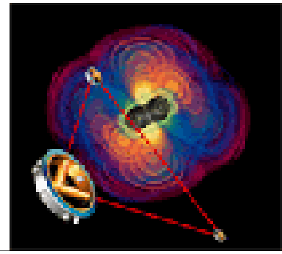


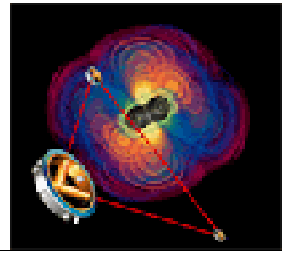
Advanced Ranging

and

Time & Frequency Transfer Techniques

for LISA

Noordwijk, The Netherlands, 12 – 15 Jul 2004



TIMETECH

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Germany

Phone: 0049-711-678 08-0
Fax: 0049-711-678 08 99

1.Background

SIRIO: Microwave Ranging and Time Transfer Experiment & Laser Ranging, 1979

MITREX: PN-coded Two-Way Time Transfer via Satellite (TWSTFT): since 1981

- USNO, NIST, SYRTE, NPL, PTB, VSL, China, Taiwan: **Accuracy 1ns**

PRARE: Precise Range and Range-Rate Equipment (ERS-2, LEO, 1995)

- Geodetic Mission: **Orbit to 3 cm, Stability: 1cm**

SATRE: Satellite Time and Ranging Equipment, since 1991

- Operates via "Occupied Transponders": **Jitter 3 cm, Stability: 1cm**
- NO dedicated resources needed at the S/C
- SES-ASTRA: Trilateration System for Co-located Geo Satellites
- INMARSAT

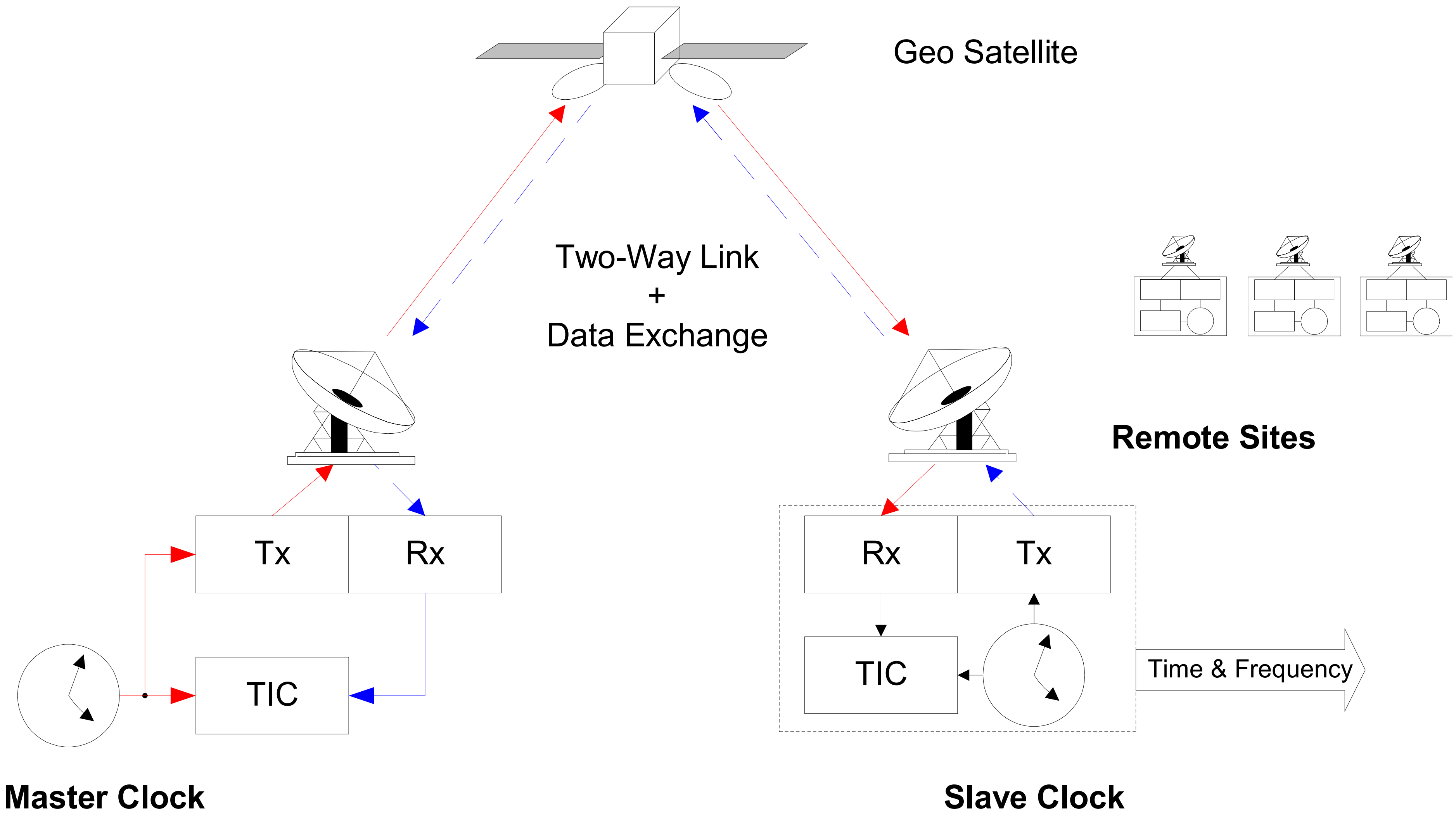
ACES-MWL: Monitor Cs-Fountain (PHARAO) on-board ISS (ongoing): **TDEV: 5.6 ps/d**

2.Key Properties of Pseudo-Noise Coded Signals

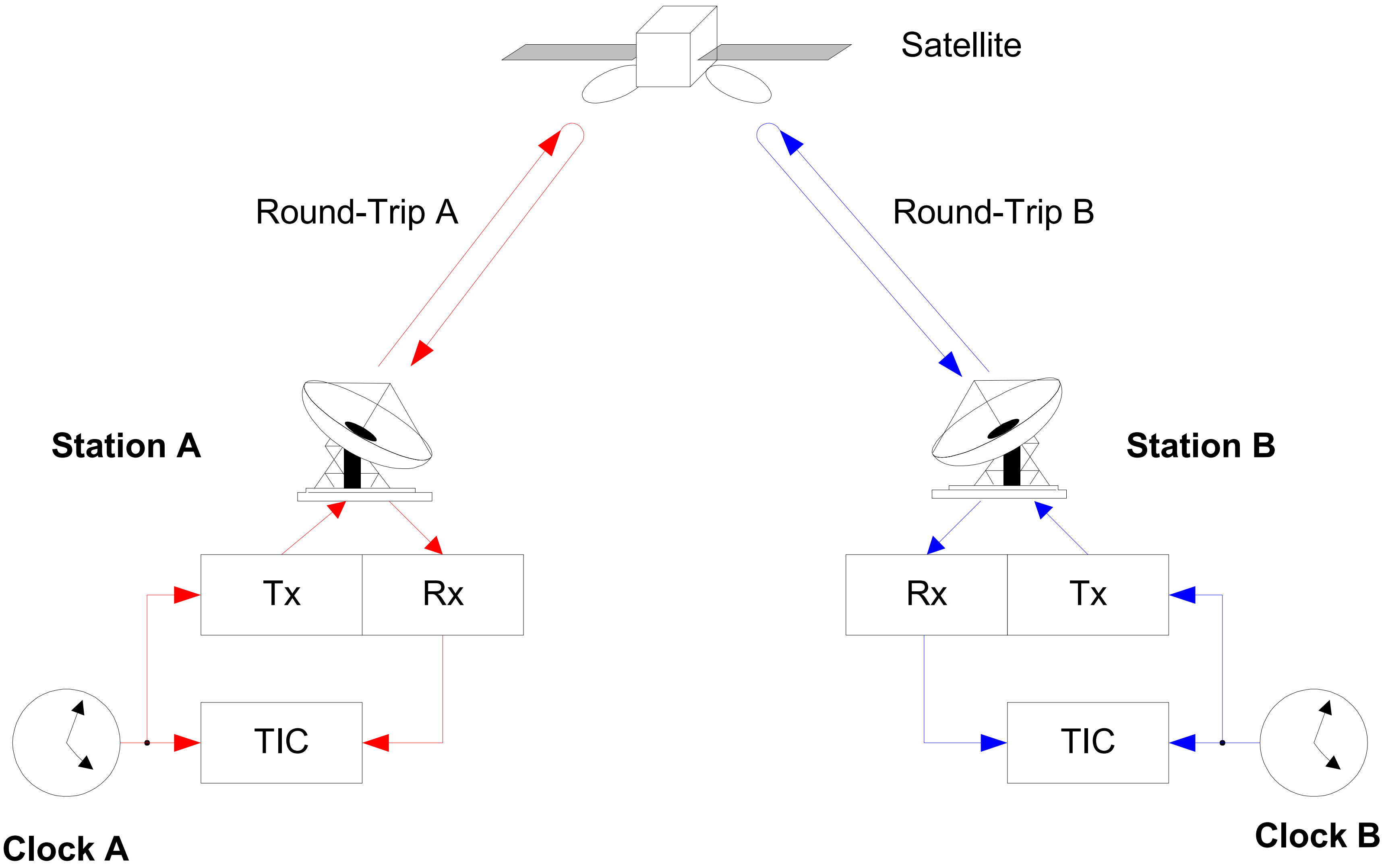
- Coherent communication system, using autocorrelation techniques & matched filter
- Near ideal demodulation process with insignificant implementation loss
- Ranging signal significantly lower than thermal noise in Rx bandwidth
- Highly tolerant against interference, multiple signals on same frequency
- Add data transmission modulated onto PN-code
- Instant ambiguity resolution, even at distances within the solar system
- Suppress Multi-Path signals within correlation length (beyond 1 chip)
- Measure code-phase and carrier phase simultaneously:
    - DRVID capability: **Group vs Phase Delay** in single frequency band
    - Detect Multi-Path and Signal reflections (signal scattering)

- **System Stability: 300ps / Chiprate [MChip]**

3.Applications: TWSTFT and Time Synchronisation

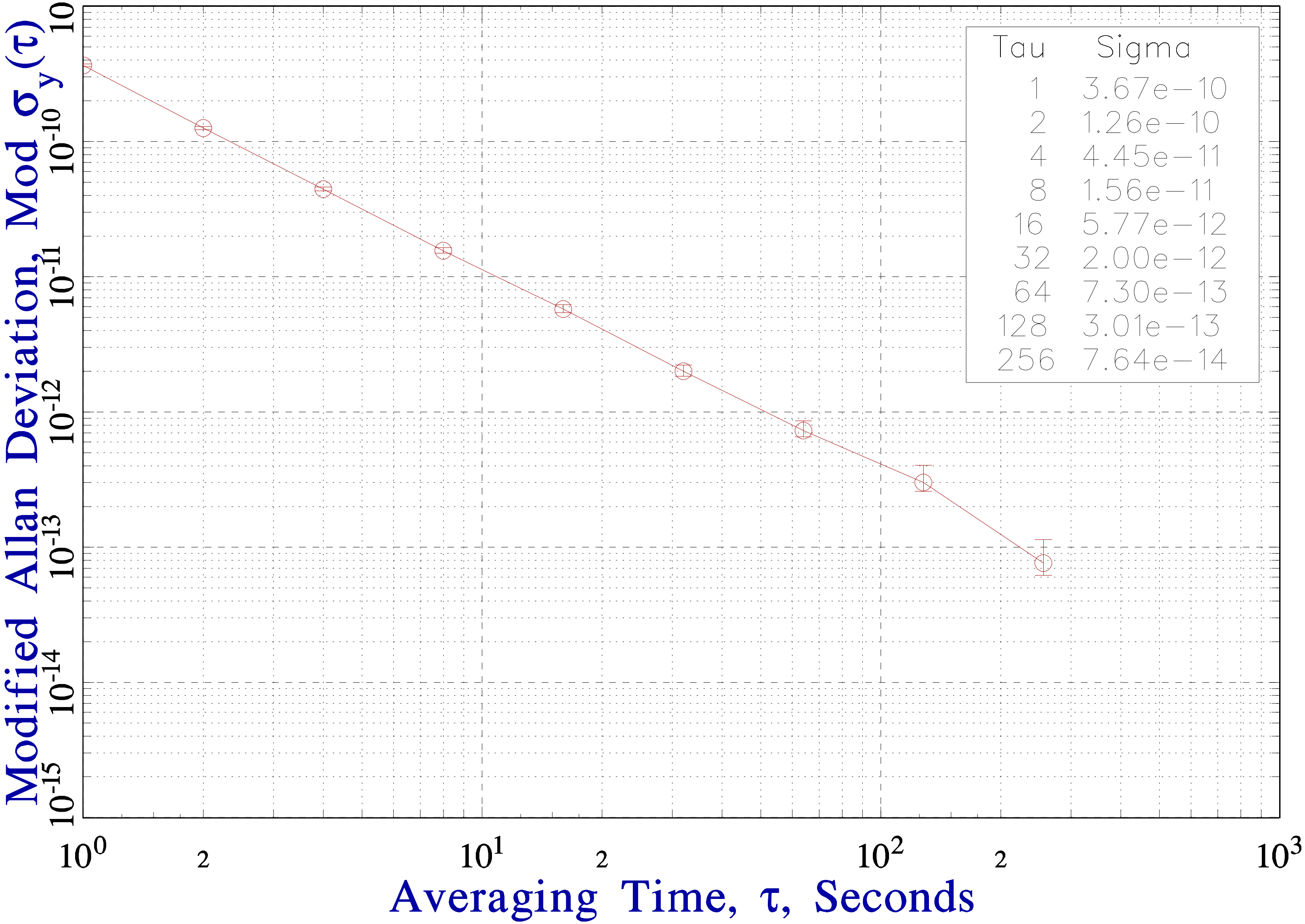


4.Applications: Satellite Ranging -> Trilateration using 3 Sites

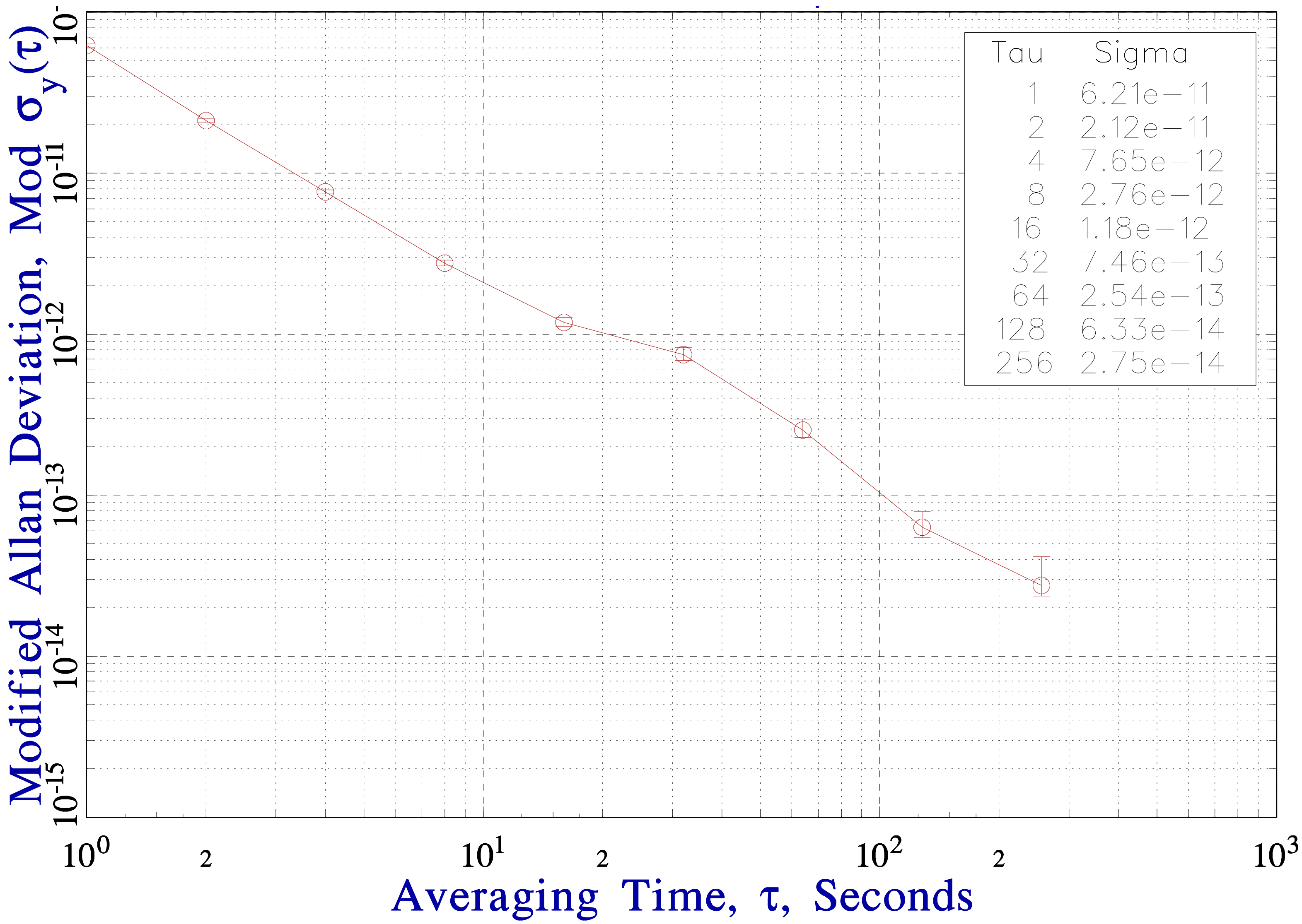

Satellite
Round-Trip A
Round-Trip B
Station A
Station B
Tx
Rx
Rx
Tx
TIC
TIC
Clock A
Clock B

5.Antenna Systems: Very small appertures required

6.Code Phase Performance, 2.5 MChip/s


Modified Allan Deviation, Mod σy(τ)
10-10
10-11
10-12
10-13
10-14
10-15
Averaging Time, τ, Seconds
10^0
2
10^1
2
10^2
2
10^3
Tau Sigma
1 3.67e−10
2 1.26e−10
4 4.45e−11
8 1.56e−11
16 5.77e−12
32 2.00e−12
64 7.30e−13
128 3.01e−13
256 7.64e−14

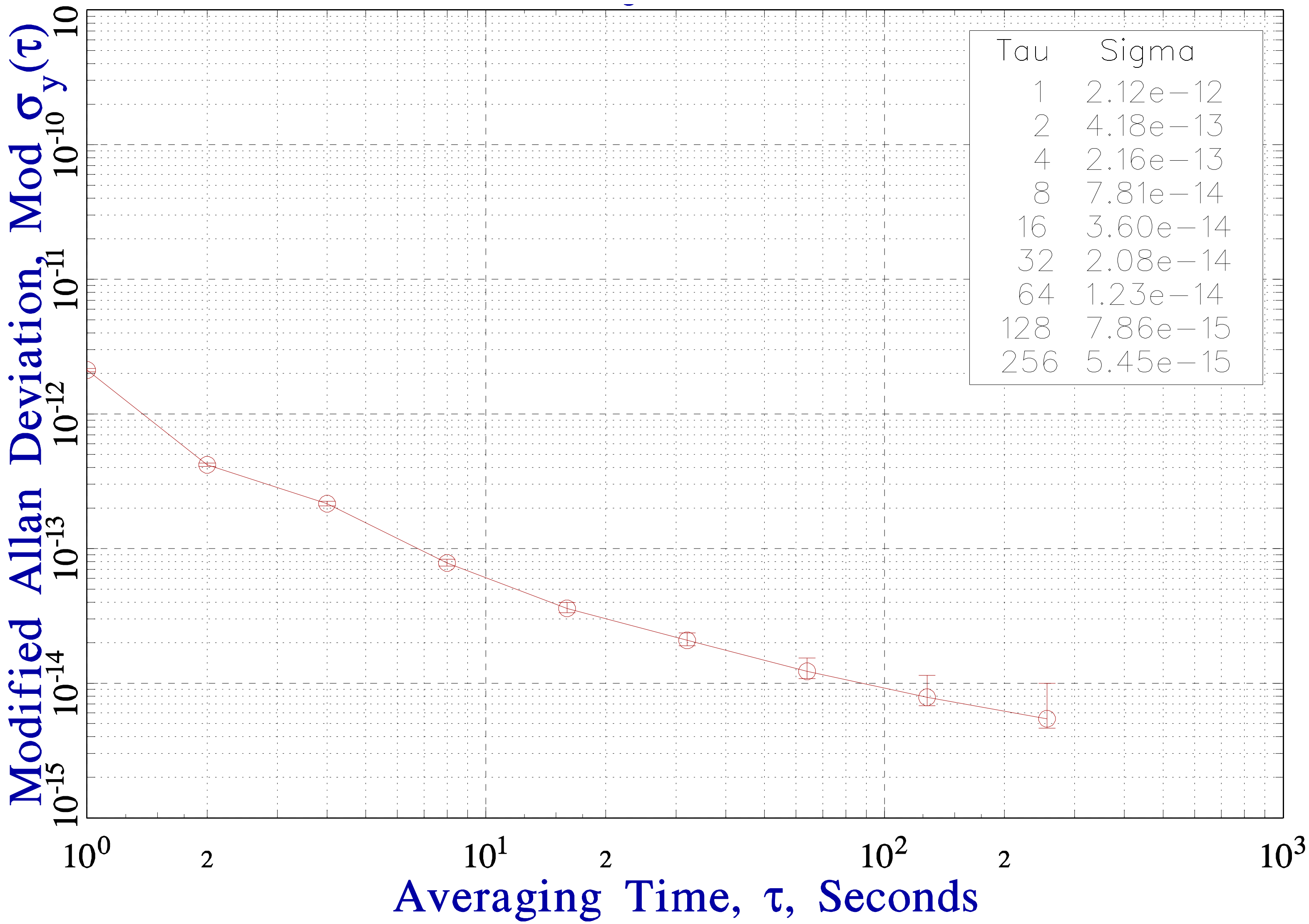
7.Code Phase Performance, 20 MChip/s



Modified Allan Deviation, Mod $\sigma_y(\tau)$
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{0}
2
10^{1}
2
10^{2}
2
10^{3}
Averaging Time, τ, Seconds
Tau Sigma
1 6.21e−11
2 2.12e−11
4 7.65e−12
8 2.76e−12
16 1.18e−12
32 7.46e−13
64 2.54e−13
128 6.33e−14
256 2.75e−14

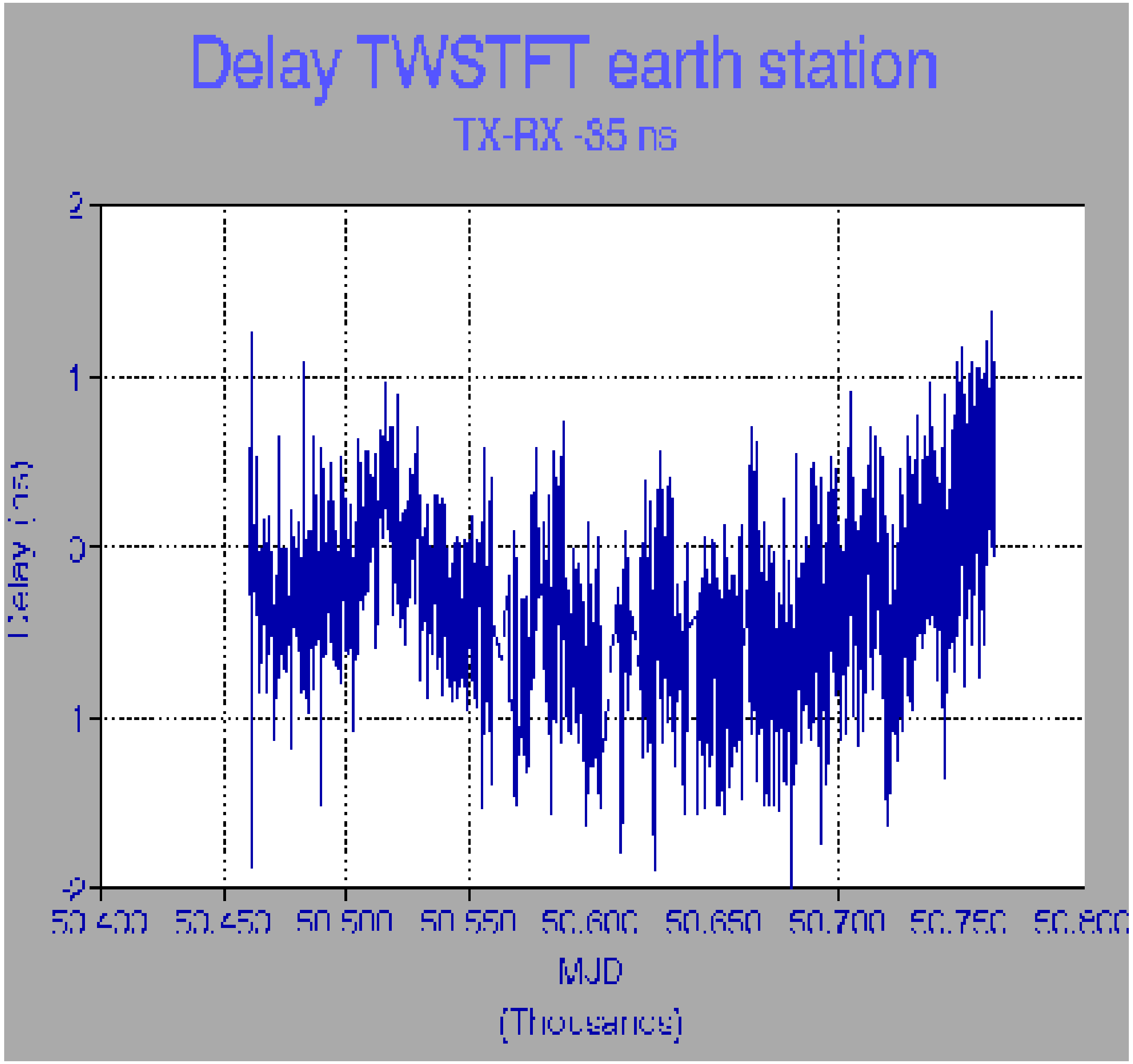
8.Carrier Phase Performance, PN+Data modulation, independent of chip rate

TIMETECH


Tau Sigma
1 2.12e−12
2 4.18e−13
4 2.16e−13
8 7.81e−14
16 3.60e−14
32 2.08e−14
64 1.23e−14
128 7.86e−15
256 5.45e−15
Modified Allan Deviation, Mod σy(τ)
Averaging Time, τ, Seconds
10^0
2
10^1
2
10^2
2
10^3
10^-15
10^-14
10^-13
10^-12
10^-11
10^-10
10

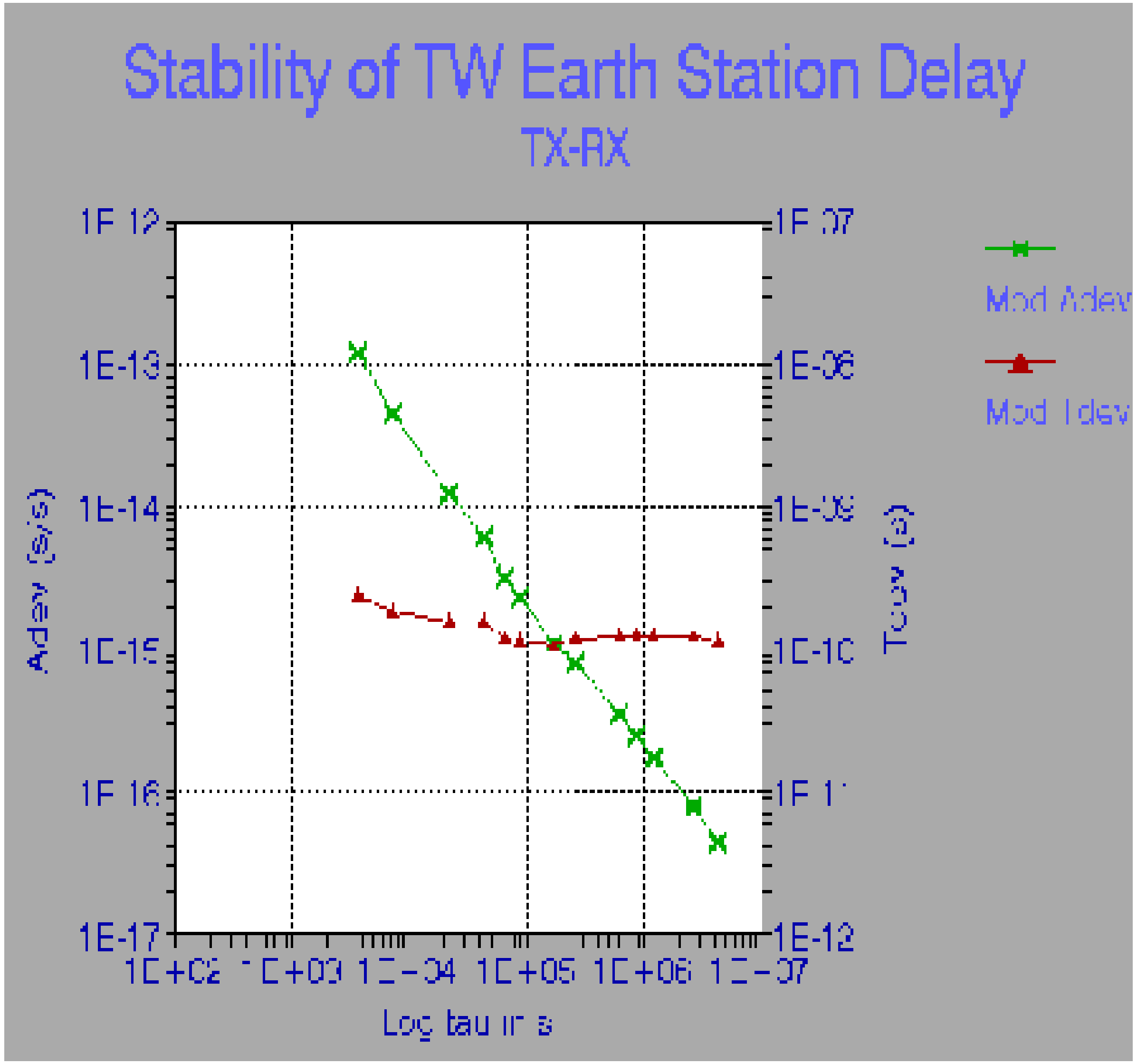
9.TWSTFT Ground Station Stability during 1 years (2.5 MChip/s)

TIMETECH



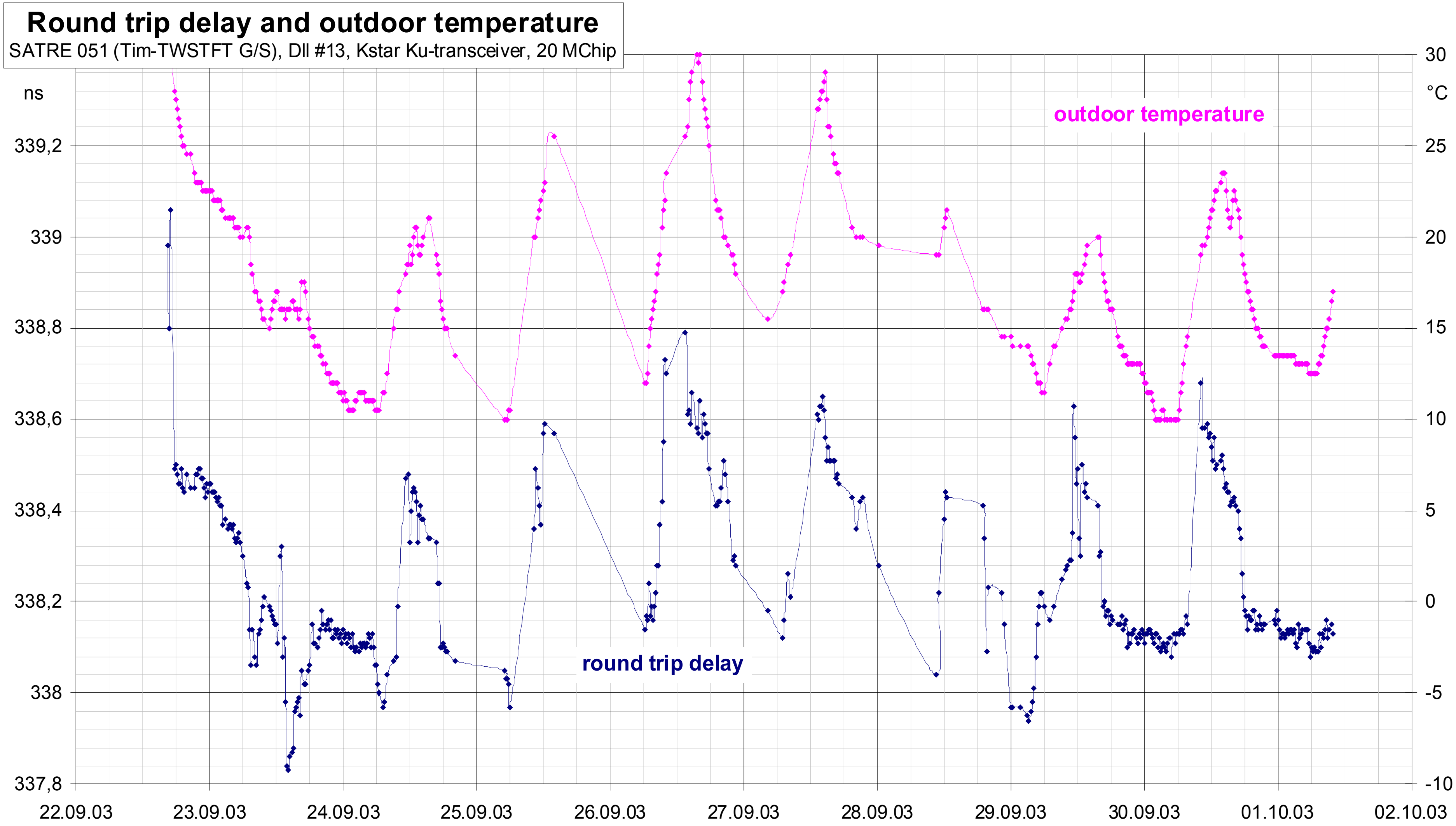
Courtesy VSL, 1ns /div

10.Typical ADEV / TDEV of VSAT Ground Station used for TWSTFT



Courtesy VSL, TDEV 120ps

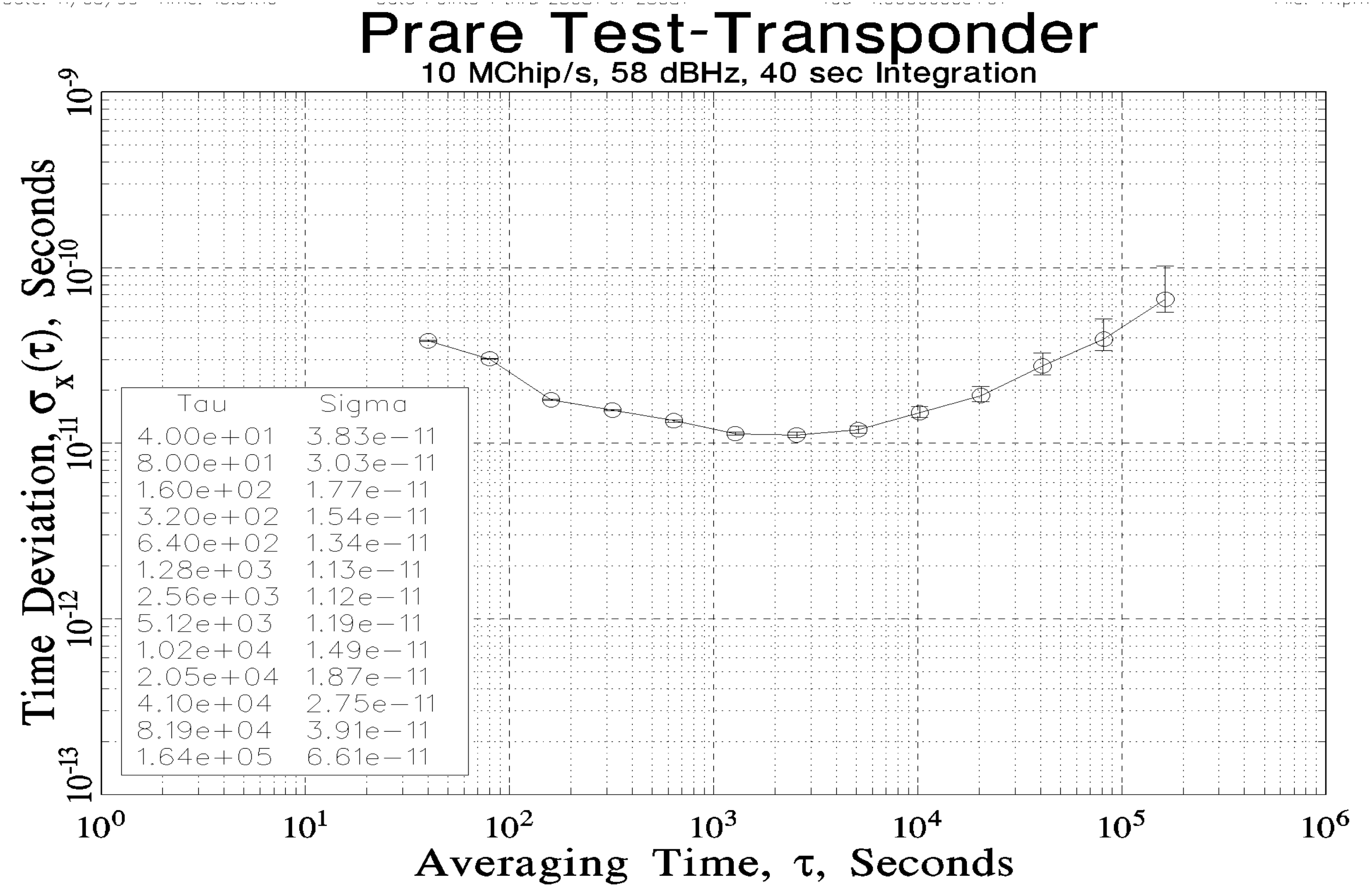
11.Station Round Trip Delay correlates well with Temperature



Round trip delay and outdoor temperature
SATRE 051 (Tim-TWSTFT G/S), Dll #13, Kstar Ku-transceiver, 20 MChip
ns
°C
outdoor temperature
round trip delay
339,2
339
338,8
338,6
338,4
338,2
338
337,8
30
25
20
15
10
5
0
-5
-10
22.09.03
23.09.03
24.09.03
25.09.03
26.09.03
27.09.03
28.09.03
29.09.03
30.09.03
01.10.03
02.10.03

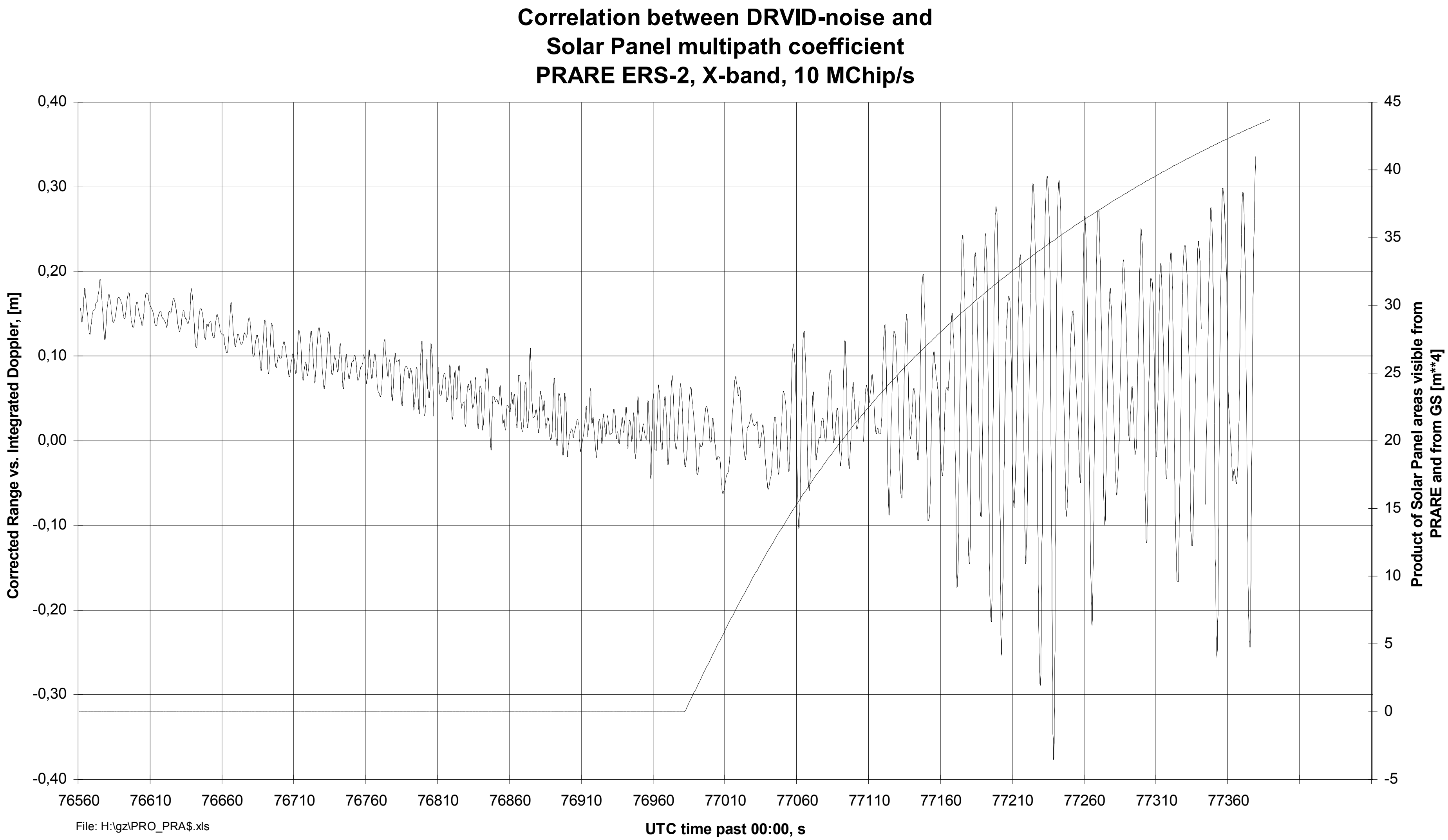
12.G/S Delay Monitoring Equipment

13.PRARE Instrumental Delay (TDEV)



Tau	Sigma
4.00e+01	3.83e−11
8.00e+01	3.03e−11
1.60e+02	1.77e−11
3.20e+02	1.54e−11
6.40e+02	1.34e−11
1.28e+03	1.13e−11
2.56e+03	1.12e−11
5.12e+03	1.19e−11
1.02e+04	1.49e−11
2.05e+04	1.87e−11
4.10e+04	2.75e−11
8.19e+04	3.91e−11
1.64e+05	6.61e−11

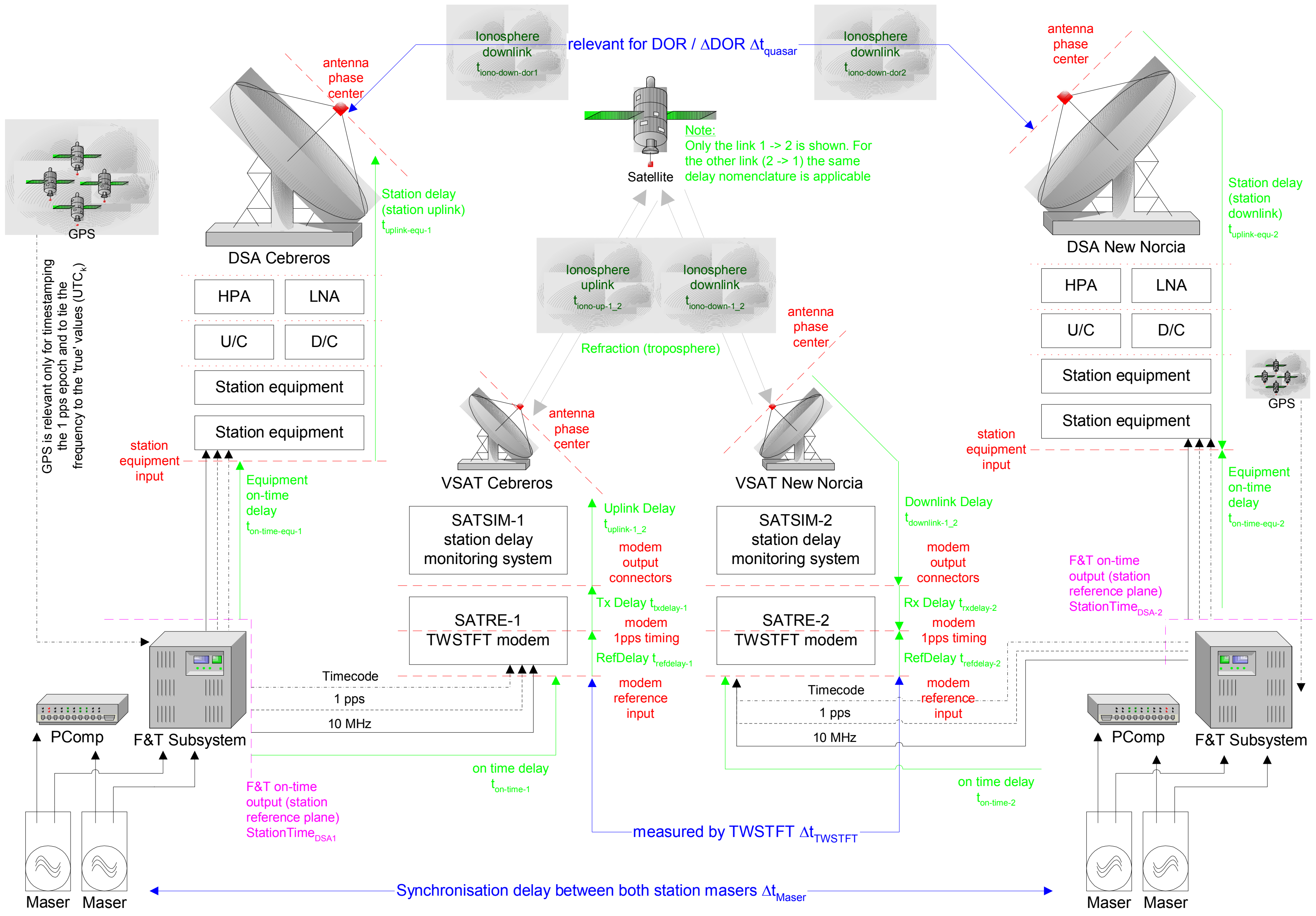
14.Use of DRVID to Detect Ionosphere & Multipath (PRARE on ERS-2)



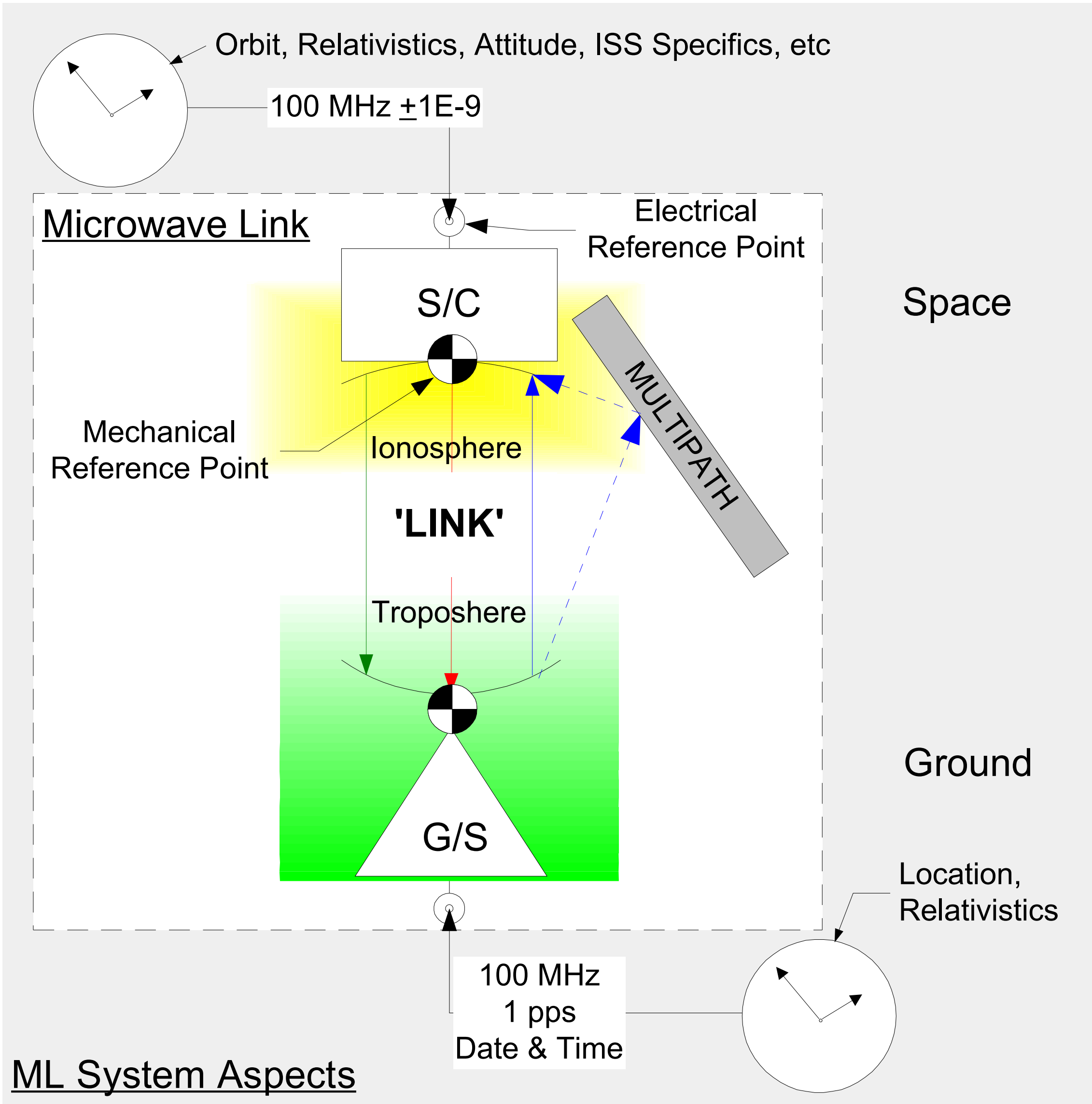
Correlation between DRVID-noise and
Solar Panel multipath coefficient
PRARE ERS-2, X-band, 10 MChip/s
Corrected Range vs. Integrated Doppler, [m]
Product of Solar Panel areas visible from PRARE and from GS [m**4]
0,40
0,30
0,20
0,10
0,00
-0,10
-0,20
-0,30
-0,40
45
40
35
30
25
20
15
10
5
0
-5
76560
76610
76660
76710
76760
76810
76860
76910
76960
77010
77060
77110
77160
77210
77260
77310
77360
UTC time past 00:00, s
File: H:\gz\PRO_PRA$.xls

15.DS Tracking Stations augmented by TWSTFT + Delay Monitoring (proposal)

Advanced Ranging and Time & Frequency Transfer Techniques



16.Candidate Technology for LISA: ACES Microwave Link (LEO / ISS)



- Accept Clocks “AS IS”
- Orbit Induced Effects
  - Distance
  - Velocity
  - Acceleration
- Link-Induced Effects
  - Ionosphere
  - Troposphere
  - Multipath
- Environment
  - Temperature
  - Micro-Vibration
  - Relativistcs

17.ACES MWL Performance Objectives

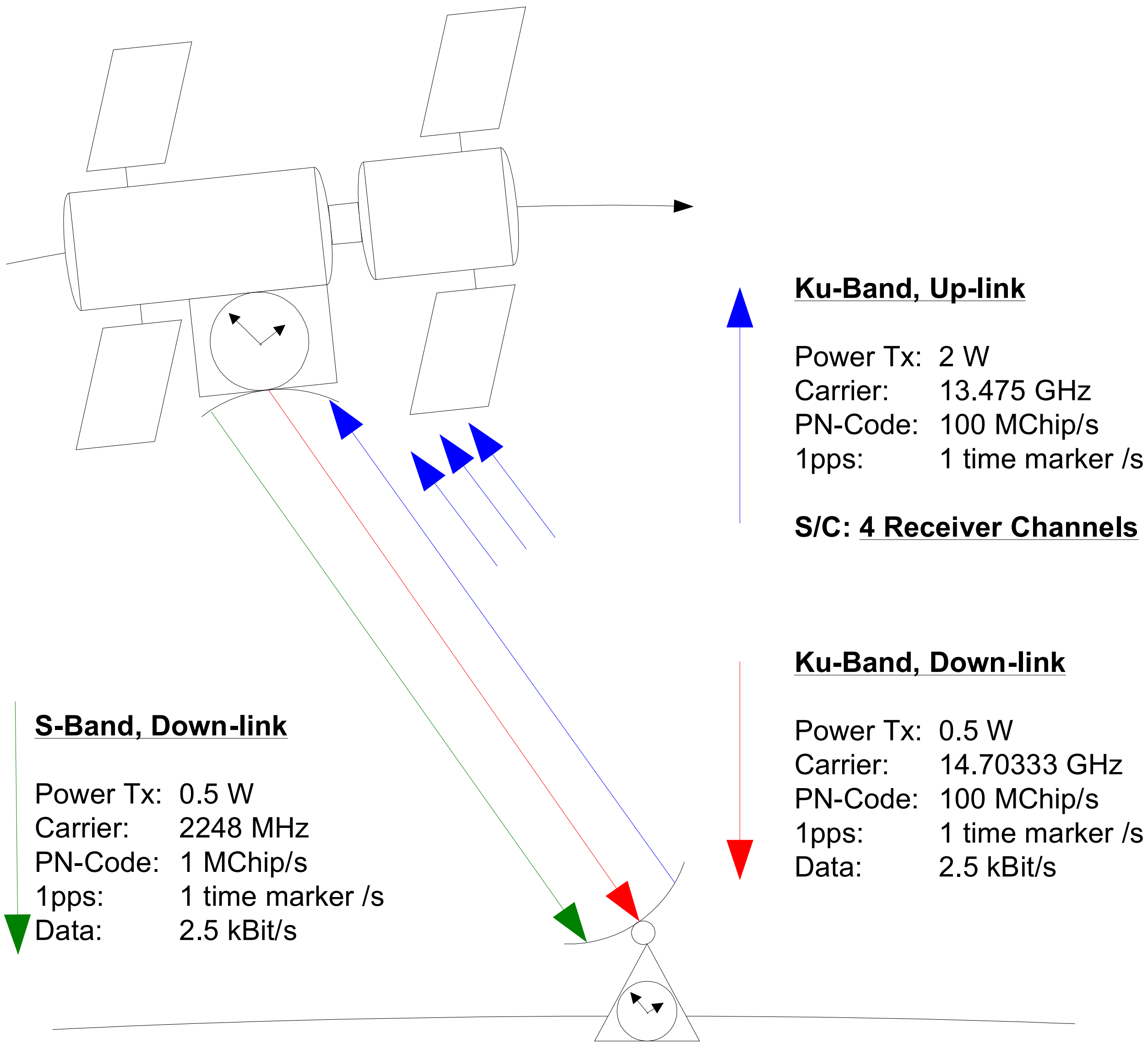
Time Transfer Performance

- Short Term 230 fs /pass (300 s)
- 1 day 5.6 ps
- 10 days 16 ps

Ranging Performance (estimated)

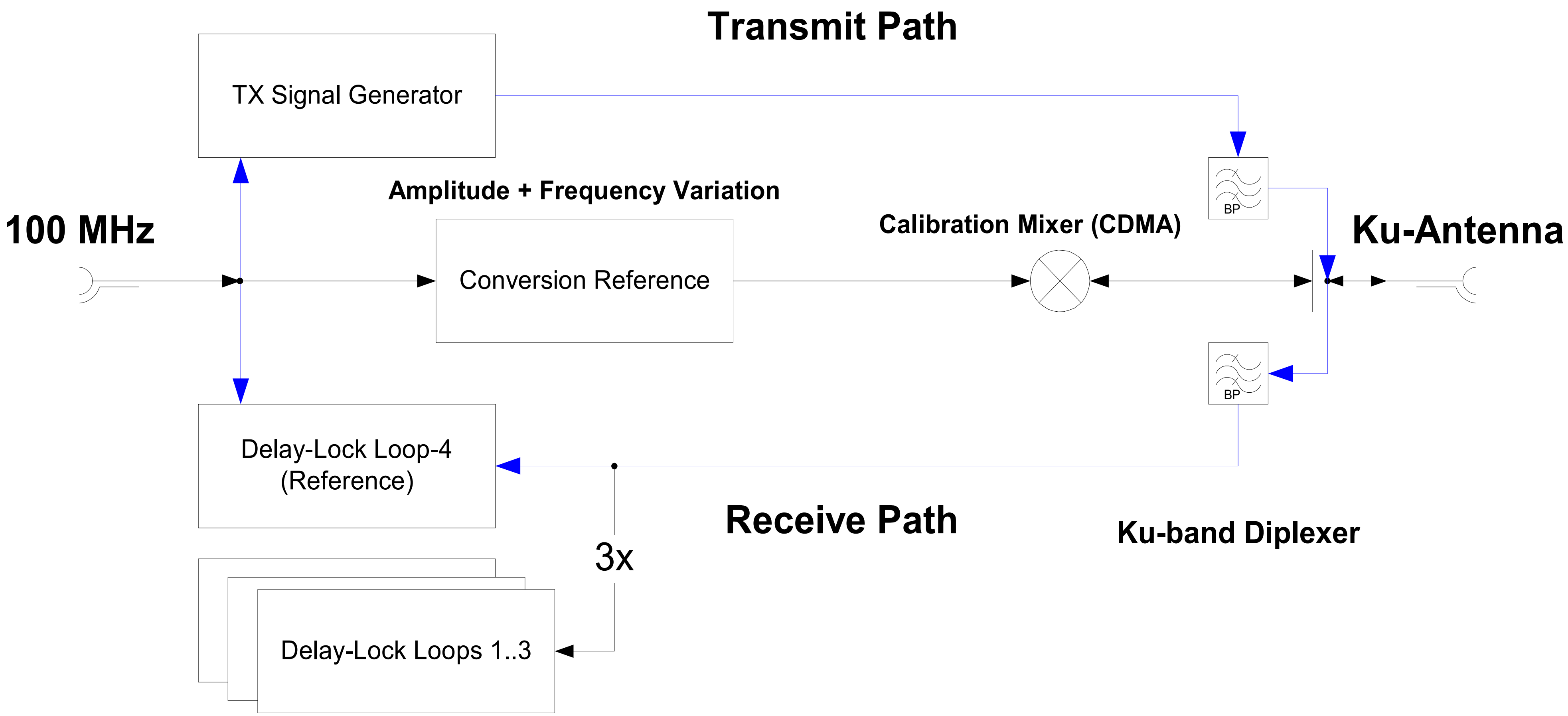
- Accuracy: 3 .. 10 cm (with / without optical calibration)
- Stability: 1 cm
- Instrumentation significantly better than PRARE (up to 10 times improvement)
- Orbit reconstitution limited by LEO effects (drag, geo-potential etc)

18.ACES MWL: Signal Links

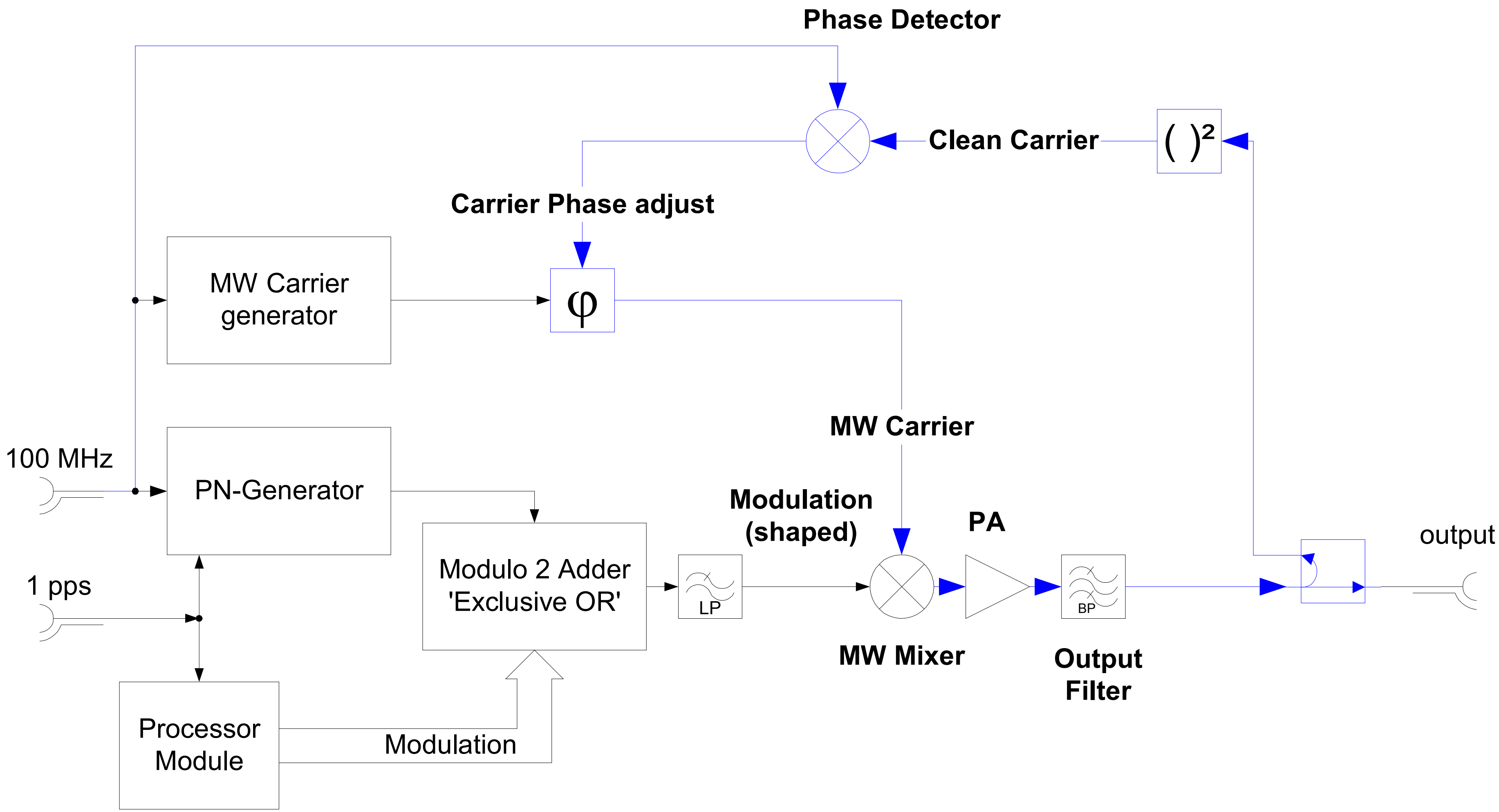


Ku-Band, Up-link
Power Tx: 2 W
Carrier: 13.475 GHz
PN-Code: 100 MChip/s
1pps: 1 time marker /s
S/C: 4 Receiver Channels
Ku-Band, Down-link
Power Tx: 0.5 W
Carrier: 14.70333 GHz
PN-Code: 100 MChip/s
1pps: 1 time marker /s
Data: 2.5 kBit/s
S-Band, Down-link
Power Tx: 0.5 W
Carrier: 2248 MHz
PN-Code: 1 MChip/s
1pps: 1 time marker /s
Data: 2.5 kBit/s

19.Real-Time Tranponder & G/S Delay Monitoring

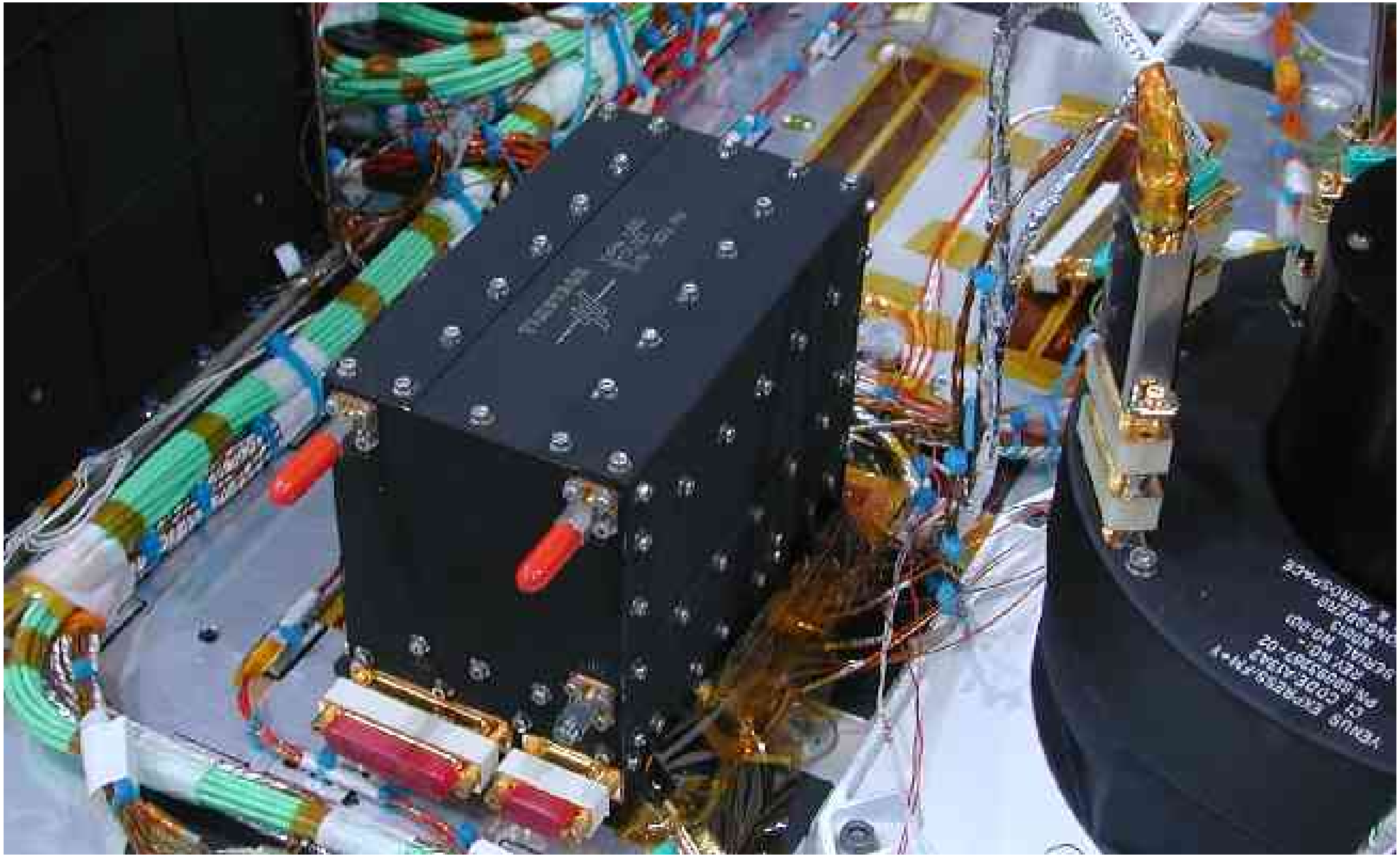


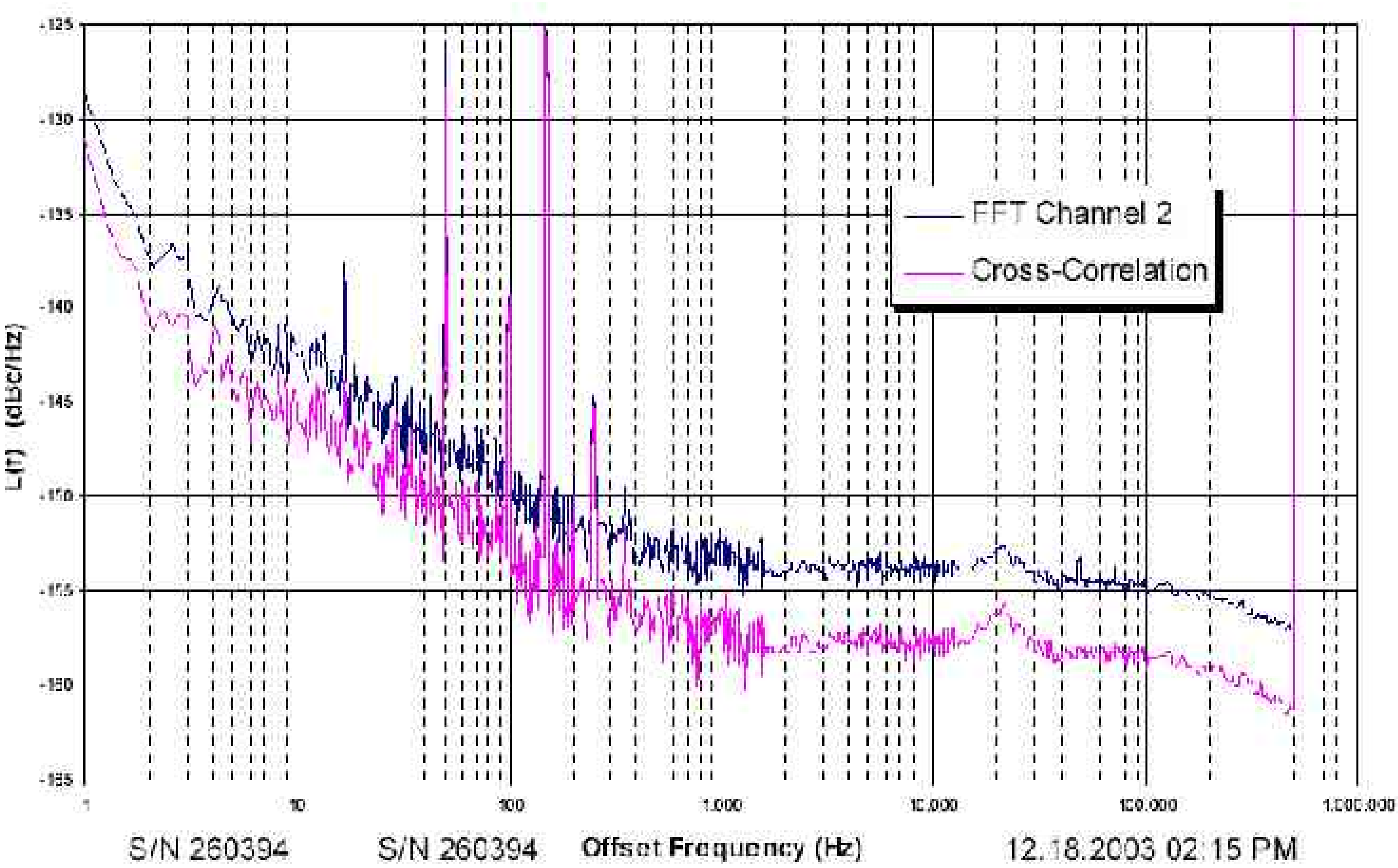
20.Coherent Signal Generation, PN & Data Modulation, Phase Stabilisation



◄──── 200 MHz ────►

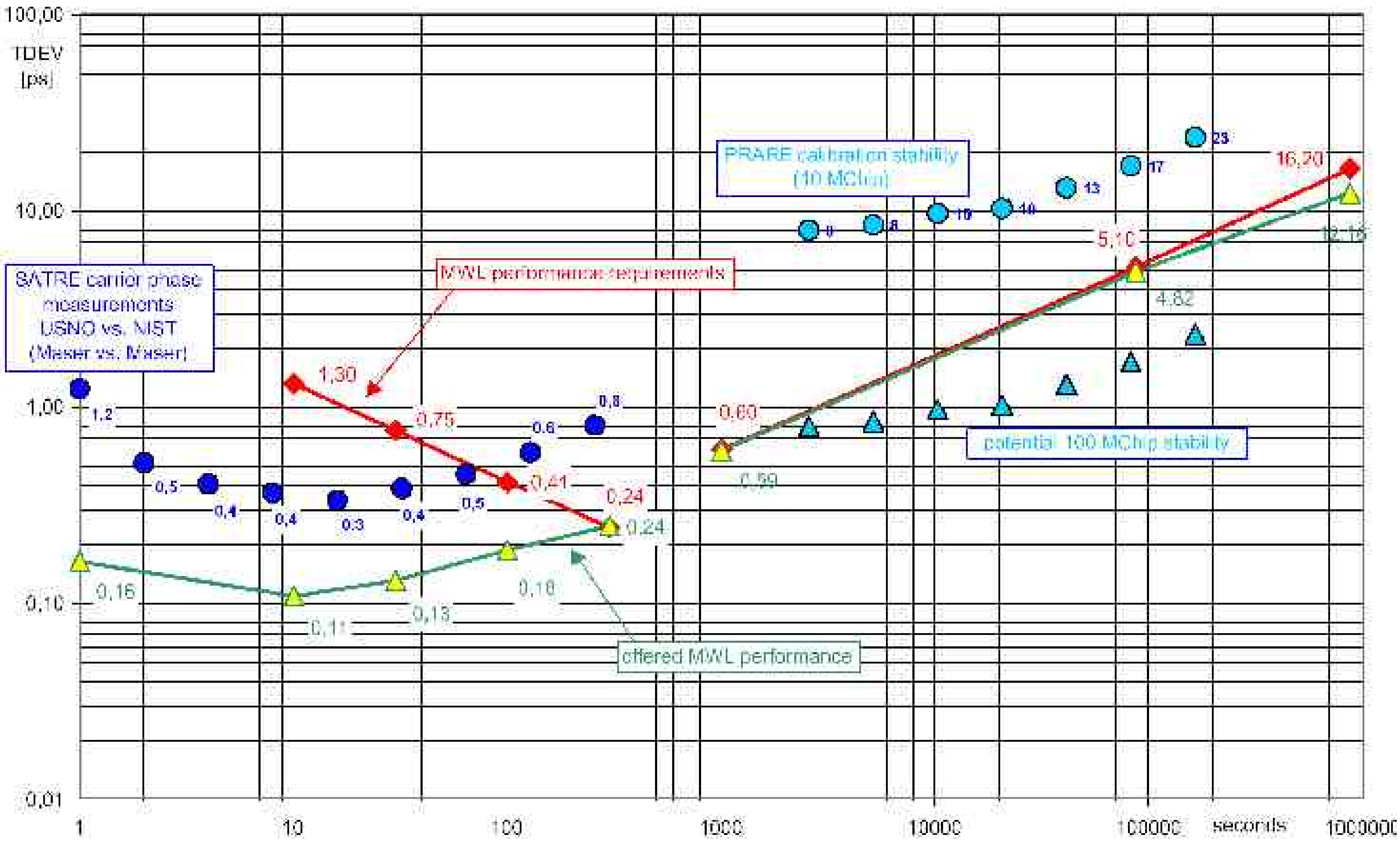
21.On-Board Ultra Stable Oscillators for one-way ranging




-125
-130
-135
-140
-145
-150
-155
-160
-165
L(f) (dBc/Hz)
1
10
100
1,000
10,000
100,000
1,000,000
FFT Channel 2
Cross-Correlation
S/N 260394
S/N 260394
Offset Frequency (Hz)
12.18.2003 02:15 PM

22.Performance Perspective (TDEV [ps])

Advanced Ranging and Time & Frequency Transfer Techniques



23.Conclusions

- Use Coherent PN-Coded RF Signals, rather than ranging tones
- Use **highest possible** Chip Rate (up to 100 MChip/s): -> Precision & Accuracy
- Perform code- and carrier phase measurements (group vs phase delay)
- Add (real-time) delay monitoring to G/S and S/C, correlate with temperature
- Perform TT&C & Ranging (round-trip) and Time-Transfer (two-way) **simultaneously**
- Multi-Path is deemed the most significant error source within G/S and S/C
- PN-coded signals suppress multi-path, carriers / tones DO NOT
    - Signal suppression is for distances beyond chip-length **(100 MChip/s: > 3m)**
    - Signal suppression is equally well for code-phase and for the carrier signal
- **Good RF links outperform the best clocks presently available**