ACES WORKSHOP 2022

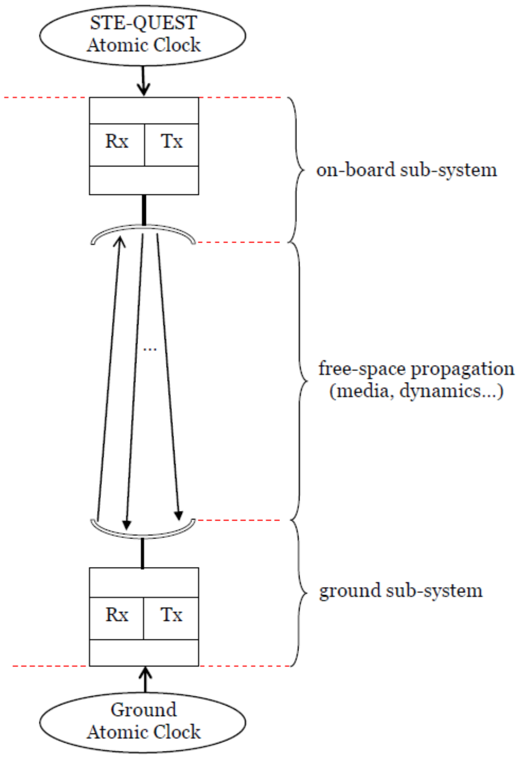
HIGH PERFORMANCE TIME & FREQUENCY LINK - MICROWAVE (HERO)

20/10/2022

Date: 27/10/2022
Ref:
Template: 83230347-DOC-TAS-EN-007

INTRODUCTION

- HERO is an ESA project with the aim to develop at Breadboard-level an upgraded version of the ACES microwave link (MWL) and it was originally designed for the STE-QUEST mission.
  - STE-QUEST goals included the measurement of gravitational red-shift by remote comparison of state-of-the-art atomic clocks located on a spacecraft and on ground.
  - This remote comparison is performed through the transfer of highly stable and accurate time and frequency signals in both the optical and microwave domain.
- The MWL architecture is based on a asynchronous (non-coherent) 2-way links including:
  - 4 single-frequency (K-Band) uplinks from 4 geographically distributed ground terminals, sharing the same frequency band using CDMA signals for both multiple access and time and frequency transfer.
  - 1 dual-frequency (X- and K-Band) downlink with full earth coverage, with CDMA signals for time and frequency transfer.
- STE-QUEST / HERO MWL requires more stringent performance w.r.t. ACES leading to the following driving design requirements:
  - Use of higher signal frequencies (from Ku-Band to K-Band)
  - Use of higher chip rates (from 100 Mcps to >200 Mcps)
  - Transceiver fully digital implementation



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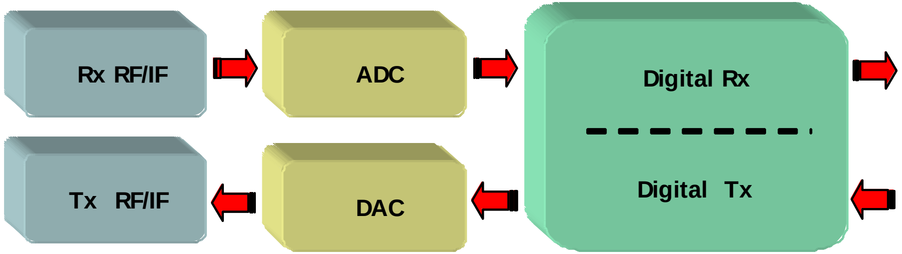
BACKGROUND & PRODUCT PLATFORM

/// **Software-defined radio** architecture offers large flexibility enabling full on-board configurability in view Deep Space mission requirements.

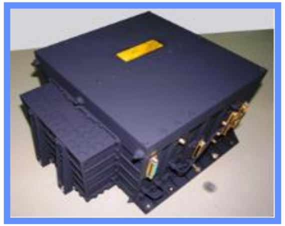


/// Convergence to **digital platform** based on the **System-on-Chip** involves all TAS-I Radio-communication product lines:

Spread-Spectrum TT&C

Deep Space TT&C

Radio Science

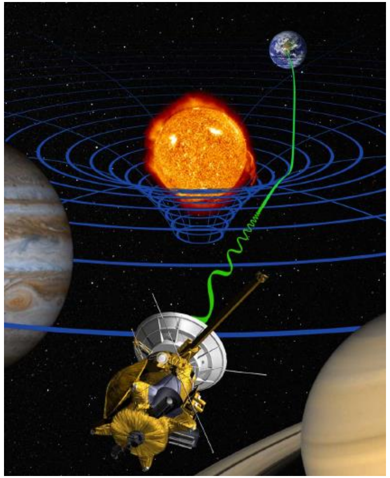


Communication P/L

IN-FLIGHT STATE-OF-ART (1)

/// Radio-science Transponder

- Ka-Band Translator and Transponder (KaT) support fundamental physics experiments in the following fields:
  - Celestial mechanics
  - Planetary geodesy
  - Relativistic gravity
- KaT enables accurate range (< 10 cm) and range rate (<0.1 μm/s) measurement allowing extremely accurate deflection of the radio signal due to relativistic effect.



- Turn-around ratio = 3360/3599
- Doppler shift = >± 4 MHz
- Receiver Threshold:
  - -135 dBm @ 1.2 kHz/s
  - -140 dBm @ 100 Hz/s
- Output Power: >34 dBm
- Power Consumption: ≤ 45 W
- Allan Deviation: < 4×10^{-16} @ 1000 sec
- Regenerative PN Ranging: up to 25 Mcps
- Self-calibration capabilities for on-board group delay: accuracy <0.1 ns

Fully Analogue KaT
Cassini

Digital platform

Ka-Band Translator
JUNO

PN Ranging &
On-board calibration

Ka-Band Transponder
MORE (BepiColombo)
3GM (JUICE)

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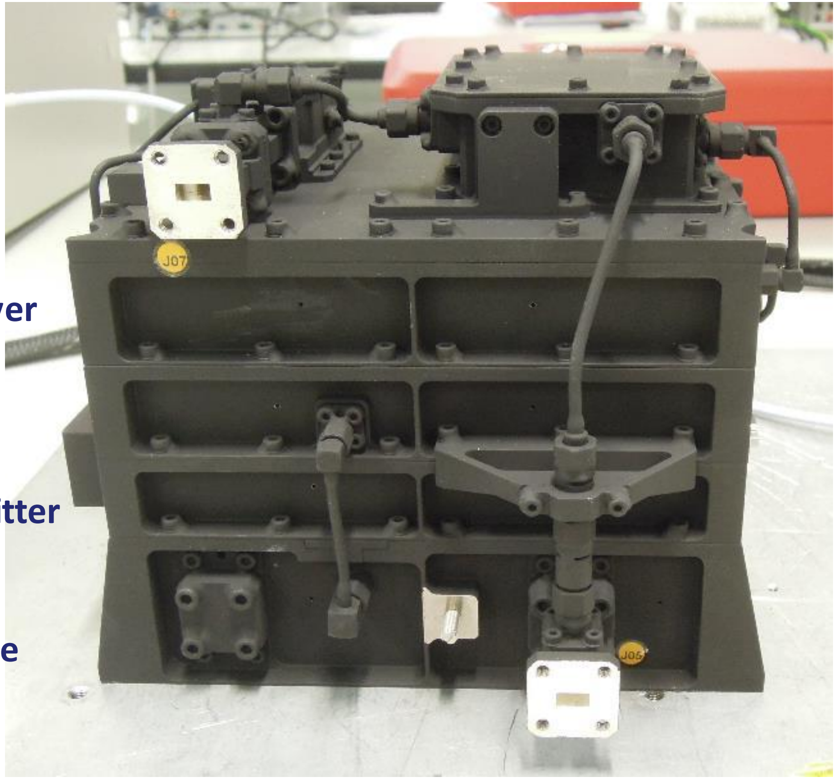
IN-FLIGHT STATE-OF-ART (2)



Receiver

Digital

Transmitter

Baseplate

- Mass: 3.4 kg
- Dimensions: 215.6 x 187.7 x 139.3 mm^3

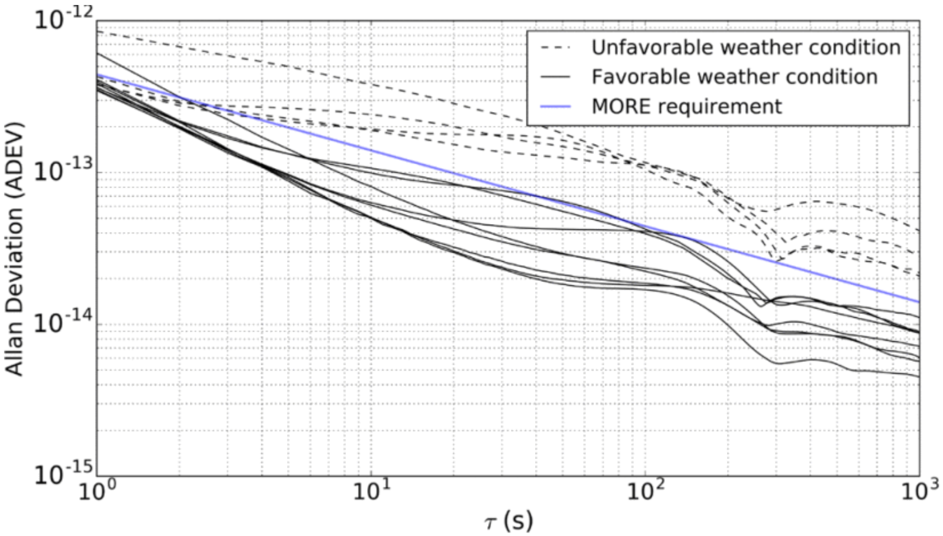
IN-FLIGHT STATE-OF-ART (3)

/// First in-orbit results

TAES-202000398 1

Report on first inflight data of BepiColombo's Mercury Orbiter Radio-science Experiment

Paolo Cappuccio, Virginia Notaro, Andrea di Ruscio, Luciano Iess, Antonio Genova, Daniele Durante, Ivan di Stefano, Sami W. Asmar, Sabatino Ciarcia and Lorenzo Simone



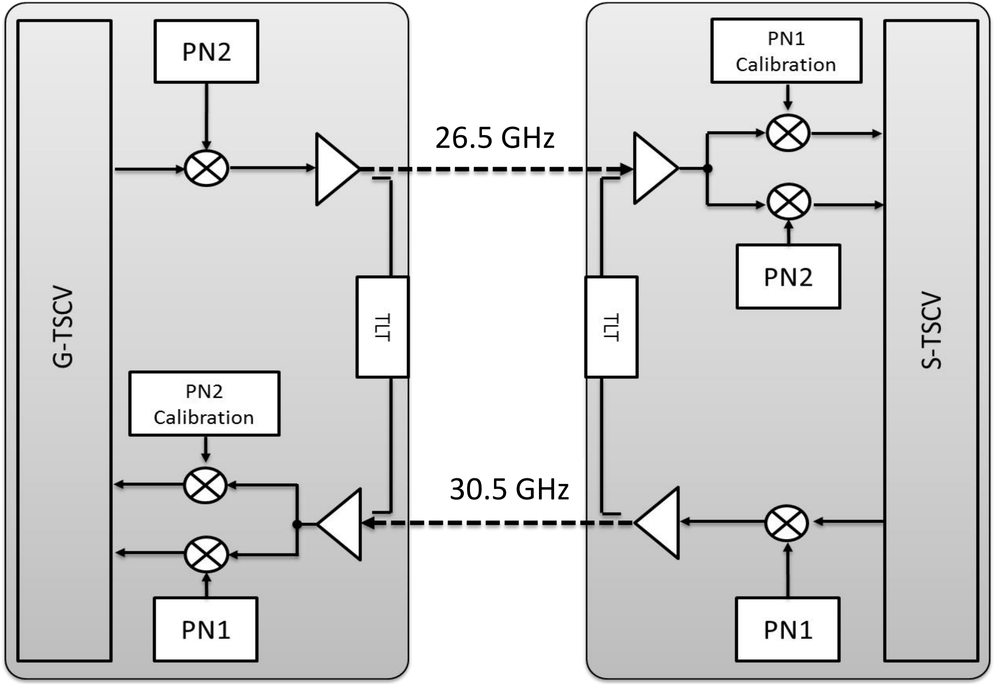
Date 2019 May	Doppler RMS (@60 s)	PN Range 24 Mcps RMS (@4 s)
2	0.048 mm/s	25.4 mm
8	0.040 mm/s	8.0 mm
14	0.006 mm/s	8.0 mm
15	0.007 mm/s	N. A.
16	0.016 mm/s	8 mm
17	0.030 mm/s	9 mm
20	0.038 mm/s	12.9 mm
21	0.008 mm/s	20.0 mm
22	0.005 mm/s	N. A.
23	0.007 mm/s	7.5 mm
24	0.014 mm/s	7.8 mm
29	0.016 mm/s	7.7 mm

HERO: OVERVIEW (1)

/// HERO Transceivers support Two-Way Satellite Time and Frequency Transfer (TWSTFT).

/// Main features

- **Spread-spectrum modulation format**
- **Earth-to-Space link = 26.5 GHz**
- **Space-to-Earth link = 30.5 GHz**
- **Chip rate = 200 Mcps**
  - Code length = 20000 chips
  - Code Period = 0.1 ms
- **Code chip rate and carrier are coherently synthesized**
- **Data Period = 0.1 ms (coherent with code epoch)**
  - The low-rate data at 10 kbps is used to solve the ambiguity due to the PN code length.
  - As the relevant data period is coherently related with the code period, it is possible to demodulate the data using directly the Code Epoch (relevant to the RX Code generator) instead of a dedicated Bit Synchronizer (DTTL, Data Transition Tracking Loop).



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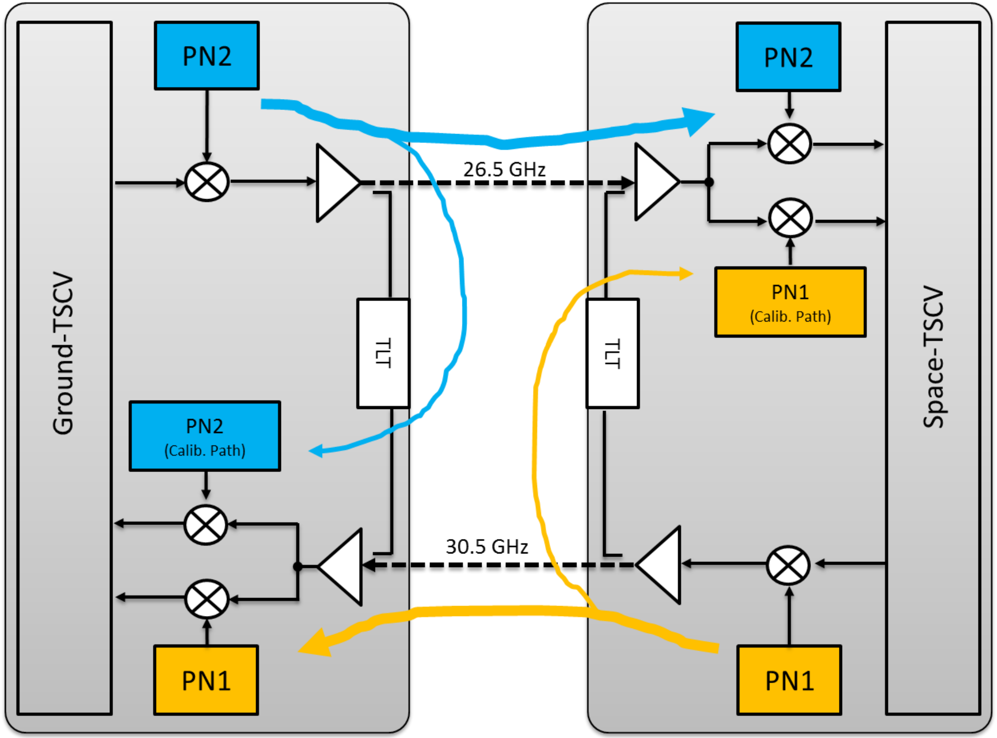
HERO: OVERVIEW (2)

/// Transceiver(s) main features, cont'd

- **Built-in Test Loop Translator (TLT) for on-board group delay calibration purpose.**
- **A digital demodulator for Calibration purpose is implemented on both Transceivers.**
  - The Calibration path on the receiver side is de-spread using the same code used in transmission that will be orthogonal with respect the useful received one.



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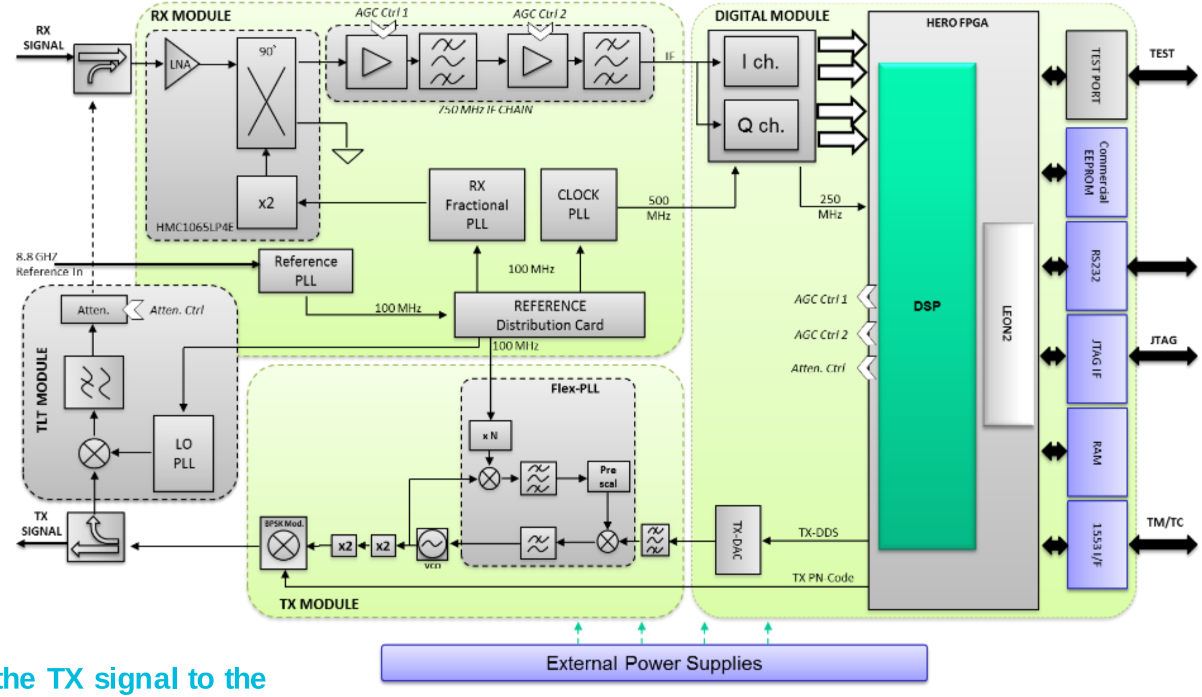
HERO: OVERVIEW (3)

/// Top-level Architecture

- The **RX module** is in charge of low-noise amplification of the incoming signal in K-band and of the frequency down-conversion at IF frequency (750 MHz).
- The **TX module** inputs are the baseband modulating code generated by the FPGA and a low-frequency Reference Tone able to steer the transmitted frequency.
- The **Digital module** represents the core of the Transceiver and is based on a System-on-chip approach: a dedicated FPGA includes the specific signal processing functions required by the Microwave Link as well as a general purpose Processor (LEON2FT) which is in charge of low-rate processing and equipment managemen.

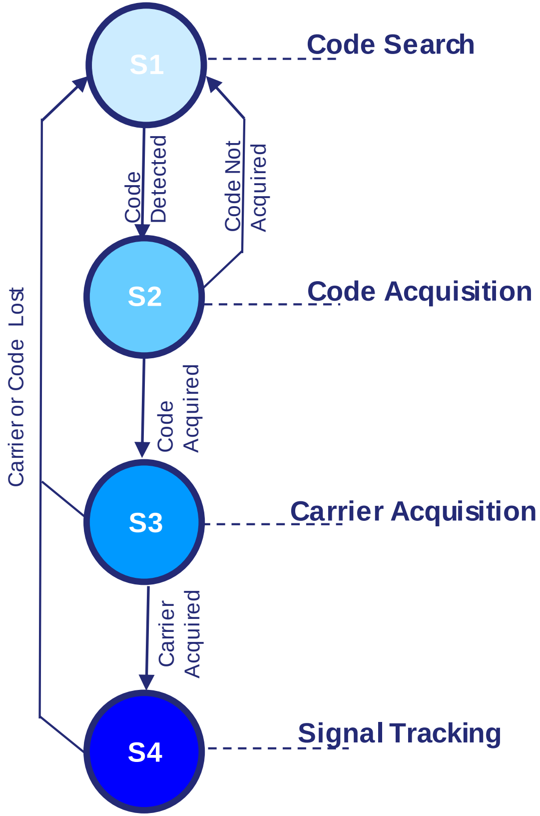


- The **TLT module** is in charge of translating the TX signal to the RX frequency for on-line calibration.

HERO: OVERVIEW (4)

/// The LEON2FT 32-bit processor implements a Software State Machine featuring:

- **S1: Code Search**
  - Sequential detection
  - Digital AGC
- **S2: Code Acquisition**
  - Non-coherent code tracking loop & lock detector
  - Digital AGC
- **S3: Carrier Acquisition**
  - Non-coherent code-tracking loop & lock detector
  - Digital AGC
  - Costas loop with *frequency* detector
  - Carrier lock
- **S4: Signal Tracking**
  - Coherent code-tracking loop & lock detector
  - Digital AGC
  - Costas loop with *phase* detector
  - Carrier lock
  - Data demodulation



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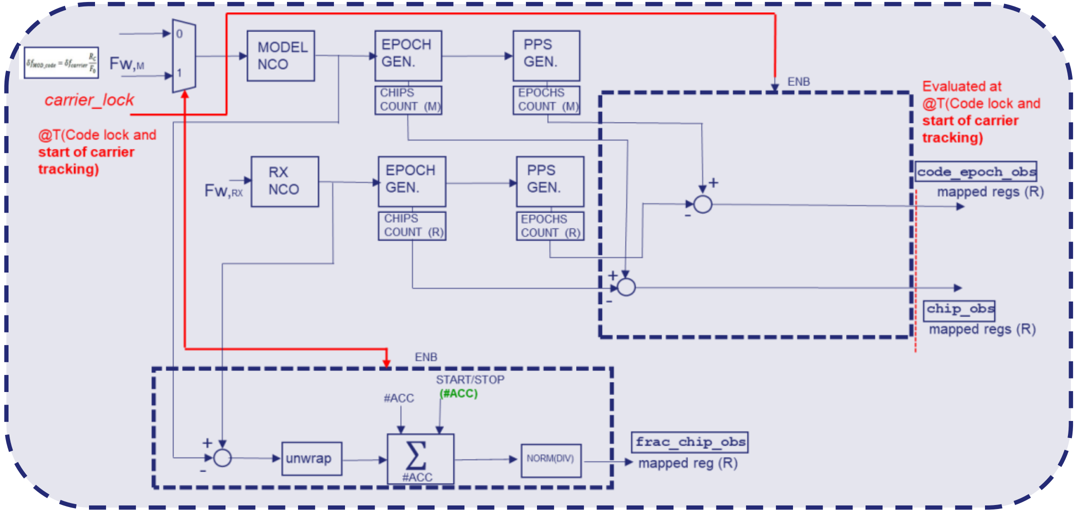
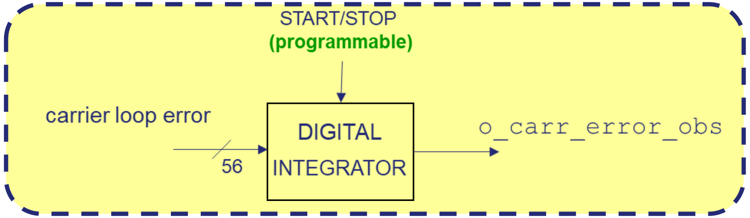
HERO: CARRIER & CODE OBSERVABLES (1)

/// **Time relationship between the "received PPS" and "local PPS" is estimated by means of Code and Carrier observables.**

- **Code Observables: provide the outstanding time interval as 1) # of epochs, 2) # of chips and 3) intra-chip offset.**
  - Doppler pre-steering performed on the Model Code allows achieving an accuracy of a few ps over 1 second integration time thus solving carrier ambiguity in K-Band (carrier period ~ 30 ps).



- **Carrier Observable: it simply integrates the carrier loop stress to estimate the phase de-tuning between the received carrier and the local carrier over 1 PPS.**
  - To ensure phase continuity (*) the carrier loop is closed at PPS event.



(*) It means that using available observables it is possible to retrieve the carrier phase evolution even in presence of a temporary tracking loss.

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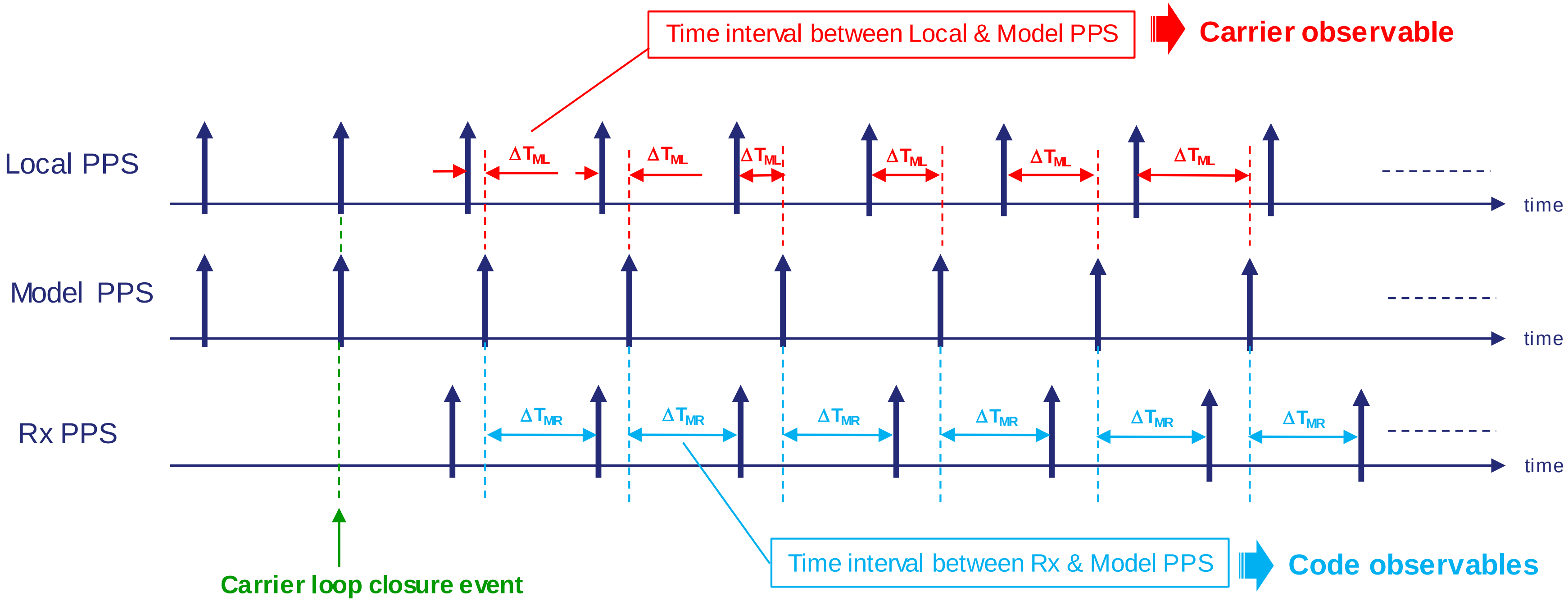
HERO: CARRIER & CODE OBSERVABLES (2)

/// Measurement timeline



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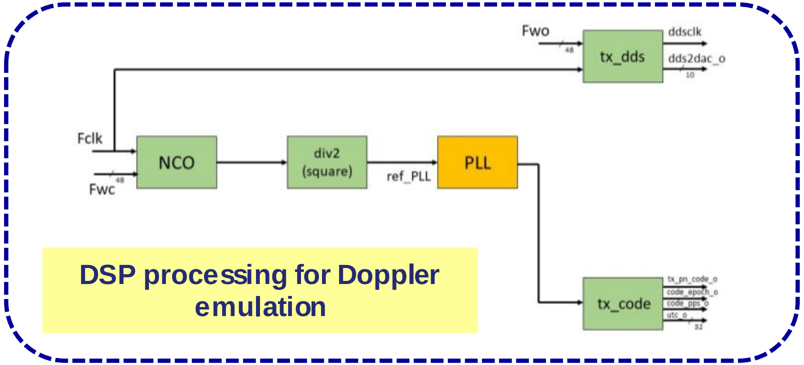
HERO: CARRIER & CODE OBSERVABLES (2)

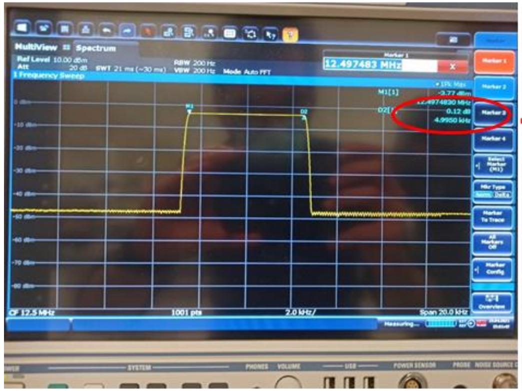
- **HERO's Transceivers include <u>Doppler emulation capabilities</u>. It allows avoiding the use of complex and high-cost channel emulator in order to validate the Radio-science performance in presence of signal dynamic (i.e. Doppler and Doppler rate).**

- **Doppler emulation is implemented by synchronous DSP processing at code and carrier level and validated by means of RF spectral measurements.**



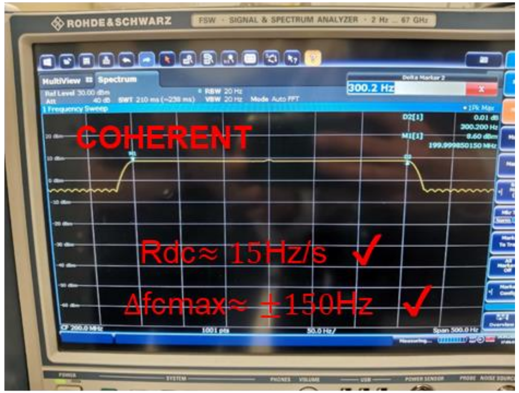
DSP processing for Doppler emulation

BASEBAND CARRIER



Ka CARRIER

CHIP RATE

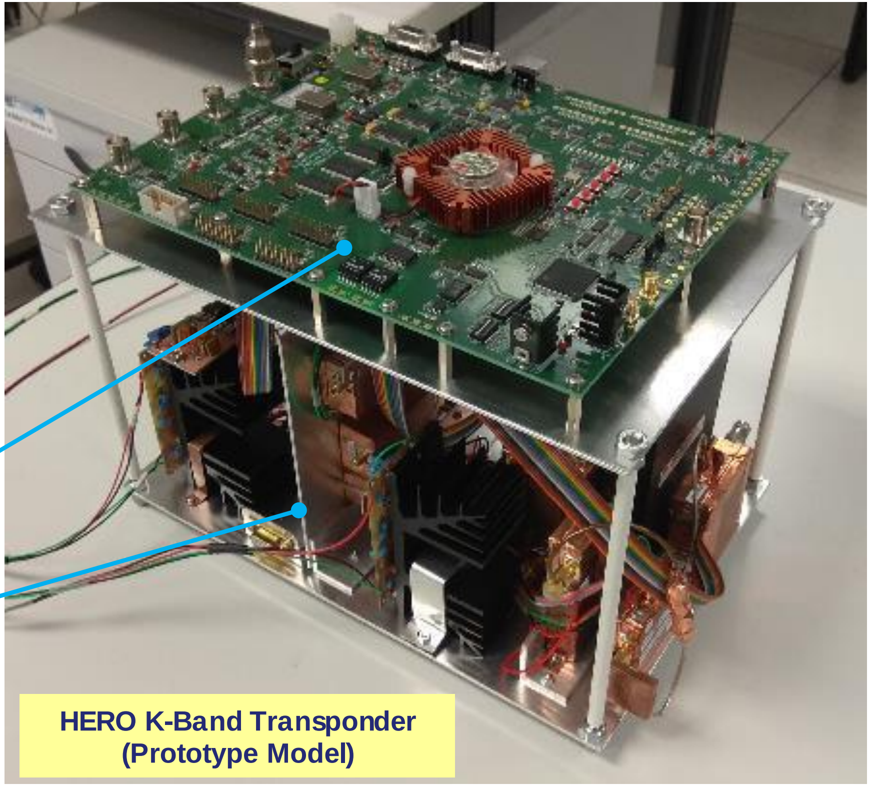


HERO BREADBOARD TEST BENCH (1)

- **Validation at Breadboard-level (TRL4) of STE-QUEST / HERO MWL has been accomplished in the frame of relevant ESA Study “High Performance Time and Frequency Link – Microwave”.**
  - RF interfaces in K-Band
  - Digital signal processing implemented on COTS FPGA
  - Test Loop Translator module
  - Built-in post-regulators

Digital Board

RF Sections (Rx/Tx)



HERO K-Band Transponder (Prototype Model)

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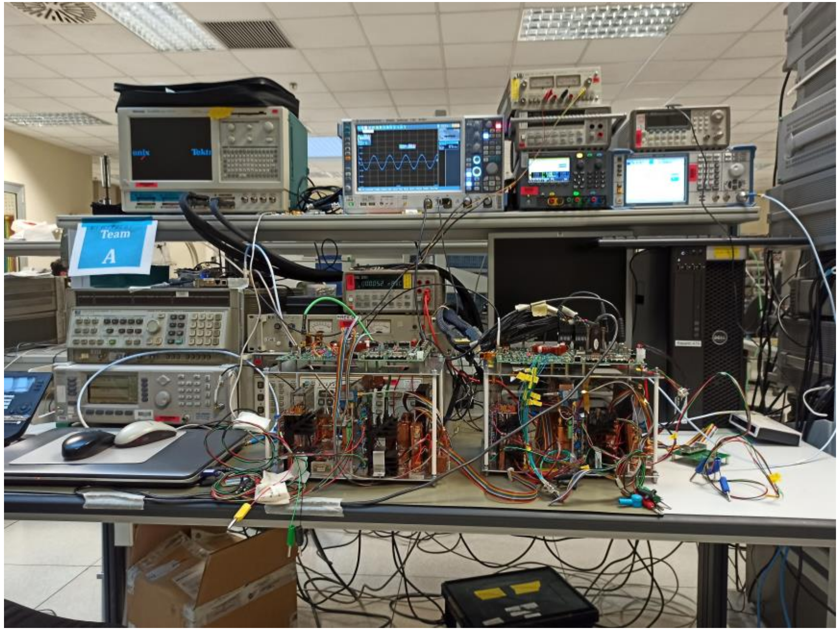
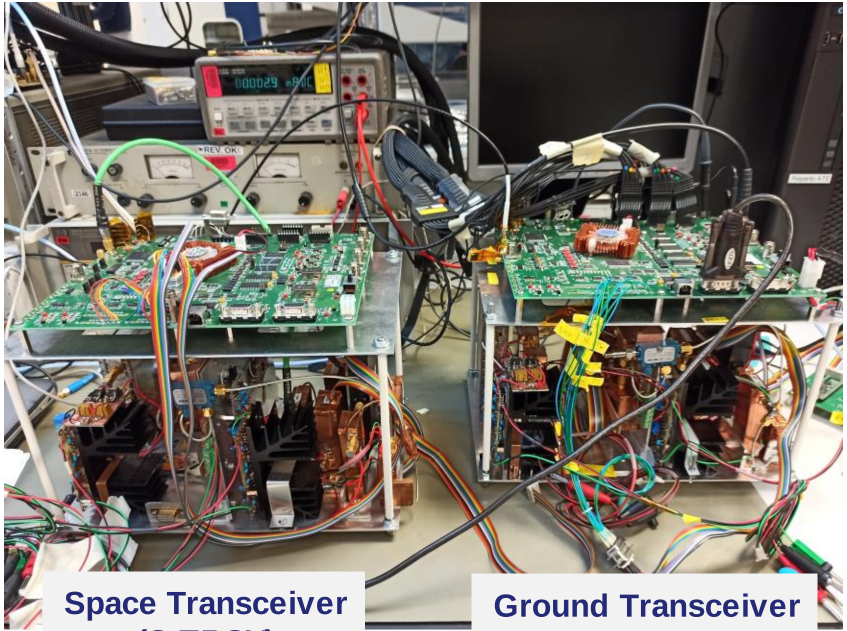
HERO BREADBOARD TEST BENCH (2)

/// **The end-to-end performance have been validated by two HERO Transceivers:**



HERO Test-Bench



Space Transceiver
(S-TRSV)

Ground Transceiver
(G-TRSV)

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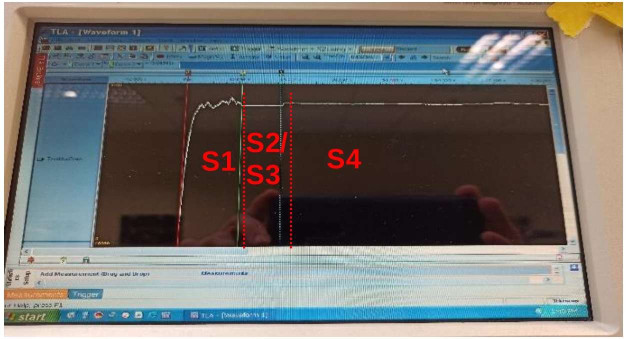
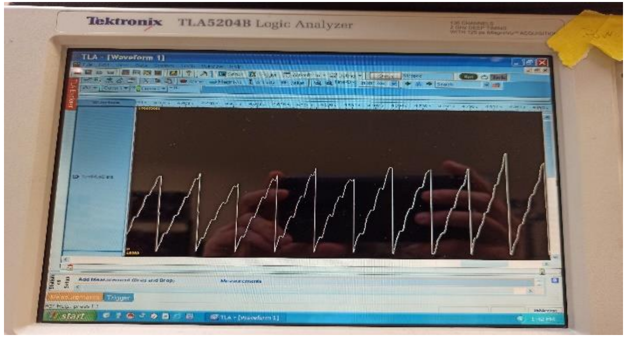
HERO BREADBOARD TEST RESULTS (1)

/// Rx test results at minimum signal-over-noise power spectral density ratio: $S/N_0 = 55$ dBHz

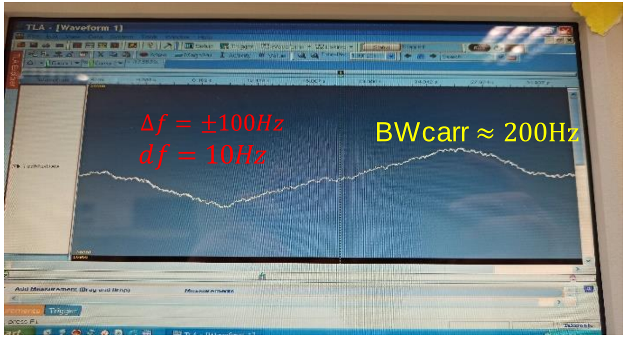
Digital AGC



Code Lock

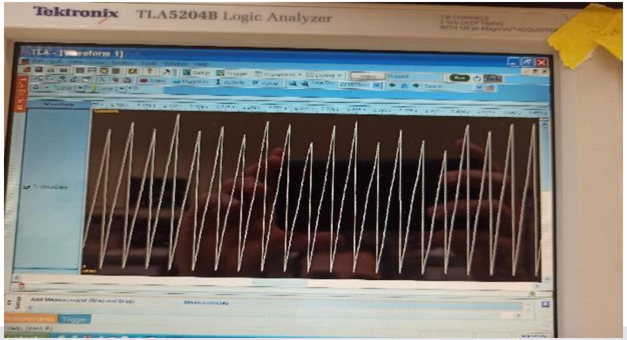


Carrier Loop Stress

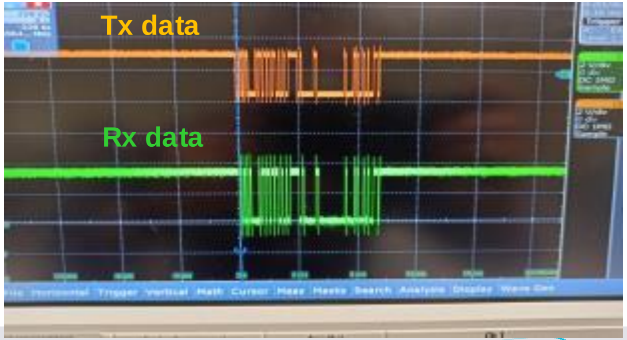


Code Loop Stress

Carrier Lock



Demodulated data



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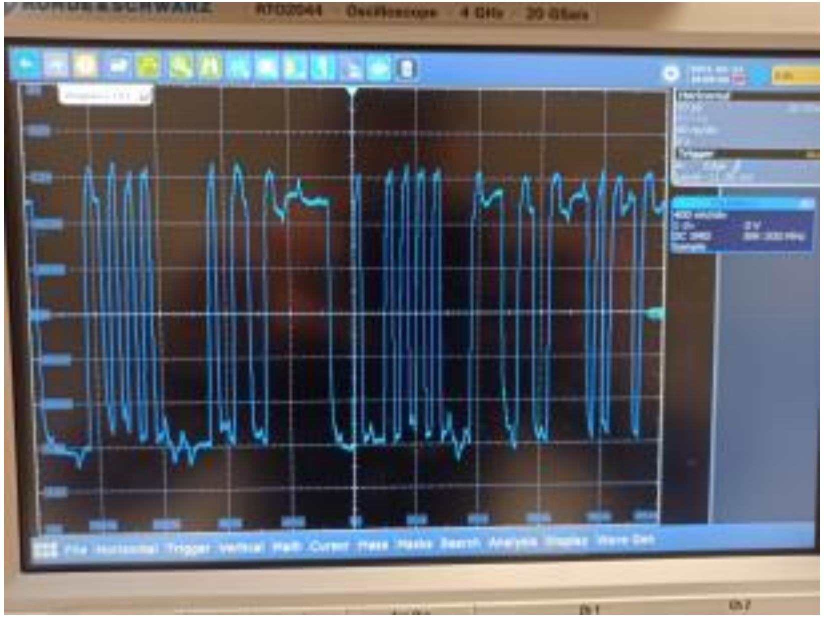
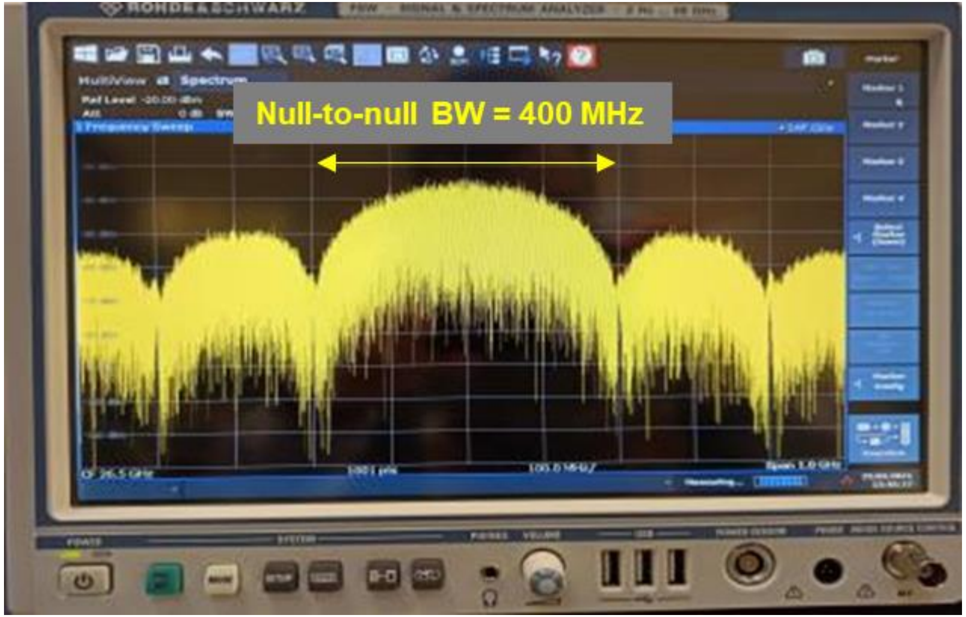
HERO BREADBOARD TEST RESULTS (2)

/// The TX carrier suppression and BW measurements have been carried out in K-Band

/ Null-to-null BW: 400 MHz



Transmitter PN Code



Transmitter Spectrum

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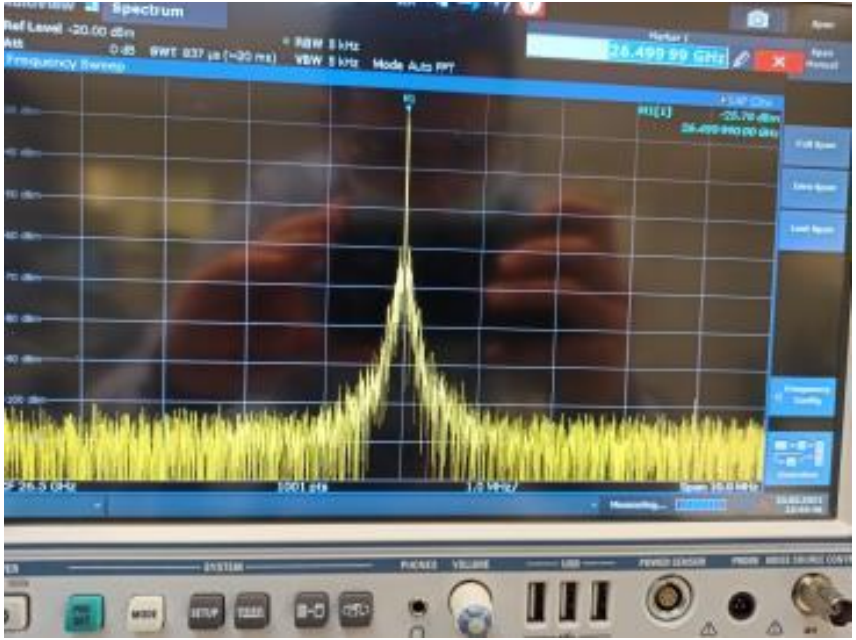
HERO BREADBOARD TEST RESULTS (3)

/// **The TX carrier suppression and BW measurements have been carried out in K-Band**

/ **Carrier suppression: >40 dB**

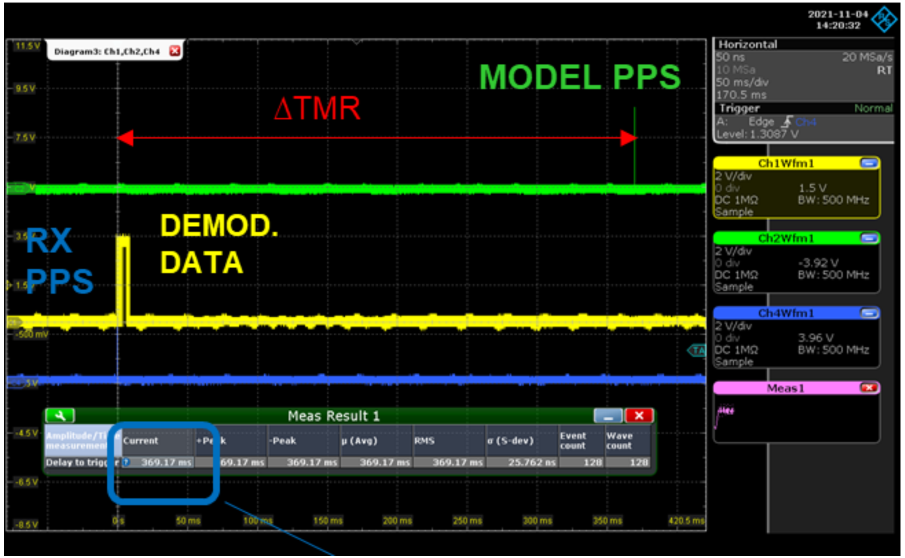


Unmodulated carrier

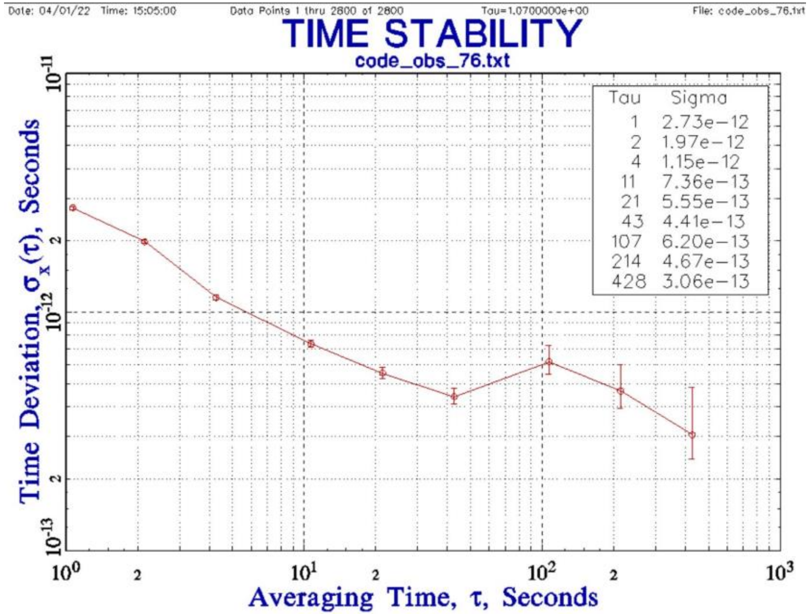
Modulated carrier

HERO BREADBOARD TEST RESULTS (4)

- Code observables have been validated by means of a state-of-art digital oscilloscope used to measure the time interval between the Model PPS and the Rx PPS.



- Code observables accuracy is better than 1 ps at 10 seconds of integration time.



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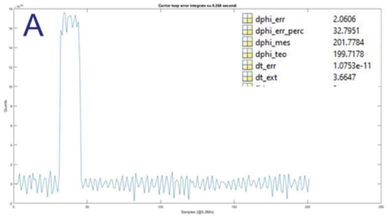
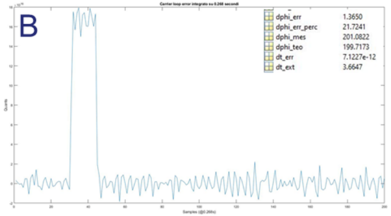
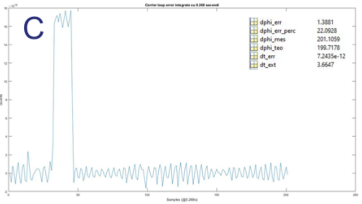
HERO BREADBOARD TEST RESULTS (5)

/// **Carrier phase measurements have been validated by applying a frequency step on the Rx carrier NCO over a known time interval.**

- ΔW=5e9 → Δf=8.6736 Hz;
- Ndump=14600
- C/N_0 = 85 dBHz

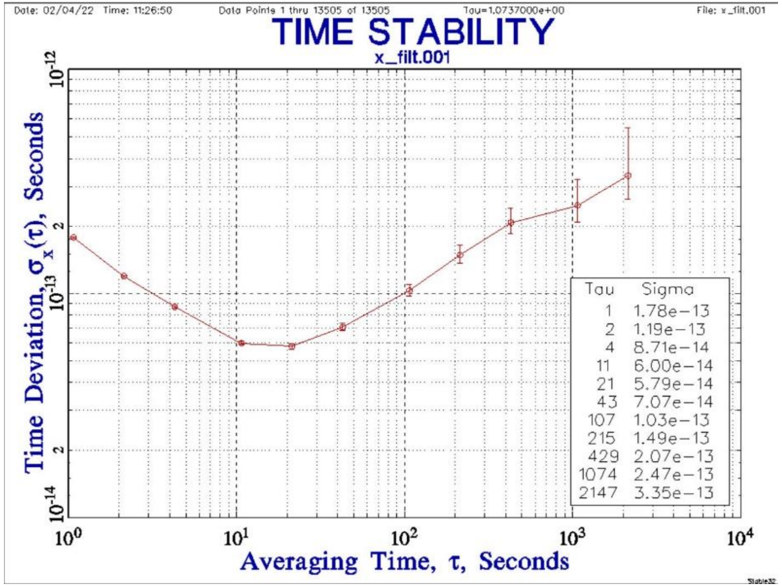






Legend:
- **dphi_err**: measure phase error [rad]
- **dphi_err_perc**: measure phase error %
- **dphi_mes**: measured phase shift
- **dphi_teo**: injected phase shift
- **dt_err**: measure time error [s]
- **dt_ext**: SW loop stress time duration [s]

/// **Carrier phase accuracy is ~60 fs for 10 s of integration time.**



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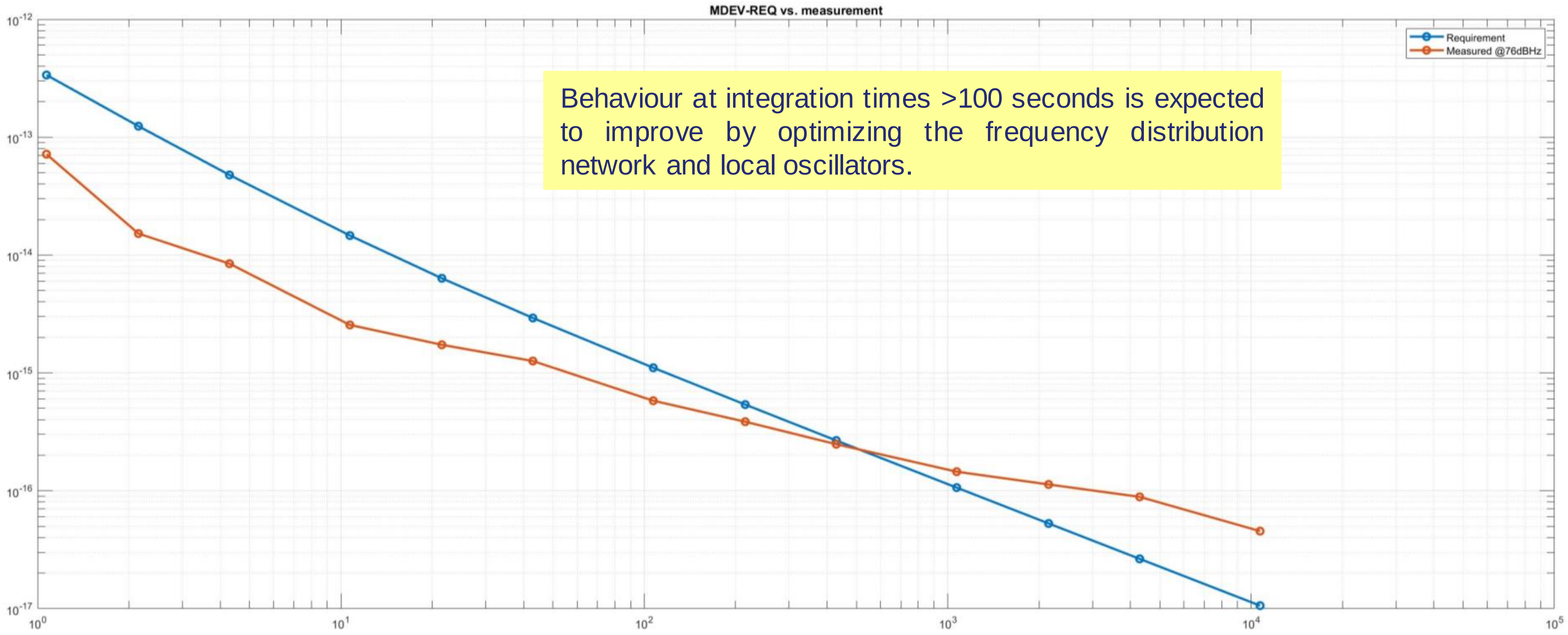
HERO BREADBOARD TEST RESULTS (6)

/// Carrier frequency stability has been characterized by means of the ModADEV tool:



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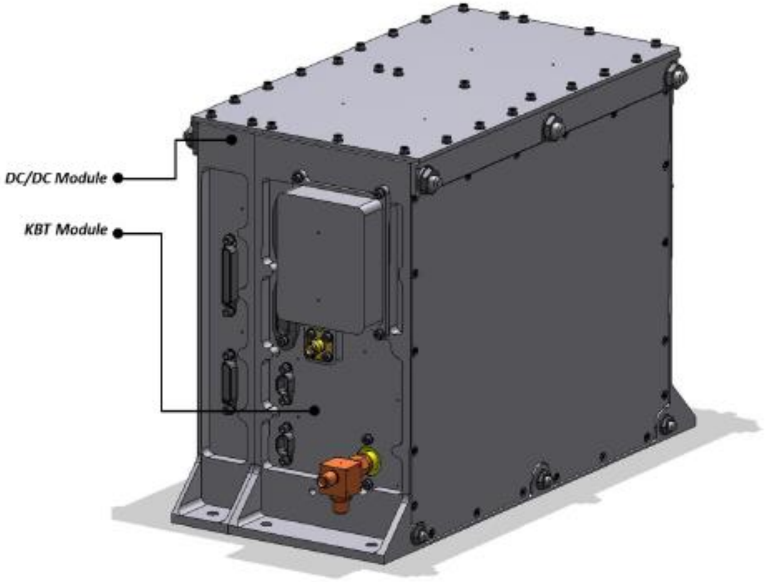
ROAD-MAP TO FLIGHT (1)

/// **In the frame of Lunar Gateway program, TAS-in-Italy is designing and developing the K-Band Transceiver for Lunar communications.**

- **Proximity link communication in K-Band (Rx: ~27.4 GHz, Tx: ~23.4 GHz)**
- **Autonomous radio capabilities for link establishment between the Lunar vehicles and the Lunar Platform**
- **High data rate Modem:**
  - SRRC-OQPSK demodulator up to 50 Mbps
  - SRRC-OQPSK modulator up to 20 Mbps
- **LDPC coding/decoding and frame synchronization**
- **SpaceWire interfaces towards platform for user and housekeeping data**
- **Support to antenna pointing and tracking with accuracy better than <0.5 dB.**
- **Mass: <3.5 kg**

/// **Schedule milestones**

- **EQM 1Q/2023**
- **PFM 3Q/2022**
- **FM 4Q/2023**



/// **The Transceiver is composed by two hardware modules:**

- **DC/DC Converter**
- **KBT Module, housing RF sub-assemblies (Rx / Tx) on one side and Digital boards on the other side.**

ROAD-MAP TO FLIGHT (2)

/// HERO FM can be derived from KBT product platform with the following changes:

- **K-Band Rx (27.4 GHz) and K-Band Tx (23.4 GHz) hybrids to be tailored for 26.5 GHz & 30.5 GHz using the same "die" components.**
- **Local OCXO (100 MHz) replaced by external frequency reference.**
- **Intermediate frequency passes from 150 MHz to 750 MHz.**
- **TLT to be added adopting an add-on mechanical module as pursued on BepiColombo MORE KaT.**
- **Minor re-design of the Digital Board, but same ADC (ADC08D1520) and same FPGA (PolarFire) will be used.**
- **VHDL and embedded firmware upgraded to support 4 PN channels (CDMA mode) in addition to the calibration channel.**

/// Note

- **I/Q DAC on Tx side are not requested on HERO**
- **HMC8191 will be used as QPSK modulator (in-phase channel for useful signal, quadrature channel for calibration) exploiting its large modulation BW (5 GHz)**

/// Industrial Response

- **HERO EQM can be available respectively at To+20.**
  - To be devoted to Ground Station: Rx = 30.5 GHz, Tx =26.5 GHz.
- **HERO FM can be available respectively at To+26.**
  - To be devoted to Space Station: Rx = 26.5 GHz, Tx =30.5 GHz.