SELENEの同一ビームVLBI観測ための受信アンテナ位相特性の精密計測

Same-Beam Differential VLBI Using Two Satellites of SELENE

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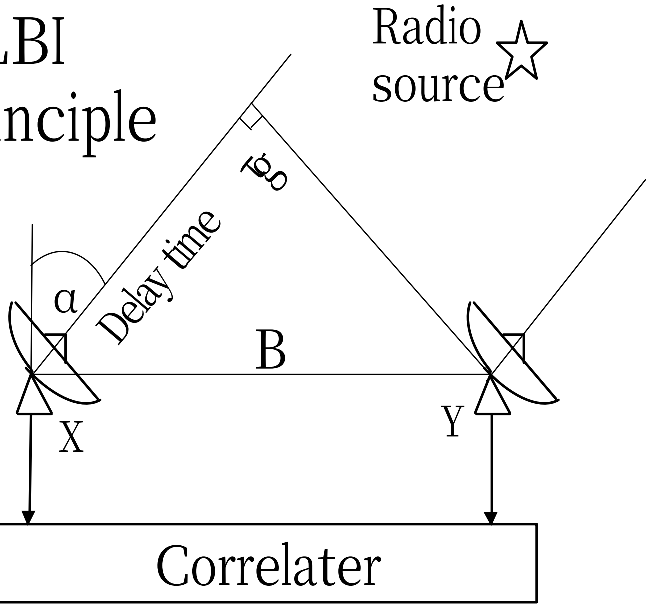
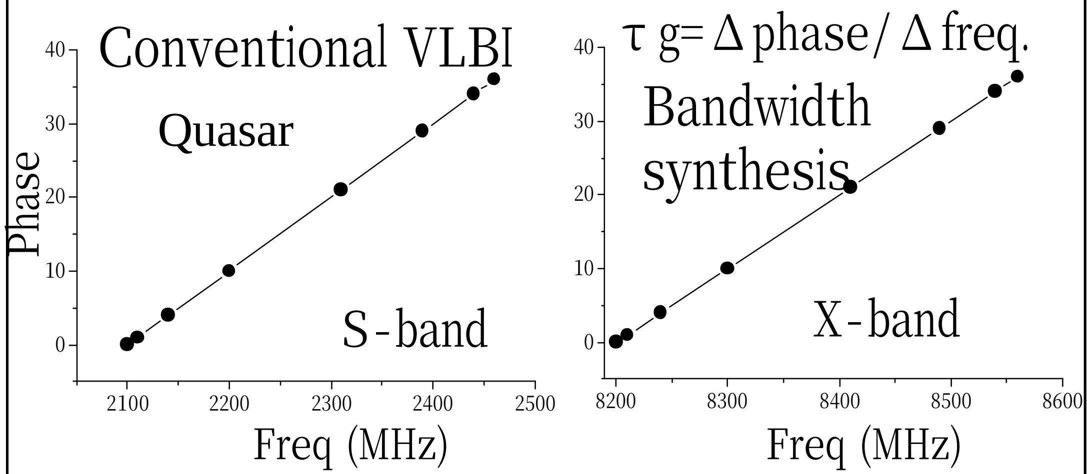
VLBI principle



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



When error of phase is 10 deg,
Error of **group delay** 10/360/**300M**=**100ps**

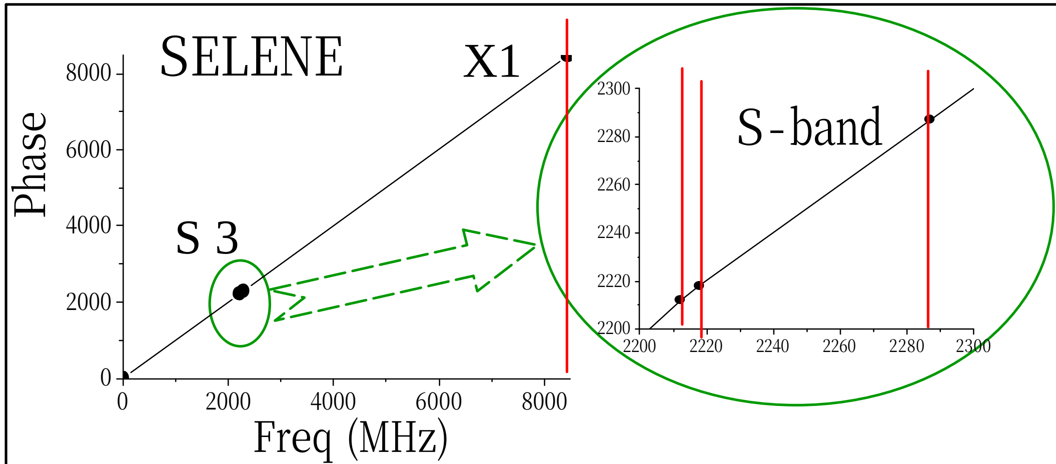
τg=Phase/frequency

⇩

2π ambiguity

⇩

Error of phase have to be less than
4.3 deg in S-band

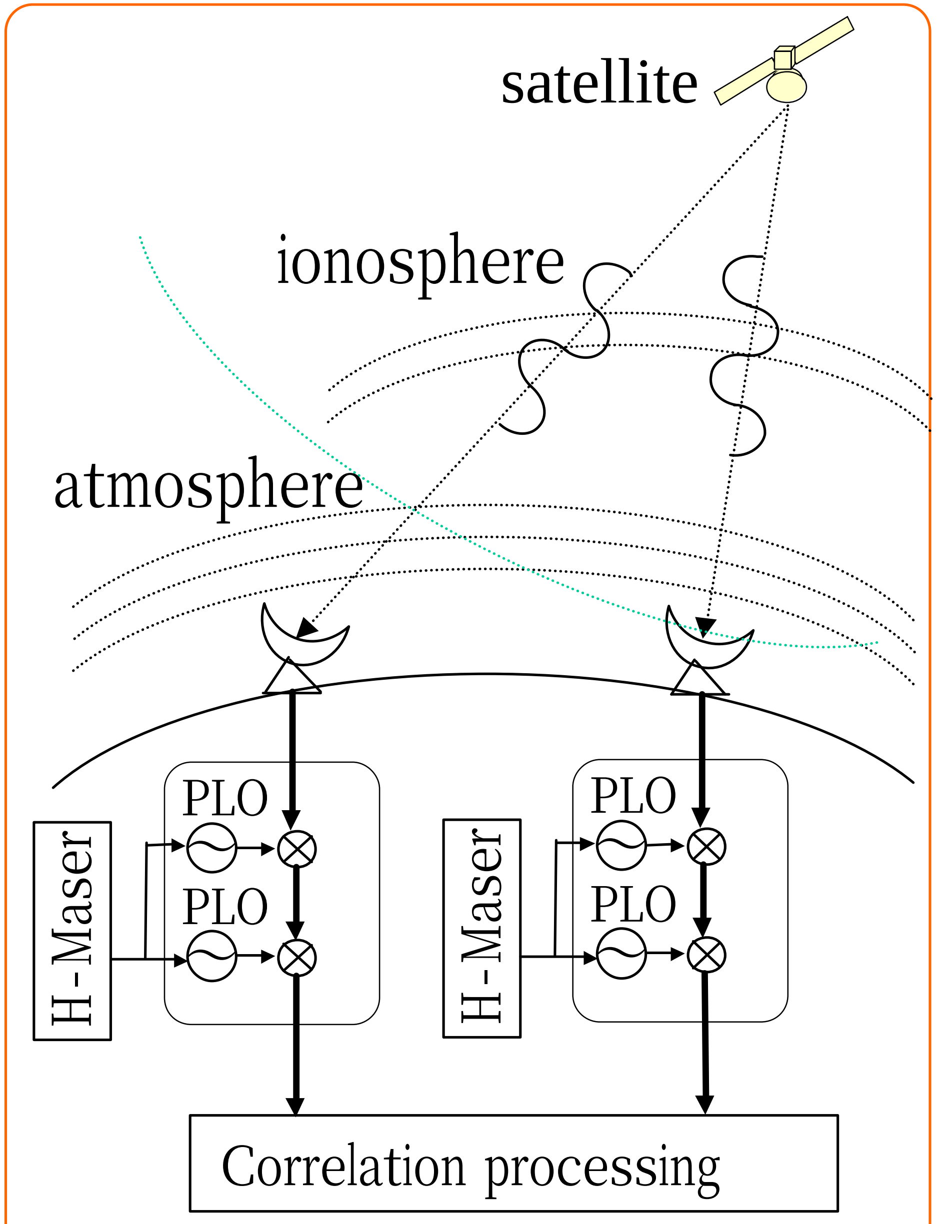


When error of phase is 10 deg
Error of **phase delay** 10/360/**8456M**=**3ps**

Origin of phase fluctuation

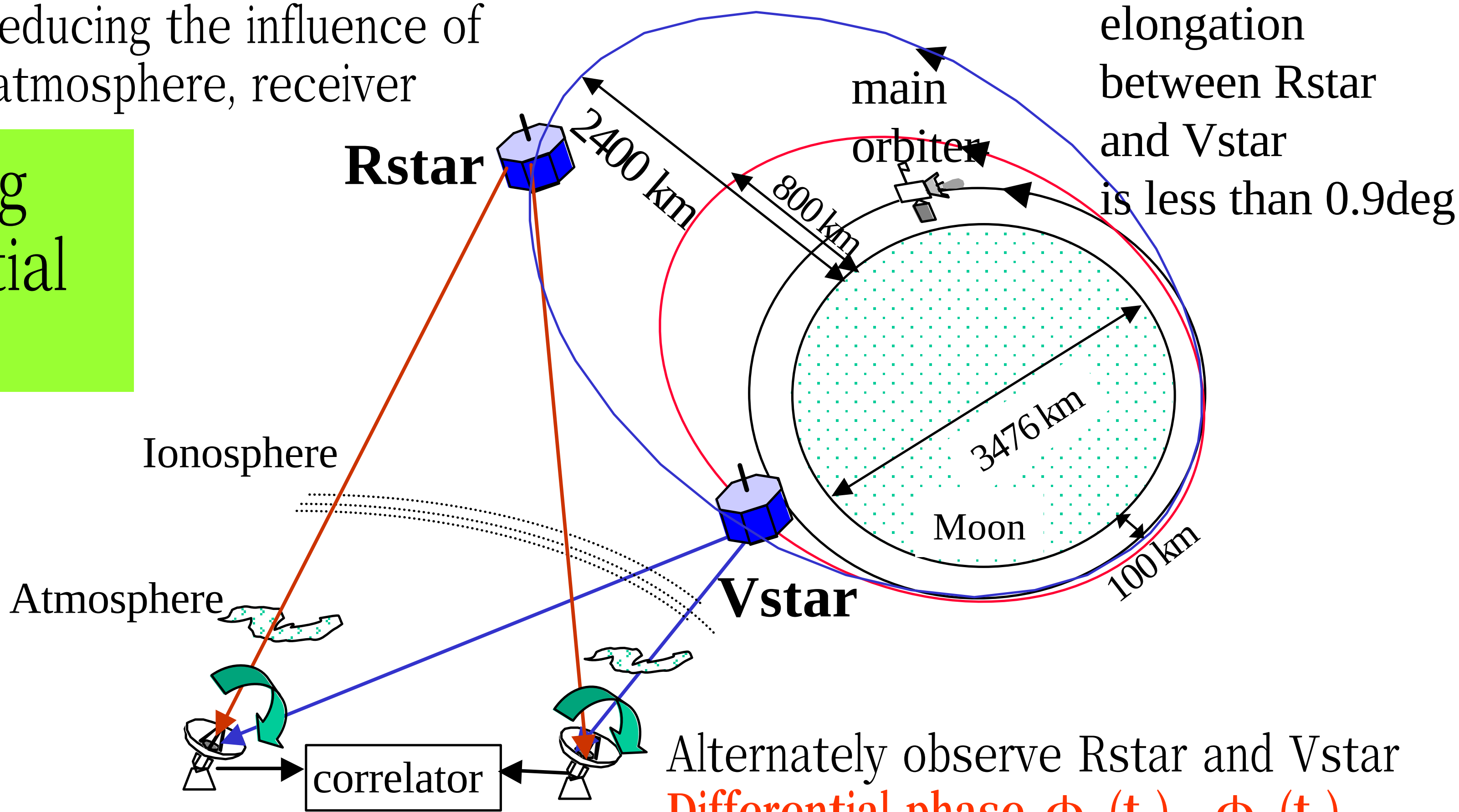
- frequency variation of radio wave (temporal、spatial)
- ionosphere
- atmosphere
- thermal noise
- phase variation in receiver

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



Method for reducing the influence of
ionosphere, atmosphere, receiver

Switching Differential VLBI



Alternately observe Rstar and Vstar

Differential phase $\phi_R(t) - \phi_V(t)$

Switching
Differential VLBI

↓

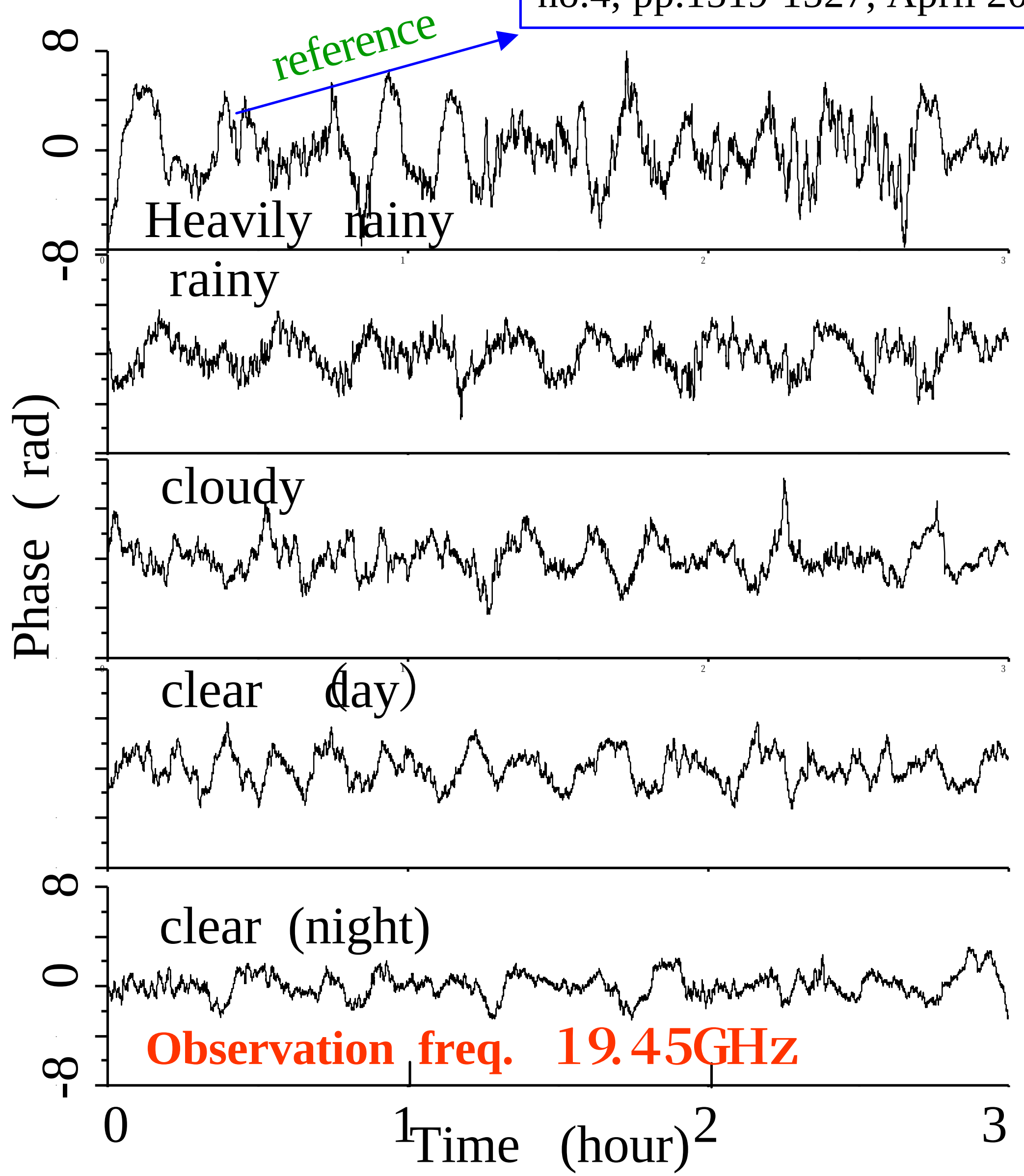
reducing the influence of
ionosphere, atmosphere, receiver

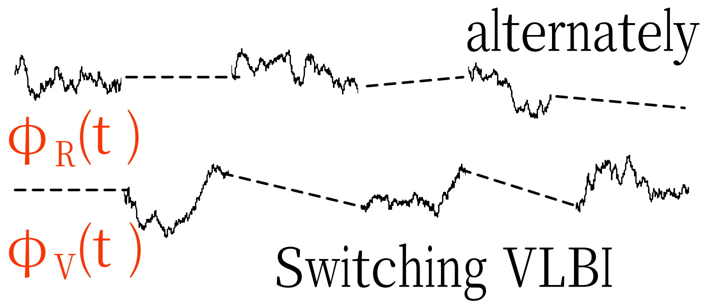
→ reference

Y. Kono, et. al , ``Precise positioning of spacecraft by multi-frequency VLBI'', Earth Planets Space, vol.55, pp.581-589, 2003.

Atmospheric phase fluctuation

Qinghui Liu, et. al, ``Statistical characteristics of atmospheric phase fluctuations observed by a VLBI system using a beacon wave from a geostationary satellite", **IEEE Trans.**, Antenna and Propa., vol.53, no.4, pp.1519-1527, April 2005.

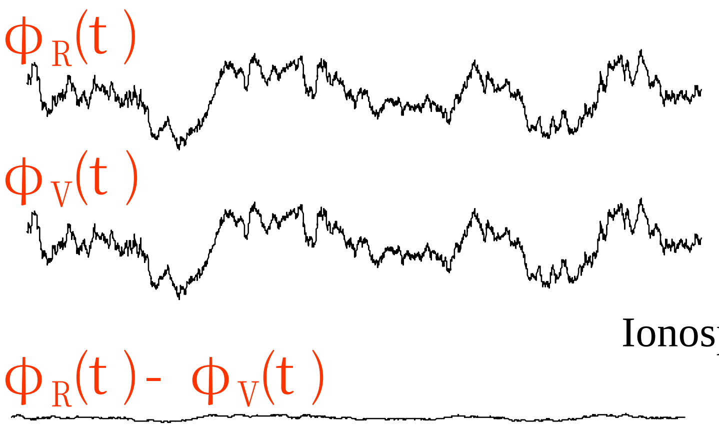


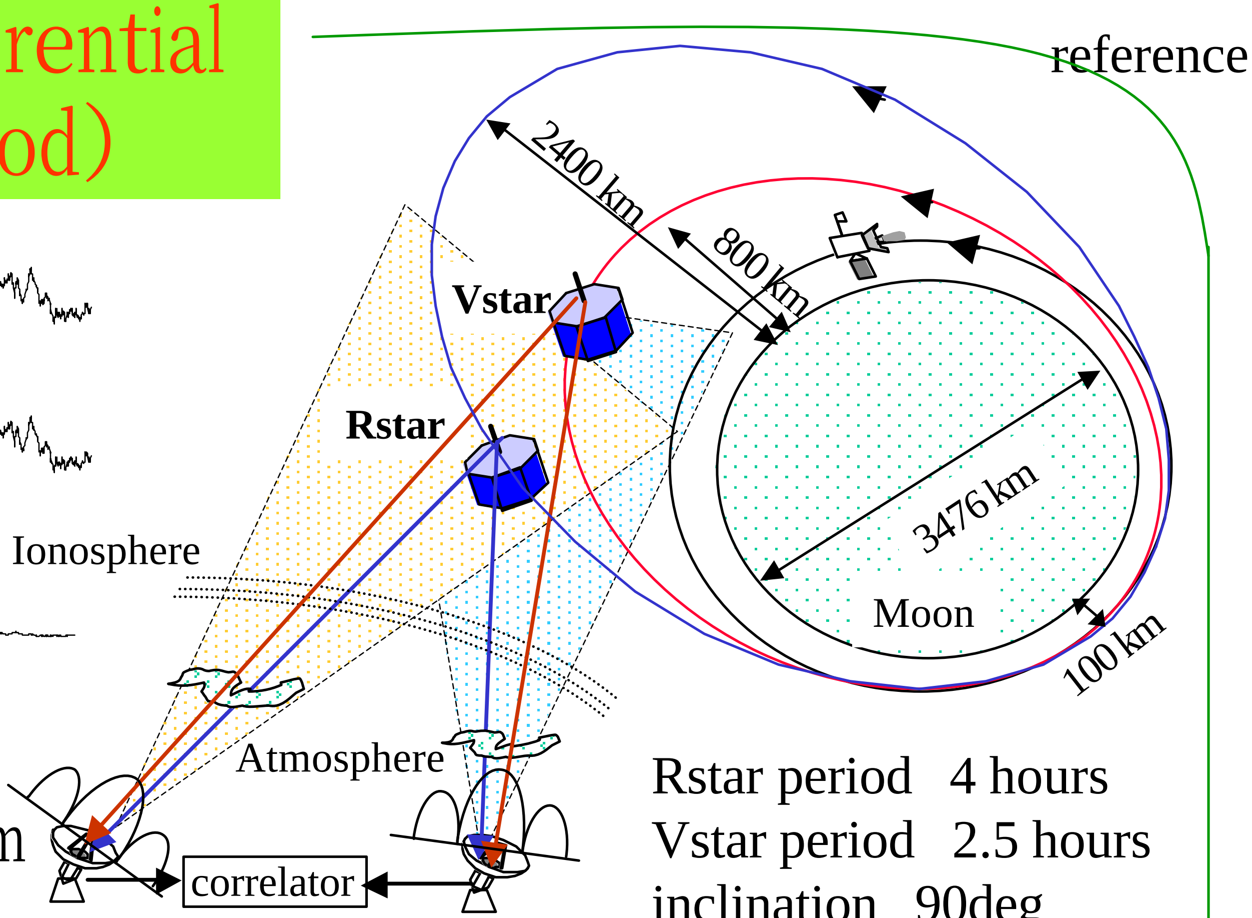


Using switching VLBI observation

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 (New method)





Rstar period 4 hours
Vstar period 2.5 hours
inclination 90deg

In same beam VLBI

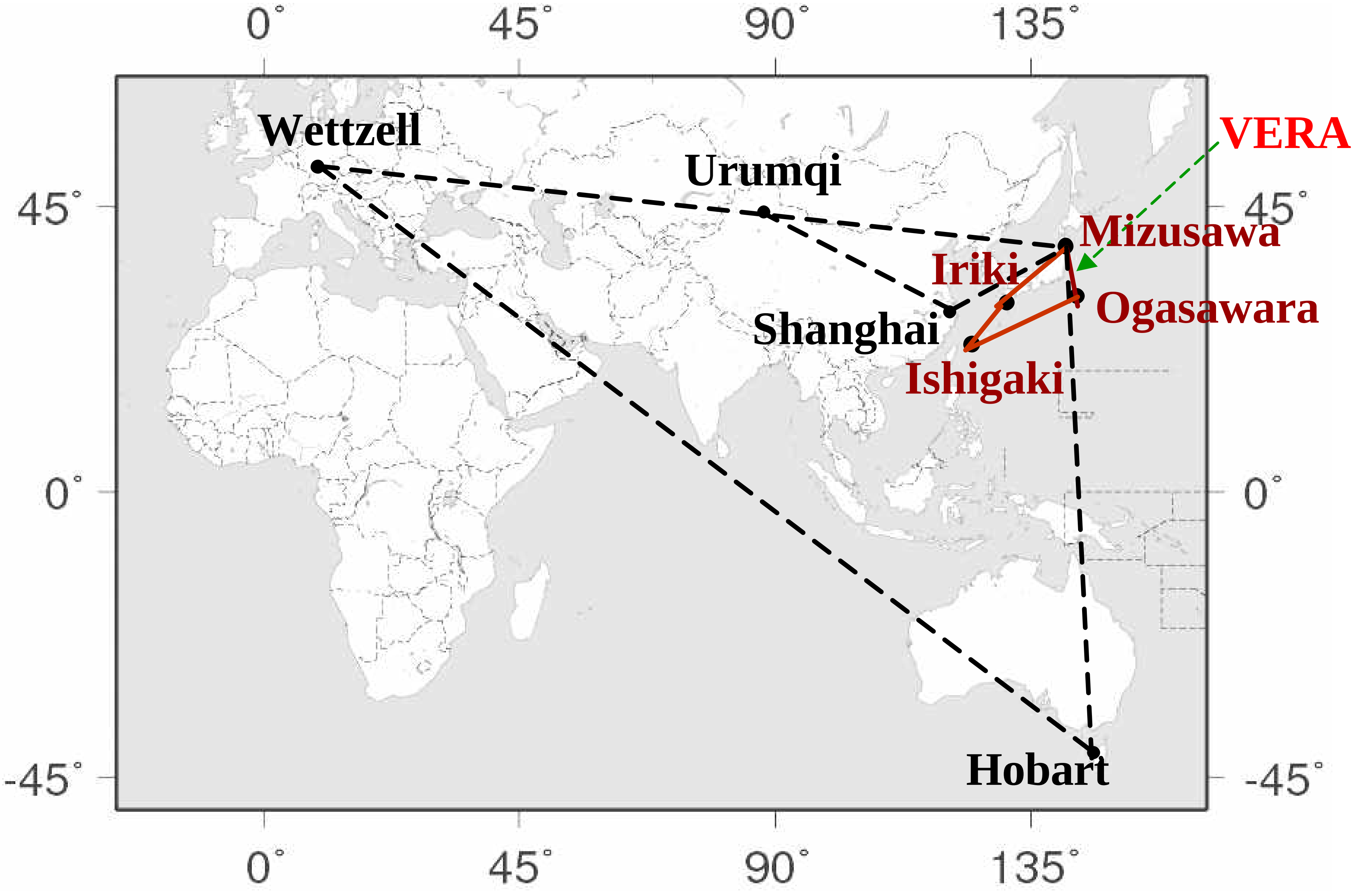
- Rstar and Vstar can be observed simultaneously
- System is nearly same
- Elongation is small

Influences of the receiver, atmosphere and ionosphere are nearly canceled

Qinghui LIU et. al
"Same beam differential VLBI technology using two satellite of SELENE spacecraft",
IEICE, vol.J89-B, pp.602--617, 2006

Chance for same beam differential VLBI observation of SELENE

VLBI station of SELENE



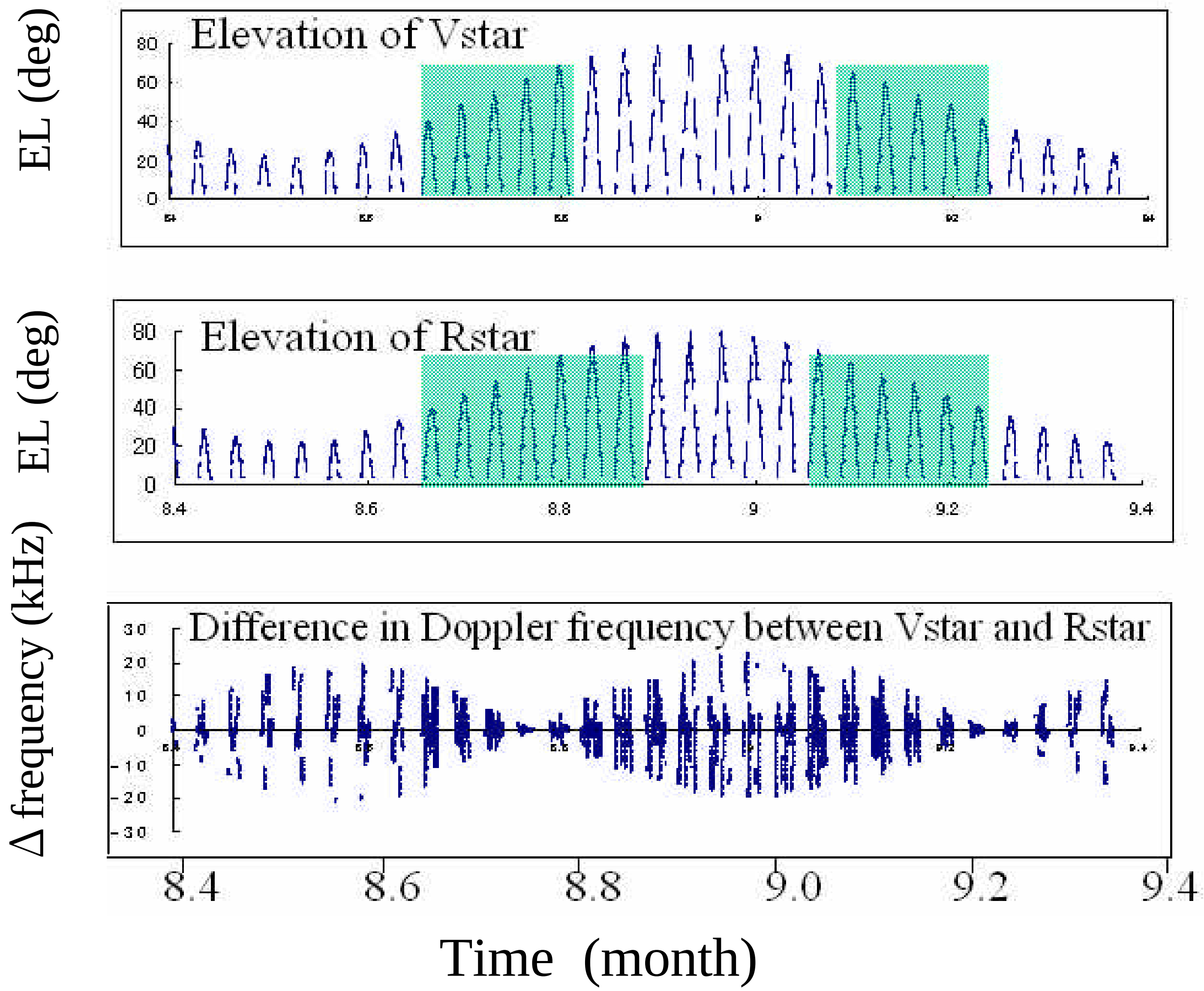
Chance for same beam differential VLBI observation of SELENE
Elevation of Vstar and Rstar , and difference in Doppler frequency

Continuous observation in one month

Vstar 10 days
Rstar 13 days

Difference of frequency in S-band between Rstar and Vstar

< **22kHz**



Difference in AZ and EL between Vstar and Rstar

Chance for same beam VLBI

⇩

Continuous day

-- several times covering day

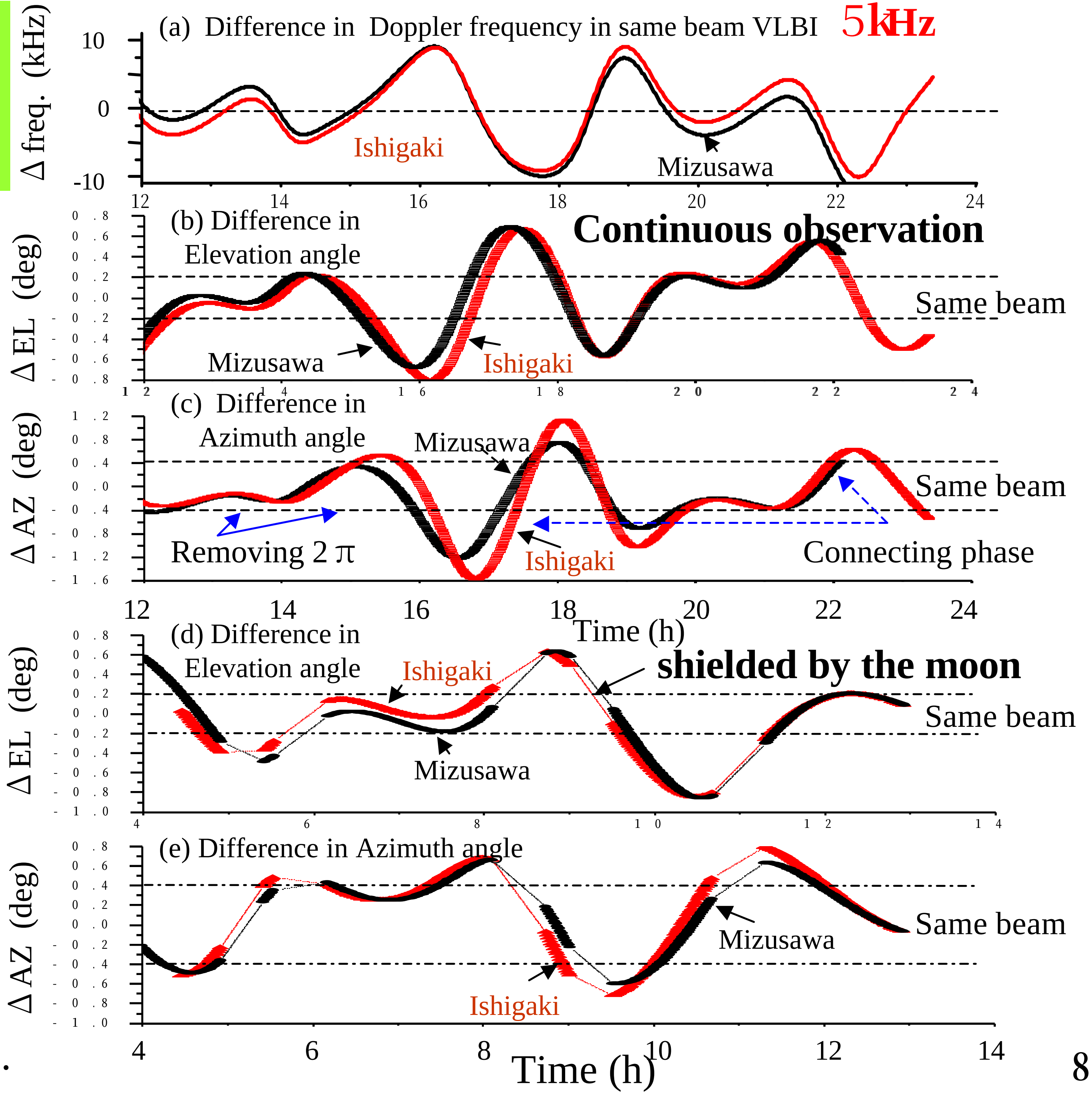
-- >50% paths

⇩

Enough for removing 2π ambiguity

⇩

Once the same beam VLBI observation in performed, 2π ambiguity in whole path can be resolved by connecting phase.



Procedure and conditions for obtaining phase delay in X-band

Differential phase
$\phi_R(t) - \phi_V(t)$

2π ambiguity

ionosphere

phase error

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

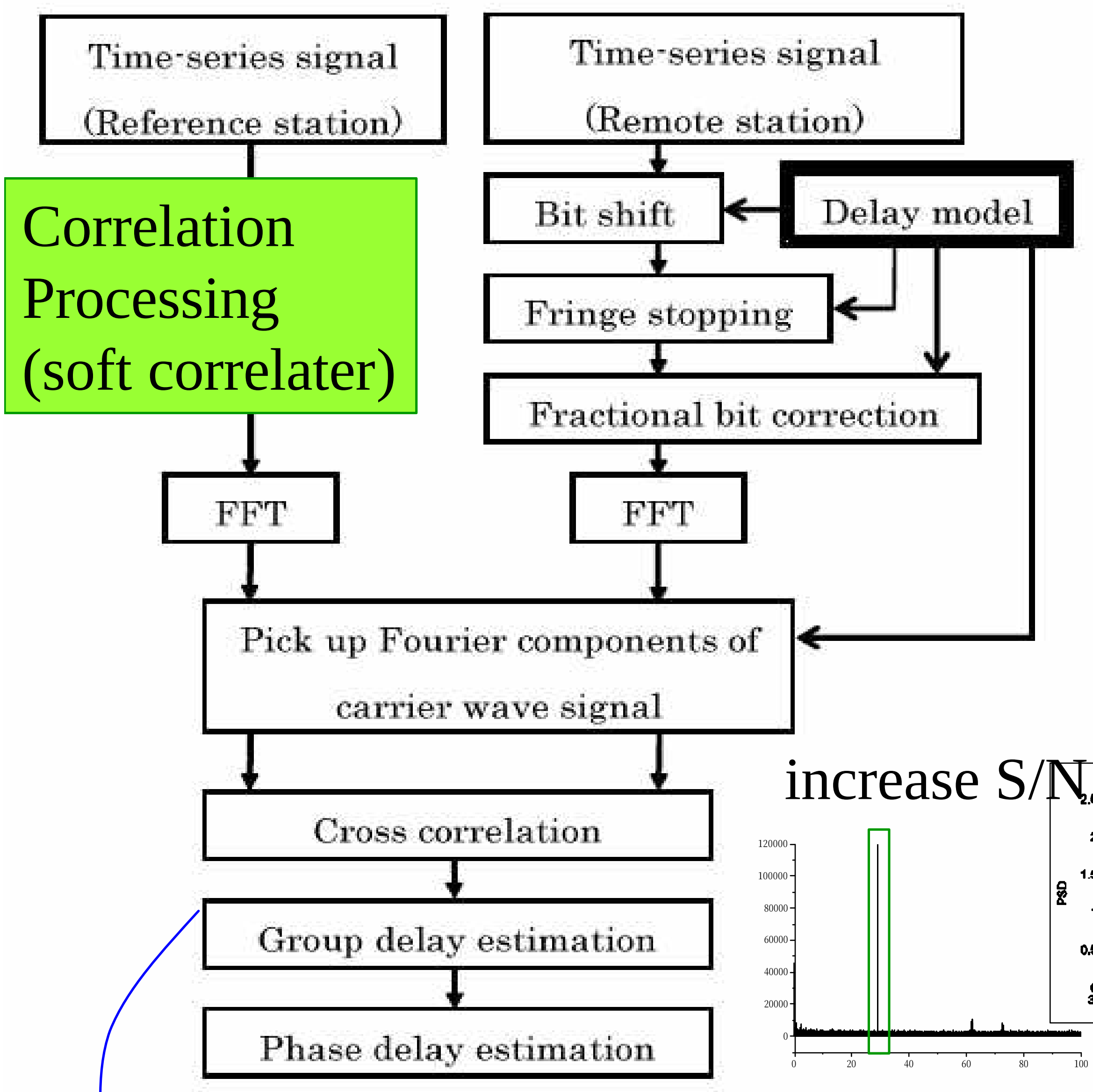
s1: 2212, s2: 2218, s3: 2287, x: 8456 MHz

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

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	$0.04926\lvert[[\sigma_s]]\rvert + 0.000618\lvert\Delta D_s\rvert < 0.5$	Eq.2
3. N_{s1} 2212MHz	$0.1159\lvert[[\sigma_s]]\rvert + 1.1917\lvert\Delta D_s\rvert < 0.5$ <4.3 deg	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

Finite distance delay model

Correlation Processing (soft correlater)



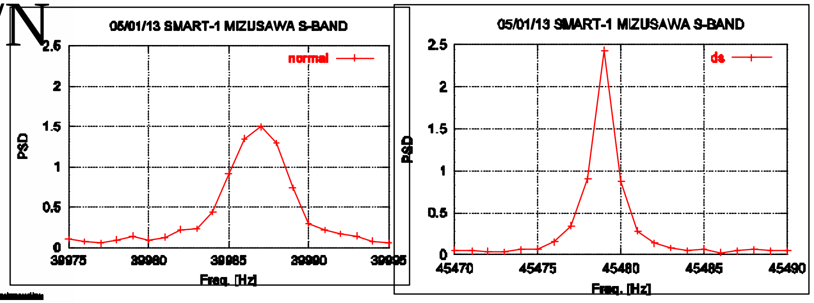
New technique--

Doppler stopping (DS)

Frequency variation caused by Doppler effect is compensated, and spectrum of carrier is concentrated to a bandwidth of only several Hz

increase S/N

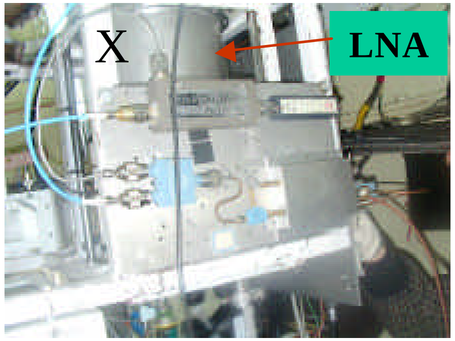
Before DS After DS



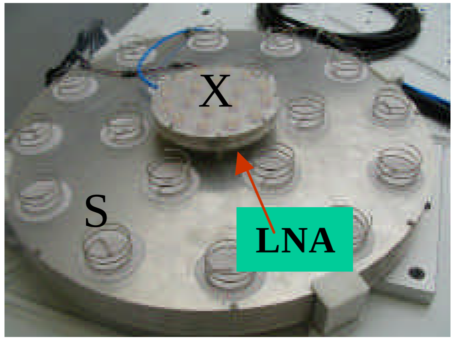
F. Kikuchi et al, ``VLBI observations of narrow bandwidth signals from the spacecraft", Earth Planets Space, vol.56, pp.1041-1047, 2004.

Observation system

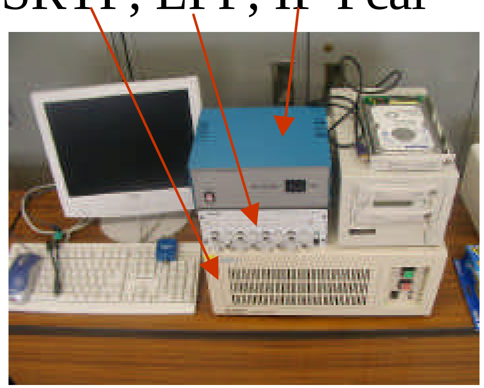
Urumqi LNA

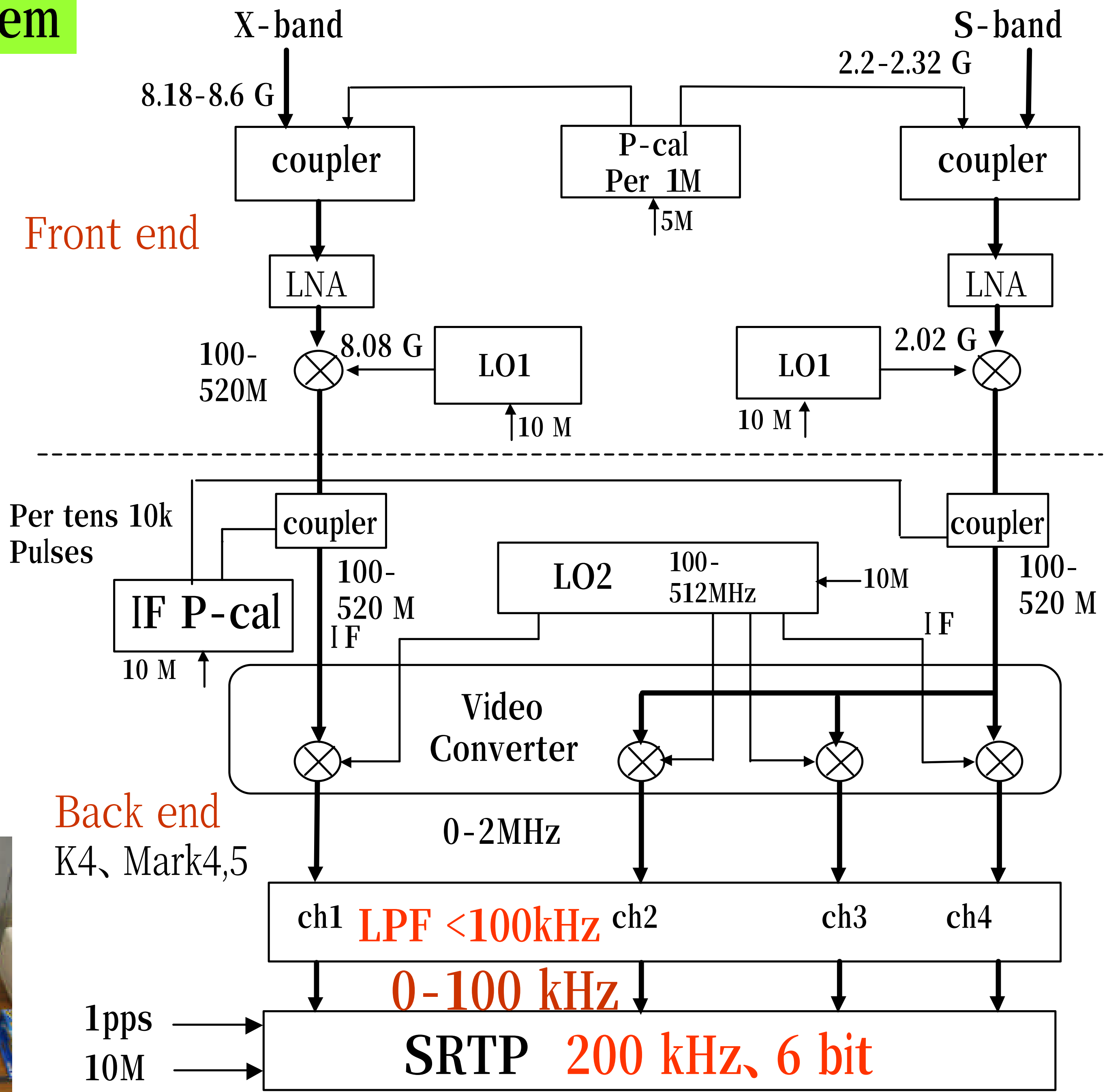


VERA feed



SRTP, LPF, IF Pcal

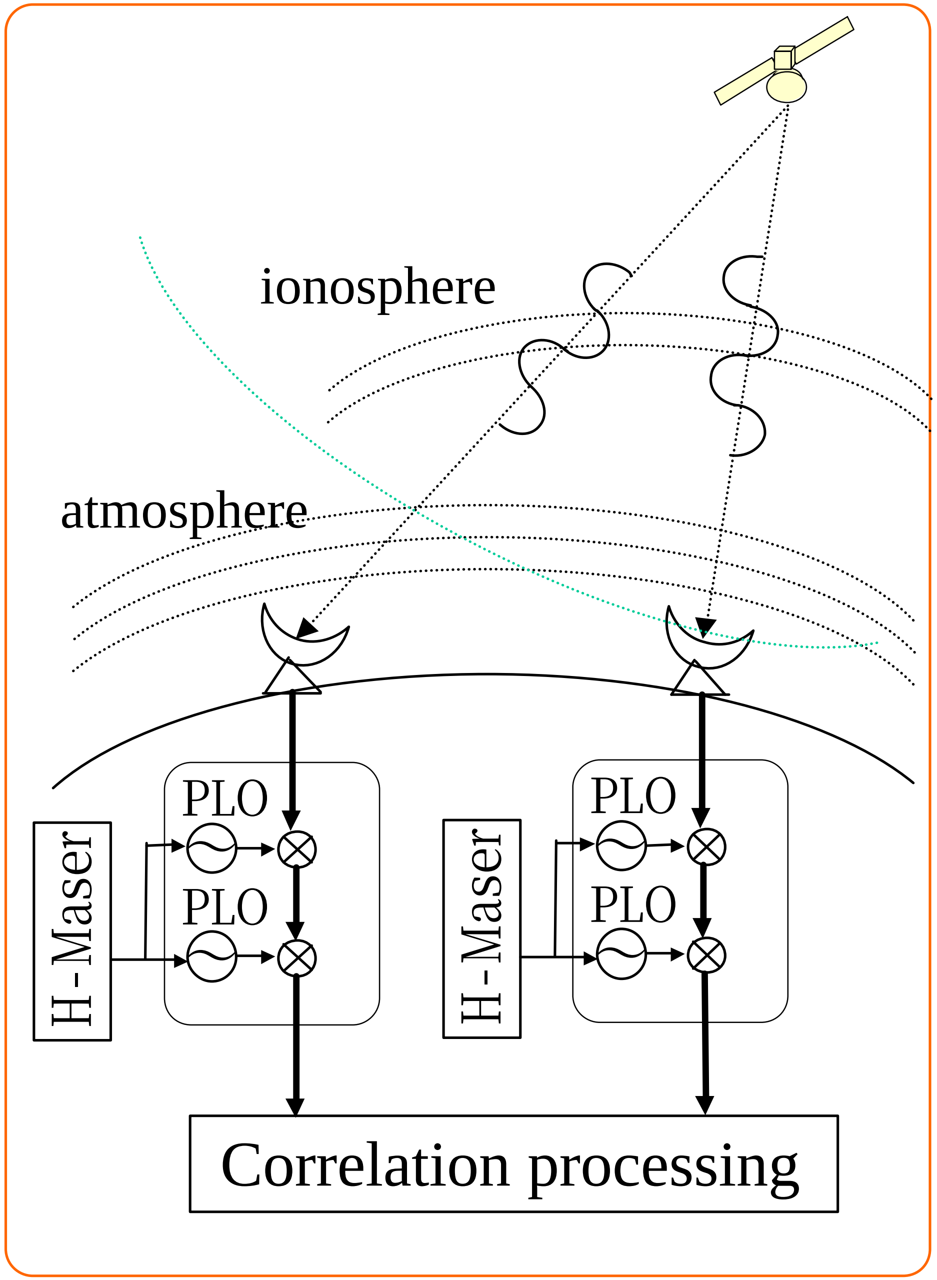




whether conditions of Eq.1-4 are possibly satisfied by using same beam VLBI??

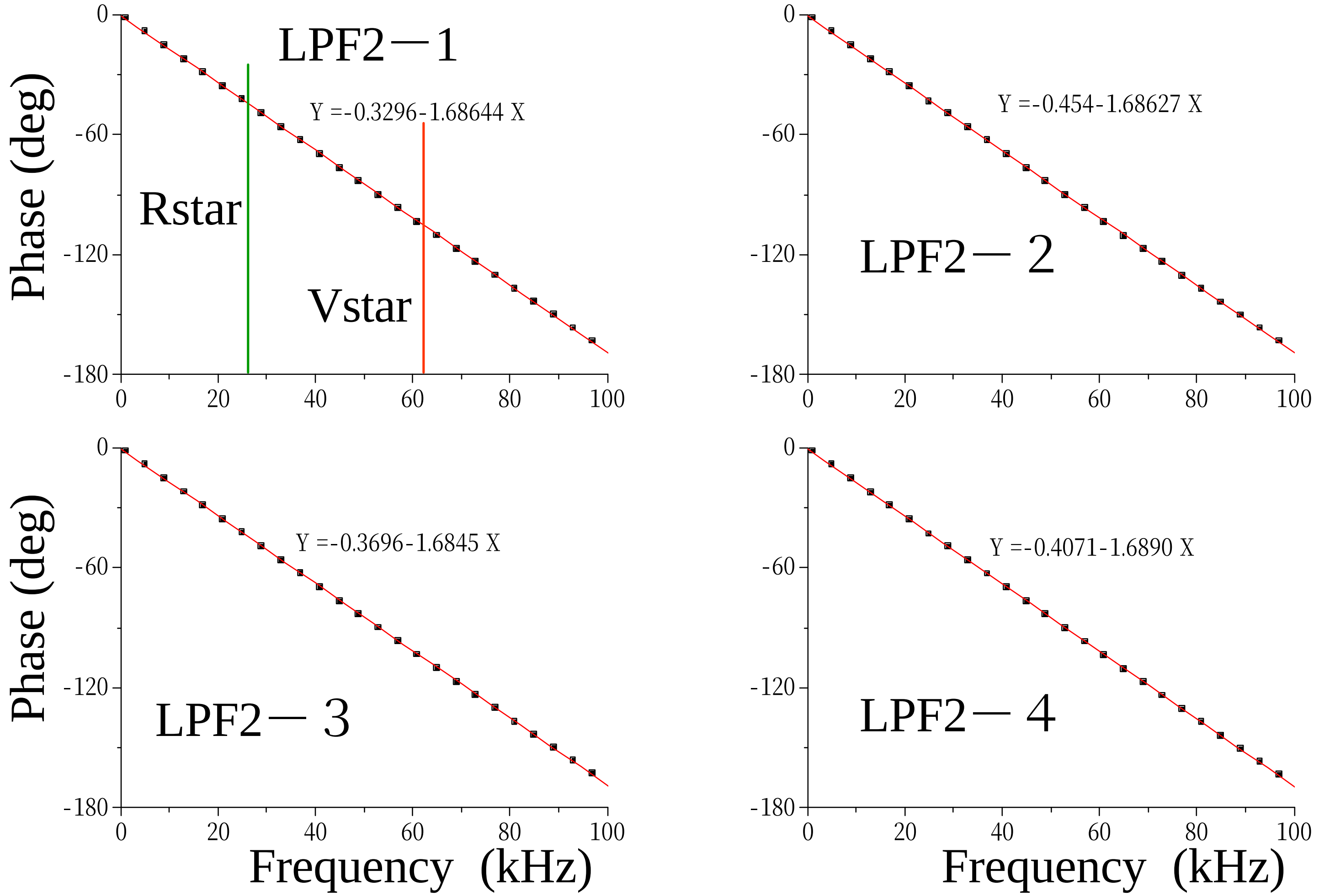
Possible factors influencing correlation phase and delay

- phase variation in receiver
- ionosphere fluctuation
- atmospheric fluctuation
- thermal noise
- phase characteristics of receiving antenna
- phase characteristics of transmitting antenna



Variation in phase and delay in receiver

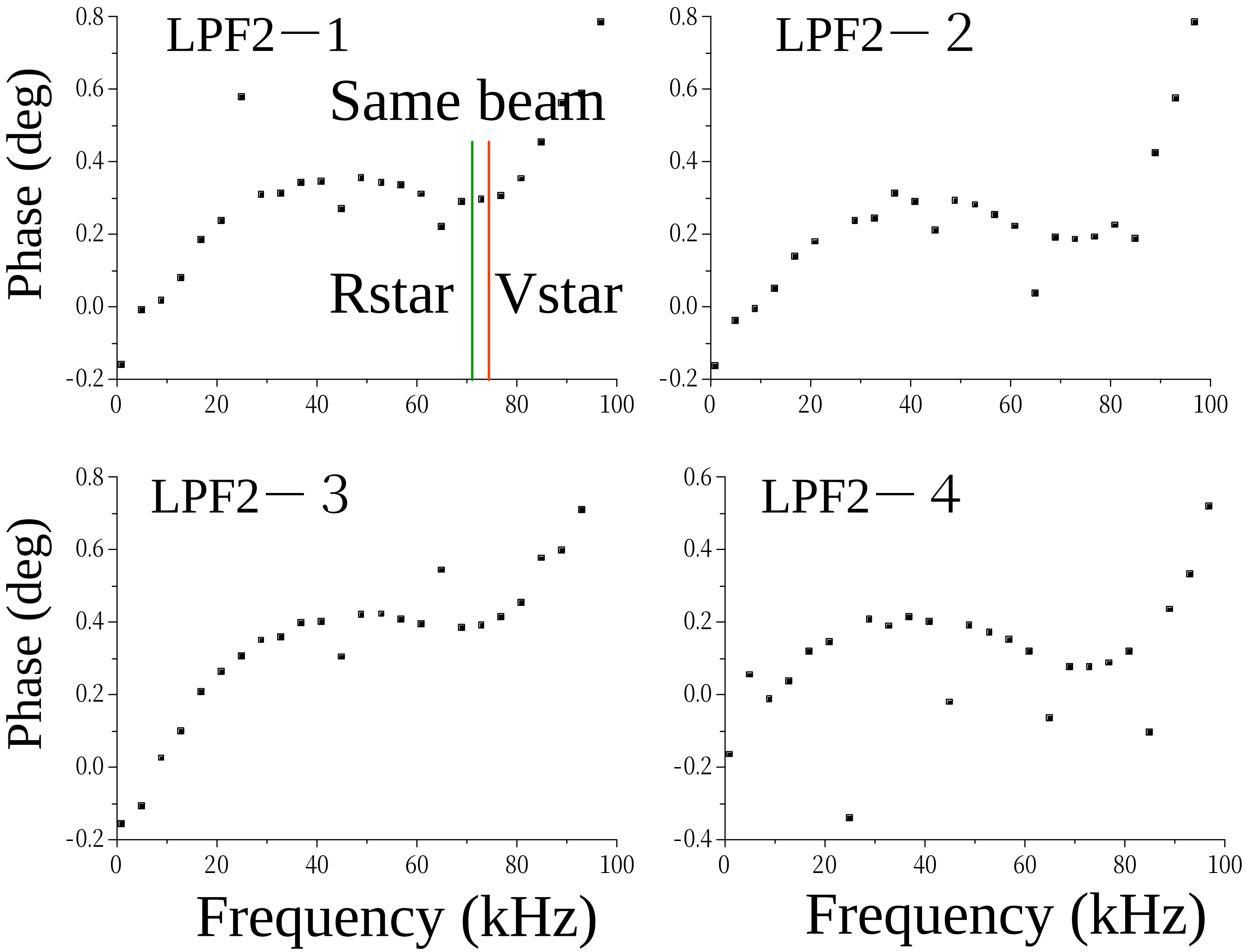
Bessel type LPF： phase-frequency characteristics is nearly linear

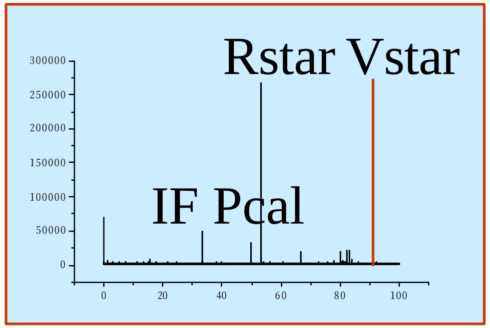


The bandwidth of LPF (**100kHz**) is the narrowest in the receiver, phase-frequency characteristics of the receiver is mainly determined by LPF .
（video converter ：2MHz, front-end ：hundreds MHz）

Variation in phase and delay in receiver

Phase variation after subtracting the linear component





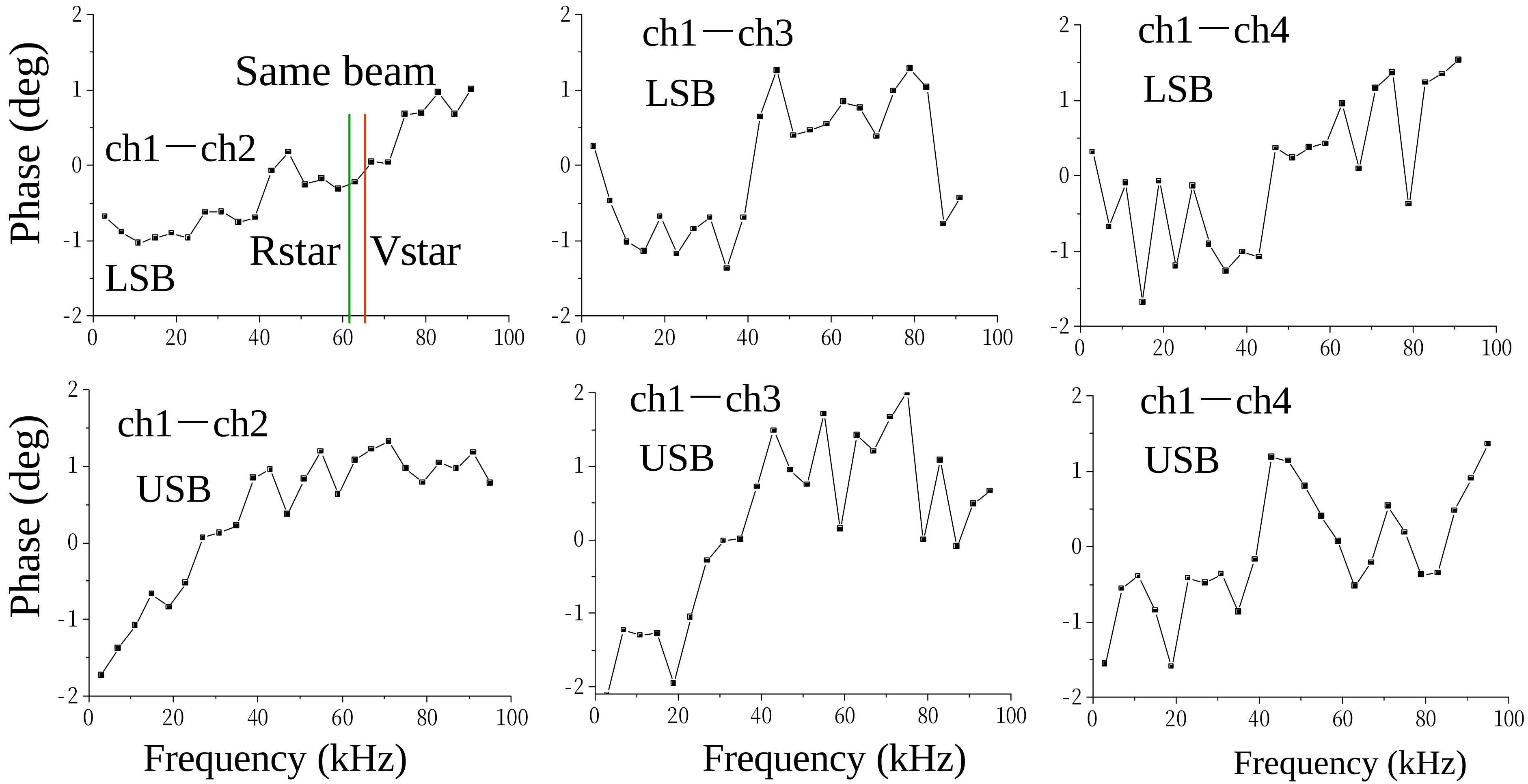
Influence on $\phi_R(t) - \phi_V(t)$

In whole bandwidth of 0--100kHz phase variation ±0.5deg

Same beam 5kHz phase variation **0.1deg**

Variation in phase and delay in receiver

Difference of phase among channels in backend：±2deg



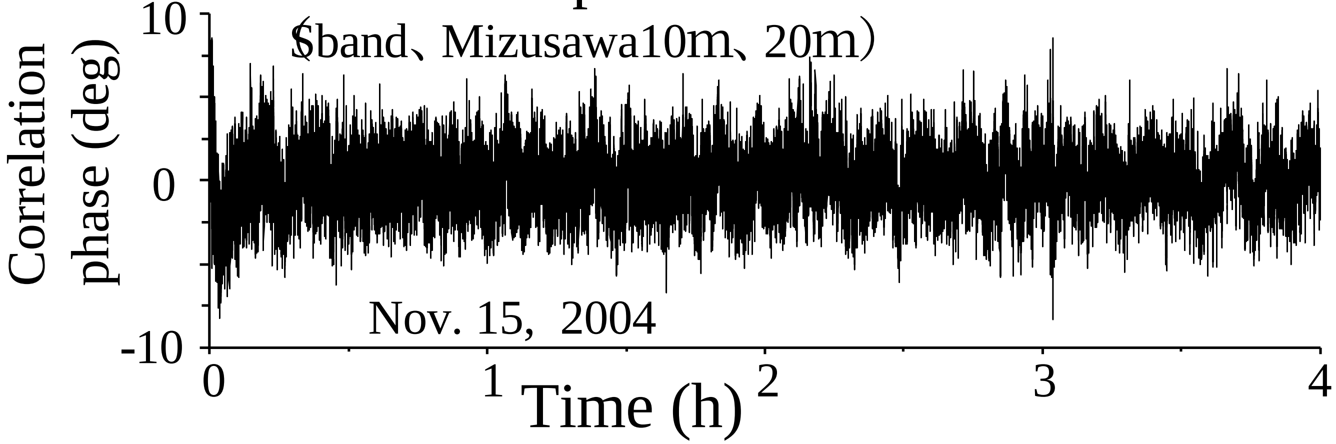
Influence on $\phi_R(t) - \phi_V(t)$

In whole bandwidth of 0--100kHz phase variation ±2deg
same beam (5kHz) phase variation <**1deg**

Variation in phase and delay in receiver

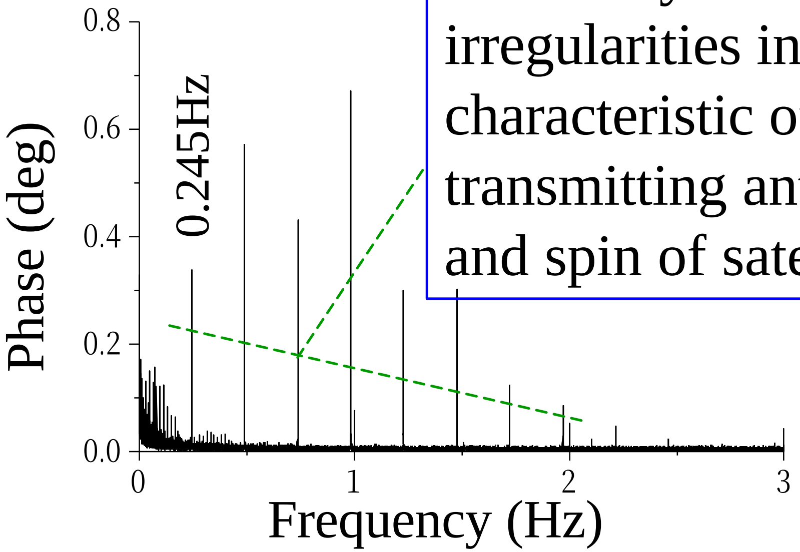
Correlation phase and Spectrum on a short baseline of 26m

Correlation phase fluctuation



$\phi_R(t) - \phi_V(t)$

integral time	phase variation
0.16s	1.7deg RMS
60s	**0.7deg RMS**



Caused by irregularities in phase characteristic of the transmitting antenna and spin of satellite

Reference

Qinghui Liu et. al
``New method of measuring phase characteristics of antenna using Doppler frequency measurement technique", **IEEE Trans.**, Antenna and Propa., vol.52, no.12, pp.3312-3318, Dec. 2004.

Influence of ionosphere

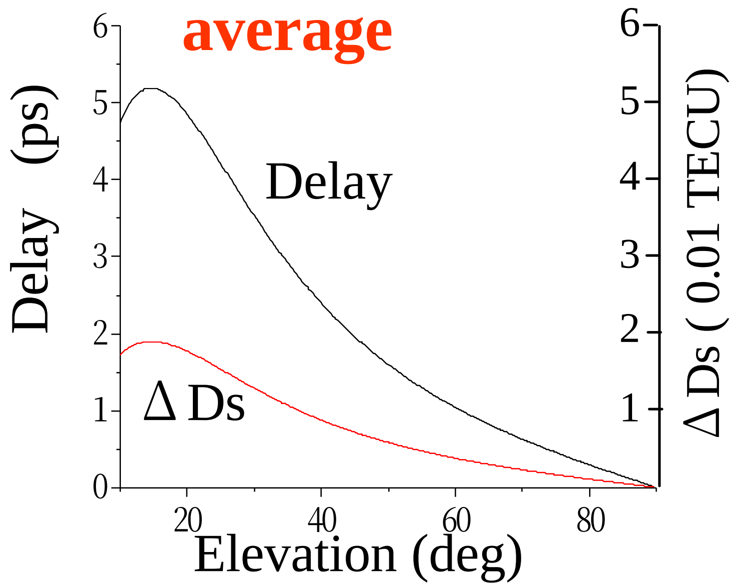
SLM Model

Zenith TEC

$$\tau_i(EL) = \frac{kD}{f^2}\frac{1}{\cos(\sin^{-1}(\frac{R\cos(EL)}{R+H}))}$$

delay

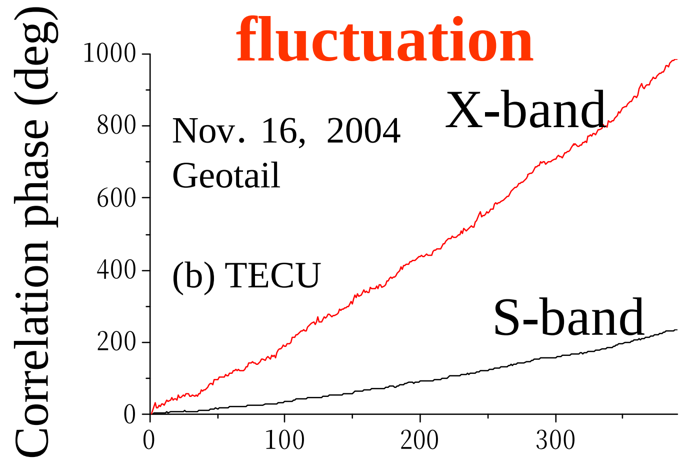
radius of earth   height

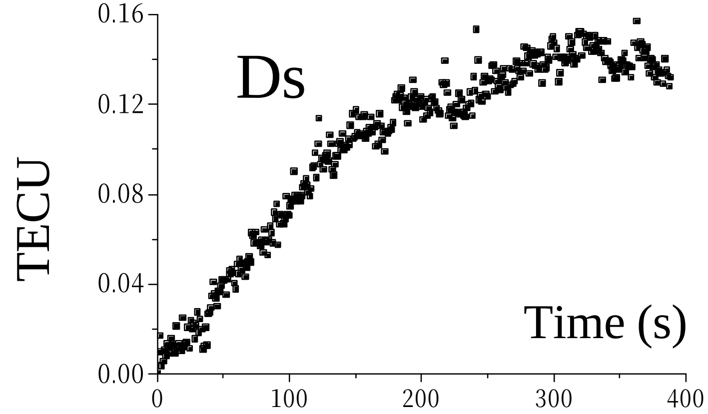


When ΔEL＝0.2 deg, estimated error=2TECU difference in delay between V- and Rstar is **5ps**、difference in TEC Ds < **0.02 TECU**

TEC at line of sight   S-band phase   X-band phase

$$D_s = \frac{f_s^2 f_x^2}{k(f_s^2 - f_x^2)}\left(\frac{\phi_s}{2\pi f_s} - \frac{\phi_x}{2\pi f_x}\right)$$

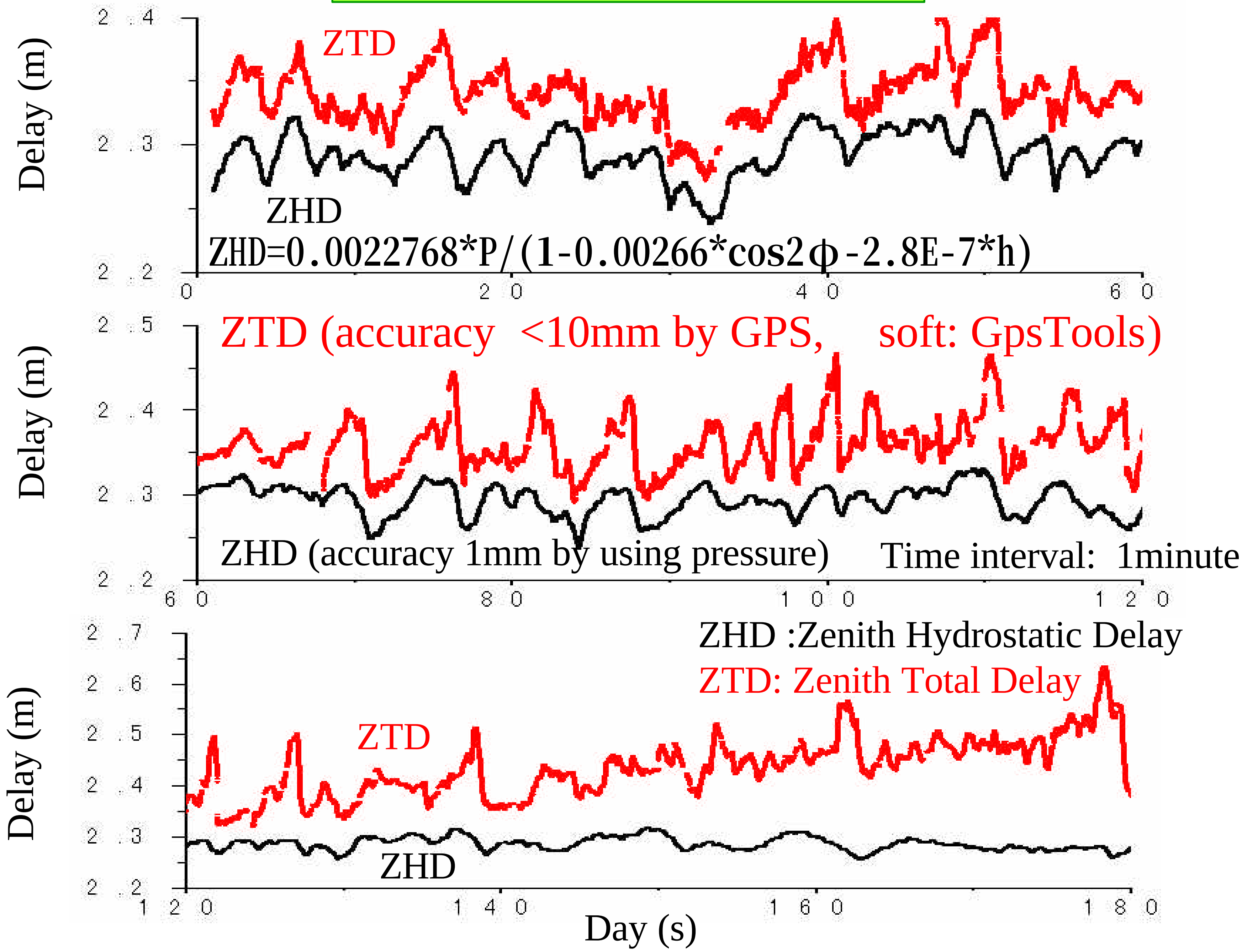




Ds estimated error<**0.1TECU**

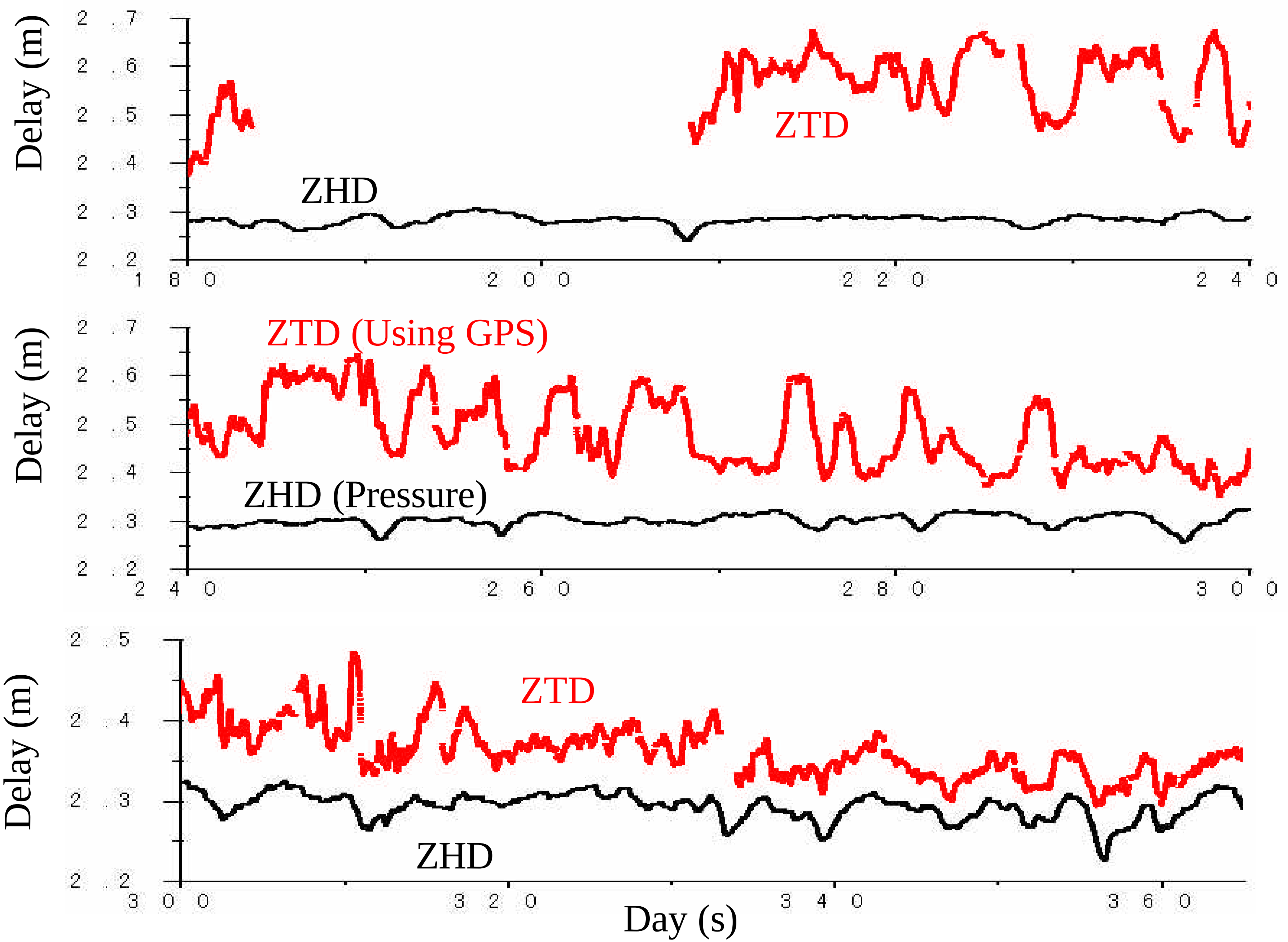
Influence of atmosphere

Mizusawa、2005

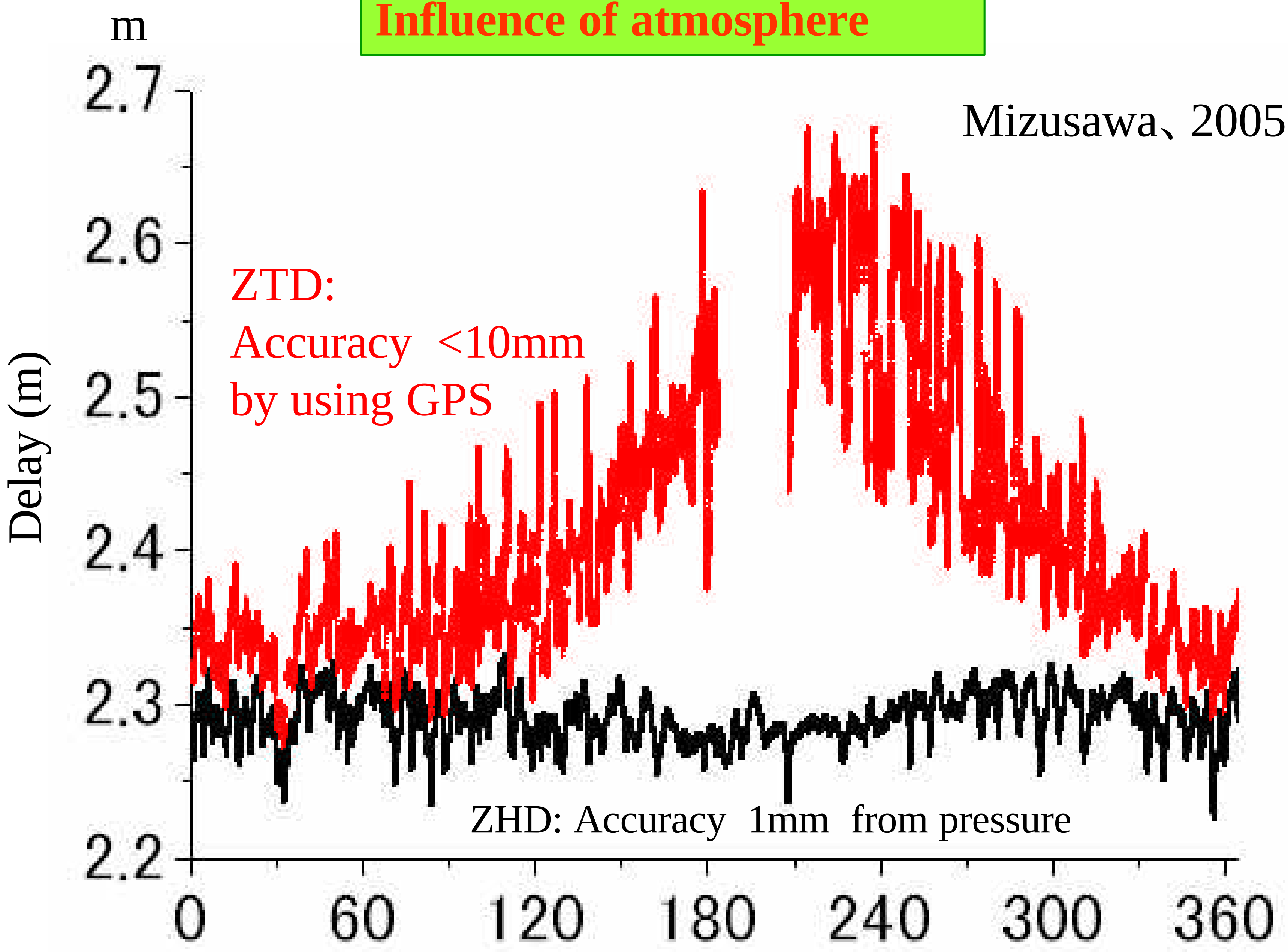


Influence of atmosphere

Mizusawa、2005

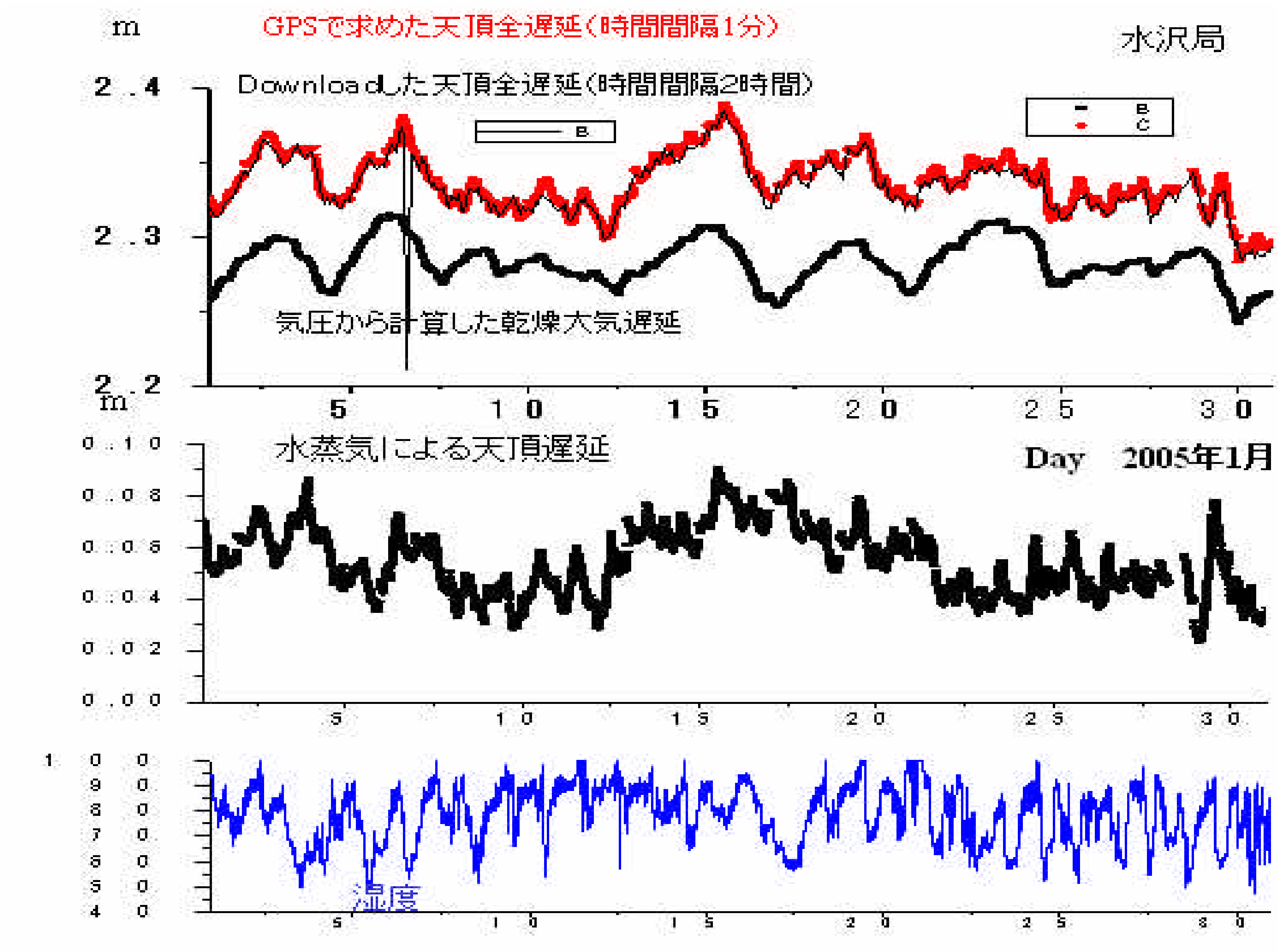


Influence of atmosphere



Influence of atmosphere

Mizusawa、2005



Influence of atmosphere

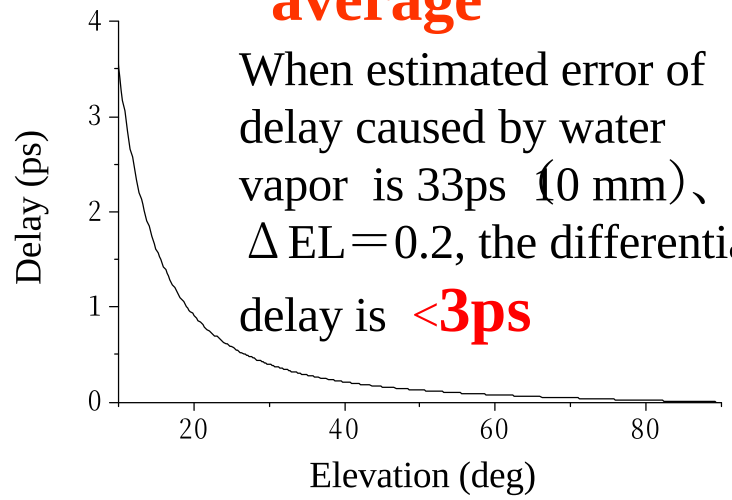
Herring-Niell Model

$$\tau_a(EL) = \tau_h m_h(EL) + \tau_w m_w(EL)$$

delay — dry atmosphere — water vapor

$$m_w(EL) = \frac{1 + \frac{a}{1+\frac{b}{1+c}}}{\sin(EL) + \frac{a}{\sin(EL)+\frac{b}{\sin(EL)+c}}}$$

a=0.00057, b=0.0015, c= 0.0467 @latitude 30 deg

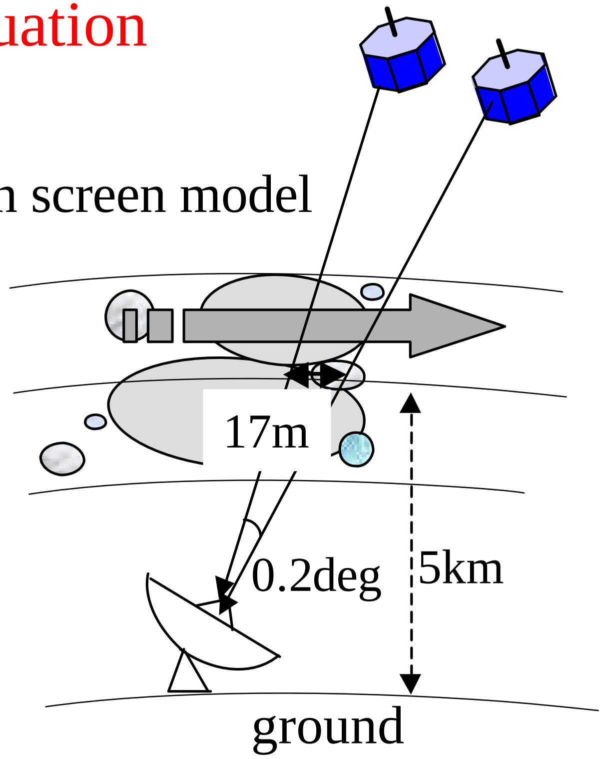


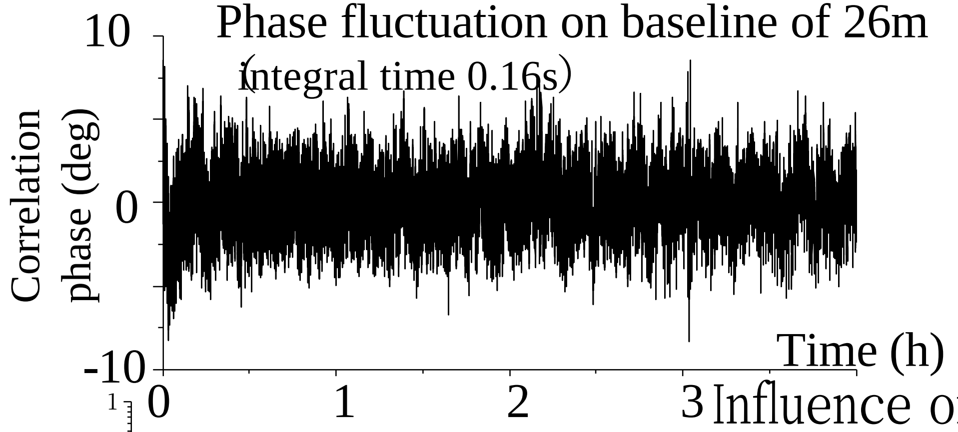
average

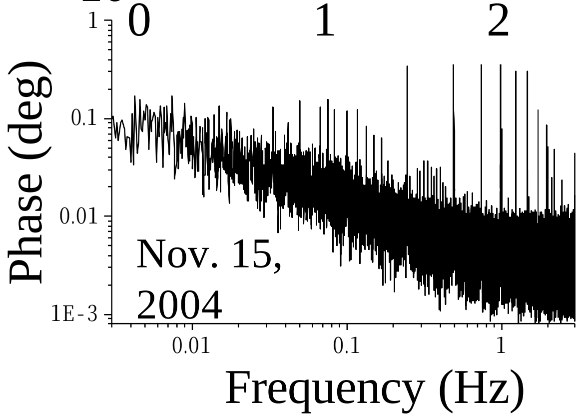
When estimated error of delay caused by water vapor is 33ps (10 mm), ΔEL=0.2, the differential delay is **<3ps**

fluctuation

Frozen screen model







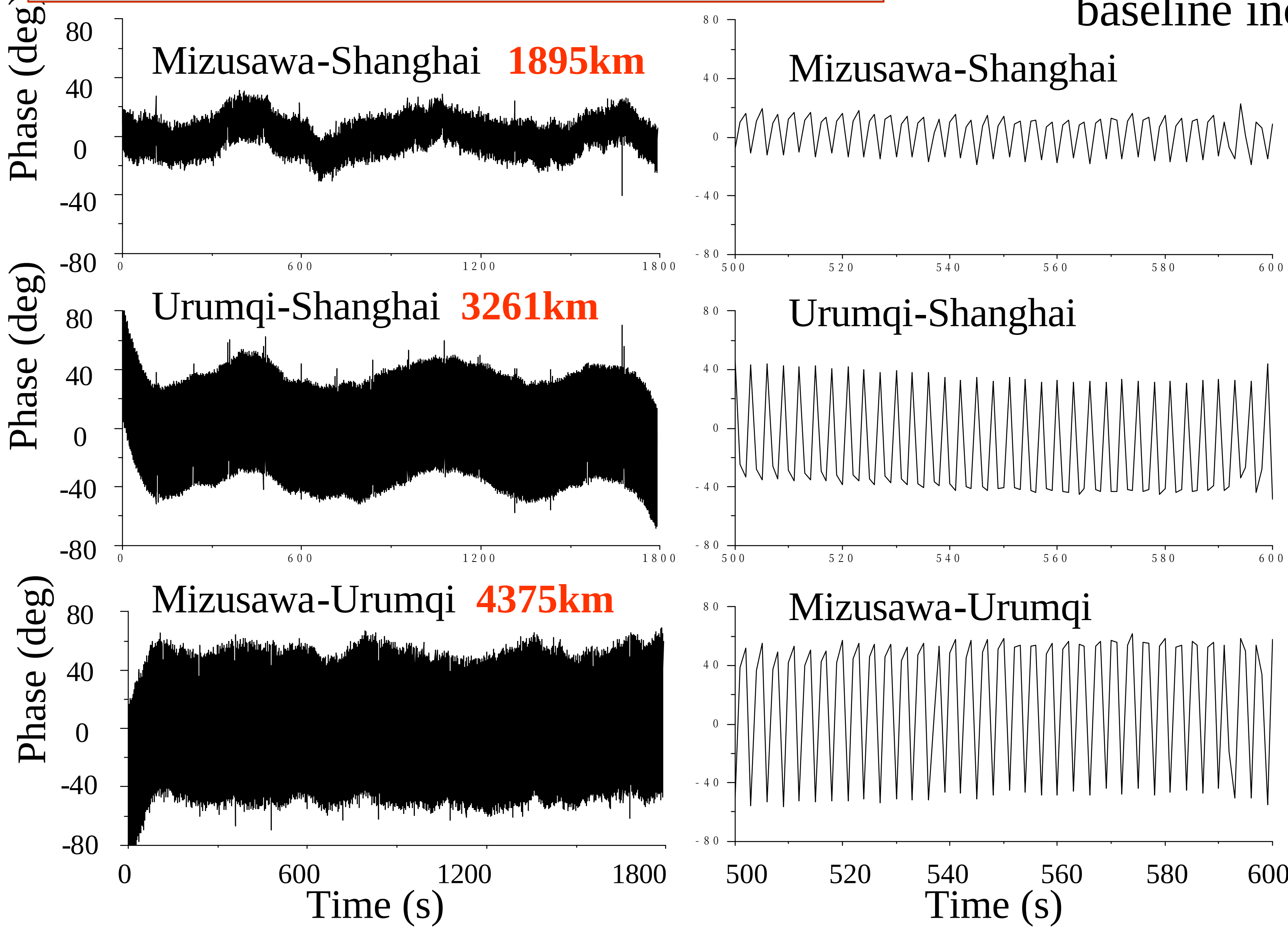
Influence on differential phase

Integral time	phase variation
0.16s	1.7degRMS
60s	**0.7degRMS**

Phase variation caused by transmitting antenna

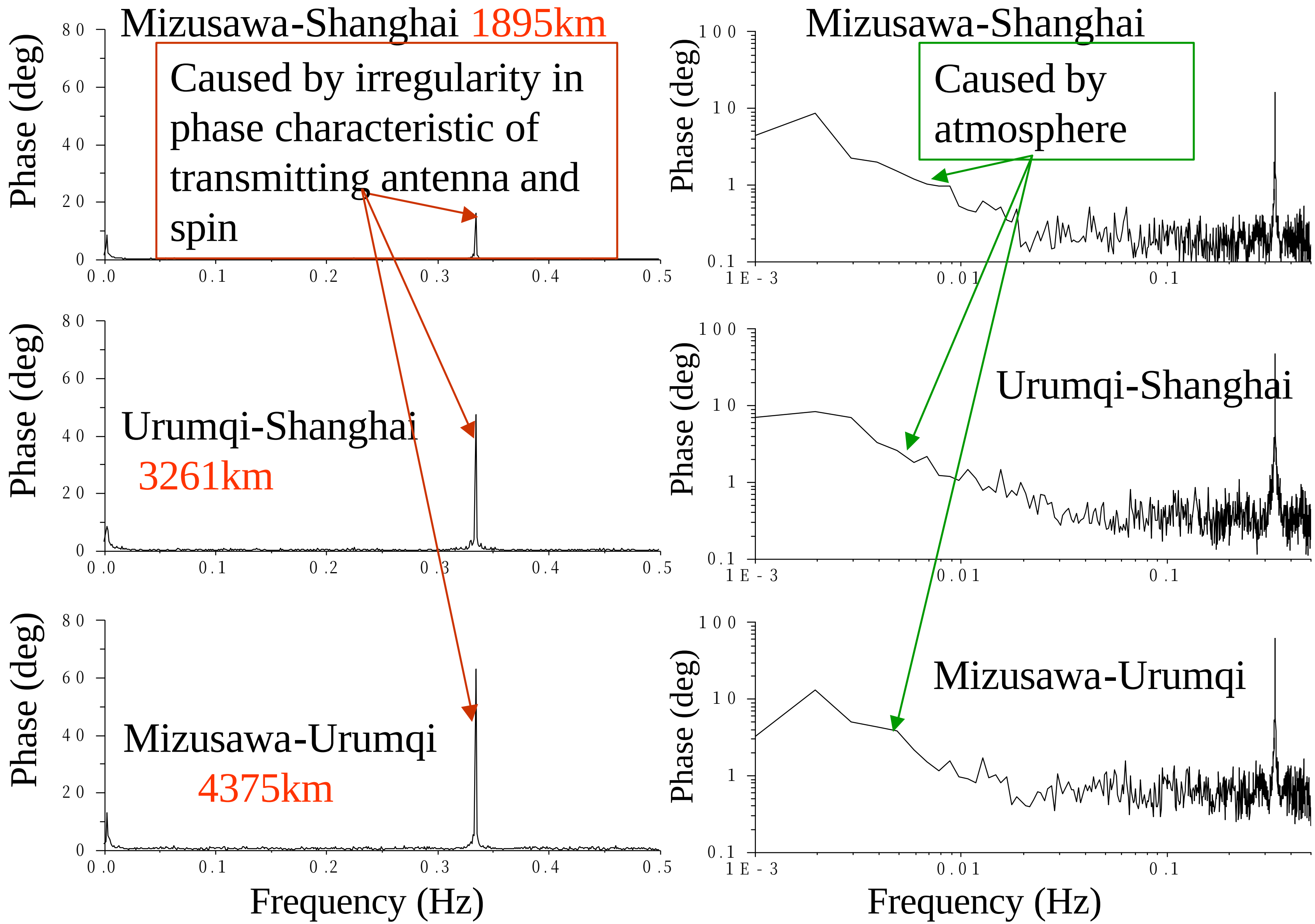
Phase variations on long baselines, Geotail, S-band

Phase variations become large as baseline increases



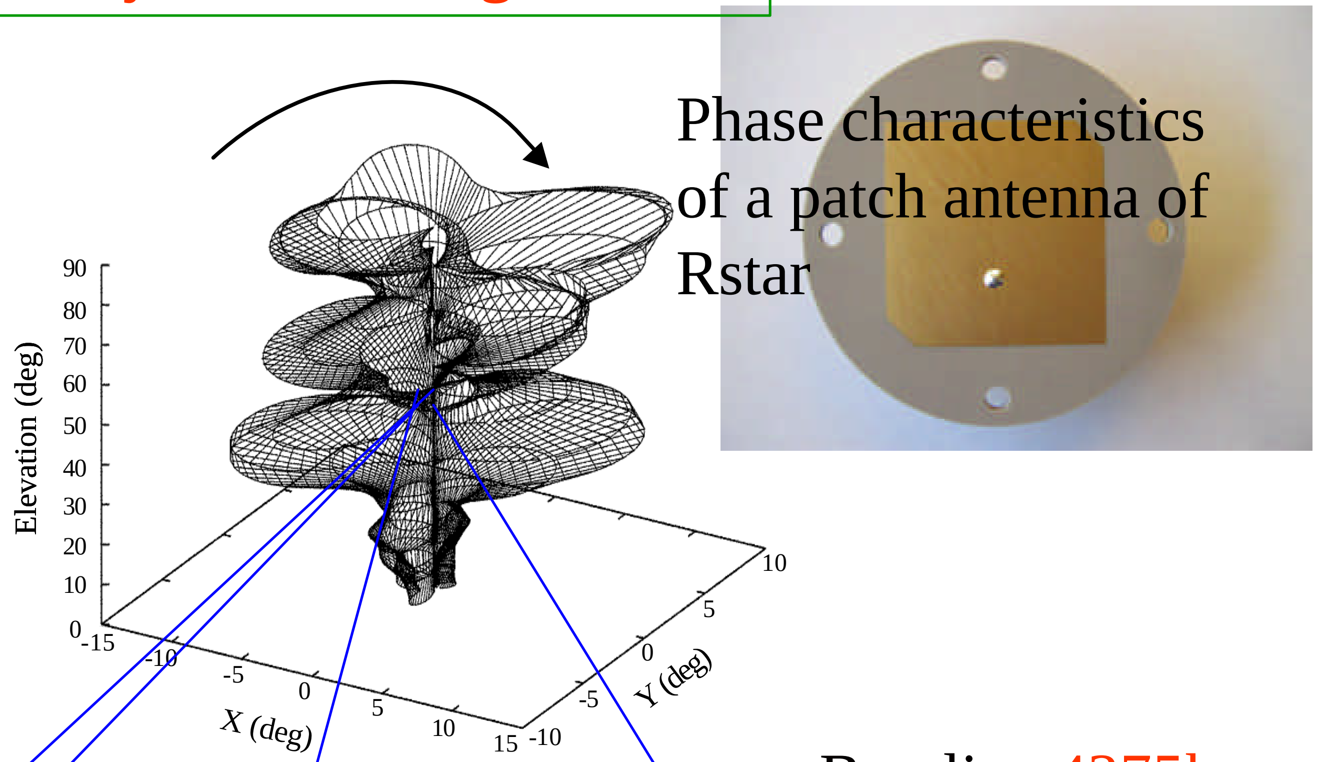
Phase variation caused by transmitting antenna

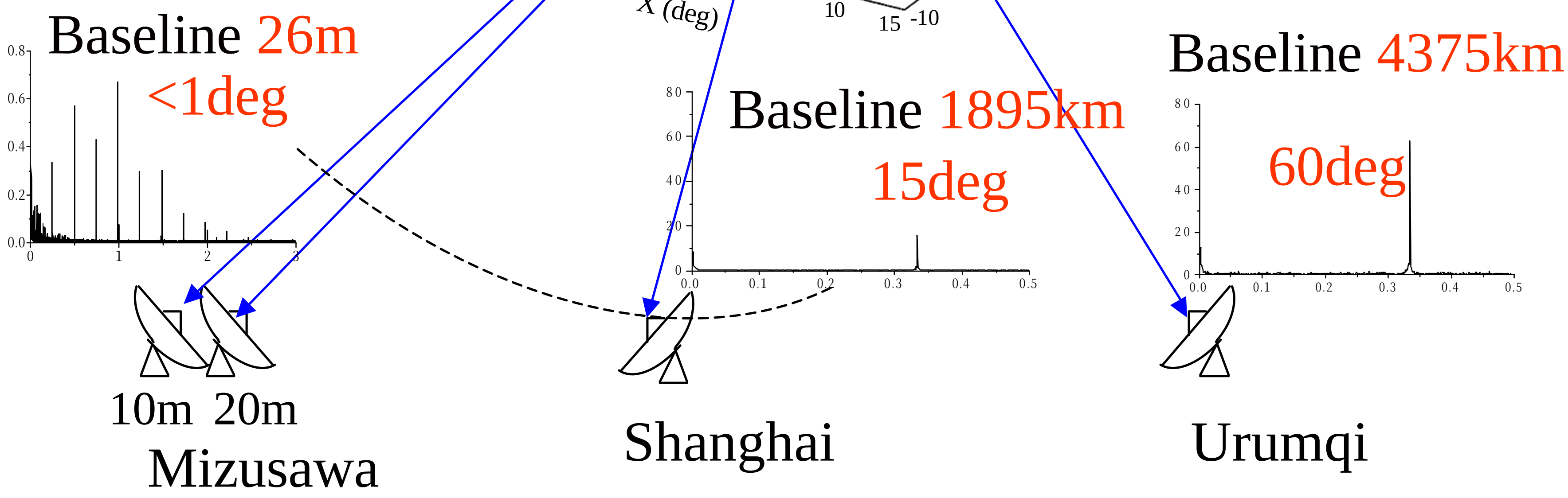
Spectrum of correlation phase on long baseline



Phase variation caused by transmitting antenna

When baseline becomes longer, the difference in direction of the two telescopes become larger, and then the correlation phase becomes larger.





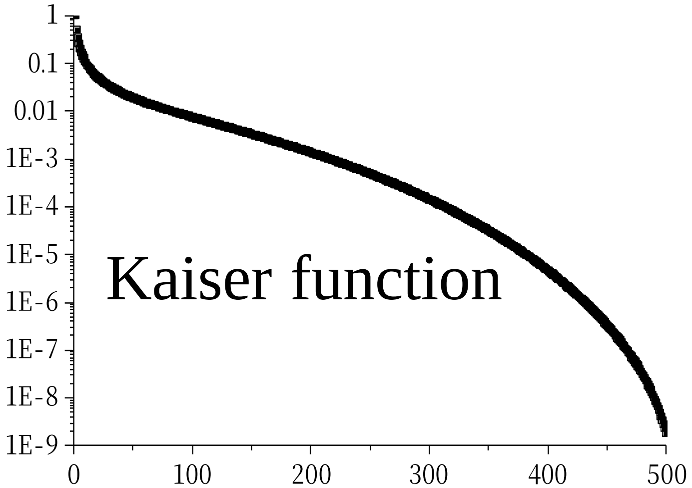
Removing phase variation caused by spin and irregularity in phase characteristics

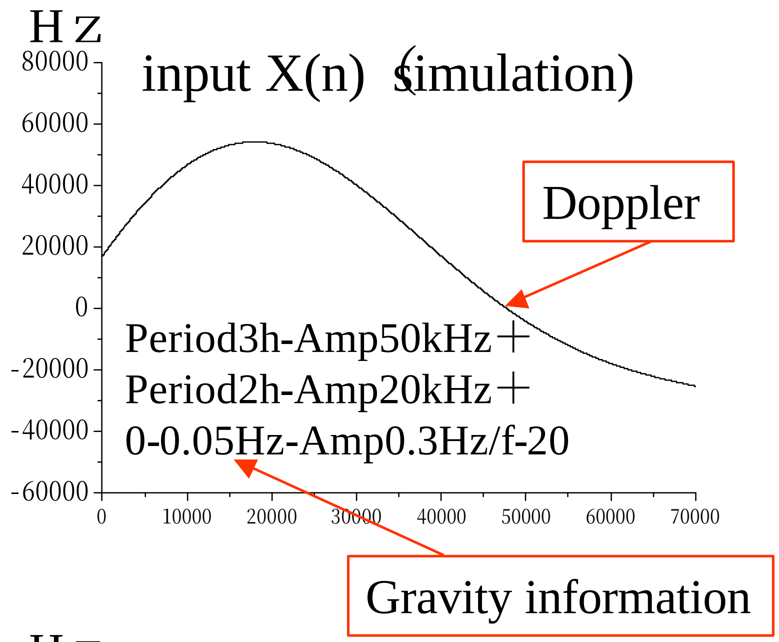
FIR-LPF using **Kaiser window function**

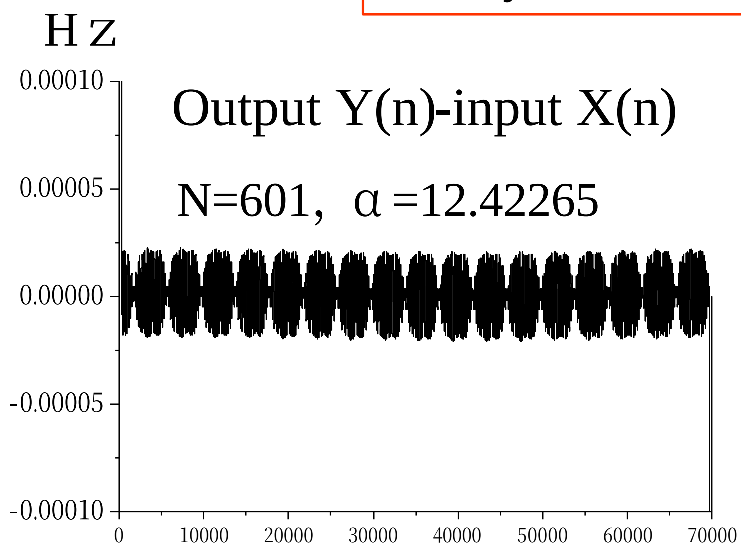
Kaiser function

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

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

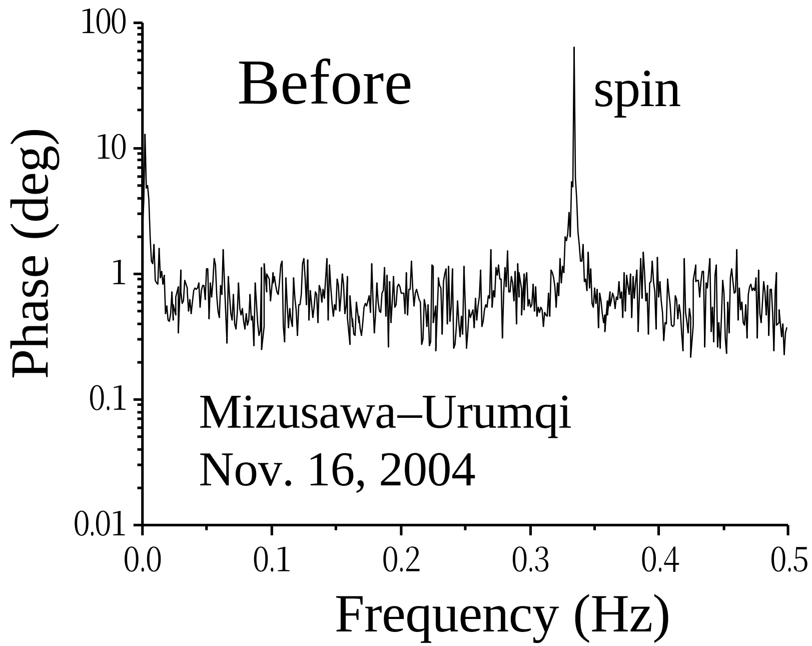


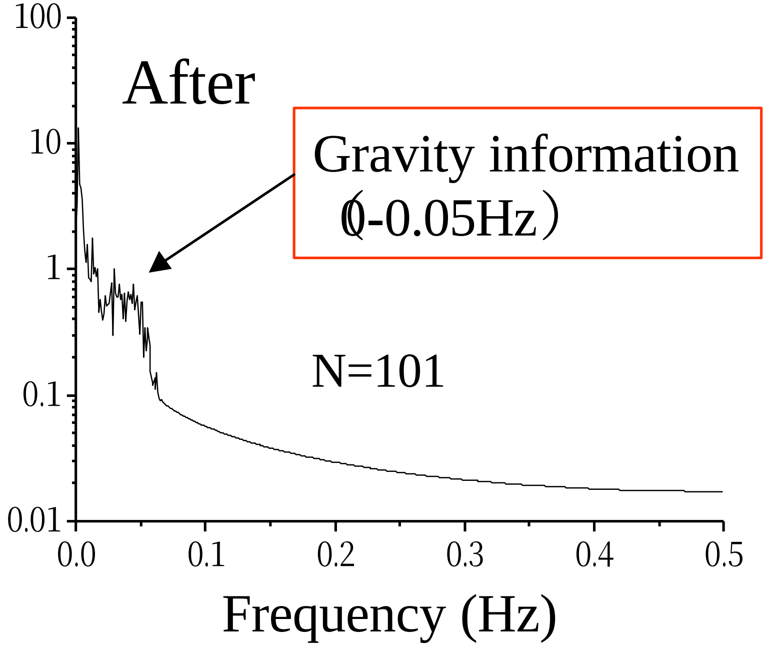




Accuracy for detecting gravity information in 0-0.05Hz →
0.00002Hz

Removing phase variation caused by spin and irregularity in phase characteristics





Gravity information of 0-0.05Hz is remained, and phase variation caused by spin is removed

Influence of irregularity in phase characteristics of transmitting on correlation $\phi_R(t) - \phi_V(t)$ can be reduced to 0.02 deg by using a LPF.

Phase variation caused by thermal noise

Integral time 100 s, bandwidth 50 Hz

	S/N (dB)		phase variation (deg)	
	Rstar	Vstar	Rstar	Vstar
S-band	19	19	0.7	0.7
X-band	17	19	1.1	0.7

Error in orbit prediction $\Delta\tau_s$

Orbit of V- and Rstar can be determined by range and Doppler measurement with an accuracy of 100m, which corresponds to delay error of $\Delta\tau_s$=1 ns

Differential delay between S- and X-band $\Delta\tau_{xs}$

Difference in positions of S- and X-band transmitting antenna 3.5 ps
ionosphere 4.7 ps

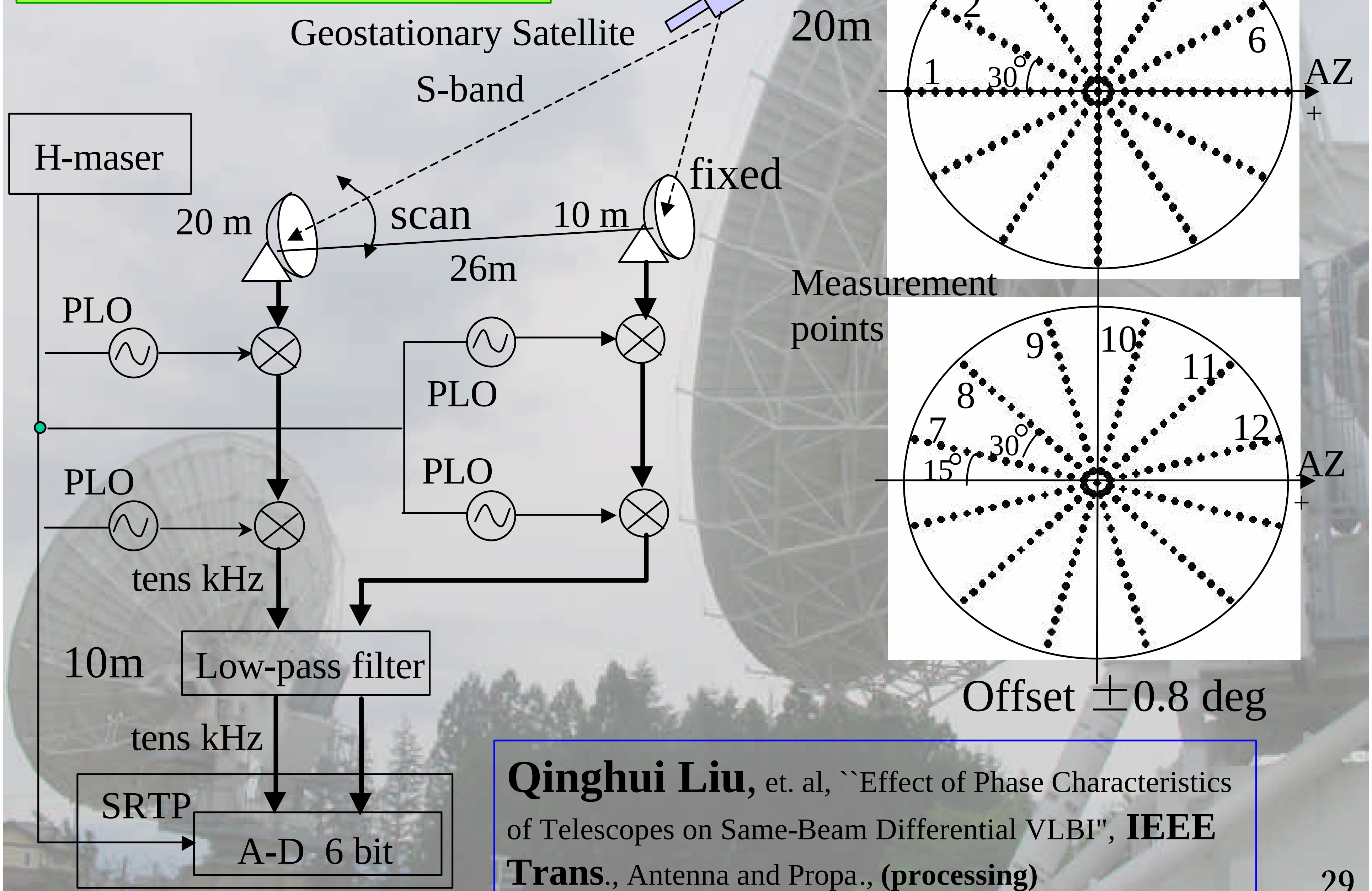
total **0.0082 ns**

other

Clock offset of H-masers at two stations is canceled

Position error of telescope is only several cm、can be ignored

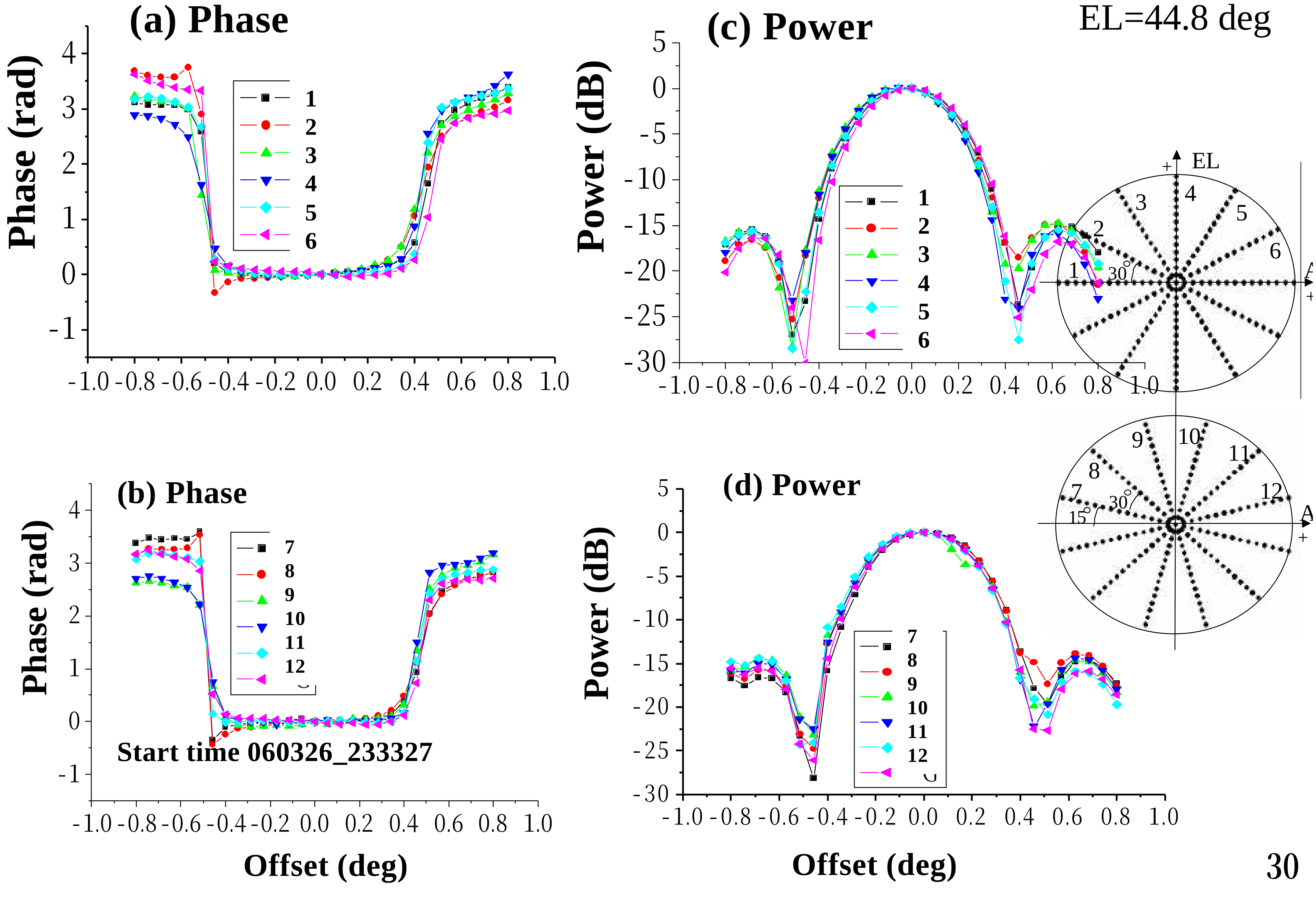
Phase variation in main beam of receiving antenna



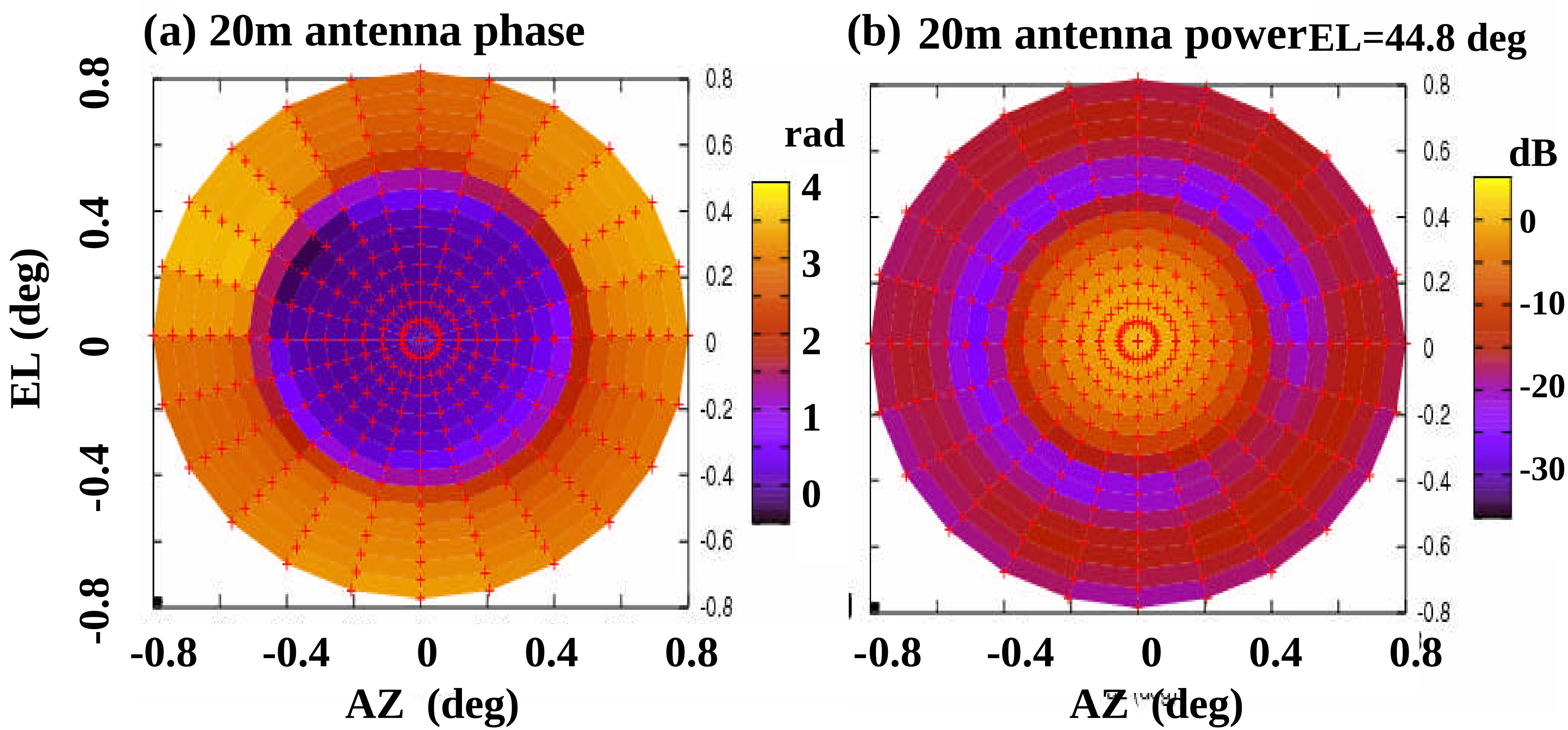
Qinghui Liu, et. al, ``Effect of Phase Characteristics of Telescopes on Same-Beam Differential VLBI", **IEEE Trans**., Antenna and Propa., **(processing)**

Phase and power characteristics of receiving antenna

20m telescope,
S-band
EL=44.8 deg



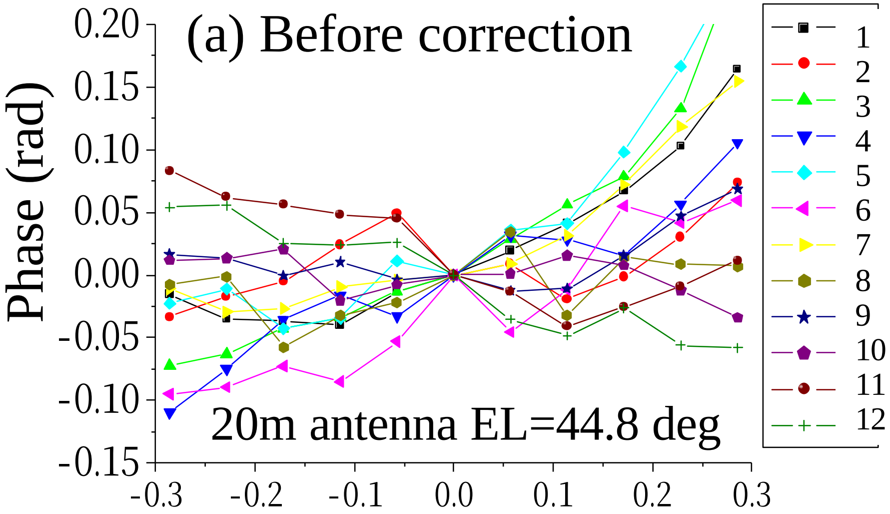
Phase and power characteristics of receiving antenna

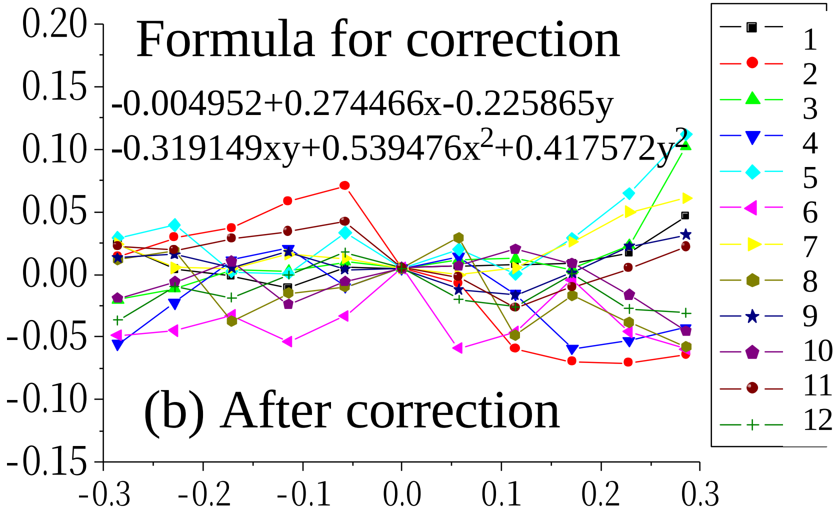


Phase variation in main beam of receiving antenna

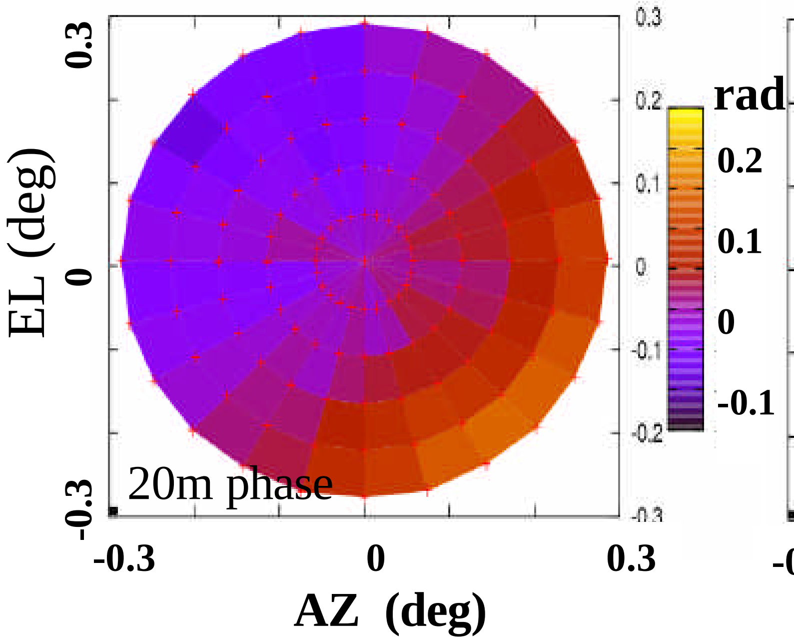
Before correction, phase variation 0.06 rad

After correction, 0.03 rad = 1.7degRMS

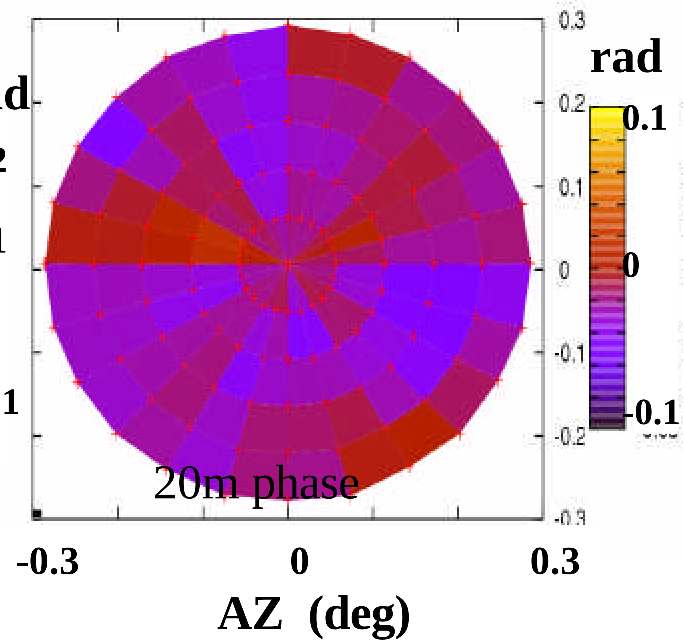


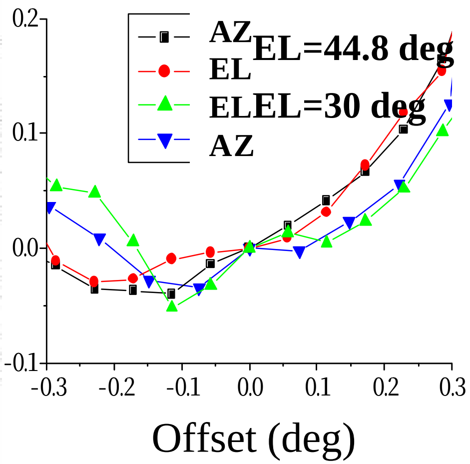


(a) before correction



(b) after correction EL=44.8 deg

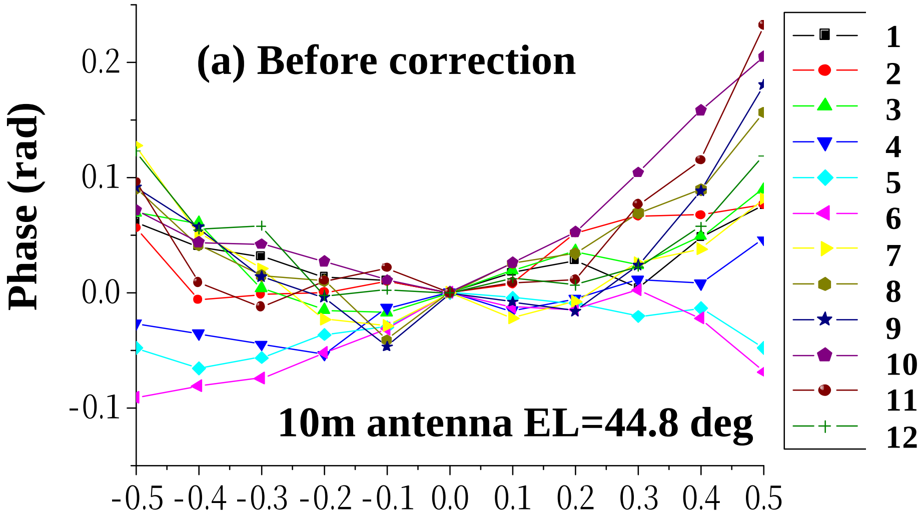


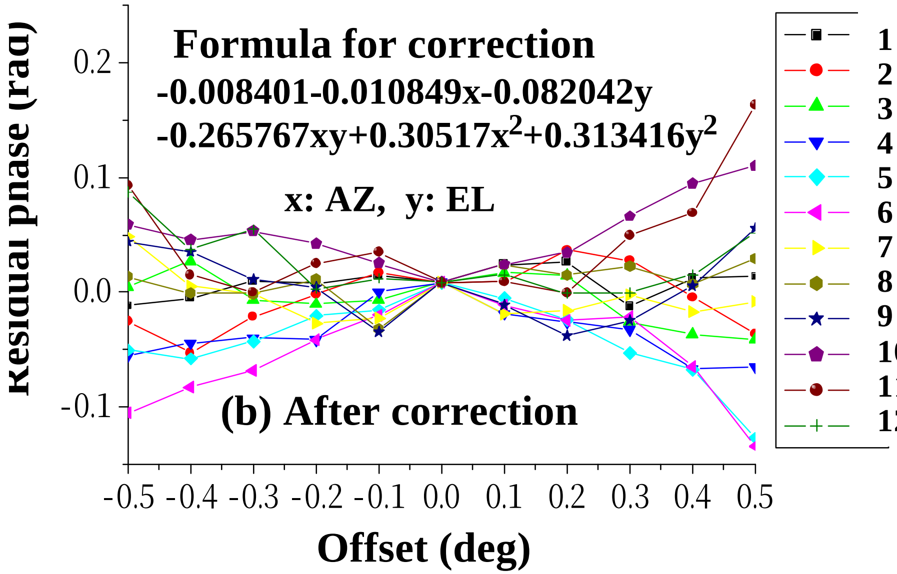


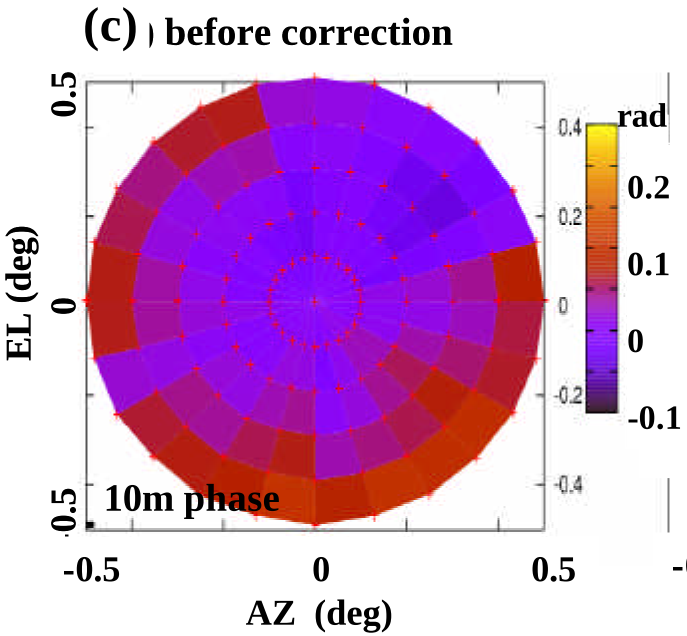
Phase and power characteristics of receiving antenna

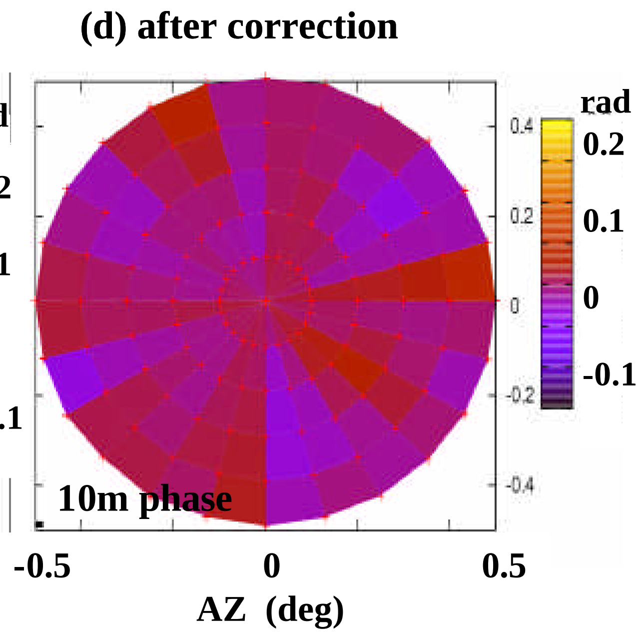
Before correction, phase variation 0.055 rad

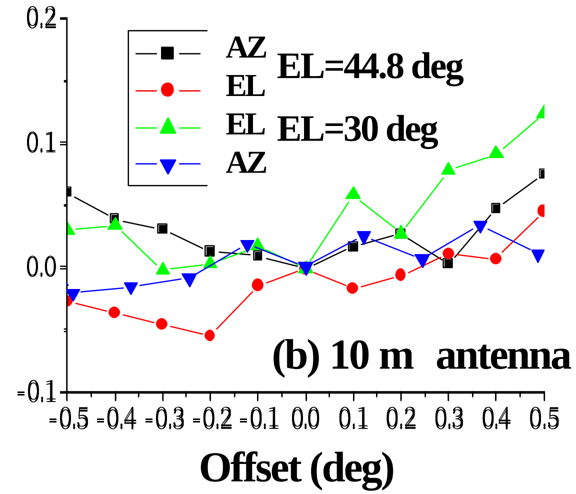
After correction, 0.04 rad = 2.2degRMS



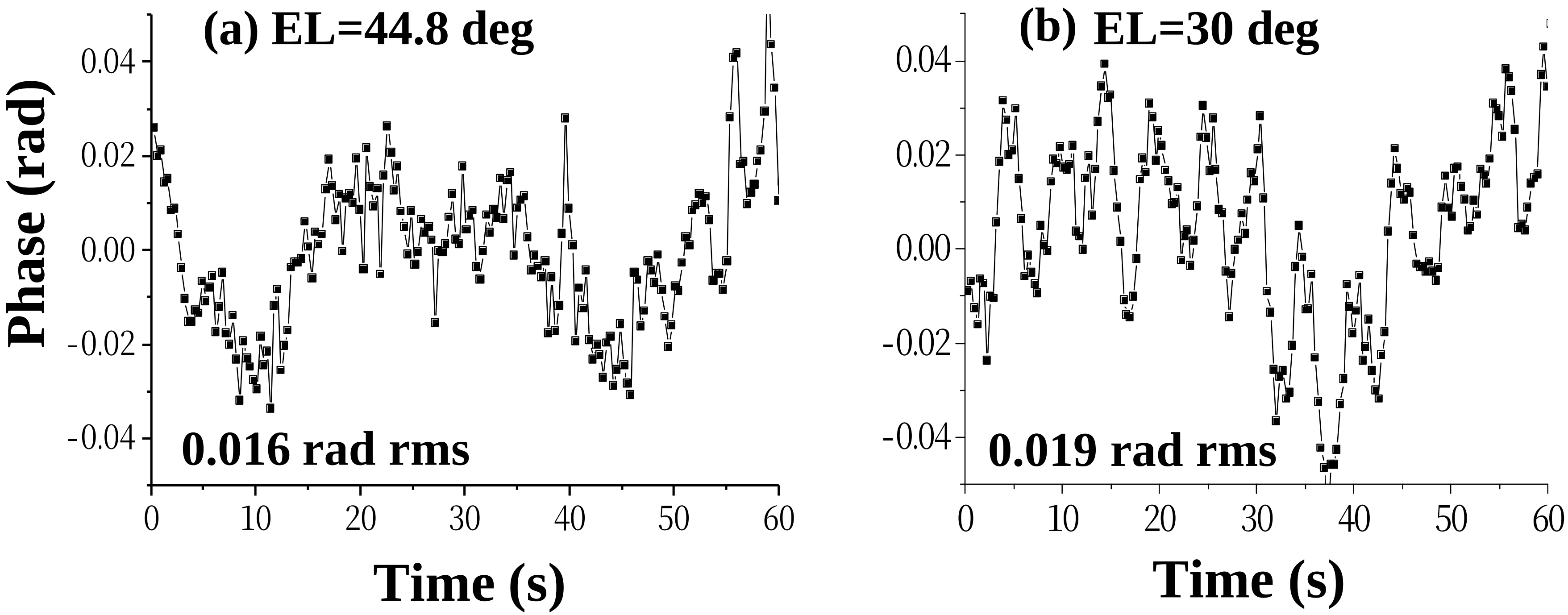








Phase and power characteristics of receiving antenna



Conclusion

Phase error in S- and X-band in same beam differential VLBI

Error Source	Phase error [[σs]] deg	Phase error [[σx]] deg
Receiver	1	1
Atmosphere	0.7	2.8
Receiving antenna	**1.7**	**1.7**
Thermal noise	0.7	0.7, 1.1
Transmitting antenna	0.02	0.02
Root sum square	**2.2**	**3.7**

errors

ΔDs	Δτs	Δτxs	[[σs]]	[[σx]]
0.1TECU	1ns	0.0082ns	3.1deg	5.2deg

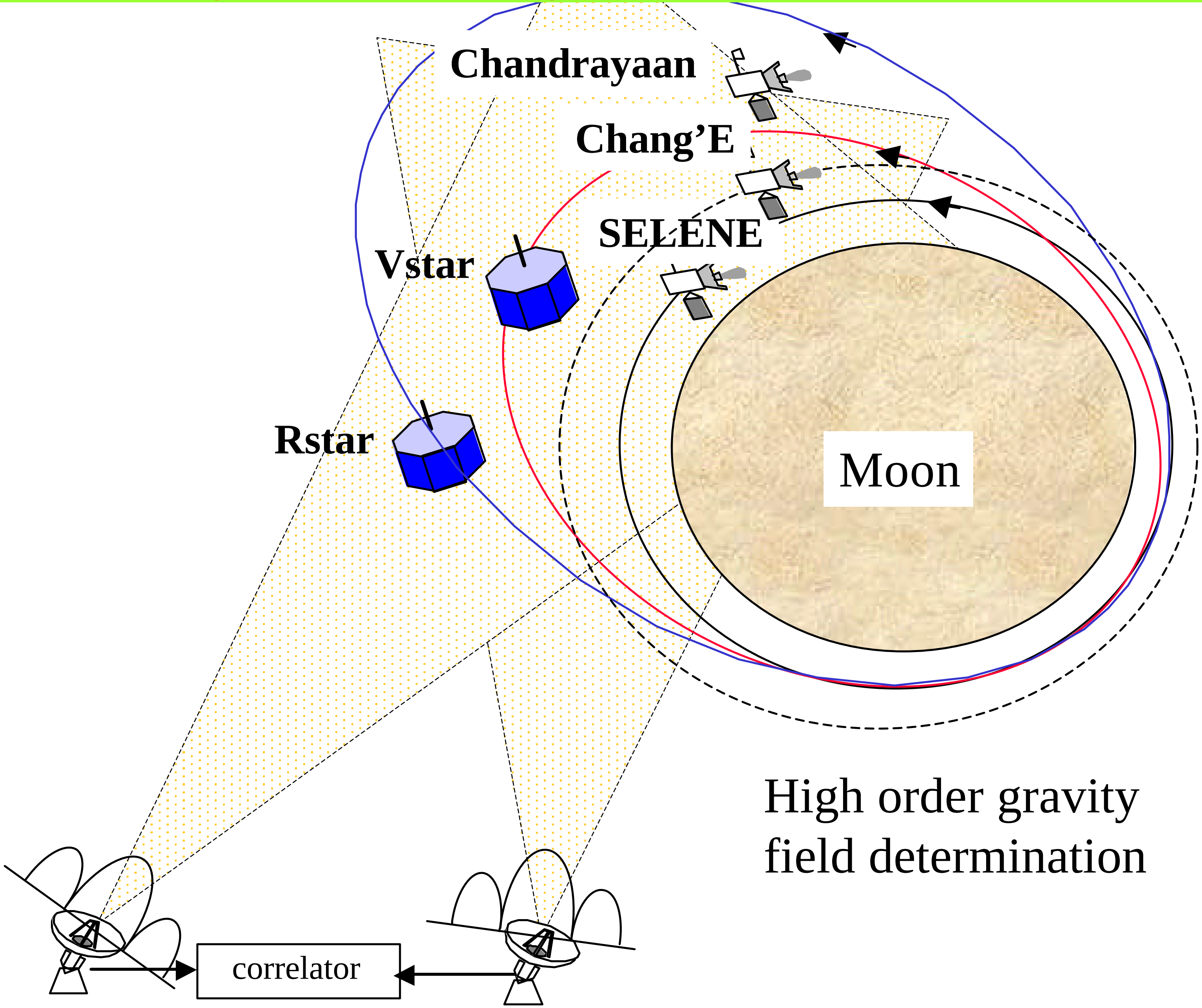
Satisfied condition for removing 2π

Condition	Eq.(1)	Eq.(2)	Eq.(3)	Eq.(4)
Available	**0.02**	**0.16**	**0.48**	**0.34**
Required	0.5	0.5	0.5	0.5

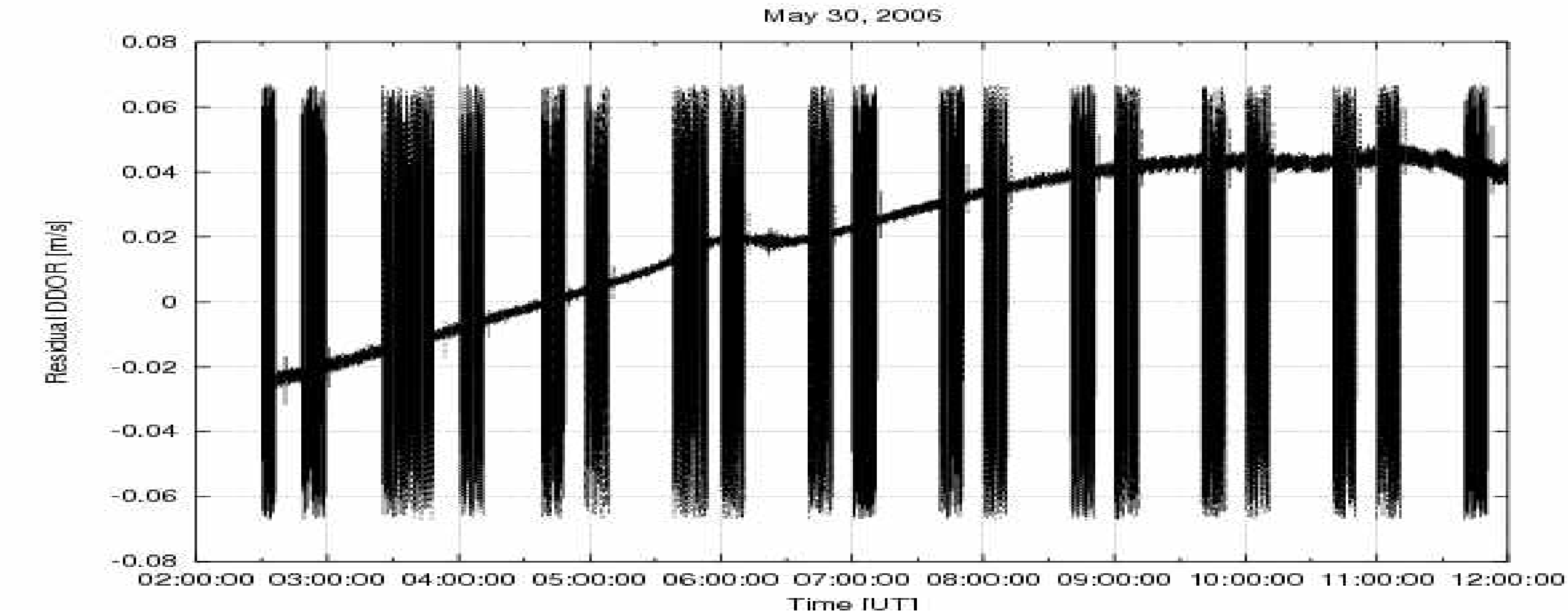
2π problem can be solved by same beam VLBI

Difference in delay can be obtained with an accuracy of several ps, relative position of R- and Vstar can be determined with an accuracy of tens cm.

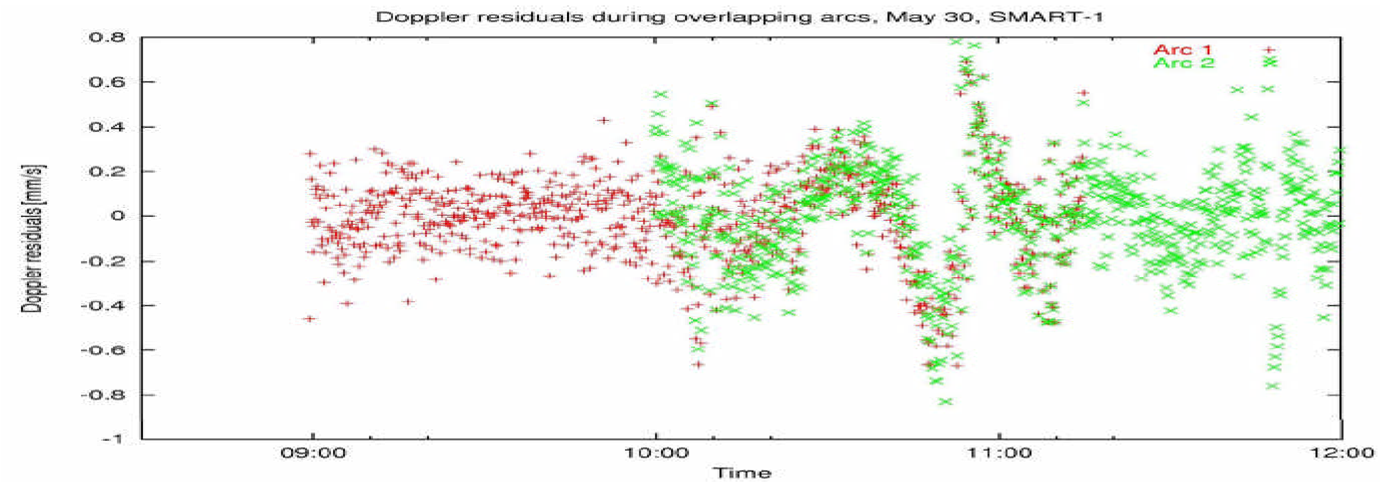
Interesting studies using same beam VLBI technology

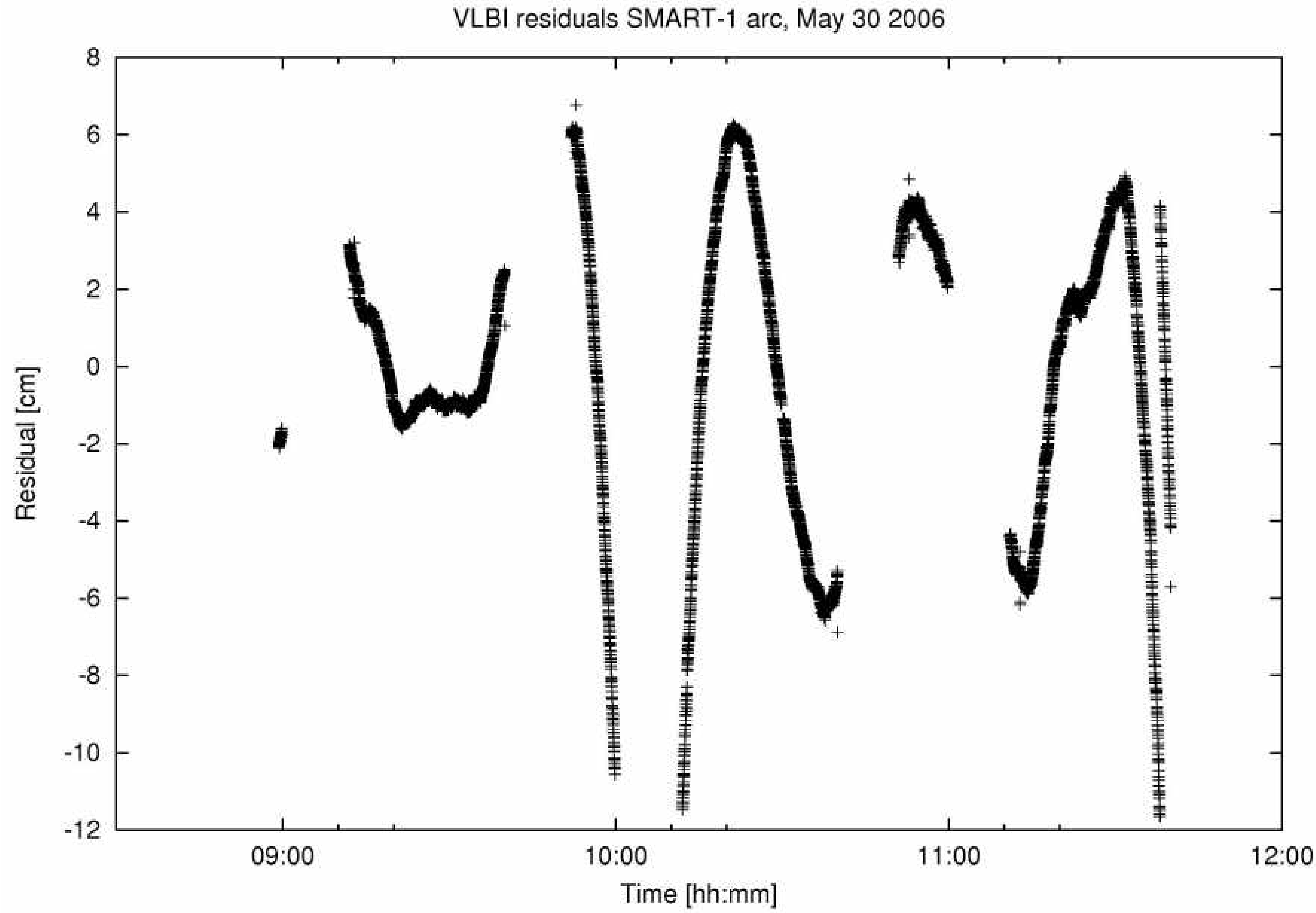


High order gravity field determination

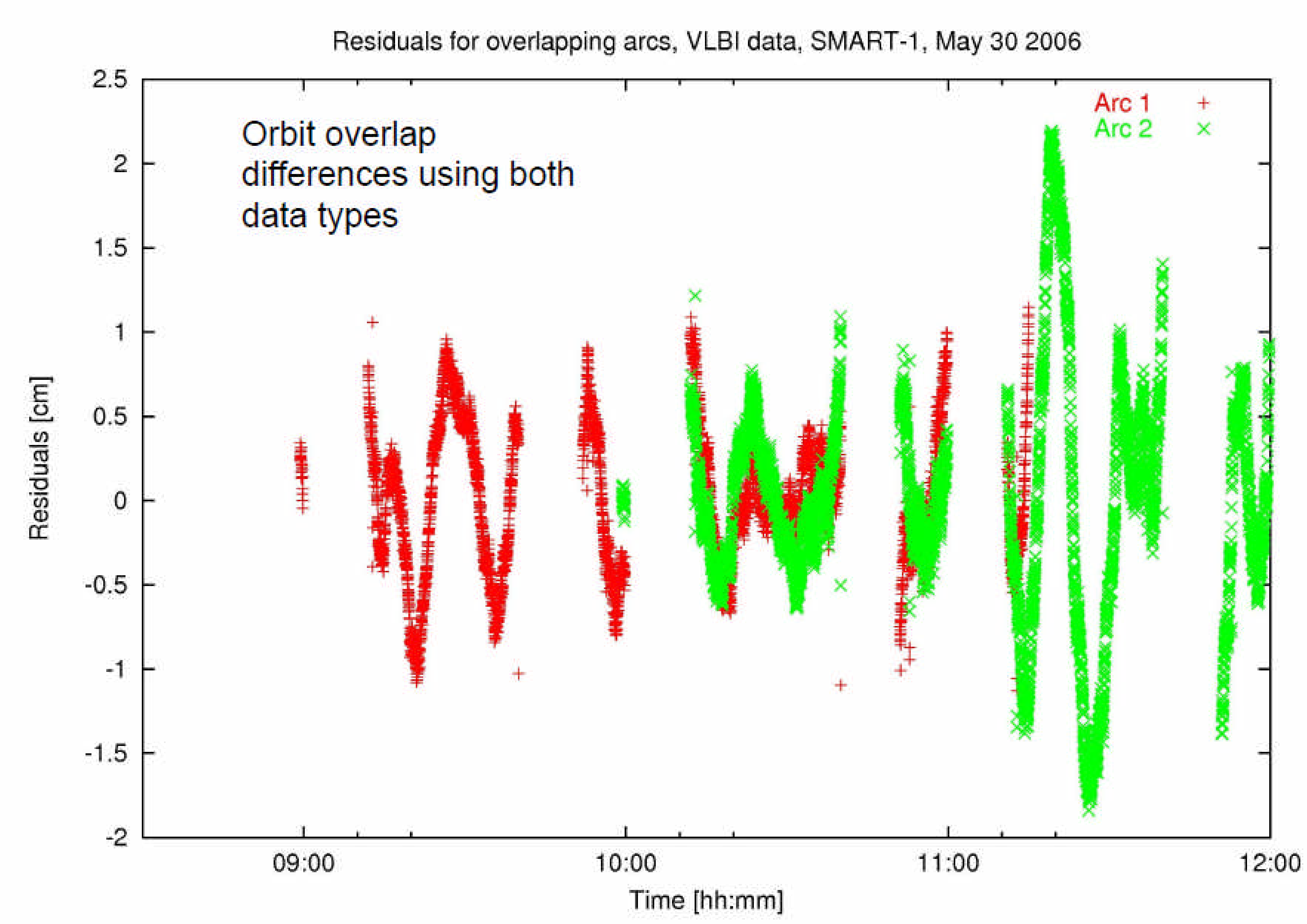


The residual DORR on MIZUSAWA10m – SHANGHAI baseline.
Estimated DORR is sum of predicted DORR and the residual DORR.





VLBI residuals SMART-1 arc, May 30 2006
Residual [cm]
8
6
4
2
0
-2
-4
-6
-8
-10
-12
09:00
10:00
11:00
12:00
Time [hh:mm]


Residuals for overlapping arcs, VLBI data, SMART-1, May 30 2006
Orbit overlap
differences using both
data types
Arc 1
Arc 2
Residuals [cm]
Time [hh:mm]
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
09:00
10:00
11:00
12:00