On the Use of C-band for GNSS

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Use of C/L and S-band for GNSS-Reflectometry and Earth Remote Sensing

- C-band is reserved in the ITU Radioregulations to be used for RNSS from 5000 to 5030 MHz since the year 2000.
- The band 5000 – 5010 MHz is used for the Galileo Uplink
- The band 5010 – 5030 MHz is reserved be used for transmitting navigation services
- Based on the results of the ESA C-band studies (2007-2010), the C-band is still kept reserved for future services. The option to extend this band to 5150 MHz is under discussion.
- Aim of this presentation is to show the specific features of C-band in addition to L-band and to stimulate to the science community to analyse the use of C-band (and S-band) in addition to L-band for Reflectometry measurements
- Question A: Is there an advantage to use C-band instead or in combination with L-band for Reflectometry?
- Question B: Have there been made already investigations to use more than one band for Reflectometry?
- As baseline for a discussion on the C-band scientific use the results of the ESA C-band study are shortly summarized.

Results of the ESA study
Assessment of the Use of C-band for GNSS

1. Aims of the C-band Project
2. Market Analysis for C-band and Identification of C-band Services
3. Constellation Analysis for an optimal C-band service provision
4. C-band Signal and Message Design
5. Analysis of appropriate Payload Concepts and Trade-off
6. User Terminal Architectures for different Services
7. Spacecraft Accommodation
8. Overall Performance
9. Conclusions

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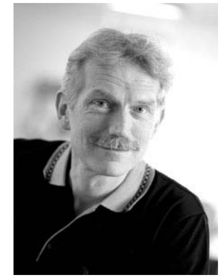

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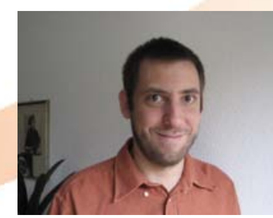

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Authentication
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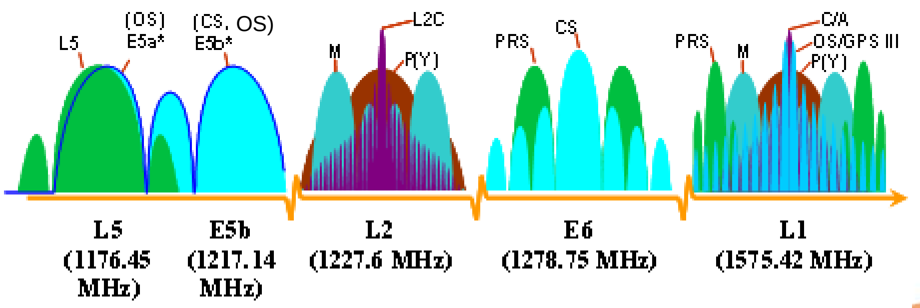
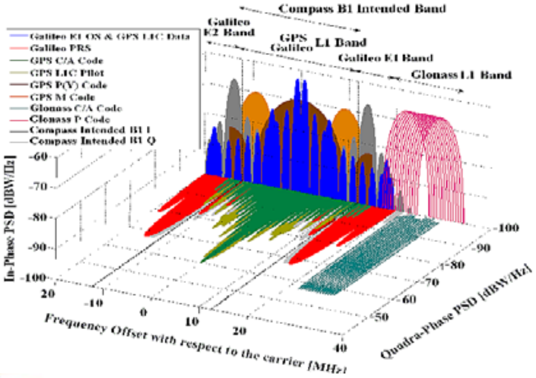
Background

- One main reason which speaks for C-band is the fact that this frequency range (5010 - 5030 MHz) is rather untouched compared to L-band, where existing and new navigation satellite systems proliferate.
- The C-band team lead by Astrium was responsible for a system study analyzing the performance of a C-Band navigation system in addition to L-Band on a future GNSS Constellation.





Advantages of C-Band compared to L-Band

- **Significant smaller ionospheric effects**
  - Reduced vulnerability supports integrity monitoring and carrier smoothing.
  - Single frequency receivers are sufficient as an ionospheric correction is not required.
  - C-band is more robust against ionospheric scintillations!
- **Smaller receiver antennas are possible that lead to**
  - Reduced vulnerability and to higher jamming resistance against unintentional interference.
- **A larger Doppler effect leads to**
  - Better speed accuracy at same C/No.
- **The smaller carrier wavelength leads to**
  - Better carrier phase accuracy for the same C/No.
- **The Multipath performance compared to L-band is improved:**
  - Less specular reflections in C-band
- **No in-band PFD limitation requirement in 5010 – 5030 MHz.**

Drawbacks of C-Band

- Link budget is more critical as:
  - Free-space loss is larger (10 dB)
  - Rain attenuation is larger (< 4 dB)
  - Foliage and wall penetration are larger (> 4 dB)
  - Signal dynamics is enhanced due to higher signal frequency
  - Oscillator phase noise in the receiver is increased.
- Out-of-band emission requirements especially for the radio astronomy band are very stringent.
- Galileo uplink signal from 5000 to 5010 MHz needs to be sheltered.

Aims of the C-Band Project

- The provision of a C-band navigation signal on a future GNSS would make sense:
  - If a set of new services can be offered
  - If there is a market for these services
  - If the C-band link budget deficiencies can be solved
- Is satellite navigation in C – band able to overcome at least some of the L – band problems? Which services can be offered and what technology is needed in space and on ground?
- Can the drawbacks of C-band be compensated by improvements of the system (constellation-, signal-, message, payload- and user receiver design)?

C-Band Services Baseline

Services baseline was selected based on a detailed market analysis: 2 services!

- A global Service with Precision and Robustness SPR and
- A Regional Robust Service RRS.

The SPR shall:

- Provide a signal with additional robustness, protection and precision for GNSS users using vulnerable critical infrastructures:

- Examples: aviation (NPA to precision landing), maritime (AIS), timing in synchronized networks, land (transportation systems, road tolling, etc.

- Support professional satellite navigation in cases where one or more L-Band frequencies are degraded.

- Provide additional correction data for high-precision single-frequency positioning with 1 m horizontal position accuracy.

C-Band Services Baseline

- The RRS service is defined as an additional local, flexible service which adds robustness to the Galileo L-Band services.
- Offers a high level of protection/security against threats which lead to a reduction e.g. of human safety in a local geographic area of interest (e.g. natural disaster).
- Two high-power spot beams provide coverage anywhere on earth with "footprints" 1,500-kilometer in diameter.
- Characteristics of the RRS:
  - Enhances acquisition in foliage and canopy
  - Includes the ability to implement anti-jamming and anti-spoofing techniques
  - Access control to prevent misuse of technologies.
- For both C-band services the ionospheric delay errors are a factor 10 less in the UERE budget compared to L-band, satellite clock and tropospheric delay errors become dominant. Hence value added correction data shall be enclosed in the navigation message:

  Fast satellite clock corrections and low rate compressed meteorological model data per service zone.

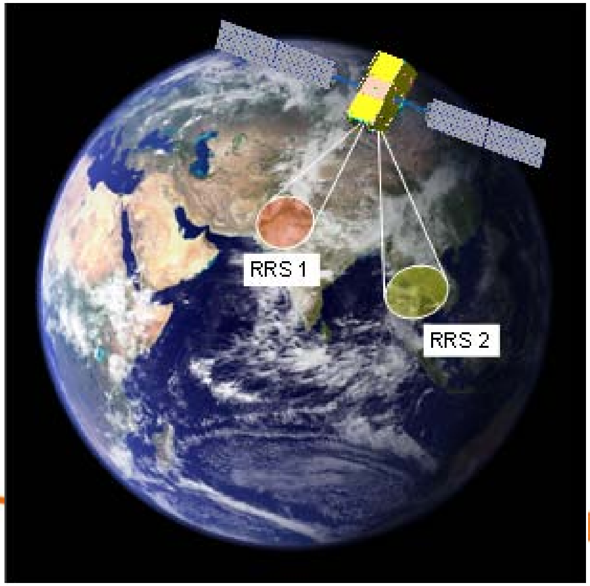
Which Constellation is the best?

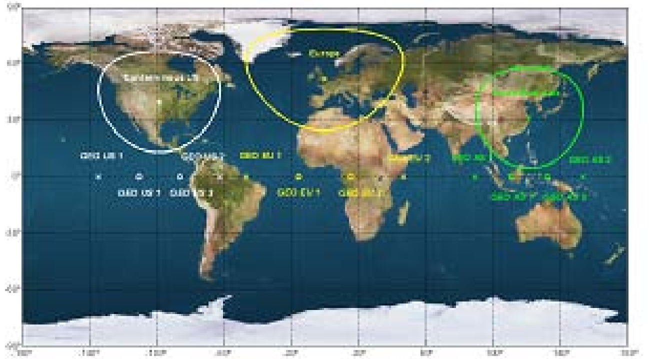
1. Aim was to provide an optimal satellite constellation for the RRS and SPR services.

2. Performance of different constellations has been analysed in order to provide global, semi-global and regional coverage.

3. Semi-global coverage was an option for the SPR in order to serve users in the three major industrial areas of the northern hemisphere, and requiring less satellite power compared to a global SPR.

4. MEO-, GEO-, IGSO- and Molniya constellations were considered as well as beam steering and beam switching modes for SPR and RRS.





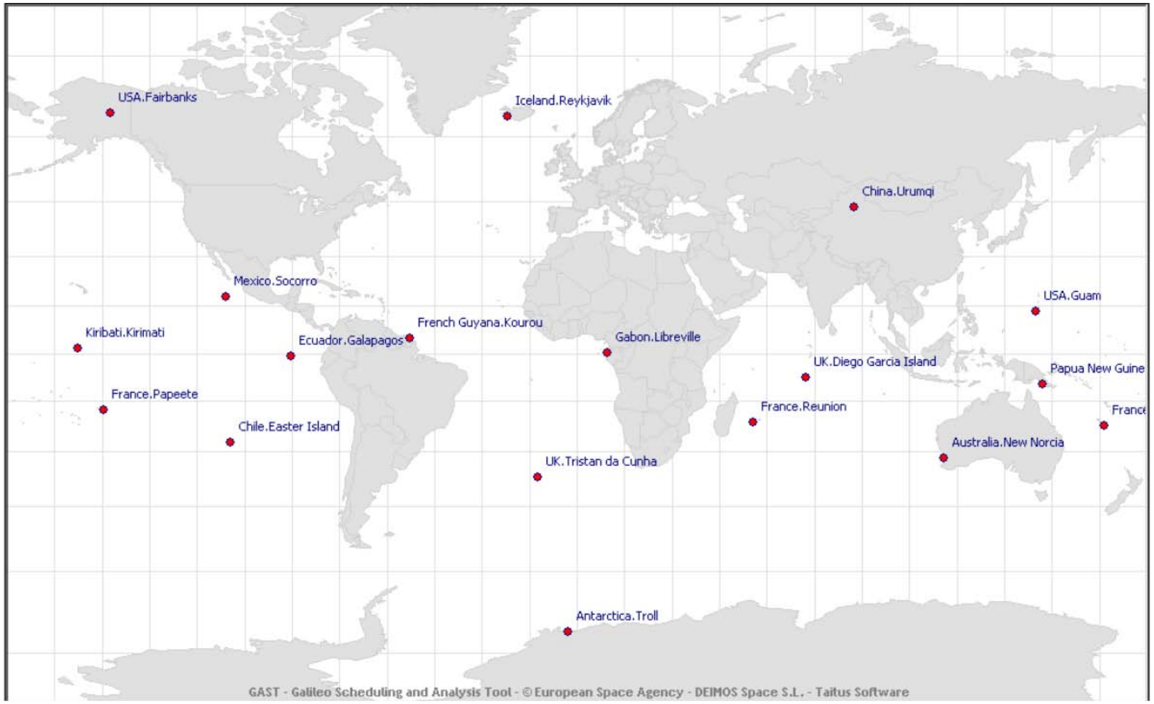
5. Best performance for spot-beam RRS and global SPR is achieved by a MEO constellation with 27 satellites.

C-Band Ground Segment (1)

- Required for the monitoring of C-band signals. Will provide new navigation message data incl. improved tropospheric corrections based on numerical weather data, plus data for RRS spot beam operations.
- C-band Sensor Stations will include signal tracking capabilities in order to determine the biases associated with the spacecraft, C-band antenna and RF chain.
- Using directional antennas for the C-band GSS, C-band measurements will be less noisy, hence will improve the ODTS performance of the GNSS constellation.
- An enhanced GSS architecture will consist of a worldwide network of GSS for L-band OD&TS, plus a subset of upgraded GSSs with C-band tracking capabilities.
- C-band GSS will be more robust against jamming due to larger free-space loss.

C-Band Ground Segment (2)

In order to find the optimum subset of GSS for C-band, an analysis was performed maximizing the constellation visibility and depth of coverage DOC, (the number of GSS, which are simultaneously tracking a specific satellite). Simulations show that 12 GSS are sufficient.

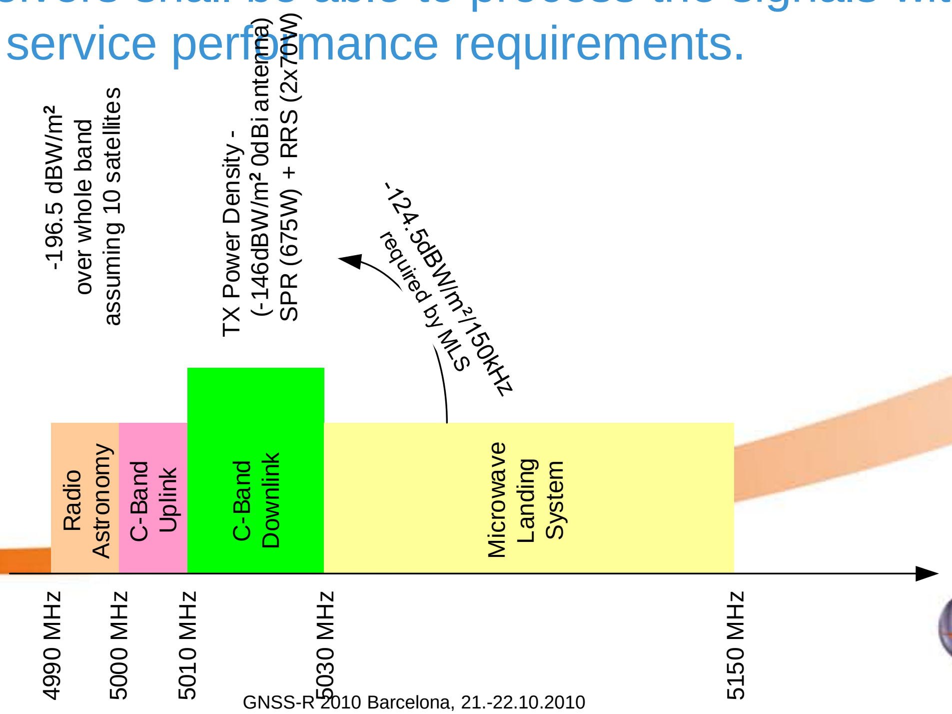


Locations of the C-band preliminary GSS network

A DOC value of 3 is guaranteed with 98.6% availability, sufficient for OD&TS performance estimation purposes.

What are the requirements for the C-Band Signal Design?

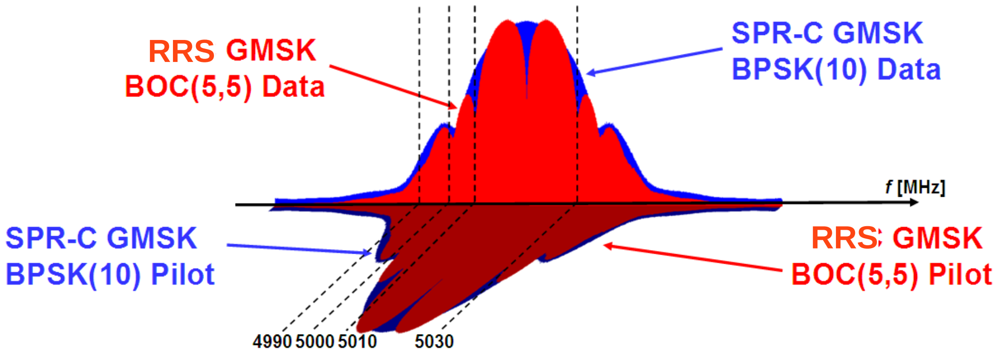
- Signals have to be compatible with the ITU requirements:
  - Radio Astronomy (RA)
  - Microwave Landing Systems (MLS)
- Signals have to be compatible with the requirements of the Galileo Mission Uplink Receiver (decoupling of antennas)
- Payload impact on signals shall be small (distortion, non-linearities of signals).
- C-band user receivers shall be able to process the signals within the required time fulfilling the service performance requirements.



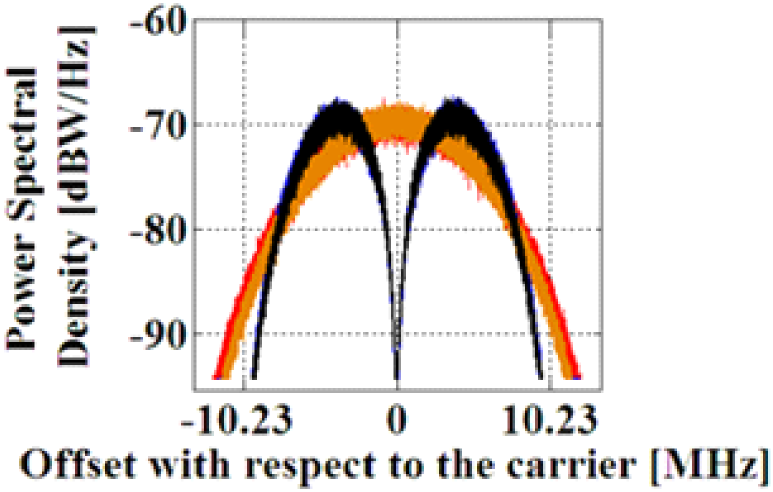
C-Band Signal Design

- More than 20 different signal types have been analyzed. For example Gaussian Minimum Shift Keying (GMSK), Minimum Shift Keying (MSK), Raised Cosine (RC), and Phase Shift Keying (PSK).
- Payload amplifier distortions and non-linearities were considered.
- Special attention was paid for the OMUX filter design in order to achieve feasible filter slopes.

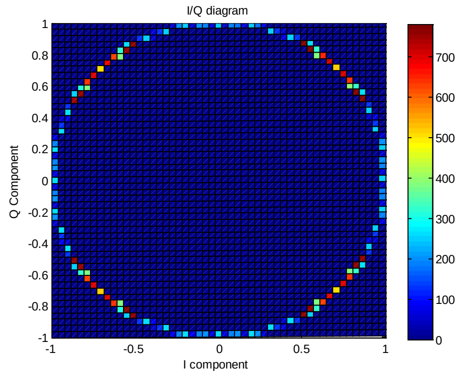
C-Band Signal Baseline



Spectrum of the selected C-Band Signal Plan



GMSK power spectral density as function of carrier offset, red: SPR, blue: RRS)



I/Q Phase Diagram for SPR signal => constant envelope

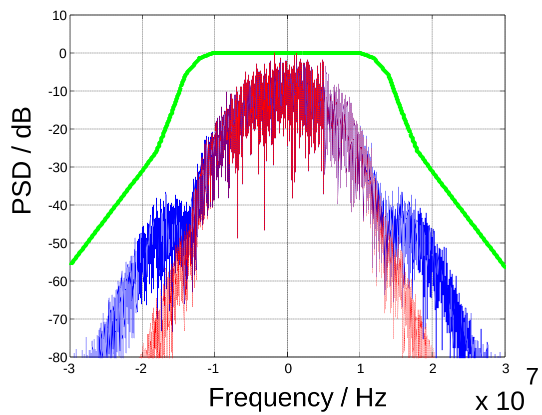
Compatibility: C-band GMSK signals are optimized to use the full 20 MHz bandwidth, they allow spectral separation between the two services and fulfil the ITU and Mission Uplink requirements.

C-Band Signal Baseline

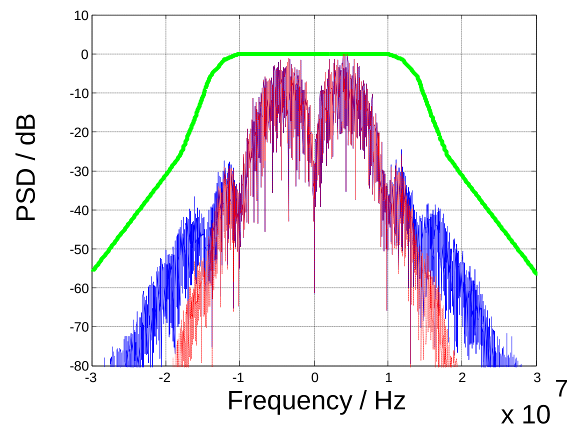
Feasibility can be assured for GMSK only using a filter with a slope of 25 dB/10 MHz. Such filters are available today, hence signals can be implemented!

Performance of Inter chip interference is comparable to Raised Cosine.

C-band Multipath has been estimated by simulations, needs to be verified by measurements. First estimates show a reduction by 25% compared to L-band.



Signal Out-Off band Emission
cut-off by a payload output filter
for SPR: GMSK-BPSK(10)



Signal Out-Off band Emission
cut-off by a payload output filter
for RRS: GMSK-BOC(5,5)

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C-Band User Terminal Design

Aims:

- Design of UT Architectures for SPR and RRS for different user markets
- Perform Analysis for Signal Acquisition and Tracking, achieving the required performance in terms of acquisition, tracking, noise, multipath.
- Provide User Terminal Link budgets in order to verify the user requirements.

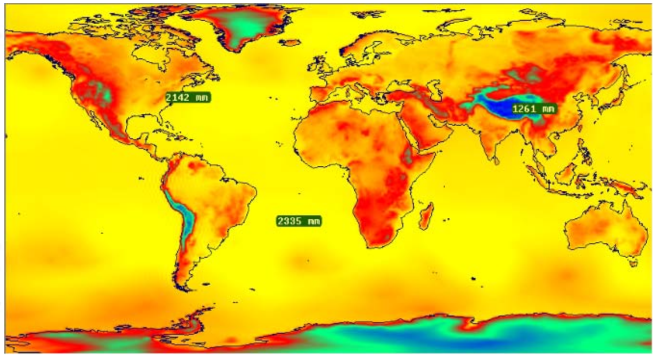
Tropospheric Delay Corrections to improve UERE Budgets

- So called “Blind” models are foreseen for Galileo, they use a climatologic data base (look up tables).
- They work under normal conditions: 5cm failure in zenith, 50cm at 5°elevation (ESA study within GSTB V1).
- They fail under extraordinary conditions, where residuals reach 15 to 25 cm, which means 1.5 m to 2.5 m at 5° elevation.
- Hence better tropospheric corrections are required, esp. for C-band, which is more sensitive than L-band.

<u>Idea is:</u>

- To retrieve tropospheric delay corrections from numerical weather data.
- Resample these data on a grid for the broadcast message format and hence supply a better compensation of this error.
- Initial studies have shown that use of numerical weather data lead to an accuracy of 1.5 cm for tropospheric corrections in the mid-latitudes.

Concept of Tropospheric Delay Corrections



Grid of pressure /zenith hydrostatic delay as seen on July 28, 2008, at 12:00 UTC; values in millimetres.

3D-Numerical weather data

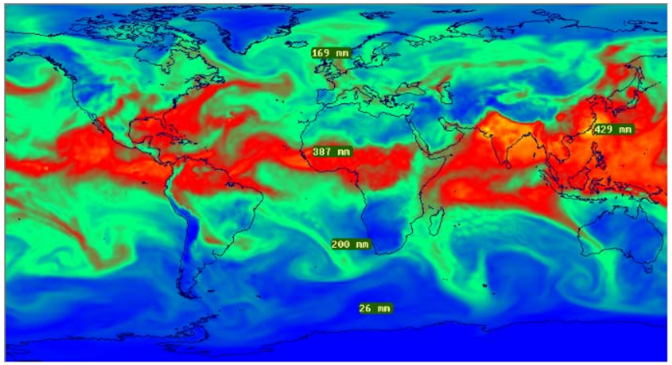
↓

2D-Tropo grid

↙ ↘

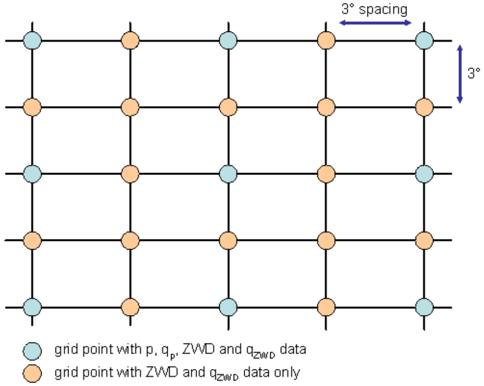
ZHD | ZWD

↓ ↓



Grid of zenith wet delays (surface) as seen on July 28, 2008, at 12:00 UTC; values in units of millimetres.

Embedded into broadcast message: Efficient distribution scheme for individual satellites that allows broadcast of the various granules relevant to the user at a particular location in a minimum of time.



- Difference between actual quantity and blind model will be transmitted.
- Optimization for different regions is possible: polar regions, tropics, ocean, land.
- Rain-rate information can be also integrated in the message.

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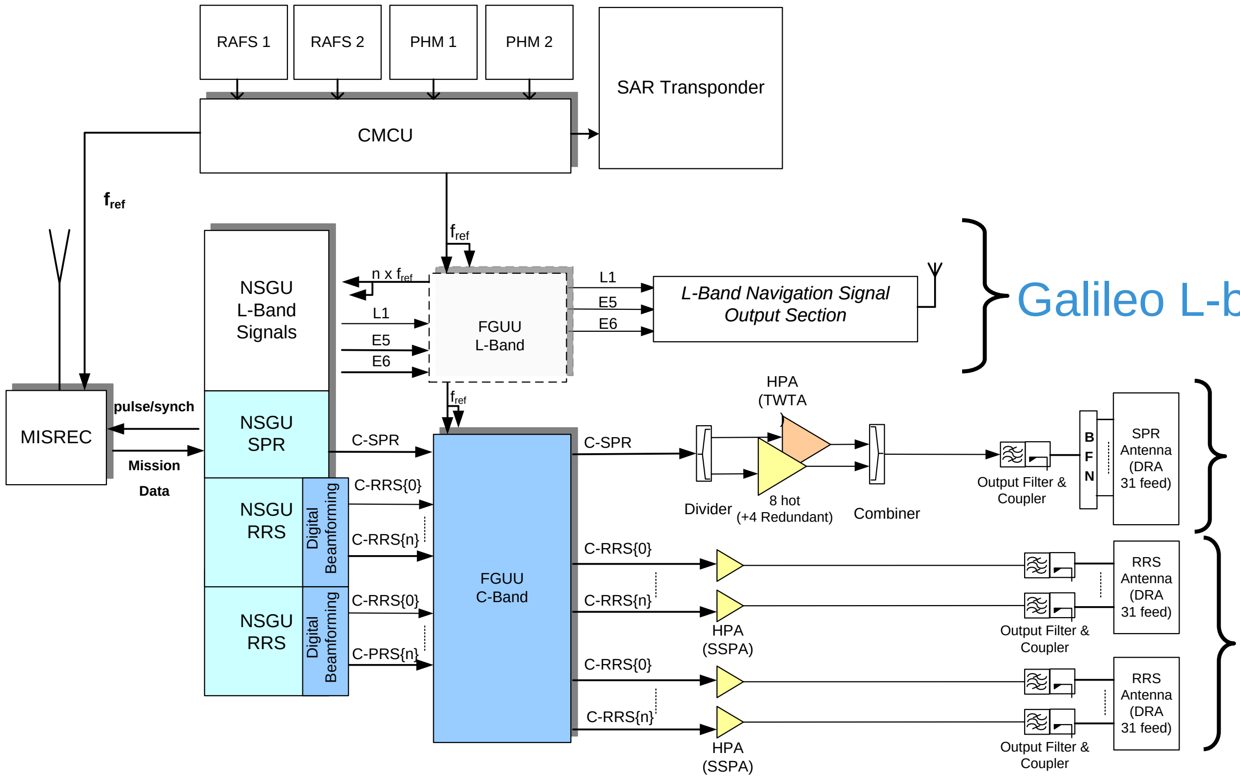
C-Band Payload Design

two different service concepts are possible:

	Service Concept	Required Tx Power
1	Two spot-beam RRS (1500 km)	140 W
2	Global SPR and two spot-beam RRS (1500 km)	815 W

L-band- and C-band PL Architecture with DBF



Galileo L-band services

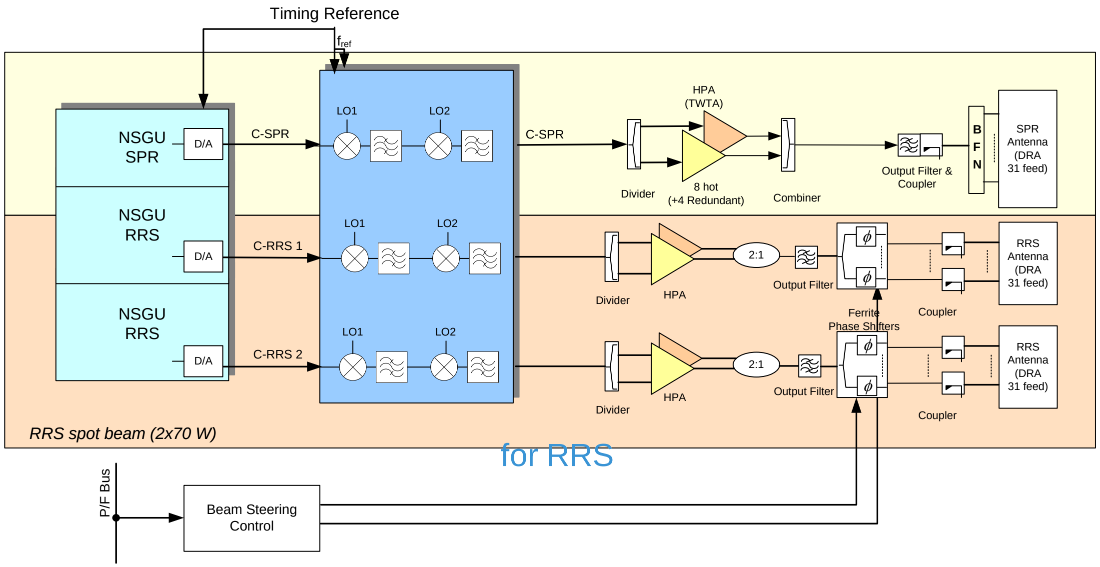
C-band global SPR

2 C-band spot-beam RRS (BFN)

For the C- band RRS services three different payload architectures were investigated:

1. Architecture 1: Digital Beamforming DBF
2. Architecture 2: RF high Power beamforming
3. Architecture 3: Use of a single reflector antenna with mechanical steering.

Selected Architecture for RRS: RF high-power beam forming network



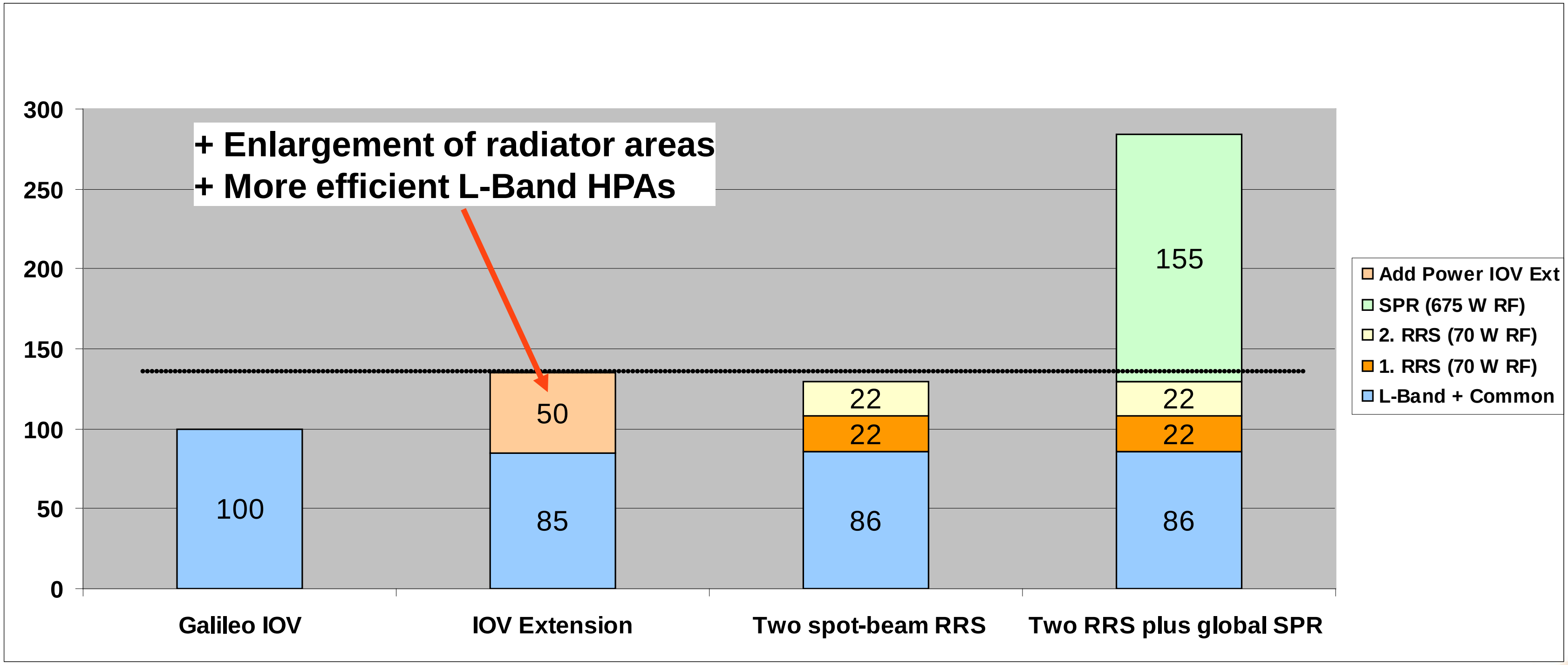
for RRS

Beamforming of RRS signals is done after amplification using ferrite phase shifters. Eases calibration of the payload and allows the use of TWTAs.

Compared to DBF this option has one disadvantage as characteristics of the phase shifters drift with temperature and time.

However compared to DBF fewer sources of phase- and amplitude tracking errors exist as this solution relies on a single RF chain up to the high-power phase shifters.

C-Band Payload Trade-off



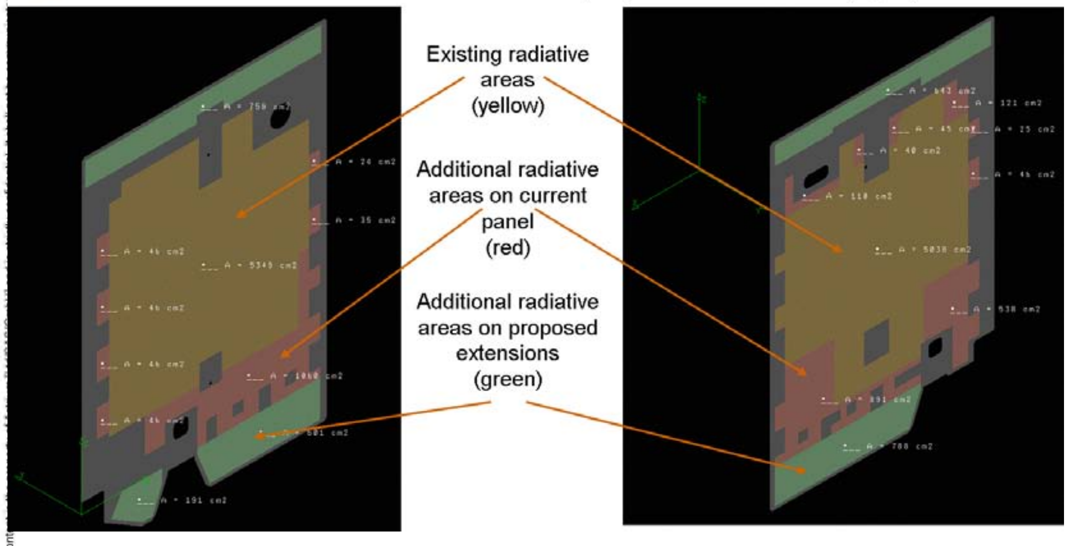
Power of different payload concepts relative to a Galileo IOV satellite:

Two independent C-band RRS services would fit on an enhanced Galileo IOV satellite!

Spacecraft and Launcher Accommodation Concept 1: two RRS services

Increase of the radiator area on the Galileo IOV satellite

- Identified Radiator Areas on PF+Y-Panel (left) and PF-Y Panel (right)



Could be realized by an enhanced Galileo IOV satellite. Two of them would fit on a Soyuz launcher, four would fit into an ARIANE 5 launcher.

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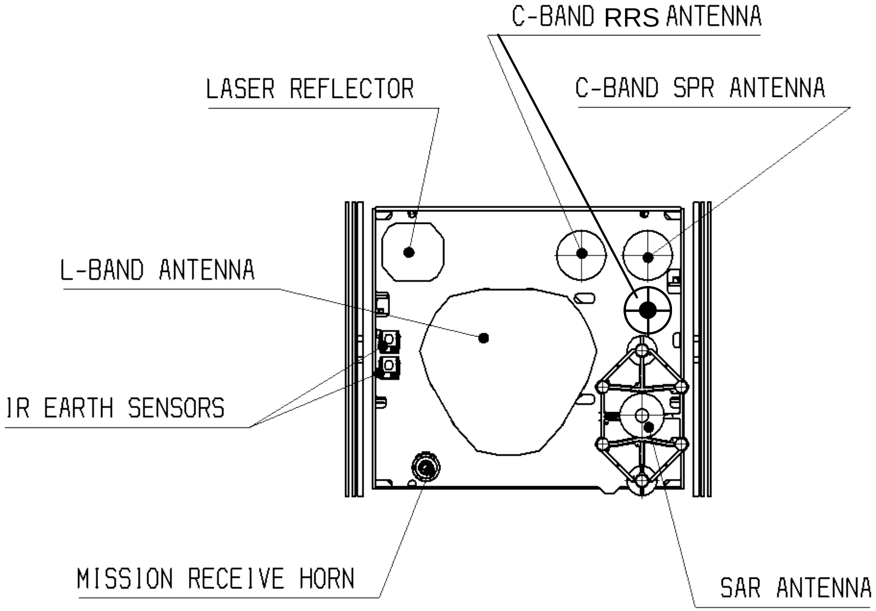
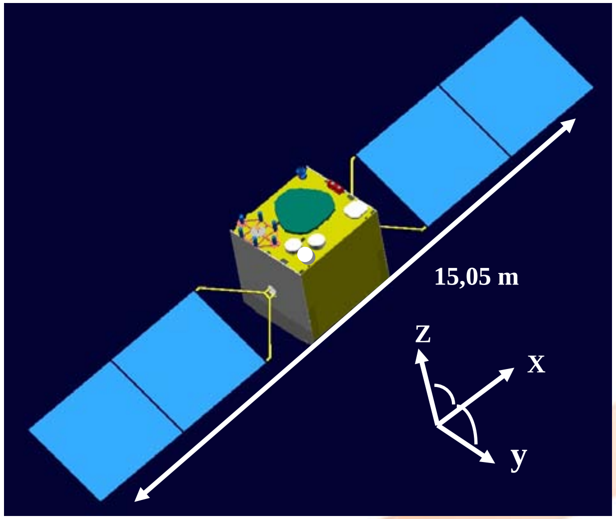
Spacecraft and Launcher Accommodation Concept 2: global SPR and two RRS services

About 3 kW DC power are required, a EUROSTAR 3000 bus is proposed, Power consumption, size and mass are comparable with GPS III.



View on the C/L band antenna side



3-d view of the satellite

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C-Band Performance

Link budgets (Pre-correlation C/No) calculated for different applications

Service	Application/description	Pre-correlation C/No dBHz	C/No threshold, dBHz	Delta dBHz
SPR	1: Exploration land mission in the tropics	31.2	28.7	2.5
SPR	2: Oceanographic mission in the tropics	38.2	28.7	9.5
SPR	3: Agriculture in the mid latitudes	33.1	28.7	4.4
RRS	4. Environmental Mission in the tropics	31.1	29.5	1.6
RRS	5. Airborne mission in the tropics	38.1	29.5	8.6
RRS	6. Airborne Mission in the mid latitudes	39.4	29.5	9.9

C-Band Project Conclusions

- A detailed system analysis was performed to show advantages and technical impact of a C-band navigation system in addition to Galileo L-band.
- Shortcomings of Galileo L-band are covered by a global C-band Service of Robustness and Precision SPR and by two independent spot-beam Regional Robust Services RRS.
- The two spot-beam C-band RRS services and the Galileo L-Band services fit on an enhanced Galileo IOV Satellite Platform!
- Galileo Ground Segment is enhanced by upgrading 12 GSS with C-band equipment in order to provide improved ODTS and C-band service operations.
- Most appropriate signal for both services (best performance, use of the full available 20 MHz bandwidth) is a Gaussian Minimum Shift Keying GMSK!
- C-band user terminal analysis shows feasibility to achieve required acquisition and tracking performance considering technical development until 2020.
- Use of numerical weather data to improve the UERE budgets is a real added value for C-band and L-band!

Use of C/L and S-band for GNSS-Reflectometry and Earth Remote Sensing

- Besides the possibility to offer new services, the C-band is:
  - more sensitive due to the tropospheric variability,
  - less sensitive to the ionosphere and
  - less impacted by multipath compared to the L-band.
- These features should allow mapping the ionosphere and the troposphere using L- and C-band or even three navigation signals in L-, S- and C-band.
- Shortcomings of Galileo L-band are covered by a global C-band Service of Robustness and Precision SPR and by two independent spot-beam Regional Robust Services RRS.
- The allocation of the S-band for world wide transmittance is an agenda topic at the World Radio Conference 2012 for world wide transmittance.
- Environmental and interference aspects of L, S and C-band are analysed within the EGEP in two other studies:
- ID7: Assessment of C-band satellite-to-indoor propagation and shadowing by vegetation, and
- ID22: Characterisation of Interference in S- and C-band.

Use of C/L and S-band for GNSS-Reflectometry and Earth Remote Sensing (cont'd)

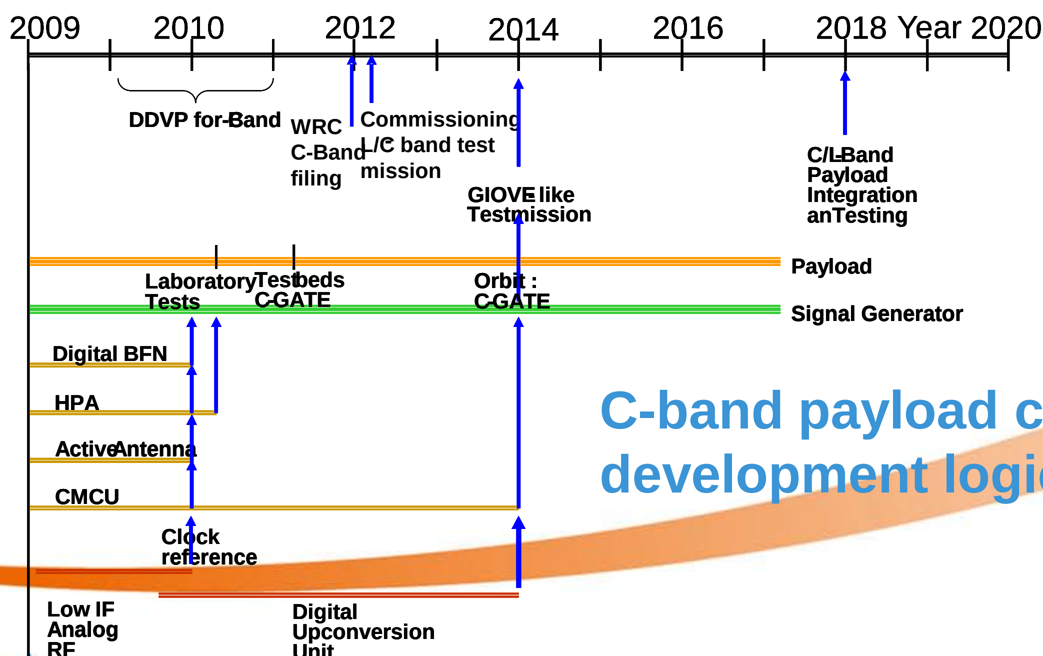
- Use and impact of other frequencies than L-band for Reflectometry has not been analysed so far.
- For example it is expected that due to the higher frequency of C-band compared to L-band the signal reflected from the ocean- and land surface will look different.
- The ocean will look "smoother" to the C-band signal than to the L-band, hence different wave numbers will be resolved by both bands.
- Different surface behaviour / penetration depth for different signals are expected.
- Combined observations might be utilized, e.g., for extended snow & ice or soil moisture surface characterisation and monitoring.

Use of C/L and S-band for GNSS-Reflectometry and Earth Remote Sensing (cont'd)

- Simulation studies and ground based experiments will help to better understand the interaction of these signals with the environment and to develop necessary retrieval algorithms and models (EGEP ID 50, ID 51).
- Space-borne measurements from a Low Earth Orbit (LEO) would allow global coverage and especially can contribute to climate change monitoring.
- An experimental mission from a MEO or LEO - realized for example on ISS - would be of high interest to test critical technologies and C-band performance.
- Such a mission would allow studying different designs with different receiver and antenna setups and would allow verifying new retrieval algorithms using L-, S- and C-band for GNSS Reflectometry and radio-occultation, respectively.

C-Band Future Outlook

- Decision on the C-band future required. If yes:
- Development and pre-testing of C-band critical user terminal and payload technology would be necessary before preparing a test mission from space
- A roadmap to develop and proof critical technology has been identified and elaborated.
- For the payload it is essential to bring it into space soon after the WRC 2012, which has the aim to secure the frequency reservation of the C-Band 5000-5030 MHz for satellite navigation.



C-band payload critical technology development logic

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DISCLAIMER:

The work reported in C-band study has been supported under a contract of the European Space Agency in the frame of the European GNSS Evolutions Programme. The views presented in the paper represent solely the opinion of the authors and should be considered as R&D results not necessarily impacting the present EGNOS and Galileo system design.

Thank you very much!