Long-baseline frequency comparison by a two-way microwave link

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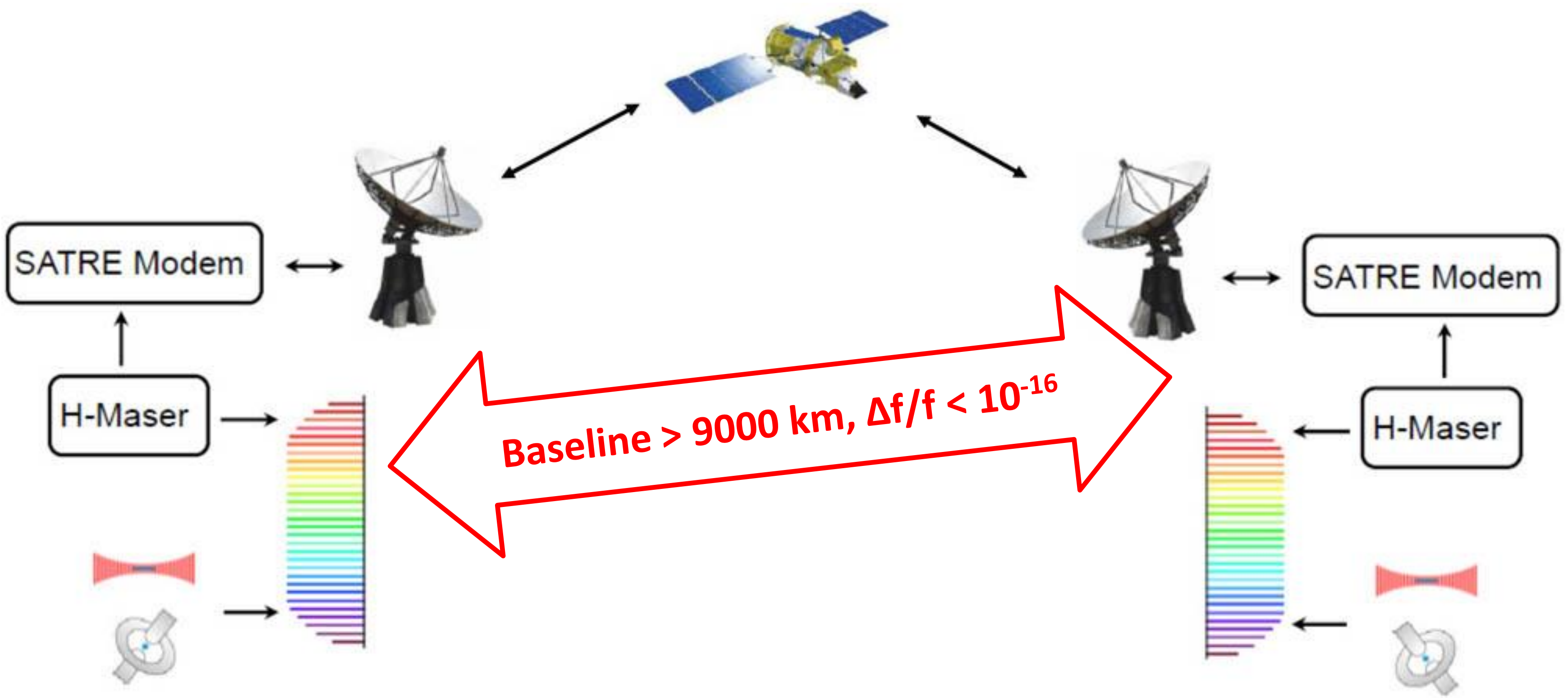
Motivation



Source: http://projects.npl.co.uk/itoc/project-structure/wp5/

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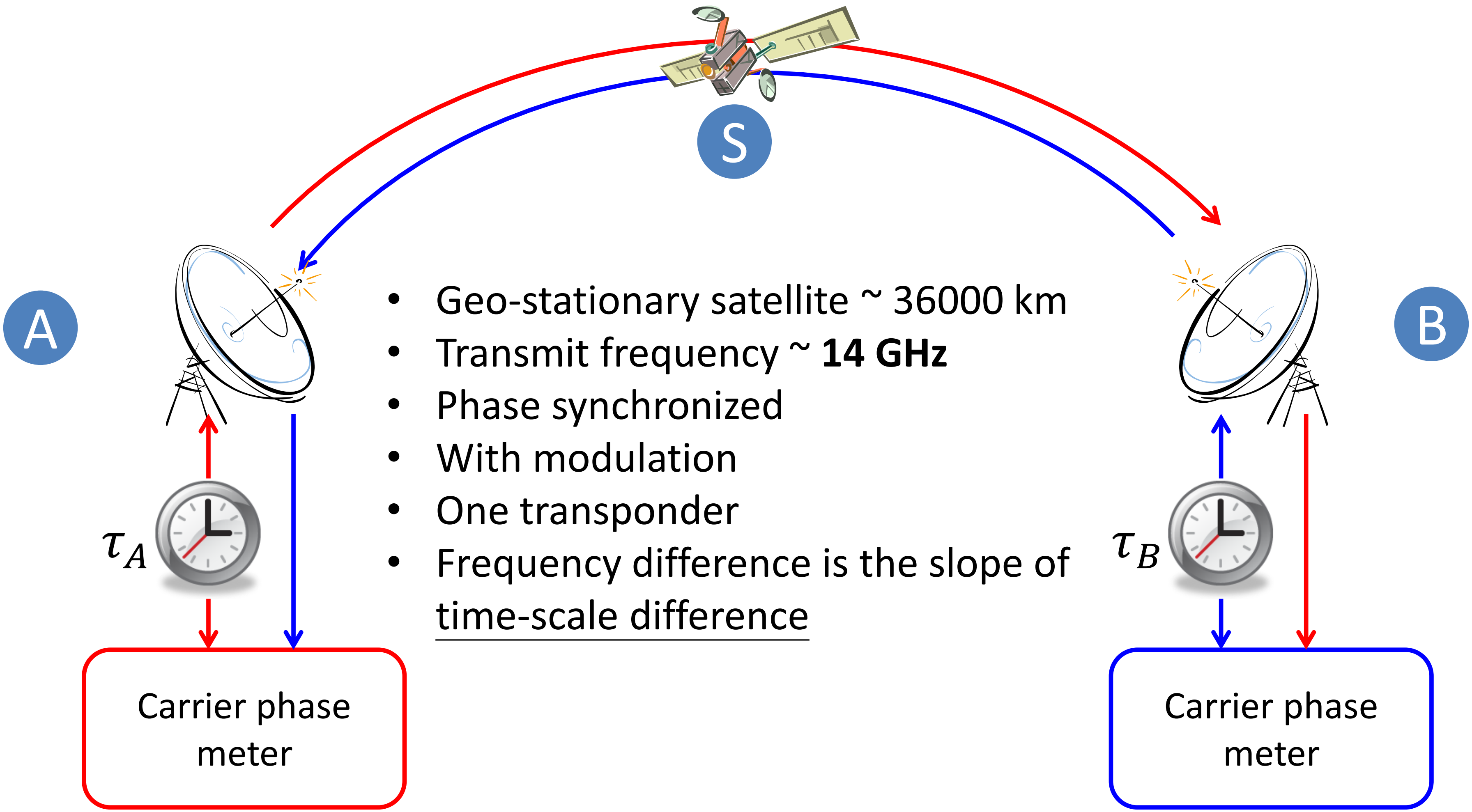
The two-way microwave link



- Geo-stationary satellite ~ 36000 km
- Transmit frequency ~ **14 GHz**
- Phase synchronized
- With modulation
- One transponder
- Frequency difference is the slope of <u>time-scale difference</u>

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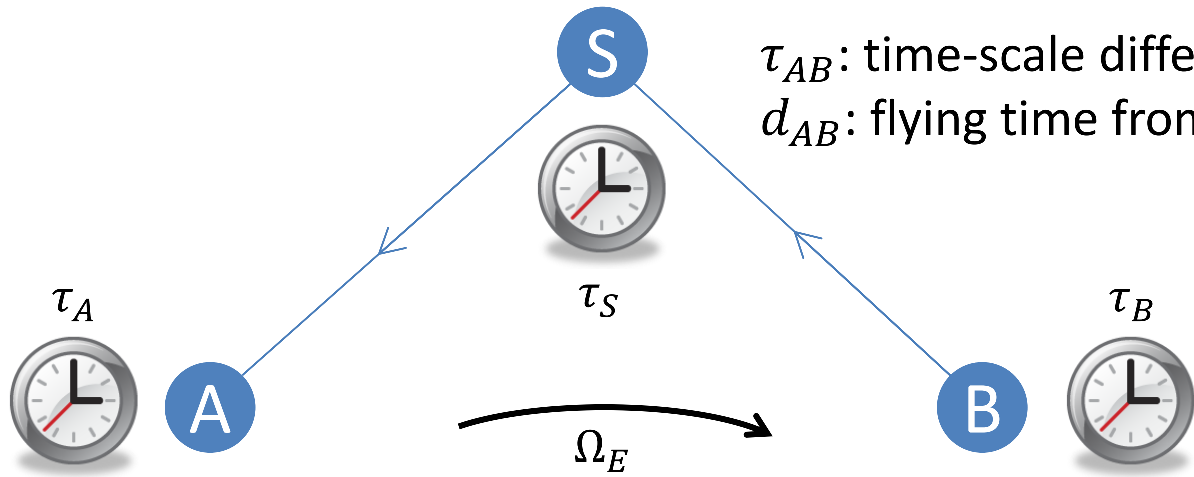
Understanding of time-of-arrival



τ_{AB}: time-scale difference, $\tau_A - \tau_B$
d_{AB}: flying time from A to B via S

Destination	Source	Path	Time-of-arrival	Source	Path	Time-of-arrival
A	A	A→S→A	d_{AA}	S	S→A	$d_{SA} + \tau_{AS}$
	B	B→S→A	$d_{BA} + \tau_{AB}$			
B	B	B→S→B	d_{BB}	S	S→B	$d_{SB} + \tau_{BS}$
	A	A→S→B	$d_{AB} - \tau_{AB}$			

When **B** transmits a signal at $t = 0$ along **B**'s time scale
A will see the signal at $t = d_{BA} + \tau_{AB}$ along **A**'s time scale

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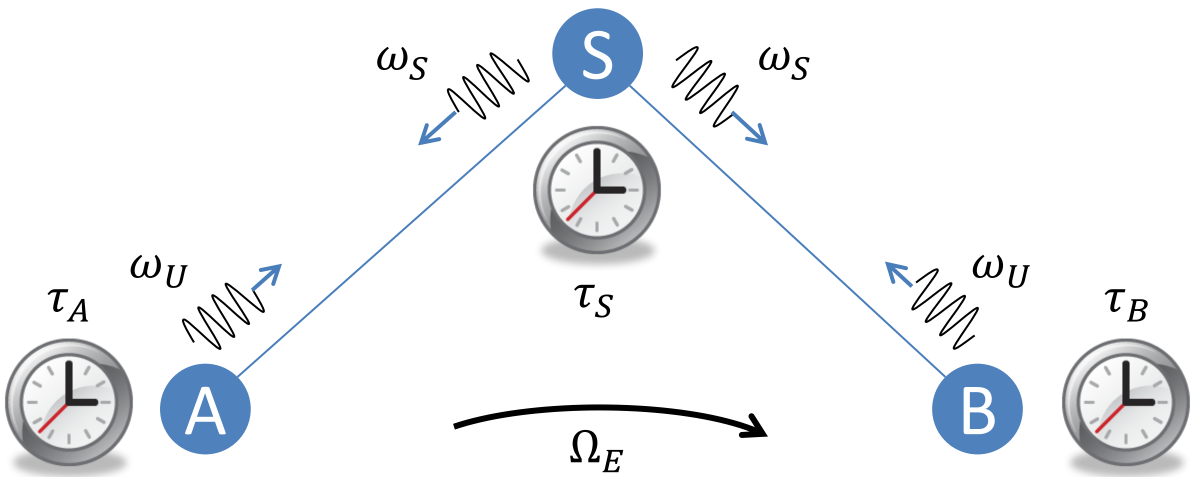
Two-way carrier phase (TWCP)



Path	Notation	Phase
A→S→A	$\theta_{AA}(t)$	$\omega_U(t - d_{AA}) - \omega_S\big(t - (d_{SA} + \tau_{AS})\big)$
B→S→A	$\theta_{BA}(t)$	$\omega_U\big(t - (d_{BA} + \tau_{AB})\big) - \omega_S\big(t - (d_{SA} + \tau_{AS})\big)$
B→S→B	$\theta_{BB}(t)$	$\omega_U(t - d_{BB}) - \omega_S\big(t - (d_{SB} + \tau_{BS})\big)$
A→S→B	$\theta_{AB}(t)$	$\omega_U\big(t - (d_{AB} - \tau_{AB})\big) - \omega_S\big(t - (d_{SB} + \tau_{BS})\big)$

$$\tau_{AB} = \frac{\omega_+(\theta_{AB}(t) - \theta_{BA}(t)) - \omega_-(\theta_{AA}(t) - \theta_{BB}(t))}{\omega_+^2 - \omega_-^2} + Sagnac$$

where $\omega_+ = 2\omega_U - \omega_S$, $\omega_- = \omega_S$

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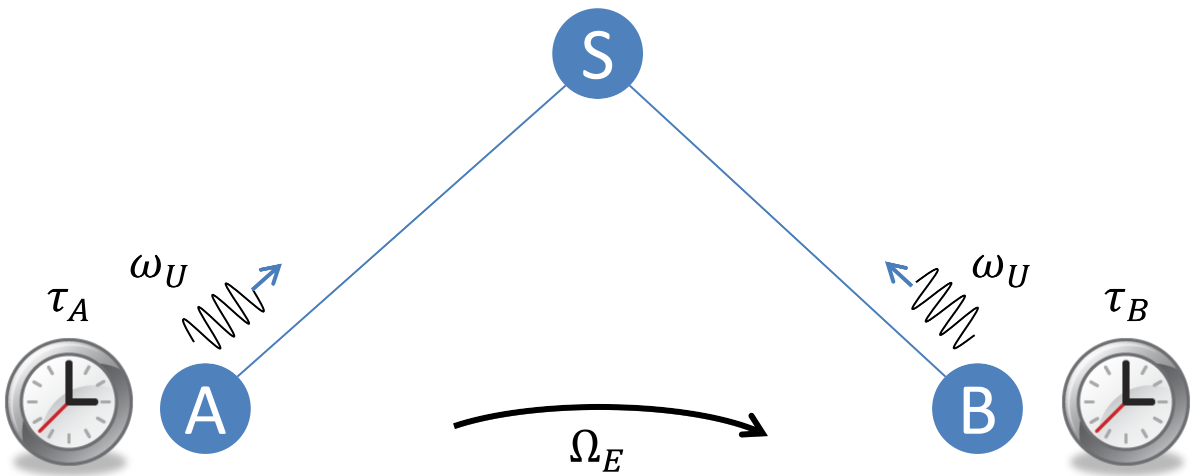
TWCP assuming ω_S is free



Path	Notation	Phase
B→S→A	$\theta_{BA}(t)$	$\omega_U\big(t-(d_{BA}+\tau_{AB})\big)$
A→S→B	$\theta_{AB}(t)$	$\omega_U\big(t-(d_{AB}-\tau_{AB})\big)$

$$\tau_{AB} = \frac{\theta_{AB}(t)-\theta_{BA}(t)}{2\omega_U} + Sagnac$$

Resolution is better than $1/(2 \cdot 14GHz)$ $(\approx 36\, picoseconds)$

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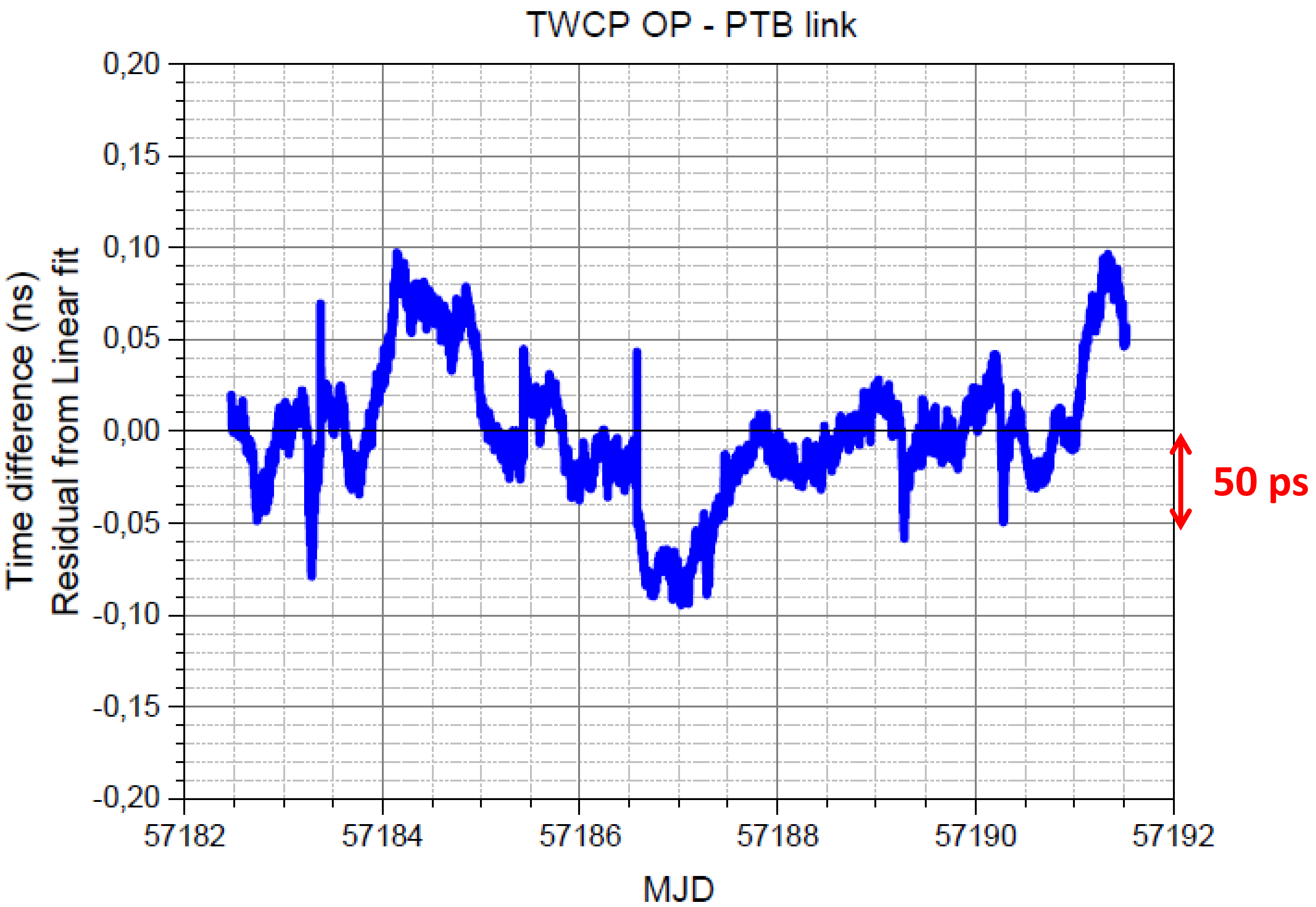
TWCP results



Source: J. Achkar *et al.*, *Proc. 2016 CPEM*

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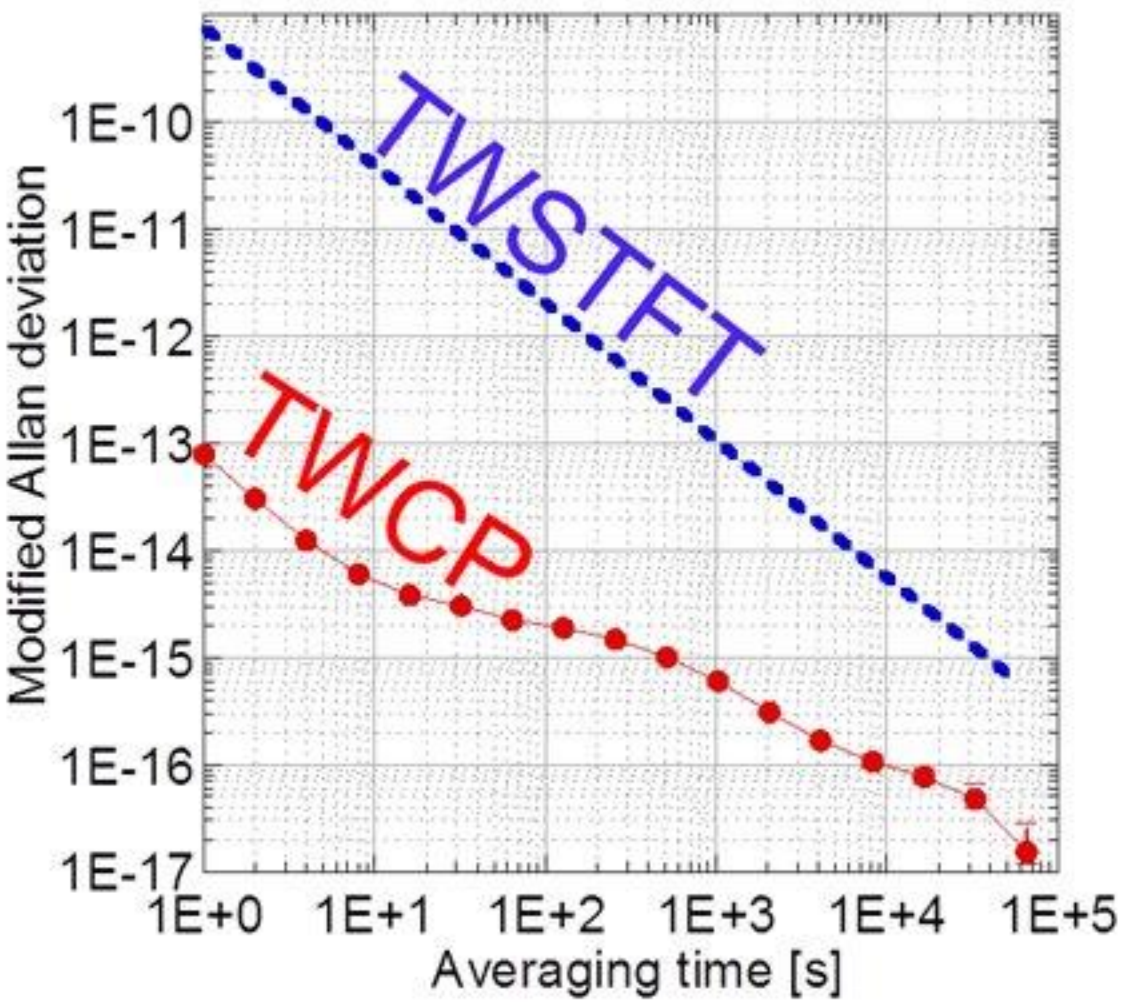
TWCP results (co-located clocks)



1×10^{-16} @ 3 h

3×10^{-17} @ 1 d

Source: http://www2.nict.go.jp/sts/tft/rsc_twcp_en.html

TWCP results

- [1]In a short baseline, the stability reached 10^{-16}
- [2]In an NICT-PTB, the stability of GPSCP-TWCP reached the 10^{-16} level
- [3]In an OP-PTB, a frequency instability of 4×10^{-16} is reached at 1 day
- [4]In an NICT-KRISS, IPPP-TWCP reaches the 10^{-17} level at 5×10^{5} s

1. M. Fujidea *et al.*, *IEEE TUFFC*, 59 **12** (2012)
2. M. Fujieda *et al.*, *Metrologia* 51 (2014)
3. J. Achkar *et al.*, in *Proc. 2016 CPEM*
4. M. Fujidea *et al.*, *IEEE TUFFC*, 65 **6** (2018)

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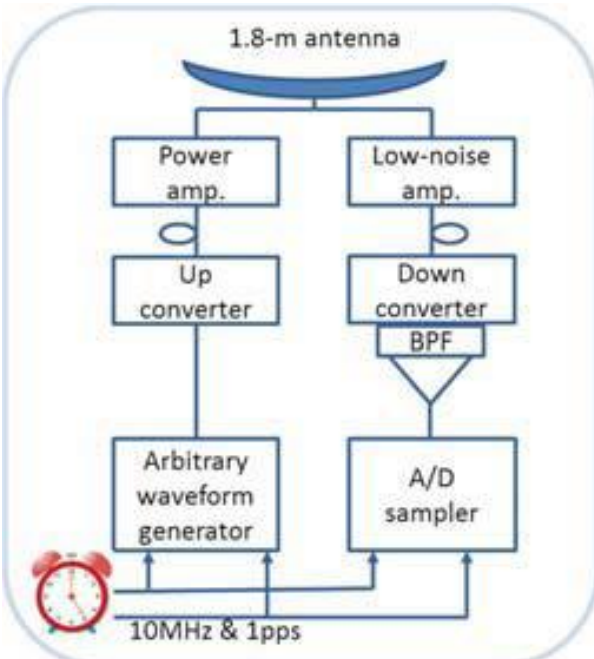
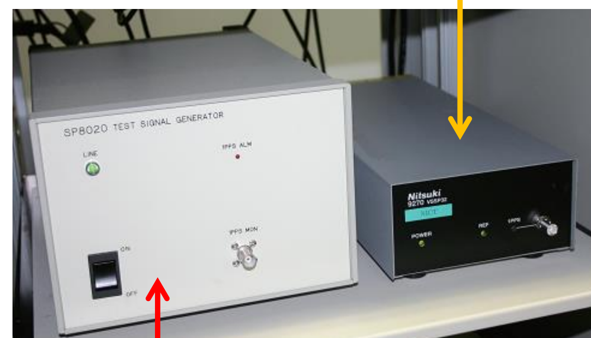
NICT TWCP instruments



The earth station in NICT

Analog-to-digital sampler (64 Msps)



Arbitrary waveform generator (102.3 Msps)

software

Source: J. Amagai and T. Gotoh, *J. Natl. Inst. Inf. Comm. Tech.*, 57 **3/4** (2010)
M. Fujidea *et al.*, *IEEE TUFFC*, 65 **6** (2018)

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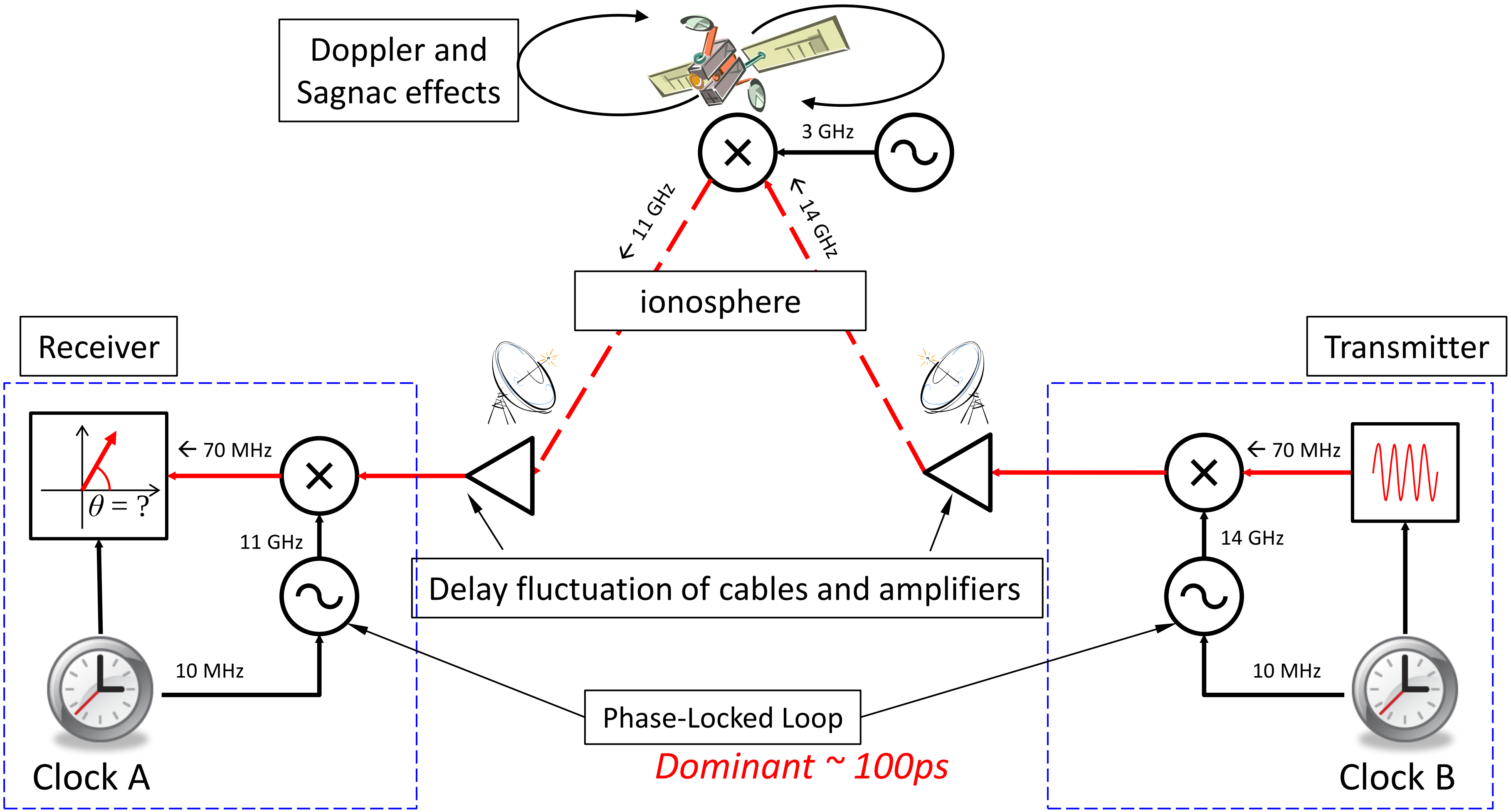
Systematic uncertainty ~ 1×10^{-15}



Temp.-controlled

See M. Fujieda *et al.*, *Metrologia* 51 253-262 (2014) for more details

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On the improvement of uncertainty

- Development of transmitter and frequency converters for more stable/accurate signal
- Instruments in air-conditioner
- Correction on ionosphere effects
- Use of Ka-band (~ 30 GHz) may provide twice higher resolution

Summary

- A microwave link system via geo-stationary satellite and the TWCP are introduced
- The stability of frequency comparison of OP-PTB can reach a level of 10^{-16} at one day
- Development is ongoing for higher resolution and lower uncertainty
- I acknowledge NICT and OP colleagues for their technical advices

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