The European ΔDOR System

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Outline

1. **Principles of ΔDOR measurement**
2. **European ΔDOR S/W Correlator:**
   - History
   - S/W Modules: Translator and Correlator
   - Translator Module
     - Cross-agency Operability
   - Correlator Module:
     - S/C and Quasar data processing
     - Wideband capability
     - Low-SNR capability
3. **Performances**
4. **Conclusions**

1. Principles of ΔDOR (1)
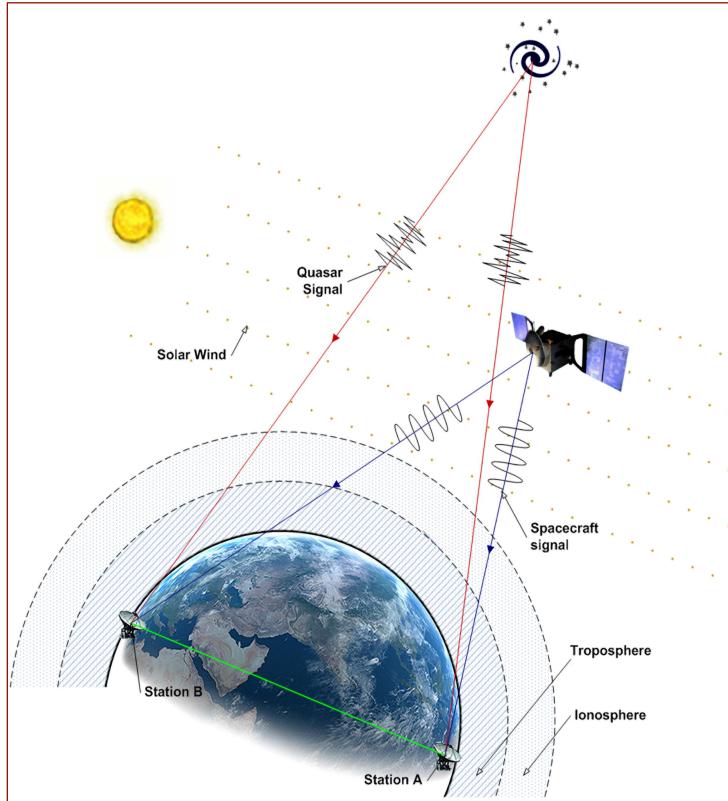
ΔDOR stands for **Delta-Differential One Way Ranging**

DOR is the measure of the differential phase delay of a spacecraft (S/C) signal, recorded simultaneously at two geographically separated ground stations.

The signal arrival time between two stations.

$$\tau = \frac{1}{c} B \cdot \hat{s} = \frac{1}{c} B \cos\vartheta$$

The measurement is affected by errors that prevent its use for navigation (synchronization between station clocks)

$$\boxed{\Delta DOR = DOR_{SC} - DOR_{QS}}$$ Calibrated observable

Differential one way range
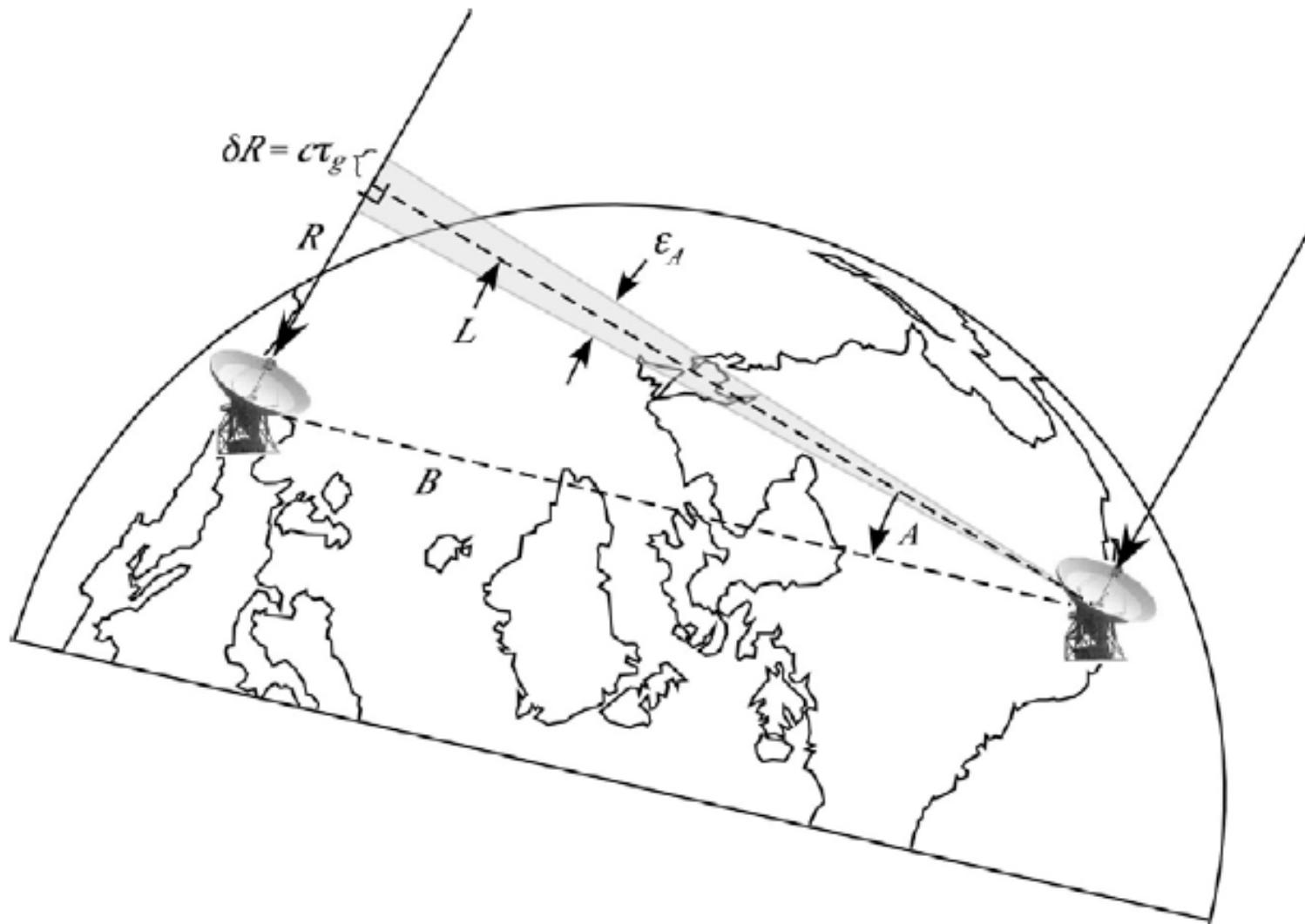
δR. Differential one way range; A: angle between B and L

ΔDOR measurement (1)

The differential one way range provides information about the angular location of a target spacecraft

Errors:
- Clock offset
- Instrumental group delay
- Media effects

Calibrate the measurement ⟶ DOR of a reference source whose direction is well known, typically a quasar whose position is well known and catalogued

ΔDOR measurement (2)

Acquisition sequence

- – Pointing to a target spacecraft
- – Antennas quickly move to the quasar
- – Antennas are returned to the target spacecraft

DOR results are differenced ⟶ most of the errors are cancelled ⟶ accurate technique for *orbit determination*

ESA resources for ∆DOR support

- Two Ground Stations to form a "baseline"
- DDOR compatible IFMS and ESU at each GS
- GS Data Retrieval S/W
- Correlator Machines
- FD Group to produce "models"
- Quasar catalogue
- A Flying S/C
- DDOR S/W Correlator
- A trained S/W Correlator operator

ΔDOR S/W Correlator Interfaces
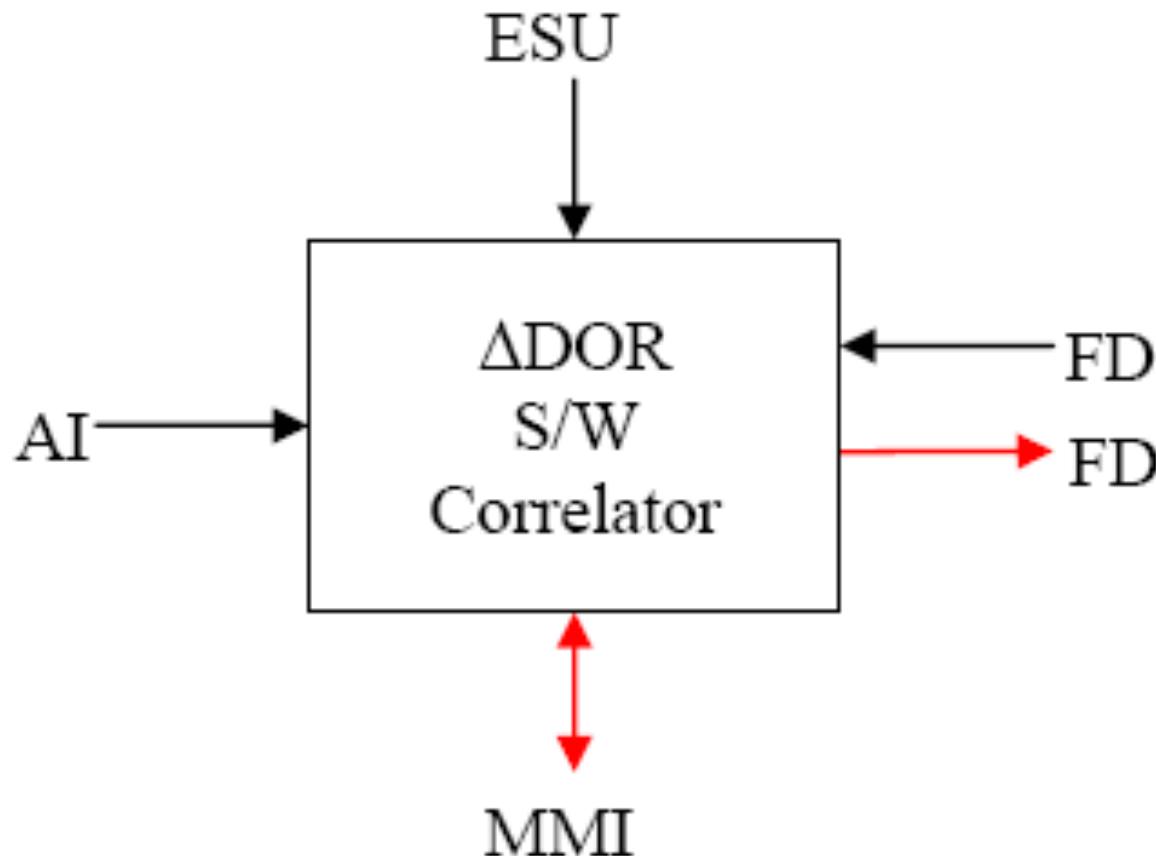
# 1. Principles of ΔDOR (2)

Observation Sequence: Quasar - S/C - Quasar (or S-Q-S)
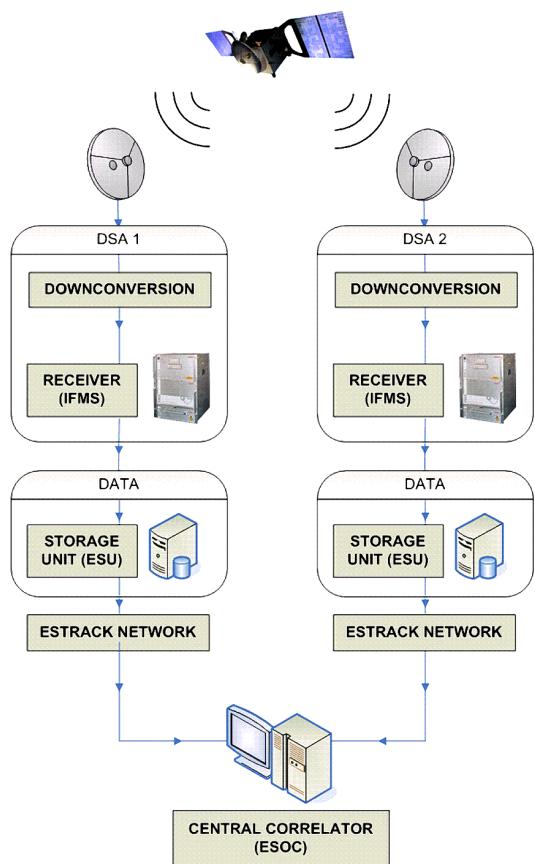
S/C Signal: Telemetry Harmonics or DOR tone

Quasar signal: White noise embedded in the receiver noise

DOR tone or TM Harm

DOR tone or TM Harm

Carrier

DOR tone or TM Harm

DOR tone or TM Harm

50kHz   50kHz   50kHz   50kHz   50kHz

2MHz   2MHz   2MHz   2MHz   2MHz

Total Spanned Bandwidth
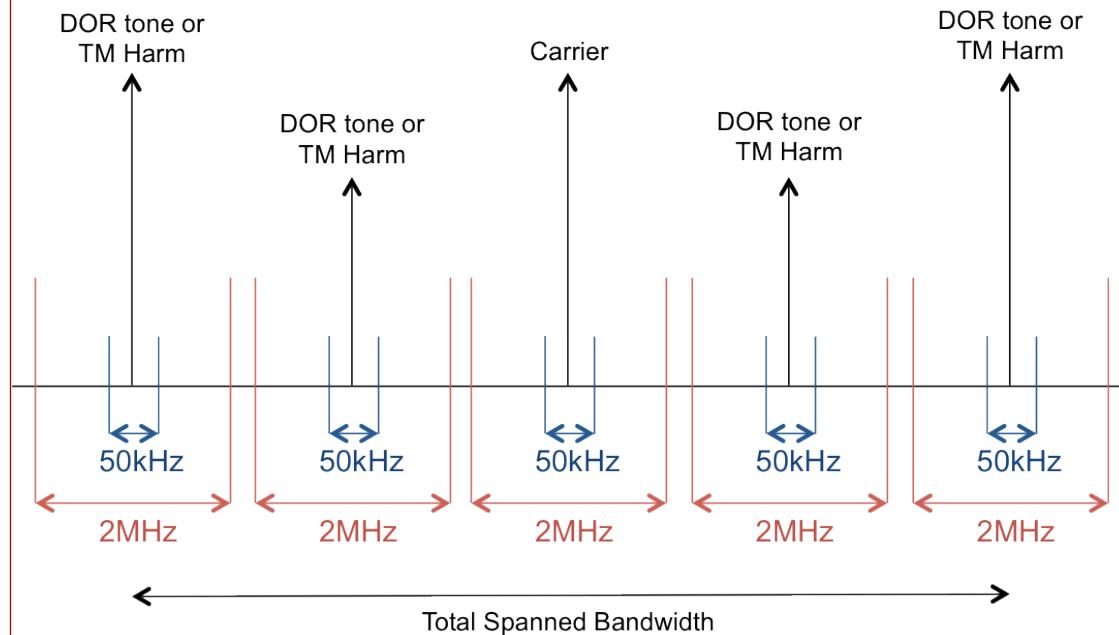
2.1 European ΔDOR S/W Correlator: History

- ## 2005/2006 Correlator development

  - Test with Rosetta S/C (2005)

  - Operational with Venus Express Orbit insertion (2006)

- ## 2007/2008 Translator development

  - ESA-NASA operability with Phoenix S/C (2008)

- ## 2010/2012 ΔDOR enhancement

  - ESA-NASA wideband acquisition of Juno S/C (2012)

2.2 ΔDOR S/W Correlator: Translator and Correlator Modules

Raw data format

- JPL - VSR
- ESA - IFMS
- VLBI – Mark V

ΔDOR S/W Translator Module

Output data format RDEF

ΔDOR S/W Correlator Module

Flight Dynamics Group

Dynamic model

ΔDOR observable
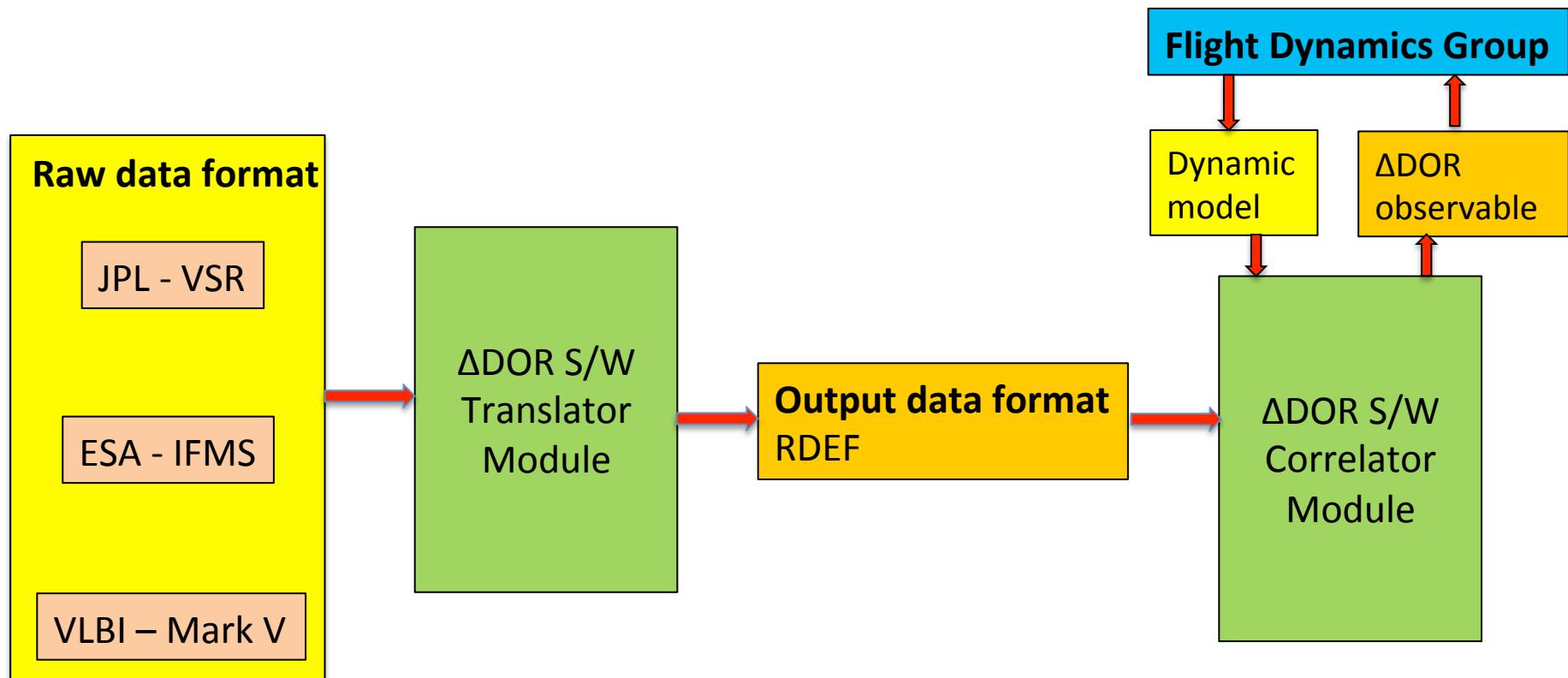
2.3 Translator module: Cross-Agency operability

$$\sigma_\vartheta = \frac{c}{\boxed{B}\cos\vartheta}\sigma_\tau$$

- **Baseline length**

- **Ortogonality**

Consultative Committee for Space Data Systems (CCSDS) establishes a
Raw Data Exchange Format (RDEF)

FD – Dynamic model for S/C

FD model for the spacecraft signal correlation:

$$S_N = e^{i\left[2\pi\left(f_t - f_{loN}\right)t - k\rho_N\left(t\right) + \phi_0\right]}$$

where:

- f_l is the transmitted frequency

- f_{loN} is the local oscillator frequency

- Φ_0 is the initial phase on board

- $\rho_N(t)$ is the range provided by FD for the station L at time t

$$\rho_N = \int_{t_0}^{t} \dot{\rho}(t)\,dt$$

FD – Dynamic model for EGRS

FD model for EGRS signal correlation - differential one way range:

$$\tau = \frac{r_{12}}{c} + RLT_{12} - (ET - ST)_{t_2} + (ET - ST)_{t_1} + \tau_{T_2} - \tau_{T_1}$$

where:

- r_{12} is the (Newtonian) distance that the quasar wave front travels from station 1 to station 2

- RLT_{12} the relativistic light-time delay

- $(ET-ST)_{t1}$ is the difference between ephemeris time and station time at time t1 at station 1

- T_{T1} is the delay due to the troposphere at station 1.

2.4 Correlator module: S/C and Quasar data processing

Spacecraft correlation

- Frequency estimation of the strongest channel (Highest SNR), generally the carrier. Comparison between PLL reconstructed phases and model provided by Flight Dynamic (FD) Group

- Reconstruction of the signal/tones of all channels (filtering). Heterodyne integrator driven by frequency prediction (FD+estimated freq.)

- Phasor stopping. Multiplication of the extracted phasor by a counterotating phasor (FD model + est. frequency)

- Correlation, channel by channel, of the phasors of station A and B to compute a phase delay.

- Ambiguity resolution to find SC DOR. Linear fit of all the phases

Quasar correlation

- The data stream from each station is, channel by channel, delay- and Doppler-compensated (fringe rotation) using the model provided by FD.

- Correlation of data streams of station A and B, channel by channel, for a range of delays (few μs) across zero

- Bandwidth synthesis of the correlation function, leading to phase delay (Quasar DOR $\tau_{Q)}$ and delay rate.

2.5 Correlator module: wideband capability

$$\sigma_\tau = \frac{1}{2\pi\Delta f}\sqrt{\frac{2}{P/N_0 \cdot T_{OBS}}}$$

Increasing the spanned bandwidth (the distance between the external channels) is a powerful method to improve the measurement accuracy (both S/C and Quasar)

Standard configuration

8.4-8.5 GHz

X-band/Ka-band D/C

540-640 MHz

L-band DC

55-85 MHz

Intermediate Frequency Modem System (IFMS)

MAX 28MHz

f

Wideband configuration

X-band/Ka-band D/C

LDC   LDC

IFMS   IFMS

28MHz   **28MHz**

f
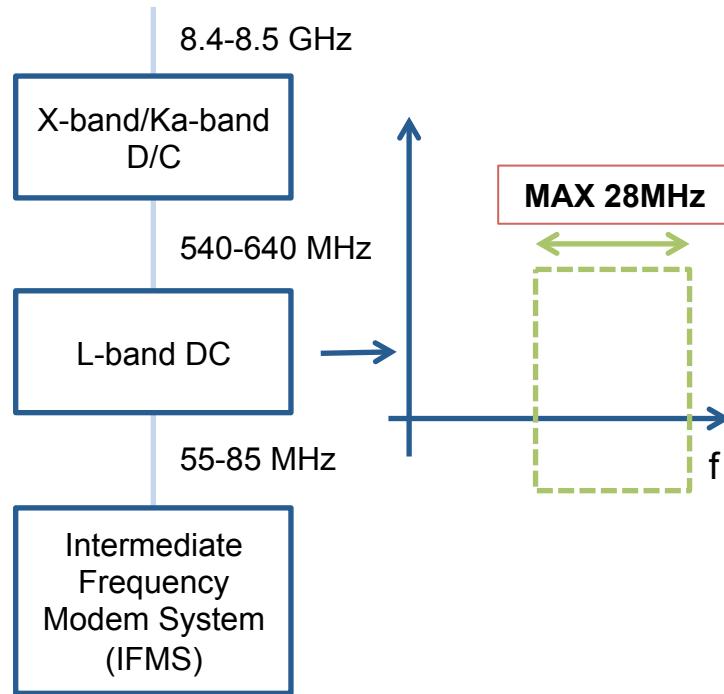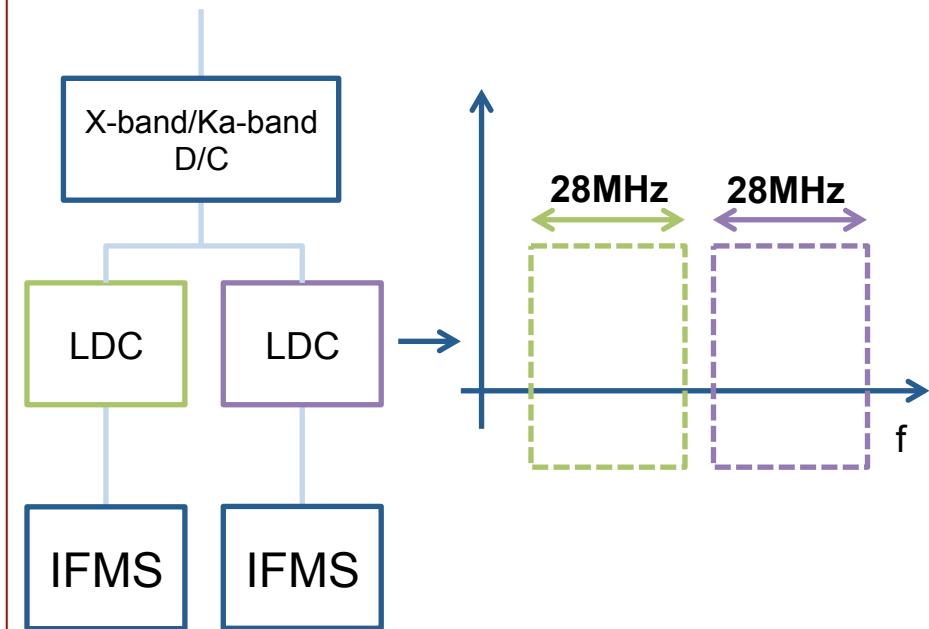
2.5 Correlator module: wideband capability

Recorded signal:

$$\Phi^{i^{S,Q}}_{sig_{A,B}} = \boxed{\Phi^{i^{S,Q}}_{0_{A,B}}} + \boxed{2\pi \cdot f^i_{lo}(t - t_0)^{S,Q}_{A,B}} + \boxed{\Phi^i_{CLK}} + \boxed{\Phi^{i^{S,Q}}_{\tau}}$$

Known
Unknown
SC Unknown/QS Known

Correlation:

$$\Delta\Phi^{i^S} = \Delta\Phi^{i^S}_0 + \Phi^i_{CLK} + \Delta\Phi^{i^S}_\tau$$

$$\Delta\Phi^{i^Q} = \Delta\Phi^{i^Q}_0 + \Phi^i_{CLK}$$
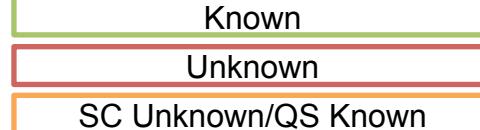
Standard configuration (Single LDC)

$$\Delta\Phi^{i^S}_0 \neq \Delta\Phi^{i^Q}_0$$

$$\Delta\Phi^{1^{S,Q}}_0 = \Delta\Phi^{2^{S,Q}}_0 = ... = \Delta\Phi^{n^{S,Q}}_0$$

Standard Algorithm

$$\Delta\Phi^{i^Q} = \Delta\Phi^{i^Q}_0 + \Phi^i_{CLK} \rightarrow \Phi^i_{CLK}$$

Linear fit of $\Delta\Phi^{i^S} = \Delta\Phi^{i^S}_0 + \Delta\Phi^i_\tau$

Wideband configuration (Multiple LDCs)

$$\Delta\Phi^{i^S}_0 = \Delta\Phi^{i^Q}_0$$

$$\Delta\Phi^{1^{S,Q}}_0 \neq \Delta\Phi^{2^{S,Q}}_0 \neq ... \neq \Delta\Phi^{n^{S,Q}}_0$$

Phase subtraction Algorithm

$$\Delta\Phi^{i^S} - \Delta\Phi^{i^Q} = \Delta\Phi^i_\tau$$

Linear fit of $\Delta\Phi^i_\tau$

2.5 Correlator module: wideband capability – VEX test

Test: Venus Express (VEX) acquisition on Aug 1° 2012

Carrier
2nd harm
-14th harm
20th harm

LDC2 · · · · · · LDC3

IFMS2 (NB CONF) · · · · IFMS3 (WB CONF)
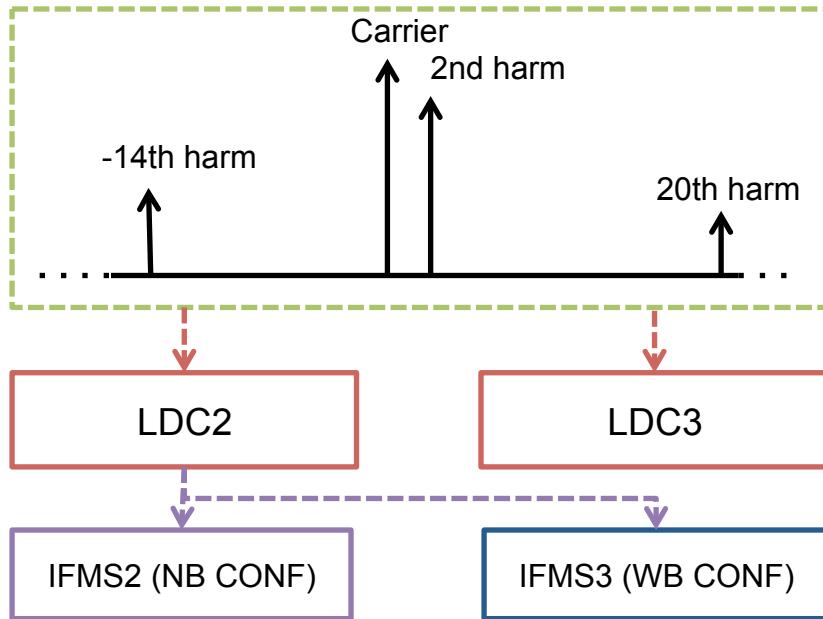
**IFMS2**- Narrow band configuration
    All four channels from LDC2

IFMS3- Wideband configuration
   3 channels from LDC3 (Carrier, 20° harm and -14° harm)
    1 channel from LDC2 (2° harm)

	DDOR (ns)	Sigma (ns)
IFMS2 Std corr.	1.05	0.52
IFMS3 WB corr.	0.45	0.5
IFMS3 (3ch) Std corr.	0.55	0.54
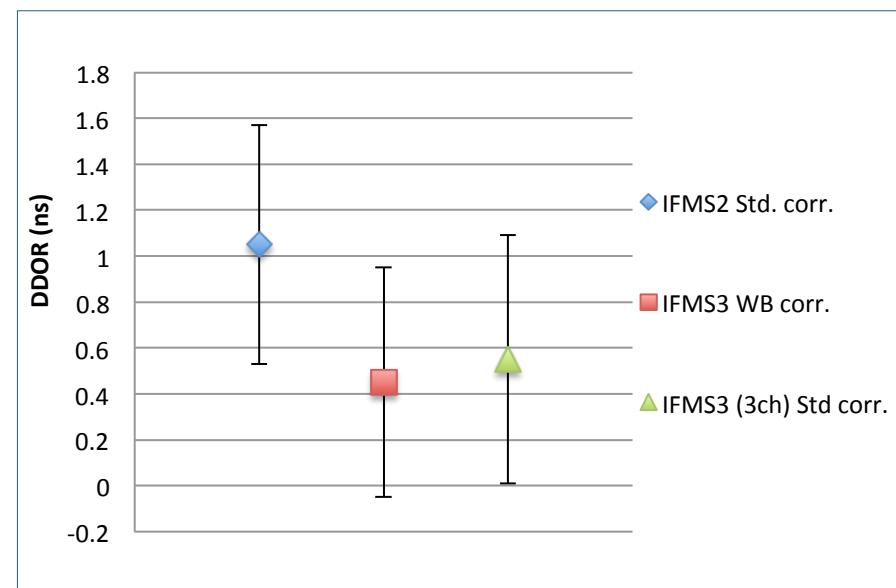
2.5 Correlator module: wideband capability – JUNO ESA-NASA acquisition

Test: JUNO ESA-NASA acquisition on Sep 23rd 2012

Carrier

19 MHz tone

3rd tel. harm

38 MHz tone

. . . .

LDC1

Carrier
3° Telemetry
harmonic
19 MHz Tone

LDC1

38 MHz Tone
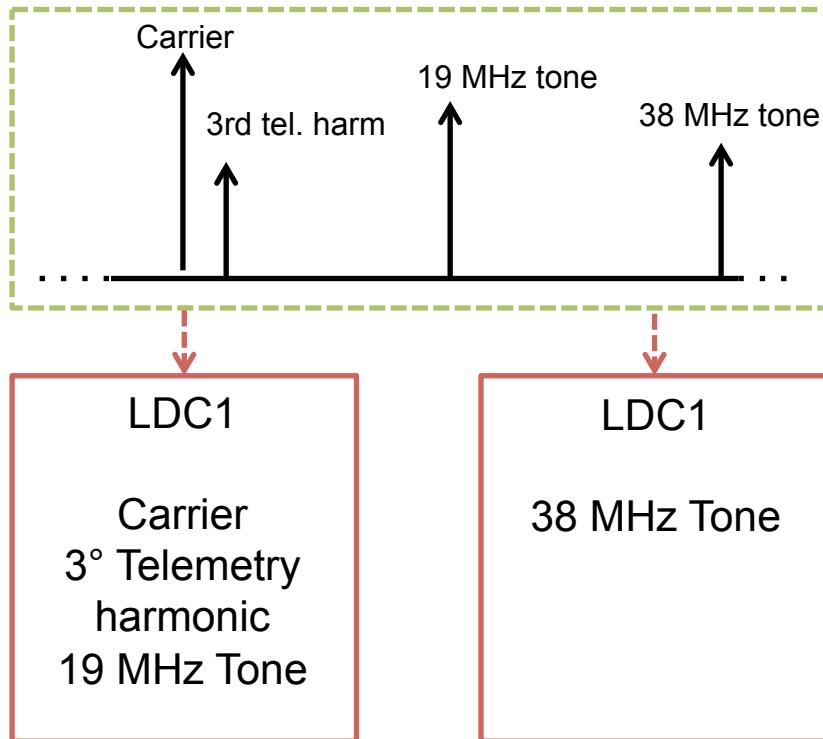
	DDOR (ns)	Sigma (ns)
1° Acquisition	1.1	0.009
2° Acquisition	1.043	0.009

First real ESA wideband acquisition. Successful exchange of RDEF data between agencies.

2.5 Correlator module: low-SNR capability

Standard algorithm (PLL)

PLL and Ft estimation (FD comparison) — Ch 1

FD

Ft (ch=1)
Ft (ch=2)
Ft (ch=3)
Ft (ch=4)

PLL slave — Ch 1, Ch 2, Ch 3, Ch 4

Rec.Sig
Rec.Sig
Rec.Sig
Rec.Sig

FD
FD
FD
FD

Phasor Stopping — Ch 1, Ch 2, Ch 3, Ch 4

Stpd phasor
Stpd phasor
Stpd phasor
Stpd phasor

FD
FD
FD
FD
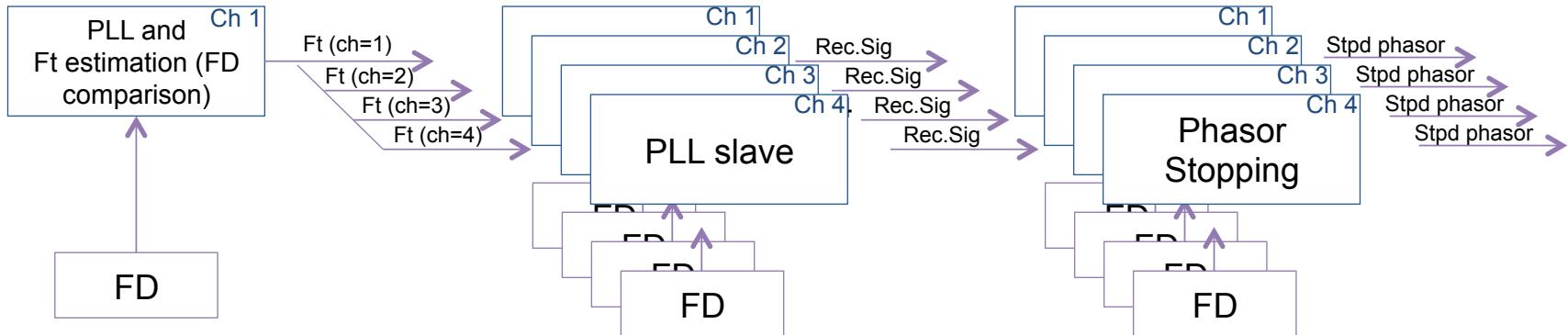
Low-SNR Algorithm (PLL free)

Recorded signal:

$$\Phi^{SC} = \omega_c t - \frac{\omega_c}{c}\rho - \omega_{LO}t + \Phi_0$$

$$\rho = c_0 + c_1 t + c_2 t^2$$

Stopping:

$$\Phi^{SC} = (\omega_c - \tilde{\omega}_c)t - \frac{\omega_c - \tilde{\omega}_c}{c}(c_1 t + c_2 t^2) + \hat{\Phi}_0$$

Frequency estimation:

$$\omega_{FFT} = (\omega_c - \tilde{\omega}_c) - \frac{\omega_c - \tilde{\omega}_c}{c}c_1 \approx \omega_c - \tilde{\omega}_c$$

Stopping and Ft estimation (FFT) — Ch 1

FD

Ft (ch=1)
Ft (ch=2)
Ft (ch=3)
Ft (ch=4)

Stopping and Filtering (FFT) — Ch 1, Ch 2, Ch 3, Ch 4

Stpd phasor

FD
FD
FD
FD
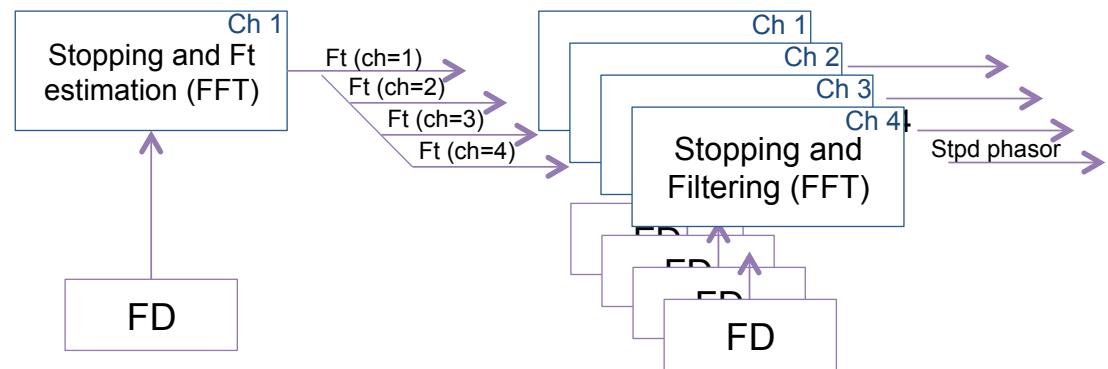
2.5 Correlator module: low-SNR capability

Test: Montecarlo Simulations

Carrier @ 30dBHz
Subcarrier @ 20dBHz
2 external harmonics @ **5 dBHz**

30dBHz
20dBHz
5dbHz
5dbHz
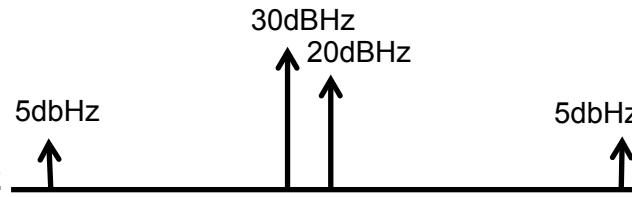
Carrier @ 30dBHz
Subcarrier @ 20dBHz
2 external harmonics @ **3 dBHz**

30dBHz
20dBHz
3dbHz
3dbHz
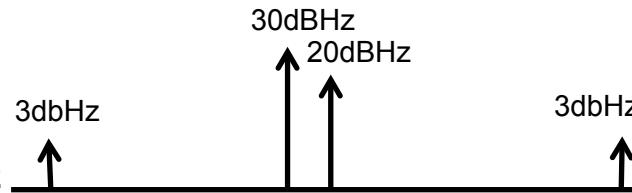
$$\sigma_\tau = \frac{1}{2\pi\Delta f} \sqrt{\frac{2}{P/N_0 \cdot T_{OBS}}}$$

	Number of points	Th. sigma (ns)	Th. 3-sigma (ns)	Computed Sigma (ns)
5dBHz	80	3,16	9,48	**6,74**
3dBHz	132	3,99	11,97	**9,3**
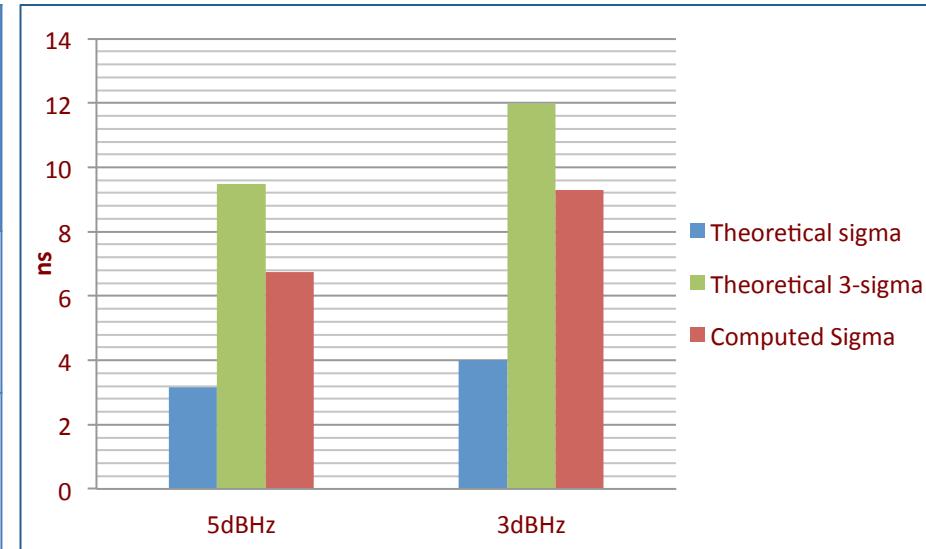
3. Performance: VEX Orbit Insertion (2006)

VENUS EXPRESS DELTA-DOR RESIDUALS
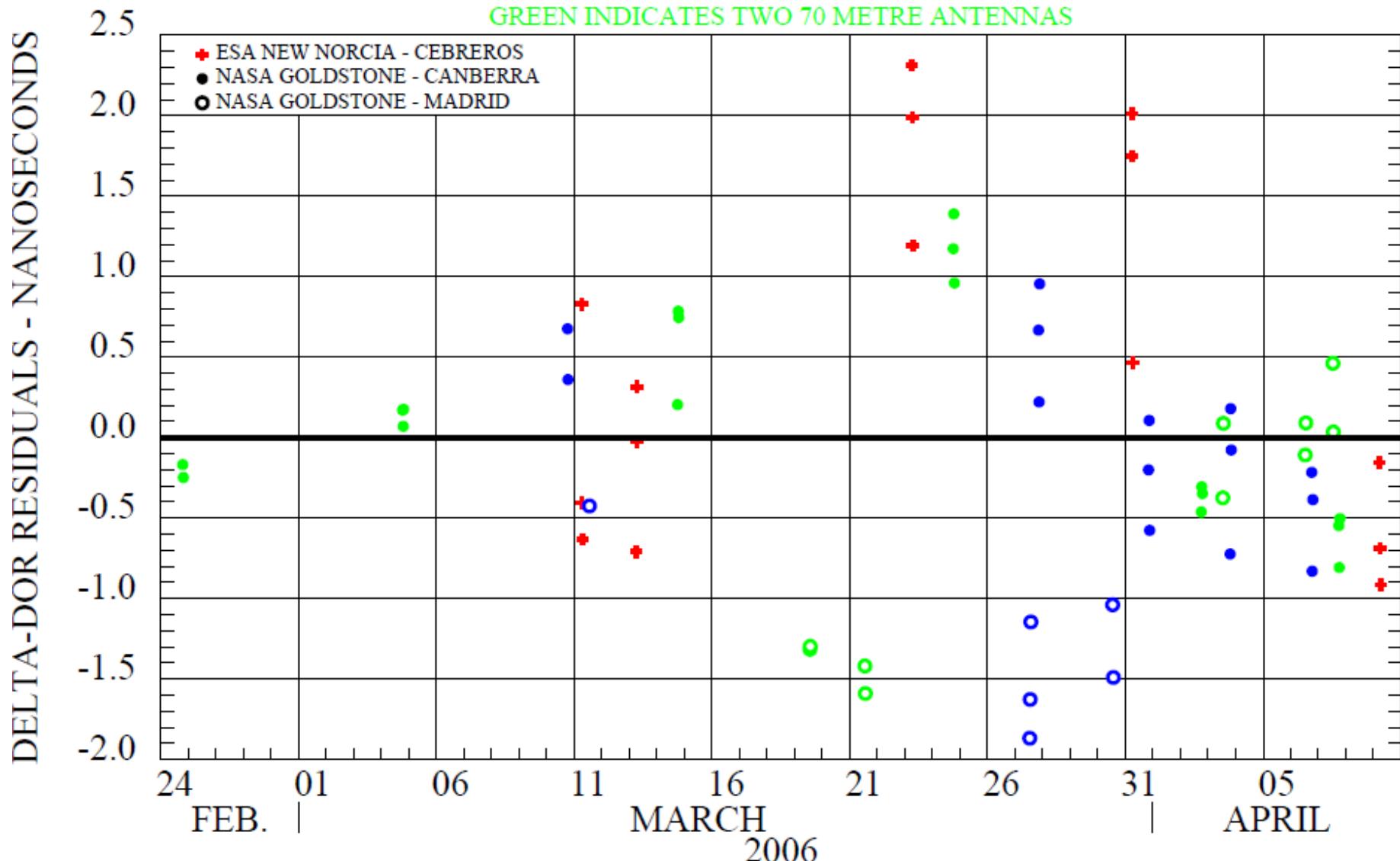
postfit.boa (show: cut this session)
N=90 M=1.37505e-12 RMS=5.05364e-11 SD=5.05177e-11 Min=-2.5298e-10 Max=1.99529e-10
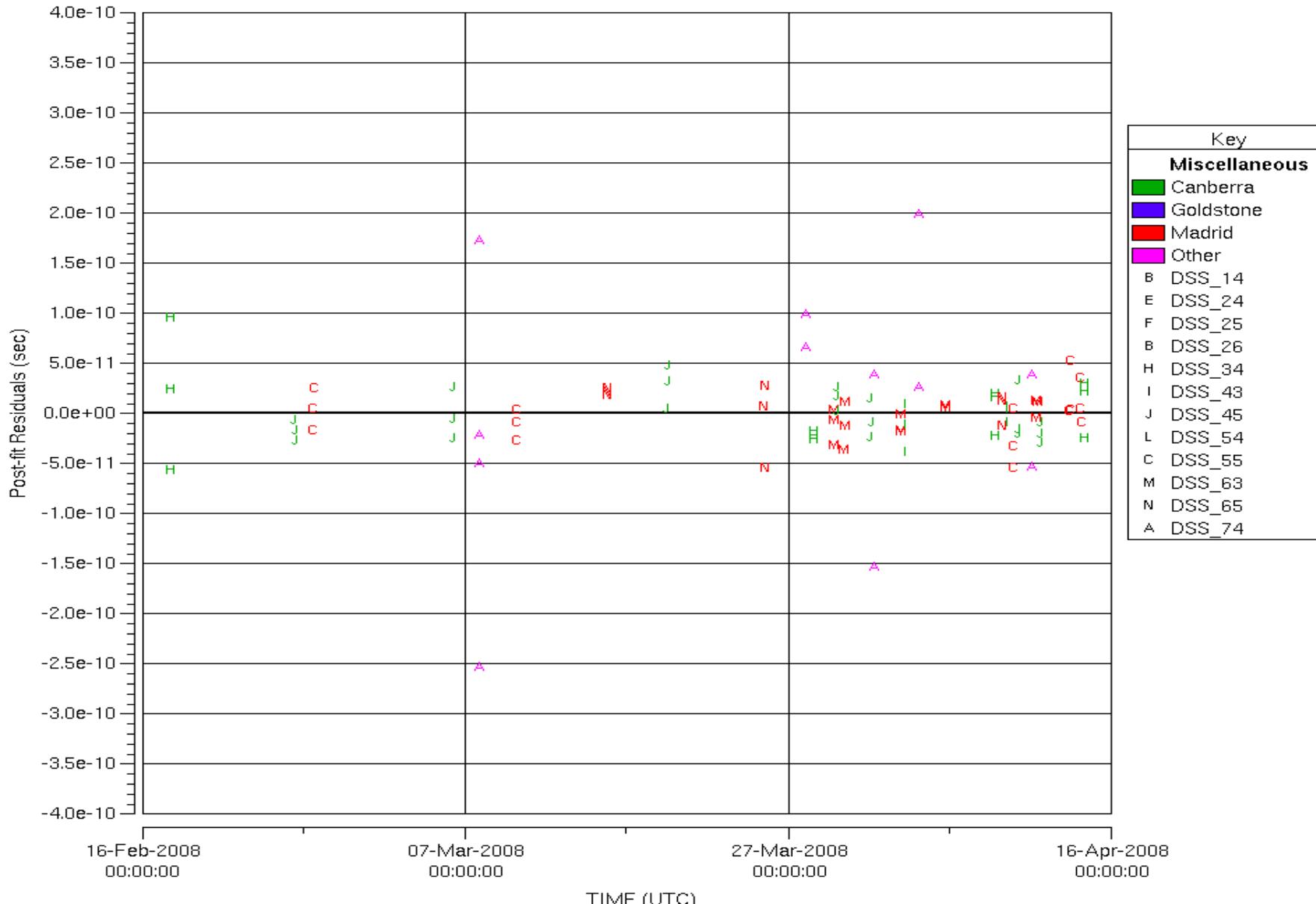
4. Conclusions

- ESA S/W ΔDOR Correlator meets the CCSDS recommendations
- ESA S/W ΔDOR Correlator is able to correlate data acquired at ESA deep space ground stations in wideband configuration, increasing remarkably the measurement accuracy (as proved in the Juno test).
- ESA ΔDOR SW Correlator can correlate data at very low SNR (ESA requirements: up to 13dbHz/1dBHz, but the capability allows to correlate data up to few dBHz)
- The ESA-NASA JUNO test demonstrated the full integration of ESA ΔDOR system in a cross-agency operability scenario.