ESA activities for future GNSS Radio Occultations receivers

21 September 2017
IROWG-6 Estes Park

M.Tossaint / J. Rosello - ESA Future Missions EOP-ΦMP

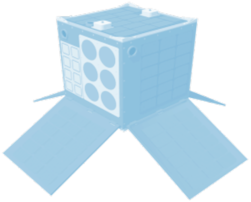
European Space Agency

Table of contents

ESA projects RO

- METOP & SG
- Simulation studies
- Assimilation studies

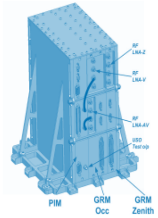
I



ORORO concept

- New mission concept & technology
- + GNSS-R

II



MQ RO receiver

- Medium Quality design & impact on RO products

III

AGGA-5

- AGGA-4 for sale since 2014
- New requirements
- New design & technology

IV

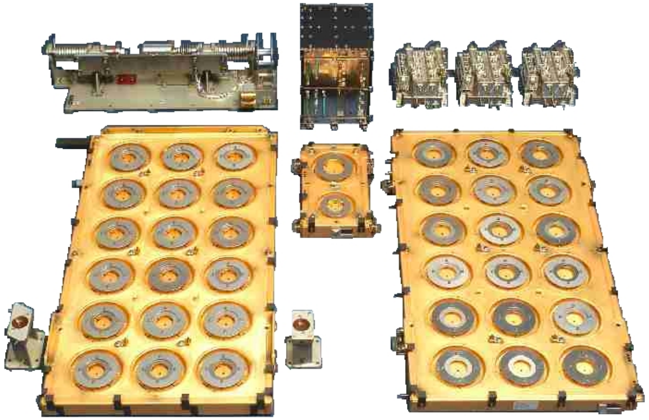
E2E simulator – How did we get there ?

PART I

EUMETSAT funded

ESA funded

Paves the way to design ORORO or Spire-type or ?



MetOp-GRAS a/b/c

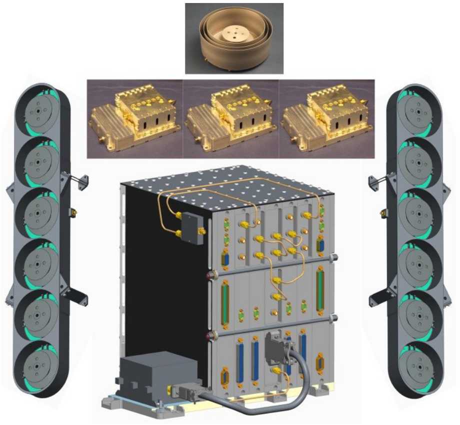
Dataset for optimisation of tracking strategies for RO
Mar-2012 (DMI, ECMWF, RUAG)

Consolidation of future RO critical elements
Jan-2015, (RUAG)

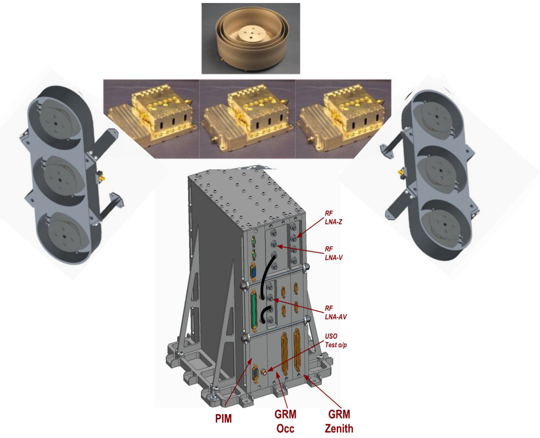
Used to develop MetOp-SG
(RUAG)

Used in GOPALS
Mar-2015,
(RUAG)

MetOp-SG



GOPALS



Two key questions ?

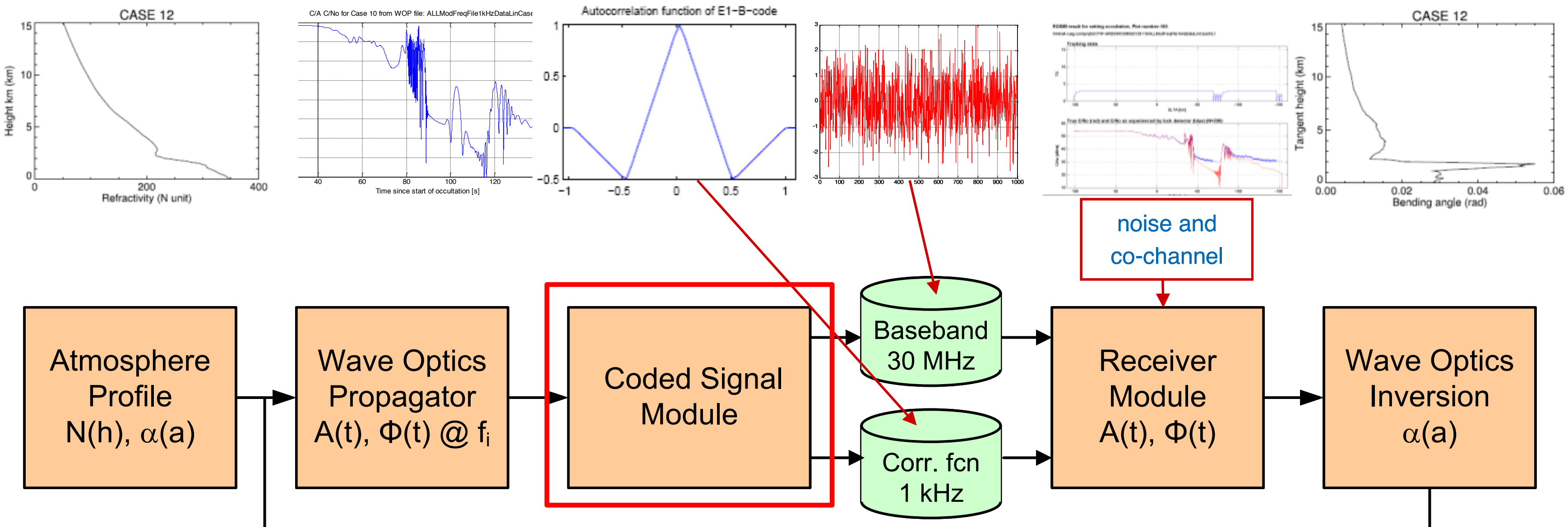
How can we **model/understand** the error sources (Rx & inversion algorithms)?

- Developing an End-2-End simulator that gives a truth against to compare, including realistic data sets.

How can we assess the **impact of increasing the number of RO measurements** available?

- Background: improvements in MetOp-SG, Rx for multi-GNSS signals, and also Cicero-GeoOptics, Spire, Planet...
- Ensemble Data Assimilations (EDA) vs. Observation System Simulation Experiments (OSSE).
- New questions arising: do RO systems of reduced performance contribute equally?

E2E simulator scope



noise and co-channel

Atmosphere Profile N(h), $\alpha(a)$

Wave Optics Propagator $A(t), \Phi(t)$ @ f_i

Coded Signal Module

Baseband 30 MHz

Corr. fcn 1 kHz

Receiver Module $A(t), \Phi(t)$

Wave Optics Inversion $\alpha(a)$

Model Atmosphere

Δ

Retrieved Atmosphere

Error Characteristics

Ref. Atmospheres
55 ECMWF cases

Wave Optics
Forward Model DMI

PRN Code
Modulation

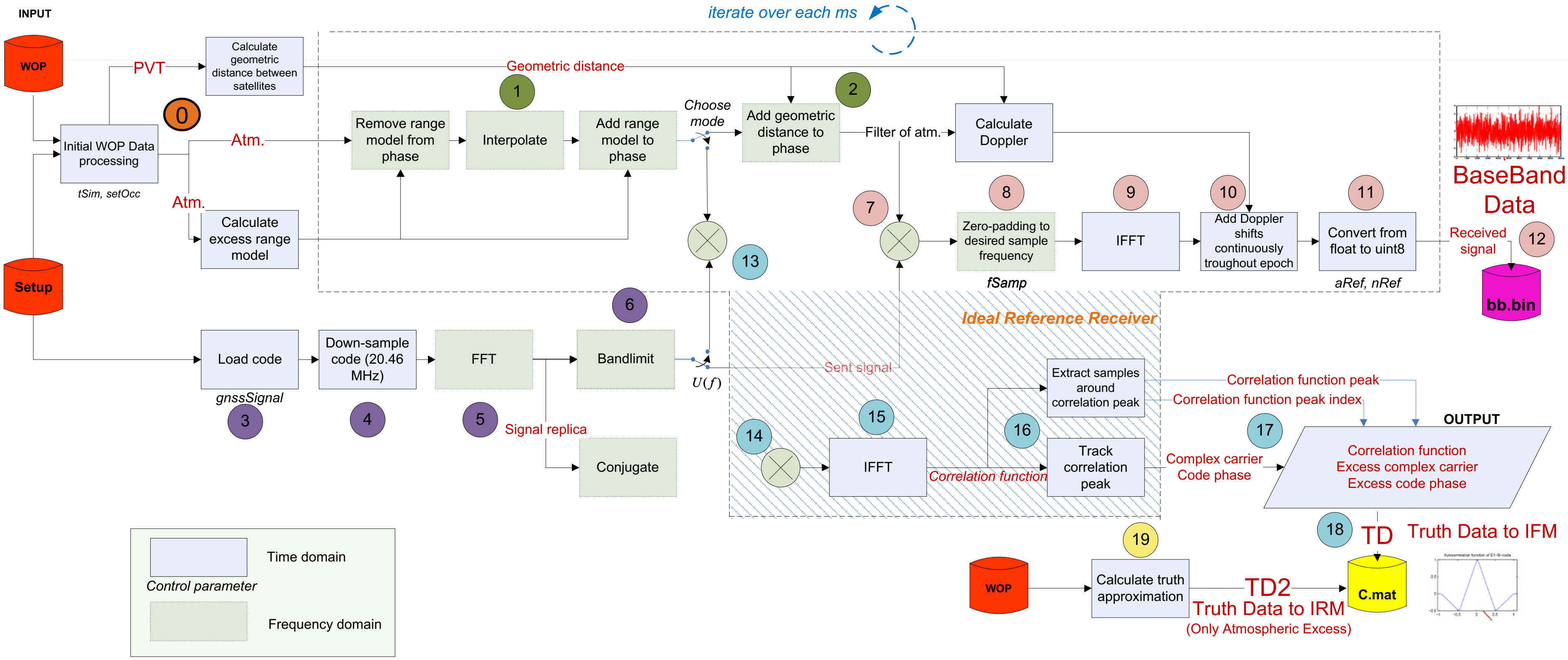
Instrument Model Design
Reference for GRAS-2
(ESA studies)

Retrieval
Algorithm

Zoom on the Coded Signal Module (CSM)

INPUTS
- 0 - Atmospheric excess carrier range
- 1-2: Geometric pseudorange (linear distance) of the signal
- 3-6: Code replica function (without geometry)

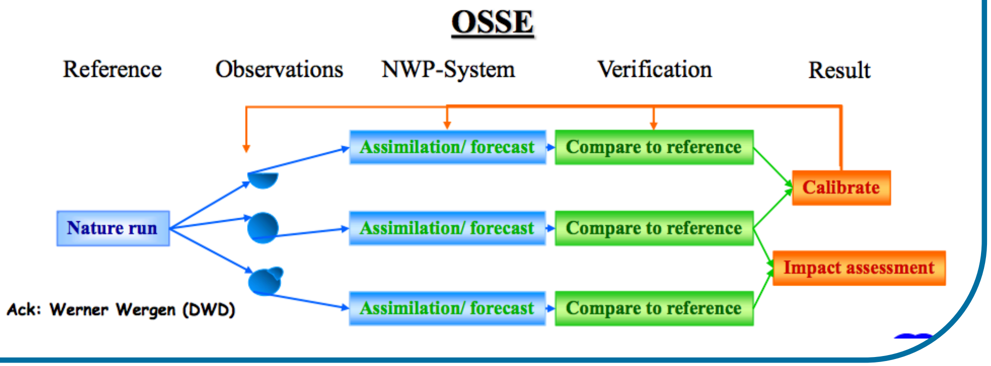
OUTPUTS
- 7-12: Baseband signal from ADC (incl. Doppler) at MHz
- 13-18: True data (at AutoCorrelation peak) at kHz



Comparing EDA & OSSEs

OSSEs: simulate all observations from a known truth - *the nature run*.

- The simulated observations are assimilated into an NWP system, and **individual analysis and/or day "n" forecast errors**, **ε**, can be computed because the truth is known (*nature run*).
- The **statistics** of the analysis/forecast errors can be computed by averaging errors, **ε**, over the experiment.

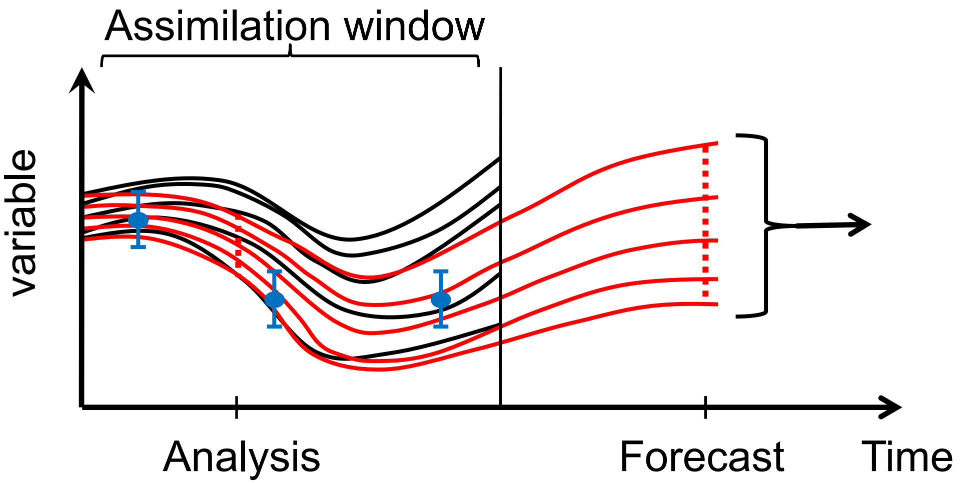


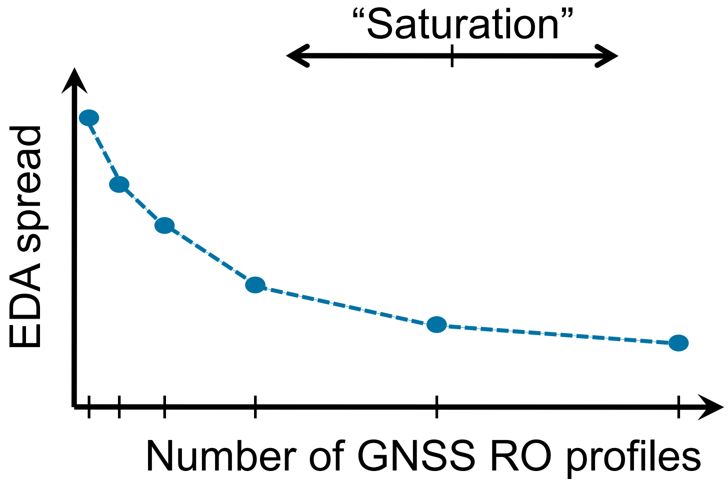
Ack: Werner Wergen (DWD)

EDA: We directly estimate the analysis and forecast error covariance matrices

- The PDF of the errors rather than the actual forecast errors - based on the assumed observation/model error statistics.
- The EDA is an error propagation exercise.

Example: EDA based GNSS-RO impact



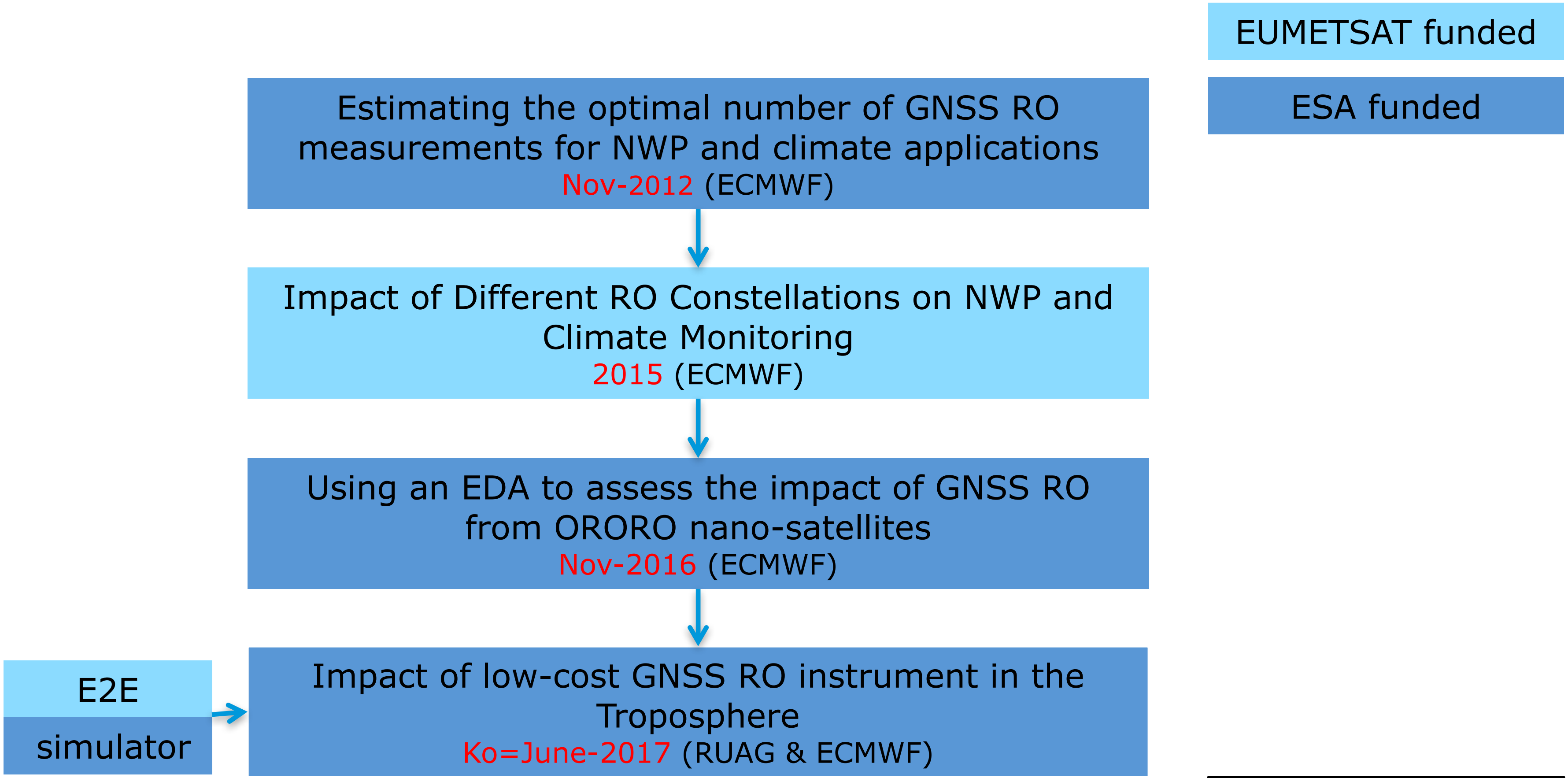


- Aim to investigate ensemble spread as a function of GNSS-RO number.
- Identify, if and when the impact begins to "saturate".
- This was the output of the ESA Study with ECMWF called:

  Estimating the optimal number of GNSS RO measurements for NWP and climate applications

European Space Agency

EDA analysis – How did we get there ?



EUMETSAT funded

ESA funded

Estimating the optimal number of GNSS RO measurements for NWP and climate applications
Nov-2012 (ECMWF)

Impact of Different RO Constellations on NWP and Climate Monitoring
2015 (ECMWF)

Using an EDA to assess the impact of GNSS RO from ORORO nano-satellites
Nov-2016 (ECMWF)

E2E simulator

Impact of low-cost GNSS RO instrument in the Troposphere
Ko=June-2017 (RUAG & ECMWF)

Paves the way for evaluating ORORO or Spire or ?

Impact of Different RO Constellations on NWP and Climate Monitoring (2015)

Scenario	LEO Satellites	GNSS Satellites	Info
4	EPS-SG A1, B1	GPS, Galileo	2 EPS-SG satellites, about 2,800 occultations /day
6	EPS-SG A1 RO-Night	GPS, Galileo	2 RO satellites, about 2,800 occultations/day; check 2 RO in one orbit plane to 2 RO in different ones
7	EPS-SG A1, B1	GPS, Galileo GLONASS BeiDou	2 EPS-SG satellites, about 5,100 occultations /day; maximum number of occultations in one orbit, is a saturation visible in one orbit?
8	EPS-SG A1, B1 COSMIC-2 Eq	GPS Galileo	2 EPS-SG satellites, 6 COSMIC-2 Equator satellites, about 10,500 occultations/day; check impact of few occultations at high/mid latitudes
9 CORE	EPS-SG A1, B1 COSMIC-2 Eq + Po	GPS,Galileo	2 EPS-SG satellites, 6 COSMIC-2 Equator satellites, 6 COSMIC-2 Polar satellites, about 18,000 occultations/day + 16, 32k and 64k observ. with 2 and 3 urad error observ.
10	EPS-SG A1, B1 RO-Night RO-Early Morning	GPS, Galileo	4 RO satellites, about 5,400 occultations/day; check 4 RO coverage compared to COSMIC-2 Polar, Equator
11	EPS-SG A1, B1 COSMIC-2 Eq RO-Night RO-Early Morning	GPS, Galileo	10 RO satellites, about 13,300 occultations/day; check how 4 sun-synchronous RO satellites compensate for no COSMIC-2 Polar
13	EPS-SG A1, B1 Sentinel-6	GPS, Galileo	2 EPS-SG satellites, one Sentinel-6 (Jason-CS) satellite, about 3,800 occultations/day
14	EPS-SG A1, B1 COSMIC-2 Eq, Po Sentinel-6	GPS, Galileo	2 EPS-SG satellites, 6 COSMIC-2 Equator satellites, 6 COSMIC-2 Polar satellites, one Sentinel-6 (Jason-CS) satellite, about 19,000 occultations/day
15	EPS-SG A1, B1 COSMIC-2 Eq, Po Sent.6, LEO-1,2,3 (06:00,10:30,13:30)	GPS, Galileo	2 EPS-SG satellites, 6 COSMIC-2 Equator satellites, 6 COSMIC-2 Polar satellites, Sentinel-6 satellite, one early morning LEO, one in close by EPS-SG orbits, one in early afternoon orbit, about 22,800 occultations/day

Using an EDA to assess the impact of GNSS RO from ORORO nano-satellites (2016)

Core = 18k occ. with 0.5 urad BA error
Others with 2 or 3 urad BA error

Temperature spread values

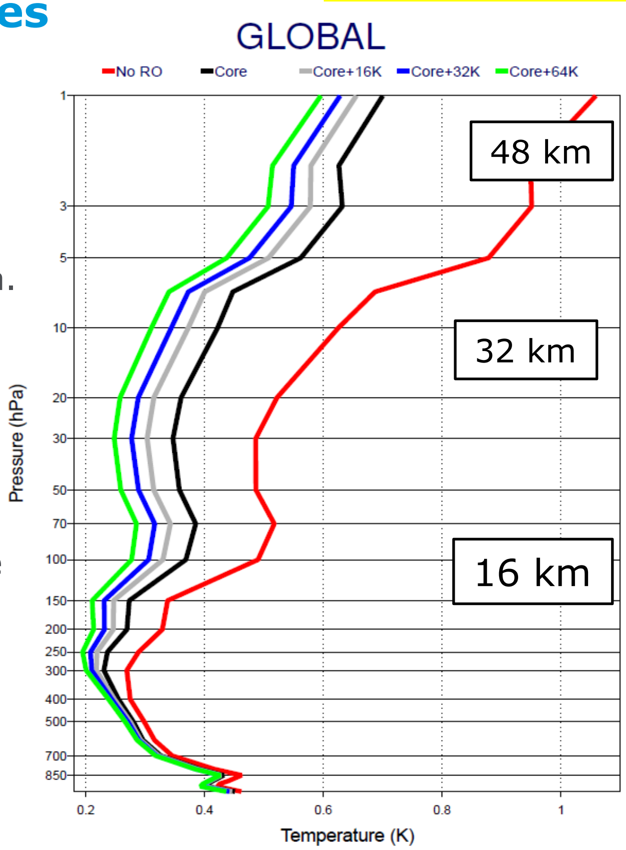
Globally averaged, but the hemispheric results are similar.

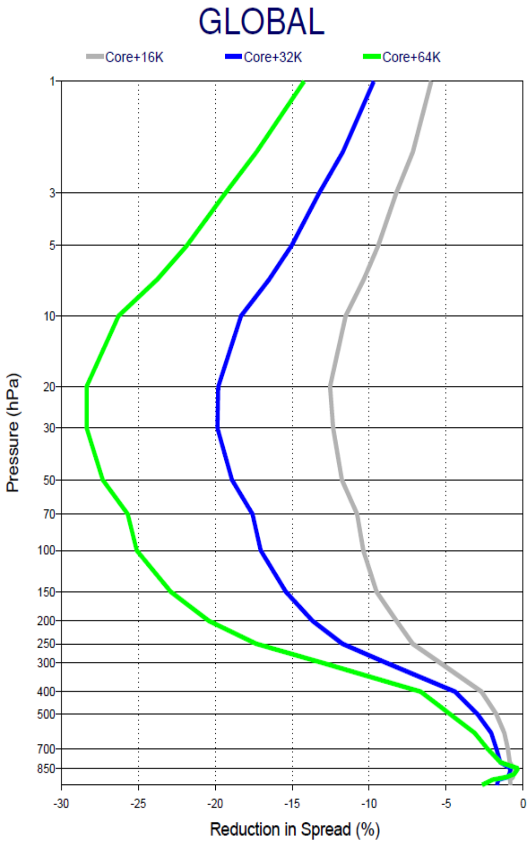
The core observations produce a big reduction in spread, but the ORORO clearly have some impact up to 1 hPa.

$$100\times\frac{EDA_{core+nK}-EDA_{core}}{EDA_{core}}$$

Largest impact of ORORO between 100 hPa to 10 hPa, but clearly some impact up to 1 hPa.

Spread reduction with 64k ORORO
- 25% at 100 hPa
- 15% at 1 hPa

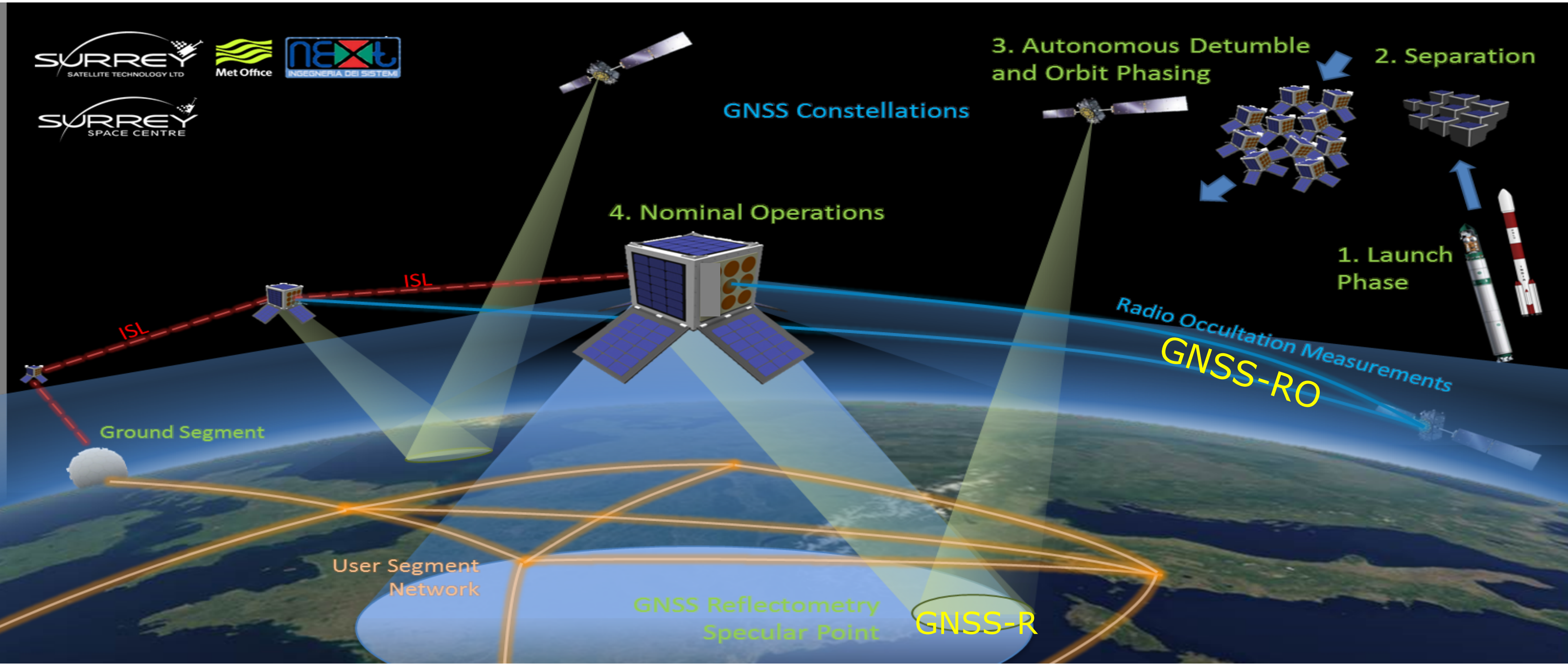




Will ORORO perform as well in the troposphere? What limits tropospheric impact? Receiver or Retrieval?

ORORO Mission concept

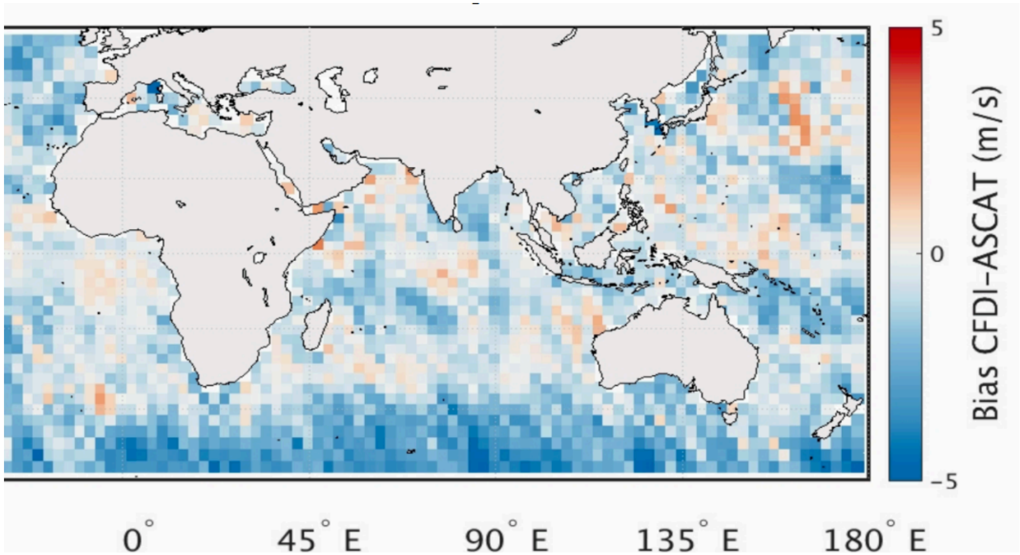
PART II

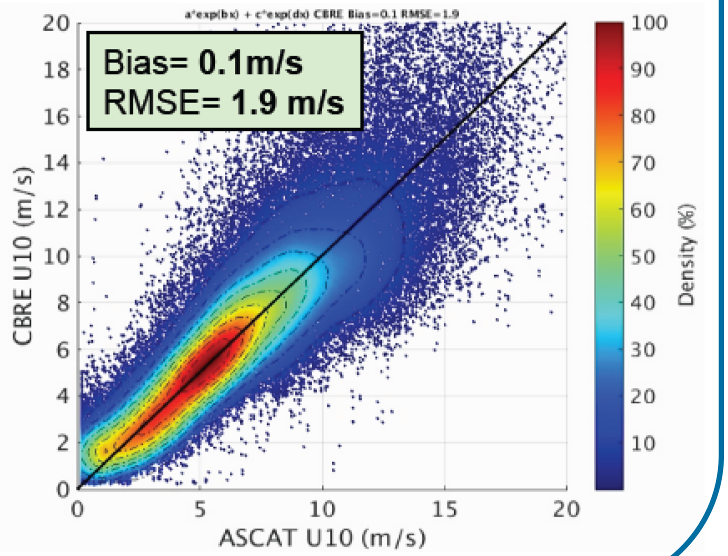


Increase temporal resolution for impact on NWP

GNSS-Reflectometry (Sea Wind & Sea State)

Too early for impact, but very promising results from using UK TDS-1 mission by UK National Oceanographic Centre (G. Foti et al. GNSS-R 2017)





GNSS Radio Occultation

ECMWF latest results from ESA study as shown before.

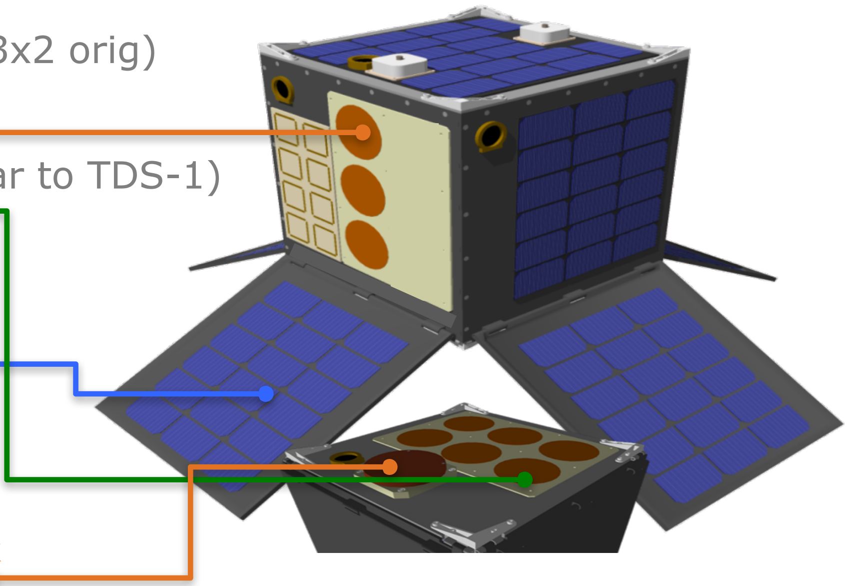
The Impact of different RO Constellations on NWP, S. Healey, Oct. 2016, ESA Ctrct 4000116920

Requirement drivers

Revisit time

- RO: Large number of occultations, target 100,000 (MetOp sees ~700 occ./day)
- GNSS-R: 6 to 12 hours for Global NWP & Climate Monitoring < 1% gap equator
  - → Recommendation to have 3 planes x 10 nanosat per plane, each < 30 kg

Good measurements → good SNR → Reasonable antenna size → 3x3x3 (27U) CubeSats



RO antenna: 3x1 Cubes: 30 cm x 10 cm (3x2 orig)

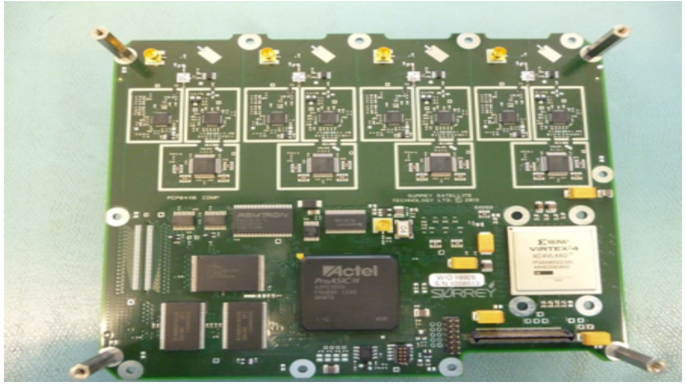
GNSS-R antenna: 3 x 2 Cubes (very similar to TDS-1)

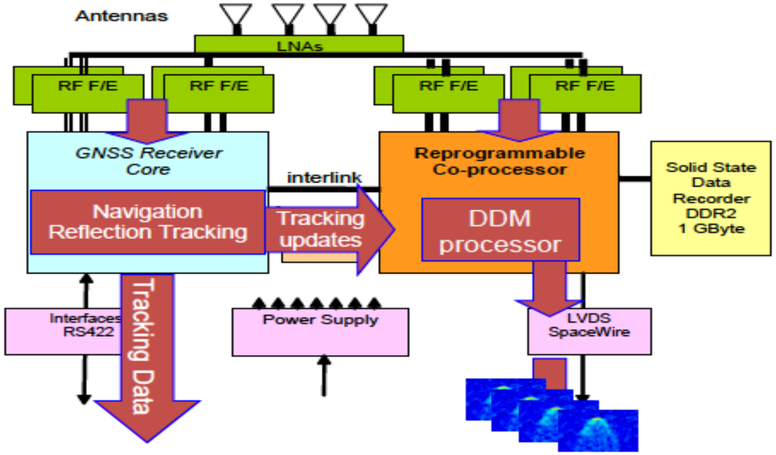
Solar Arrays

S or X-band downlink

ORORO Payload (SSTL)

Antennas: RO, GNSS-R (~13 dBi), POD





GNSS-Receiver (study funded by EOP started in Q1-2017)

- One board GNSS-RO (2 μrad target) + GNSS-R + POD & planning of observations.
- No redundancy at satellite level (redundancy is at constellation level).

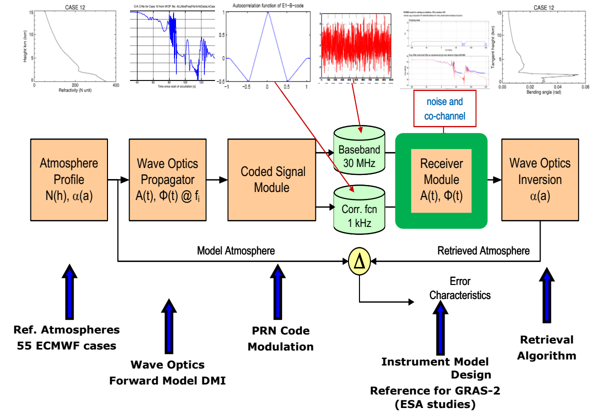
GNSS signals

- Minimum is GPS + Galileo (goal is also Beidou and Glonass)
- GNSS-R: only L1 (for scatterometry, but dual-freq. for extension to altimetry)
- GNSS-RO: dual frequency (L1, L5) - POD also dual freq.

See: http://smosstorm-project.oceandatalab.com/files/Workshop/Session%206%20-Future/ORORO%20Met%20Office%2016%20v2.pdf

Impact of low-cost GNSS RO instrument in the Troposphere

PART III



Atmosphere Profile N(h), α(a)

Wave Optics Propagator A(t), Φ(t) @ f_i

Coded Signal Module

Baseband 30 MHz

Corr. fcn 1 kHz

noise and co-channel

Receiver Module A(t), Φ(t)

Wave Optics Inversion α(a)

Model Atmosphere

Retrieved Atmosphere

Δ

Error Characteristics

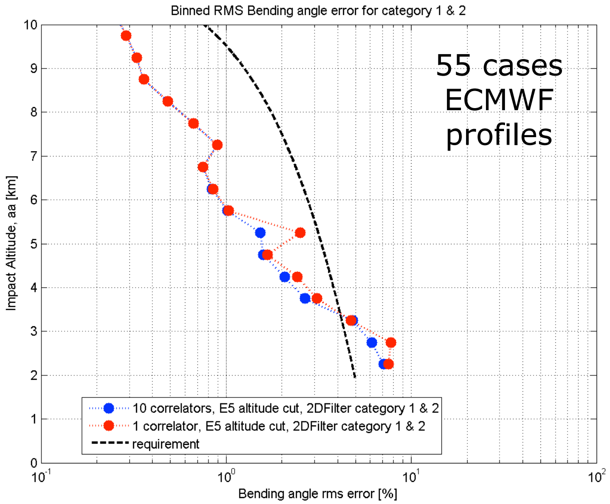
Ref. Atmospheres 55 ECMWF cases

Wave Optics Forward Model DMI

PRN Code Modulation

Instrument Model Design Reference for GRAS-2 (ESA studies)

Retrieval Algorithm



55 cases ECMWF profiles

ESA study - Kicked Off in June-2017 (RUAG + ECMWF)

Address questions like:

- Optimal design for MQ: impr. USO clocks, antenna less elements, impr. front end, higher integration (e.g. LNA)
- Compute BA error (for the 55 profiles) for High-Quality (HQ) and Medium-Quality (MQ) receivers. BA profiles from a WO/FSI inverse through a 2D field.

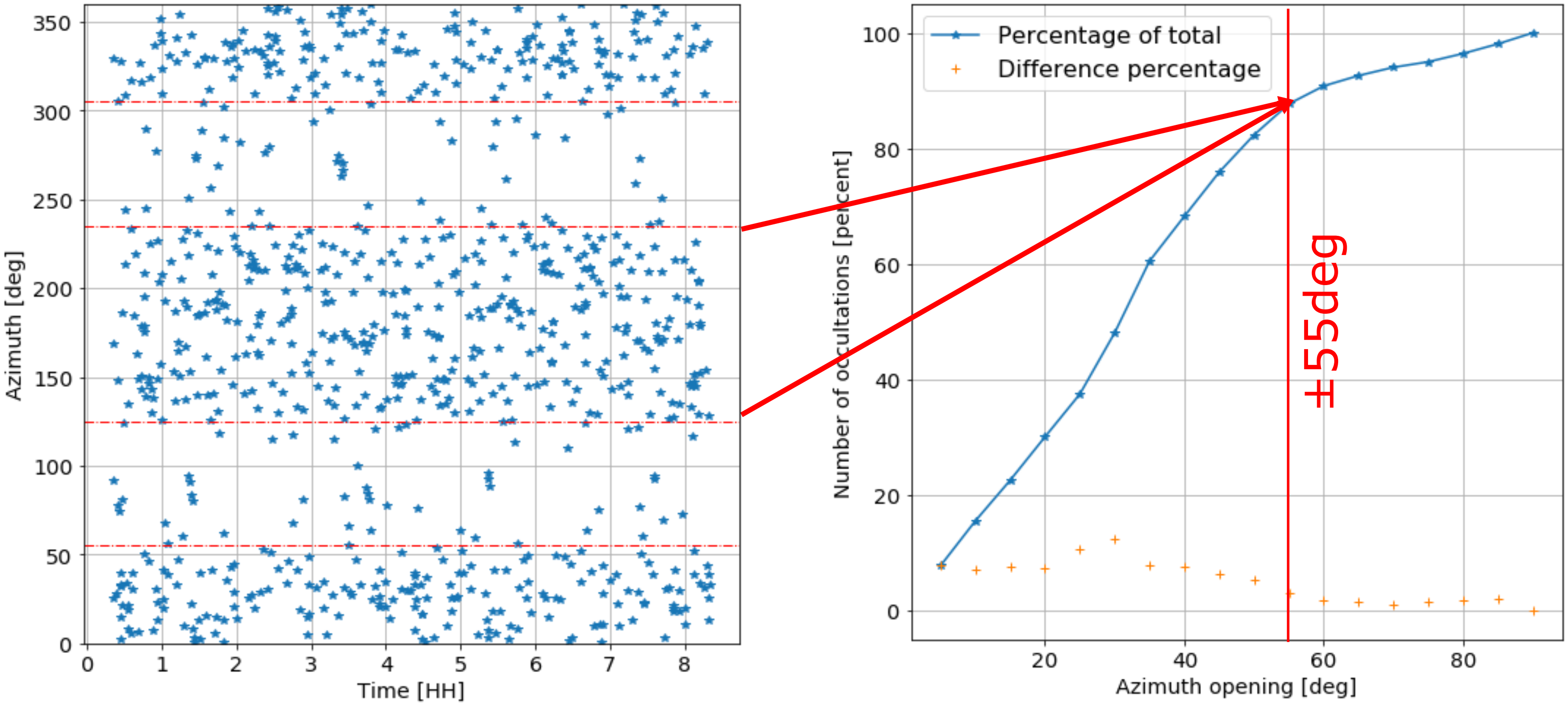
=> error contribution from Rx or retrieval?

- Do we lose the signal earlier (high SLTA) with MQ-Rx?

Useful for:

- RUAG to miniaturize their RO instruments in hosted payloads (e.g. Sentinels or Earth Explorers) or cubesats.
- Also scientifically (upcoming Spire, Planet, ORORO, etc)

Impact number antenna elements azimuth



Azimuth distribution occultations

% out of 700 total /day /const.

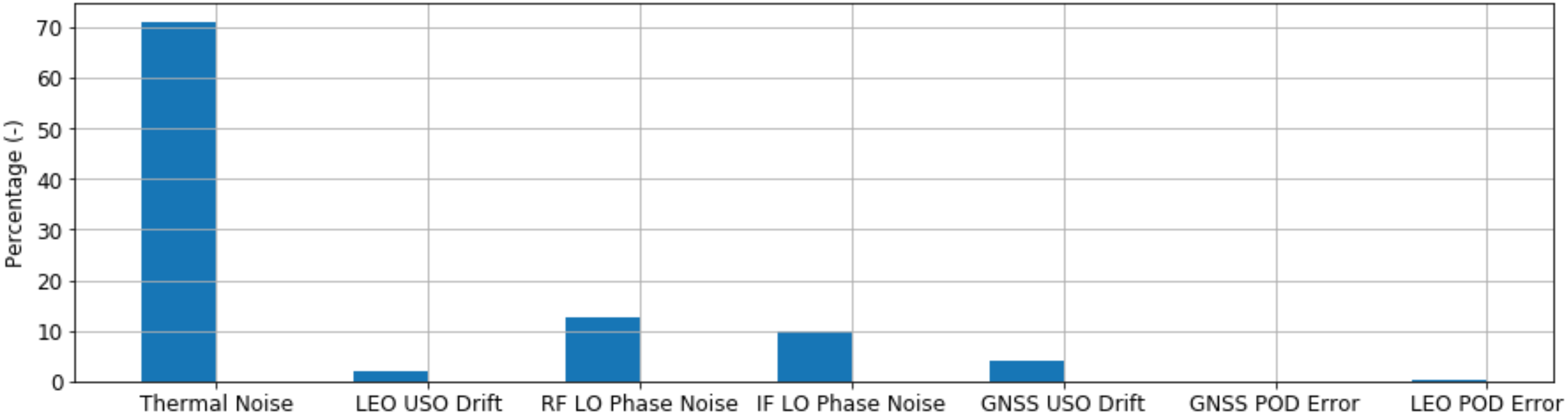
MQ RO Performance with improved clock

Assumptions

H_{LEO} 500 km
$USO_{\_AD\_GNSS}$ 1e-12
$USO_{\_AD\_LEO}$ 5e-13
$RF_{\_LO\_PN\_1Hz}$ -50dBc/Hz
$Target_H$ 35 km
L1/L5 frequency

RO Accuracy

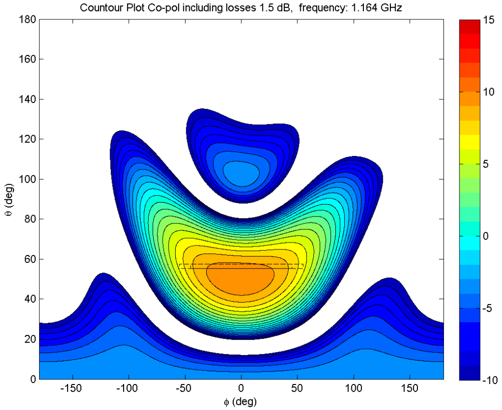
BA_{Error} 0.93 µrad
close to METOP-SG



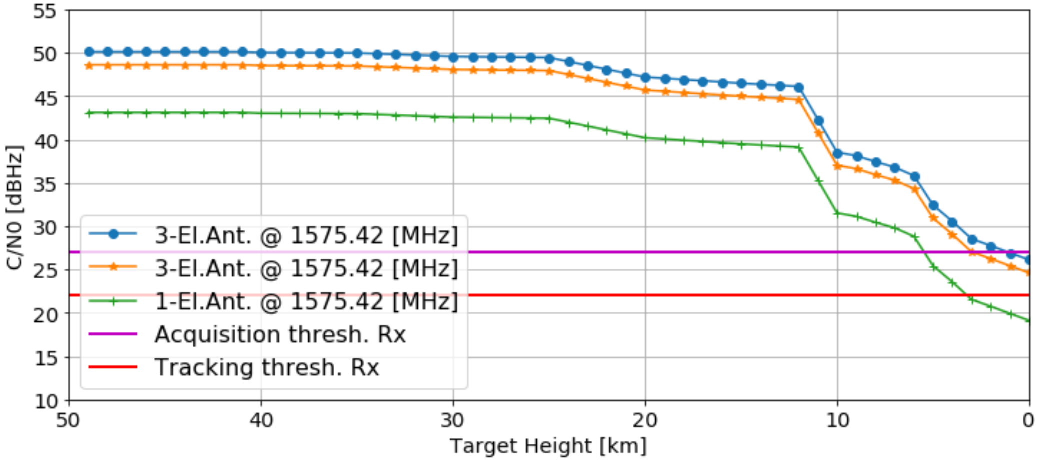
Main contributors:

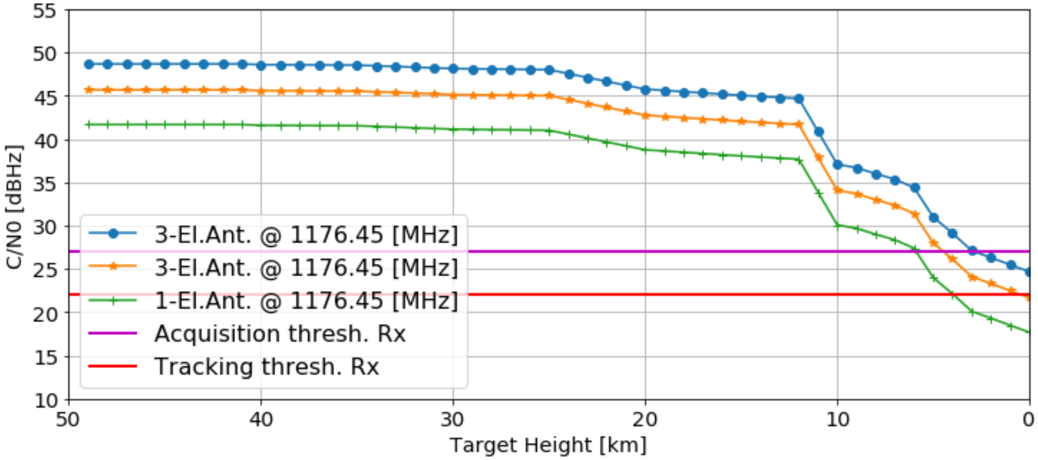
- **Thermal**->SNR->gain (antenna size)
- **Clock technology** (phase noise, ADEV)

Acq. & tracking RO with small antenna



source: 3 el Gopals/RUAG





Next Generation of AGGAs

PART IV

Top priority is to use AGGA-4, but:

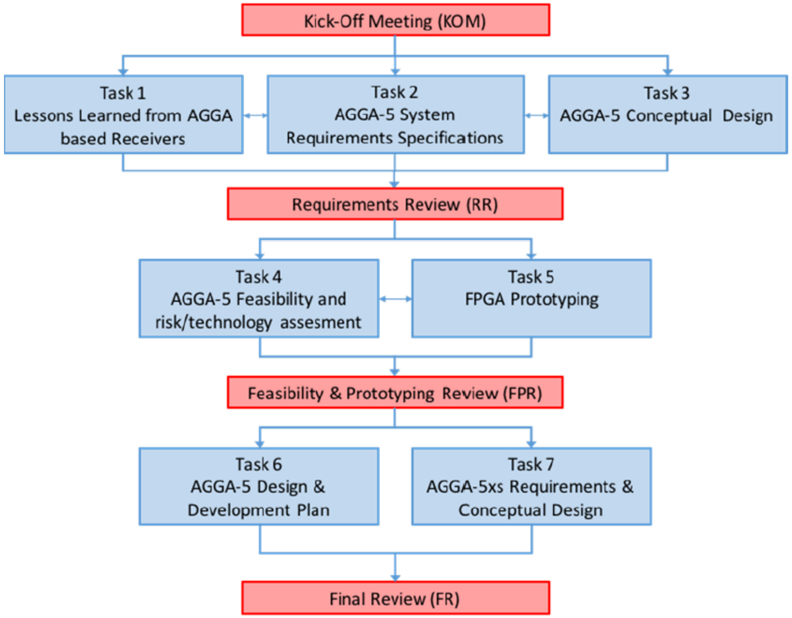
- it takes years to get a good ASIC,
- and we're getting enough feedback to start thinking of AGGA-next

AGGA-5 considerations:

- Possibilities for further integration using more gates with deep sub-micron
- As a result put more channels & frequencies
- Two types of applications:
  - Navigation: POD post processing & RT
  - Scientific: GNSS-RO, GNSS-R and Others

Timeline target dates:

- First FPGA Prototype 2020
- First ASIC Prototype 2022 (if needed)



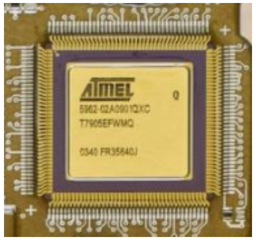
AGGA-5 Feasibility study tasks (Q3-2017)

Development activities will come at a later stage.

AGGA-4 History

AGGA-2 (Advanced GPS/Glonass ASIC)

- Started in ~1995 and manufactured by Atmel [T7905E standard component] in 2000.
- Targeted to EO applications: POD, Radio Occultation (RO) and Attitude Determination.
- Used successfully in many missions (**RO** in bold):
  - ESA: e.g. **MetOp-Gras a/b/c** for RO, GOCE, Sentinels 1/2/3, Swarm, EarthCARE, etc.
  - Non-ESA: e.g. **ROSA** in **Oceansat-2** & **MeghaTropiques**, SAC-C &D, Radarsat-2, Cosmo-Skymed

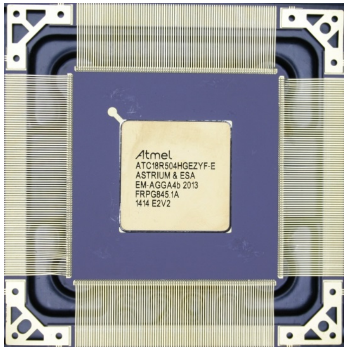


AGGA-4 (Advanced GPS / **Galileo** ASIC)

- New scientific requirements and experience
- New enhanced GNSS signals (GPS / Galileo / Compass-Beidou / Glonass)
- New .18µm ASIC technology allows more on-chip integration (e.g. LEON-µproc)

➔ Used in :

  - ESA: **MetOp-SG (RO+P/F),** S1c/d, S2c/d, S3c/d, S6, Biomass, Proba-3, Neosat, ...
  - non-ESA: CSO, SARah, Comp.Adv Sat.500, Vega-C, SAOCOM, ...

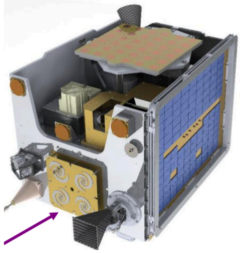


Application: GNSS-R Scatterometry

GNSS-R Scatterometry (TDS-1, NASA's CYGNSS, part of GEROS-ISS) for **wind speed**

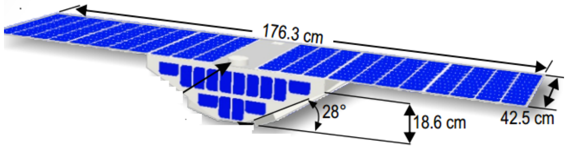
- Delay Doppler Maps (DDMs) of reflected-only signal and relying on open loop (4 in TDS-1)
- Delay = Range ➔ 128 (32 chips) correlators needed in TDS-1
- Doppler = Time Derivative of Range ➔ 20 cells in TDS-1 (500 Hz each)
  - PLL not useful in open loop, using single frequency
  - Optimal scheme for Doppler not present in AGGA-4 → needs to be added

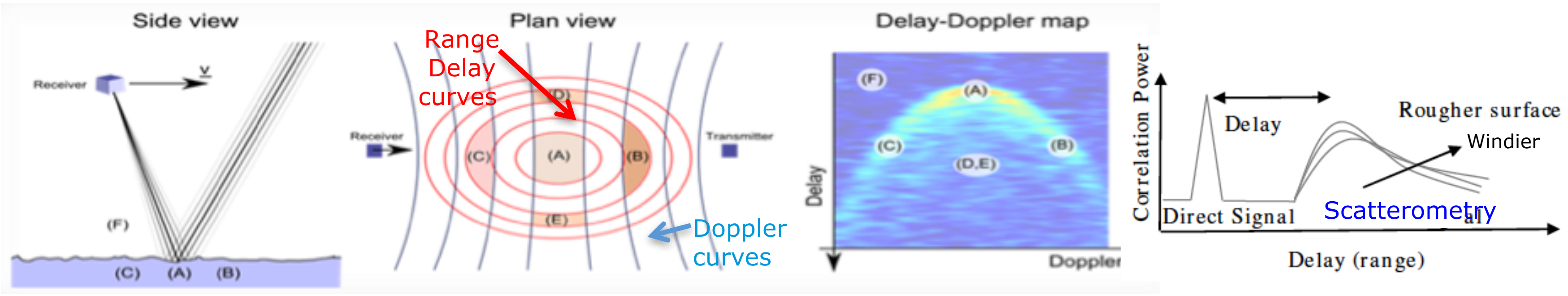
Ref: Final Report with SSTL of ESA Contract. 4000106450



TDS-1 (150 kg)
Launch Jul-2014
SSTL

CYGNSS (20 kgr)
Launch Dec-2016
NASA

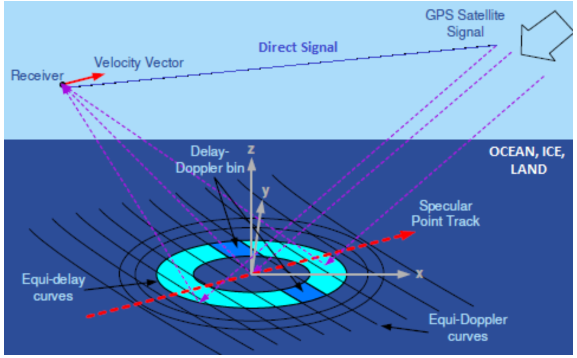


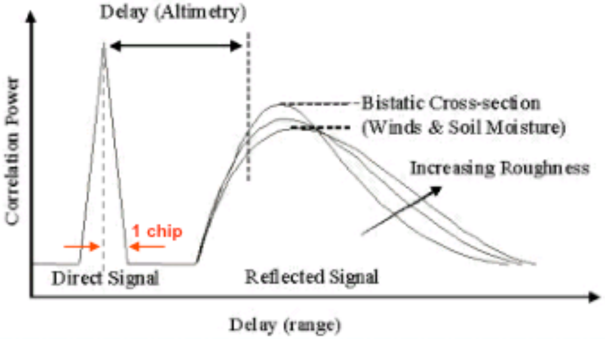


Application GNSS-R Altimetry

GNSS-R Altimetry: more complicated (former PARIS)

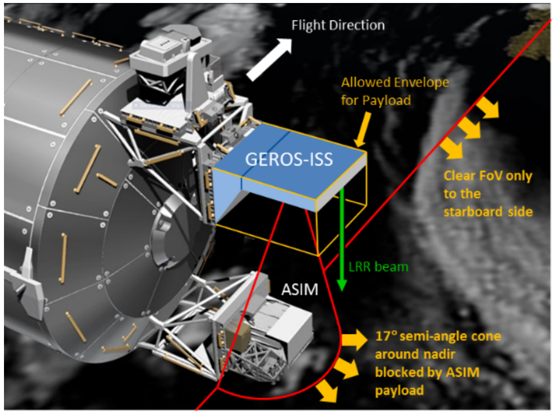
- Cross-correlation with direct signal (not with replica) is required
- → More complex (TBC if feasible for AGGA-5)





GEROS-ISS

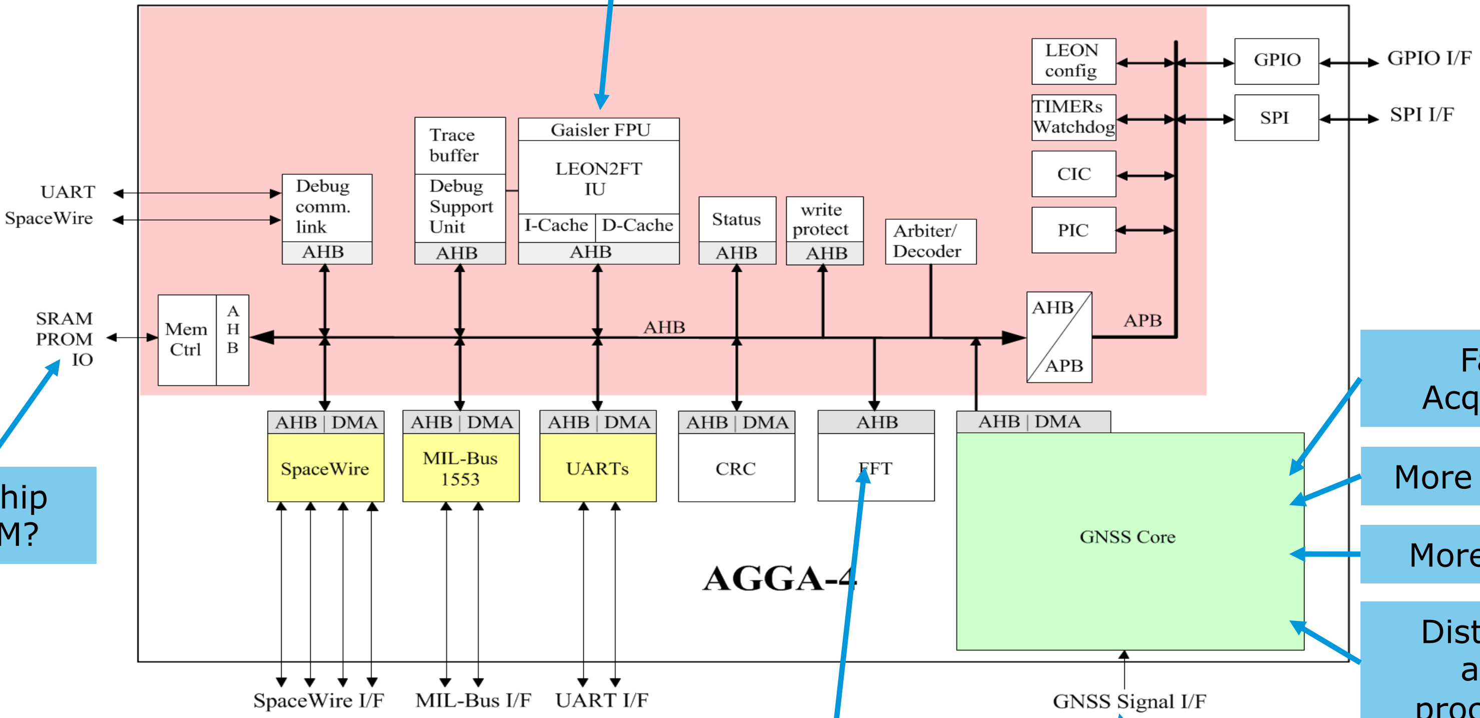
- Currently in Phase-A (launch planned for 2020)
- Aims at GNSS-R altimetry (1st objective)
- Also at GNSS-R scatterometry (2nd objective)



Integration and enhancements

More CPU Power & distributed cores ?

Deep submicron technologies and FPGA?



On Chip SRAM?

Faster Acquisition

More channels

More signals

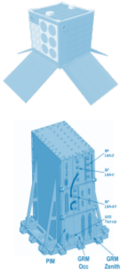
Distributed aiding processors?

Bigger FFT sizes?

LNA&mixing On chip?

Conclusion

- Long experience with METOP GRAS & METOP-SG
- Simulations & EDA analysis show there is still room for additional RO besides METOP, COSMIC-1/2, SPIRE, etc.



ESA develops new concepts for integration of RO instruments in:

- Dedicated nano-satellites
- On board computer on future EO satellites

AGGA-5 device new requirements investigated:

- POD and GNSS-RO remain the driver
- Additional applications studied like GNSS-R.
- New technology is faster, enables more channels, more flexible

THANK YOU