International Committee on Global Navigation Satellite Systems (ICG)

Atomic Time Standards, UTC and Time Transfer

Linking Satellite System Times (2)

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TIMETECH

Outline

- Motivation
- Ground-based methods using satellite transponders
  - Architecture
  - Performance
  - Calibration techniques
  - Advanced methods
- Space-based systems
  - Architecture
  - Performance, existing and future
- Status and outlook

Proposed UTC Time-Link for Galileo (2000)

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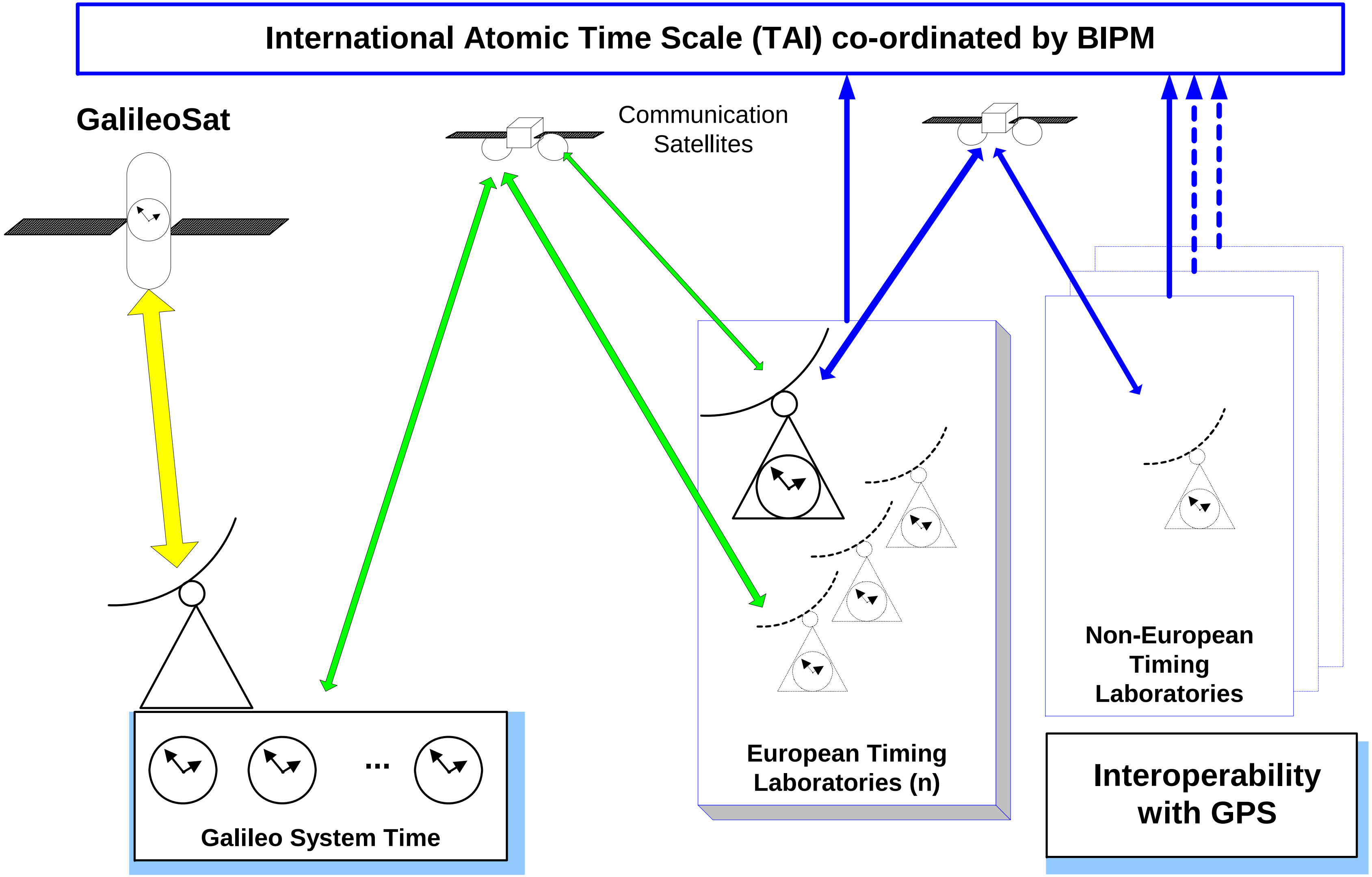
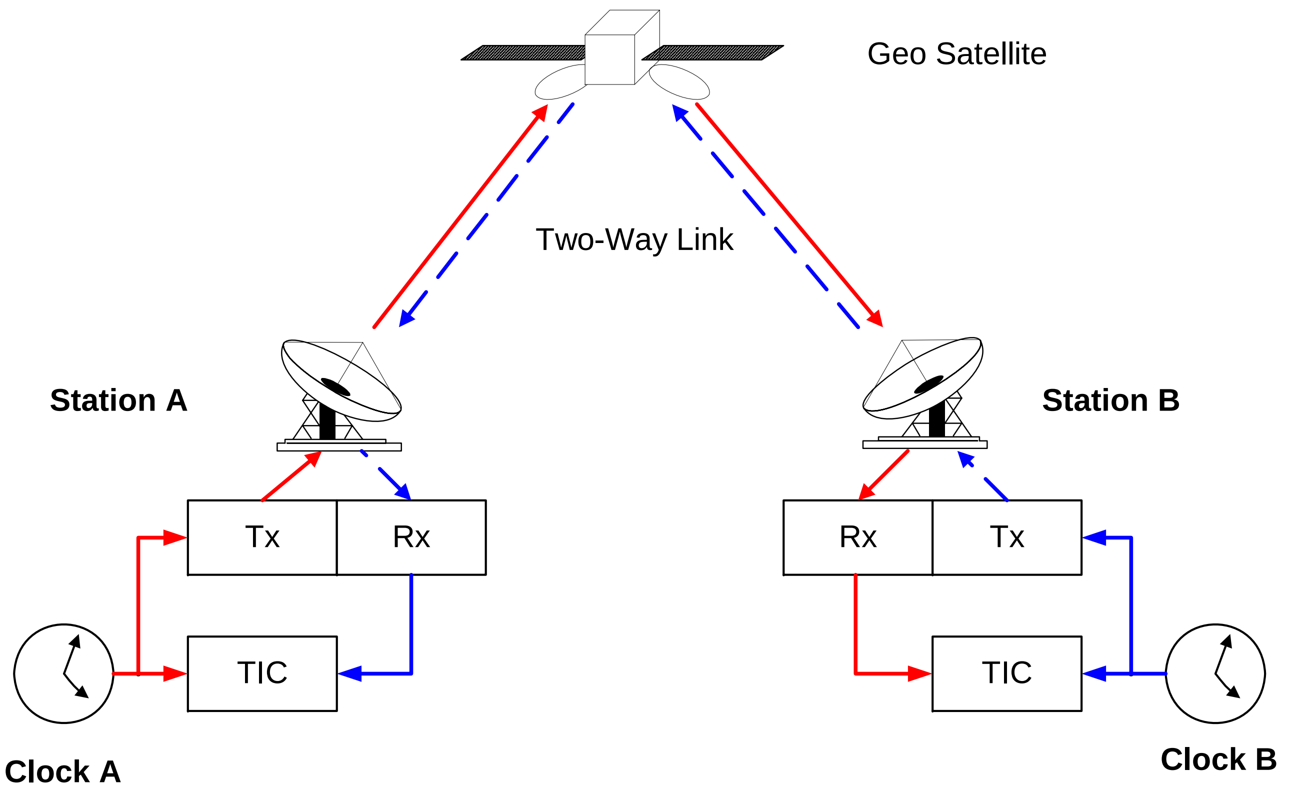


Two-Way Satellite Time & Frequency Transfer (TWSTFT)



- **Bi-directional simultaneous Signal Link between 2 clocks A and B**
- **Results is double difference between the two remote readings**
- **Link-Symmetry removes Troposphere (full) and Ionosphere (most)**
- **Result highly independent of Satellite Position and its movement**
- **Established method to compare Metrological Time-Labs since 1980**

TWSTFT outline

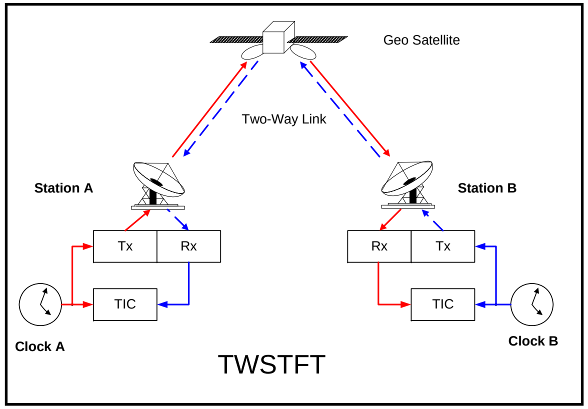
Architecture

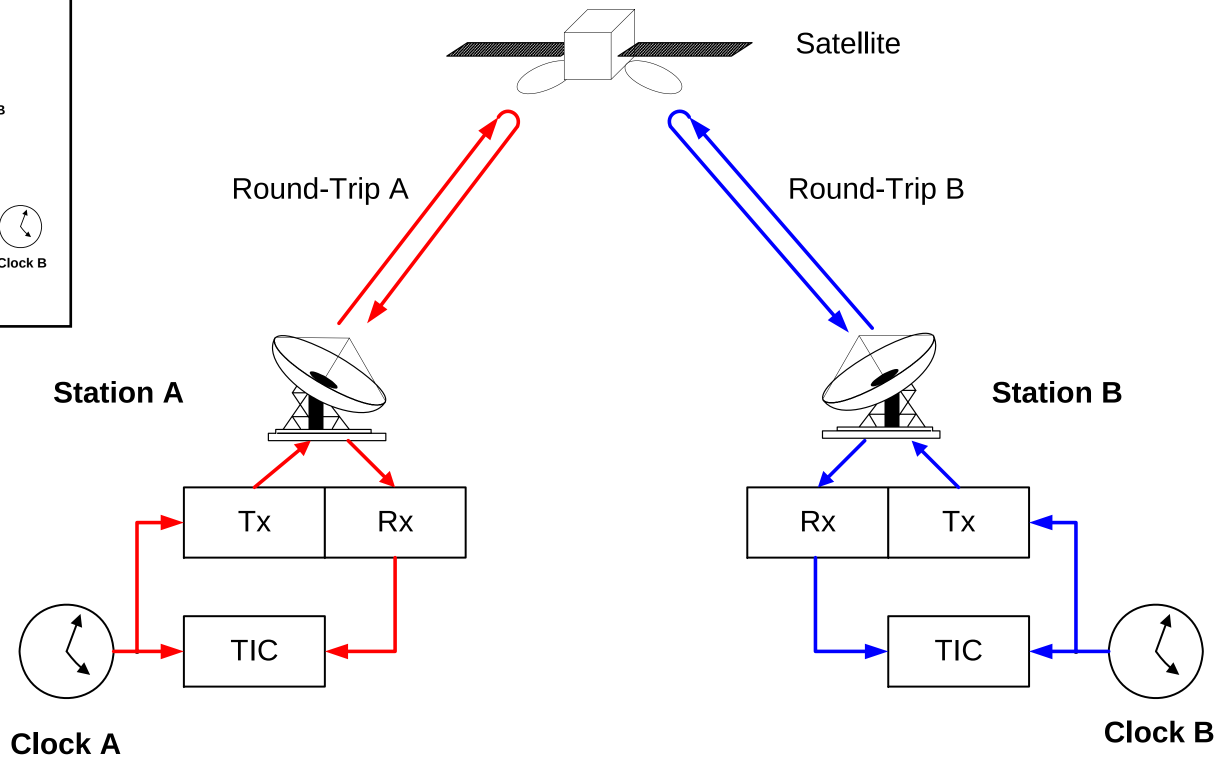
- Pseudo-noise coded signals
- Wide-bandwidth
- Microwave Signal delay time measurements
- Using commercial communication satellite transponders

Applications

- Satellite operators (ranging)
- Geodesy (orbit determination)
- Time & Frequency Metrology (National Metrological Labs)
- Deep Space Tracking and Operations (Space Agencies)
- Support of Fundamental Physics Missions (Research)

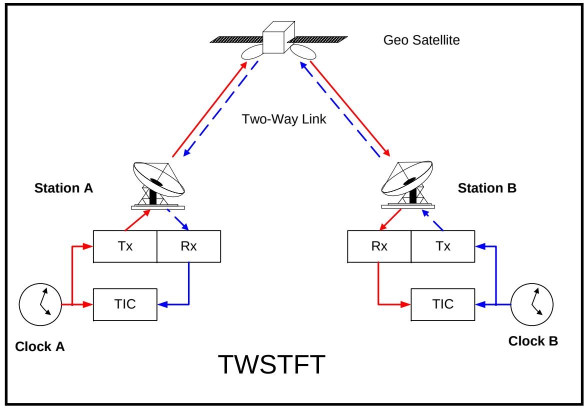
Satellite Round-Trip Ranging



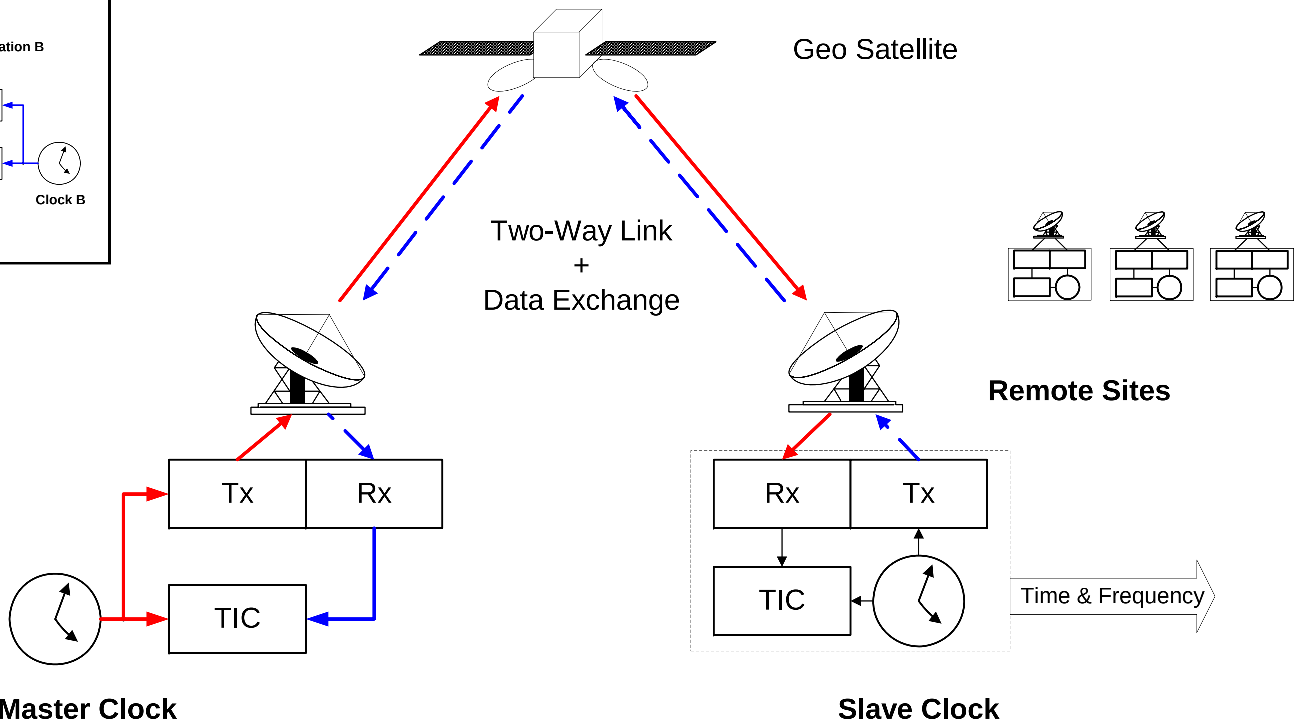


- **Station receives its own signal, determines round trip delay**
- **Ionosphere and roposphere travelled twice -> errors sum up**
- **TWSTFT: only the difference of propagation errors contribute**
- **TWSTFT has significant higher performance capability as suggested by ranging**

Time sychronisation based on TWSTFT

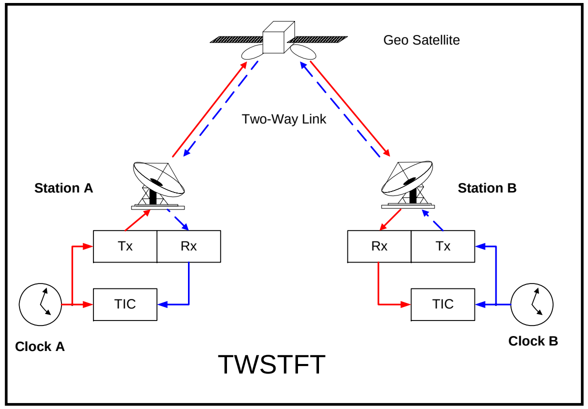


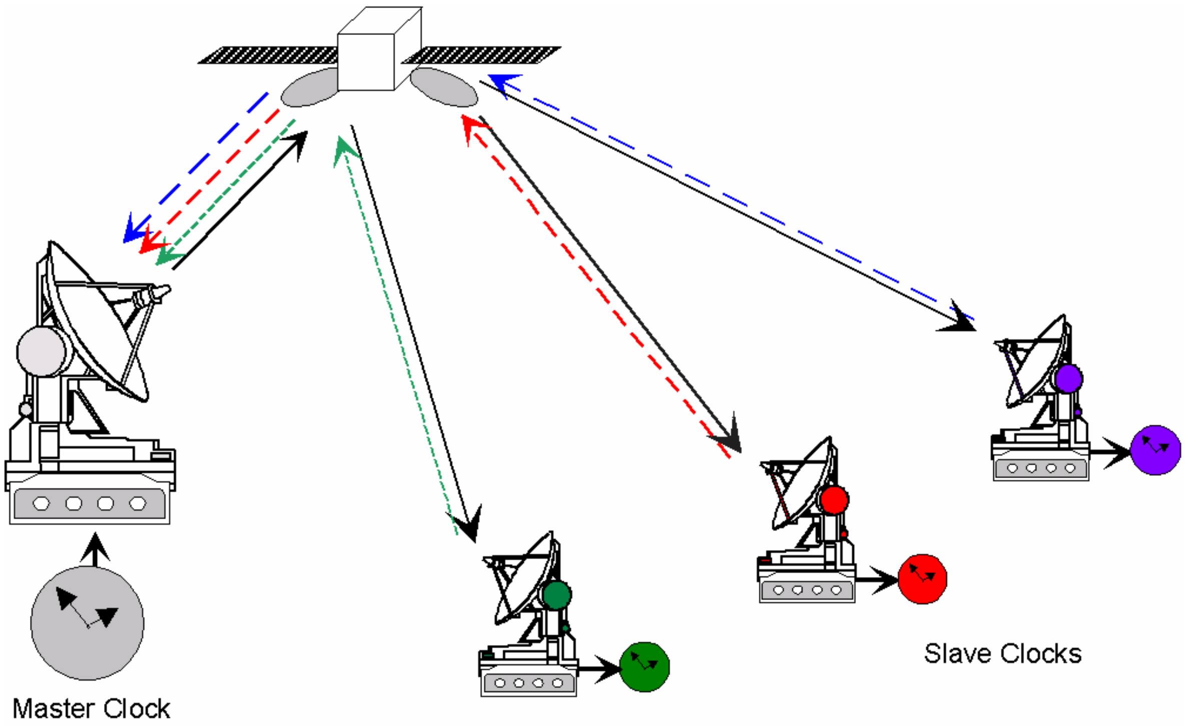
TWSTFT used to link primary clocks, time-to-alarm: < 3s
clocks remain untouched, offset data available



TWSTFT-based time synchronisation of a slave clock to master site
Time & Frequency is available physically to user at slave site
Slave Clocks can be OCXO, Rb, commercial Cs or even Maser
Time-to-alarm: < 3s

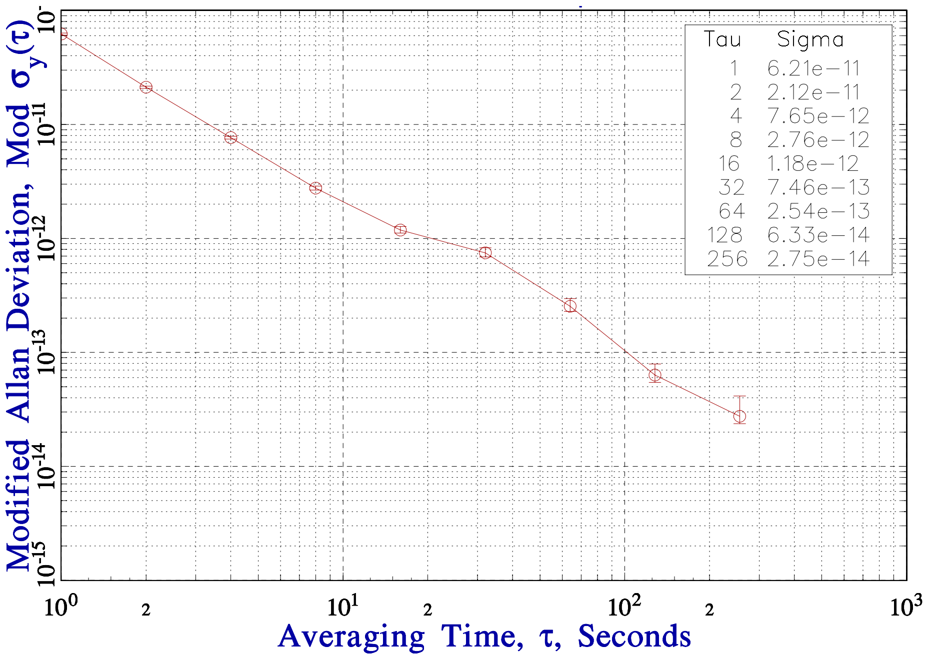
TWSTFT-based Network Time synchonisation





TWSTFT-based time network synchronisation
Multiple simultaneous links using CDMA (10..100 users)
Single satellite transponder can serve the full network in visibility
Continous operation provides best results and highest reliability

TWSTFT Results, Frequency comparison



Frequency Uncertainty
1E-13 @ 100 s

Experimental Link
USNO - NIST
Active Masers both sides
PN-code 20 MChip/s
Commercial communication satellite

TWSTFT Results, T&F Synchronisation

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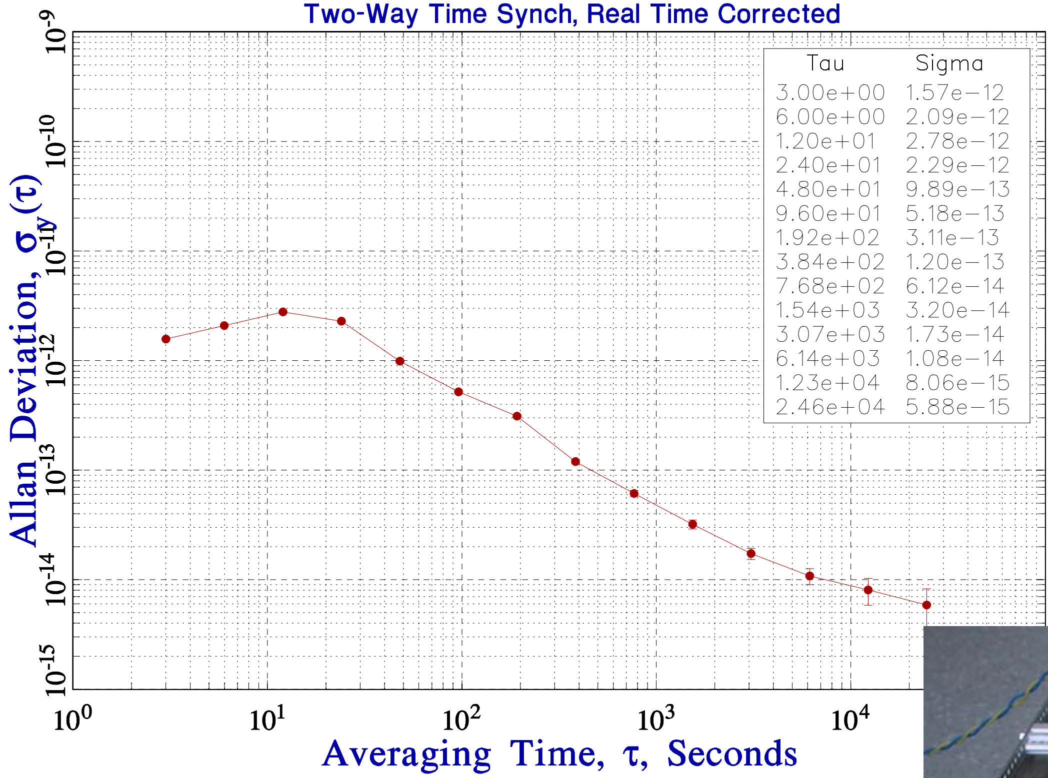
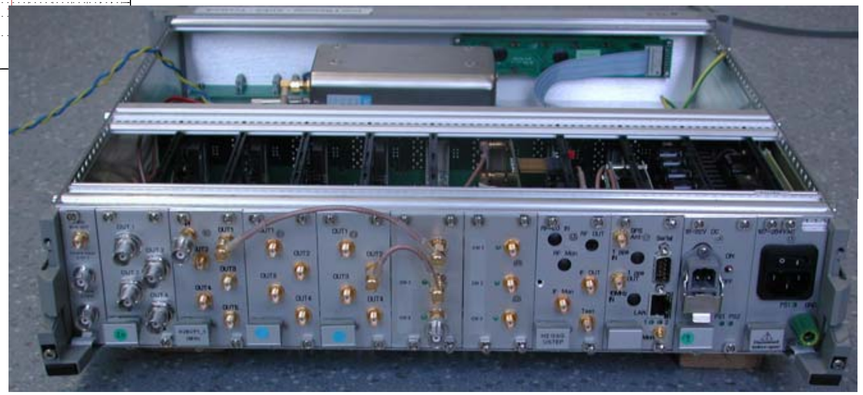


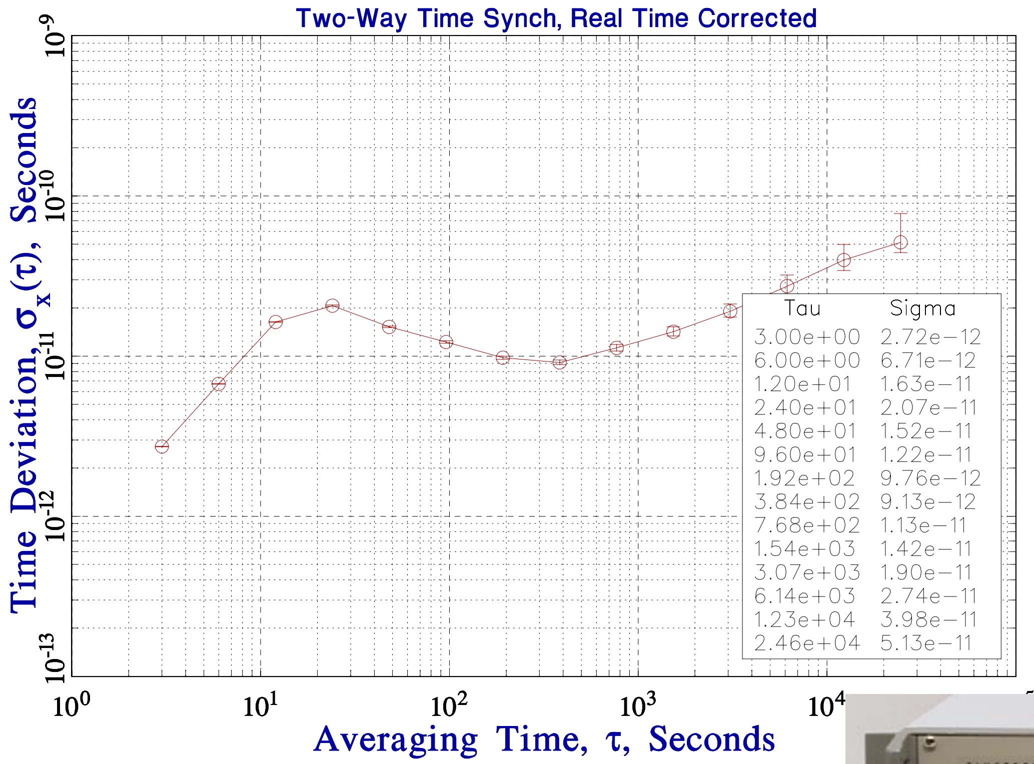
Frequency Uncertainty
1E-14 @ 10000 s

Experimental Link
PTB <-> DLR (near Munich)
Active vs passive H-Maser
PN-code 20 MChip/s
Direct TV Transponder (SES-ASTRA)
Loaded by ordinary TV signal



USO as remote slave clock

TWSTFT Results, T&F Synchronisation (2)



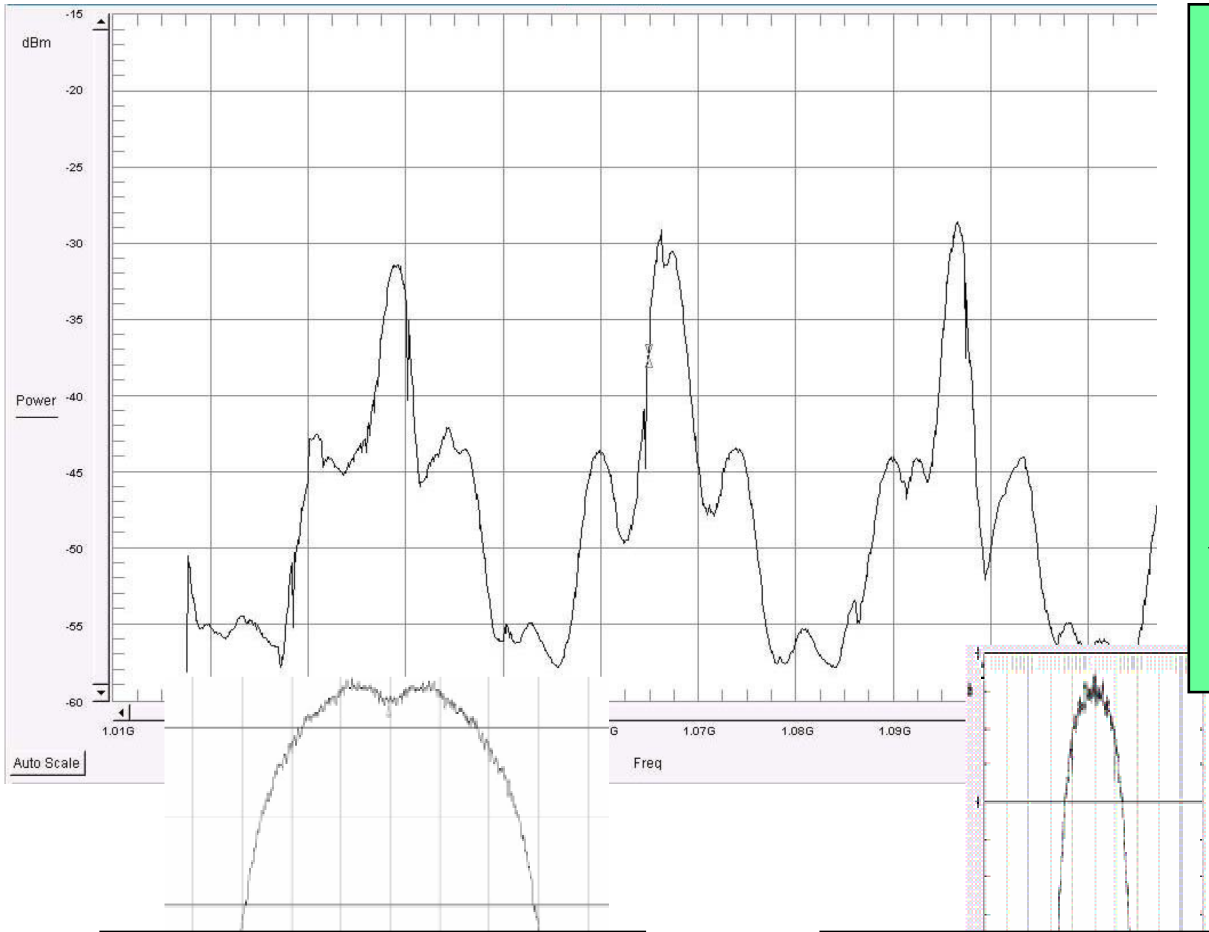
Timing Error (TDEV)
50 ps @ 8 hrs

Modem and station H/W identical for

- **Time & Frequency transfer**
- **Satellite Ranging**
- **Remote clock synchronisation**

Ranging & time transfer modem

TWSTFT via Loaded Transponder (spectral re-use)



Spectral plot of
3 direct-TV
transponder signals

Ranging and TWSTFT
signals may co-exist
on loaded transponders

SES-ASTRA: 20 MChip/s
INMARSAT: 1 MChip/s

Superposed
20 MChip/s signal

1 MChip/s
within guard band

TWSTFT Station Delay Monitoring (VSL / TimeTech)

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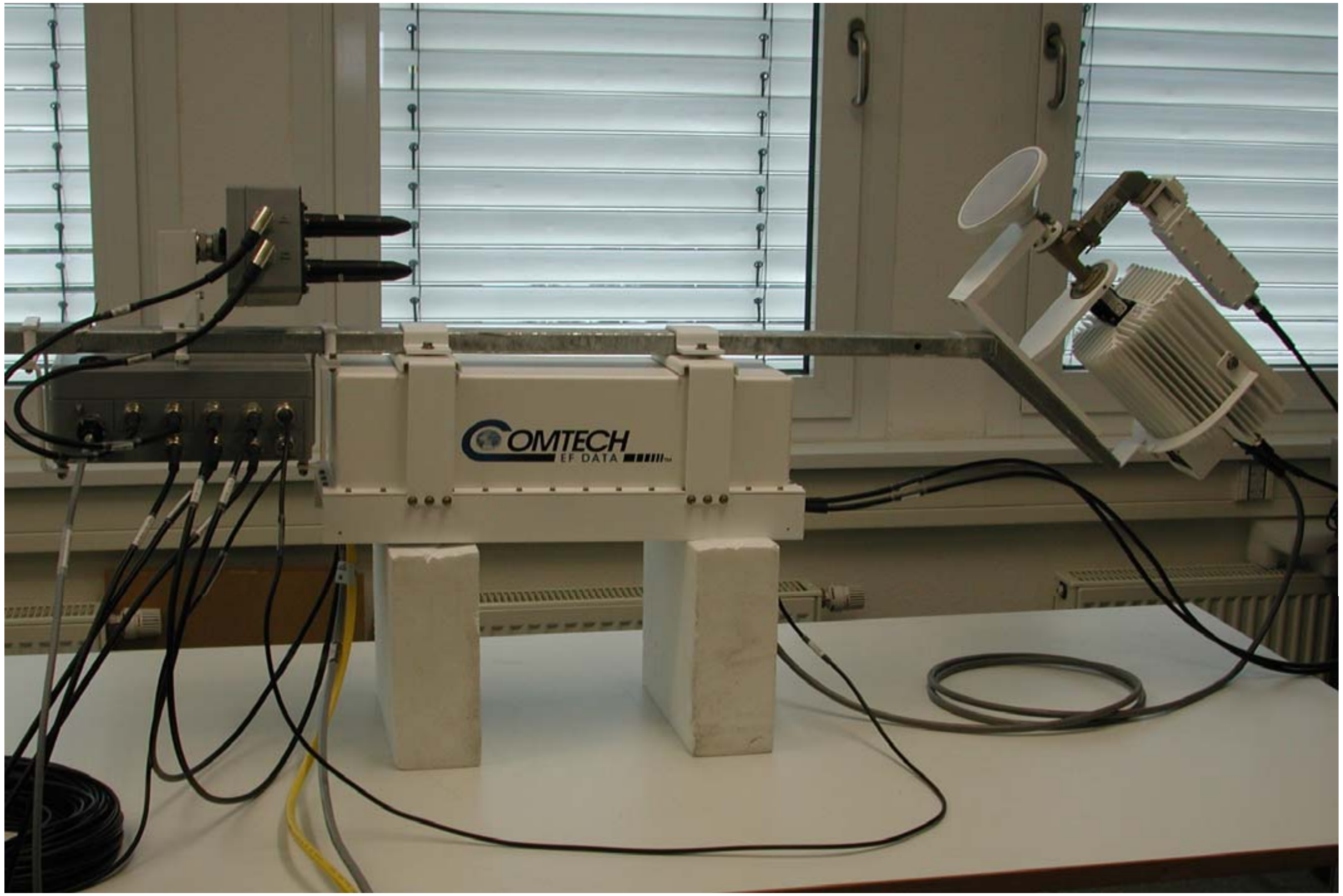
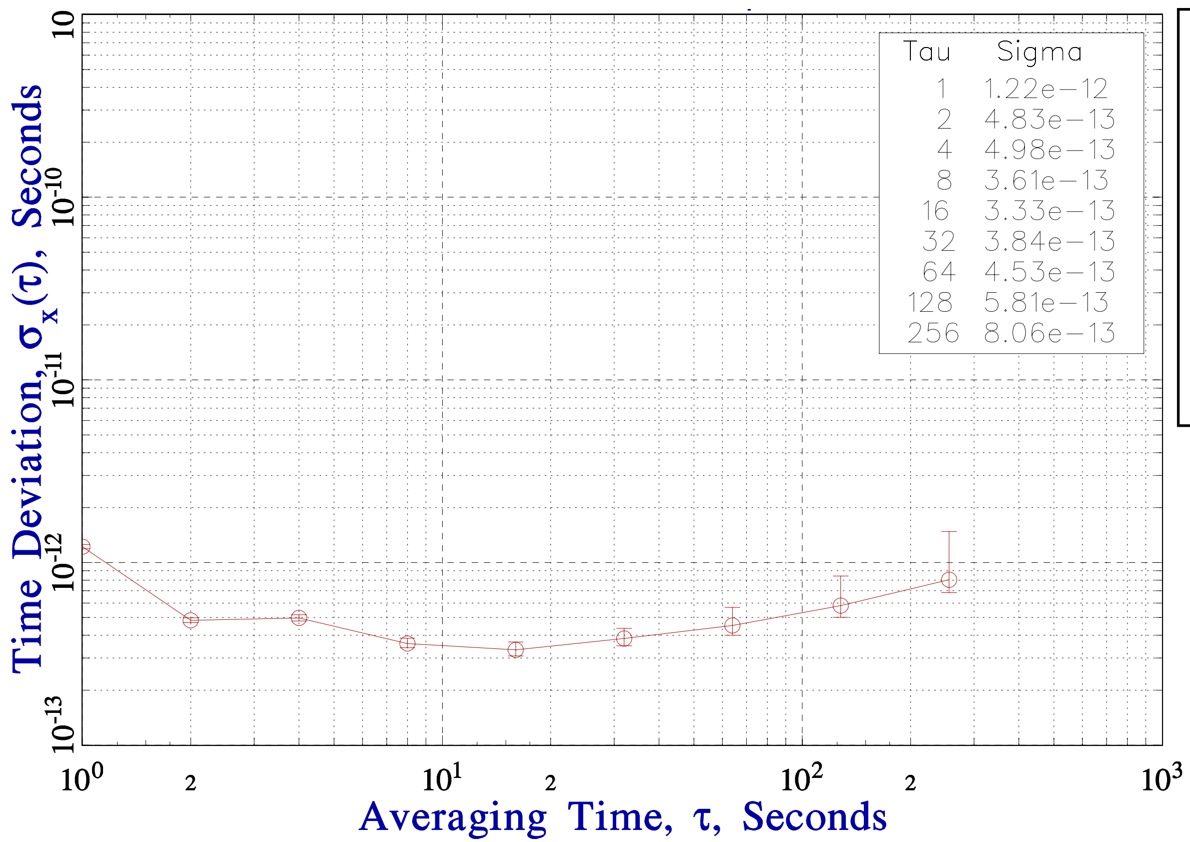


Works well together with VSAT equipment: 30 ps/day -> 10 ps/day
Determines up-link and down-link station delay independently
Ensures link calibration over extended time periods, i.e 1 yr

TWSTFT Link Calibration (USNO)

Mobile / transportable TWSTFT statio provides time transfer accuracy: 1ns
Calibration van at Vandenburg AFB contacts USNO, visits twice / yr
Mast mounted: 2 TWSTFT installations using VSAT equipment

Advanced TWSTFT using carrier phase via Comms Satellite



Timing Error (TDEV)

< 0.5 ps to 100 s

< 1 ps @ 300 s

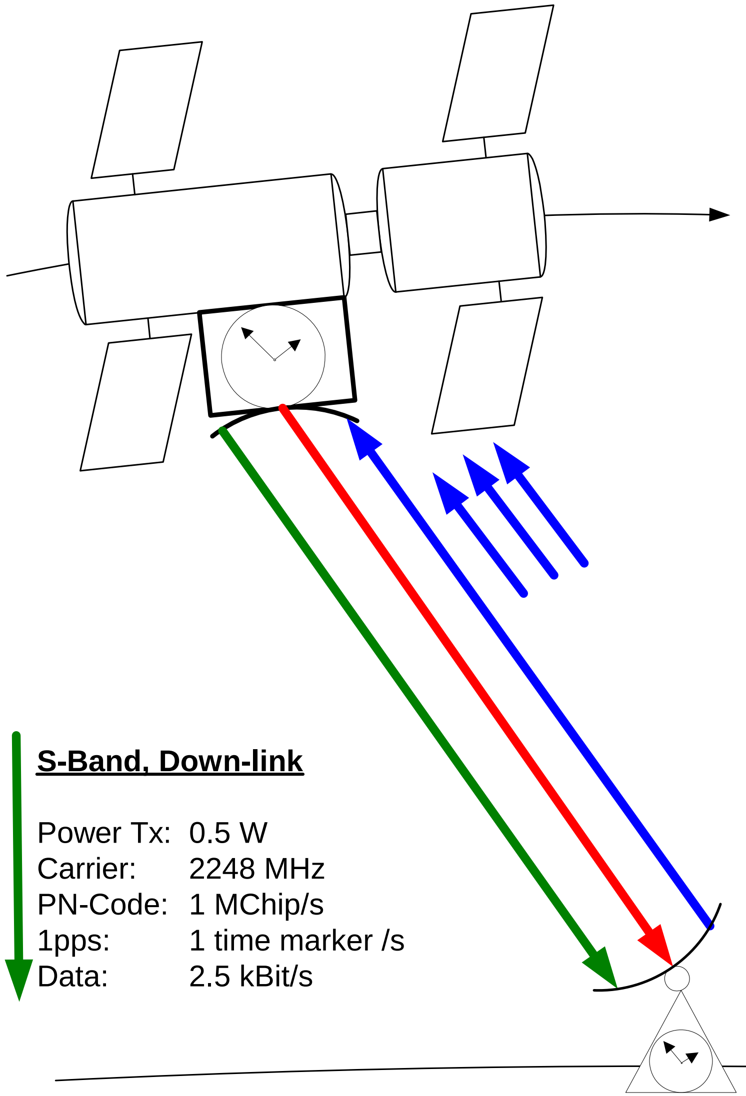
Experimental technique: Link USNO – NIST, masers both ends off-the shelf hardware, via normal communication satellite

Missing Link: Ground-Space-(Ground) time transfer (ACES-MWL)

Bi-directional Ku-band link

Wide BW: 100 MChip/s

S-band downlink only



Ku-Band, Up-link

Power Tx: 2 W
Carrier: 13.475 GHz
PN-Code: 100 MChip/s
1pps: 1 time marker /s

S/C: 4 Receiver Channels

Ku-Band, Down-link

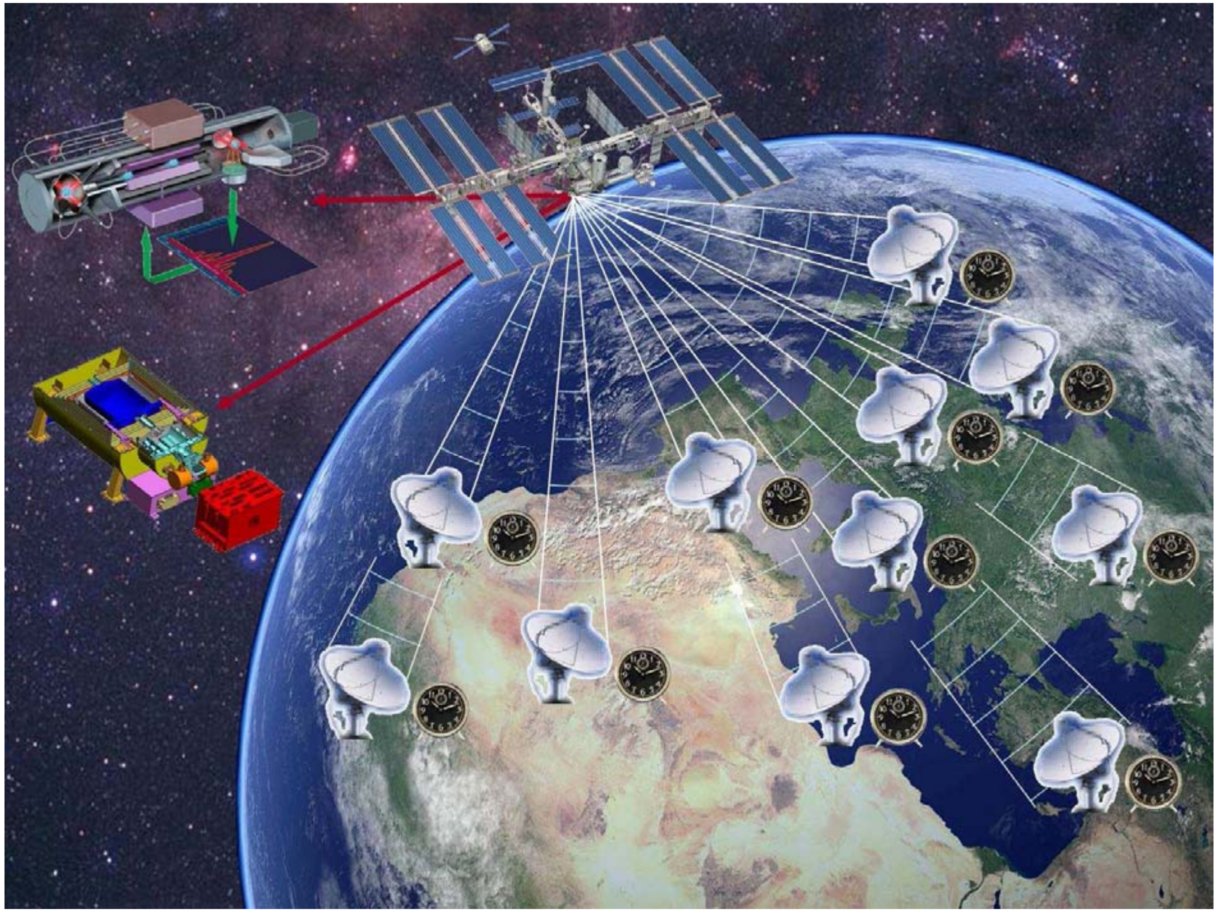
Power Tx: 0.5 W
Carrier: 14.70333 GHz
PN-Code: 100 MChip/s
1pps: 1 time marker /s
Data: 2.5 kBit/s

S-Band, Down-link

Power Tx: 0.5 W
Carrier: 2248 MHz
PN-Code: 1 MChip/s
1pps: 1 time marker /s
Data: 2.5 kBit/s

PRARE-ERS-2 Ground Station System operated 12 years in space

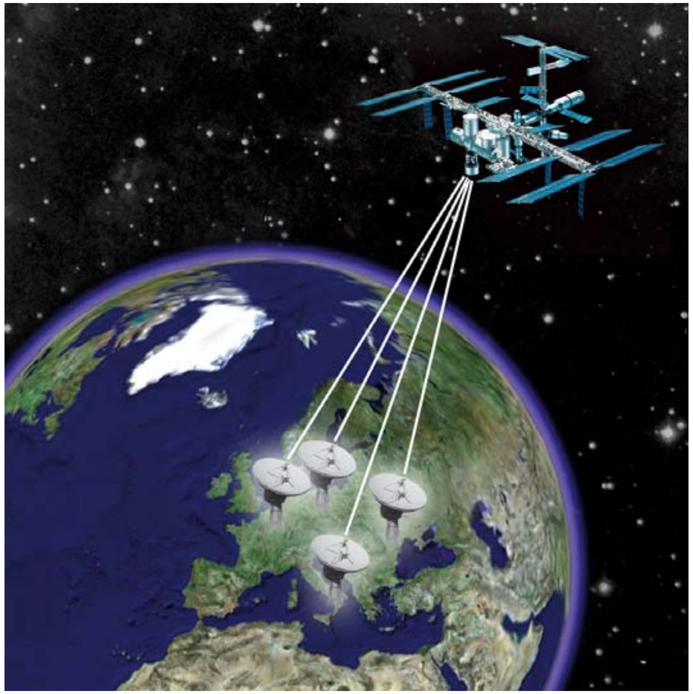
ACES Mission Outline (ESA project, ASTRIUM Prime)

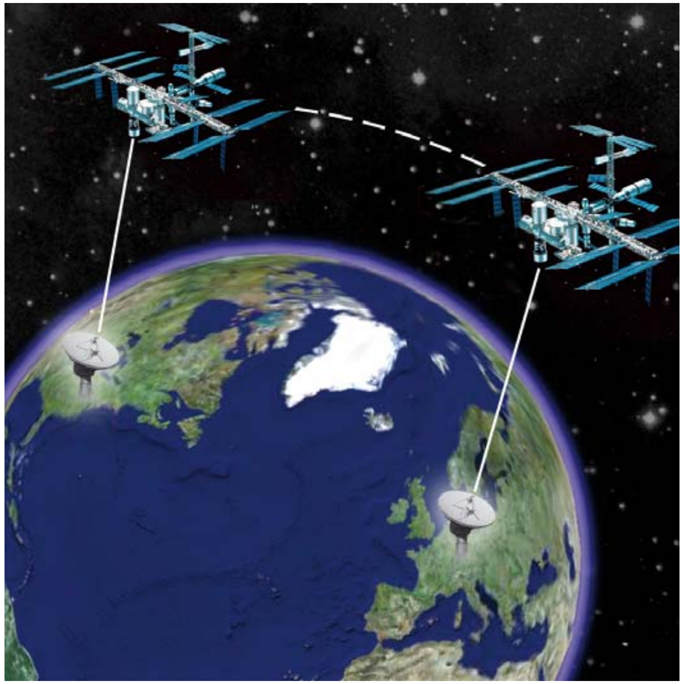


Atomic Clock Ensemble in Space

- **PHARAO** (CNES); Cold atom Cs Primary Frequency Standard (1E-16)
- **Active Hydrogen Maser** (ON, Observatoire de Neuchâtel, Switzerland)

Microwave Link Applications:
Space-based Ranging and Time & Frequency Transfer





Common View:

- Up to 4 ground clocks simultaneously
- Independent from space clocks
- Regional clock comparison

Non-Common View:

- Transport time from one ground clock to another using space clocks
- Inter-continental time and frequency comparison

ACES-MWL Carrier Phase Stability Test (TDEV)

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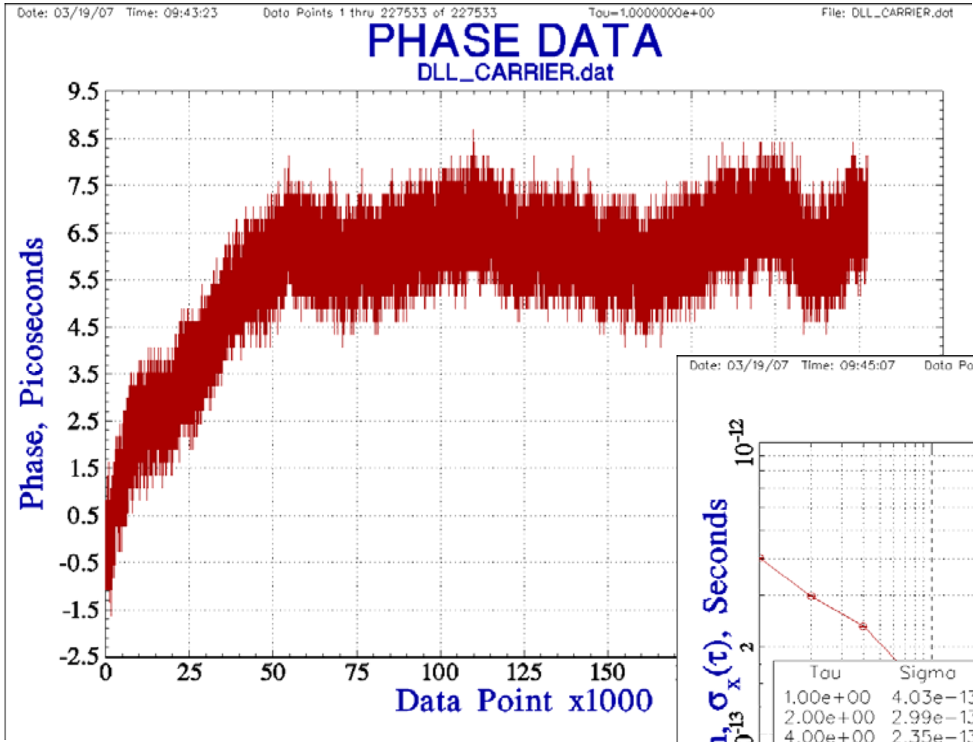
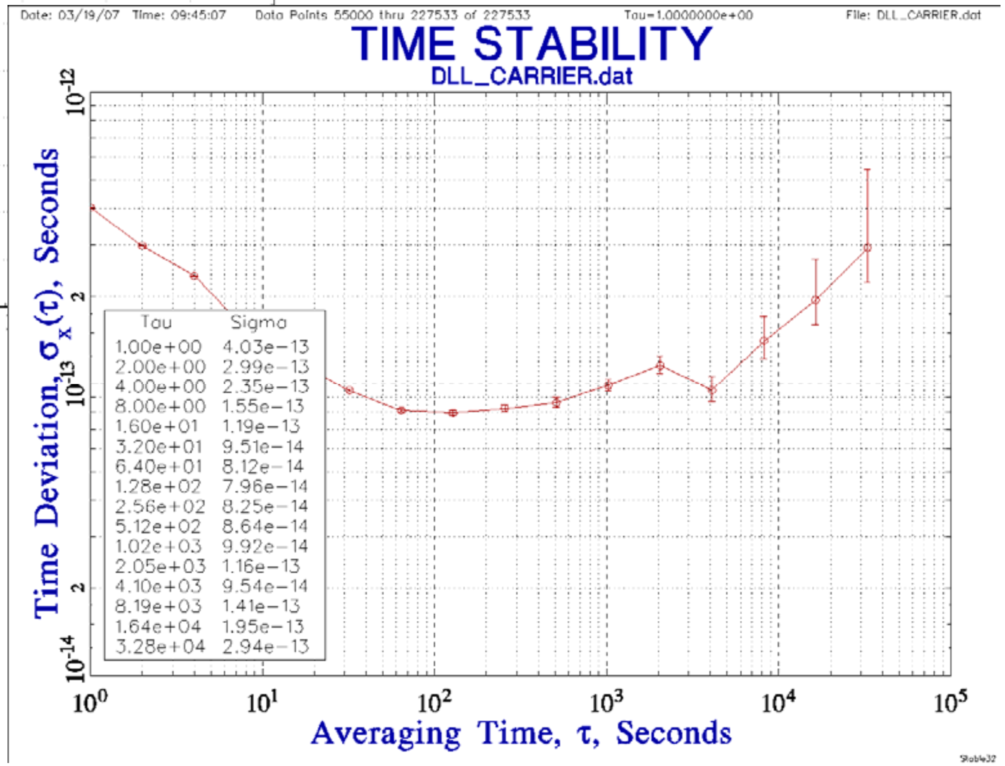


2 day measurement run

Some initial drift during system stabilisation

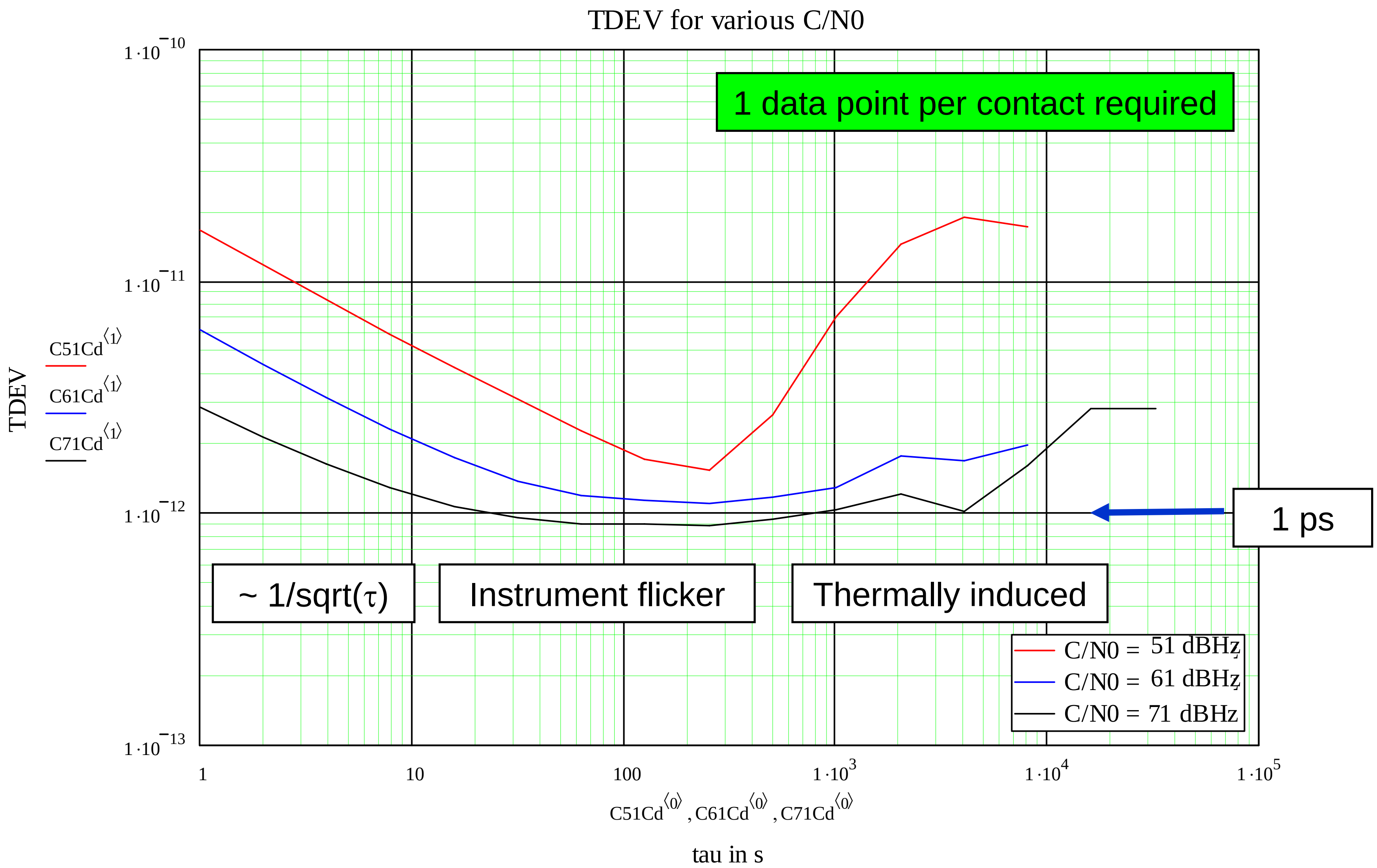


TDEV using Carrier Phase

100 fs @ 30s < τ < 4000s

EM-hardware test results

ACES-MWL Code Phase Stability Test (TDEV), 100 MChip/s



Space-Based PN Ranging, 10 MChip/s, PRARE on-board ERS-2
Proposed by NRL to fly on experimental GPS (Phase-B ~1990)

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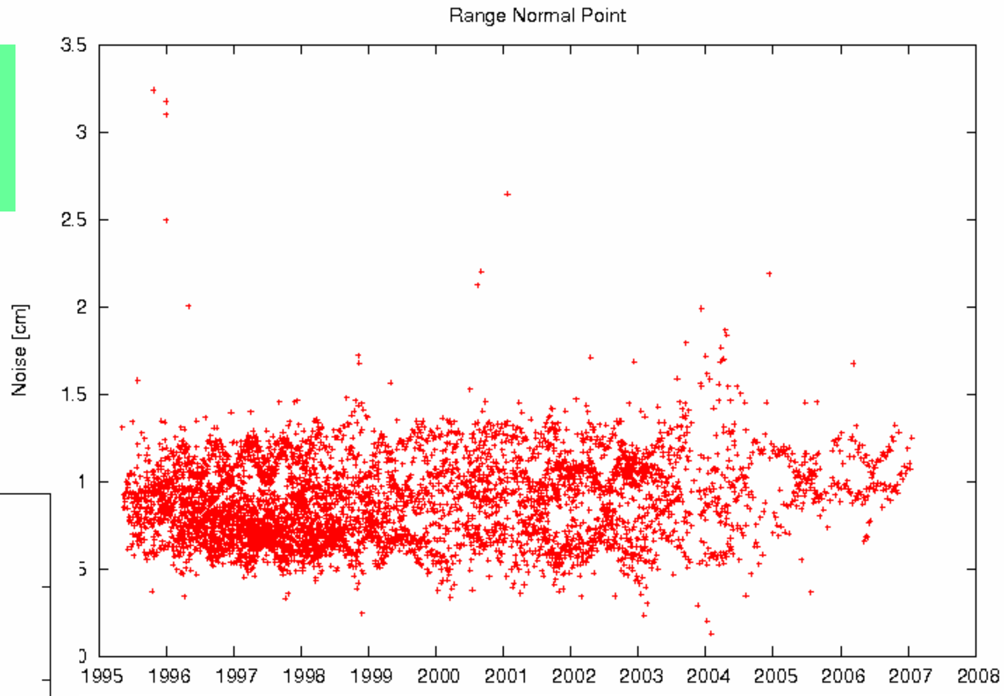
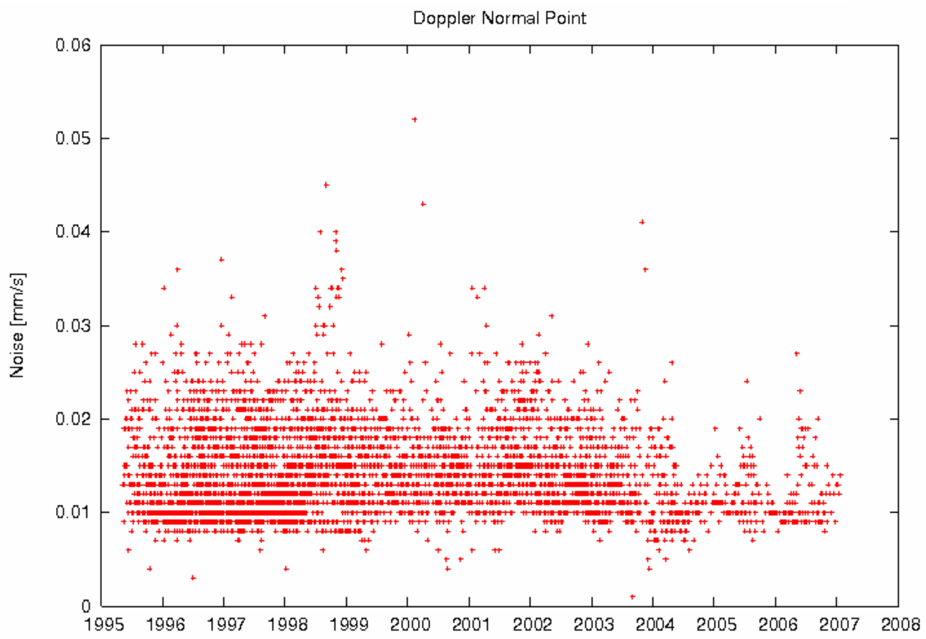
Ranging noise

0.9 cm @ 15s arcs





Range-Rate noise

0.015 mm/s @ 15s arcs

Summary

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TWSTFT provides under all-weather capability

- **Calibrated Time Links: 200 ps stability, 1 ns accuracy @ 1 yr** (BIPM)
- **Real-time**-operation, 3 s latency, results available at both ends
- **10^{-15} @ 1 day** using existing links at **2.5 MChip/s** (standard)
- **10^{-16} @ 1 day** capability using wider transponder and **20 MChip/s**
- **Further advanced techniques are currently in experimental stage**
- **Signals co-exist** on loaded transponder w/o mutual interference
- Co-operate with Sat Operators to perform **Ranging & TWSTFT**
- INSAT will have 25 MHz wide ranging transponders
- **INSAT GEOs ideal candidate to link EU – Russia – Asia – Pacific Rim**

Conlusions

Ground-based Two-Way Time and Frequency Transfer (**TWSTFT**)

- Is a readily available tool which is accepted by BIPM at the level of 1ns accuracy
- Is fully operational between major Metrological Laboratories, incl. USNO and AMC

TWSTFT is an ideal candidate to

- **Compare Satellite system time scales to provide interoperability**
- **To link Satellite system time scales to UTC(k) laboratories for accuracy**

Established, calibrated methods and networks exist:

- EU and US labs participate in an operational network via paid transponder (Intelsat)
- Links between EU-Asia-Pacific-US are scarce and some are experimental only

Availability of additional reliable transponder time for TWSTFT is highly desirable

- TWSTFT can co-exist with traffic and / or a ranging service, which may reduce cost

TWSTFT is an independent means to support and calibrate NSS, and to link satellite system times to each other and to UTC.

Outlook

A **Space-based** wide-band Ranging and TWSTFT package embarqued on a MEO navigational satellite(s) could provide **world-wide time- and frequency** comparison at the level of the best clocks presently available, i.e.

at a level of 10^{-17} and better, i.e. to pico-second level

in support of

- **Time & Frequency Metrology to highest accuracy**
- **Advancing the Timing Service (UTC) from Navigation Sat Systems**
- **Independent NSS orbit determination and on-board clock monitoring**