VLBI Measurements for Time Transfer between Time and Frequency Laboratories
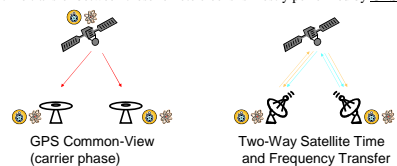
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1. Why use VLBI for Time Transfer ?

TAI is computed by the BIPM from a set of atomic clocks distributed over the world. The time transfer between these remote clocks is mostly performed by **GPS** and **TWSTFT**.

GPS Common-View (carrier phase)

Two-Way Satellite Time and Frequency Transfer

Modern cold-atom-based frequency standards have already archived the uncertainty of 10^{-15} at a few days. Moreover cold-atom-based optical clocks have the potential to realize the uncertainty of from 10^{-16} to 10^{-17} level after a few hours.

Fractional Uncertainty

10^{-10}	
10^{-12}	NICT-CsF1 ..... developing 2×10^{-15}
10^{-14}	
10^{-16}	
1950 (by P. Gill) 2000 2010	NICT optical clocks ..... developing

NICT-O1 6×10^{-15}

On the other hand, time transfer precision of TWSTFT and GPS carrier phase experiments have reached the 10^{-10}@1sec (10^{-15}@1day) level. In order to compare such modern standards by these time transfer techniques, it is necessary to **average over long periods**. Since these techniques are **not sufficient to compare next standards** improvements of high precision time transfer techniques are strongly desired.

Typical r.m.s performance   (by E. Thomas)

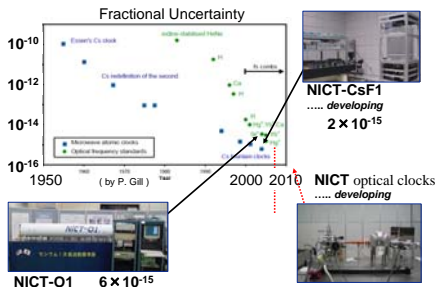| Stability (1day)	Time	Frequency
GPS (Carrier-Phase)	0.1 ns	2×10^{-15}
TWSTFT	0.1-0.2 ns	2-4×10^{-15}
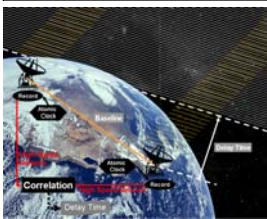
VLBI measures the arrival time delays between multiple stations utilizing radio signals from distant celestial radio sources like quasars and pulsars.
In the usual geodetic VLBI analysis, clock offsets and their rates of change at each station are estimated with respect to a selected reference station.
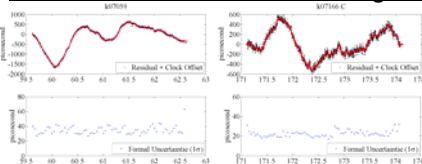
The averaged formal error (1 sigma) of the clock offsets is typically about **20 ps** when analyzing geodetic VLBI experiments which are regularly conducted by the IVS. This precision is nearly one order better than other techniques like **GPS** or **TWSTFT**.

In this study :
We compare time transfer precision between VLBI and GPS carrier phase in order to confirm the **potential of VLBI time and frequency transfer**.

2. VLBI Experiments for Time Transfer

Koganei   Kg

Kb   H-maser

Kashima
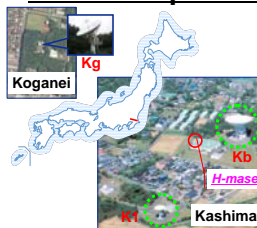
Session	DOY	Duration	Baseline	Data Quality VLBI	Data Quality GPS
K07022	22	24 h	K1-Kg	△	△
k07059	59	3 days	K1-Kg	○	△
k07166	166	1 week*1	Kb-Kg	○	× *2

*1 split into the 3 parts A: 1day, B: 2days, C: 3days (operation mistake)
*2 GPS receiver problem

Data Analysis

VLBI
- CALC/SOLVE
- single baseline (IVS : multi baseline)
- S/X combination
- reference to Kashima (IVS : Wettzell)
  - station coordinates
  - atmospheric delay /1h
  - **clock offset** /1h

GPS
- GIPSY-OASIS II
- Precise Point Positioning
  - station coordinates
  - atmospheric delay /5min
  - **clock offset** /5min

Time Defference
clock offset A – clock offset B

Formal error of th clock offset at Koganei

Session	1 σ [ps]	Average [ps]
k07022	51	K1-Kg 44
k07059	36	K1-Kg 44
k07166	A: 28, B: 40, C: 23	Kb-Kg 30

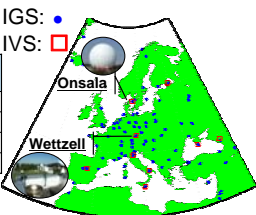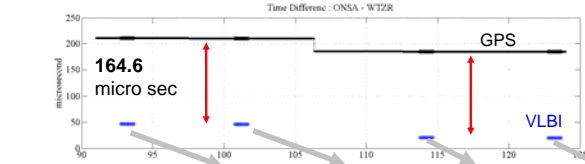### Time series of the difference between GPS and VLBI

±200ps   GPS-VLBI   ±500ps
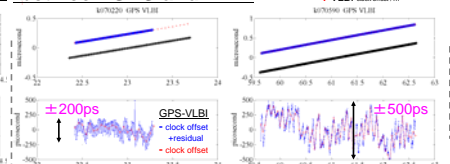
Session	k07022	k07059
GPS-VLBI [ns]	237	472
Ambiguity [ns]	100	100
α [ns]	37	28

$$GPS - VLBI = \alpha + Ambiguity \times n$$

Stability (VLBI)
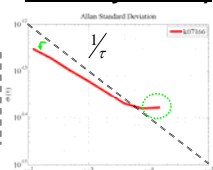
To compare with GPS using IGS and IVS data

3. Time Transfer using IVS and IGS data

IGS: •
IVS: □

Onsala
Wettzell

IVS Session	DOY	IVS	IGS
R1270	092	HhKkNyOnShTsWfWz	onsa, wtzr
R1271	100	KkNyOnTcTsWfWzZc	onsa, wtzr
R1273	113	KkMcNyOnTcTsWfWz	onsa, wtzr
R1274	122	FtHhNyOnTcWzZc	onsa, wtzr

Time series of the difference between GPS and VLBI

164.6 micro sec   GPS   VLBI

Kb-Kg 42ps@1s $\sqrt{2} \times 30ps$

Wz-On 25ps@1s $\sqrt{2} \times 16ps$

10^{-15} @half a day

Session	R1270	R1271	R1273	R1274
DOY	92	100	113	122
Duration [h]	24	24	24	24
GPS-VLBI [micro sec]	164.6423	164.6413	164.6176	164.6169
Ambiguity [ns]	50	50	50	50
α [ns]	-7.7	-8.7	17.6	16.9

? 25ns
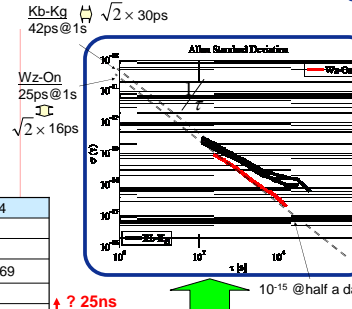
Formal error of the clock offset

GPS

VLBI   Onsala reference to Wettzell
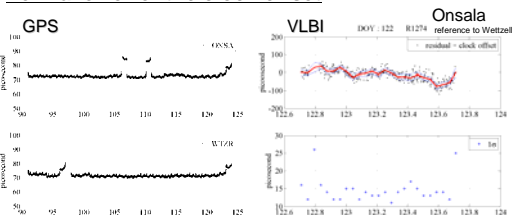
Each station (/ 5min)
- **onsa** : 77.7 ps,   **wtzr** : 71.7 ps
  - std : 1 hour
    onsa : 23 ps,   wtzr : 25 ps
    (exclude 1ns over)
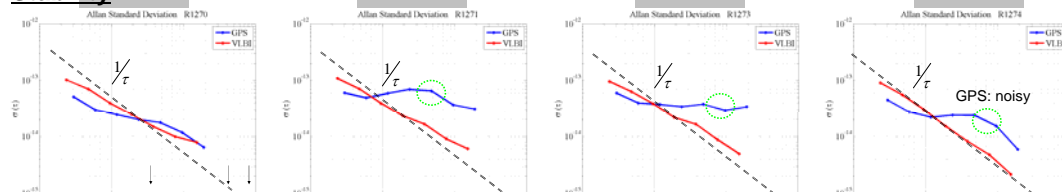
Session	1 σ [ps]
R1270	15.6
R1271	16.6
R1273	17.3
R1274	14.7
Average	16.1

Time Difference : 105.7 ps

Day-Boundary
DOY : 91-123 : 94 ps
(include 1ns over : 508ps)

Stability

GPS: noisy

4. Conclusions

We compared the results of **GPS** and **VLBI** time transfer.
- ✓ **Formal error of clock offset**
  - ➤ GPS : **106 ps**, VLBI : **16 ps**
- ✓ **Difference of GPS and VLBI**
  - ➤ Consistency between 4 times sessions : **164.6 μs**
  - ➤ Even if the results of VLBI are shifted by the multiples of ambiguity, the difference of GPS and VLBI still remains about **25ns**.
  - ➤ The variation of the difference between VLBI and GPS was agrees of about **±200ps**
- ✓ **Stability**
  - ➤ VLBI time transfer is more stable than GPS time transfer on the same baseline and same period
  - ➤ In general, the VLBI time transfer stability follows $1/\tau$ very closely

To use geodetic VLBI for comparison of primary frequency standards

Development of a compact VLBI system

- ➤ Diameter **1.6m**
- ➤ Receiving Frequency
  - **S/X-band**
- ➤ Front-fed paraboloidal reflector
- ➤ Az-El mounting
  - Max speed AzEl **5** deg/sec
- ➤ **Transportable** by human

1.6m

Collaborating with Geographical Survey Institute (GSI) Japan

see details :
Ishii et al., IVS NICT-TDC News, No.28, 2-5, 2007.

Prototype   adapt 2.4m antenna

Before   After

- Cassegrain → **Front-fed**
- X-Band → **S/X-Band**
... testing the performance

Future Image
✓ collocate small VLBI antennas for Time Transfer at Time and Frequency Laboratories

✓ Time Transfer via **e-VLBI**

QRHA
ETS-LINFGREN 3164
LINFGREN 3164-05 05
Frequency range : **2~18GHz**

NiCT   Kashima