ESTRACK: TECHNICAL ASPECTS, PERFORMANCE, LIMITATIONS AND FUTURE PROSPECTS

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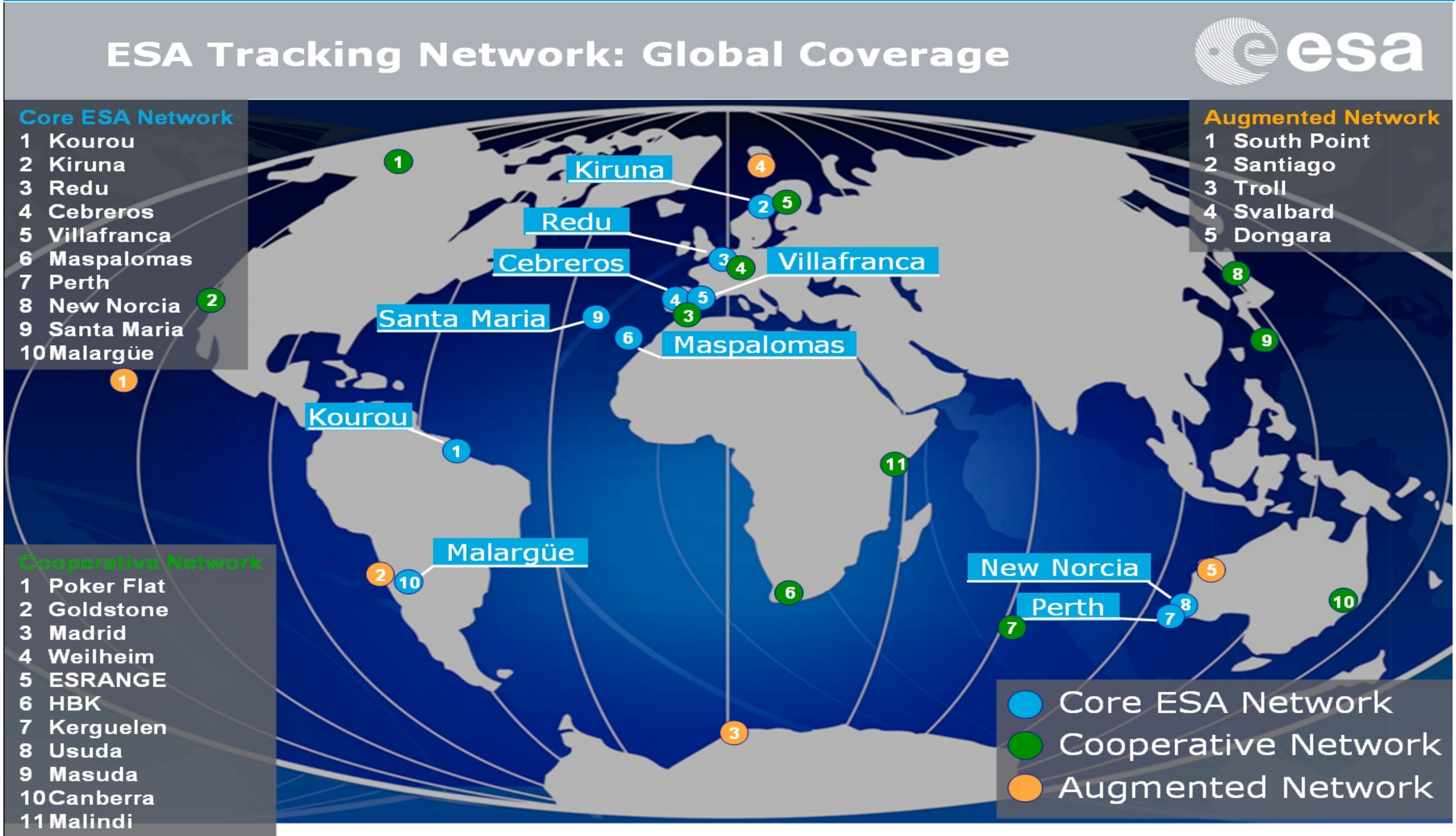
European Space Agency

TABLE OF CONTENT

OVERVIEW


ESA Tracking Network: Global Coverage
Core ESA Network
1 Kourou
2 Kiruna
3 Redu
4 Cebreros
5 Villafranca
6 Maspalomas
7 Perth
8 New Norcia
9 Santa Maria
10 Malargüe
Augmented Network
1 South Point
2 Santiago
3 Troll
4 Svalbard
5 Dongara
Cooperative Network
1 Poker Flat
2 Goldstone
3 Madrid
4 Weilheim
5 ESRANGE
6 HBK
7 Kerguelen
8 Usuda
9 Masuda
10 Canberra
11 Malindi
Kiruna
Redu
Cebreros
Villafranca
Santa Maria
Maspalomas
Kourou
Malargüe
New Norcia
Perth
Core ESA Network
Cooperative Network
Augmented Network

MAIN TASKS

- Communicate with ESA spacecraft, transmitting commands and receiving scientific data and spacecraft status information
- Gather ‘radiometric’ information to help mission controllers know the location, trajectory and speed of their spacecraft
- All phases of a mission are supported:
  - ‘LEOP’ – the critical Launch and Early Orbit Phase
  - Commissioning and routine operations
  - Deorbiting and safe disposal.

- ESTRACK also tracks rockets flying from Kourou in French Guiana.
- In a typical year, stations provide over 45 000 hours of tracking to more than 20 missions, with an enviable service availability rate above 99%.
- The capabilities of the network enable ESTRACK stations to also support missions of other space agencies in the US, France, Germany, Japan, Russia and China.

TYPICAL PROJECTS

European Space Agency

HISTORICAL DEVELOPMENT: 15M NETWORK

- On 19 May 1975, a ground station at Villafranca del Castillo, Spain, built for the International Ultraviolet Explorer satellite was assigned to ESRO to support future ESA missions.

- Later that month, ESRO merged with ELDO to form ESA, and the Villafranca station became the kernel of ESTRACK.

- The 15 m-diameter parabolic dish antenna of the Villafranca station has been part of many major ESA missions, including Marecs, Exosat, ISO, Integral and Cluster, and, more recently, XMM and ATV .

- It was later joined by similar stations in Sweden, Spain, French Guiana, Belgium and Australia, all optimized for tracking satellites near Earth. The original Villafranca location has since become ESAC, the European Space Astronomy Centre, ESA's major establishment in Spain.

HISTORICAL DEVELOPMENT: 35M NETWORK

- In the 2000s, the first of three 35 m-diameter Deep Space Antennas was built in New Norcia, Australia, followed by stations at Cebreros, Spain, and Malargüe, Argentina. These feature some of the world’s best tracking station technology and enable communications with spacecraft exploring planets, watching the Sun or located at the scientifically crucial Sun–Earth Lagrange points.

- In January 2014, ESTRACK received signals and sent commands to Rosetta, then travelling some 800 million km from Earth.

- ESTRACK routinely communicates with missions voyaging across our Solar System, including not only ESA missions like Rosetta, Venus Express and Mars Express but also partner missions like Japan's Hayabusa-2, heading towards an asteroid landing in 2018.

HISTORICAL DEVELOPMENT: OUTLOOK

- In future, the three deep-space stations will be upgraded to use ultra-high radio frequencies, necessary to boost scientific data delivery from missions like BepiColombo and Juice

- Of course, the network will continue to support Earth observation missions and perform critical LEOP and launcher tracking.

GROUND STATIONS: TT&C SERVICES

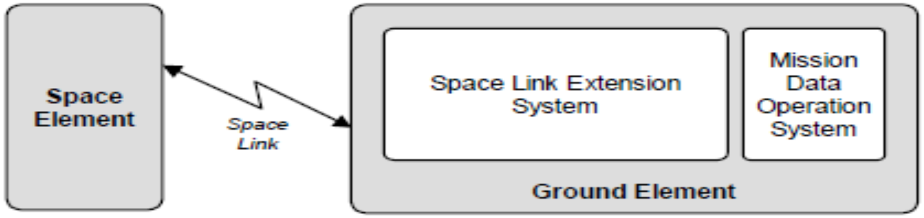
- In order to communicate with a satellite, a ground terminal is needed to transmit and receive the signal used to establish a link.
- Such link is normally established at radio frequency (RF). These are:

Band	Use	Frequency
S-band	U/L	2025-2120 MHz
	D/L	2200-2300 MHz
X-band	U/L	7145-7235 MHz
	D/L	8025-8500 MHz
Ka-band	U/L	34.2 - 34.7 GHz
	D/L (1)	25.5 - 27 GHz
	D/L (2)	31.8 - 32.3 GHz

- The ground stations are the counterpart of the on-board telecommunication systems and are used to accomplish the following functions:
  - **T**elemetry (TM) reception
  - **T**racking data production
  - Tele**C**ommand (TC) transmission

GROUND STATIONS: TM & TC

- TM and TC services are based on the use of **standard protocols**
- **SLE** (Space Link Extension) ensures interoperability of ESA stations with other Agencies



- TC services are managed by the **Forward** SLE Services :
  - **Forward Space Packet (FSP)**, which enables users to provide single packets for uplink to a spacecraft;
  - **Forward Communications Link Transmission Unit (CLTU)**, which enables users to provide CLTUs for uplink to spacecraft.
- TM services are enabled by the **Return** SLE Services:
  - **Return All Frames (RAF)**, which provides the TM frames from a single space link symbol stream;
  - **Return Channel Frames (RCF)**, which provides Master Channel (MC) or specific Virtual Channels (VCs)
  - **Return Operational Control Field (ROCF)**, which provides MC or VC Operational Control Fields (OCFs) channel

GROUND STATIONS: DOPPLER MEASUREMENTS

Velocity & Range Rate $\xrightarrow[\text{Frequency/Phase of the carrier}]{\text{Information on the}}$ $\boxed{\text{Frequency Shift}}$

The <u>observable</u> is the Carrier Frequency for Doppler measurement and estimation of

- Relative (between S/C and G/S) radial velocity: $V_R = V\cos\theta$ (θ is the angle between S/C velocity vector and line of sight)
- Relative radial range variation → Range Rate

$$F_{RX} = F_{TX}\sqrt{\frac{1-\frac{V_R}{C}}{1+\frac{V_R}{C}}} \approx F_{TX}\left(1-\frac{V_R}{C}\right) = F_{TX} + F_{Doppler}$$

Current accuracy: 0.1mm/s

F_{TX} = Transmitted Frequency F_{RX} = Received Frequency C = Speed of the light

The integrated Doppler measurement determines the change in range of a spacecraft ΔR over a given interval (T_0, T_1) by monitoring the unwrapped carrier phase change that results from the spacecraft's radial motion. For the 1-way Doppler we have:

$$\Delta R(T_0, T_1) = \int_{T_0}^{T_1} V_R\, dt = \frac{c}{F_{TX}} \int_{T_0}^{T_1} F_{Dop}\, dt = \frac{c}{F_{TX}} \left(\phi(T_1) - \phi(T_0)\right)$$

This measurement does not give an absolute measurement of range but does give a very accurate measurement of the change in range over the defined time period

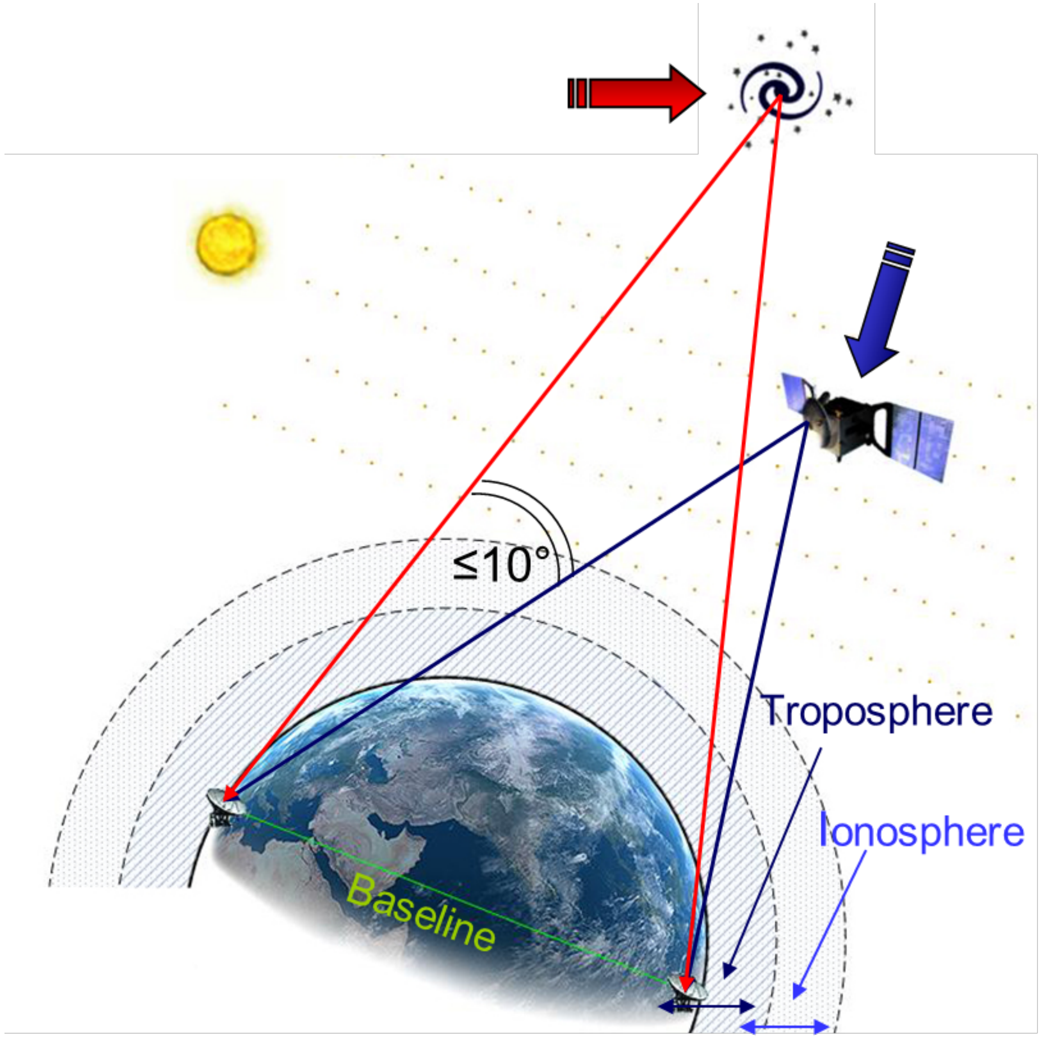
GROUND STATIONS: RANGING MEASUREMENTS

Ranging → Information on the phase of a modulating tone → **Delay**

- The primary observable is the delay of the received ranging signal w.r.t. the transmitted ranging signal
- In code ranging schemes the signal is composed by a ranging clock (tone) modulated by a code for ambiguity resolution.
- The tone phase measurement in association with the code ambiguity resolution gives a measurement of the line-of-sight range at a given time.
- The accuracy of this measurement is dependent on how accurately the G/S can measure the phase difference between the uplink tone and the received replica tone.

Current accuracy: 1 to 5 m (jitter)

GROUND STATIONS: DELTA DOR MEASUREMENTS (1/2)



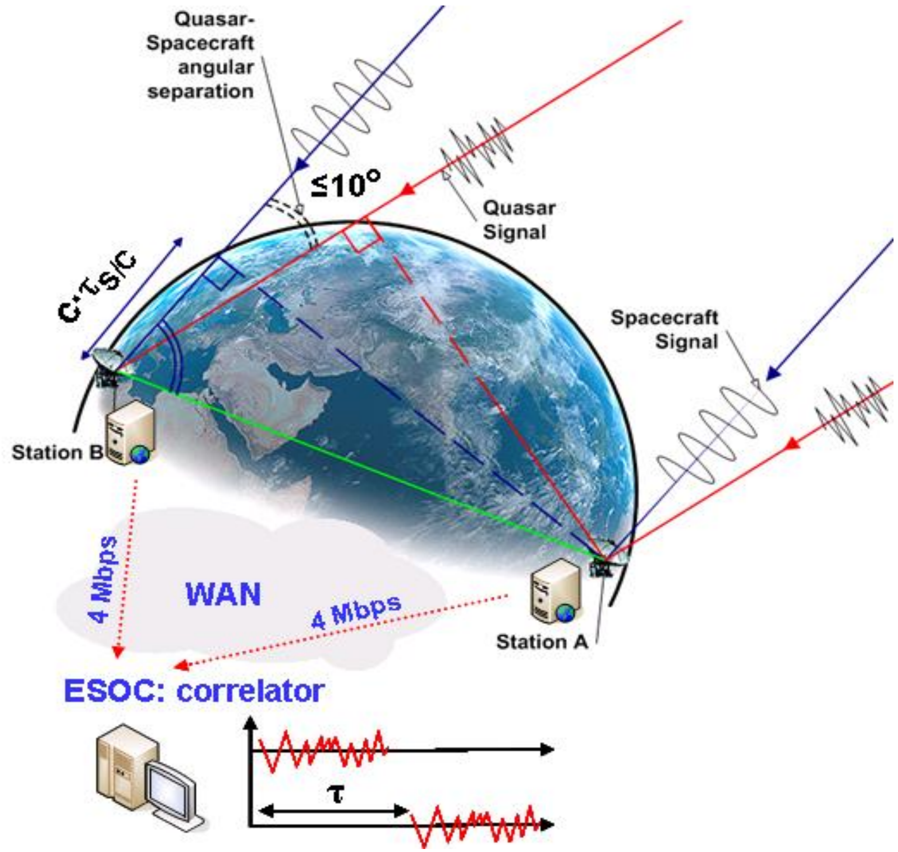
- ΔDOR stands for Delta-Differential One Way Ranging
- DOR is the measure of the difference in signal arrival time between two stations. The observable is an uncalibrated delay between the two antennas
- "Delta" is respect to a simple DOR, and refers to quasar calibration of the S/C DOR
- Since the quasar signal is recorded on the same BW of the S/C channels, ideally any errors which are station or path dependent will cancel out each other

GROUND STATIONS: DELTA DOR MEASUREMENTS (2/2)

- The extent to which these error sources cancel depends on the angular separation of the two sources being observed. The maximum angular distance between S/C and Quasar should not exceed 10 deg.

- Thus, one is able to evaluate a potentially error-free relative station delay, which leads to an accurate determination of the S/C position in the plane of the sky

- The measurement accuracy is given by:



$$\frac{\partial \vartheta}{\partial \tau} = -\frac{c}{B\cos\vartheta}$$ → Longer baselines, better accuracies

Current accuracy: 15 nrad

KEY FACILITIES: ESTRACK CONTROL CENTRE (ECC) – PART I

- At ESOC, the European Space Operations Centre, Darmstadt, Germany, the ESTRACK Control Centre oversees ESA's global ground station network, using a sophisticated remote control and automation system to reduce personnel costs and boost efficiency.
- A team of station operators are on shift 365 days per year, ensuring receipt of vital data from spacecraft operated by ESA and numerous partner agencies.

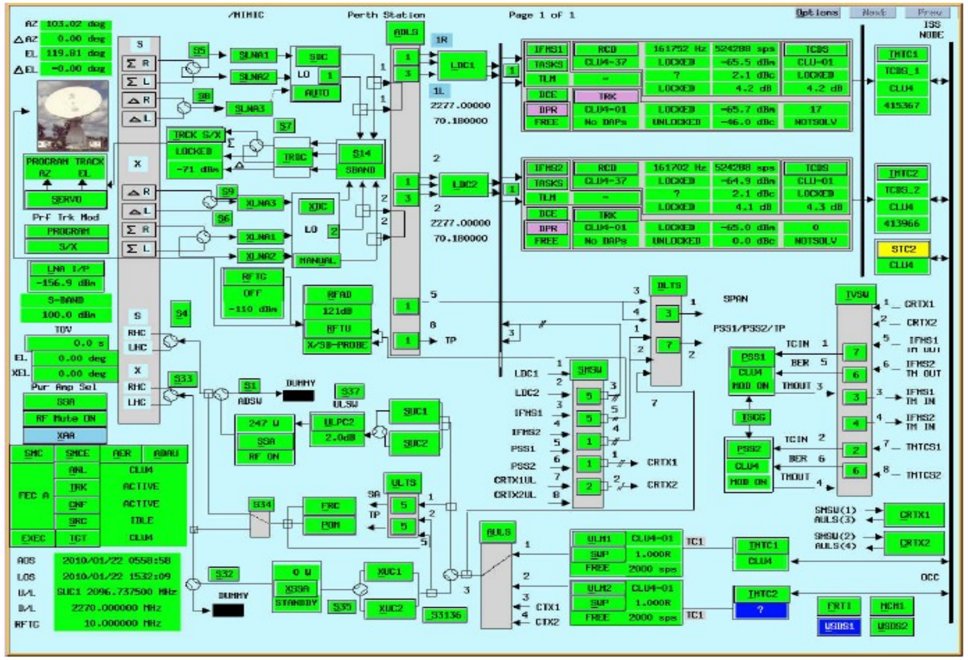
KEY FACILITIES: ESTRACK CONTROL CENTRE (ECC) – PART II

- The ground stations sub-systems are configured based on the configuration validated during RF compatibility tests

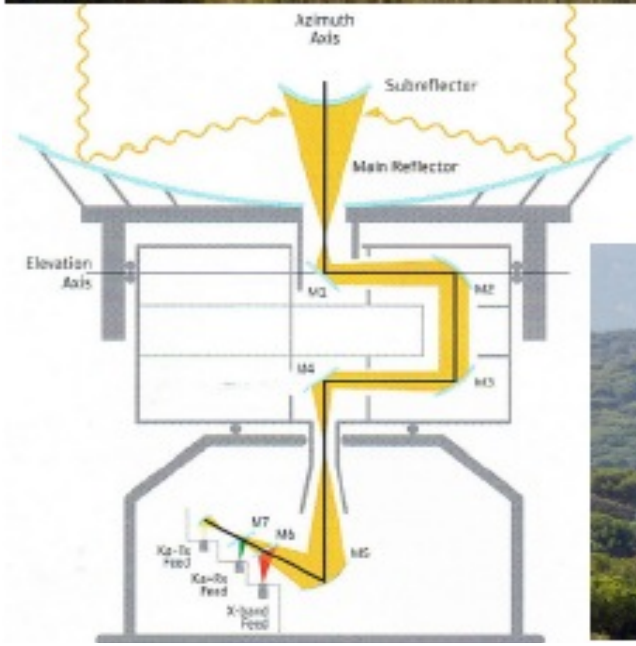
- Test and Validation of station configuration using the Portable Satellite Simulator

- Station Computer (STC) executes pre- validated procedures to configure the ground station for the mission support

- Main operational characteristics:
  - Automation
  - Reconfiguration
  - Redundancy
  - Configuration control



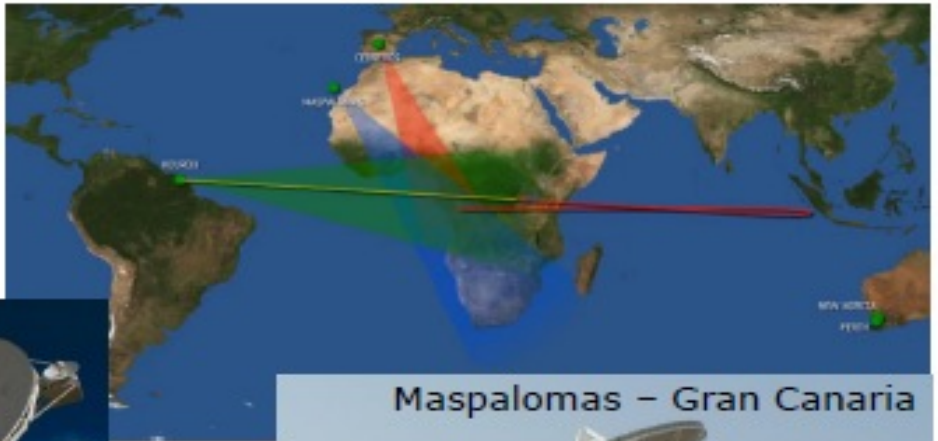
KEY FACILITIES: 35M DEEP SPACE ANTENNAE



- 360° coverage with overlap (120° apart)
- Multiband Beam Wave Guide design
- **X-Band** up/downlink
- **S-Band** up/downlink (New Norcia)
- **Ka-Band** downlink (Cebreros and Malargüe)
- **Ka-Band Up-link** (Malargüe – under construction)
- 20 kW transmit power
- Cryogenically cooled low noise amplifiers (Tsys ~6°K)
- High pointing accuracy
- Ultra-stable MASER frequency reference
- Full redundancy of all systems
- For planetary missions but also near-Earth (maximizing science data return)

KEY FACILITIES: LEOP AND NEAR-EARTH STATIONS

- S & X bands uplink and downlink (KRU, MSP, PER)
- X-Band acquisition aid 1m antenna for LEOP
- Launcher tracking in S-Band: Santa Maria and Perth
- Used routinely for near-Earth missions (Clusters, Integral, XMM) and for critical LEOP supports



KEY FACILITIES: LOW EARTH ORBIT STATIONS

- 13 to 15m antennas
- Typical users are Earth observation missions and highly inclined orbiting satellites: Cryosat, SWARM, ISS, ATV…
- Also as backup for near-Earth Science missions (Cluster, Integral, XMM)

AUGMENTED AND COOPERATIVE NETWORK

- **Augmented Network**
  The ESA augmented Network includes **additional stations rented** on an extensive period, in order to augment the data return from the satellites during the LEOP and Routine phases.
  e.g. Santiago(CEE), Dongara (SSC), Troll and Svalbard(NSC/KSAT)

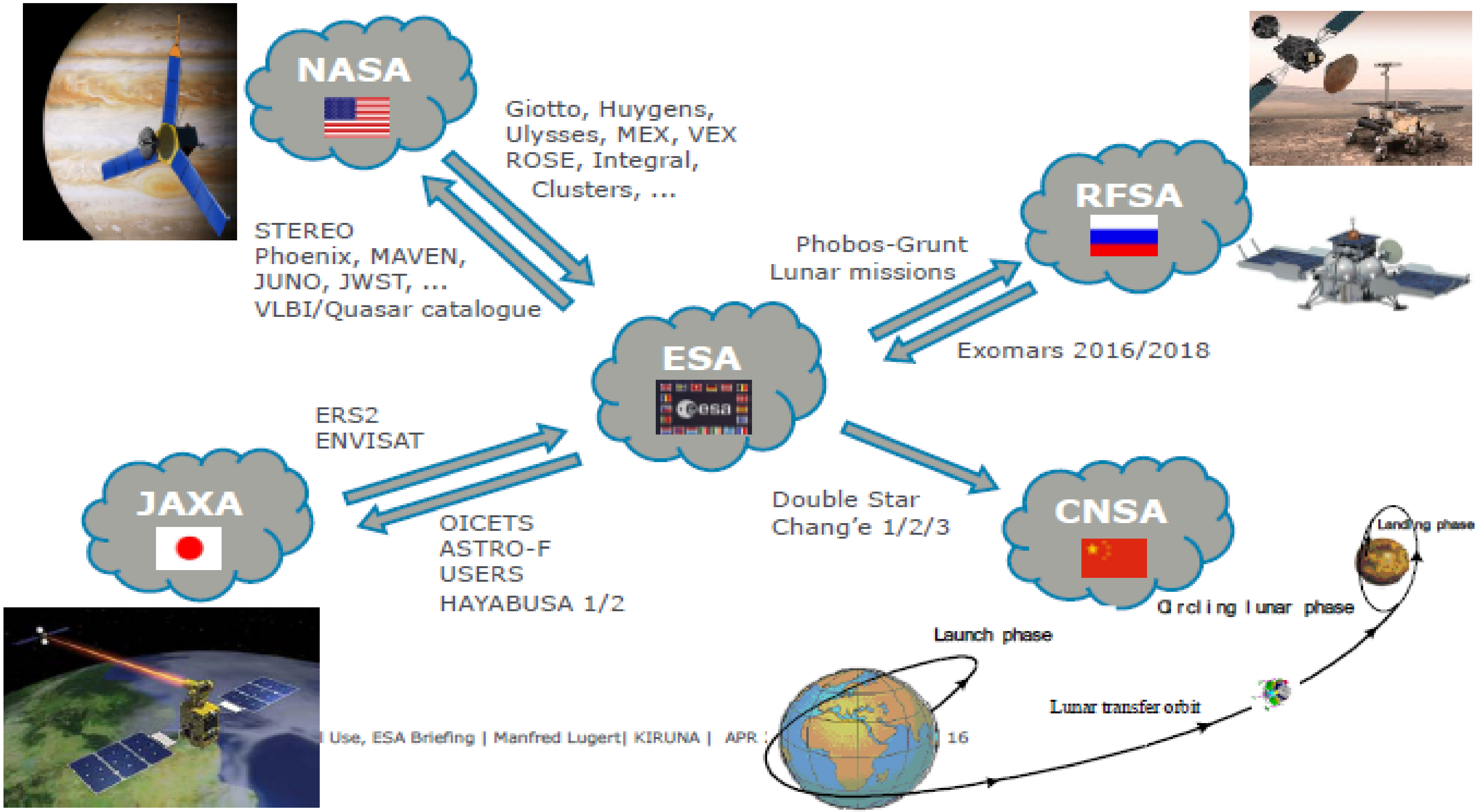
- **Cooperative Network**
  The ESA cooperative Network includes the stations of **external Space Agencies** with whom an Agreement or a Frame Contract has been concluded. It includes the following Agencies: ASI, CNES, DLR, JAXA, NASA, RFSA and SSC/Prioranet.

INTEROPERABILITY & CROSS-SUPPORT

- Interoperability is facilitated by the use of generic and **CCSDS standardized interfaces** on both Space to Ground and Ground to Ground links

- Where possible, establishing strong bi-lateral long-terms **cross-support agreements** defining the legal framework and the conditions for mutually beneficial cooperation in the areas of space communications and operations (e.g. with NASA, RFSA, JAXA, CNSA)

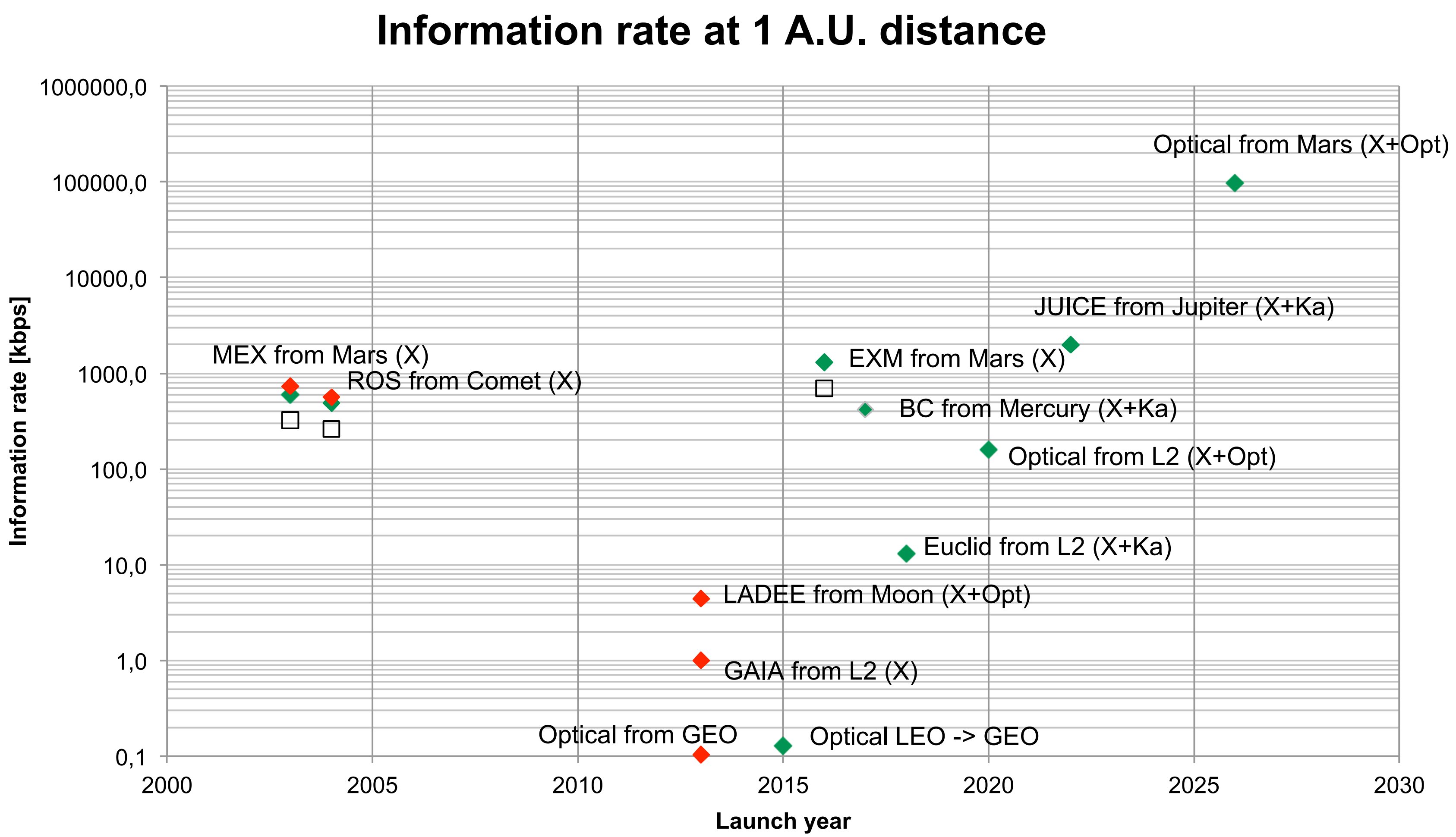
INTEROPERABILITY & CROSS-SUPPORT: SOME EXAMPLES



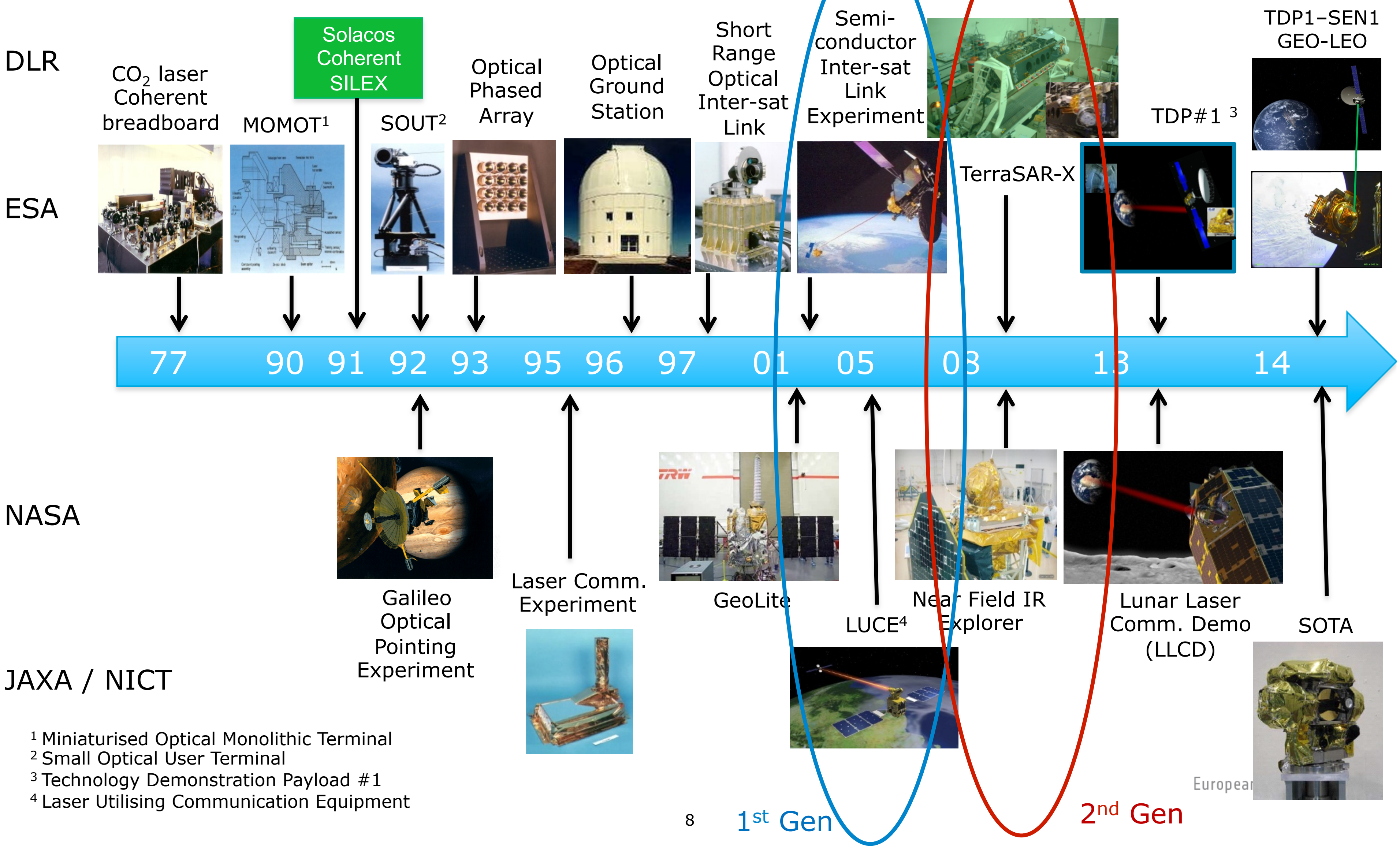
EVOLUTION OF SPACE COMMUNICATIONS

- Past Science missions: **single channel in S-band** for essential Tracking, Telemetry and Command (TTC) and Science data (*Cluster, XMM, Integral*)
- Past Earth Observation missions: two channels: S-band for essential TTC and **X-band (EO) downlink for Science data** plus Ka-band Inter-Satellite Link (*Envisat – Artemis*)
- Today's Science missions: **X-band** for essential TTC **and Science data** (*Mars Express, Venus Express, Rosetta-Comet, Herschel-L2, Planck-L2, Gaia-L2, SOLO, ExoMars*)
- Today's Earth Observation missions: **X-band** (as in the past)**; plus Optical Inter-Satellite Link** (*Sentinel – EDRS*)
- Next Earth Observation missions: S-band for essential TTC and **Ka-band downlink for Science data** (*Metop-SG*)
- Next Science missions: X-band for essential TTC and **Ka-band downlink for Science data** (*Bepi Colombo-Mercury, Euclid-L2, Juice-Jupiter); plus Radio Science with X/Ka-band links (BC, JUICE*)
- Future Earth Observations missions: X-band for essential TTC and **Ka-band (26 GHz) for Payload**
- Future Science missions option: X-band for essential TTC and **Optical downlink for Science data** (<u>*Goal: 100 Mbps from 1AU*</u>)

LINK "BENCHMARKING"



History of System and Optical Component Developments for Space



[1] Miniaturised Optical Monolithic Terminal
[2] Small Optical User Terminal
[3] Technology Demonstration Payload #1
[4] Laser Utilising Communication Equipment

THE NEXT GENERATION: *OPTICAL SPACE COMMUNICATIONS*

- Motivation:
  - Science data return, even enabling novel science missions (planetary hyper-spectral imaging…): → *Holy Grail:* ***100 Mbps from 1 AU*** *!*
  - Regulatory Freedom: *no congested frequency bands*
  - Ranging accuracy: *Ladee (NASA/MIT-LL) demonstrated accuracy << cm*
  - Time synchronization: *fundamental physics missions*
  - Inherent security: *virtually impossible to jam or intercept*
  - Synergy with scientific instrumentation: *lidar / imager as communications terminal*

- Addressing the Challenges:
  - Weather / atmosphere (extinction, scintillation): *site diversity / collaborative cross-support; active/adaptive optics / DTN to handle interruptions*
  - Acquisition and tracking: (narrow beam!): *high-power laser beacon / Earth sensor / inertial reference platform*
  - Eye-safety considerations (beacon): *readily available safety systems (ISLR's)*
  - Deep-space link budget (photon-starved…): *large ground aperture & photon-counting detectors: minimizing on-board resources*
  - Initial investment*: synchronized (not co-phased!) array (scalable!) of 4m monolithic <u>or</u> 12m segmented single-aperture "photon-buckets" promising to be competitive with array of 35m RF antennas*

OPTICAL TECHNOLOGY DEVELOPMENTS *(1/2)*

- Past projects:
  - Most strategic "deep-space" latest demonstration: Ladee: ESA participation in highly successful NASA/MIT-LL Lunar mission with optical demo:
    - Longest lasercomm link ever and highest up/down data rates ever from the Moon
    - Error-free communications up and down, even through turbulent atmosphere
    - Instantaneous link lock-up every time
    - Operations day and night, new and full moon, high and low elevation (down to 3.8 degrees), 3 degrees from sun:

      validated array of small telescopes (MIT design)

- On-going / imminent projects
  - Tesat LCT ISL Alphasat / Sentinel / EDRS operationally validated !!
  - Relevant ***DS*** ESA Mission (phase A/B1): Asteroid Impact Mission (AIM)
    - Shall embark a deep-space optical terminal demonstrator from 0.1-0.5 AU (!)
  - Standardization of Optical Space Links in CCSDS OPT WG covering:
    - High data rate scenarios (incl. ISL & data relay)
    - **High photon efficiency scenarios (→ deep space science missions)**
    - Low complexity scenarios

OPTICAL TECHNOLOGY DEVELOPMENTS *(2/2)*

- On-going / imminent projects *(continued…)*
  - Technology preparation / development activities (system, on-board, ground):
    - Deep Space Optical Communications Architecture Study - DOCOMAS (GSP)
    - Benchmarking RF and Optical Communication (in-house study)
    - End-to-End Physical Layer Simulator for Optical Communication (TRP)
    - Optical Link Budget tool (in-house study)
    - Optical Ground Station Optimization Tool (Telecom Lab Investment)
    - AIM Optel-D (O/B optical demo terminal) Concept Definition Study (GSP)
    - System Study of Optical Communication with a Hybridized Optical/RF Payload Data Transmitter (TRP)
    - Radiation hard 1550nm optical power amplifiers (ARTES)
    - Compact optical communication and imaging system (TRP)
    - Planetary communication system based on modulated retro-reflection (2xTRP)
    - Photon-Counting Ground-based Optical Communications Detector Breadboard (TRP)
    - Photon-counting Short Wave Infrared (SWIR) 2D (Tracking) Detector Array (TRP)
    - Optical Antenna Study Group (in-house study – see opt.antenna concept designs)
    - LADEE transmitter upgrade of ESA's OGS (laboratory investment)

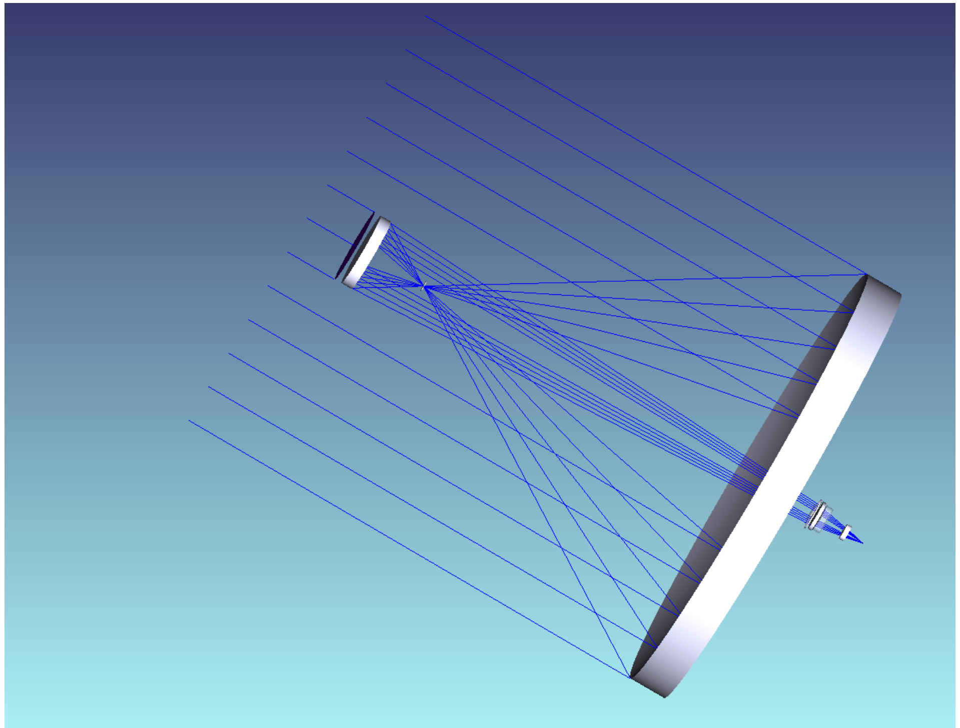
OPTICAL TECHNOLOGY DEVELOPMENT: *OUTLOOK*

- Future projects
  - Modulation and coding scheme validations for various scenarios
  - On-board and Ground-based high-rate SCPPM modems
  - Cloud free line of sight (CFLOS) analysis for various mission and ground station scenarios, including potential cooperative scenarios with NASA
  - Ground station design *to cost* and for *day & night* operation:
    - Array of 4m-class monolithic antennas
    - Segmented 12m-class single aperture antenna
  - On-board and Ground-based Detector developments
  - On-board pointing and acquisition sub-systems
  - Ground-based high-power beacon and eye-safety sub-systems
  - Ground-based highly selective filter sub-systems (1064nm & 1550nm)
  - Radiation-hard optical pre-amplifiers (1550nm)
  - Mission applications:
    - CISLunar (Moon-Earth Lagrange) missions at 0.003 AU
    - Sun-Earth Lagrange missions at 0.01 AU
    - Mars mission at 0.4 – 2.7 AU, Jupiter at 5-6 AU

DESIGN CONCEPT (A): 4 M MONOLITHIC

In-house design of a 4 m aperture ground antenna (Modified Gregorian) for an array of 7 – 9 to obtain an effective collecting area of 10 – 12m:

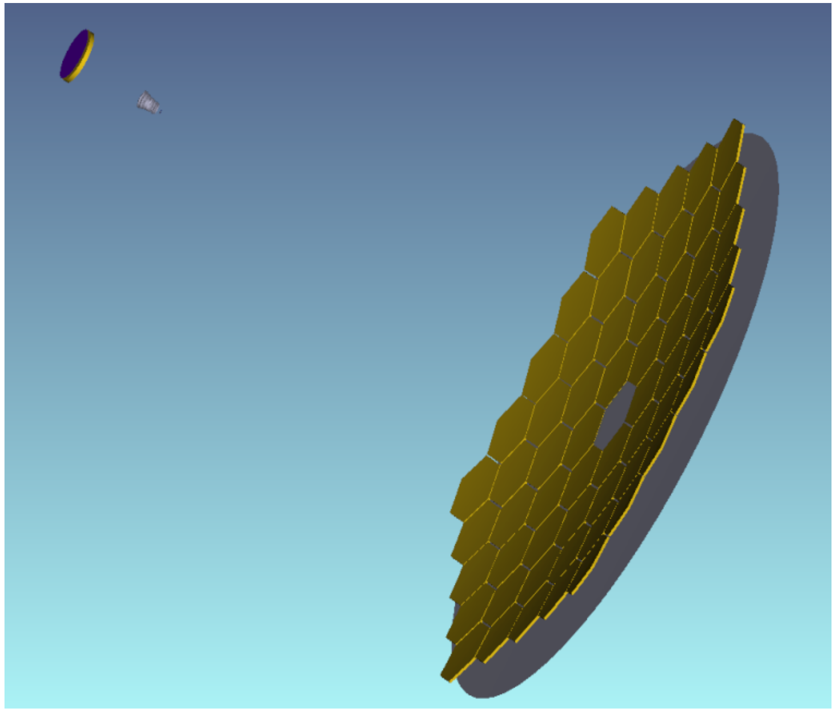
- Physical length: 5.23 m
- Aperture diameter 4.25 m
- M1: monolithic, parabolic
- M2: aspheric, diam. 0.72 m
- Refractive corrector: 4 elements, max. diam. 30 cm
- Focal length: 10 m
- Corrected FOV diam. = 0.1°
  Spectral range min. 1 – 1.6 µm
- Field stop at M1 focus blocks out-of-field solar and sky background



Design Concept (b): 11.5 m Segmented

In-house design of a 11.5 m aperture ground antenna:

- Physical length: 13 m
- Aperture diameter: 11.5 m
- M1: spherical, diam. 11.5 m, *f* = 26 m
- M2: aspheric, diam. 98 cm
- Refractive corrector: 8 elements / 7 groups, 2 aspheric surfaces, max. diam. 30 cm
- Focal length: 10 m
- Corrected FOV diam. = 0.05° (180”)
- Spectral range min. 1 – 1.6 µm



THE NEXT GENERATION: RF SPACE COMMUNICATIONS

- Main drivers:

  - Increasing data return

  - Enhanced robustness of operations

  - Increasing navigation requirements, especially in case of planetary landers

  - Support to Radio Science experiments

THE NEXT GENERATION: *RF SPACE COMMUNICATIONS*

- Increasing data return:

  - X-Band and Ka-Band cryo-feeds beyond the existing technologies (cryo-LNA), challenge is an accommodation of uplink operations in parallel on the same feed for X-Band (two technology activities on-going)

  - Antenna arraying e.g. 4x35m antenna, technically feasible but challenge is a financial impact of additional terminals (a demo performed at ESAC, an internal concept study on-going, previous concept study on possible architectures)

  - Enabling 26GHz band operations (triggered by Euclid and Earth Observation), for L2 missions a challenge is accommodating additional systems in the crowded beam-waveguide assembly (implementation on-going for Cebreros and Malargüe), for Earth Observation challenge is to build a non existing network and characterizing the propagation channel system study on going)

THE NEXT GENERATION: *RF SPACE COMMUNICATIONS*

- Enhanced robustness of operations

  - Study use of weather forecast for increasing reliability of Ka-Band operations (pre-development phase)

  - Deploy network of microwave radiometers for better statistical characterization of atmospheric attenuation and brightness temperature. Challenge: years of data are required to form usable statistics (on-going, deployed in CEB)

  - Increase of uplink transmit power, to be used especially for recovery of interplanetary missions (two studies about system architecture and amplifier design)

  - Study of novel modulation/coding techniques and system solutions to be used during superior solar conjunctions when the telecommunication link is affected by solar plasma missions (two parallel concept studies on-going)

THE NEXT GENERATION: RF SPACE COMMUNICATIONS

- Increasing navigation requirements, especially in case of planetary landers

  - Enhancement of accuracy of delta Delta DOR measurements down to 1nrad (from today's 10-20 nrad), challenge: error contributions to be tackled (e.g. phase ripple over frequency of instrumentations) are already very small. Study phase.

  - System solutions allowing calibration of solar plasma effects (e.g. use of Ka-Band uplink/downlink, or enabling triple link X/X, X/Ka, Ka/Ka, both inherited from radio science applications): challenge complexity of the on-board telecommunications system, and RS payload nature of current Ka/Ka transponder. Main output from past concept study (ASTRA)

  - Inherit large chip rate PN ranging from RS experiments. Challenge, again payload nature of RS systems

  - Improvement of clocks

THE NEXT GENERATION: RF SPACE COMMUNICATIONS

- Support to Radio Science experiments

  - Implement Ka-Band uplink (also studying solid state amplifier technology, modified beam wave guide system to cover pointing ahead), under development

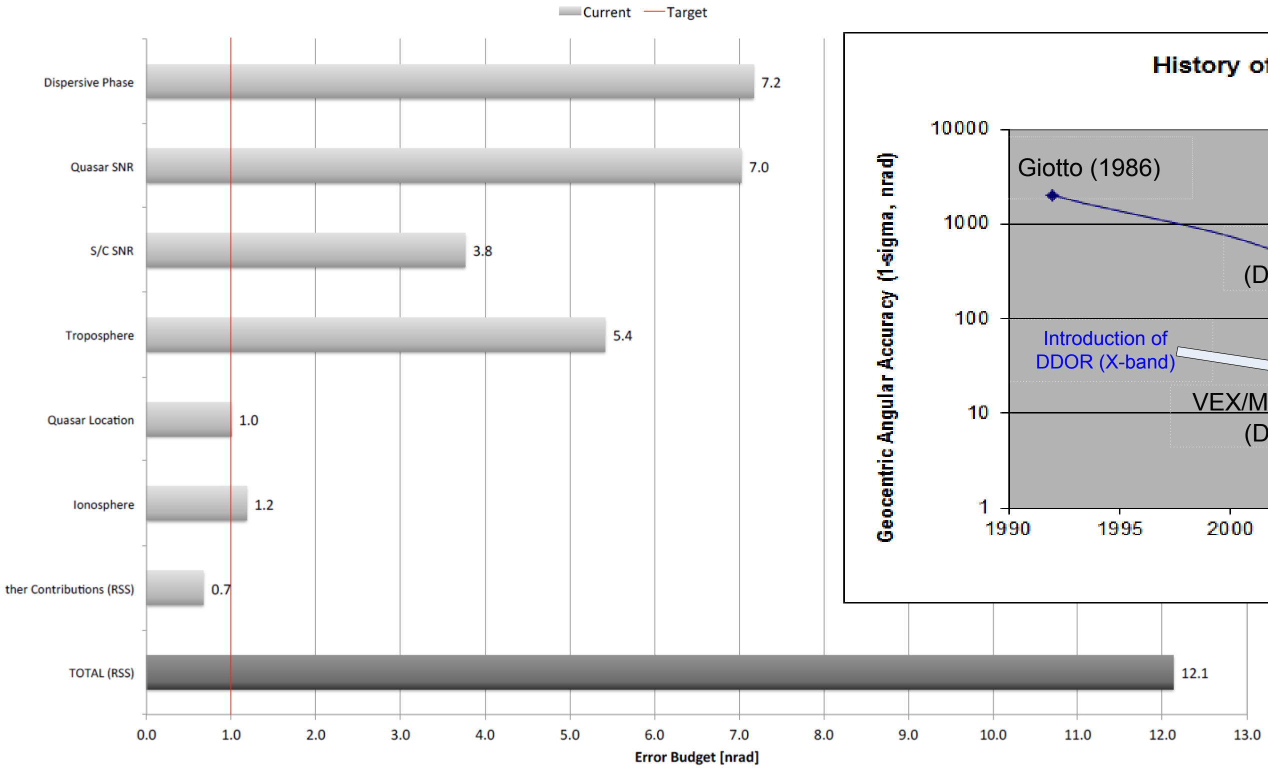
  - Implement on line ranging calibration

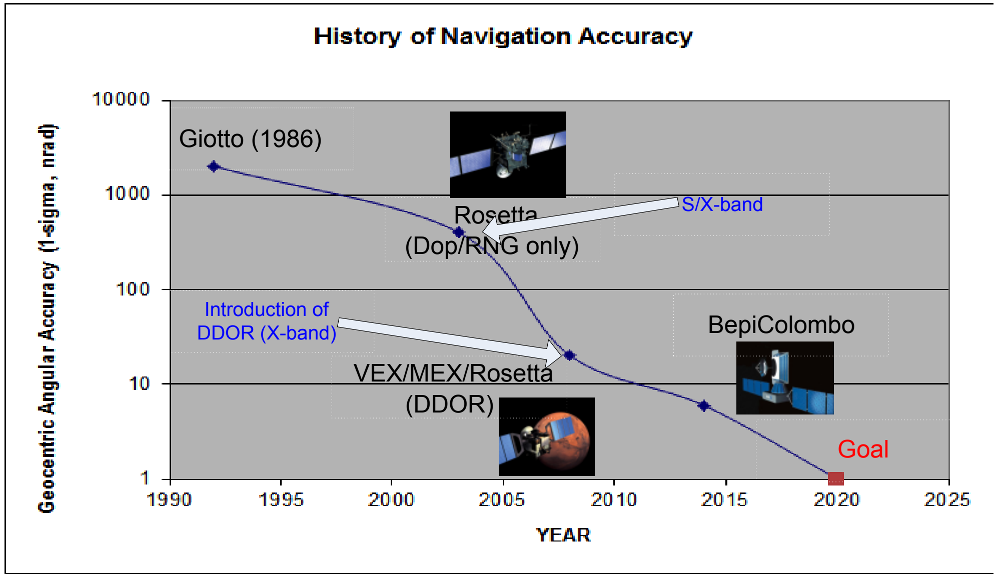
  - Deploy microwave radiometer for accurate compensation of tropospheric delay (complemented by GNSS inputs), under development

  - Implement large chip rate PN ranging (implementation on-going)

ENHANCEMENT OF ACCURACY OF DELTA-DOR

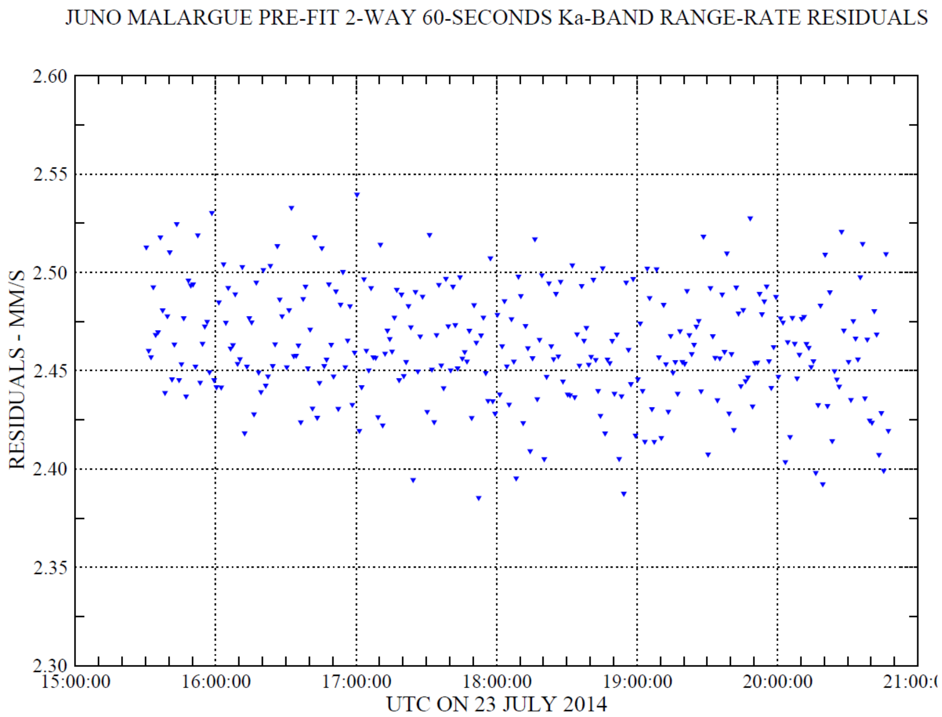
The plot on the left shows the performance of the current ESA Delta DOR system, the dispersive phase is a large contributor and its removal/reduction is the subject of an on-going technology activity. Other contributions have to be tackled as well, e.g. the troposphere delay needs to be calibrated in real time, which however is feasible under existing technology. Ultimately we want to reach the goal shown in the figure on the right.

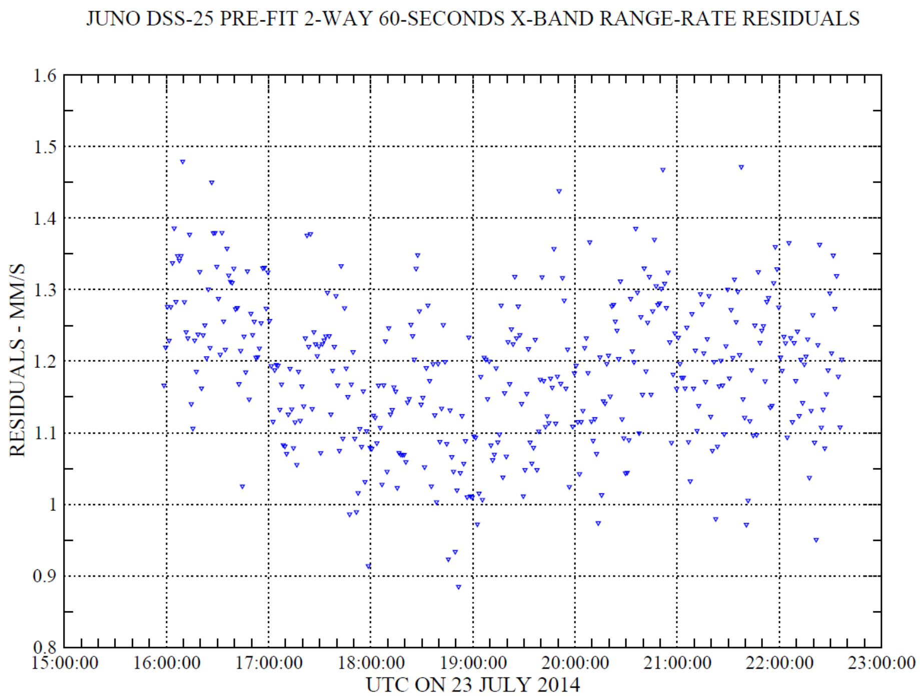




USE OF KA/KA-BAND TRACKING

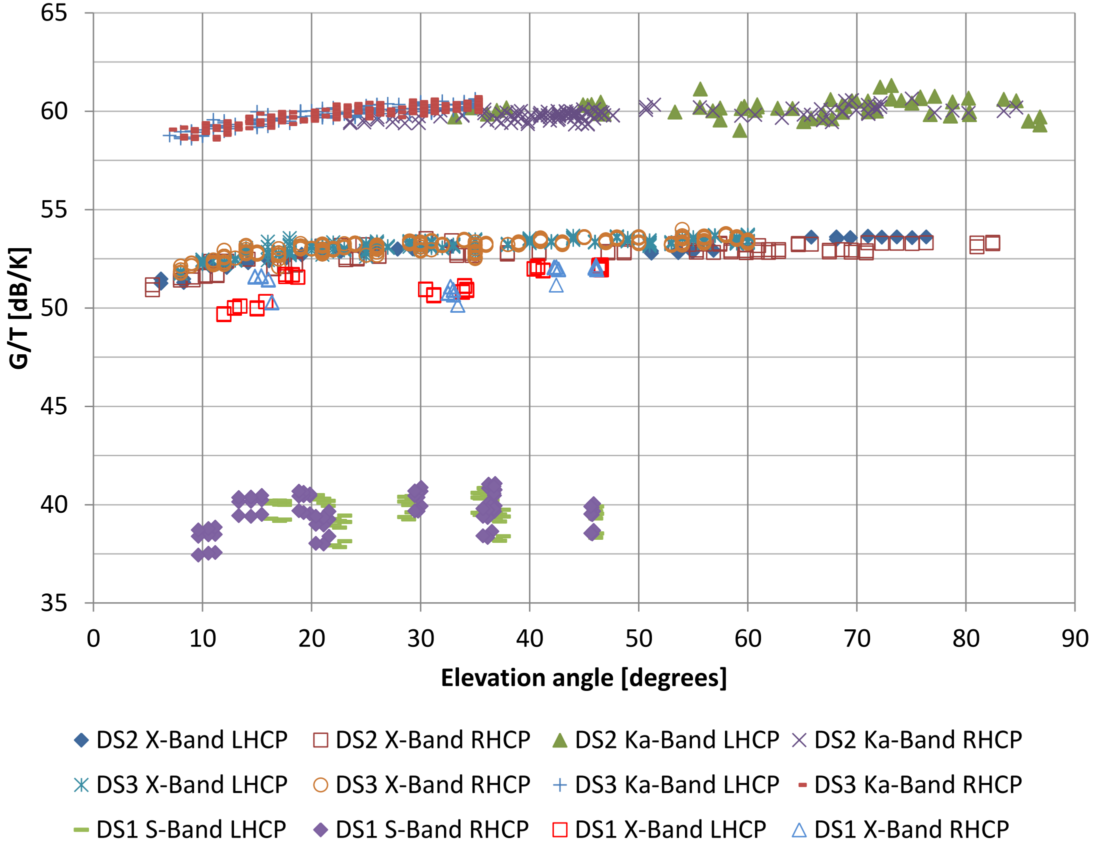
The plot on the left shows the range rate residuals obtained during a track of the NASA/JPL satellite Juno from Malargüe, when using Ka-Band uplink and downlink. The same pass was followed in X-Band uplink/downlink by the NASA/JPL antenna DSS-25. The residuals in X/X are around 3 times worse than the ones in Ka/Ka-Band, as expected due to the smaller error contribution from solar plasma.





CRYO FEED TECHNOLOGY

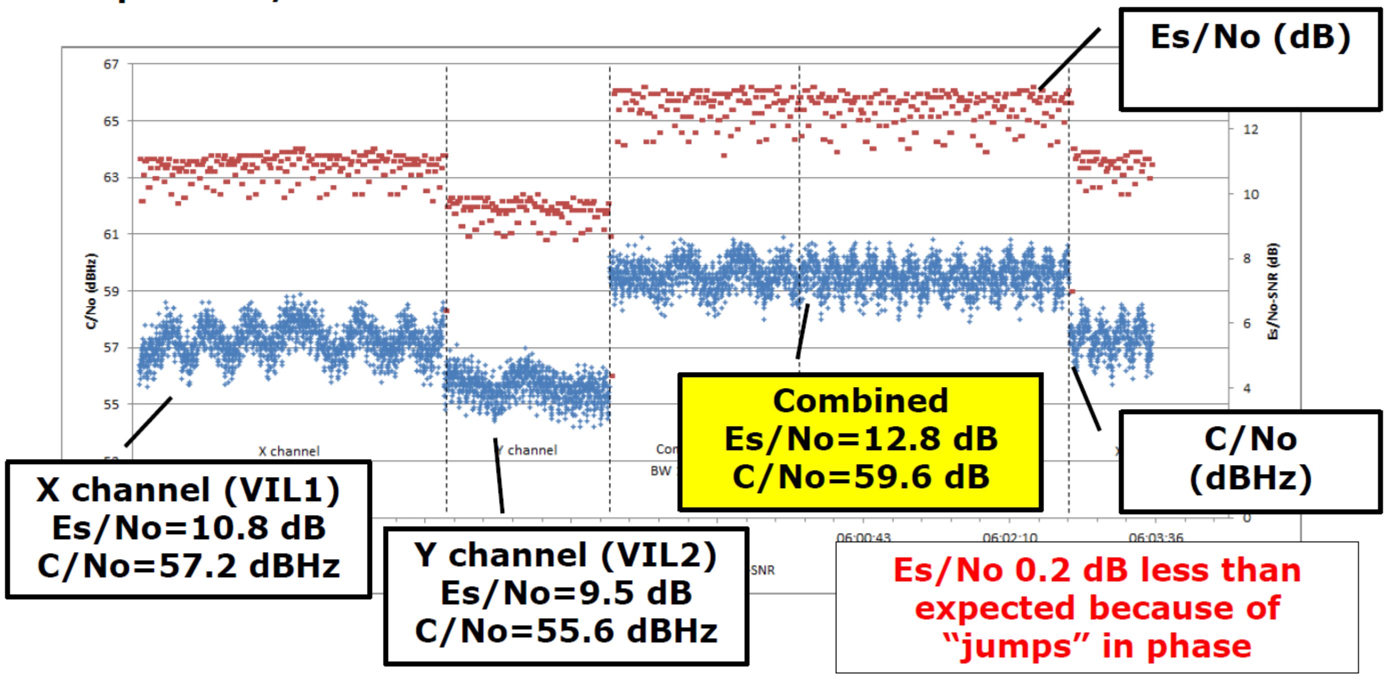
The plot shows the current G/T performance of the ESA antenna. The Ka-Band G/T is around 60 dB/K at high elevation in clear sky. By use of cryo-feed technology, an improvement of 2 to 2.5 dB could be achieved. A smaller improvement would be possible for X-Band (around 1dB) by use of the same technology.



ARRAYING

The plot shows the result of an array demonstration performed with two S-Band antenna at the ESAC site in Villafranca (Spain), while tracking a Cluster spacecraft. The objective was to put in evidence the obvious potentiality of this technique. On top of studying arrays of collocated 35m antennas, the off-line combination of signals registered by existing antenna at distant deep space sites is also under investigation.

Expected Es/No = 13.0 dB **Gain over X channel: 2.2 dB**
Expected C/No = 59.6 dBHz **Gain over X channel: 2.4 dB**



QUESTIONS AND ANSWERS