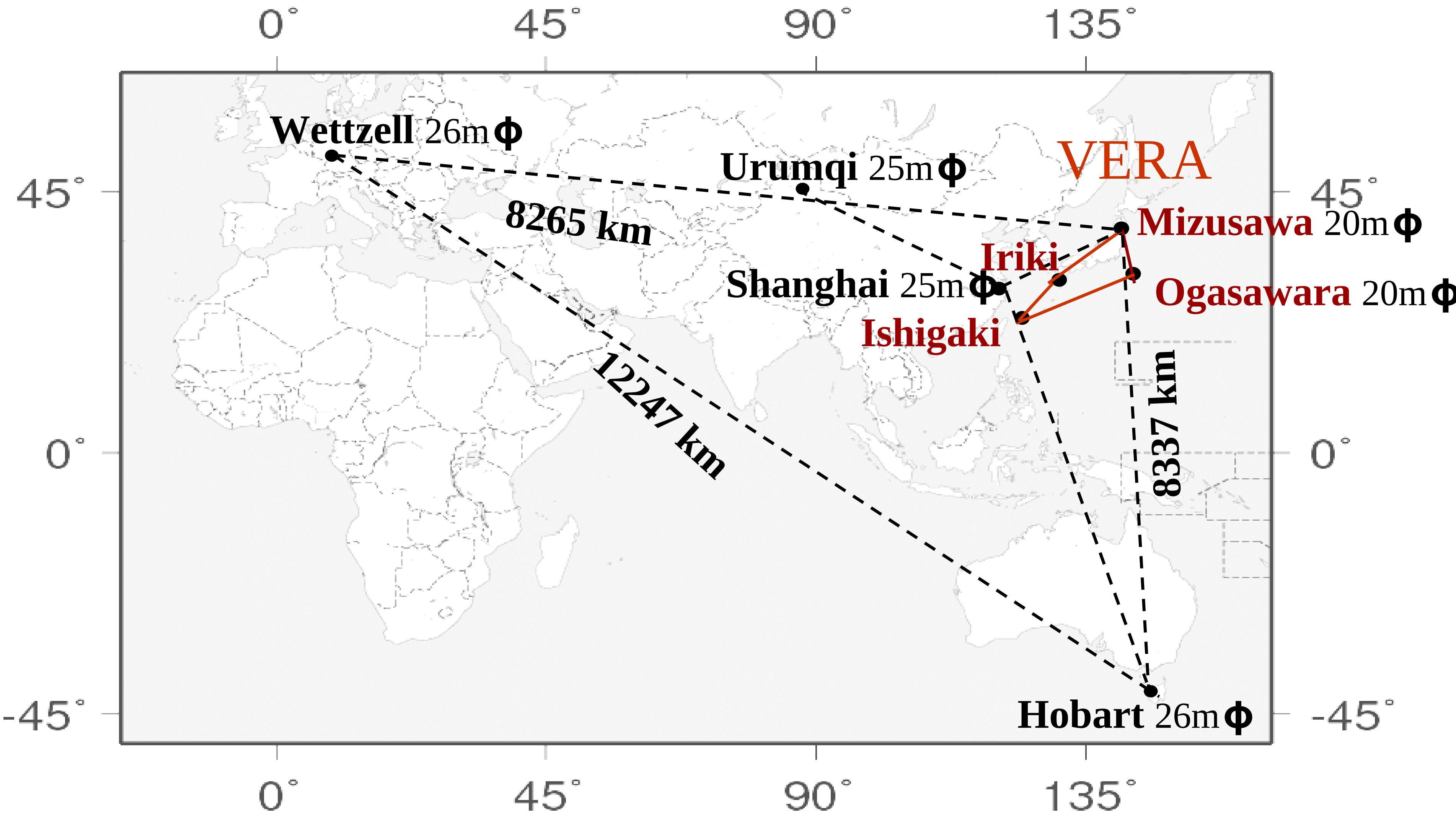
In same beam VLBI

- Rstar and Vstar can be observed simultaneously
- System is nearly same
- Elongation is small

Influences of the receiver, atmosphere and ionosphere are nearly canceled

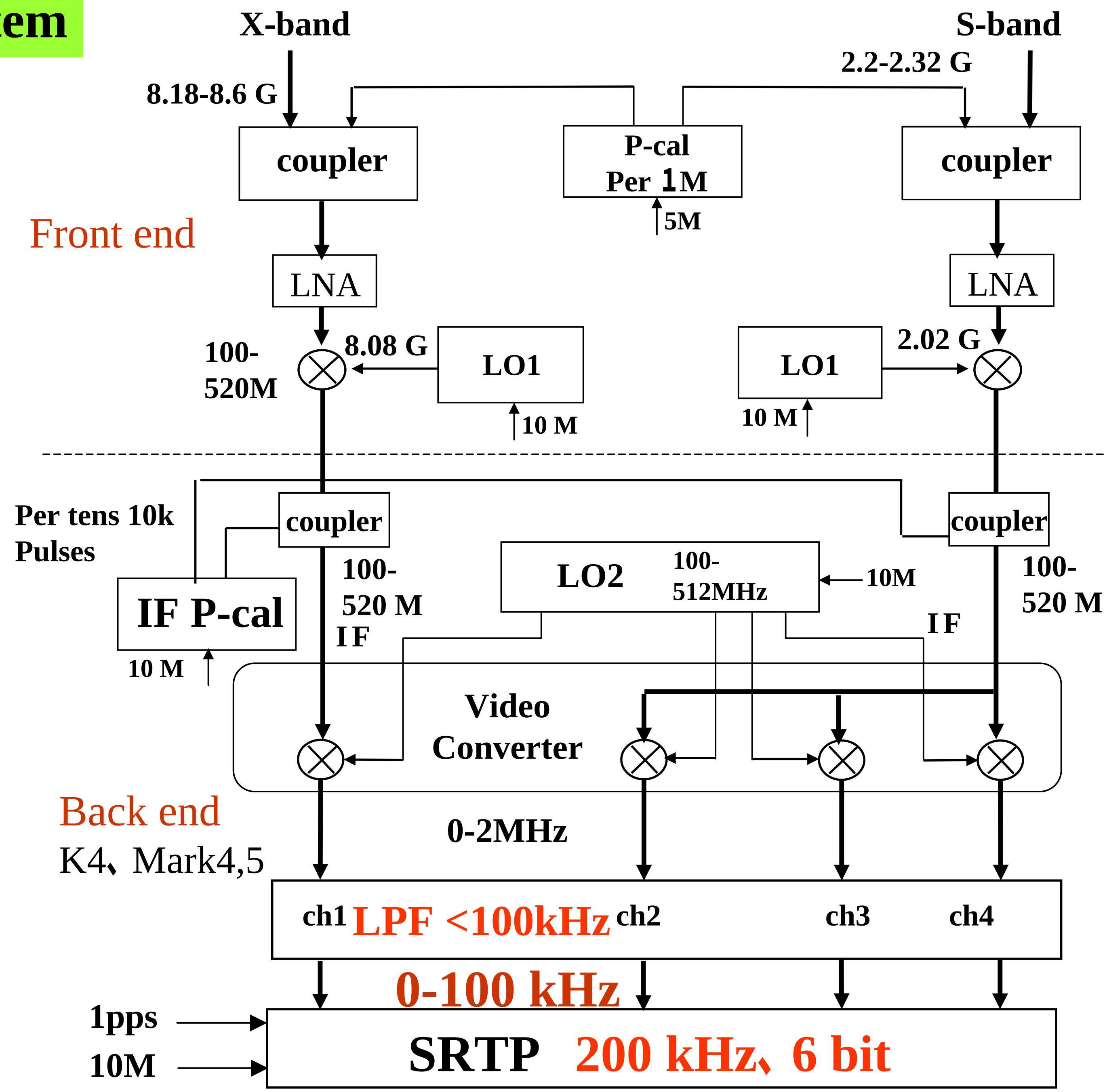
LIU et. al IEICE, 2006
LIU et. al Adv. Space Res, 2007
Kikuchi, Liu et. al, 2008

Stations for SELENE VLBI observations

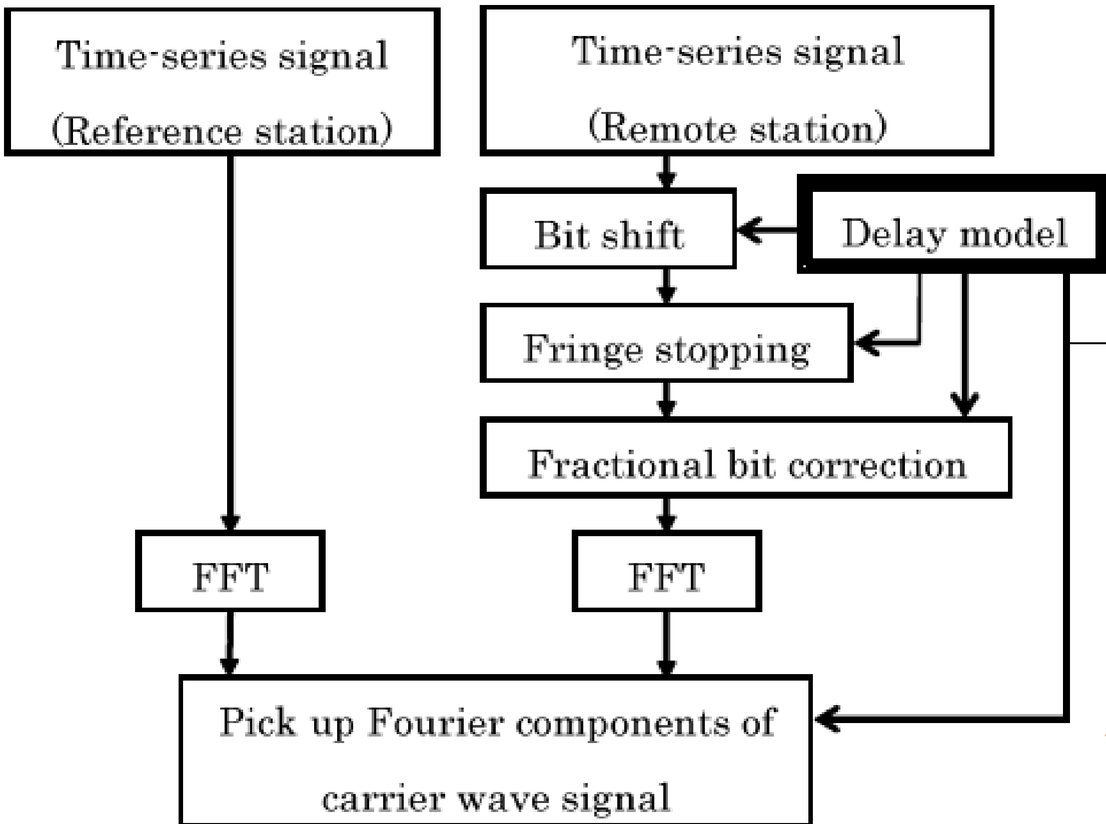


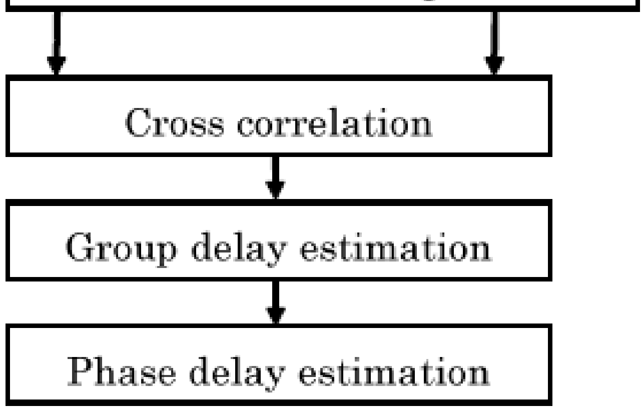
外国局： 2ヶ月； VERA：1年以上

Observation system



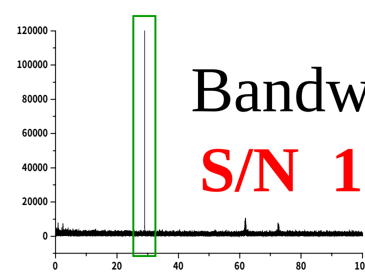
Correlation Processing (soft correlater)





F. Kikuchi et al, Earth Planets Space, vol.56, pp.1041-1047, 2004.

Only use the signal in a bandwidth of several Hz



Bandwidth B 100Hz—>10Hz

S/N 10dB UP! **P_N=kTB**

Procedure and conditions for obtaining phase delay

Differential phase
$\Phi_R(t) - \Phi_V(t)$

2π ambiguity

ionosphere

phase error

$$\Delta\phi_i = 2\pi f_i \Delta\tau_j - 2\pi N_i - \frac{2\pi k \Delta D_s}{f_i} + [[\sigma_j]]$$

s1: 2212, s2: 2218, s3: 2287, x: 8456 MHz

$$N_{s2} - N_{s1} = -\frac{\Delta\phi_{s2} - \Delta\phi_{s1}}{2\pi} - k\Delta D_s\left(\frac{1}{f_{s2}} - \frac{1}{f_{s1}}\right) + (f_{s2} - f_{s1})\Delta\tau_s + [[\frac{\sqrt{2}\sigma_s}{2\pi}]]$$

procedure	condition	
1. $N_{s2} - N_{s1}$ 6MHz	$0.001639\lvert\Delta D_s\rvert + 0.006\lvert\Delta\tau_s\rvert + 0.003928\lvert[[\sigma_s]]\rvert < 0.5$ <83 ns	Eq.1
2. $N_{s3} - N_{s1}$ 75MHz	$0.04926\lvert[[\sigma_s]]\rvert + 0.000618\lvert\Delta D_s\rvert < 0.5$ <10.2 deg	Eq.2
3. N_{s1} 2212MHz	$0.1159\lvert[[\sigma_s]]\rvert + 1.1917\lvert\Delta D_s\rvert < 0.5$ **<4.3 deg** **<0.42TECU**	Eq.3
4. N_x 8456MHz	$0.0110\lvert[[\sigma_x]]\rvert + 8.456\Delta\tau_{xs} + 2.1573\lvert\Delta D_s\rvert < 0.5$ <45.6 deg <59 ps **<0.23 TECU**	Eq.4

Sorry!

About 20 pages were deleted for VLBI

Close phase delay 20080120

VERA: Ishigaki, Iriki, Mizusawa, Ogasawara

baseline		IS-IR	IS-MZ	IS-OG	MZ-IR	MZ-OG	IR-OG	close delay (ns)	close delay
10:31-45	Start time	10:31:30	10:31:30	10:31:30	10:31:30	10:31:30	10:31:30	IS/IR-IS/MZ-MZ/IR	S/IR-IS/MZ-MZ/OG+IR/OG
	Ns2-Ns1	0	0	0	0	0	0	0	0.001
	Ns3-Ns1	0	0	0	0	0	0	MZ/IR-MZ/OG+IR/OG	S/MZ-IS/OG+MZ/IR+IR/OG
	Ns1	-7	-14	-5	7	9	2	0.001	0.002
	Nx	*	*	*	*	*	*	IS/MZ-IS/OG+MZ/OG	MZ/IR-MZ/OG-IS/IR+IS/OG
	good dela	s1	s1	s1	s1	s1	s1	0.001	-0.001
	value	-3.508	-7.045	-2.338	3.537	4.708	1.172	IS/IR+IR/OG-IS/OG	
	at time	10:37:30	10:37:30	10:37:30	10:37:30	10:37:30	10:37:30	0.002	S-band 2PI= 0.452 ns

Hobart, Shanghai, Urumqi, Ishigaki

baseline		HO-UR	HO-SH	HO-IS	SH-UR	SH-IS	UR-IS	close delay (ns)	close delay
10:31-45	Start time	10:35:30	10:35:30	10:35:30	10:35:30	10:35:30	10:35:30	IO/UR-HO/SH-SH/U	HO/UR-HO/SH-SH/IS+UR/IS
	Ns2-Ns1	0	0	0	0	1	1	0	-13.563
	Ns3-Ns1	-2	-1	0	0	2	1	SH/UR-SH/IS+UR/IS	HO/SH-HO/IS+SH/UR+UR/IS
	Ns1	-51	-38	-1	-13	37	20	-13.563	-13.563
	Nx	*	*	*	*	*	*	HO/SH-HO/IS+SH/IS	SH/UR-SH/IS-HO/UR+HO/IS
	good delay	s1	s1	s1	s1	s1	s1	0	0
	value	-29.157	-21.815	-4.4	-7.342	17.415	11.194	HO/UR+UR/IS-HO/IS	
	at time	10:40:30	10:40:30	10:40:30	10:40:30	10:40:30	10:40:30	-13.563	S-band 2PI= 0.452 ns

Correct atmospheric delay--GPS + Niell Mapping function

SELENE8局のGPSデータをIGS或いは天文台のvgrからDownload し、GpsTools 解析ソフトを用いて各局の天頂方向の大気遅延ZTDを推定する。

推定精度：10mm；　時間間隔：1分或いは5分。

		X (m)	Y (m)	Z (m)	距離 (m)	高度 (m)
水沢	VLBI	-3857241.85	3108784.791	4003900.608	189.58231	116.523
mizw	GPS	-3857164.39	3108693.067	4004047.332		117.7
入来	VLBI	-3521719.59	4132174.674	3336994.224	42.582571	573.522
irik	GPS	-3521735.46	4132137.51	3337007.646		565.287
石垣	VLBI	-3263994.73	4808056.288	2619949.219	40.688873	65.026
isgk	GPS	-3263984.04	4808036.484	2619983.118		58.65
父島	VLBI	-4491068.81	3481544.791	2887399.567	40.097662	273.048
ogsa	GPS	-4491042.33	3481573.606	2887390.838		266.157
上海	VLBI	-2831686.91	4675733.666	3275327.69	92.159441	29.43
shao	GPS	-2831733.57	4675666.07	3275369.496		22.209
ウルムチ	VLBI	228310.72	4631922.795	4367063.988	83.694217	2033.205
guao	GPS	228380.79	4631962.42	4367041.08		2048.67
Hobart	VLBI	-3950236.74	2522347.561	-4311562.54	193.62816	65.105
hob2	GPS	-3950074.52	2522418.574	-4311640.86		46.055
Wettzell	VLBI	4075539.899	931735.27	4801629.352	138.30185	669.124
wtzr	GPS	4075578.273	931852.7652	4801567.306		663.796

各局のVLBIとGPS受信機の位置。近く設置。

Correct ionospheric delay using GPS

20080115-12 MZ-IR

電離層モデル

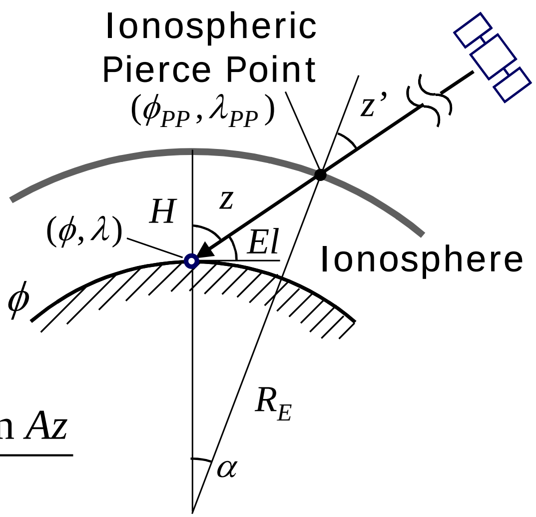
$$z = \pi / 2 - El$$

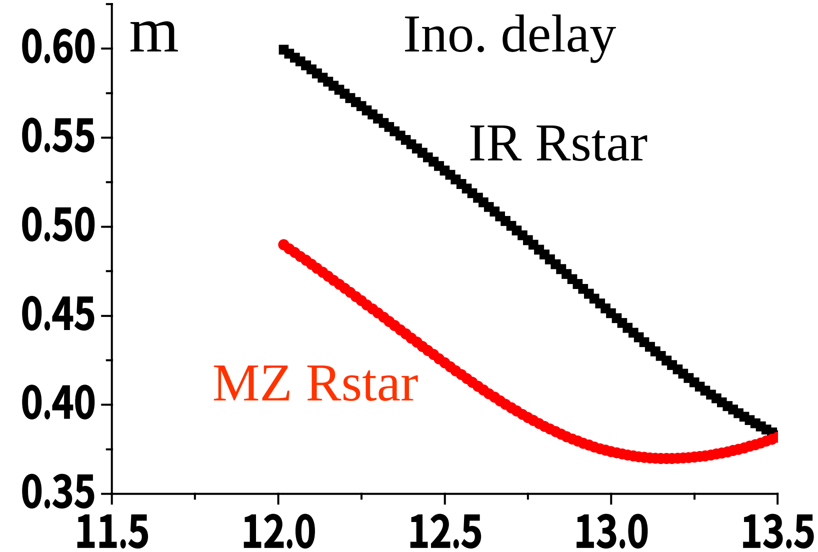
$$z' = \arcsin \frac{R_E \sin z}{R_E + H}$$

$$\alpha = z - z'$$

$$\phi_{PP} = \arcsin(\cos\alpha \sin\phi + \sin\alpha \cos\phi \cos Az)$$

$$\lambda_{PP} = \lambda + \arcsin \frac{\sin\alpha \sin Az}{\phi_{PP}}$$





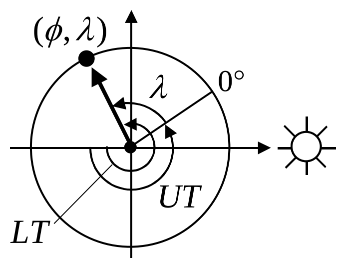
CODE GIM Model (15*15)

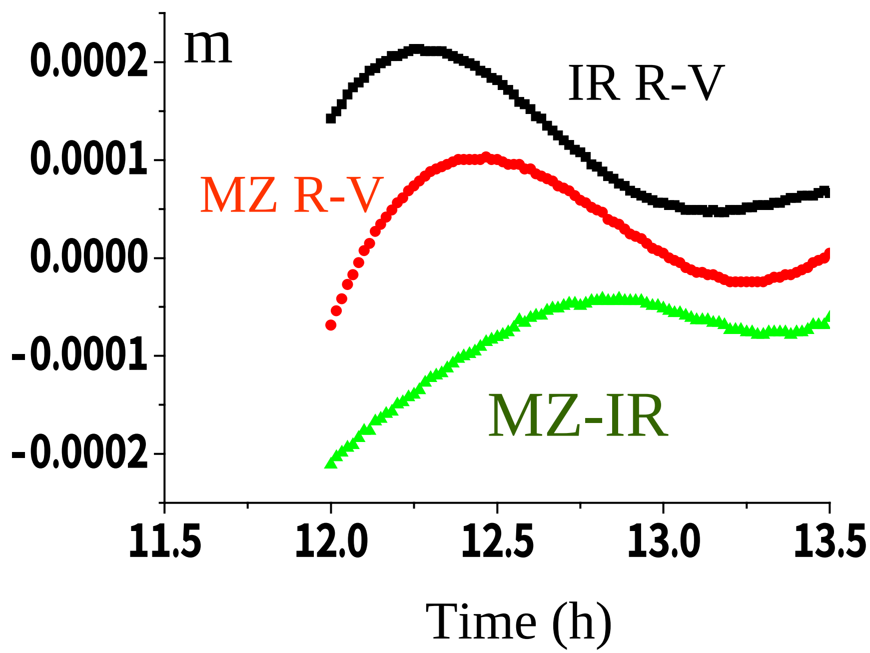
球面調和関数展開

$$TEC(UT, \phi, \lambda) = \sum_{n=0}^{nmax} \sum_{m=0}^{n} \overline{P}_{nm}(\sin\phi)(C_{nm} \cos m\lambda_s + S_{nm} \sin m\lambda_s)$$

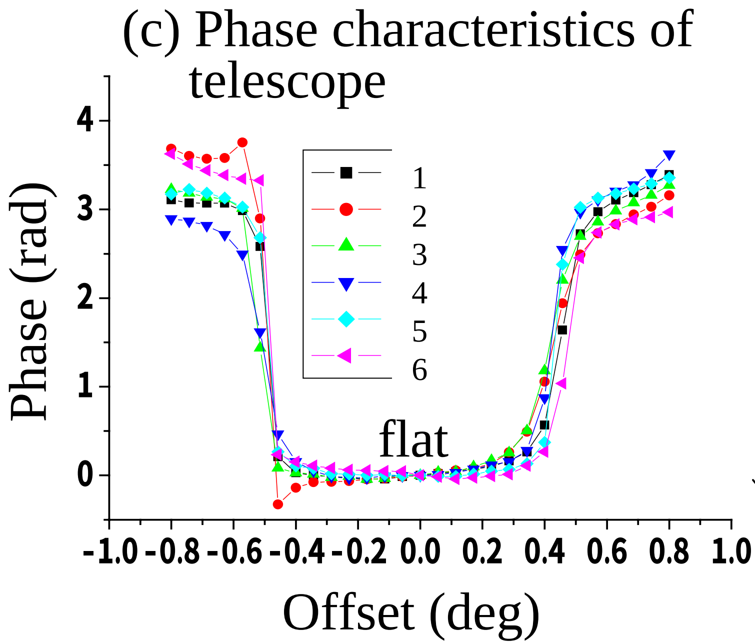
Sun-Fixed座標

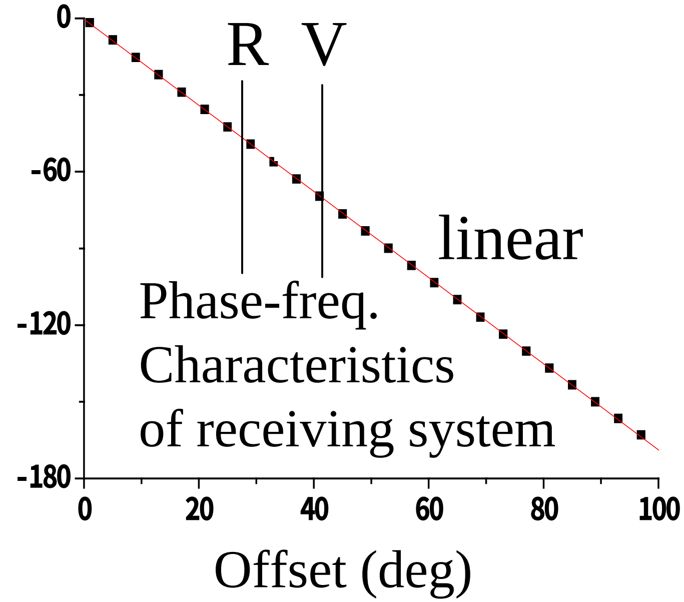
$$\lambda_s = LT - \pi \approx UT + \lambda - \pi$$



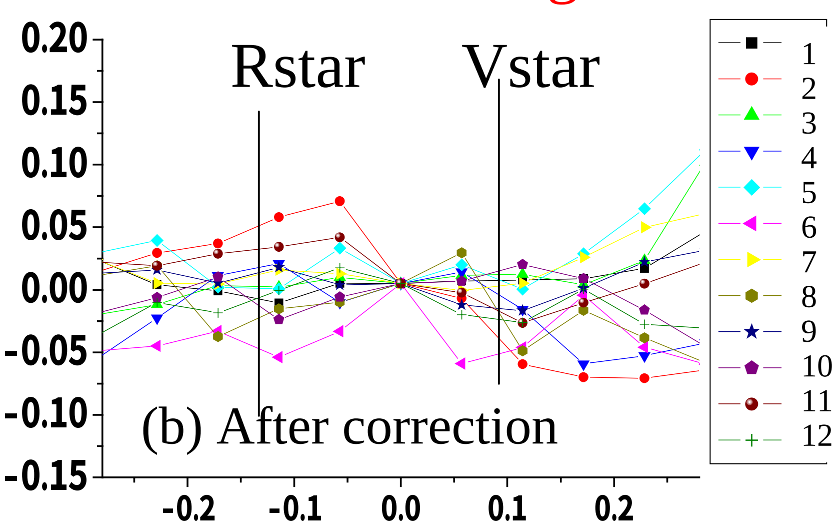


Differential phase delay bias in SELENE: several ps





After correction, 1.7degRMS



Qinghui Liu, et. al, ``Effect of Phase Characteristics of Telescopes on Same-Beam Differential VLBI", **IEEE Trans**., A&P. May 2007.

Summary

Differential VLBI technique in SELENE

1. Same-beam VLBI observations were performed
2. Differential phase delay can be obtained by

   high accuracy **several ps** + little bias <several ps
3. Orbit-determination accuracy **several meters**

Doppler + differential VLBI Data

Global gravity field (include far side and limb) will be accurately determined soon.