Wave Field Reconstruction and Prediction using X-Band Marine Radar

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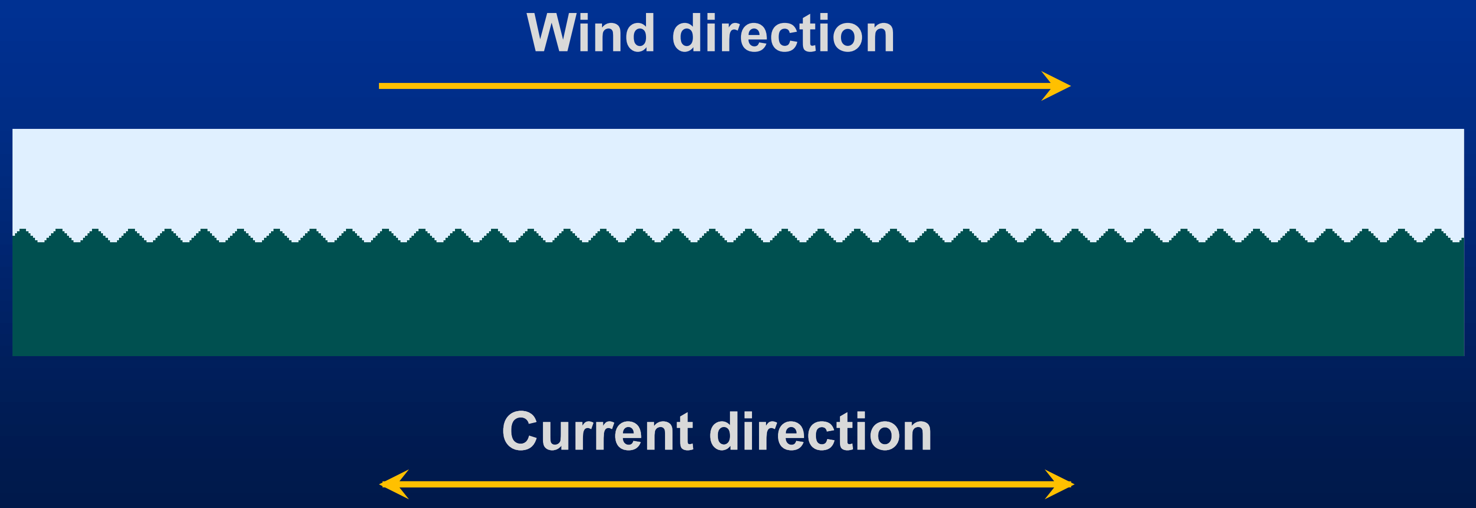
Typical use of X-Band Radars

Main Radar Imaging Mechanisms

- Bragg scattering: Image intensity $\propto$ Bragg wave intensity
- Wave-current interaction
- Contributions of longer waves
  - Tilt modulation
  - Hydrodynamic modulation
- Further modulation mechanisms

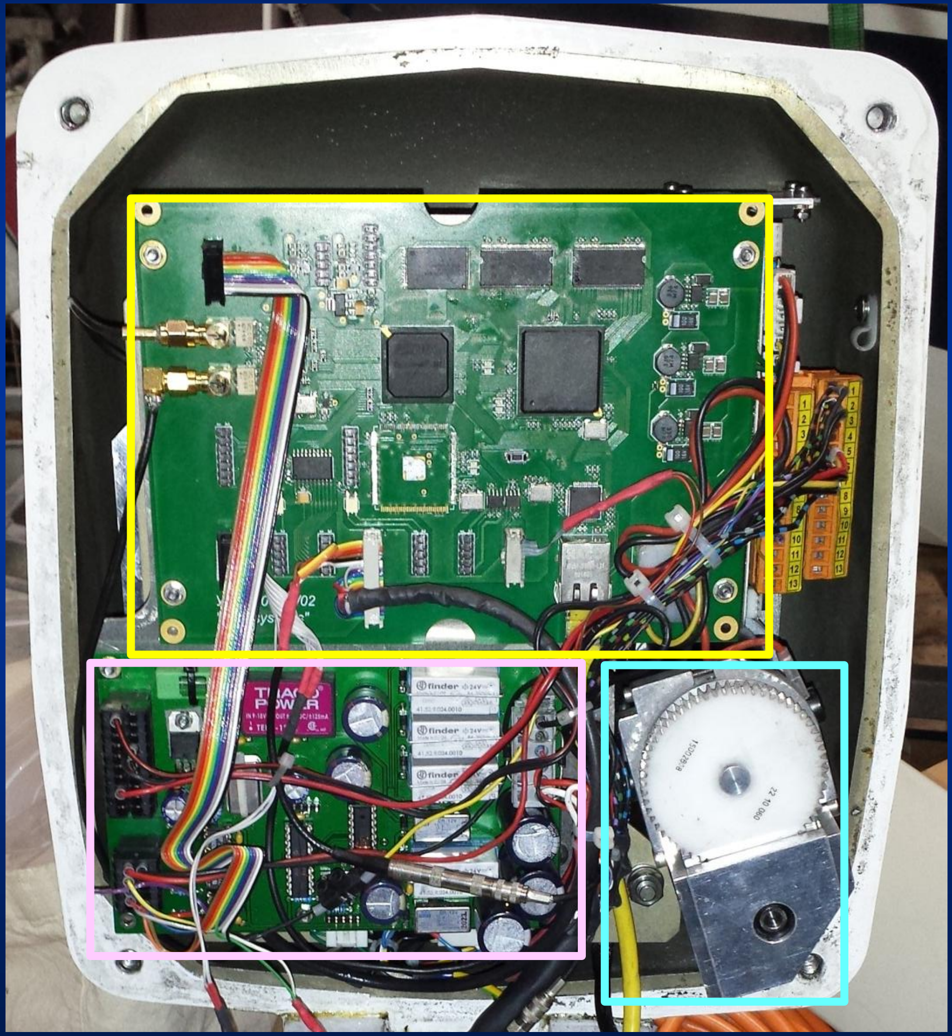


Hereon Coherent Marine Radar

Helmholtz-Zentrum hereon

Original GEM 12 kw Radar

Hereon modified Radar



- Acquisition Board
- Low noise Linear amplifier
- Step Motor
- Motor control Board
- Software for Radar data acquisition, adapted for scientific use

Hereon Marines Radar

Bunkerhill, Sylt

FS Merian

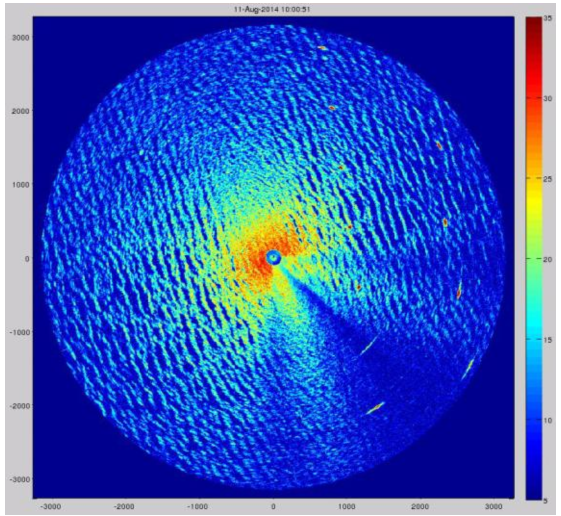
FINO-3, German Bight

X-Band (9.3 GHz)
4, 12 and 25 kW
4 - 12 feet Antenna
HH & VV-Polarization
Incoherent and Coherent
7.5 m range resolution
Up to 0.6° radial resolution

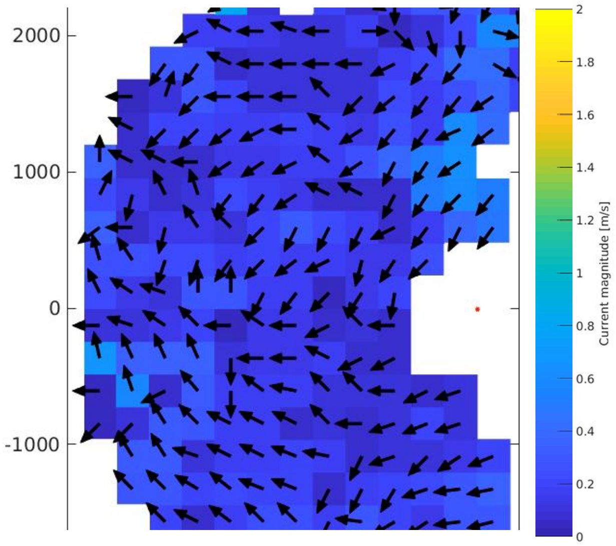
Main Marine Radar Applications

Helmholtz-Zentrum hereon

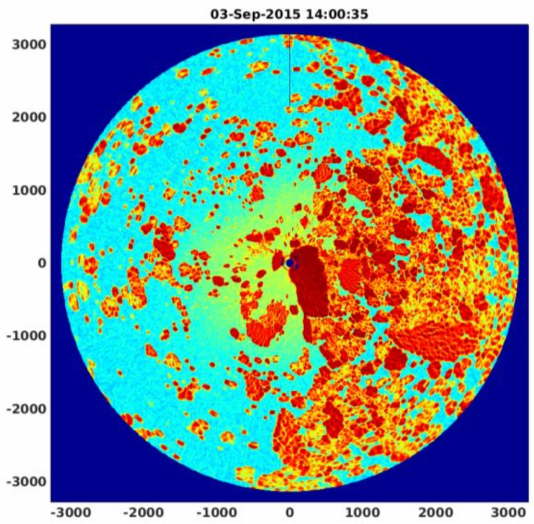
Seastate



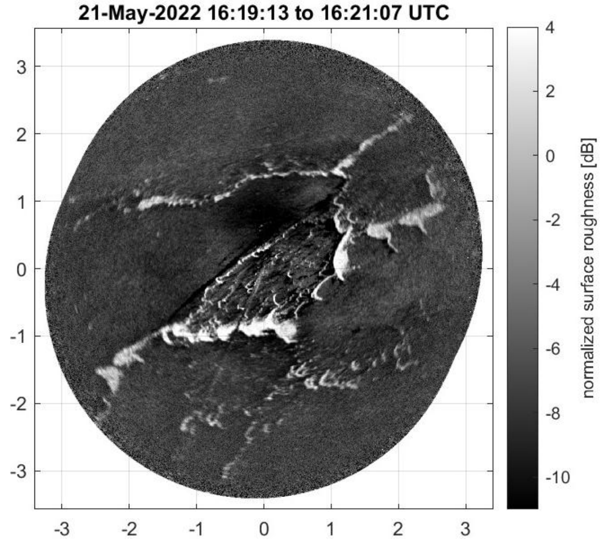
Currents



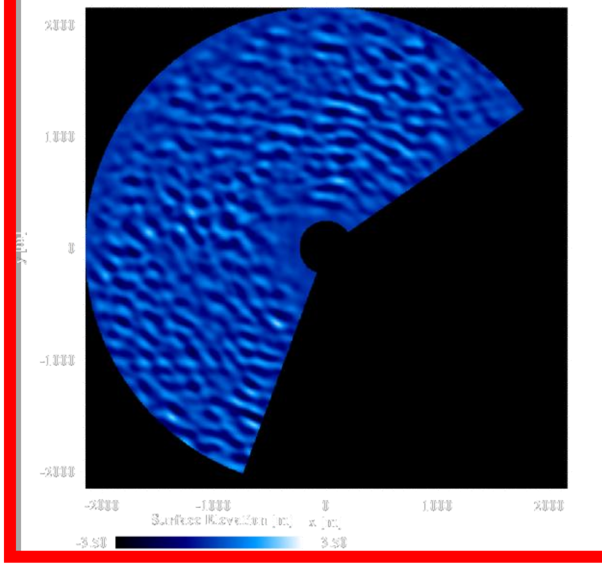
Sea Ice



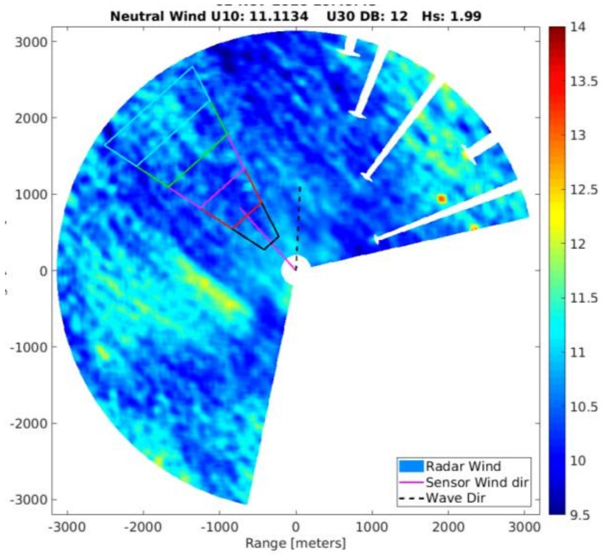
Sargassum flows



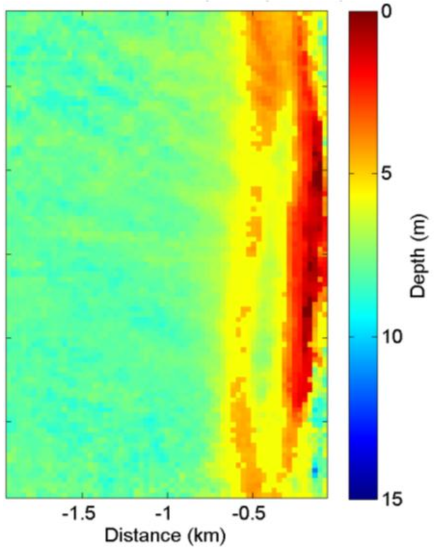
Individual Waves



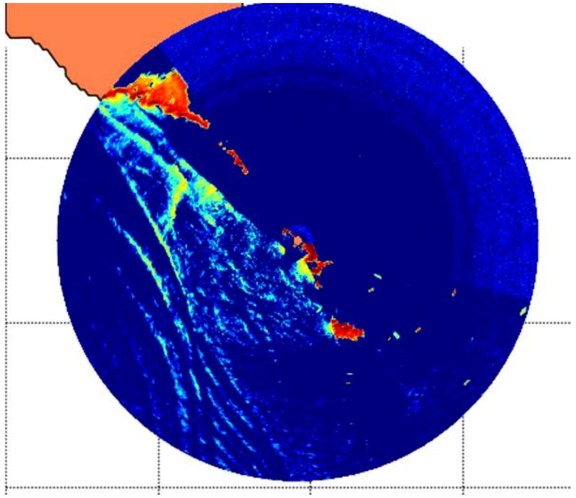
Wind



Bathymetry



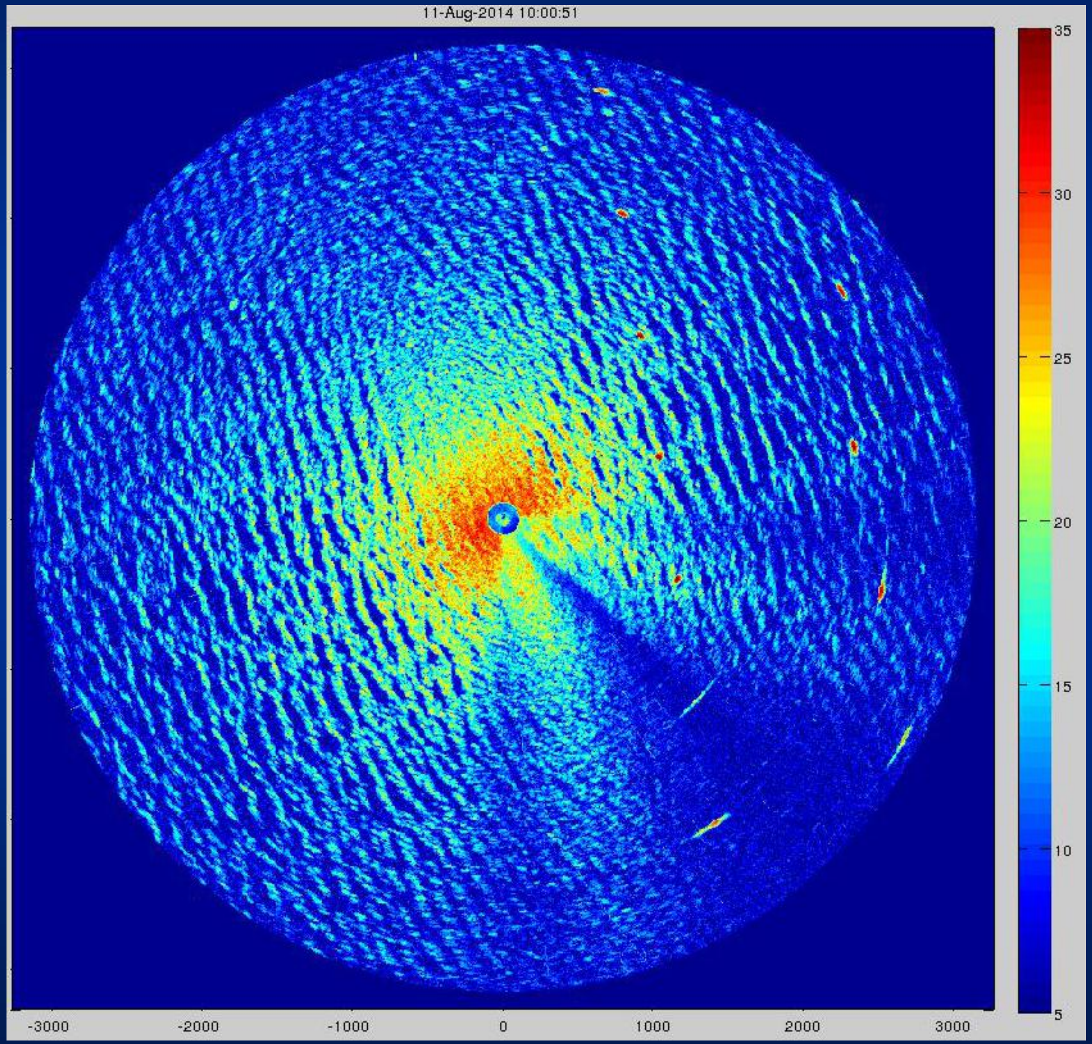
Internal Waves

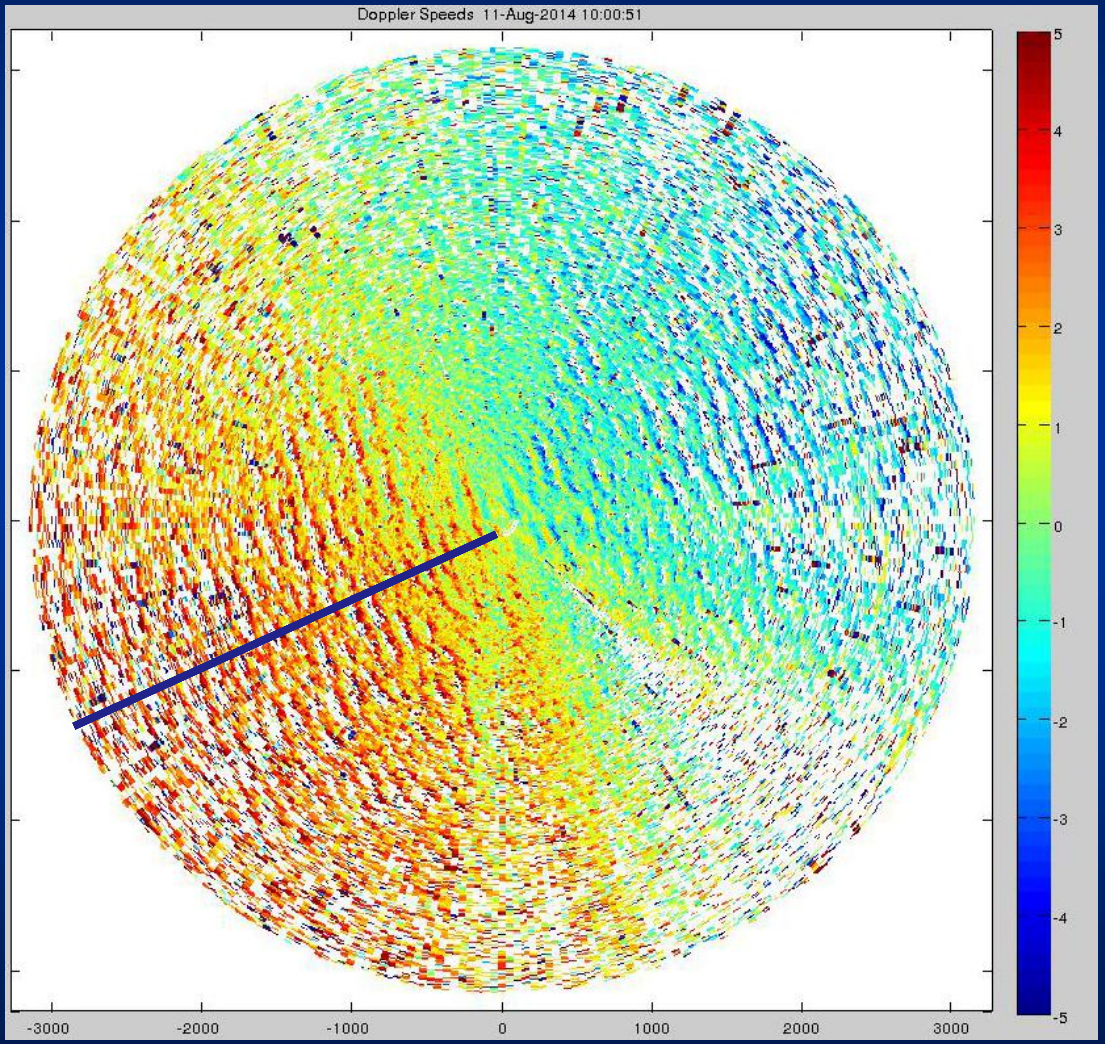


Marine Radar on FINO-3

Wave Measurements with the Coherent Marine Radar

$u_{tot} = u_{wind} + u_{cur} + u_{orb} + u_{break} + u_{shad} + u_{rest}$



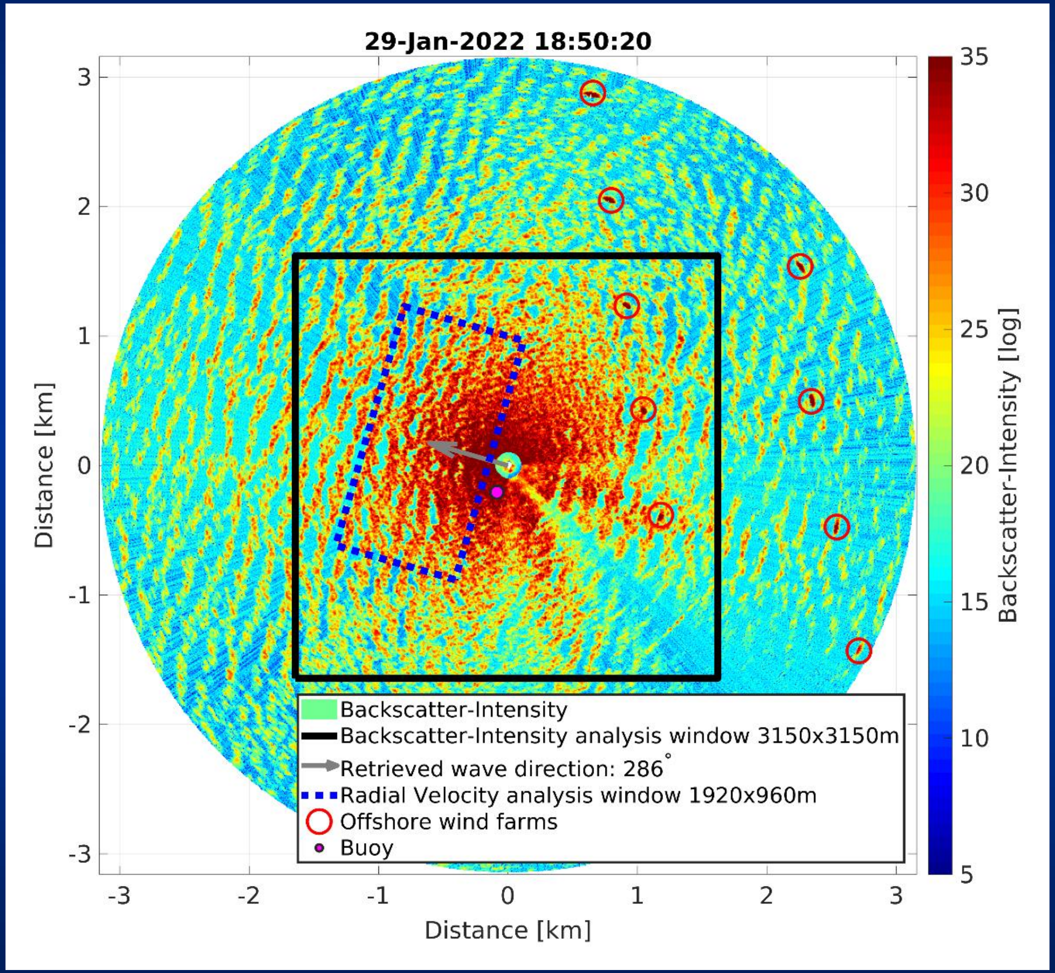


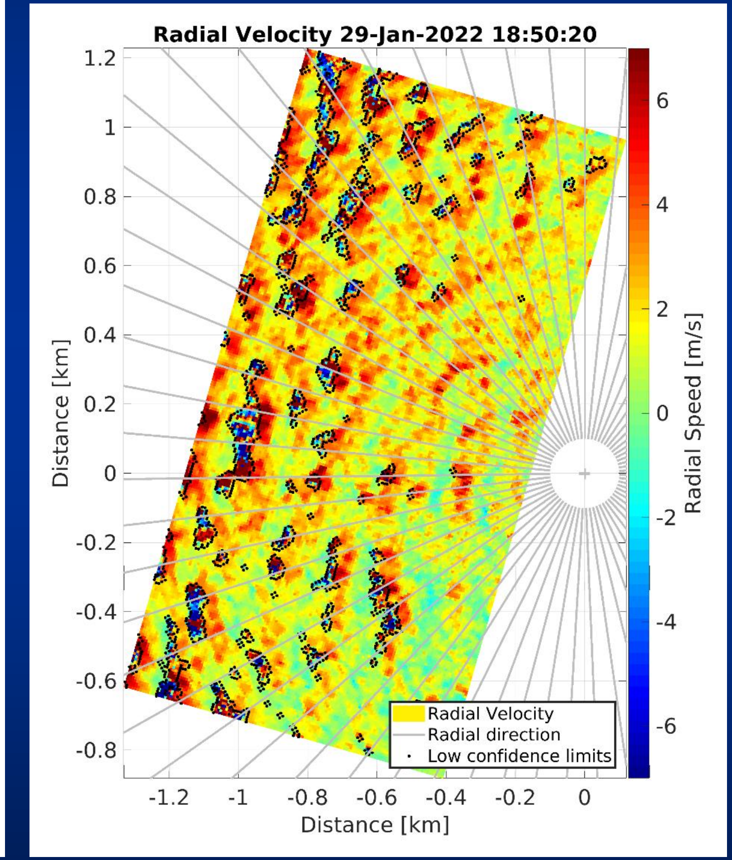
Intensity

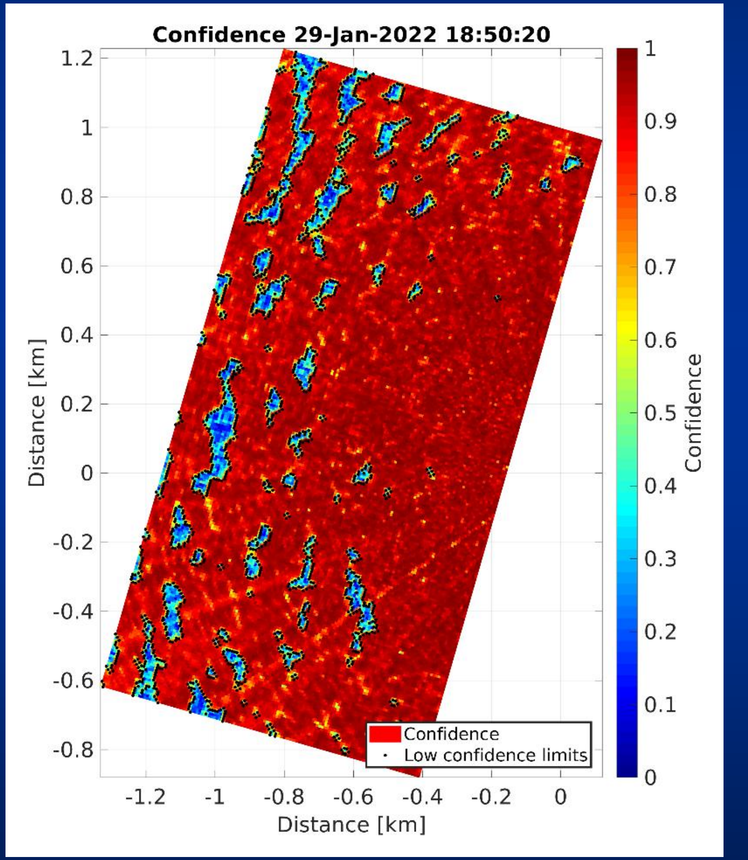
Doppler Velocity

Significant Wave Height measurements by Coherent Marine Radar

R. Carrasco, J. -C. Nieto-Borge, J. Seemann and J. Horstmann, "Significant Wave Height Retrieved From Coherent X-Band Radar: A Physics-Based Approach," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 62, pp. 1-15, 2024, Art no. 5102115, doi: 10.1109/TGRS.2024.3354042.





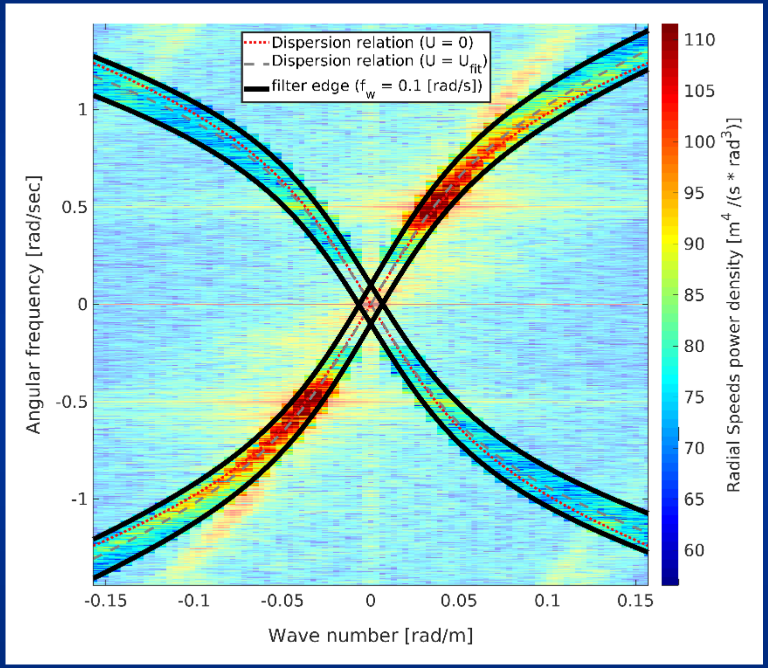


Backscatter-Intensity

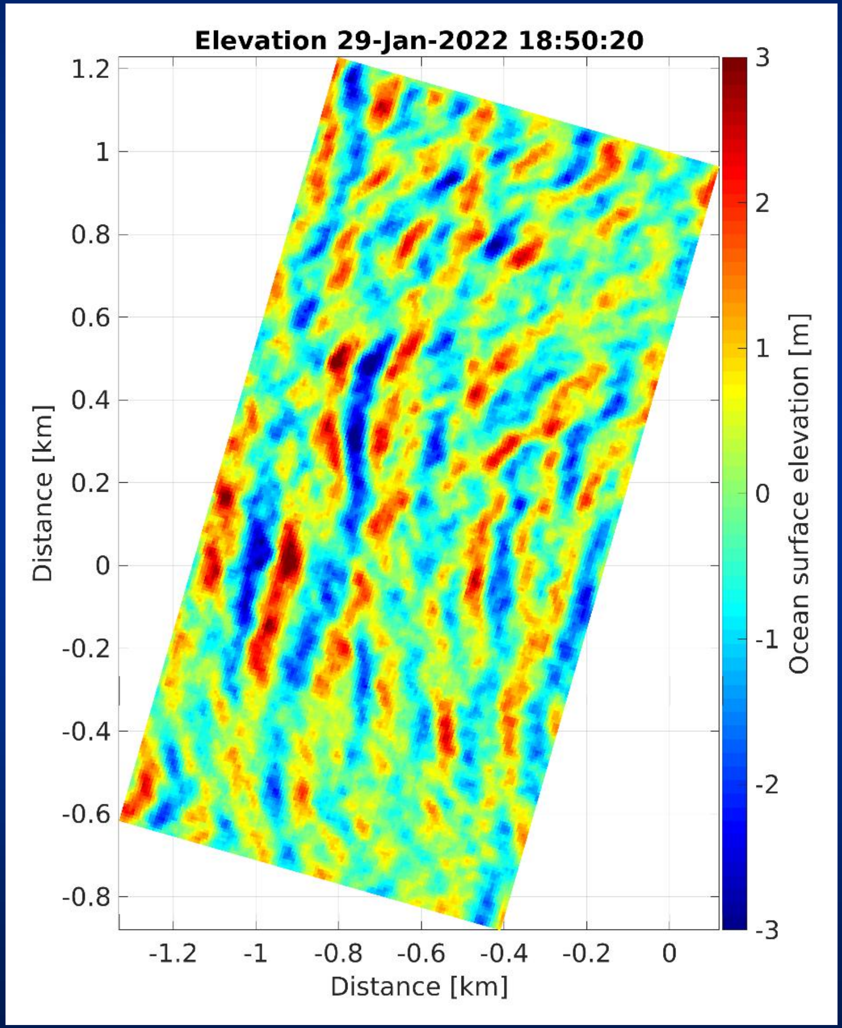
Doppler Speed

Doppler Confidence

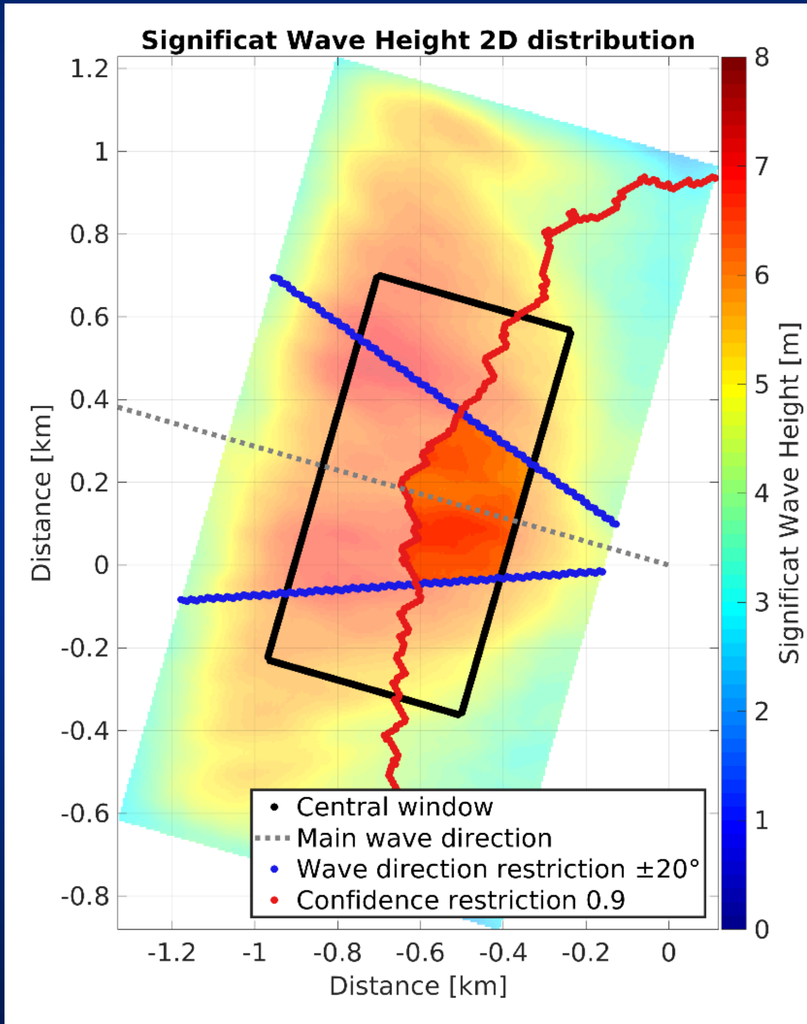
Significant Wave Height measurements by Coherent Marine Radar



Surface elevation



Hs calculation

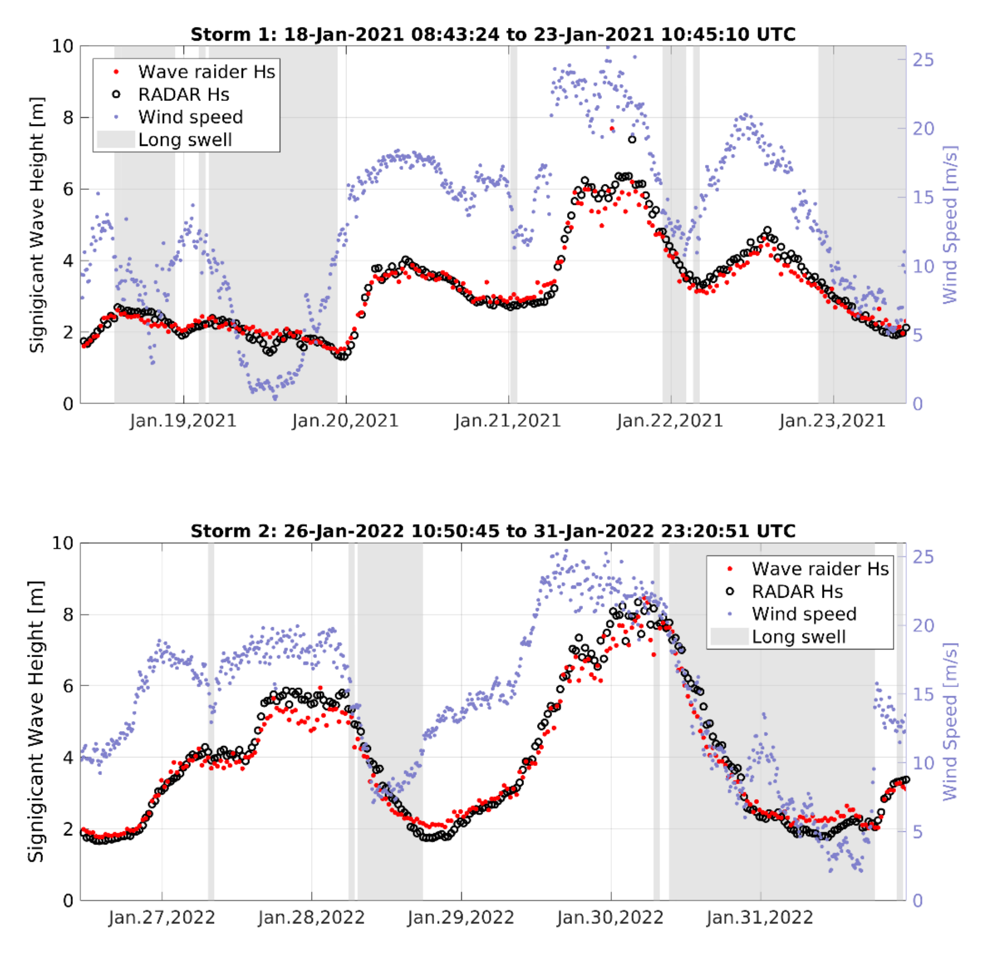


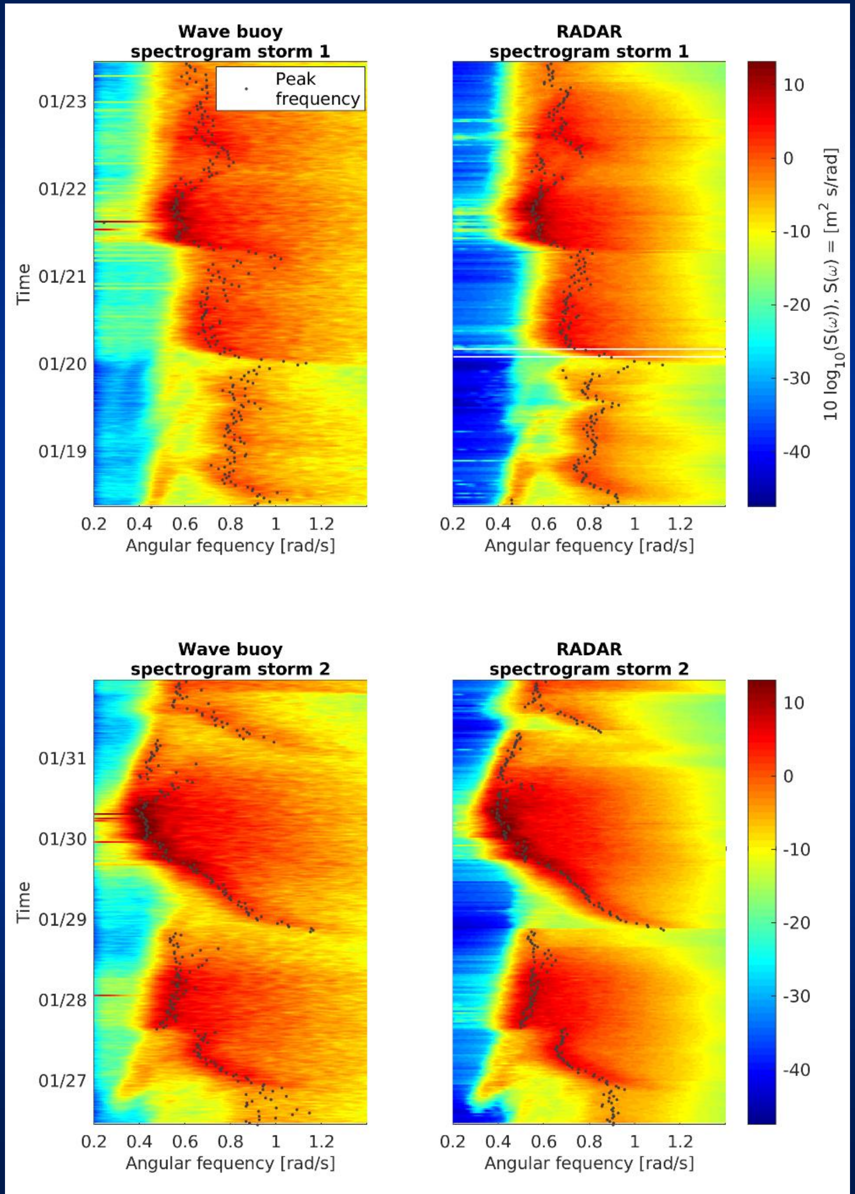
Dispersion relation filtering + linear wave theory

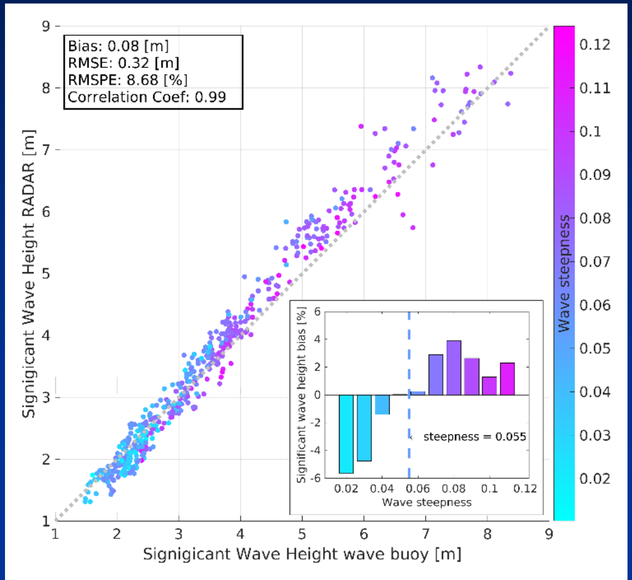
Significant Wave Height measurements by Coherent Marine Radar

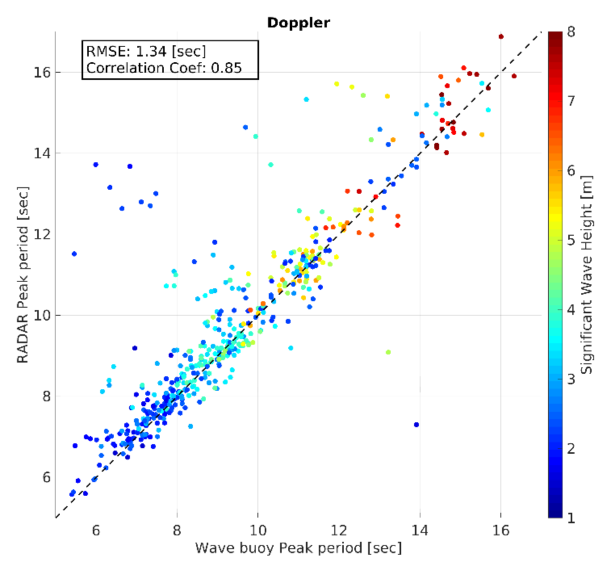
Correlation Coef: 0.99

RMSE: 0.32 m RMSPE: 8.7 %

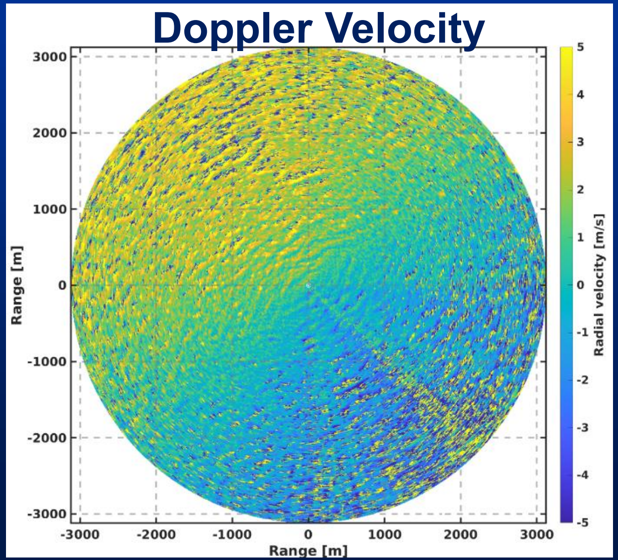


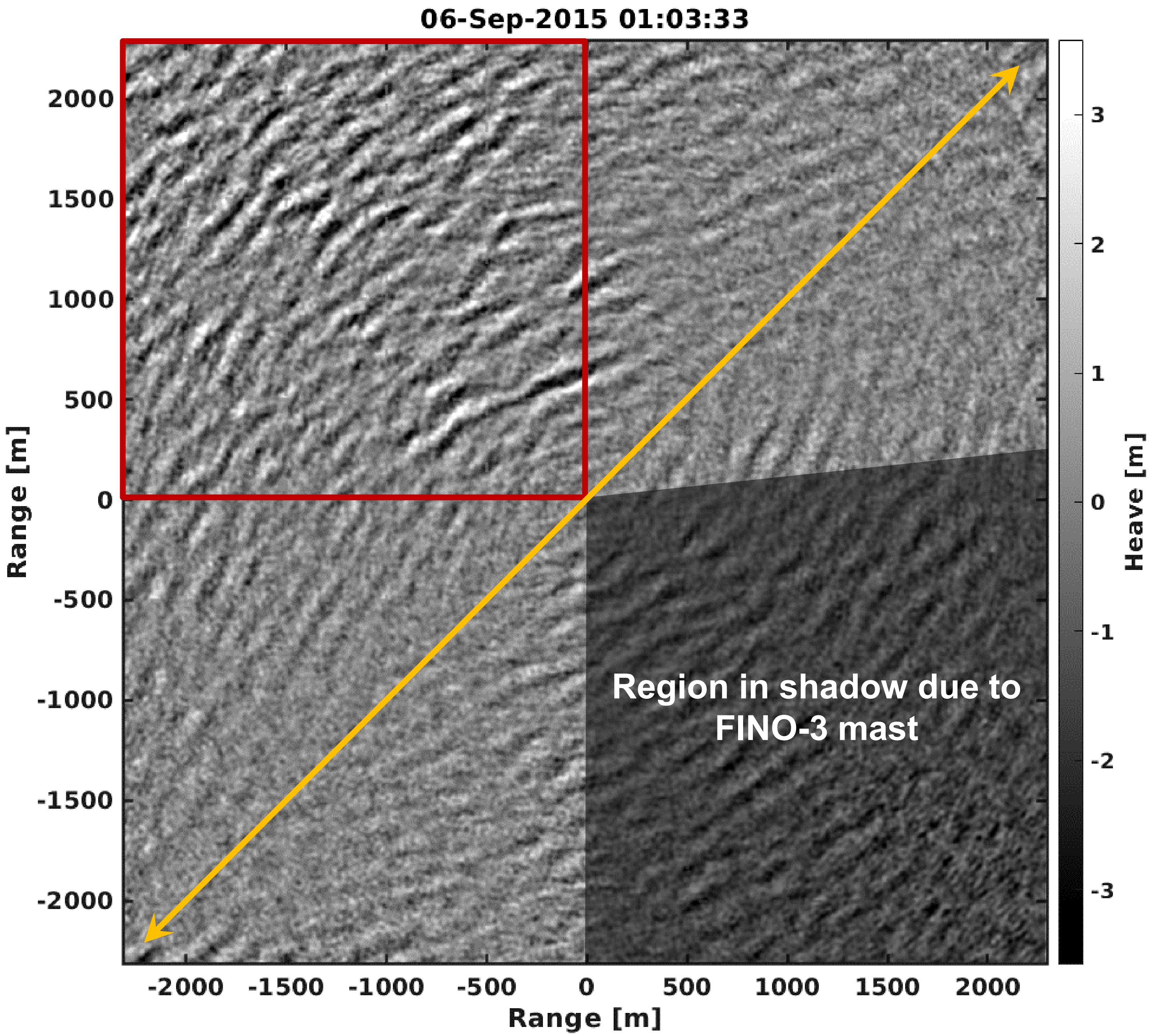




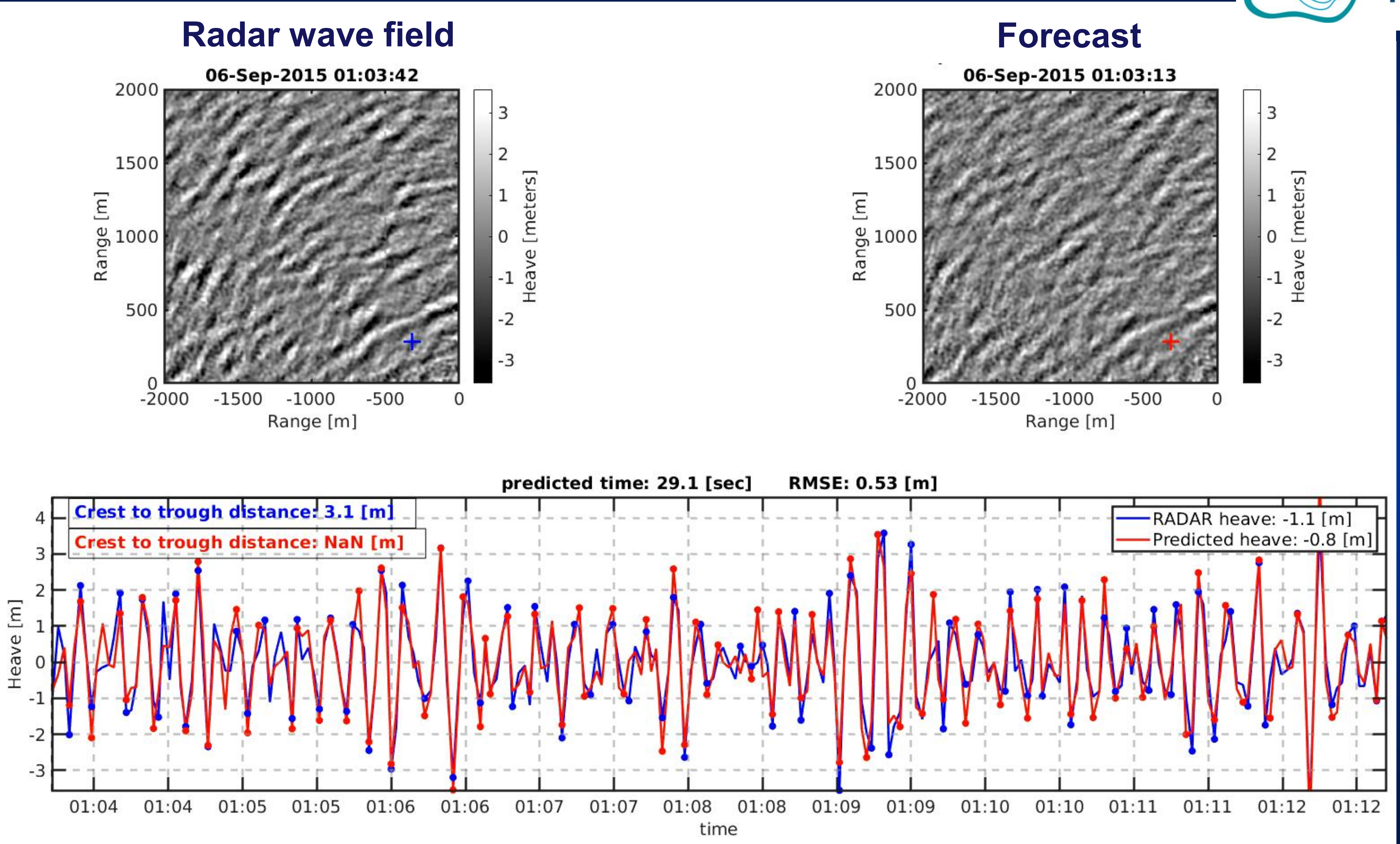


Wave fields observation in space and time



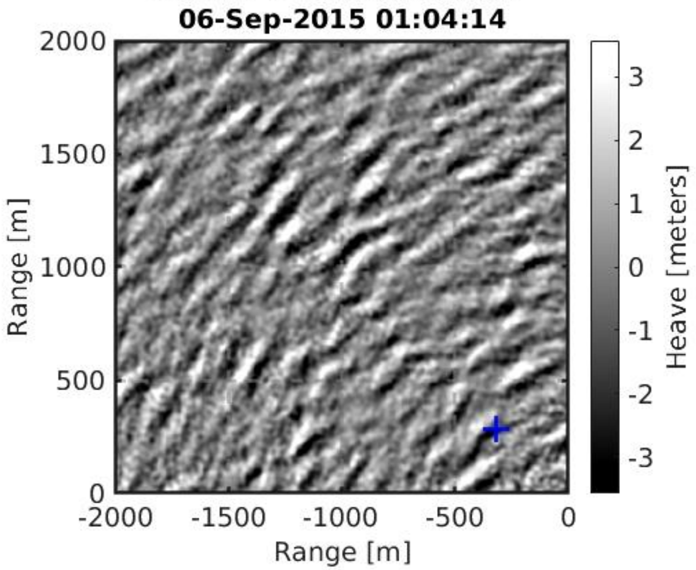


Short term prediction of wave fields over 30 s

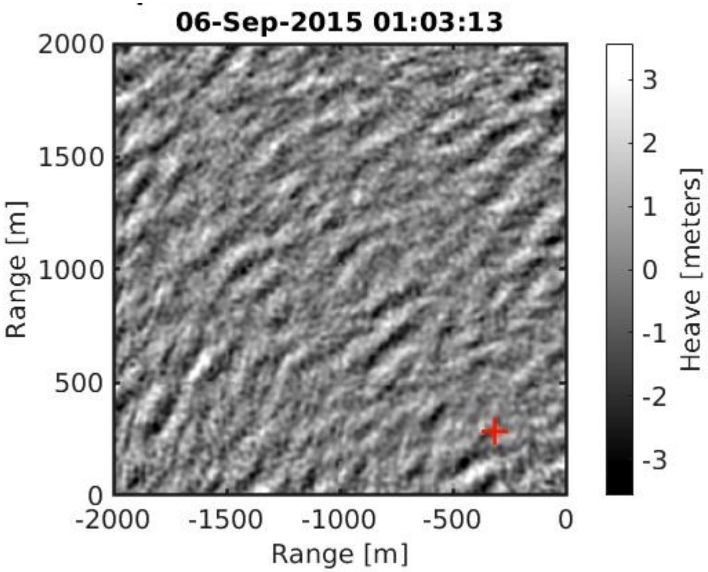


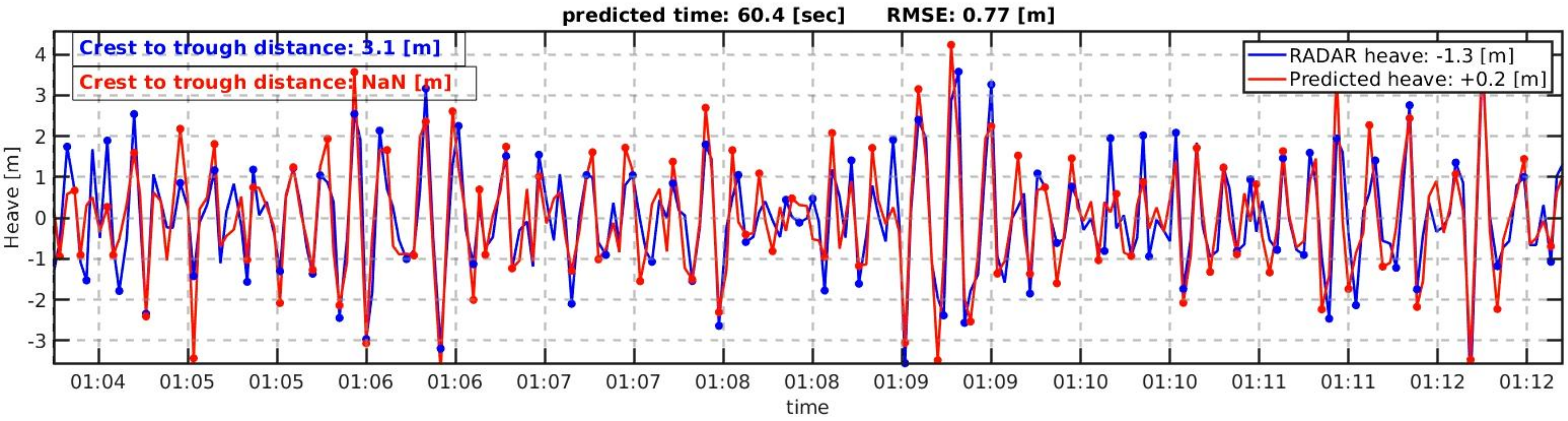
Short term prediction of wave fields over 60 s

Radar wave field

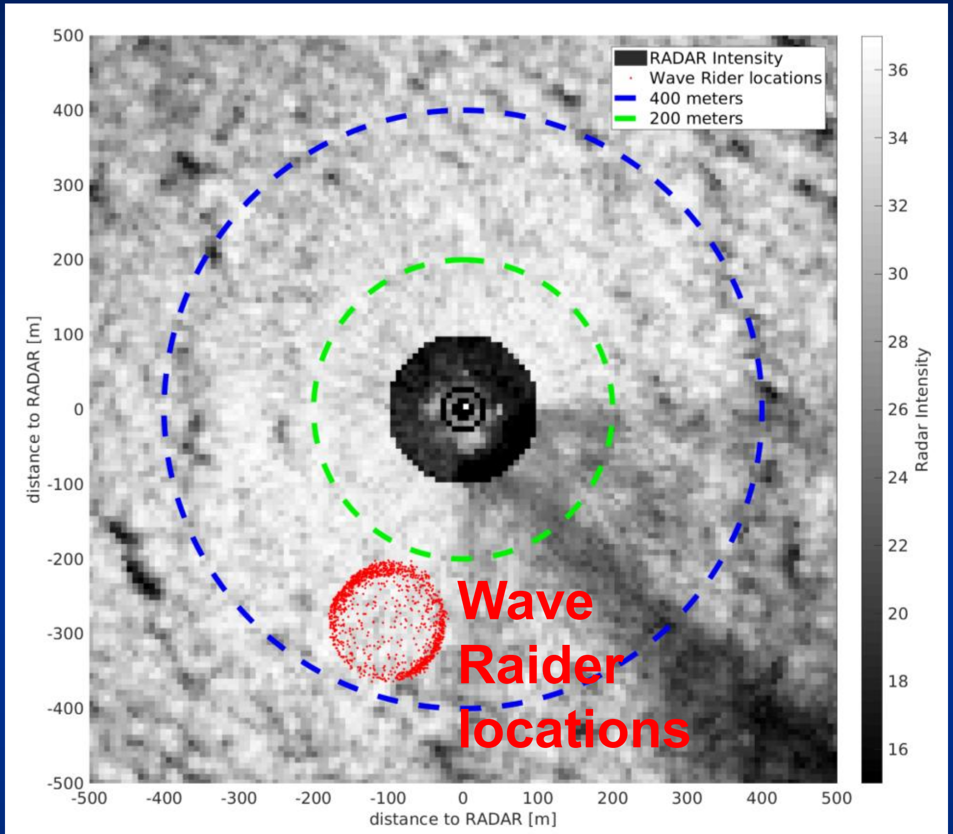


Forecast

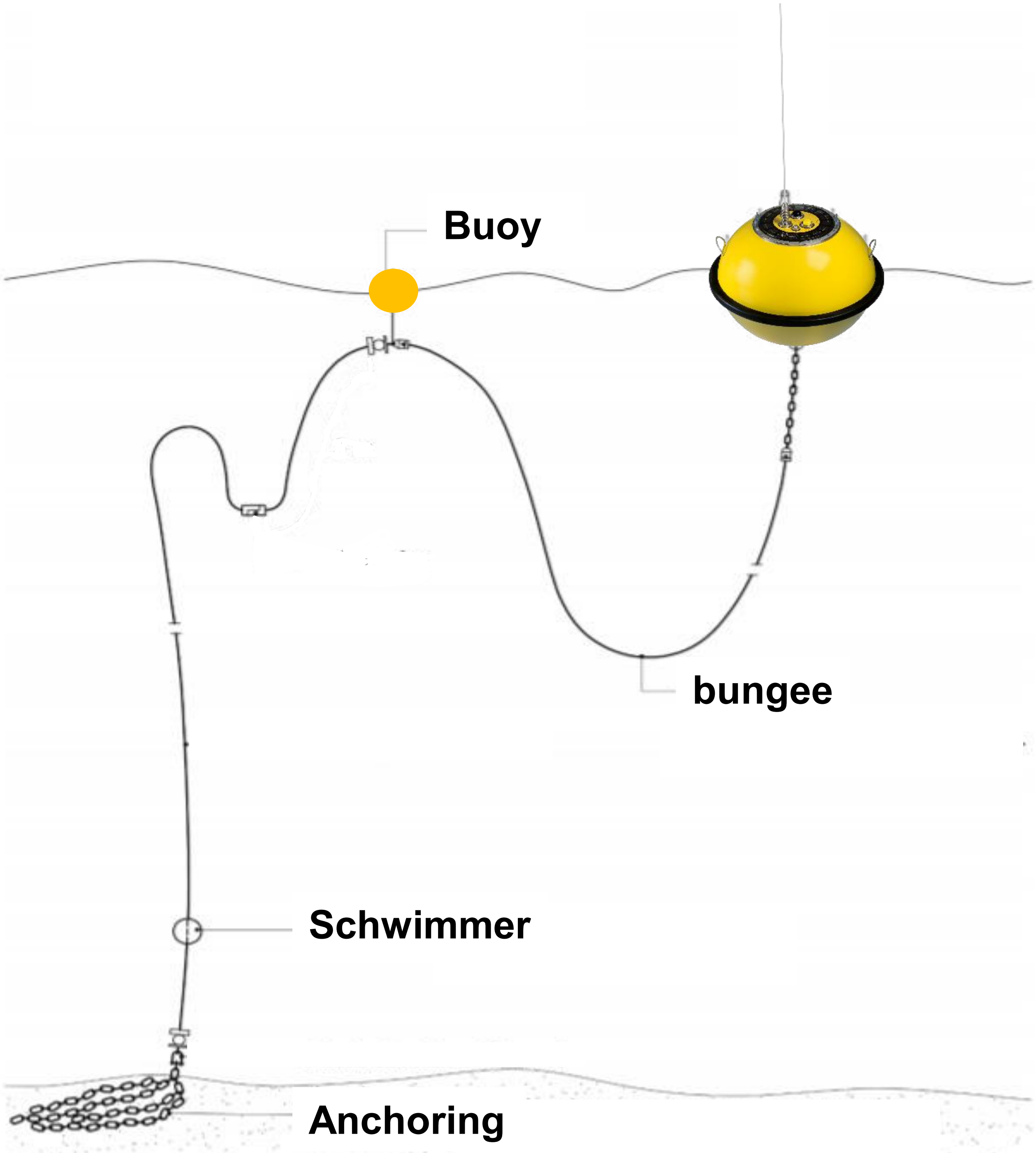




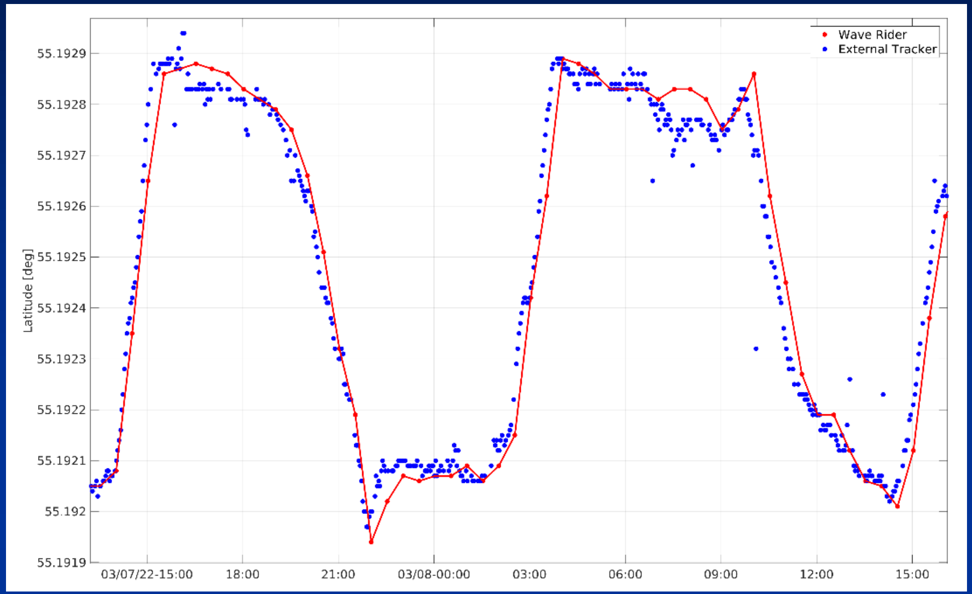
Single wave measurement validation challenges:

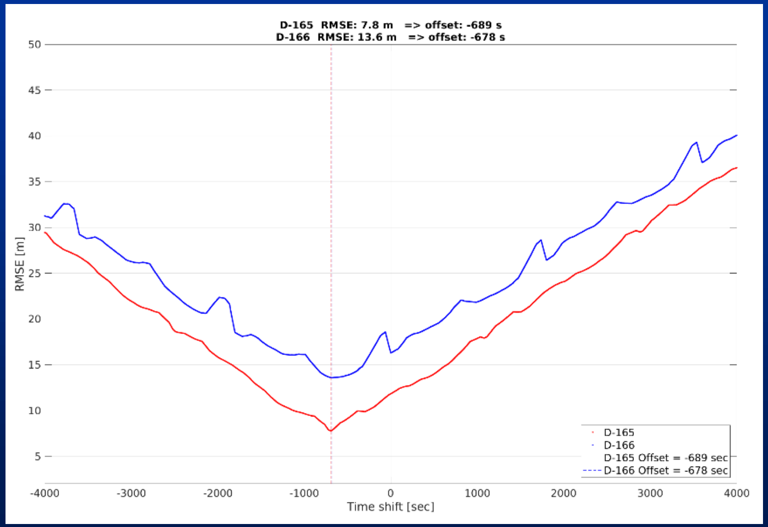


- Time delay
- Accurate Position
  - Tidal currents ~ 0.5 m/s
  - Waves orbital motion



Wave Raider + external tracker

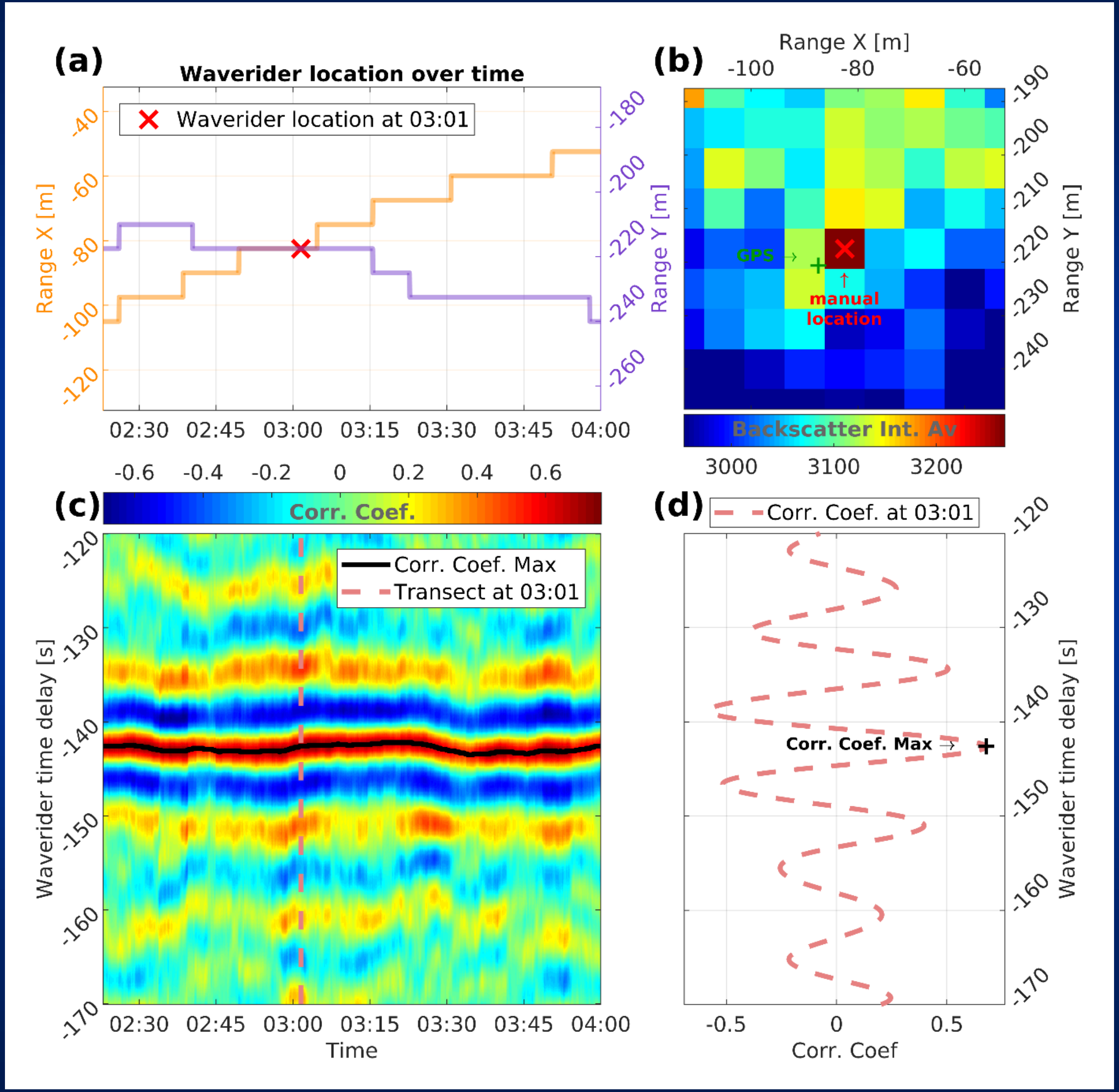




Sampling time:

- Wave Raider: 30 minutes
- External Tracker: 2.5 minutes

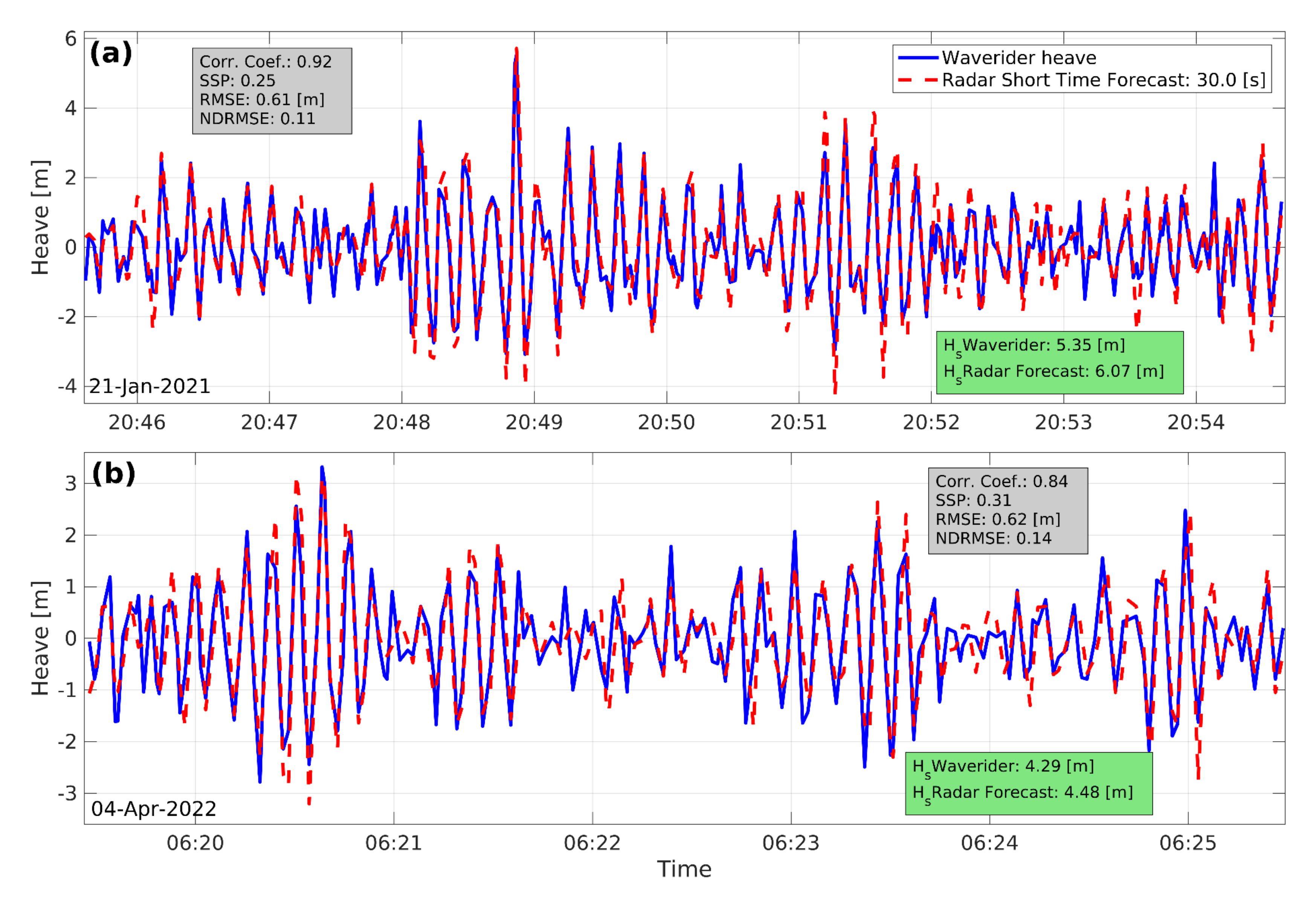
Synchronization: Wave Raider + external tracker



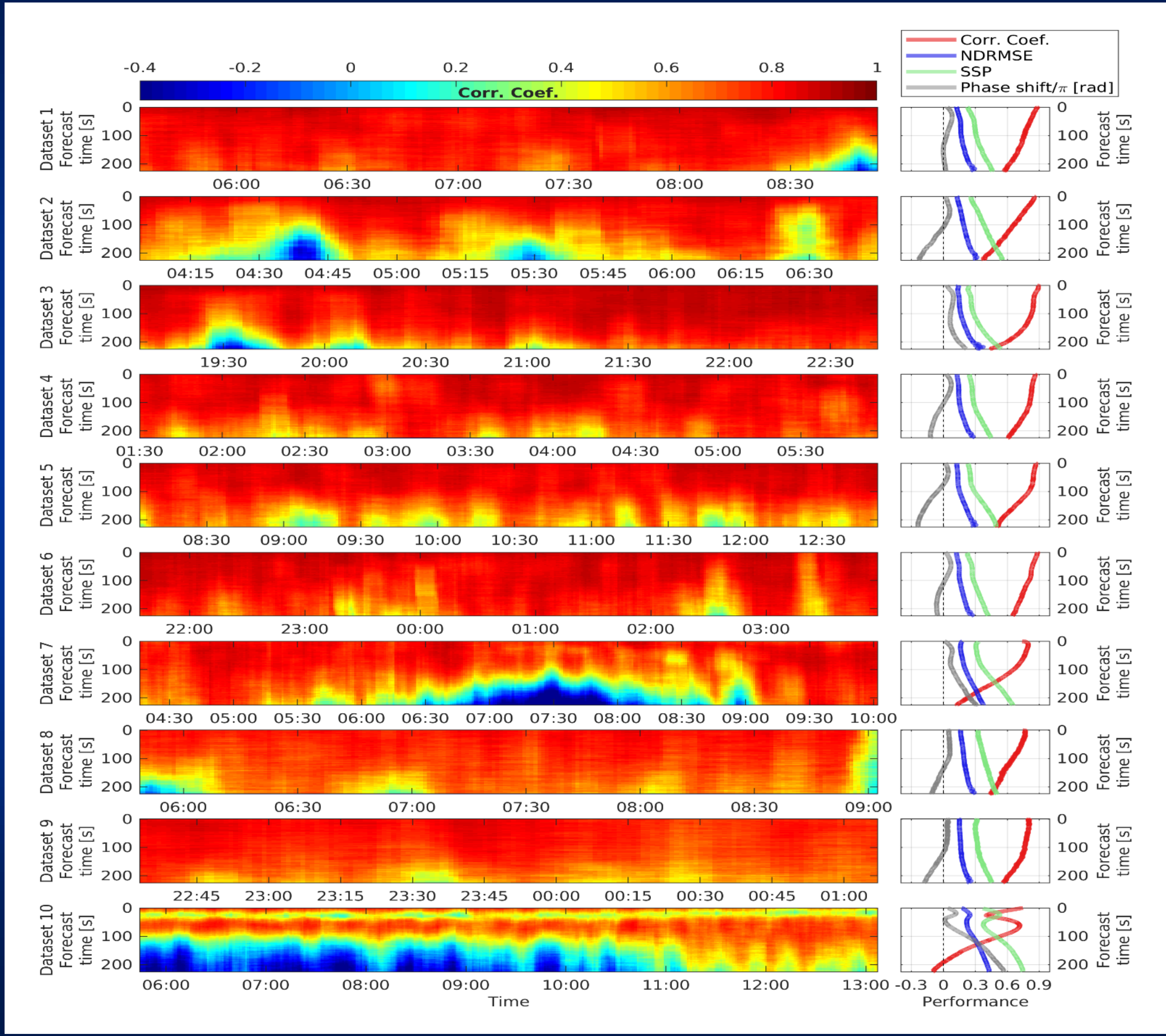
Individual waves propagation 30s

Wave field propagation by linear wave theory

$$\hat{\eta}_{pro}(k_x, k_y) = \hat{\eta}_+(k_x, k_y)e^{-i\omega(\mathbf{k})t_{pro}}$$



Feasibility study: over time domain



Red CC: forecast wave field in phase vs real wave field

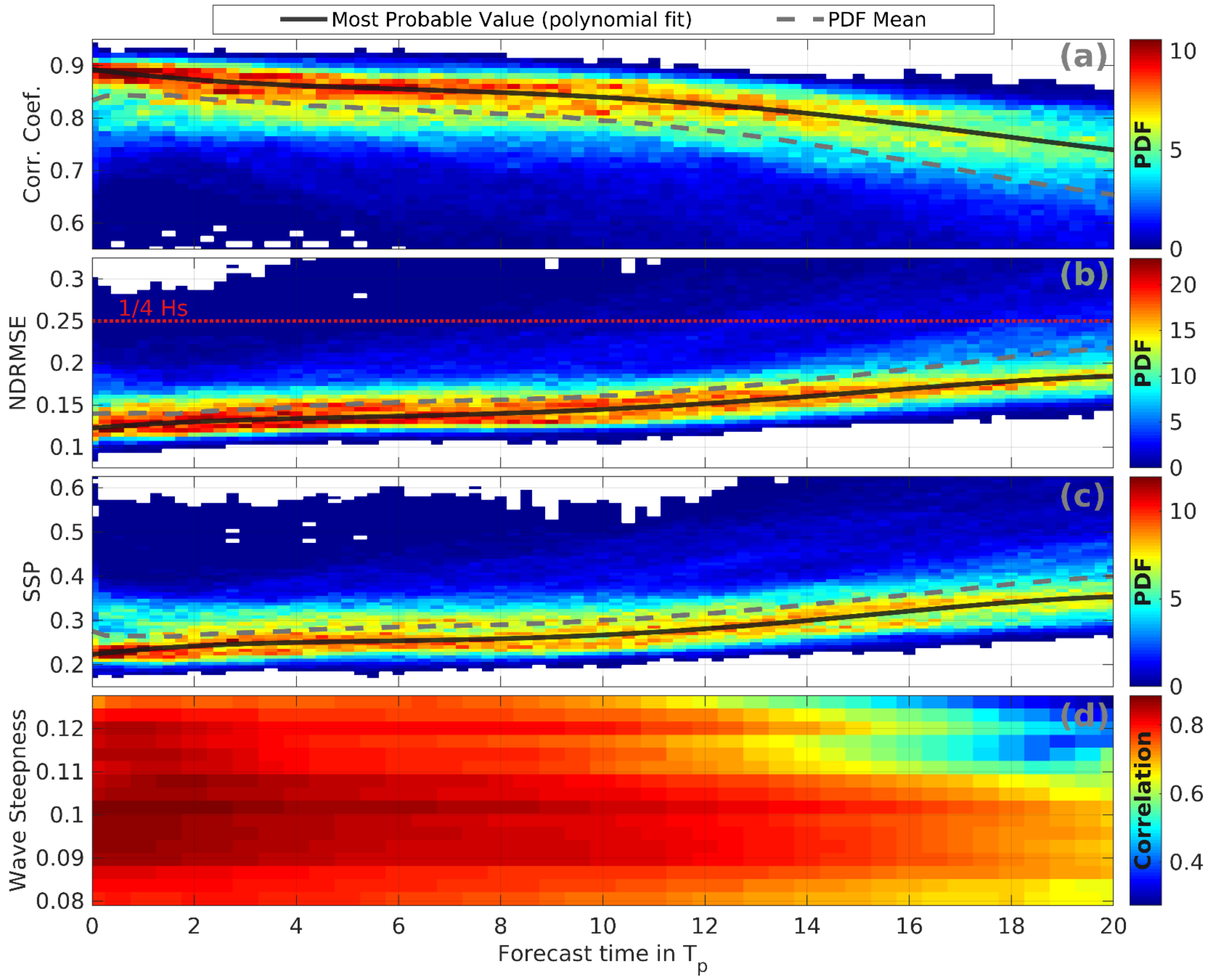
Blue CC: negative forecast wave field not in phase vs real wave field

Feasibility study: Probability Density Function

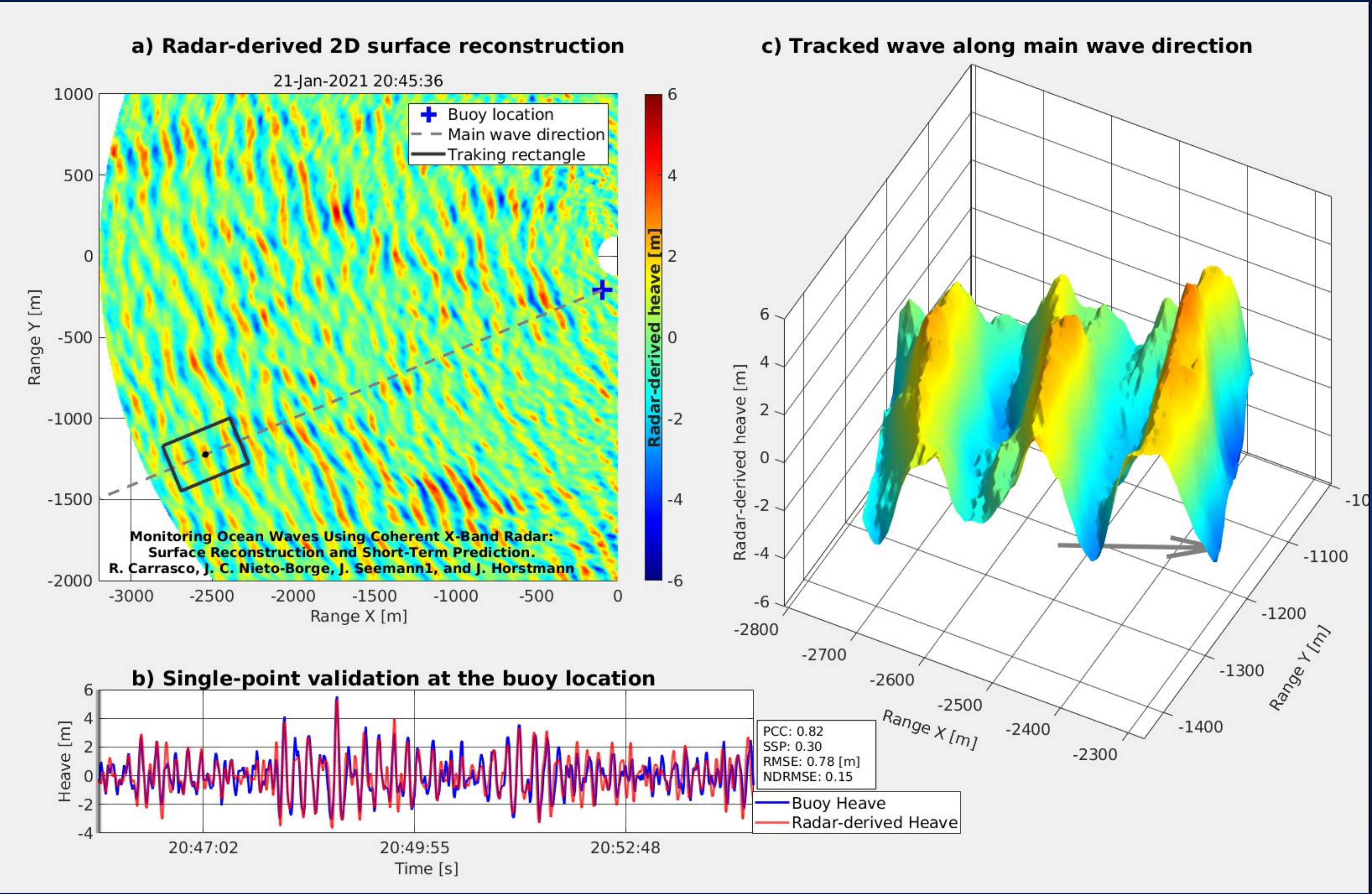
$$\mathrm{PCC} = \frac{\mathrm{cov}(\kappa, \eta)}{\sigma_\kappa \sigma_\eta}$$

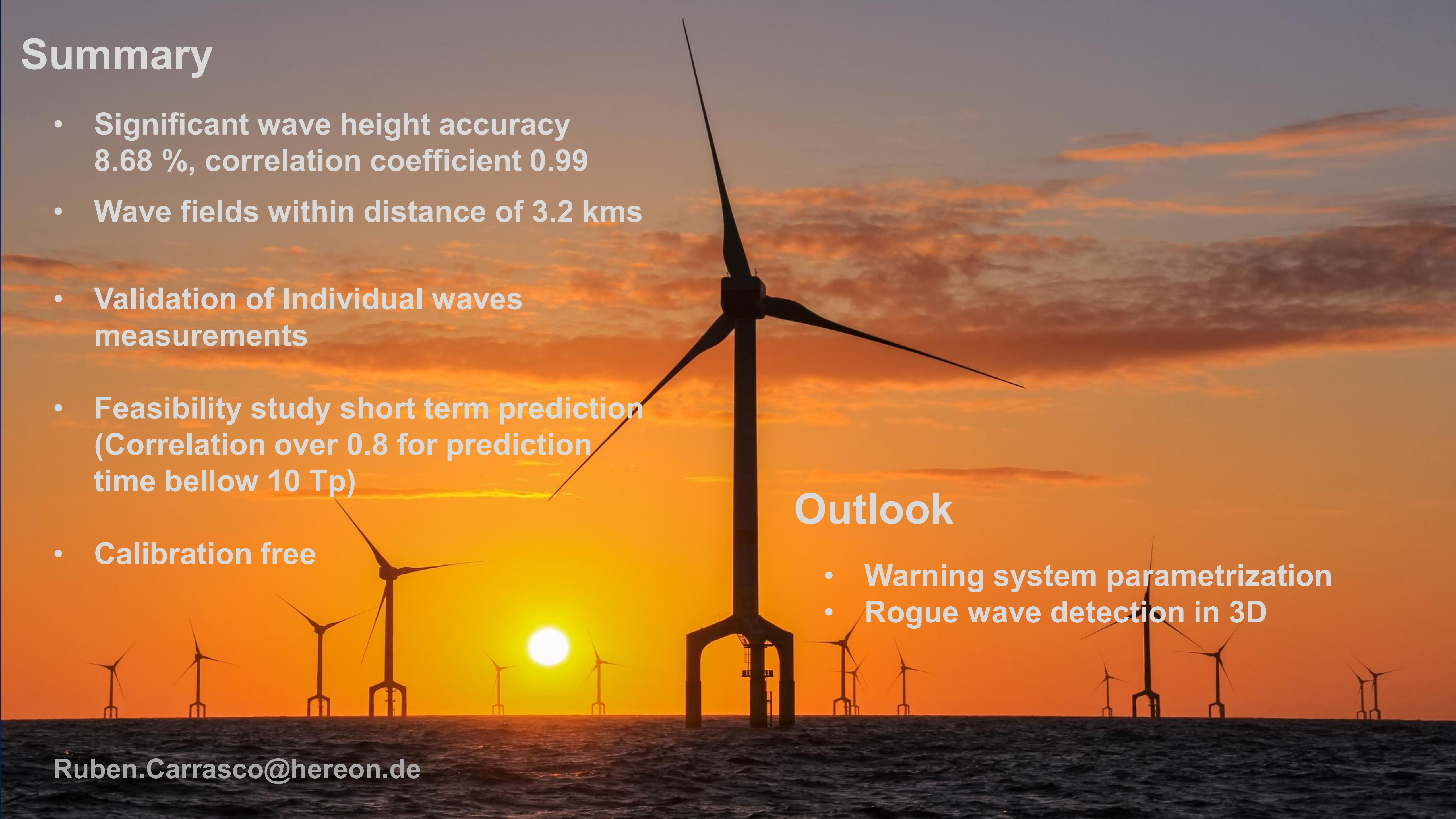
$$\mathrm{NDRMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{\kappa_i - \eta_i}{H_s}\right)^2}$$

$$\mathrm{SSP} = \frac{\left(\int |\mathcal{F}\{\kappa(t)\}(\omega) - \mathcal{F}\{\eta(t)\}(\omega)|^2 \, d\omega\right)^{1/2}}{\left(\int |\mathcal{F}\{\kappa(t)\}(\omega)|^2 \, d\omega\right)^{1/2} + \left(\int |\mathcal{F}\{\eta(t)\}(\omega)|^2 \, d\omega\right)^{1/2}}$$



Radar-derived wave field evolution





Summary

- Significant wave height accuracy 8.68 %, correlation coefficient 0.99
- Wave fields within distance of 3.2 kms
- Validation of Individual waves measurements
- Feasibility study short term prediction (Correlation over 0.8 for prediction time bellow 10 Tp)
- Calibration free

Outlook

- Warning system parametrization
- Rogue wave detection in 3D

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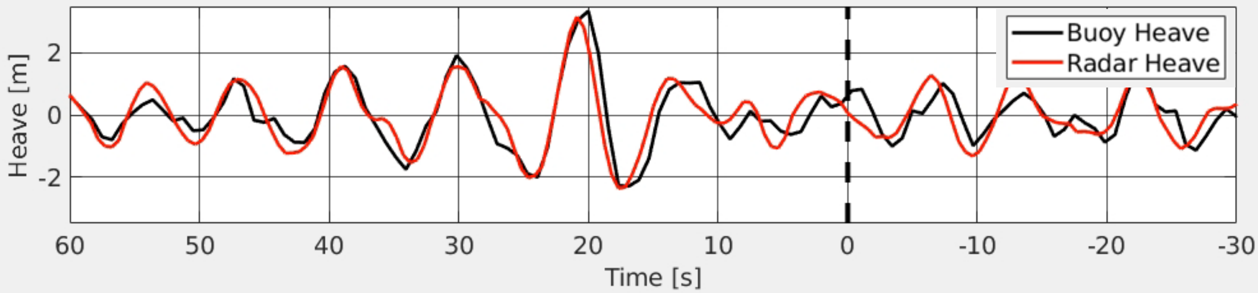
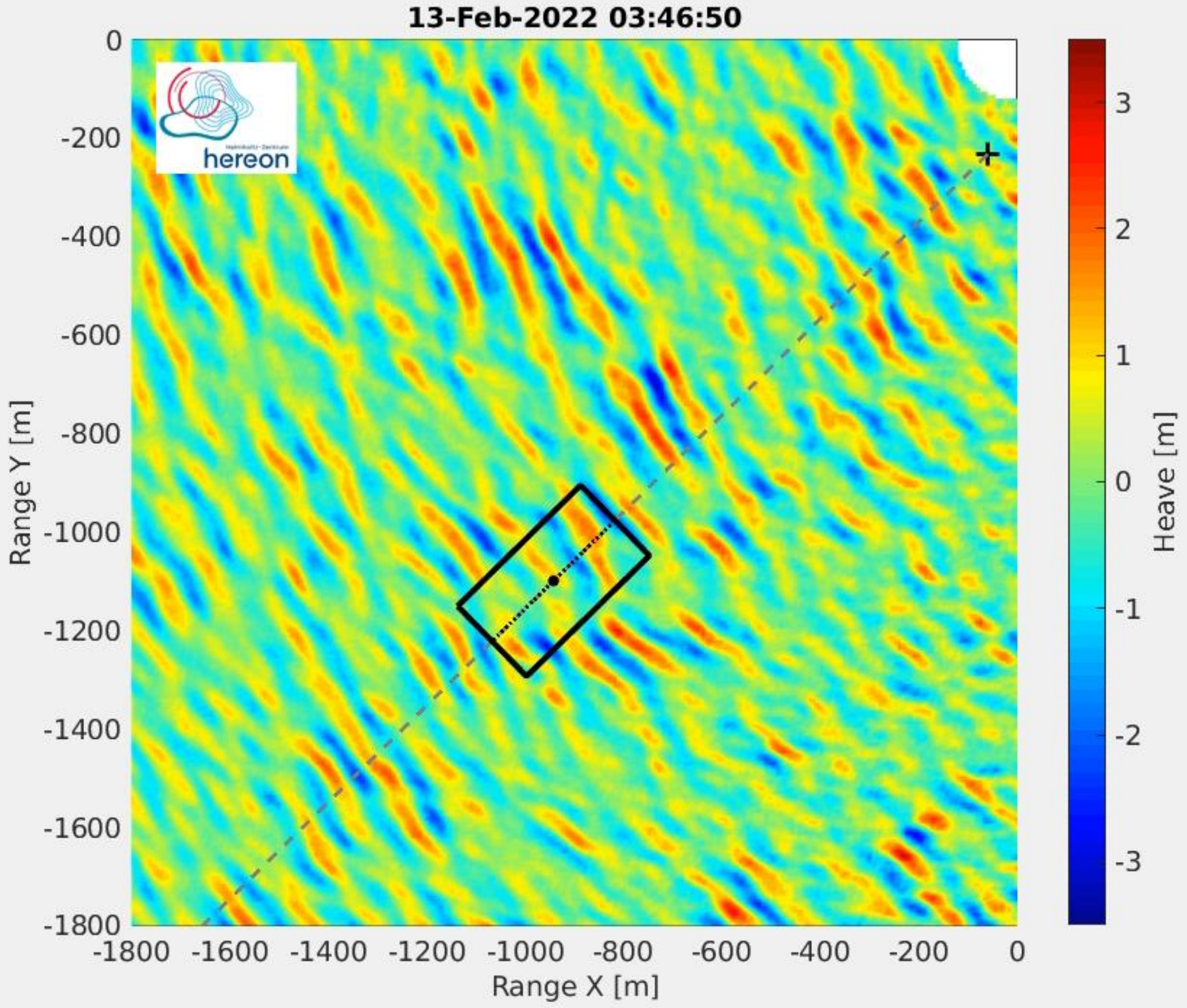
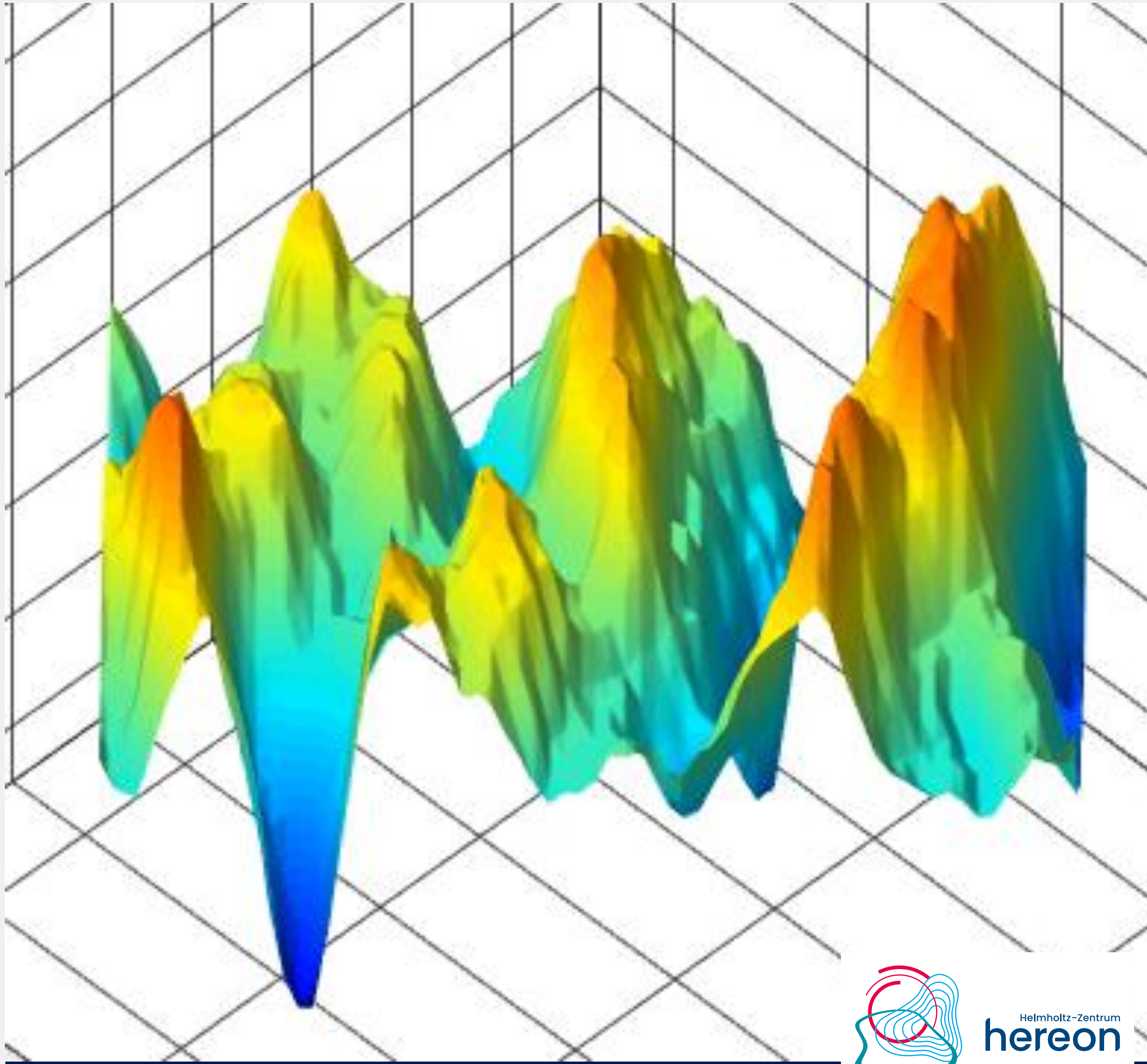
Outlook: Observation of Individual Waves in Space and Time

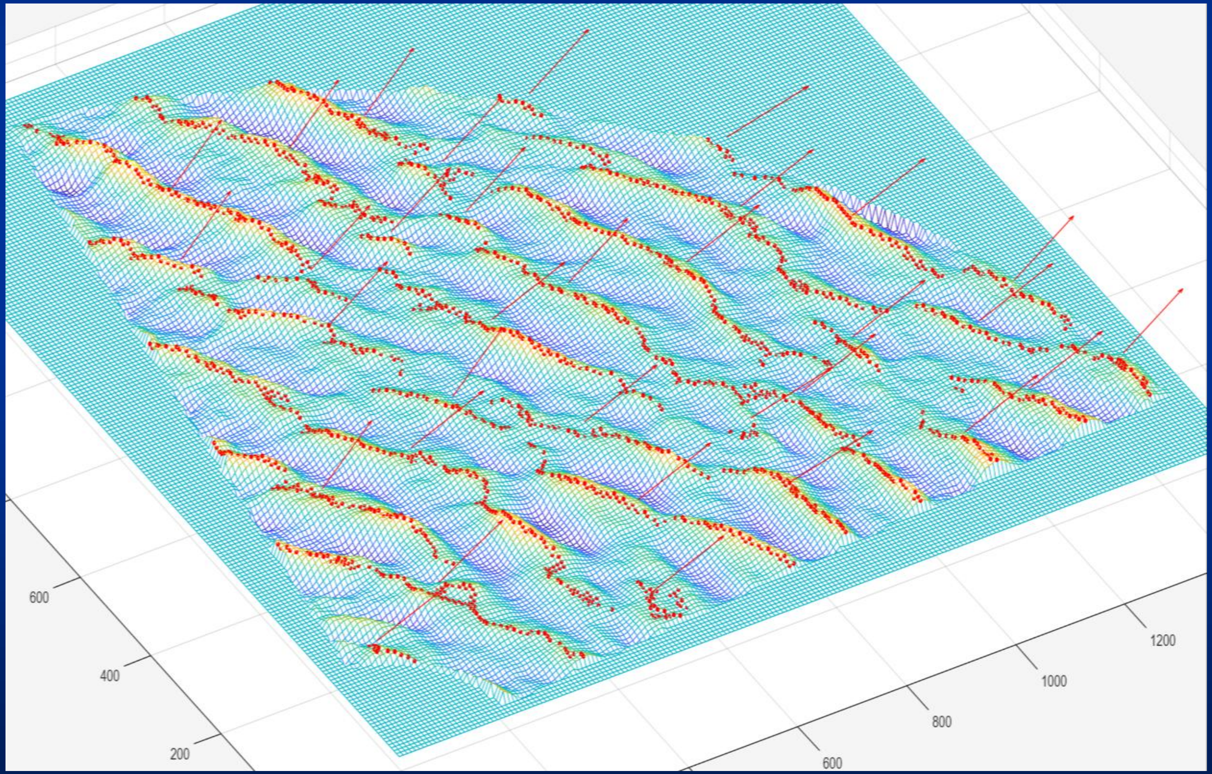




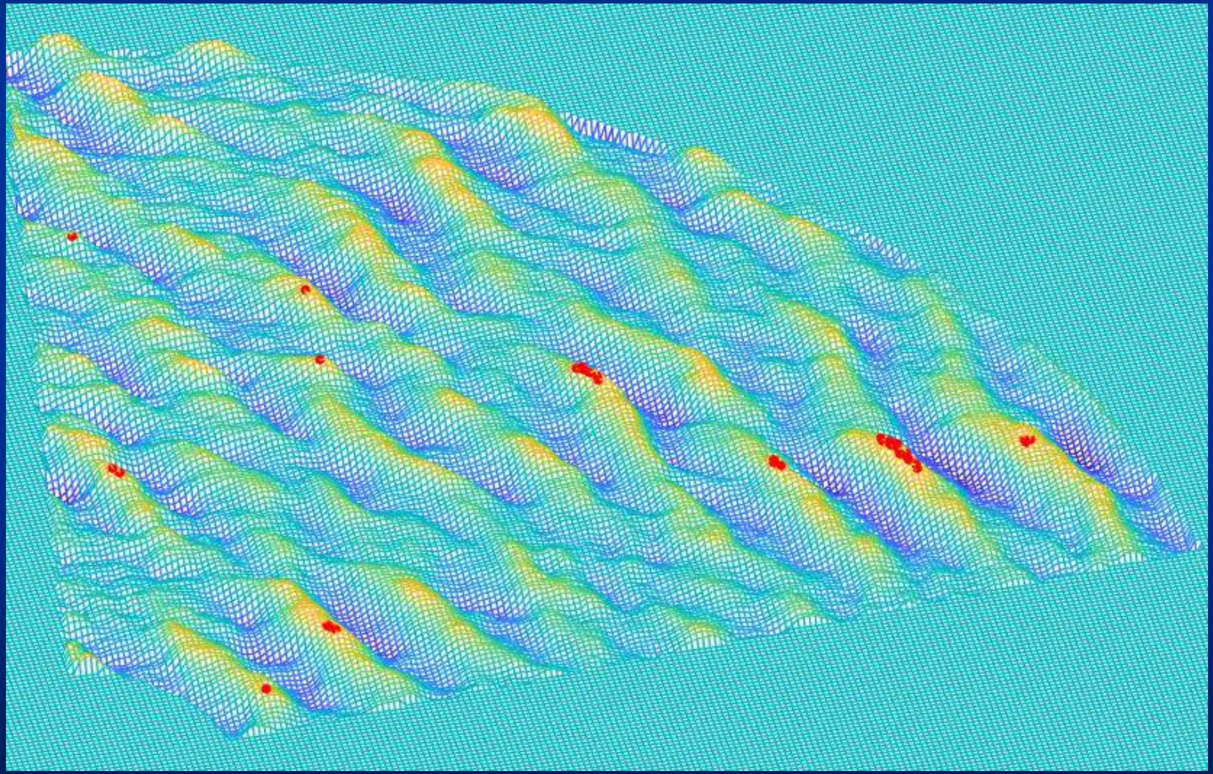


Outlook: Observation of Individual Waves in Space and Time

Wave crests and troughs



Extremes (> 5 m or steeper 0.12)



Radar-derived wave field evolution