Multi-Doppler GNSS-R altimetry with TDS-1

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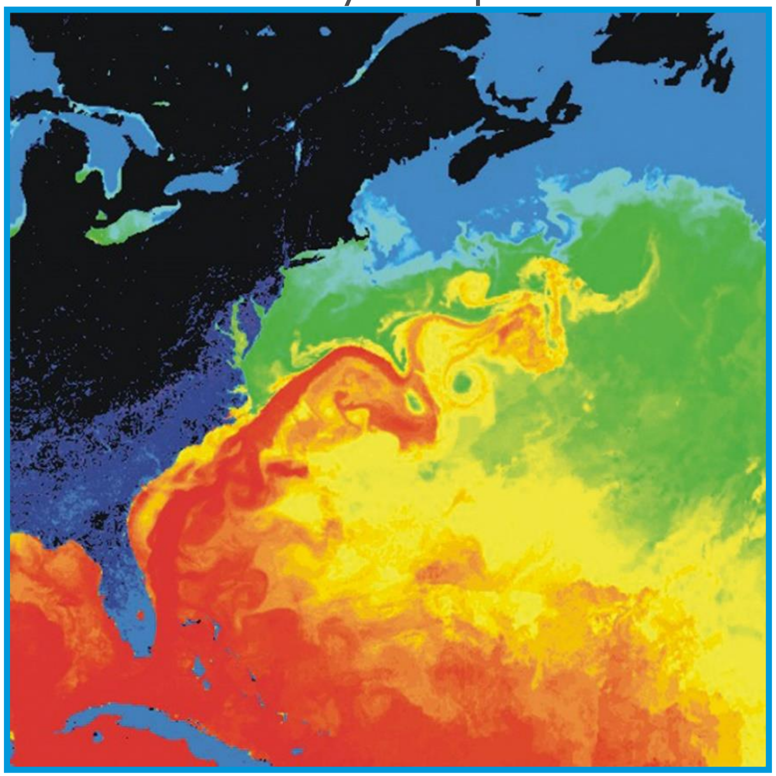
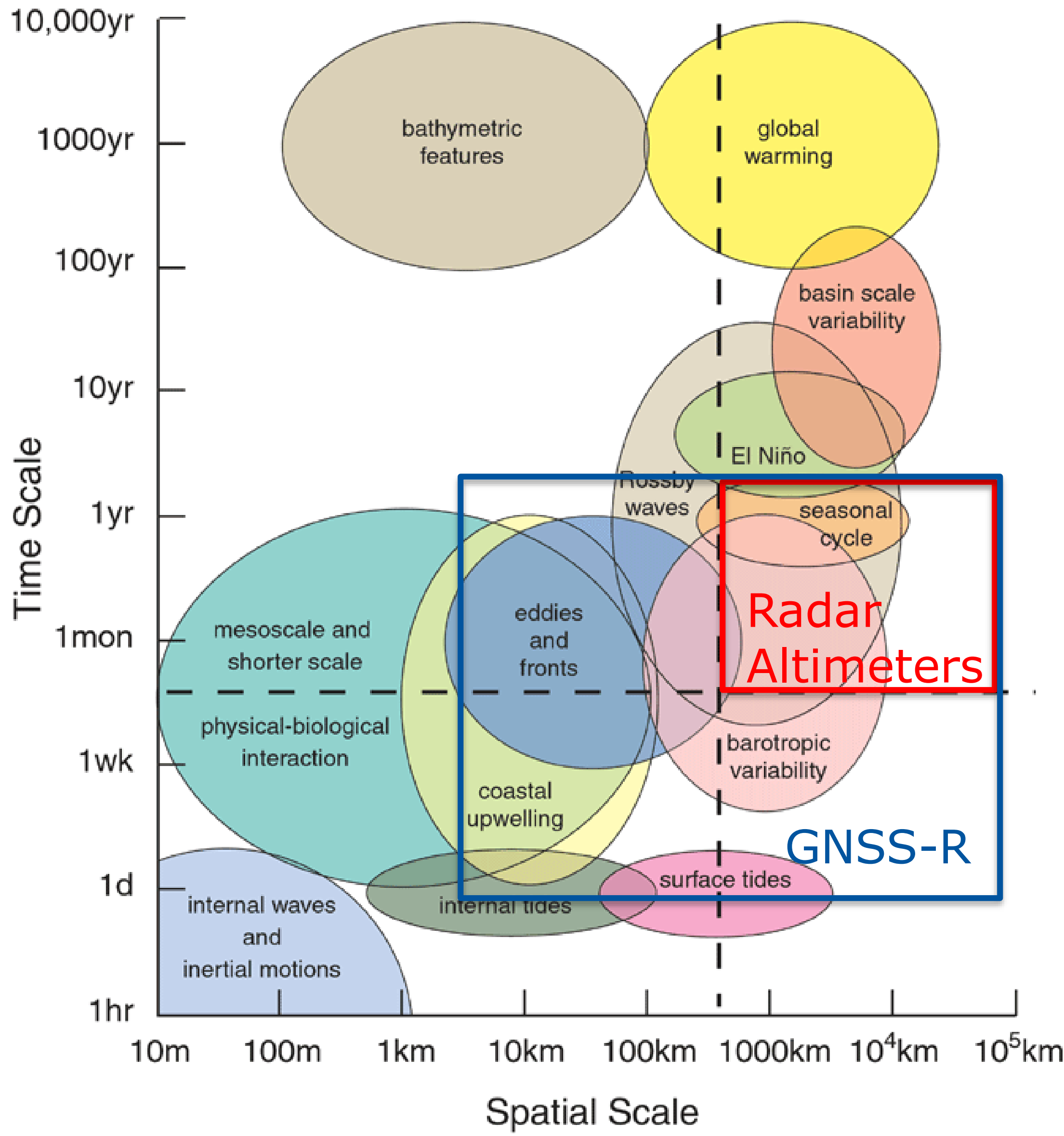
How GNSS-R can contribute to Satellite Altimetry

Why GNSS-R altimetry?

1. Conventional Radar Altimeters observe only one point on the



perform well mesoscale altimetry (eddies/fronts)

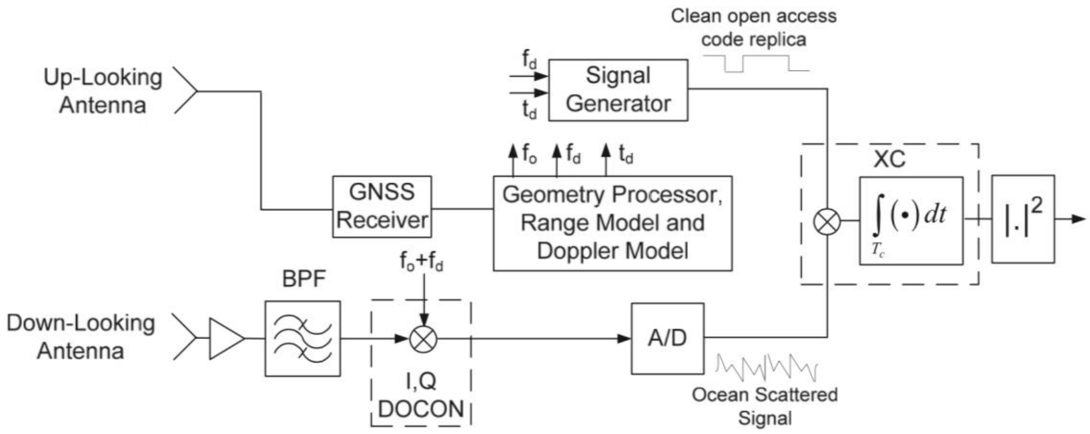


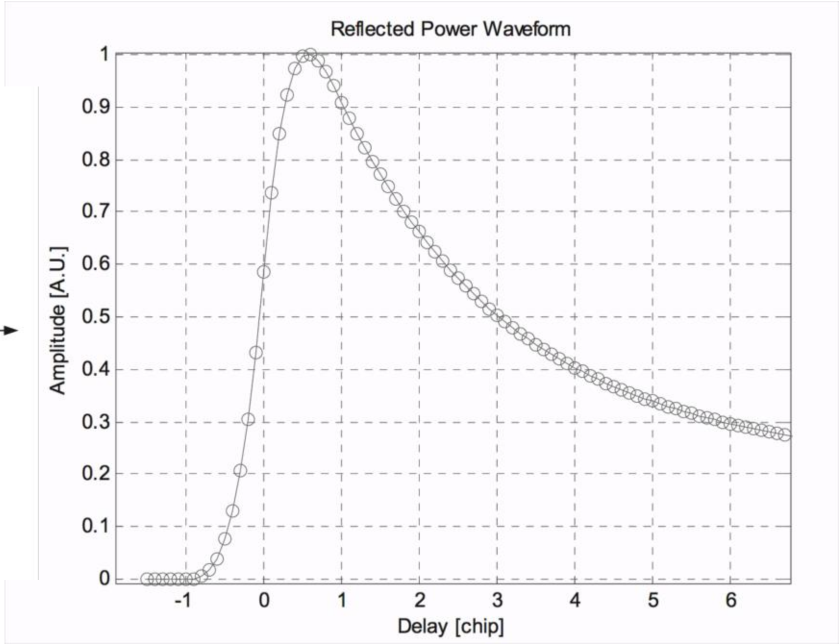
GNSS-R Multi-Doppler Altimeter: Why?

1. **Background Context:** Precision Requirement for mesoscale altimetry is of about 5cm (for a spatial resolution of 50km), which is currently not possible to achieve with state-of-the-art GNSS-R processing (which achieves about 15 cm). There is therefore a need for better precision. The proposed processing aims at improving wrt state-of-the-art.
2. **Objectives of the work:** To define a processing technique which allows to maximise the number of statistically-independent observations, for a given spatial resolution
3. **This presentation:** We propose a novel processing and retracking concept for GNSS-R altimeters based on the acquisition of the full delay-Doppler map (DDM), which allows to acquire multiple waveforms at different Doppler frequencies. This processing yields additional "multi-look" with respect to conventional GNSS-R concepts and translates into an improvement of the altimetry performance estimated to be at least 25%–30%.

The GNSS-R Power waveform

1. The primary GNSS-R product of the so-called "**power waveform**", which is the result of the <u>**cross-correlation between the navigation signal reflected from the earth and the reference signal produced on-board**</u>. Usually cross-correlations are acquired simultaneously over a wide range of Doppler frequencies, yielding to the so called Delay-Doppler Map (DDM). Sea surface height and wind speed, for example, are extracted from these observables.

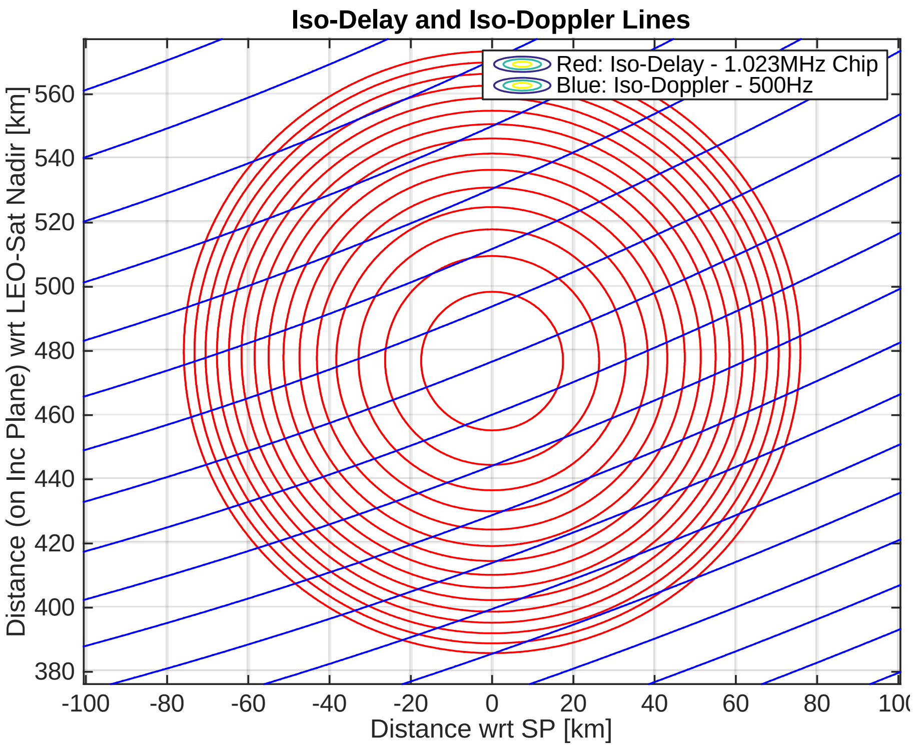




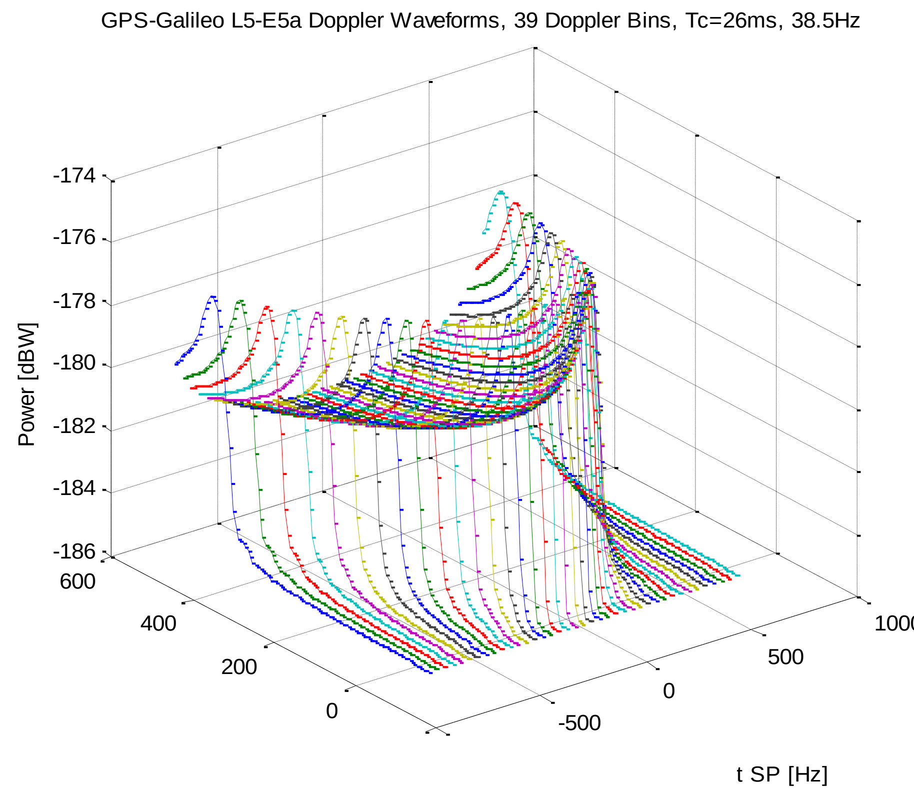
GNSS-R Waveform Example

The GNSS-R delay-Doppler Map

1. The Delay Doppler Map is a set of GNSS-R Waveforms acquired at Different Doppler bins (by shifting in frequency the reference replica):



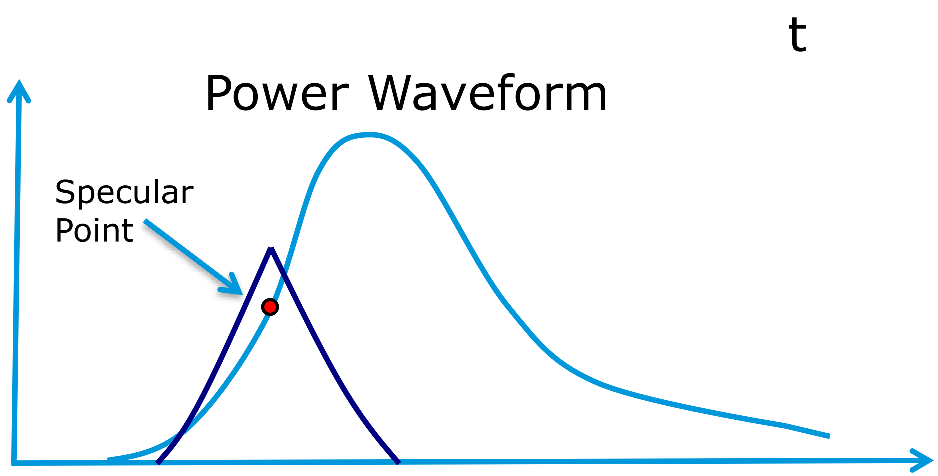
Delay Doppler Map Example

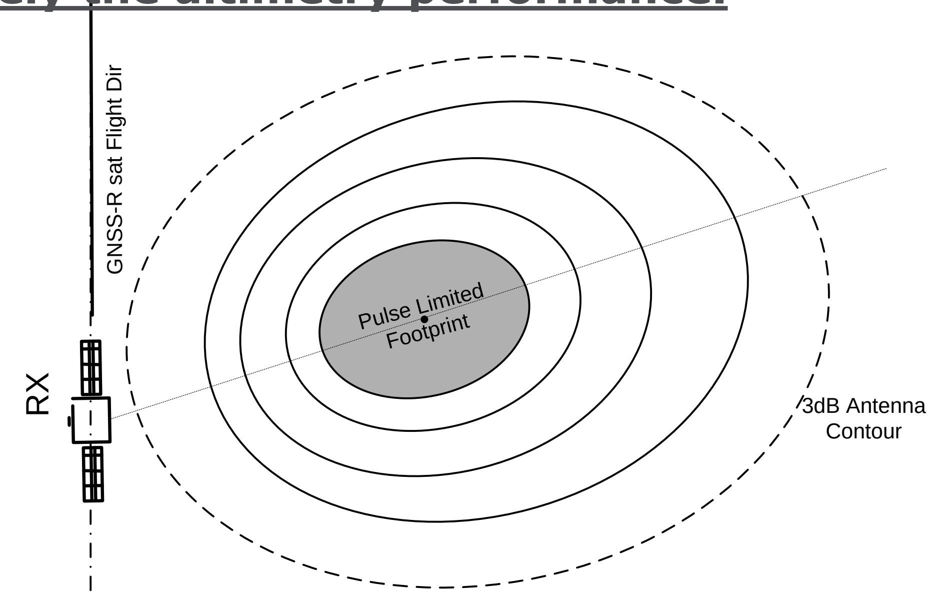


$$DM(\tau) = \langle Y(\tau) \rangle = \iint\limits_{\theta,\varphi} P_r(\theta,\varphi) \left| U\big(\tau - t_r(\theta,\varphi), f_d(\theta,\varphi)\big) \right|^2 d\Omega,$$

State-of-the-art Processing: Problem Areas

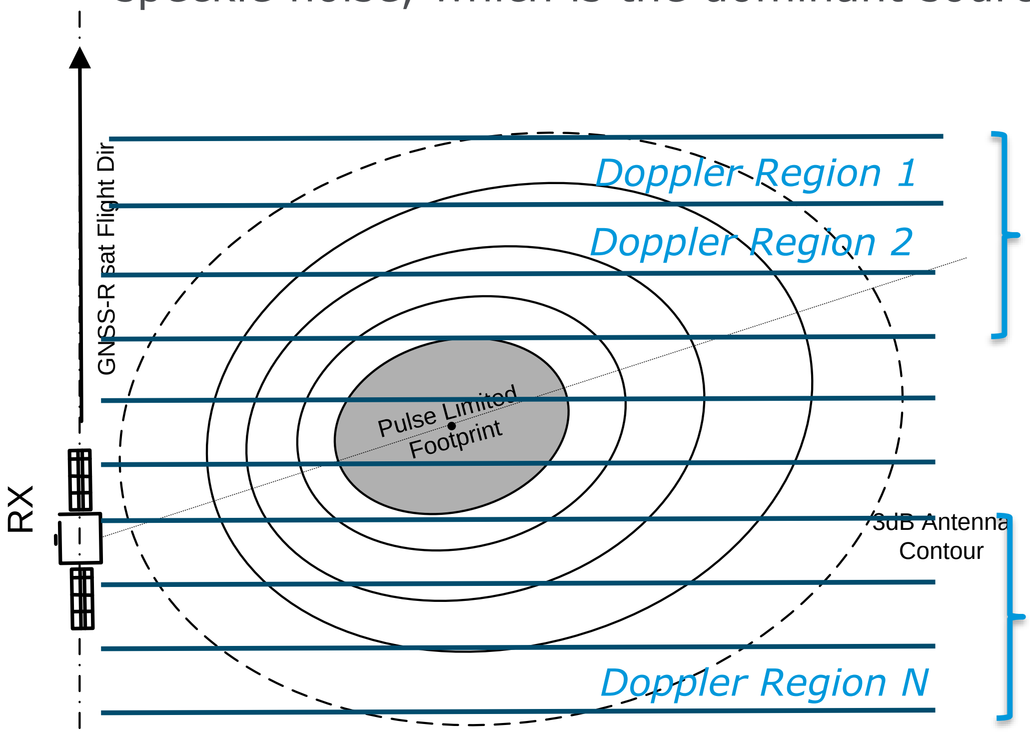
1. State-of-the-Art Limitation: The power at the specular point is given by the reflections within the "pulse limited footprint" (as shown below).
2. But the specular point region is the waveform part typically used for estimating the specular point position, i.e. for altimetry!
3. Therefore, in state-of-the-art processing, the **power scattered from outside the pulse limited footprint is not exploited for altimetry and essentially lost**!
4. **The proposed delay-Doppler processing aims at exploiting this power for improving the SNR and, ultimately the altimetry performance.**





Delay-Doppler Processing (1/2)

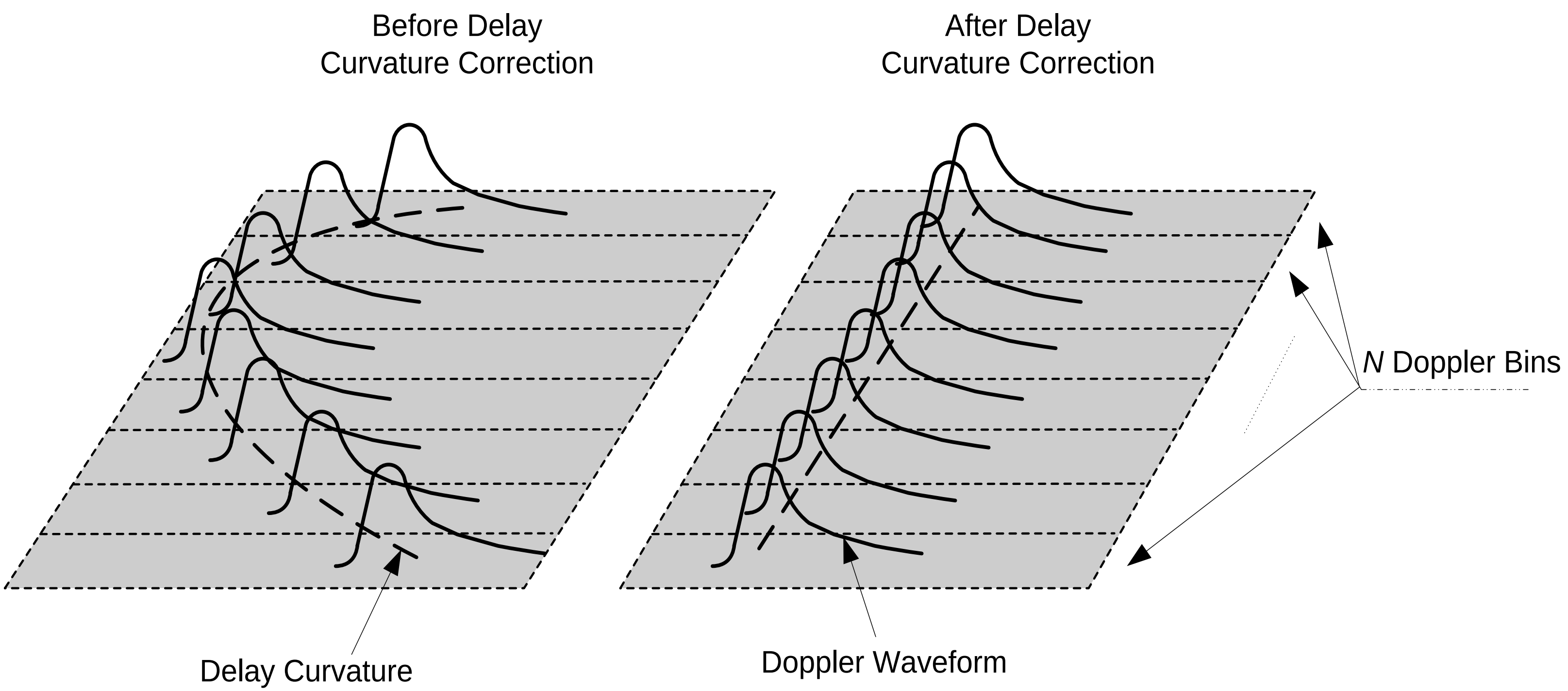
1. The proposed delay-Doppler processing performs **N parallel cross-correlations** at different Doppler frequencies, thus generating a Delay-Doppler Map. The number N is chosen to observe an ocean region as large as the antenna pattern of the GNSS-R receiver, which is much larger than the pulse limited footprint.
2. This allows to generate essentially additional “looks” of the same Earth regions, which can be used for additional averaging, thus reducing the effect of the speckle noise, which is the dominant source of error for GNSS-R



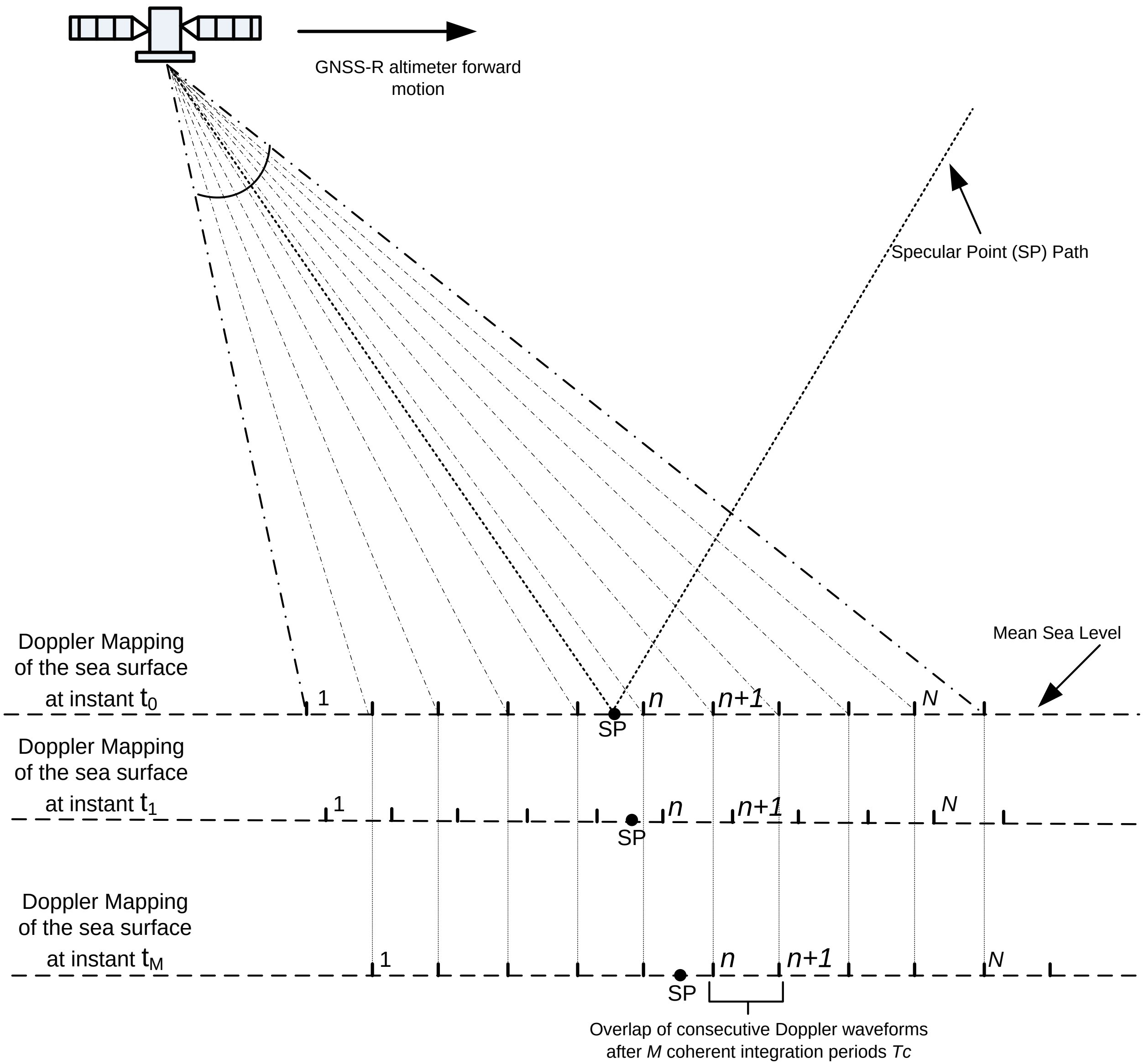
Additional Regions observed by the Delay-Doppler processing. => Extra Looks! The speckle noise is reduced!

Delay-Doppler Processing (2/2)

1. The proposed delay-Doppler processing performs **N parallel cross-correlations** at different Doppler frequencies, thus generating a Delay-Doppler Map. The number N is chosen to observe an ocean region as large as the antenna pattern of the GNSS-R receiver, which is much larger than the pulse limited footprint.
2. This allows to generate essentially additional “looks” of the same Earth regions, which can be used for additional averaging, thus reducing the effect of the speckle noise, which is the dominant source of error for GNSS-R

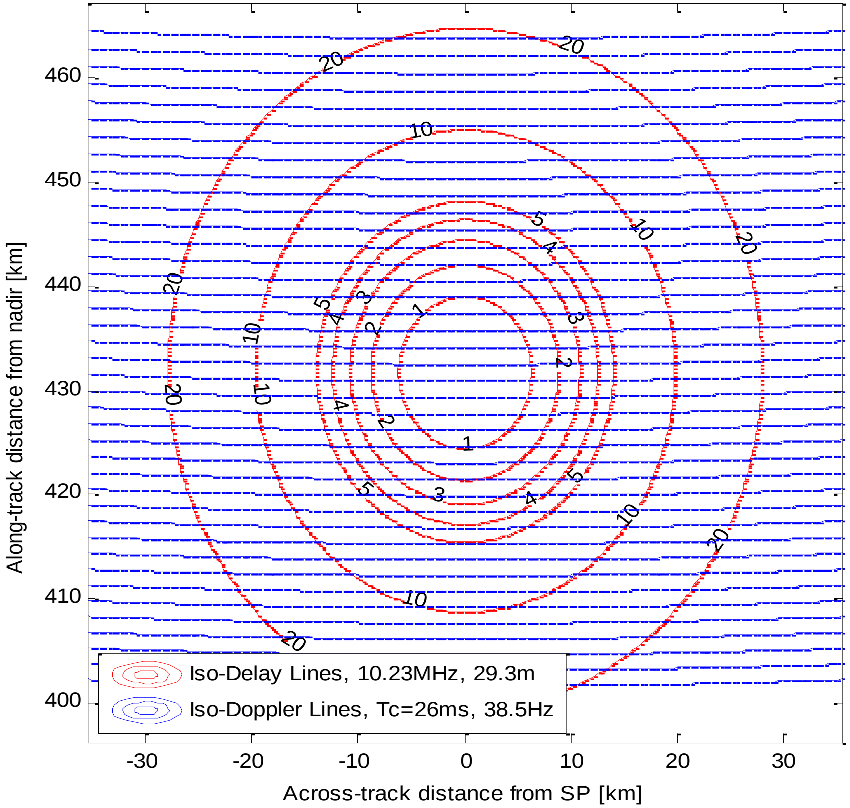


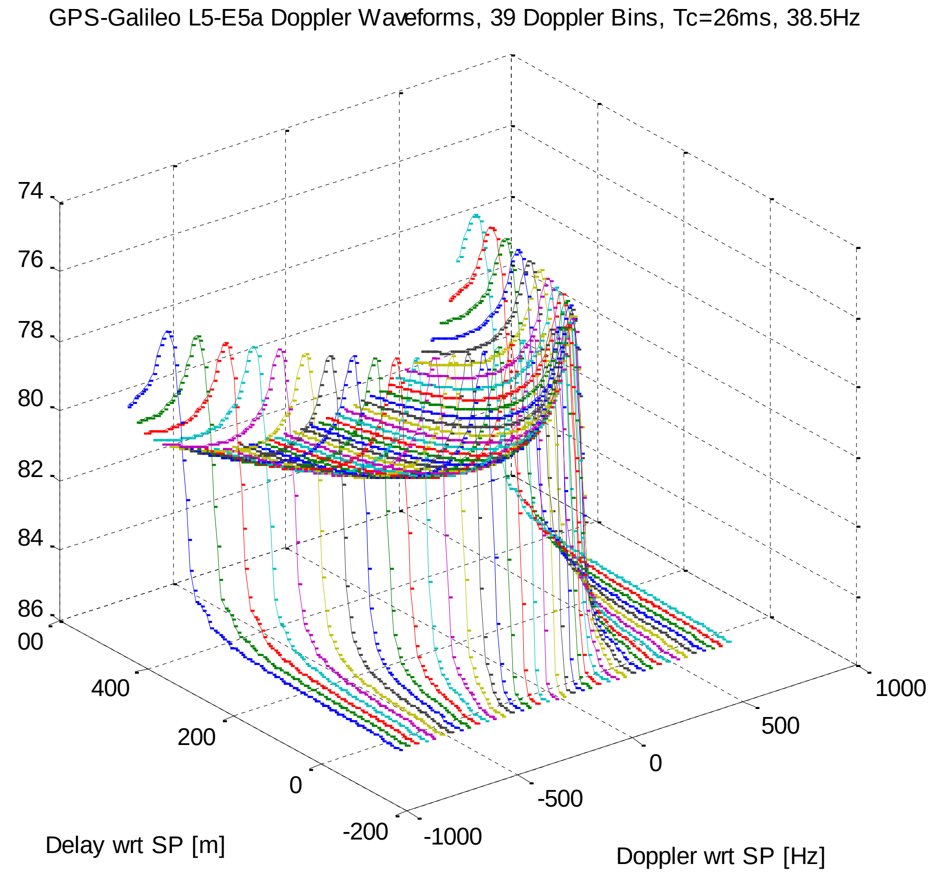
Averaging Options



Simulated DDMs

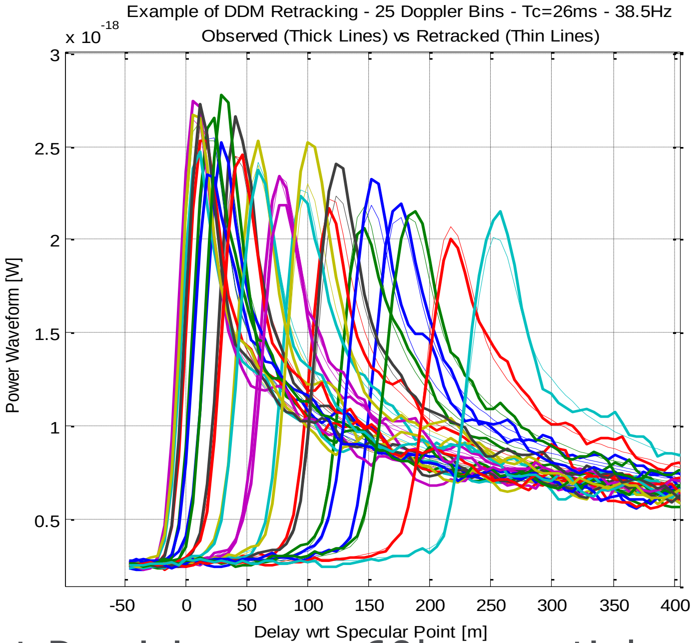
1. Example of simulated DDMs for a typical spaceborne scenario, with orbit height of 700km, Wind Speed of 10m/s, Incidence Angle of 35deg, Rx Antenna Gain of 19dBi.
2. Signal Type: GPS L5, 10.23MHz rate
3. DDM with 39 Doppler Lines of Tc=26msec,





Simulation Results

1. Detailed and realistic Montecarlo simulations have been carried out in order to assess the performance of the Delay-Doppler technique.



1. Sea Surface Height Precision over 60km spatial resolution:

	13 Doppler Bins	25 Doppler Bins	39 Doppler Bins
Delay-Doppler	12.6 cm	9.5 cm	8.7 cm
Conventional	12.4 cm		

=> **About 30% Improvement given by Delay-Doppler Processing! (8.7cm vs 12.4 cm)**

Experimental Data
TEC Demosat-1 Satellite

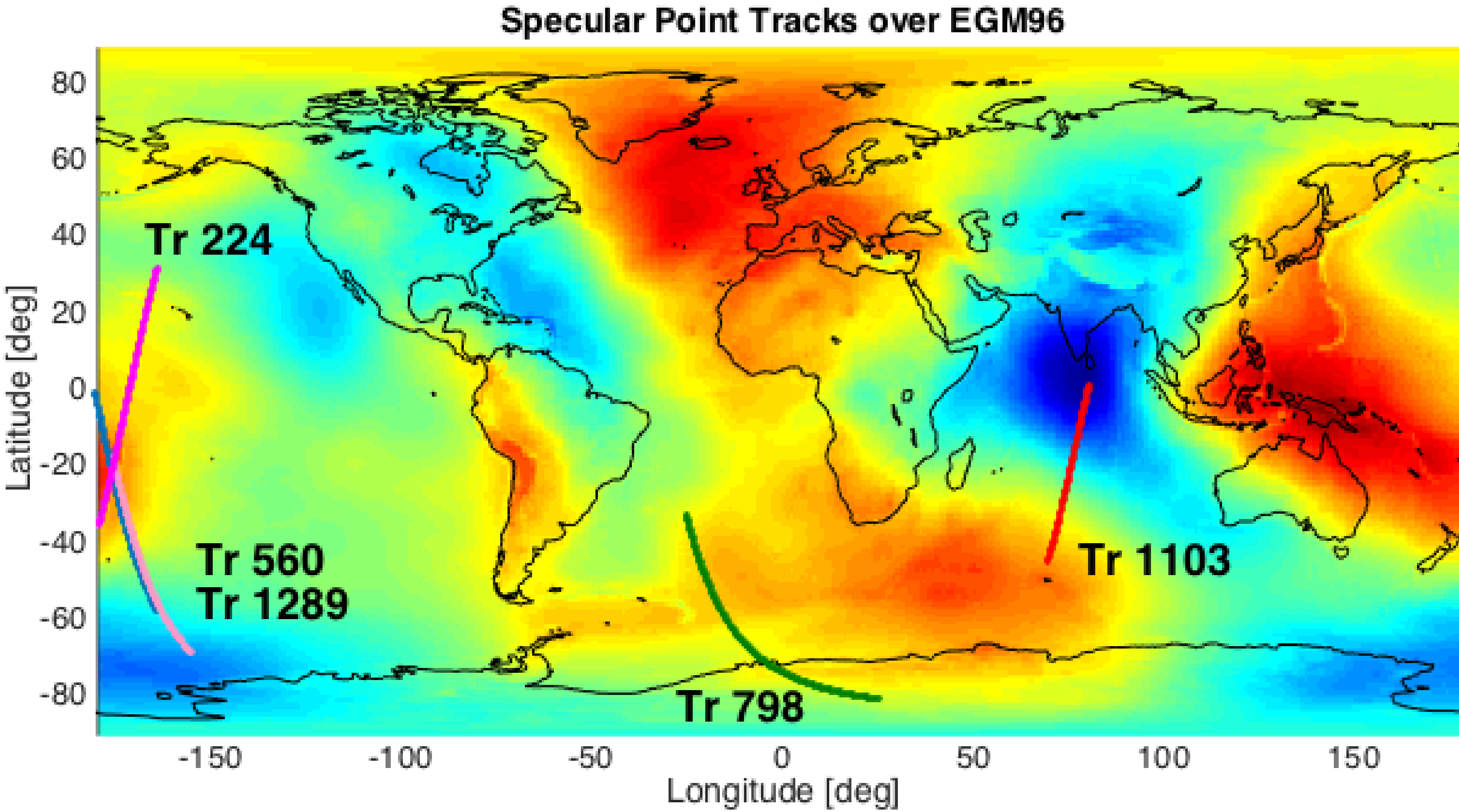
1. In order to prove the altimetry performance of the proposed multi-Doppler GNSS-R technique, measurement data collected by the SGR-ReSI instrument on-board the TEC Demosat-1 Satellite has been used. Available on www.merrbys.co.uk
2. TEC-Demosat-1 is a LEO satellite funded by the UK Space Agency and developed by SSTL, launched on July 2014.
3. TEC Demosat-1 flies in a LEO SSO orbit of target 620km

SGR-ReSI Main Characteristics

Frequencies	L1	
GNSS Signal Tracked	C/A	
Down-Looking Antenna Gain	13	dBi
Down-Looking Antenna Pointing	-6	Deg in -X direction
LNA noise figure	2.7	dB
Sampling Rate	16.367	MHz I/Q
DDM Format	32	Bits
DDM Delay Points	128	Range Bins
DDM Doppler Points	20	Doppler Bins
Coherent Integration Time	1	ms
Incoherent Integration Time	1	s
Max Number of Simultaneous Reflections	4	

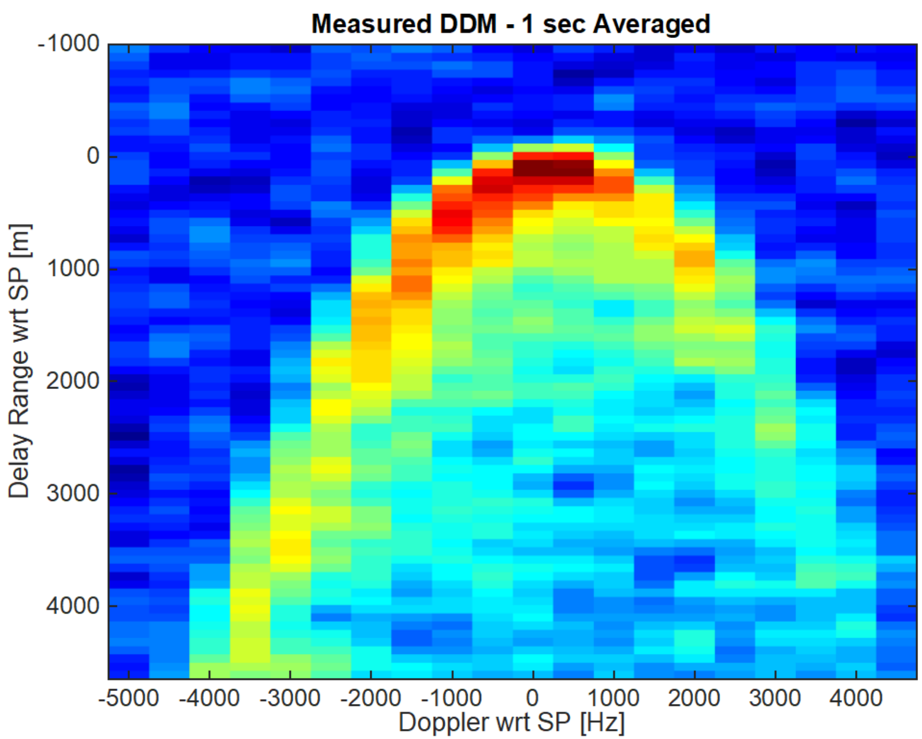
Observed SGR-ReSI Tracks

1. For analysis purposes, the data from 5 different tracks have been analysed, as shown below in the red tracks wrt the Geoid

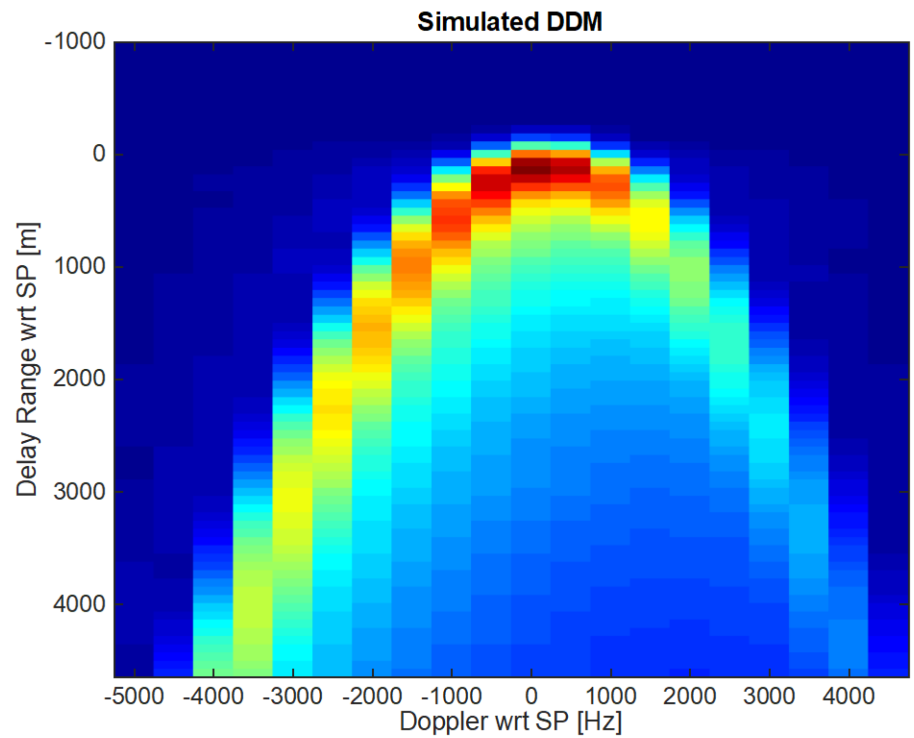


Measured vs Simulated DDMs

1. Comparison of Measured and Simulated DDM
2. SGR-ReSI, Receiver Track N. 560, Acquisition Index: 300 sec
3. Incidence Angle: 40deg



Measured



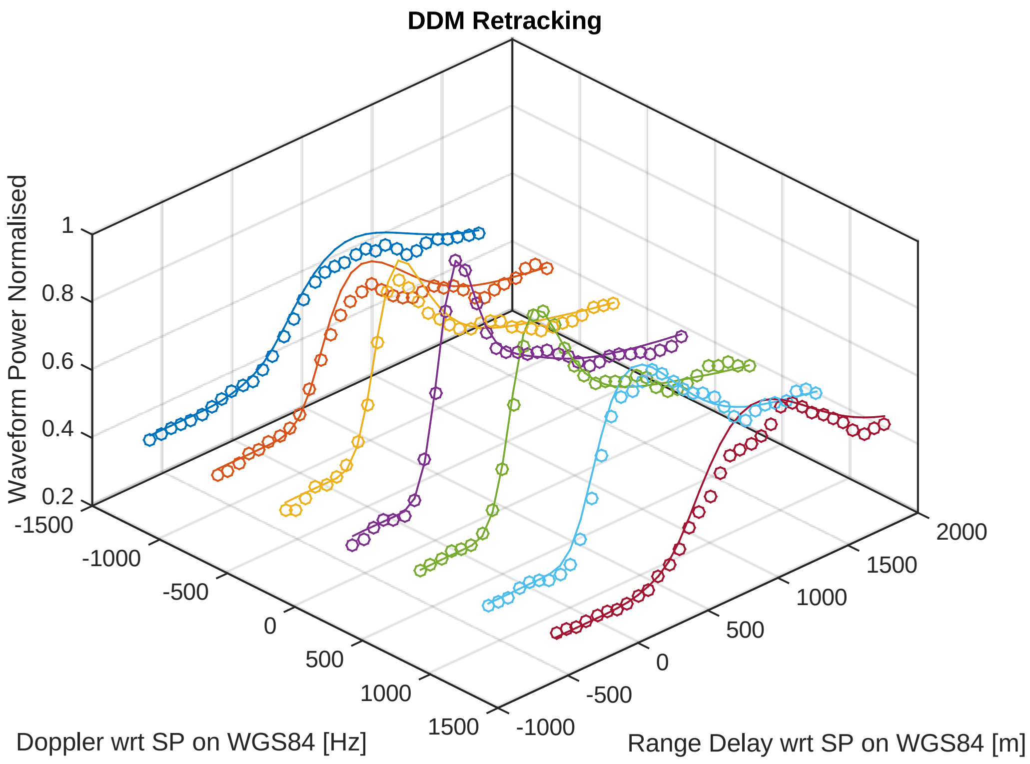
Simulated

SGR-ReSI Data Limitations

1. The SGR-ReSI Data Set has several limitations which had to be carefully considered:
    a. The Signal Acquired is GPS C/A code. It has limited BW, so it can achieve an altimetry precision of few metres (i.e. 2 to 10 metres, depending on the SNR).
    b. Precise Orbit of the GNSS-R satellite are not provided. The GNSS-R position is known with a precision of few metres. It is extracted by interpolating 0.1Hz data from on-board GNSS receiver. *-> Periodicity of estimated sea-state at 0.1Hz (and harmonics) could be observed in the data*
    c. The Doppler waveforms within the DDM are correlated. DDMs were acquired with a Doppler separation of 500Hz, despite the actual Doppler resolution is 1KHz. *-> Multi-Doppler averaging can be exploited at full, due to bin-to-bin correlation*
    d. The estimation of the Doppler of the specular point is affected by an error, due to wrong on-board geometry estimation.
2. Nevertheless these are not showstoppers for demonstrating the benefit of Multi-Doppler altimetry! *-> Relative Benefit can be still demonstrated*

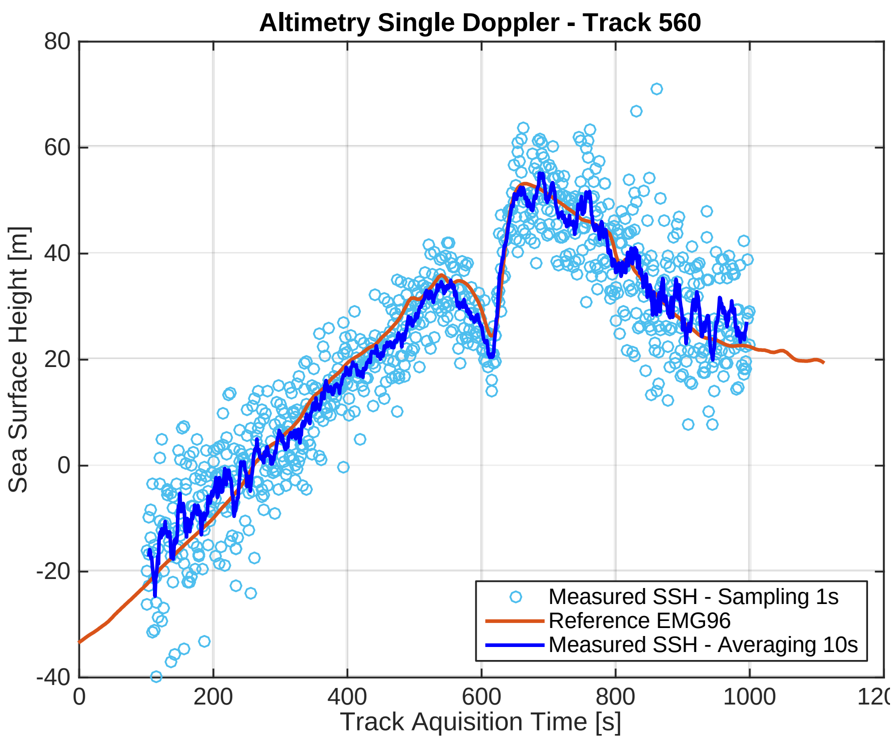
Real Retracking Example
Multi-Doppler

1. Real Example of Retracking of the DDM from Doppler bins N.8 to N.14, Track ID1103 shown here
2. The retracking has the objective of estimating the sea state parameters and the sea mean surface height by fitting a theoretical model to measured waveforms
3. Maximum likelihood estimation (MLE) or weighted least squares (WLS) estimation is used here.
4. The retracking is done separately/individually for each Doppler waveform, in order to preserve the along-track spatial resolution and to allow different along-track averaging possibilities.

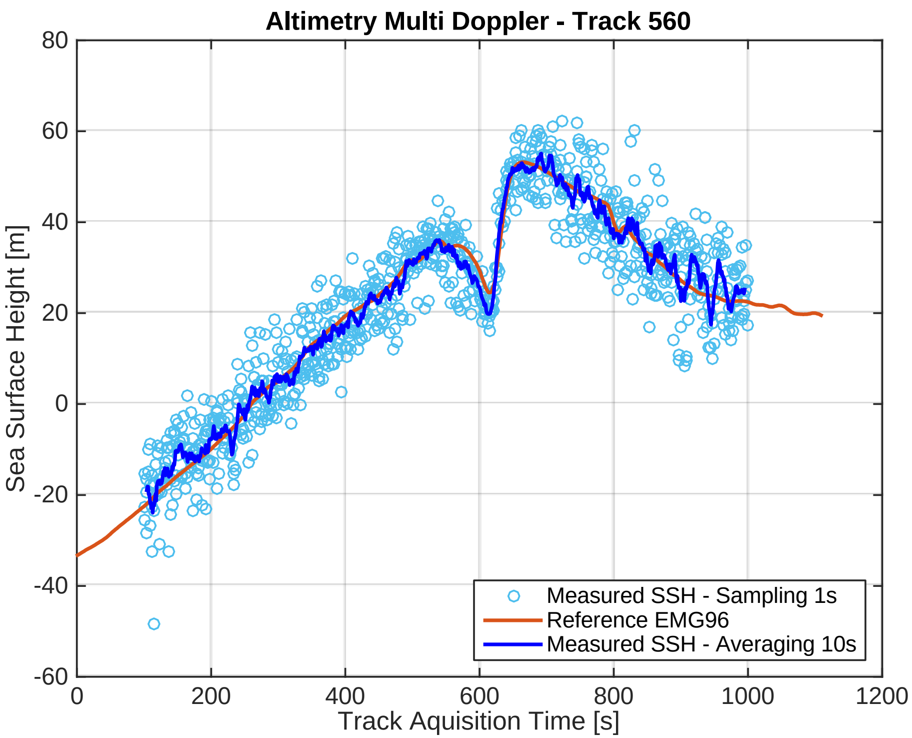


Altimetry: Experimental Validation Single Doppler (Track 1 ID 560)

1. The estimated Altimetry Profile (Sea Surface Height) obtained with both Single Doppler and Multi Doppler are shown below.
2. Multi Doppler is based on the retracking of the 5 central Doppler bins, i.e. -1000, -500, 0, 500, 1000 Hz.
3. The Geoid profile is very well followed, however slow oscillations are observed. These are very likely attributable to orbit knowledge oscillations.



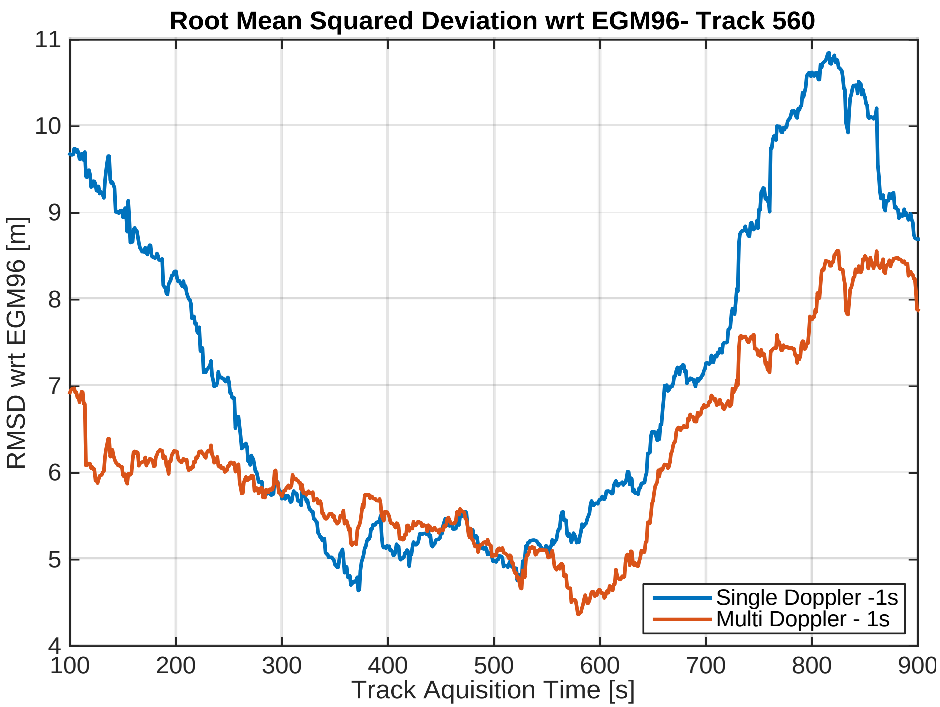
Single Doppler



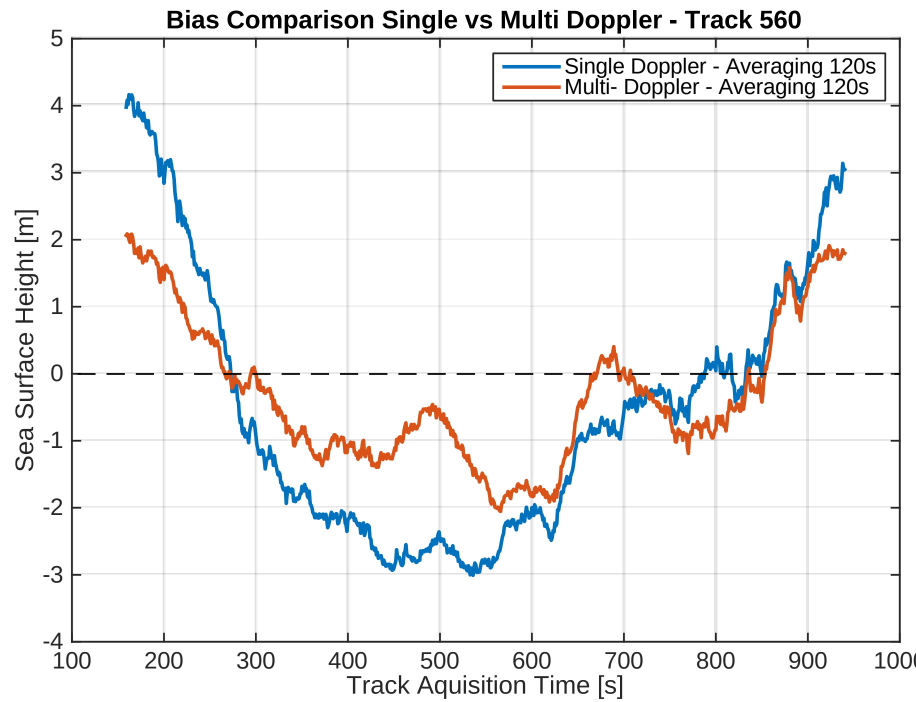
Multi Doppler

Performance Comparison
Single vs Multi Doppler

1. As shown below and as expected, the Multi-Doppler processing brings an improvement on Altimetry Error (RMSD and Bias) wrt Single Doppler.
2. In Track 1, the altimetry improvement is up to 20%, but is varying along the acquisition, and can also vanish (see 400-500s acquisition time)



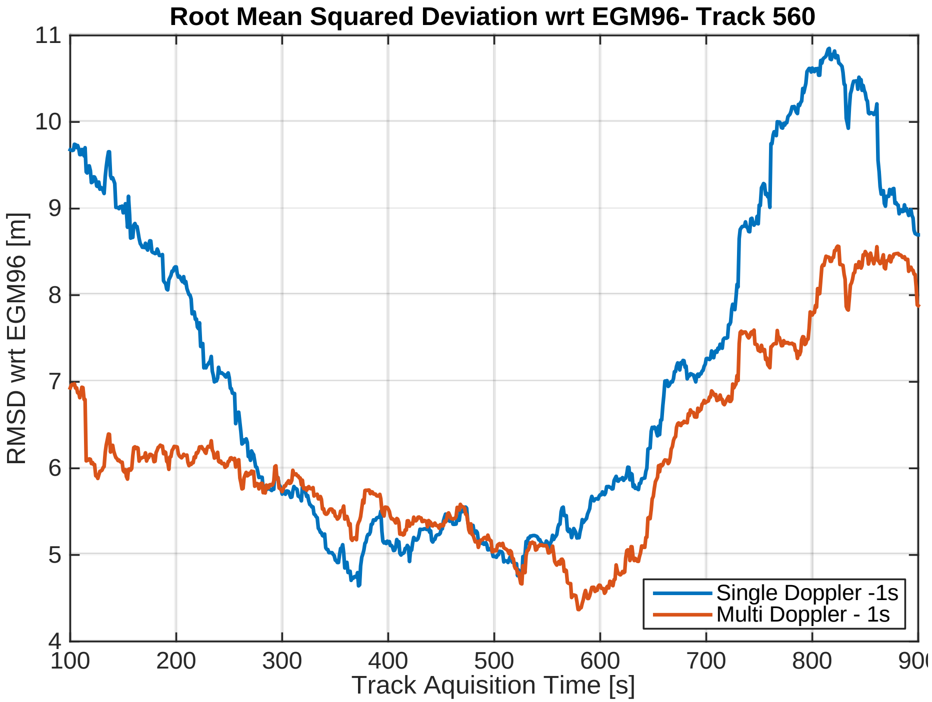
RMSD Comparison



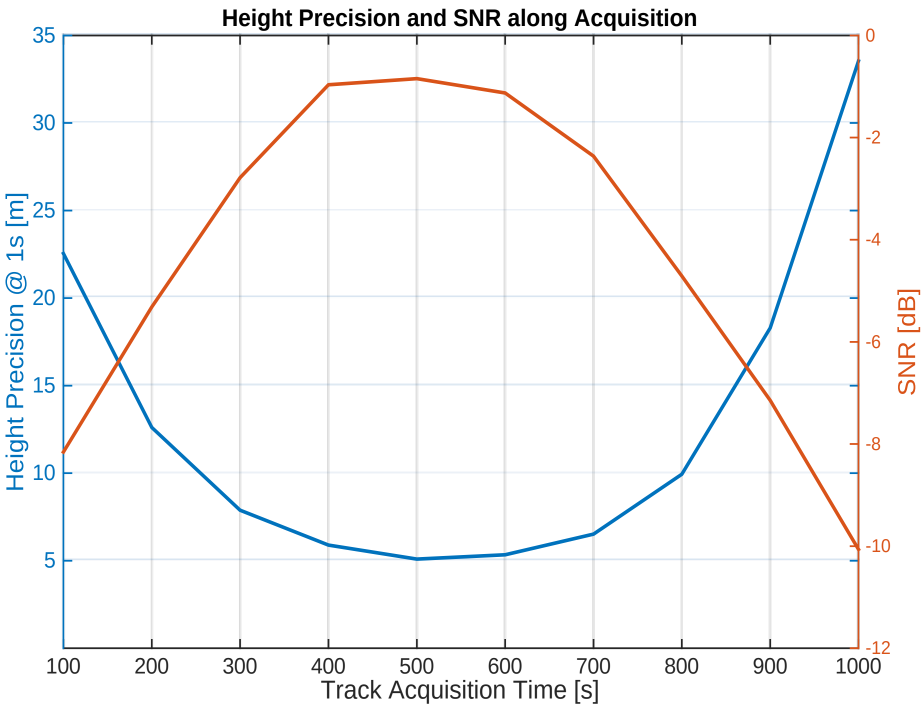
Bias Comparison

Performance Comparison
Single vs Multi Doppler

1. Is the behaviour of the RMSD along acquisition as expected? Yes, see figure on the right below, blue curve (modelled height precision SNR dependent)
2. Why the Multi Doppler Technique does not improve the performance in the region from 400-500s?
3. These two questions can be addressed by using the altimetry performance



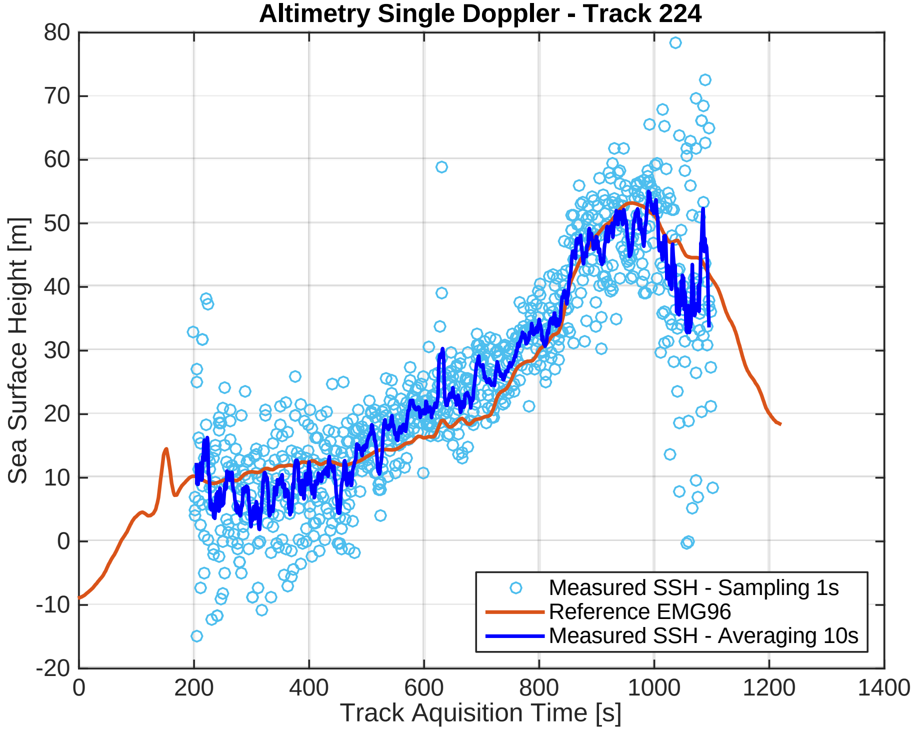
RMSD Comparison



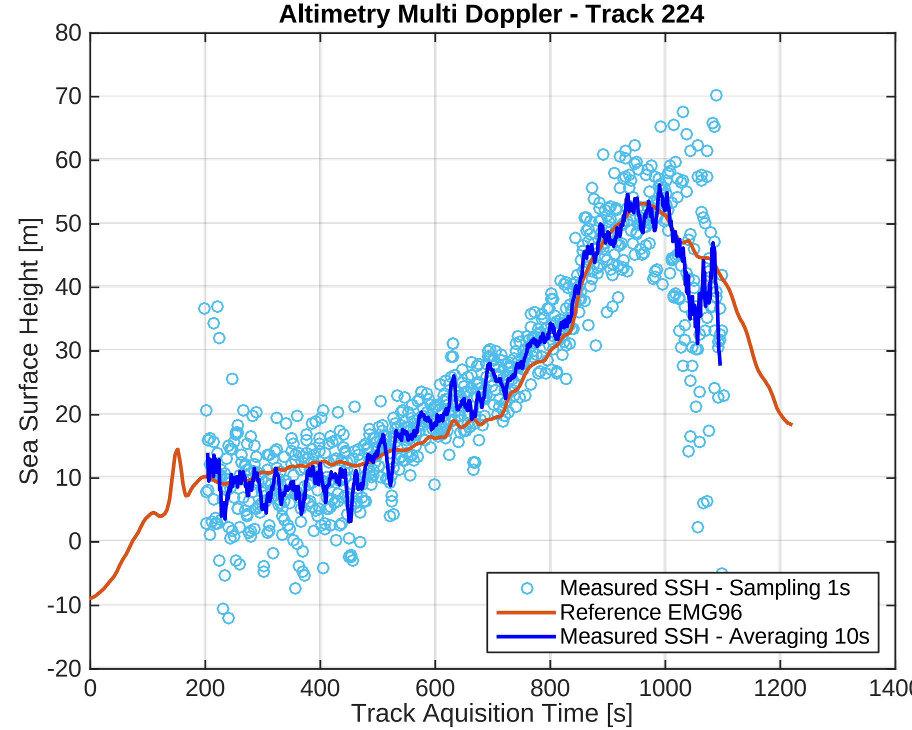
Altimetry Performance Model wrt SNR

Altimetry: Experimental Validation Single Doppler (Track 4 ID 224)

1. The estimated Altimetry Profile (Sea Surface Height) obtained with both Single Doppler and Multi Doppler are shown below.
2. Multi Doppler is based on the retracking of the 5 central Doppler bins, i.e. -1000, -500, 0, 500, 1000 Hz.
3. The Geoid profile is very well followed, however slow oscillations are observed. These are very likely attributable to orbit knowledge oscillations.



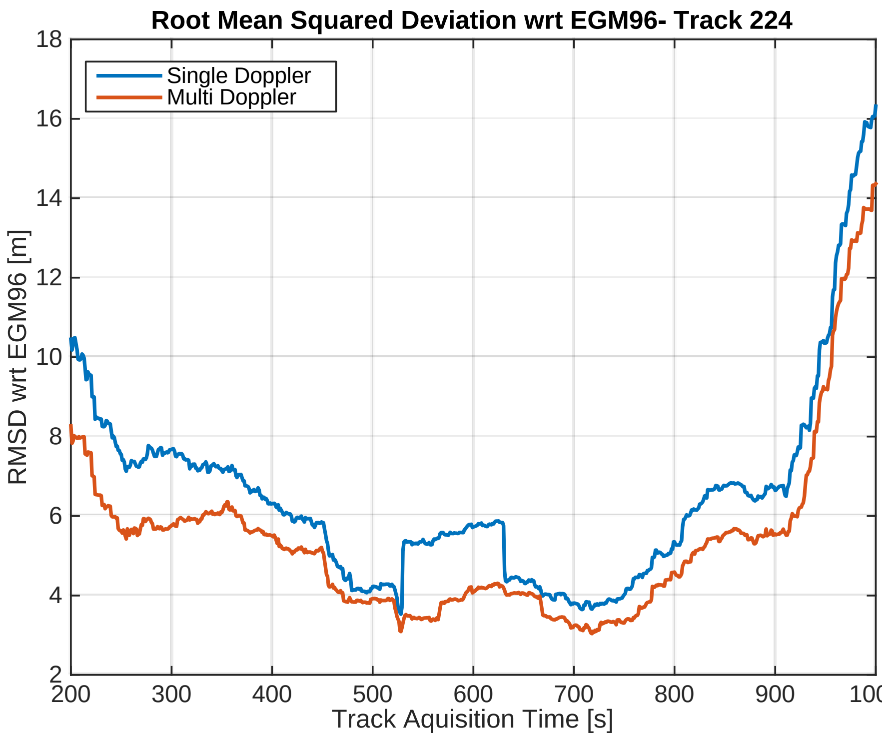
Single Doppler



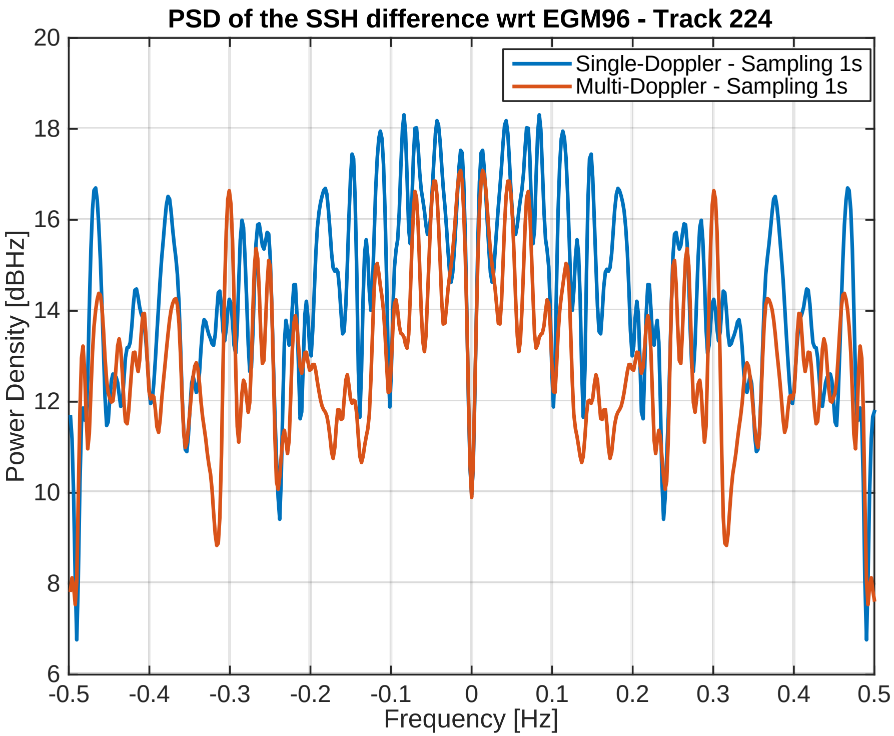
Multi Doppler

Performance Comparison
Single vs Multi Doppler

1. As shown below and as expected, the Multi-Doppler processing brings an improvement on Altimetry Error (RMSD and Bias) wrt Single Doppler.
2. In Track 4, the altimetry improvement is about 10%.



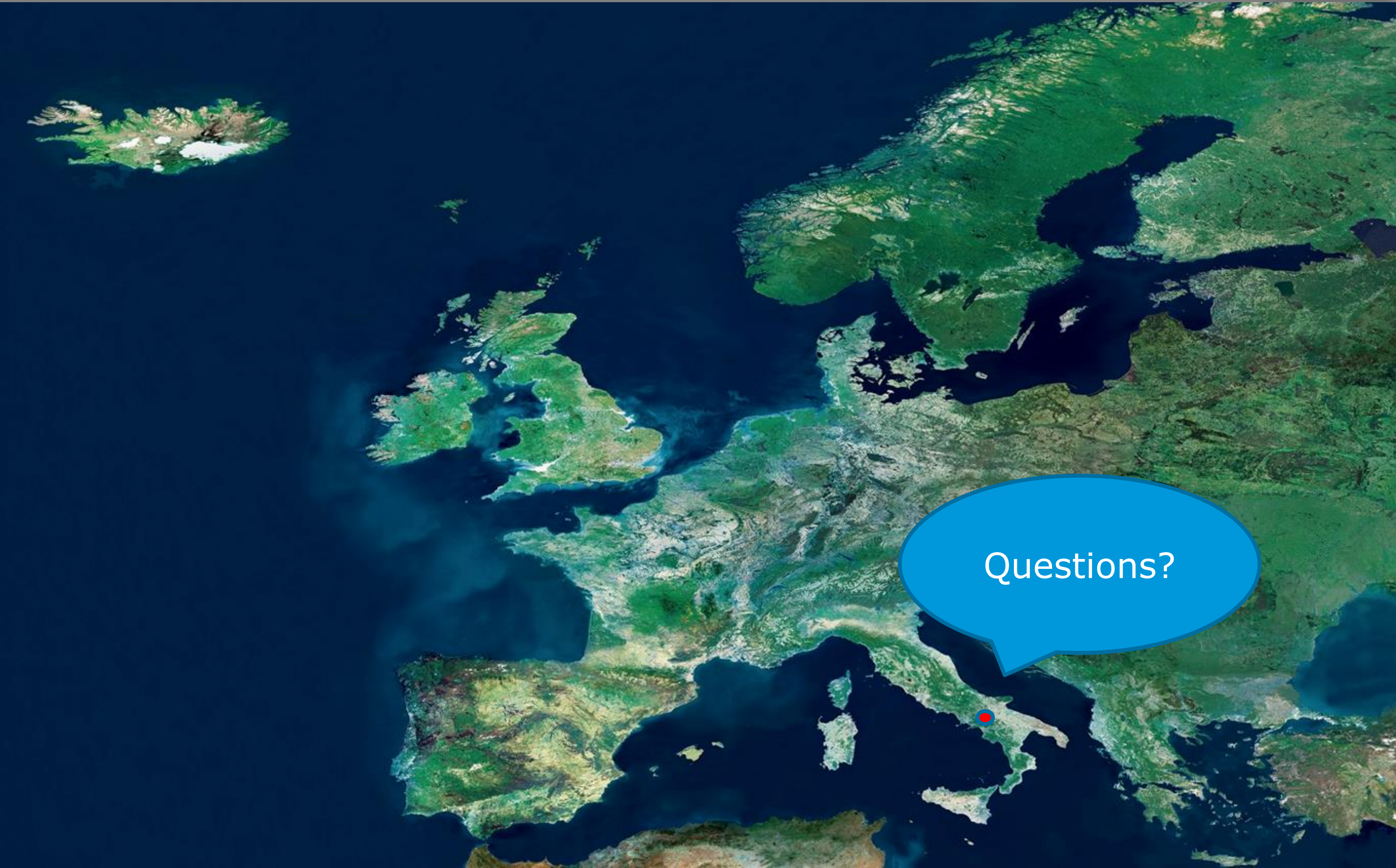
RMSD Comparison



PSD (Power Spectral Density) Comparison

Conclusions and Future Work

1. GNSS-R Altimetry from space has been demonstrated experimentally with the SGR-ReSI data set:
    a. Conventional Single-Doppler achieved state-of-the-art performance -> 3-4 metres RMSD error
    b. The Multi-Doppler technique has been presented and is able to provide a performance improvement of about 10%-20% in most cases, despite the limitations of the SGR-ReSI data set.
    c. The Multi-Doppler technique brings improvement also on the actual bias and not only on the root-mean-square noise.
2. All the work has been supported/confirmed by experimental validation with data from both spaceborne campaigns.
3. Future work shall address:
    a. Demonstration of Multi-Doppler Technique with other data sets, with e.g. GNSS signals with larger BW
    b. Combination of Interferometric and Multi Doppler processing


Questions?

Backup Slides

Measured Waveforms with high Tc

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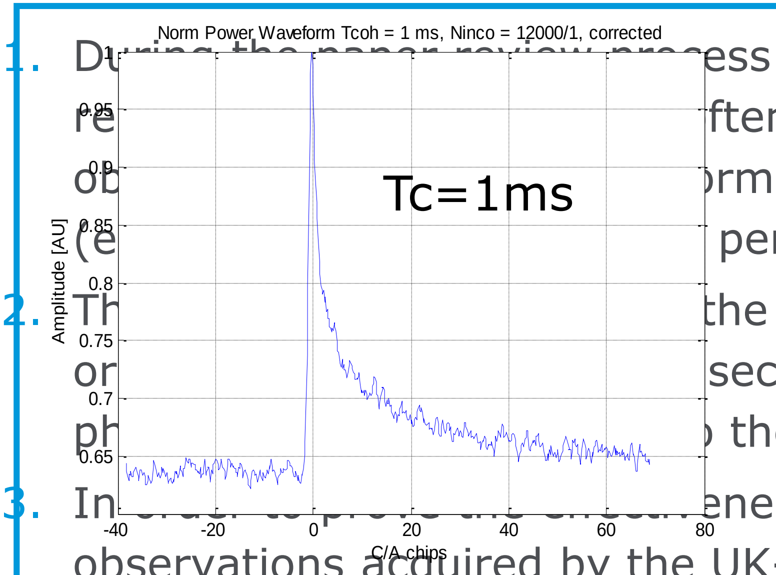
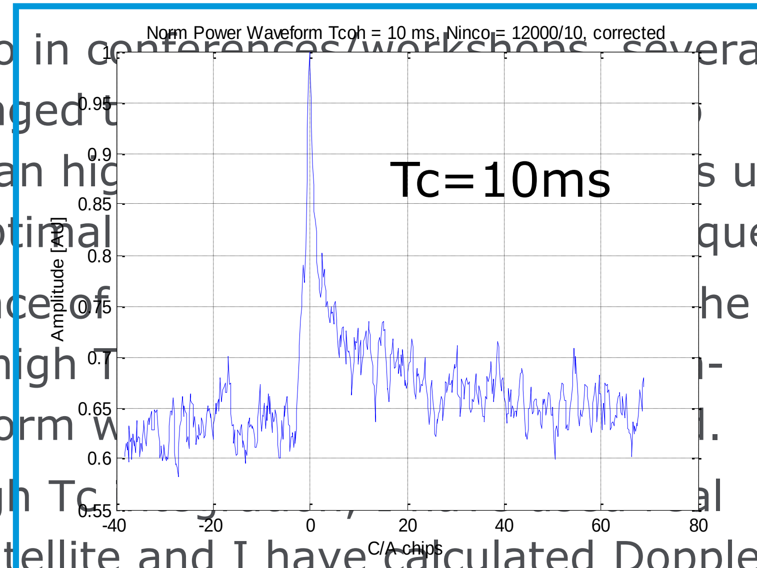
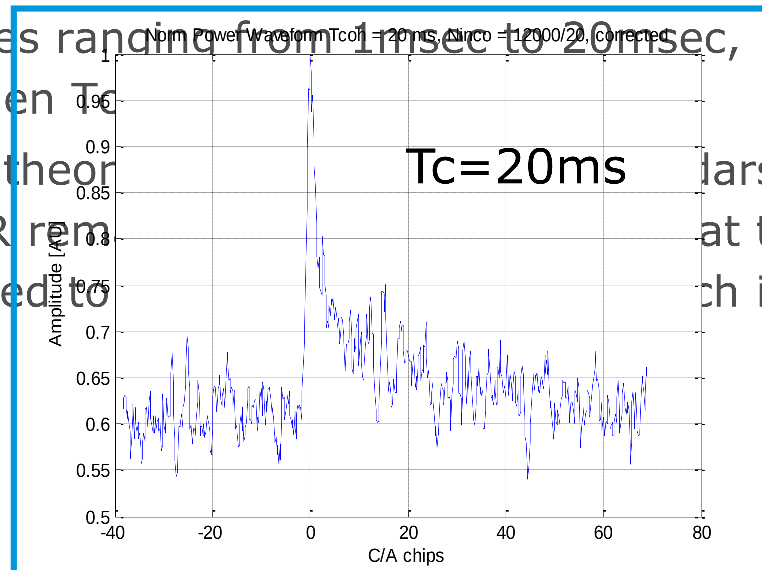




1. D... ess and also in c... several re... ften challenged t... ob... rms when an hig... s used (e... perform optimal... que).
2. Th... the coherence of... he or... sec), thus high T... n-ph... the waveform w... l.
3. In... eness of high Tc... al observations acquired by the UK-DMC satellite and I have calculated Doppler waveforms with different integration times ranging from 1msec to 20msec, showing that no loss of SNR is visible when Tc...
4. It is indeed theoretically expected (from theor... dars, extended to a bistatic case) that the SNR rem... at the maximum limit for Tc is the one associated to... ch is about 100msec.



For all Tcs, the Noise level remains constant, about 0.6, thus SNR does not decrease with Tc (as expected).