

# 位相遅延量を使った 相対VLBI補正の検証

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# 発表内容

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- 前回までの報告
  - 飛翔体VLBI観測の精度と現在の問題点
  - 2005年11月HAYABUSAのVLBI位相遅延計測
  - 群遅延を使った相対VLBI補正、電離媒質の効果
- 今回の結果
  - クエーサの位相遅延を使った改善の試みと結果
- 今後の作業

# Spacecraft Navigation R&RR + VLBI

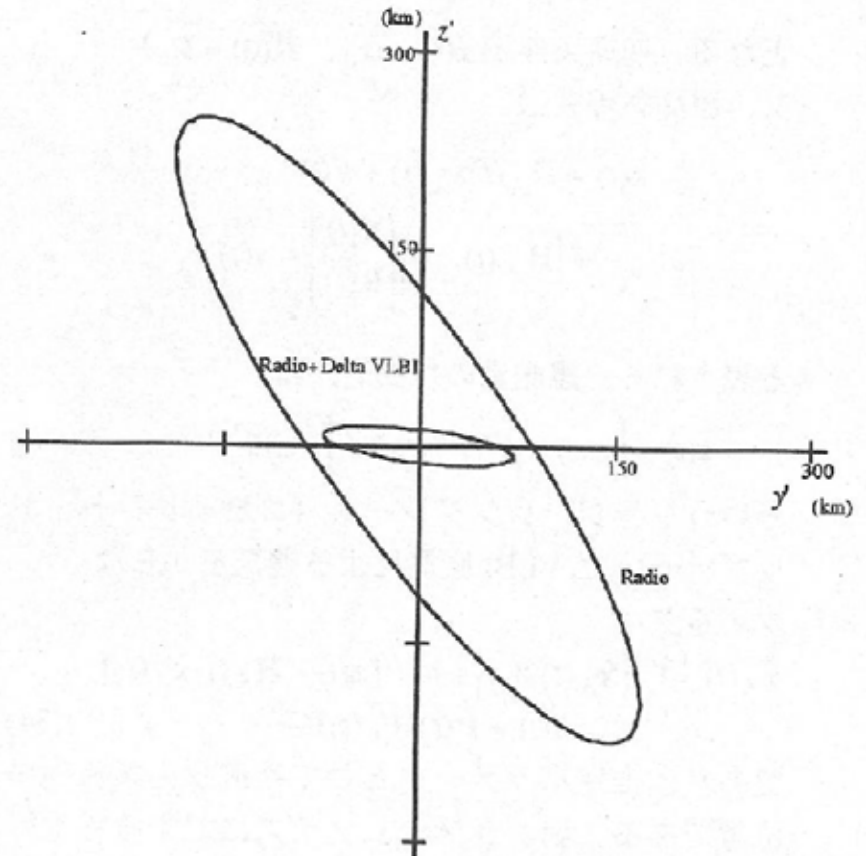
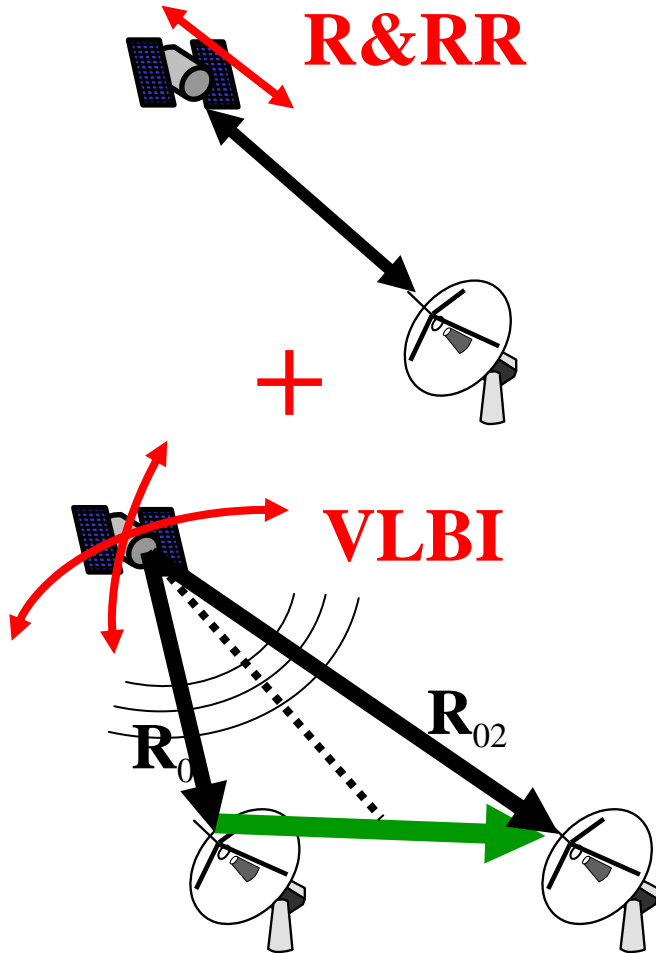
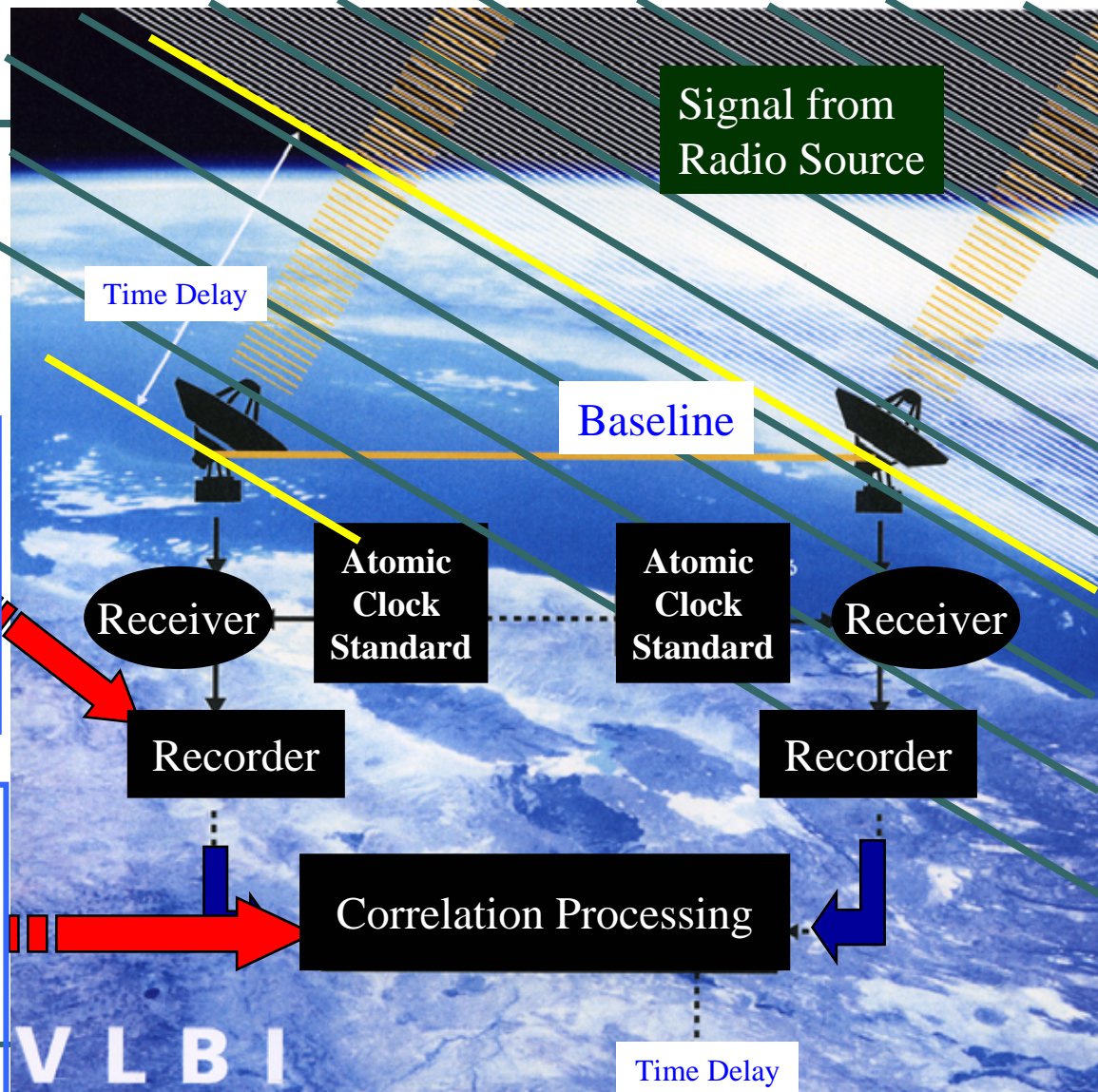


Fig. 7 誤差楕円

# VLBI = Very Long Baseline Interferometry



Radio Telescope



Atomic Time Standard (H-maser)



Huge Volume Data Recording



Correlator

**VLBI**  
Very Long Baseline Interferometry

# 背景

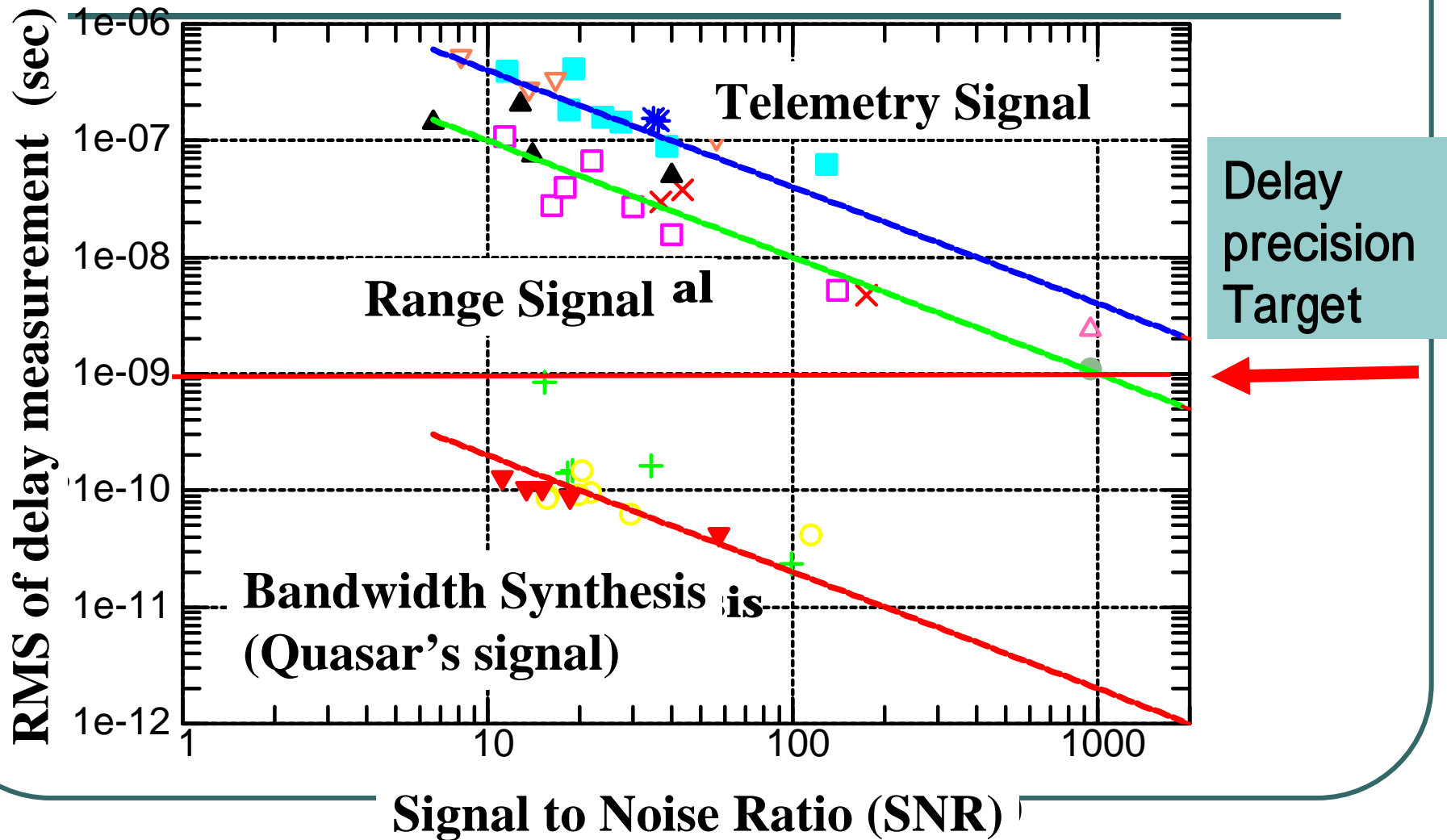
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- DDOR ( Differential Oneway Range):
  - 米国NASA/JPLではDDOR (VLBI群遅延計測) による軌道決定を行っている。
- 日本の探査機
  - DDORと同様な広帯域の送信機を装備していない=> 群遅延量の決定精度が不足
- 日本の国内基線 << DSNの基線
  - 基線長の面でも、現在の日本のVLBI軌道決定には不利

# Precision of Ground Delay

$$\sigma_{\tau} \propto \frac{1}{(SNR \times Bandwidth)}$$

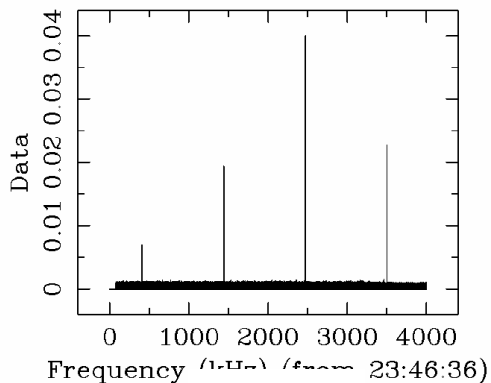
Hayabusa Observations  
In May /30 ~ July 4 2005



# VLBI Observable: Group Delay

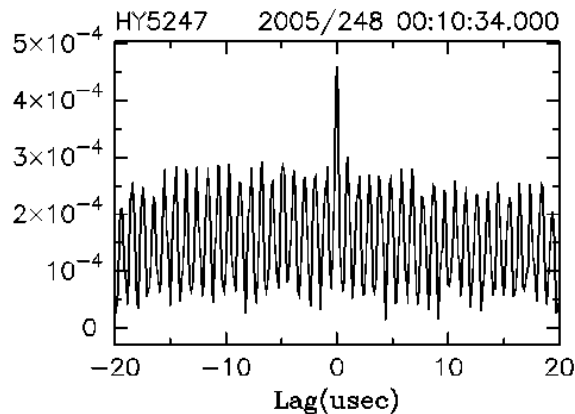
## DDOR signal

0.000 - 1.000 sec.  
8e+03 kHz-1bit Auto Cor Spectrum



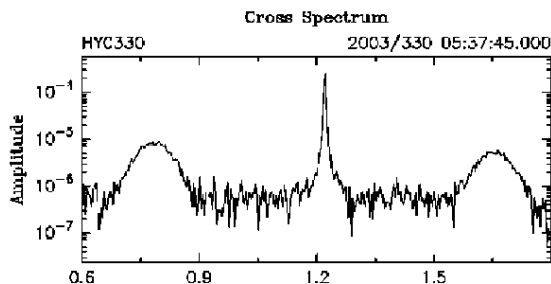
← 4 MHz →

### Fringe



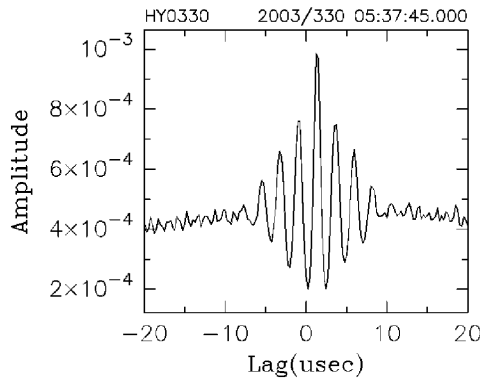
Effective Bandwidth  
450kHz

## Range signal



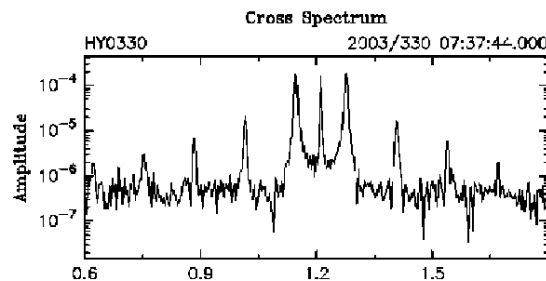
← 1MHz →

### Fringe



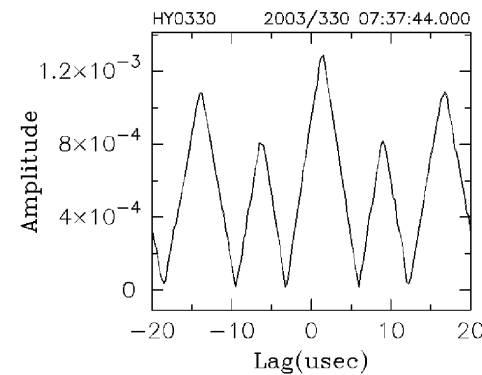
Effective Bandwidth  
100kHz

## Telemetry Signal



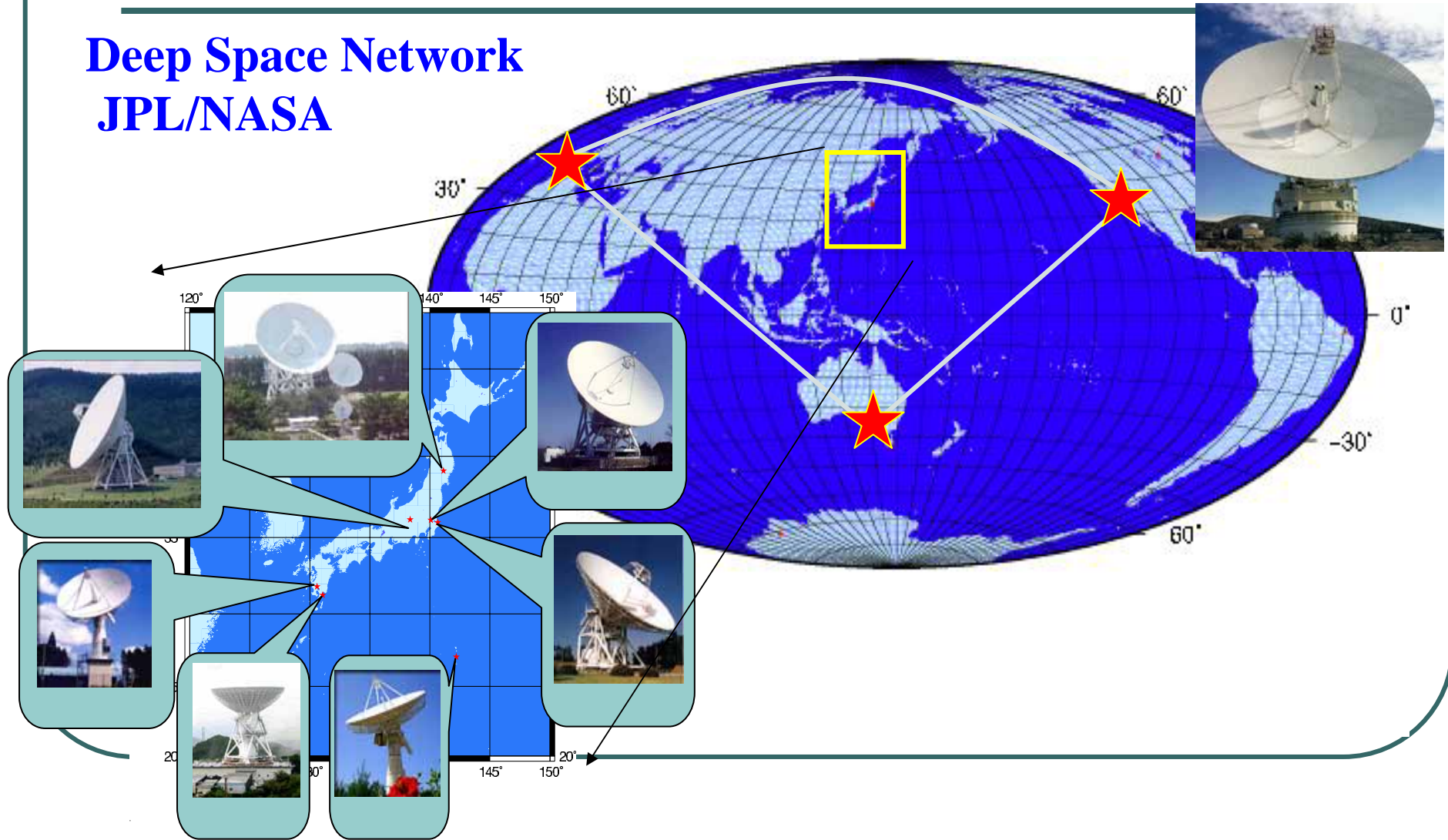
← 1MHz →

### Fringe



# Deep Space Network and Japanese Domestic VLBI stations

## Deep Space Network JPL/NASA



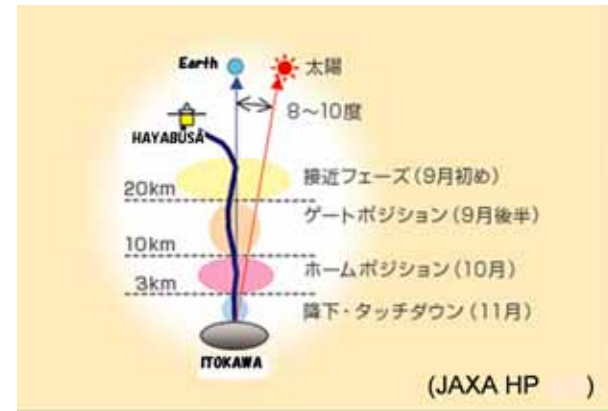


# HAYABUSAのイトカワタッチダウン

2005年11月

- 位相遅延の利用 ~ 数十ps

- イトカワの軌道はレーダ観測・光学観測などでよく決まっている。これを予報値として使えば位相遅延が使える。

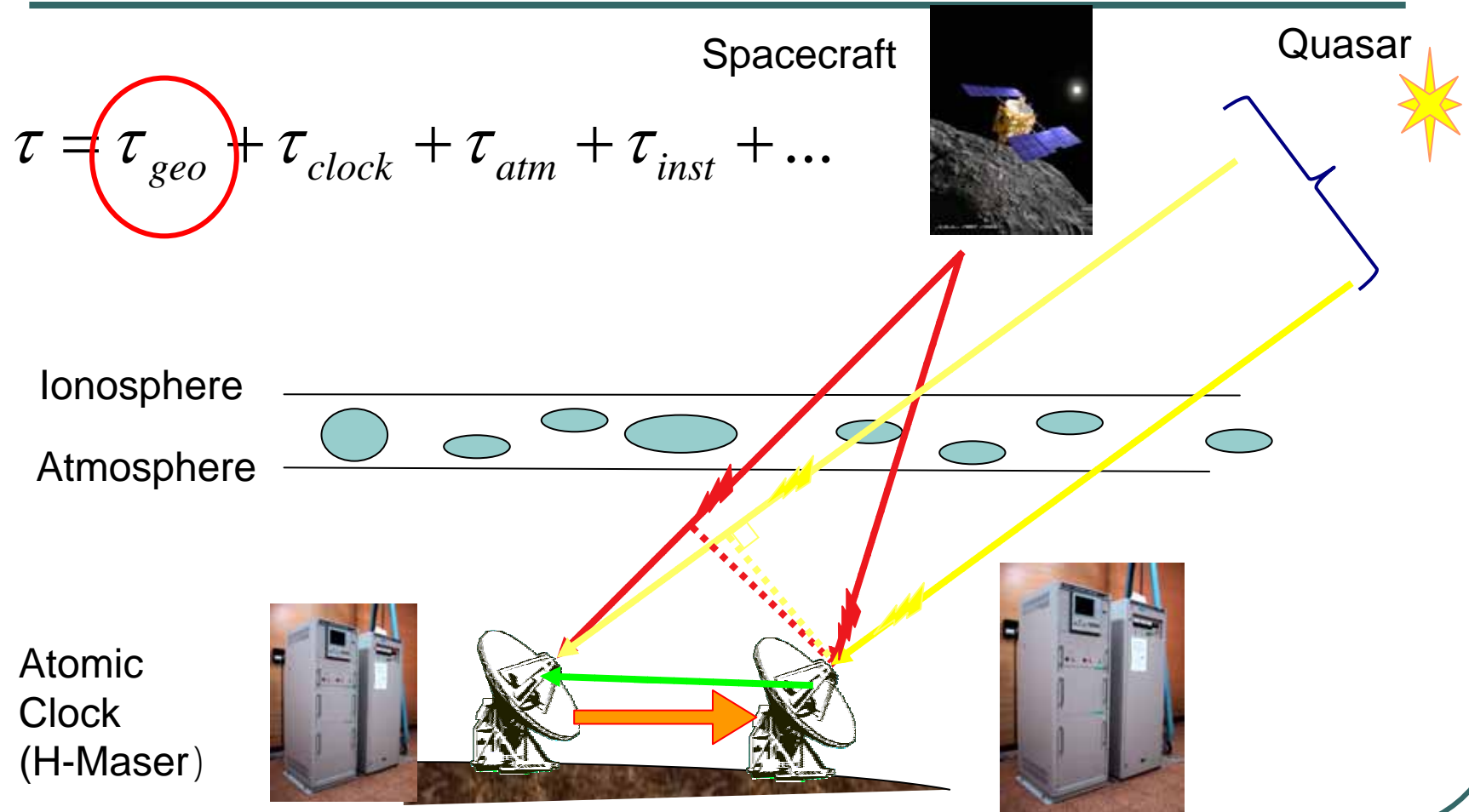


- 相対VLBIの遅延補正検証

- 観測遅延量の誤差となる、大気、クロックの補正の精度検証

$$\tau = \tau_{geo} + \tau_{clock} + \tau_{atm} + \tau_{inst} + \dots$$

# Delta-VLBI is for Calibration of Atmosphere, Clock offset



# 遅延のモデル化 ～ 仰角、時間の補間

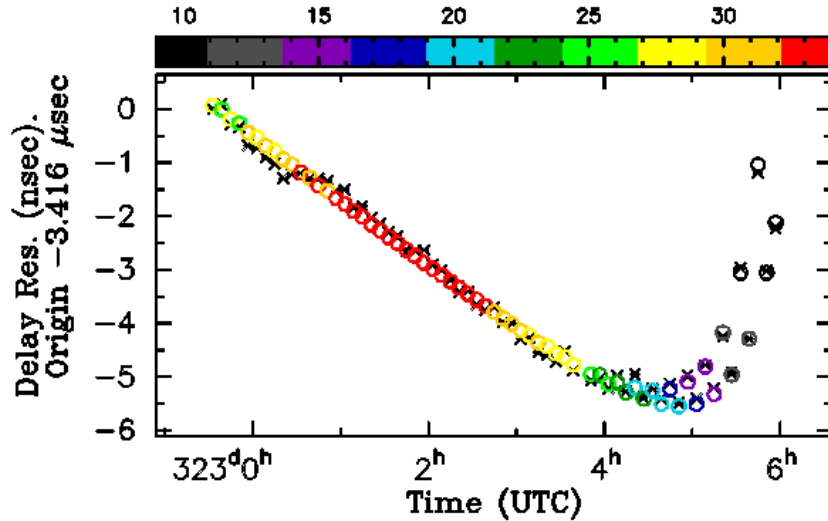
HAYABUSAの位相遅延量

区間折れ線関数  
Piece-wise linear func.

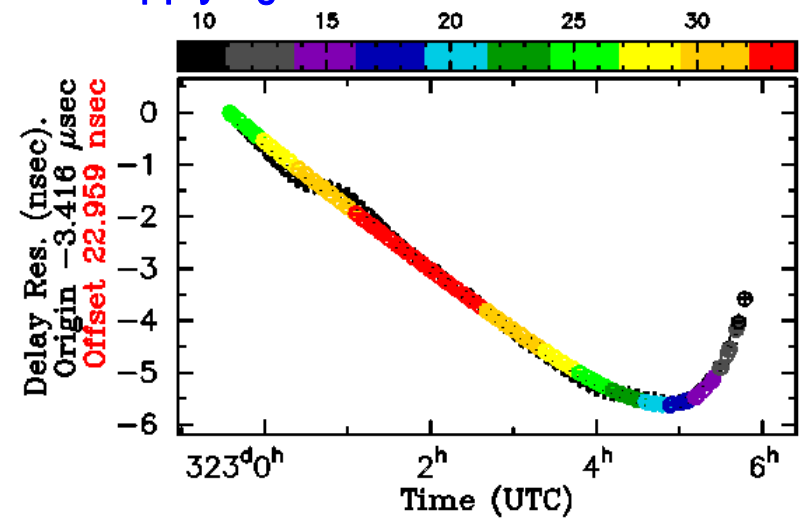
$$\tau - \tau_{geo} = (\tau_{clock}^0 + \tau_{clock}^1 t) + (\tau_{atm}^0 + \tau_{atm}^1 t) fm(El_x) + (\tau_{atm}^0 + \tau_{atm}^1 t) fm(El_x)$$

基準天体 (Quasar)の群遅延量

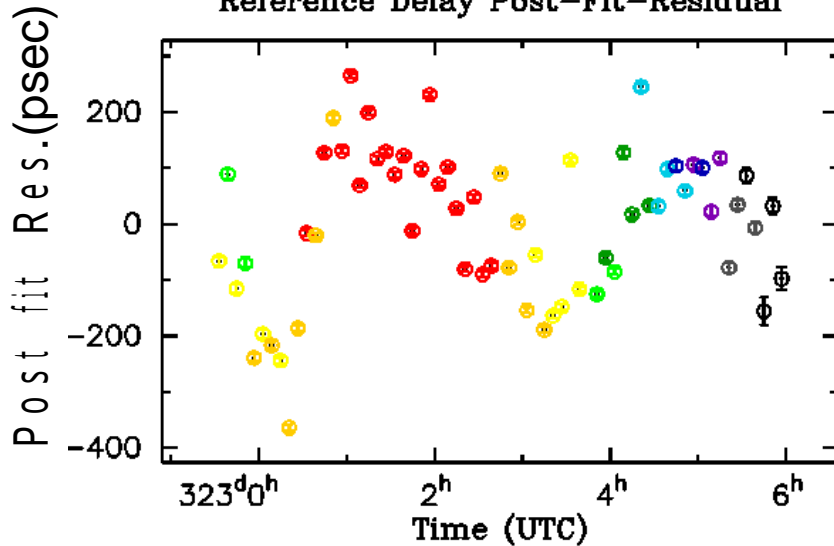
Model Fitting to Reference source



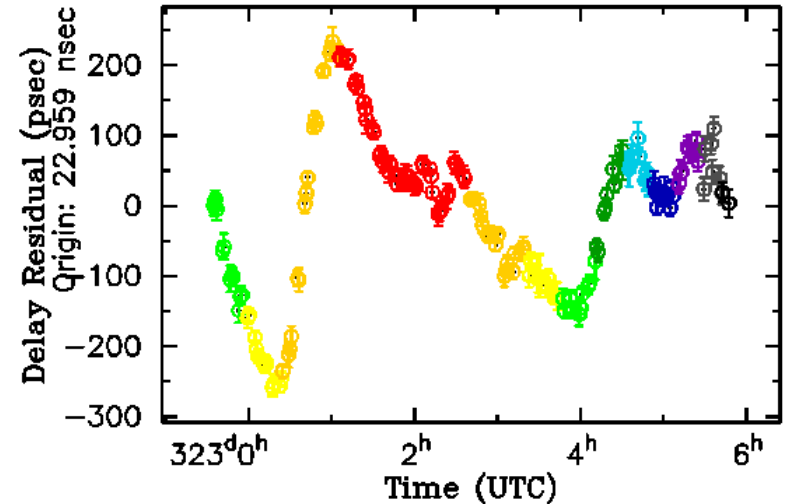
Applying to HYBS



Reference Delay Post-Fit-Residual



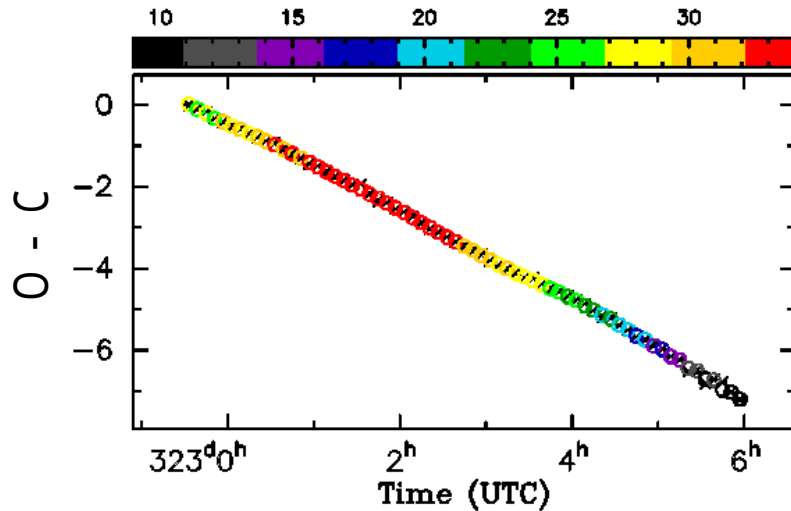
Target Delay Post-Correction-Residual



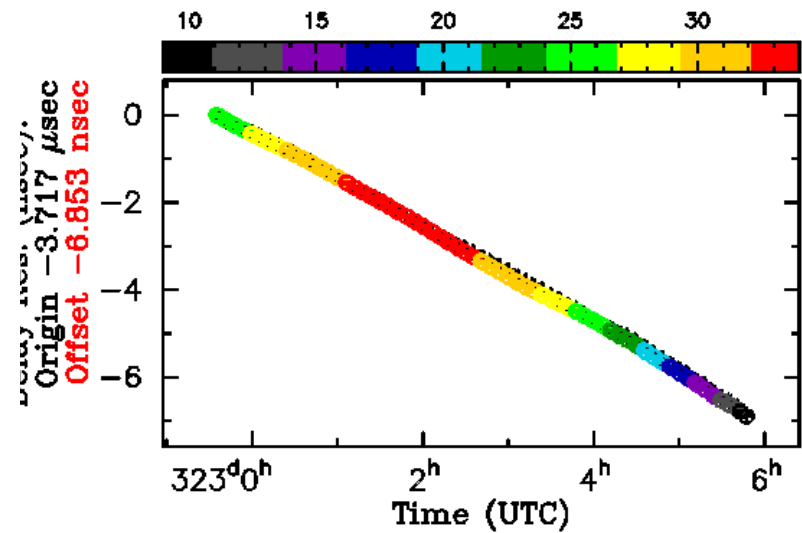
$$\tau = \tau_0 + \dot{\tau}(t - t_0) - \tau_{atm,x} fm(El_x) + \tau_{atm,y} fm(El_y)$$

Piece-wise linear

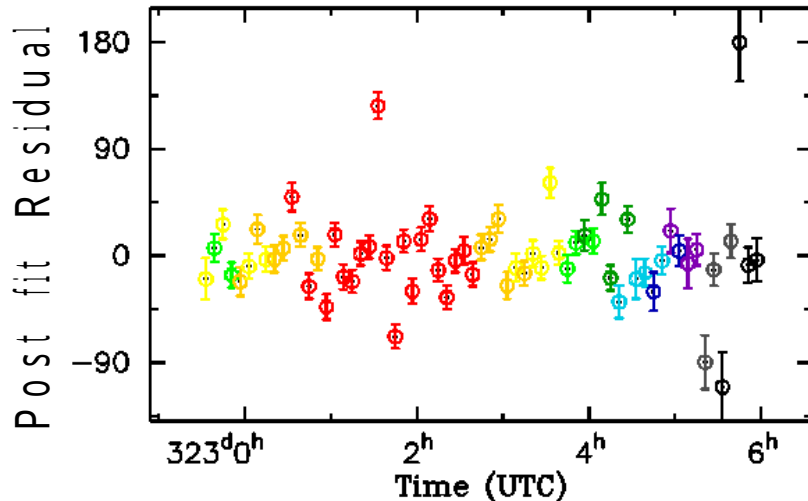
Model Fitting to Reference source



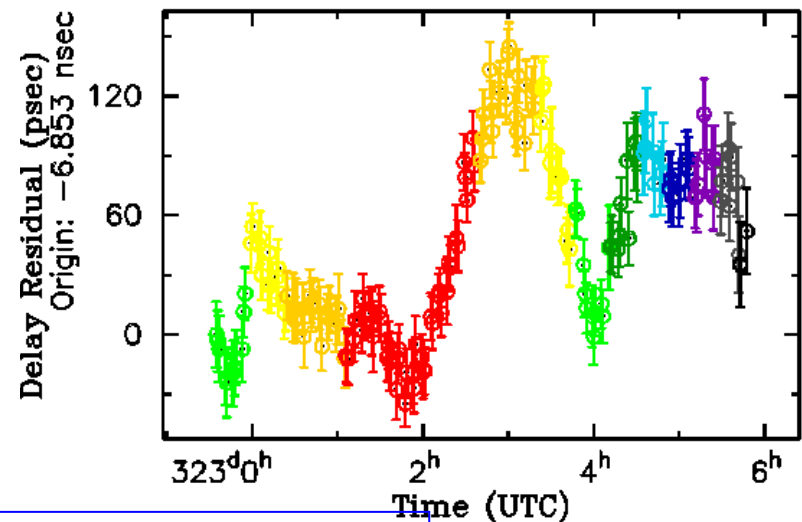
Applying to HYBS



Reference Delay Post-Fit-Residual



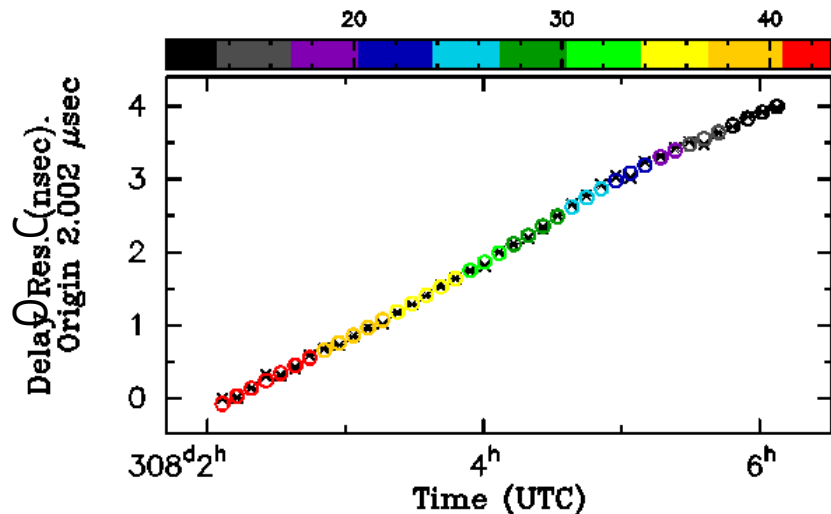
Target Delay Post-Correction-Residual



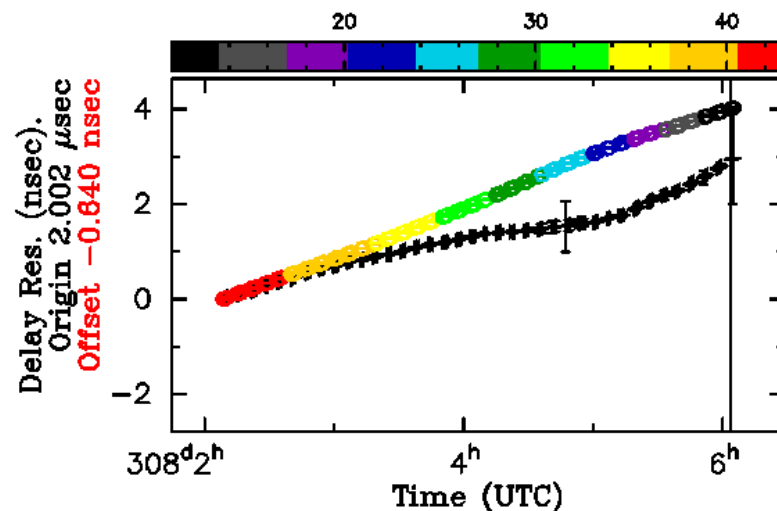
$$\tau = \tau_0 + \dot{\tau}(t - t_0) - \tau_{atm,x} fm(El_x) + \tau_{atm,y} fm(El_y)$$

Piece-wise linear

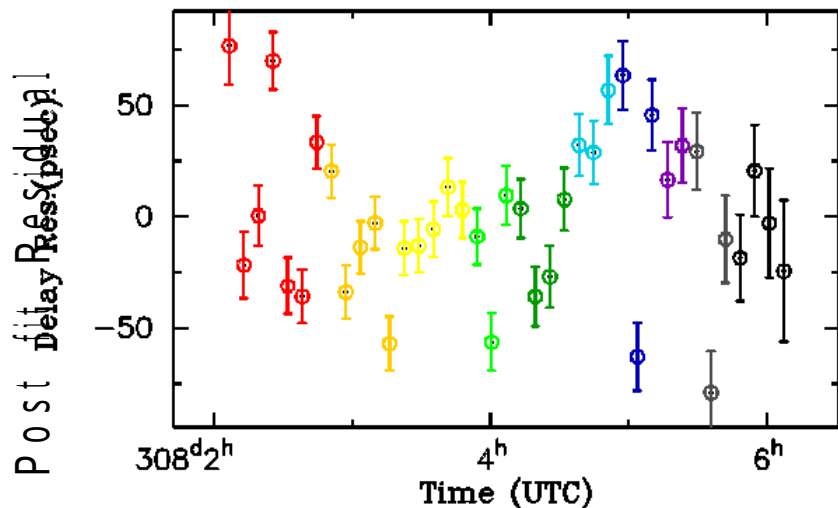
Model Fitting to Reference source



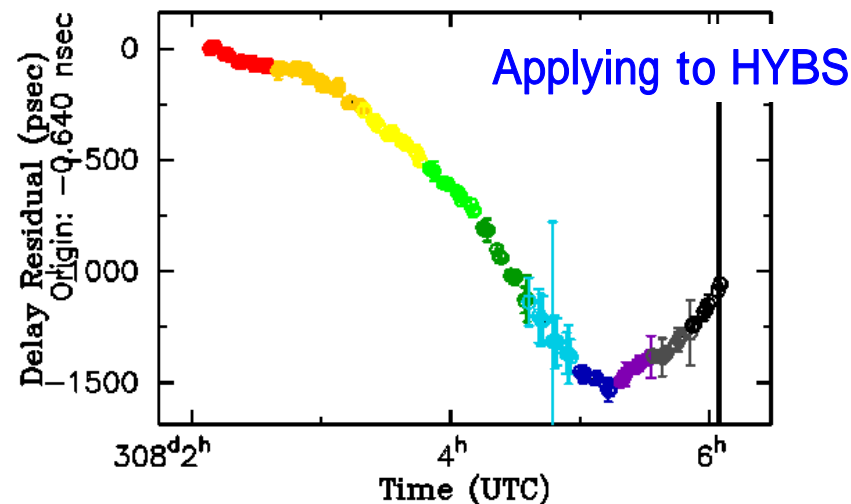
Applying to HYBS



Reference Delay Post-Fit-Residual



Target Delay Post-Correction-Residual

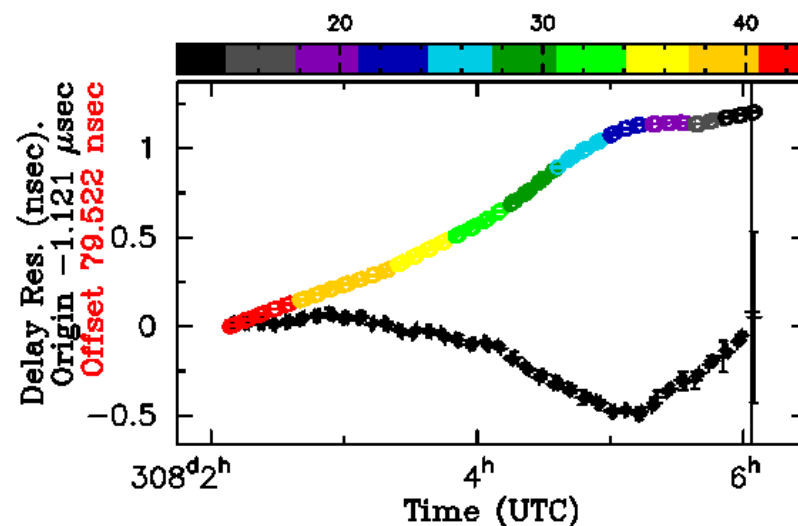
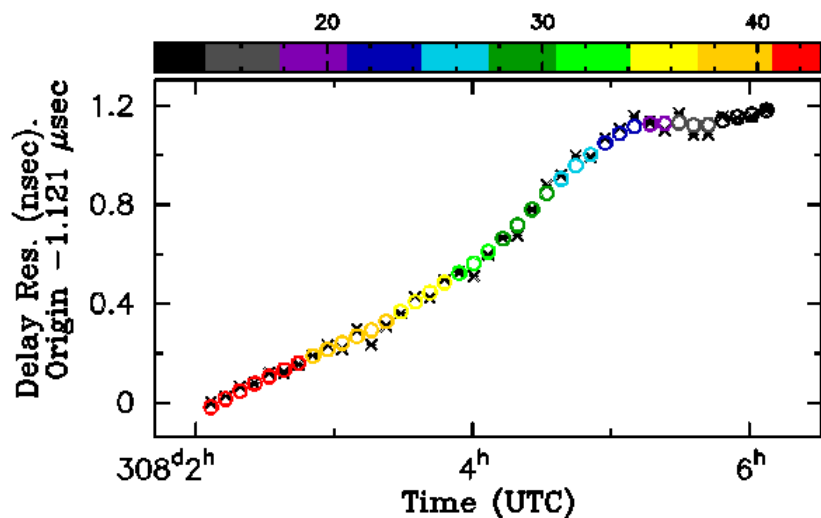


$$\tau = \tau_0 + \dot{\tau}(t - t_0) - \tau_{atm,x} fm(El_x) + \tau_{atm,y} fm(El_y)$$

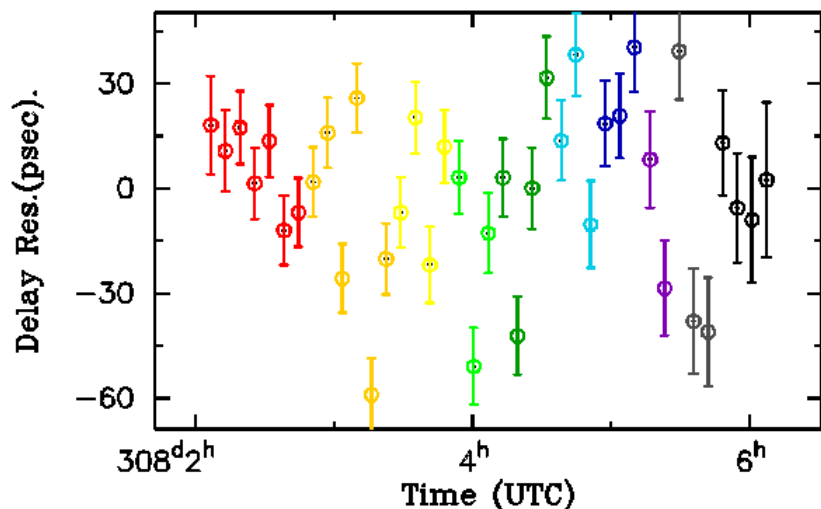
Piece-wise linear

Applying to HYBS

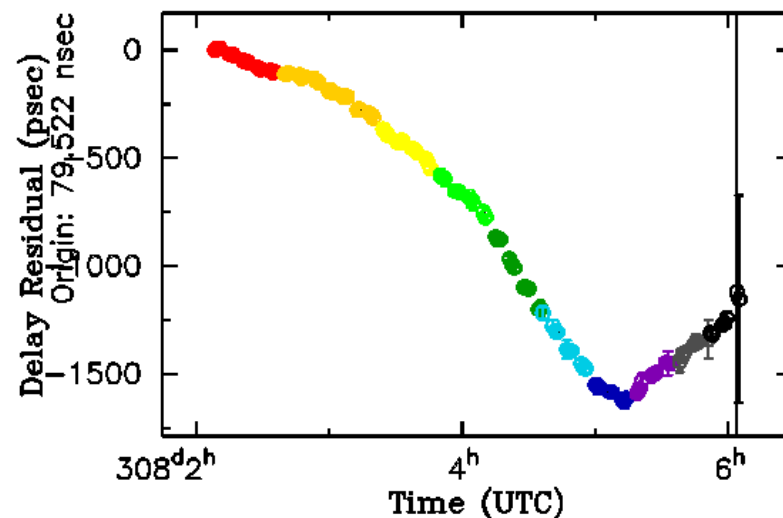
Model Fitting to Reference source



Reference Delay Post-Fit-Residual



Target Delay Post-Correction-Residual



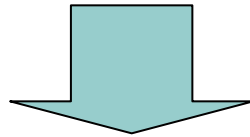
$$\tau = \tau_0 + \dot{\tau}(t - t_0) - \tau_{atm,x} fm(El_x) + \tau_{atm,y} fm(El_y)$$

Piece-wise linear

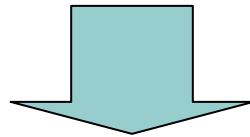
# Delta-VLBI: データ処理の手順

$$\tau_{HYBS} - \tau_{geo} = \tau_{clock} + \tau_{atm} - \tau_{ION} + \dots$$

$$\tau_{QSO} - \tau_{geo} = \tau_{clock} + \tau_{atm} + \tau_{ION} + \dots$$



$$\tau^O_{QSO} - \tau^C_{QSO} = \tau_{clock} + \tau_{atm} + \tau_{ION} + \dots$$



$$(\tau^O_{HYBS} - \tau^C_{HYBS}) - (\tau^O_{QSO} - \tau^C_{QSO}) = \Delta\tau^{Rsd}_{HYBS} - 2\tau_{ION} + \alpha$$



# 大気、電離層、クロック モデル化

## Phase Delay of HAYABUSA

区間折れ線関数  
Piece-wise linear func.

$$\begin{aligned} \tau - \tau_{geo} = & (\tau_{clock}^0 + \tau_{clock}^1 t) \\ & + (\tau_{atm}^0 + \tau_{atm}^1 t) fm_{atm}(El_x) + (\tau_{atm}^0 + \tau_{atm}^1 t) fm_{atm}(El_x) \\ & + (\tau_{ion}^0 + \tau_{ion}^1 t) fm_{ion}(El_x) + (\tau_{ion}^0 + \tau_{ion}^1 t) fm_{ion}(El_x) \end{aligned}$$

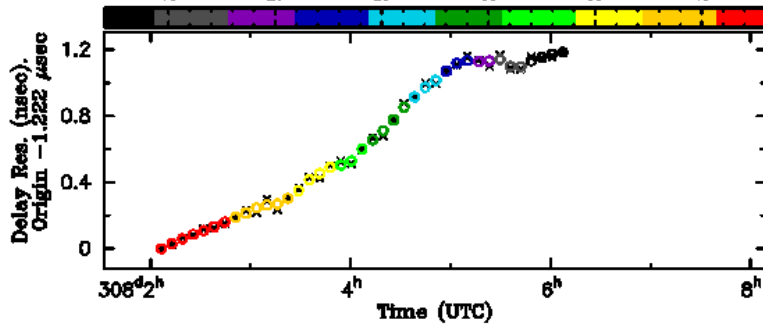
Group Delay of  
Quasars

Group Delay +  
Phase Delay of QSO

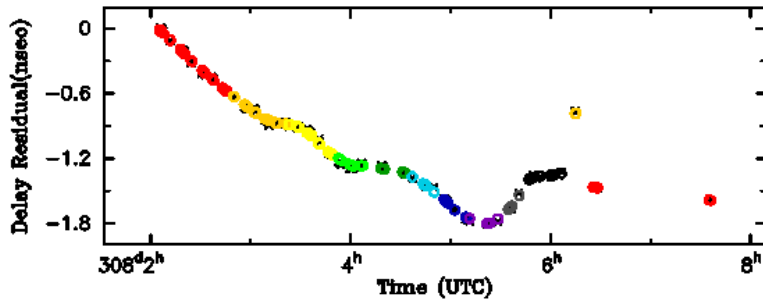
# 2005/11/4 Tsukuba32-Chichijima10

Applying to HYBS

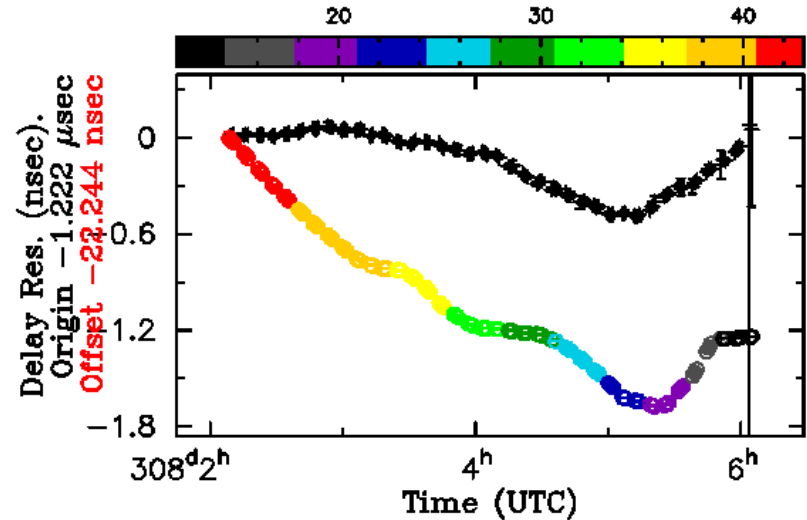
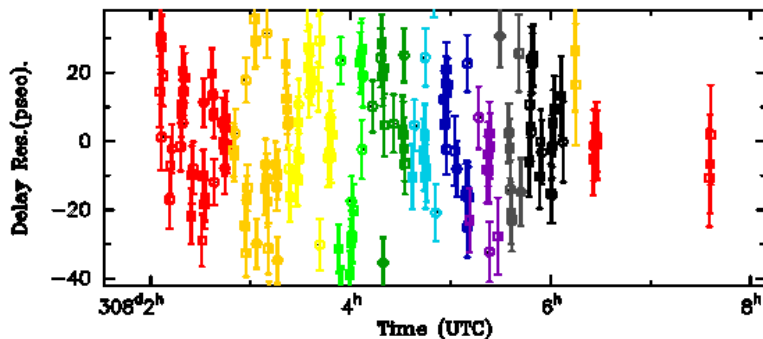
## Model Fitting to Reference source



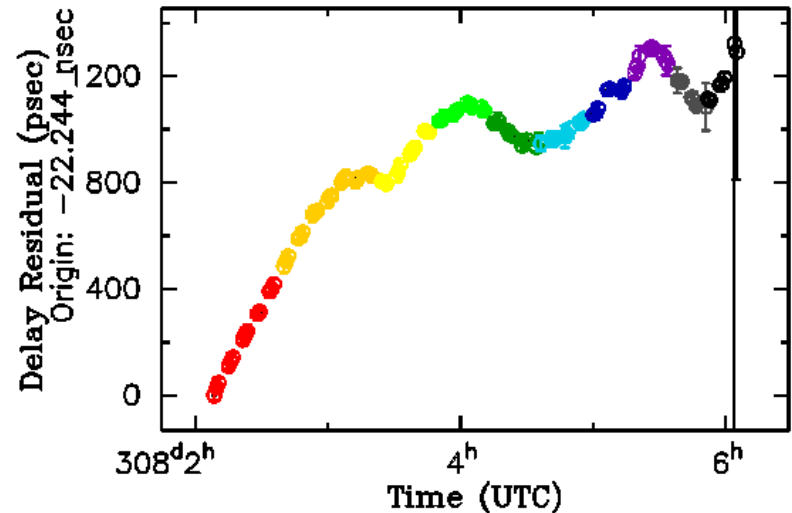
Reference Source Phase Delay Residual and Model



Reference Delay Post-Fit-Residual



Target Delay Post-Correction-Residual

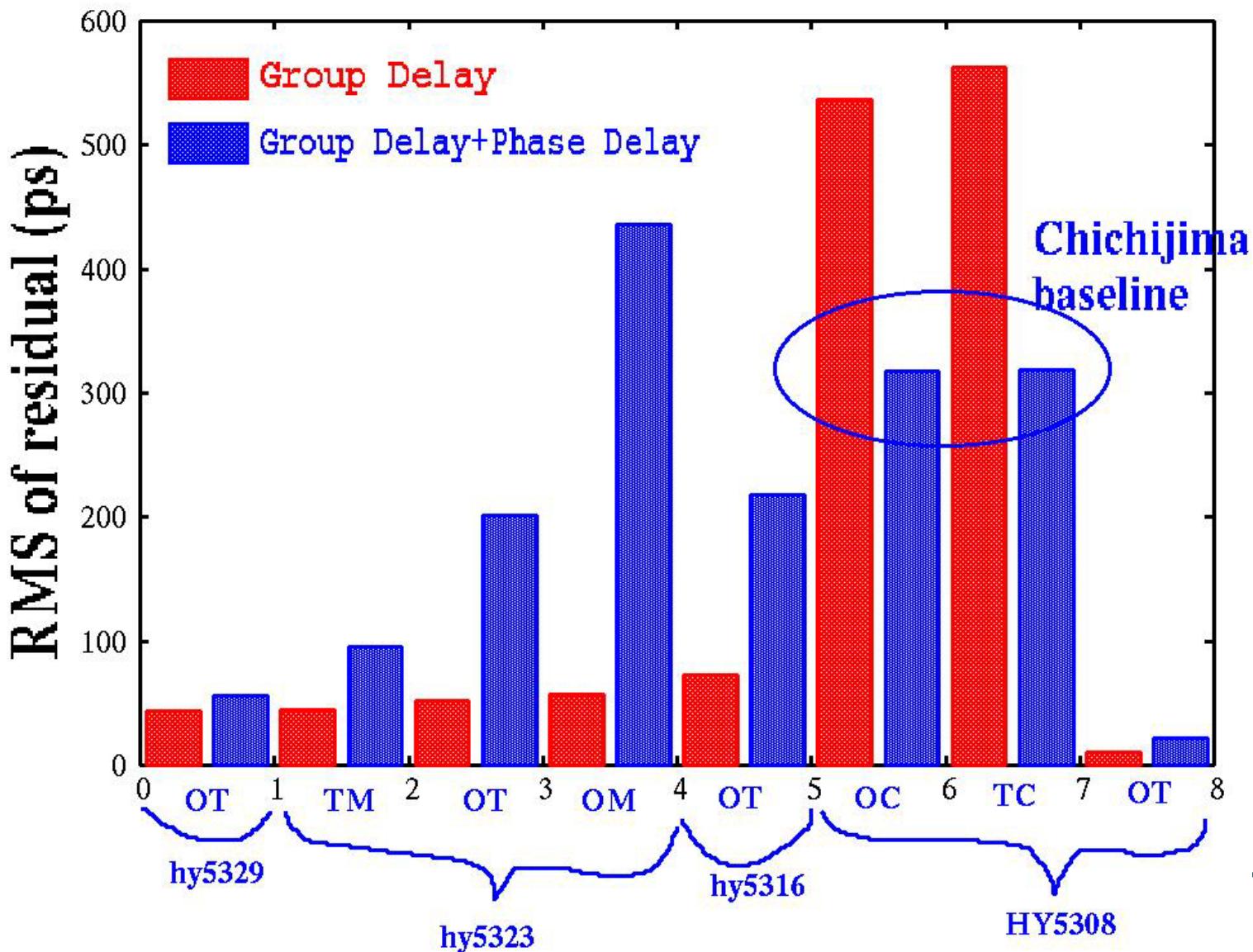


$$\tau = \tau_0 + \dot{\tau}(t - t_0) - \tau_{atm,x} fm(El_x) + \tau_{atm,y} fm(El_y)$$

Piece-wise linear

# 統計的比較

## 群遅延 と 群遅延 + 位相遅延



## 位相遅延を使った補正評価の結果と教訓

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- HAYABUSAの位相遅延をクエーサの群遅延量、位相遅延量 + 群遅延補正した精度は、サブナノ秒程度 ~ NASA / JPLと同程度
- 低仰角・低緯度の観測時にはS / X 2周波観測が必要

## 現在 残っている仕事

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### ● 計測遅延精度の向上

- 次期飛翔体の送信機が広帯域されることに期待
- レプリカ信号を使ったSNR向上による遅延精度改善
  - 相関振幅で1桁程度の改善が期待される！
  - レンジ信号 M系列擬似拡散信号のデコード開始

### ● 長基線を使った実証観測

- 海外とのVLBI観測
  - 中国上海、ウルムチでのK5/VSSP観測システム導入
  - オーストラリアとのVLBI観測など

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ご静聴ありがとうございました。