Satellite radar altimetry and the quasi-geoid

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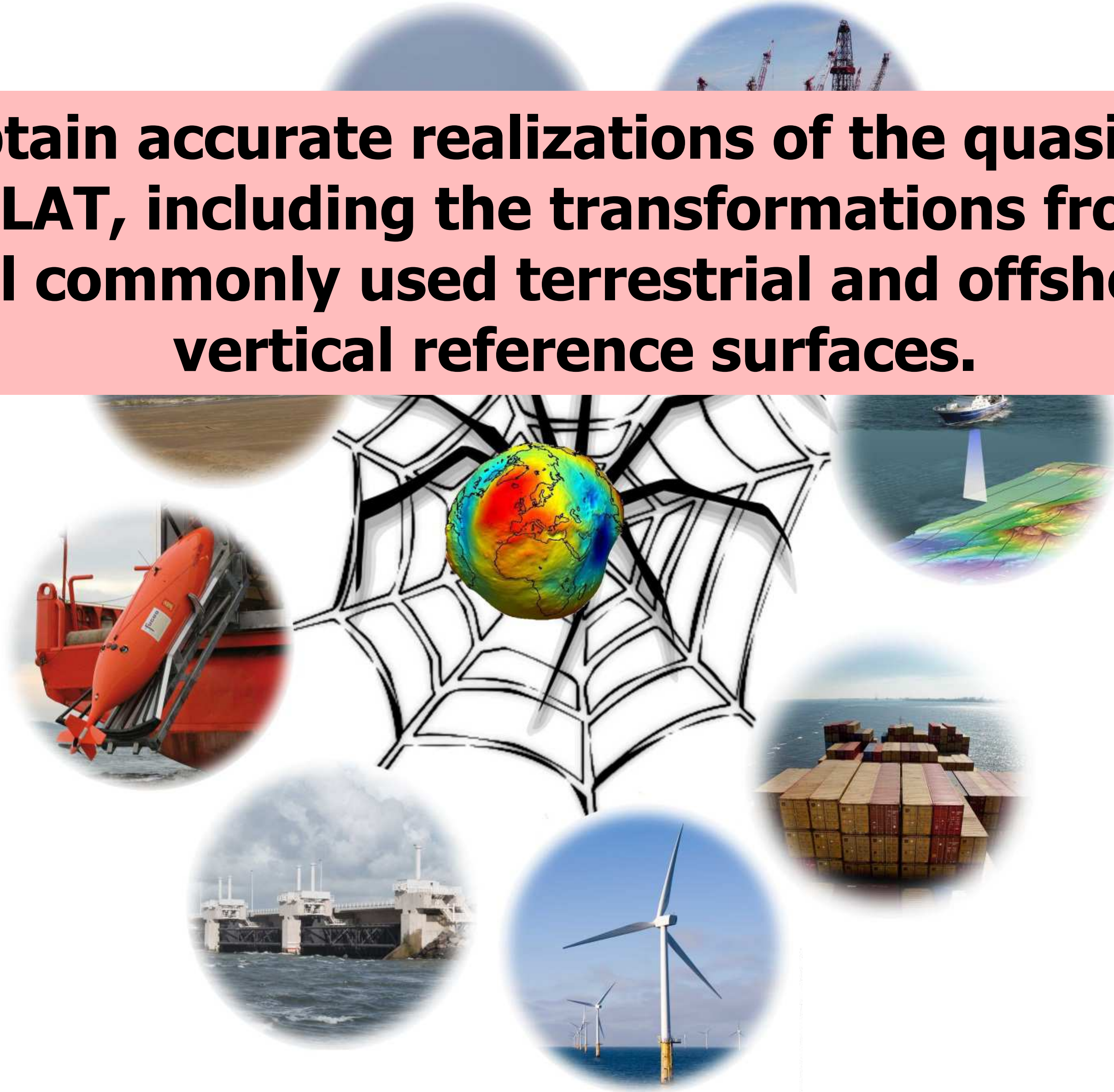
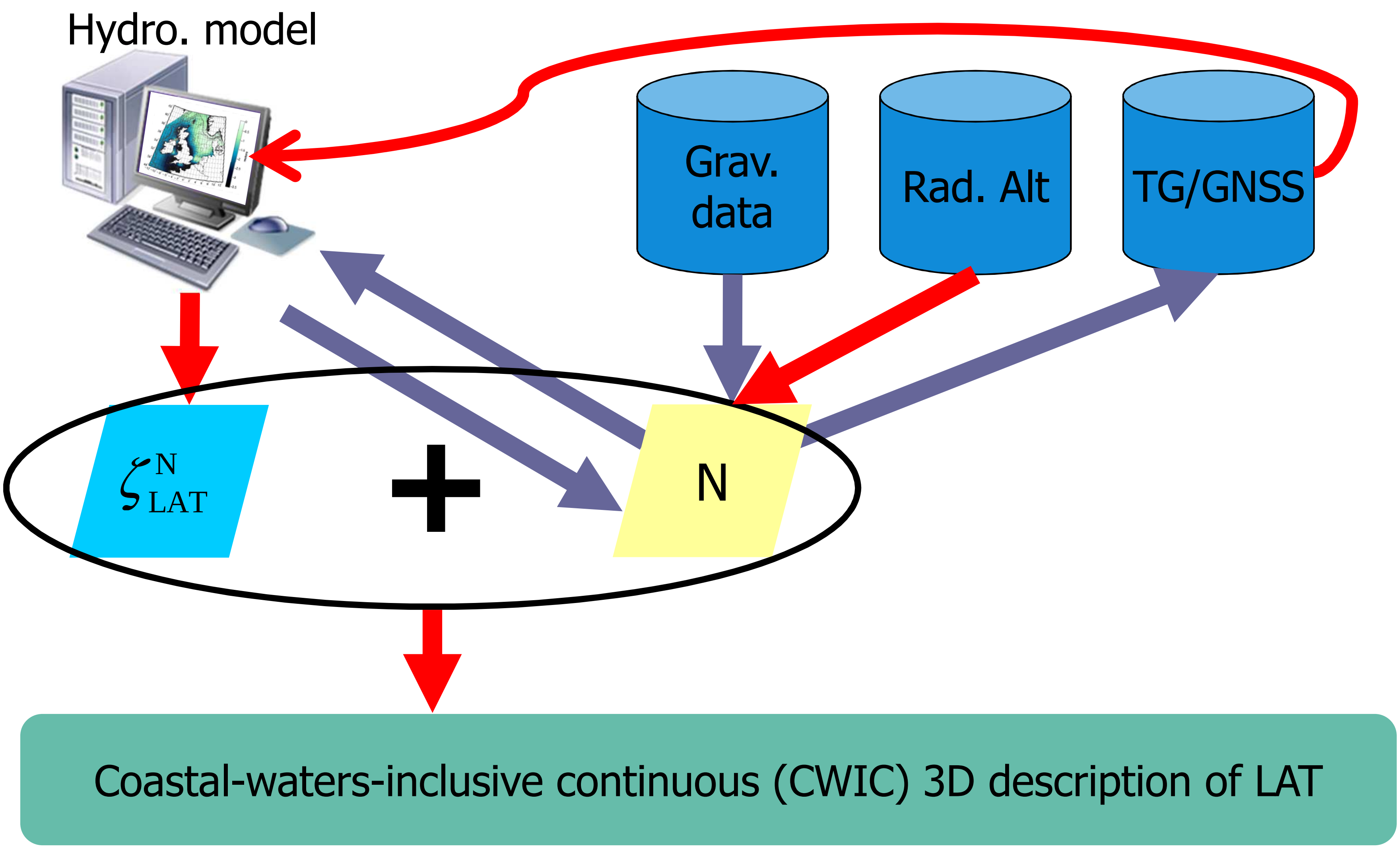
The NEVREF project

To obtain accurate realizations of the quasi-geoid and LAT, including the transformations from/to all commonly used terrestrial and offshore vertical reference surfaces.



Our approach to realize h_{LAT} and N



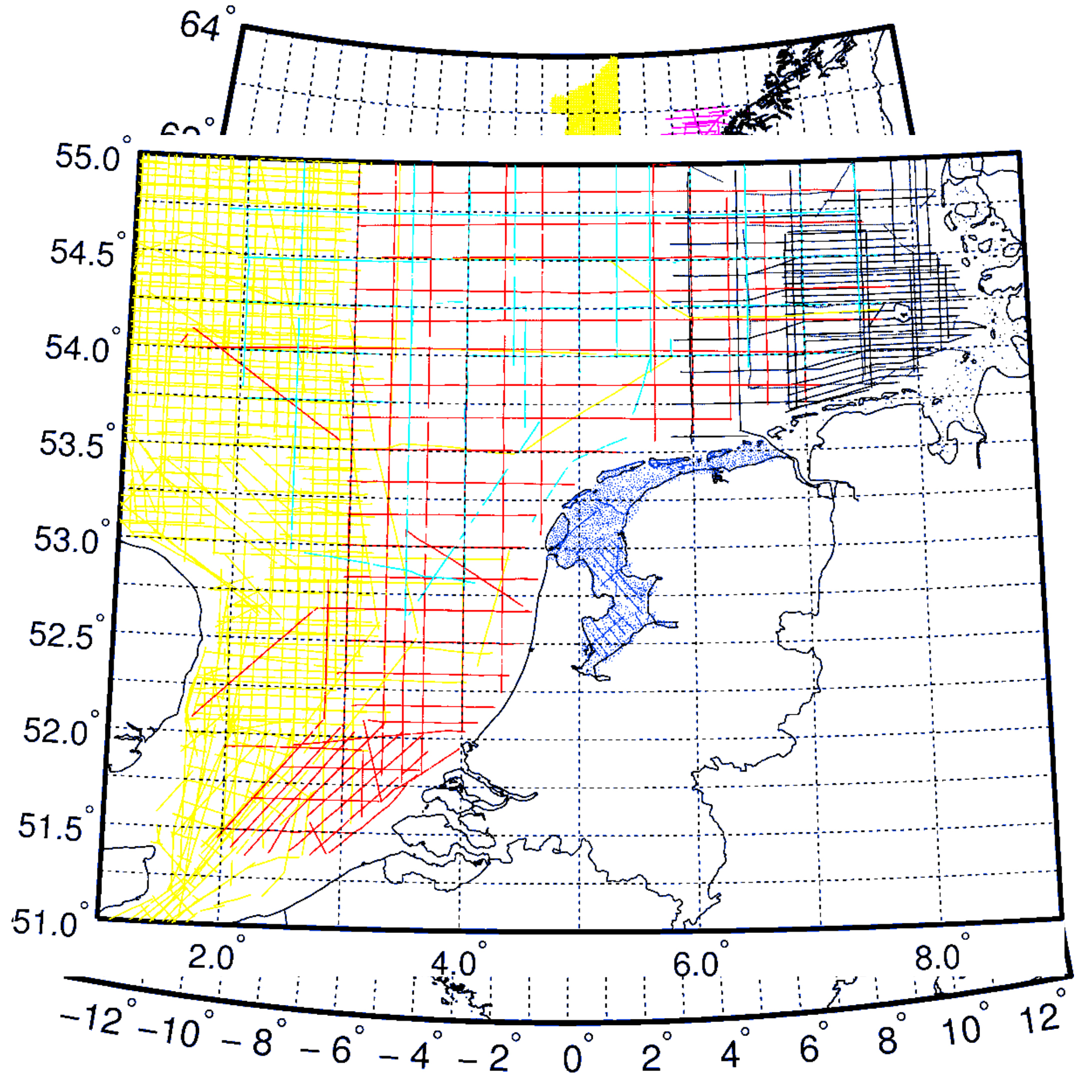
Why we need RA data? (1)

→

wavelength

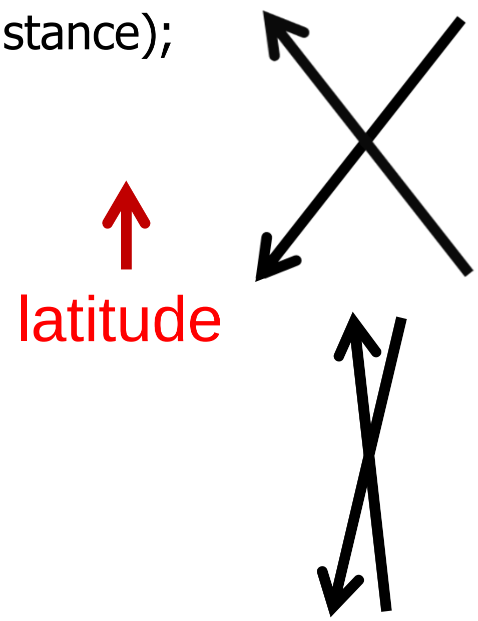
Why we need RA data? (2)

- Poor data coverage (North Sea is exception);
- Data gaps;
- Old data sets;
- Heterogenous quality;
- Redundancy.



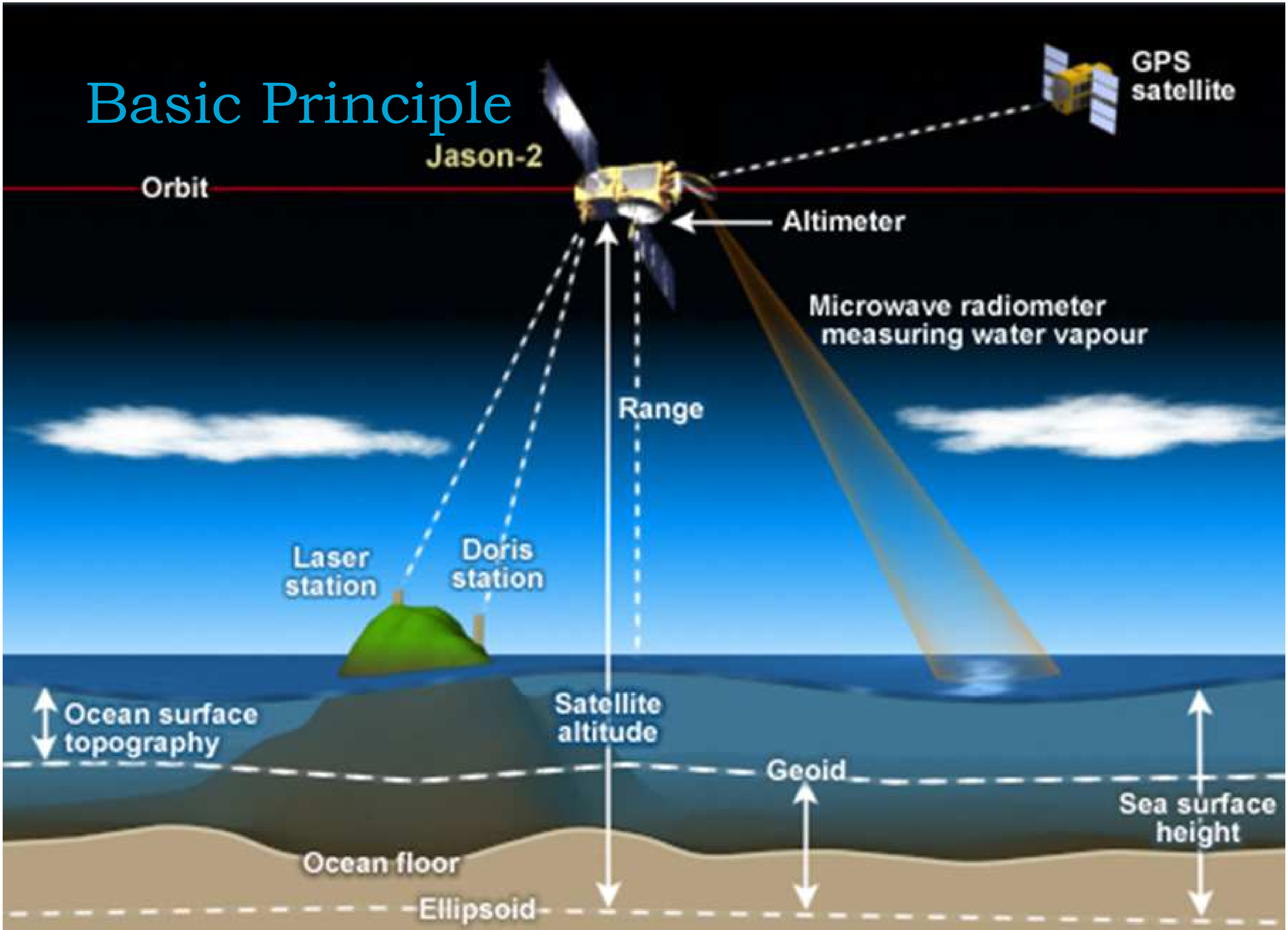
RA data and QG computations (2)

- Gravity field, and hence QG, accuracy depends on four factors (Sandwell et al., 2013):
  - altimeter range precision (a gravity field precision of 1 mGal for 12 km full wavelength requires a radar altimeter range having a precision of **6 mm over 6 km** horizontal distance);
  - spatial track density;
  - diverse track orientation;
  - the accuracy of the coastal tide models.



Altimeter range precision

Basic Principle



Taken from: http://www.ppi.noaa.gov/bom_chapter3_fig_3-7/

Corrections to be applied

Correction	How?	Order of magnitude (cm)
Propagation corrections		
Ionosphere	Dual freq. Meas.	0 - 50
Wet troposphere	Radiometer	0 - 50
Dry troposphere	Meteorological models	230
Surface corrections		
Electromagnetic bias	Models	0 – 50
Geophysical		
Dynamic topography	Models	100-2000
Solid earth tides	Models	50
Pole tides	Models	2
Tidal loading	Models	30

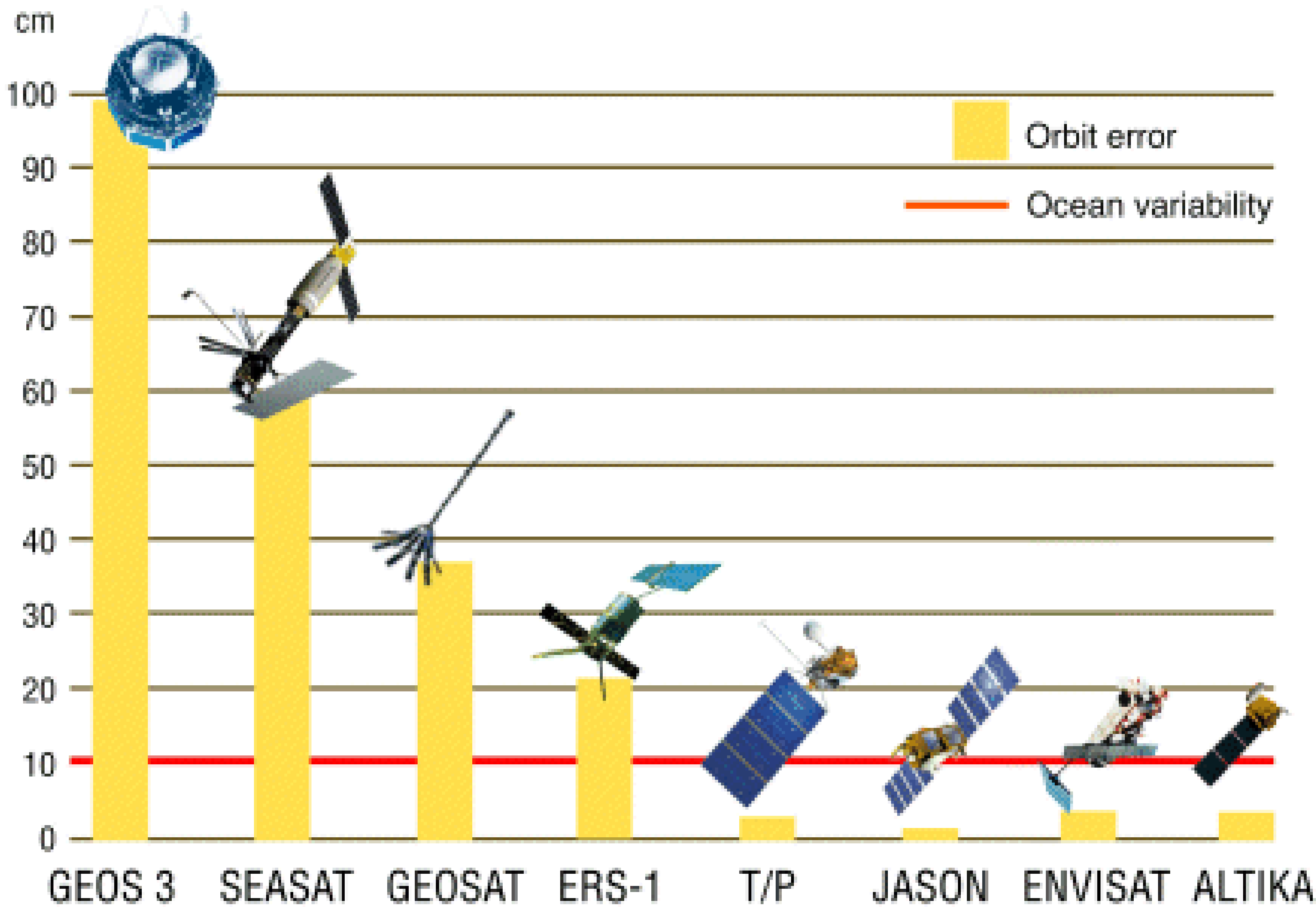
Taken from: http://earth.eo.esa.int/brat/html/alti/dataflow/processing/geophys_corr/welcome_en.html

Estimated maximum errors

Signal or Error Source	Length (km)	Height (cm)
Gravity signal	12–400	1–300
Orbit errors[a]	8000–20,000	400–1000
Ionosphere[b,c]	>900	20
Wet troposphere[d]	>100	3–6
Sea-state bias[e]	>20	<0.6
Inverse barometer[f]	>250	<5
Basin-scale circulation (steady)[g]	>1000	100
El Niño, interannual variability, planetary waves[h]	>1000	20
Deep ocean tide model errors[d,i]	>1000	3
Coastal tide model errors[c,i]	50–100	<13
Eddys and mesoscale variability[j]	60–200	30–50
Meandering jet (Gulf Stream)[g]	100–300	30–100
Steady jet (Florida Current)[g]	100	50–100

Taken from: Sandwell and Smith, 2009

Estimated maximum errors



Taken from: http://www.aviso.oceanobs.com/en/missions/past-missions.html

Estimated maximum errors

Signal or Error Source	Length (km)	Height (cm)
Gravity signal	12–400	1–300
Orbit errors[a]	8000–20,000	400–1000
Ionosphere[b,c]	[illegible]	[illegible]
planetary waves		
Deep ocean tide model errors[d,i]	>1000	3
Coastal tide model errors[c,i]	50–100	<13
Eddys and mesoscale variability[j]	60–200	30–50
Meandering jet (Gulf Stream)[g]	100–300	30–100
Steady jet (Florida Current)[g]	100	50–100

Use sea surface slopes → deflections of the vertical in north and east directions!

Taken from: Sandwell and Smith, 2009

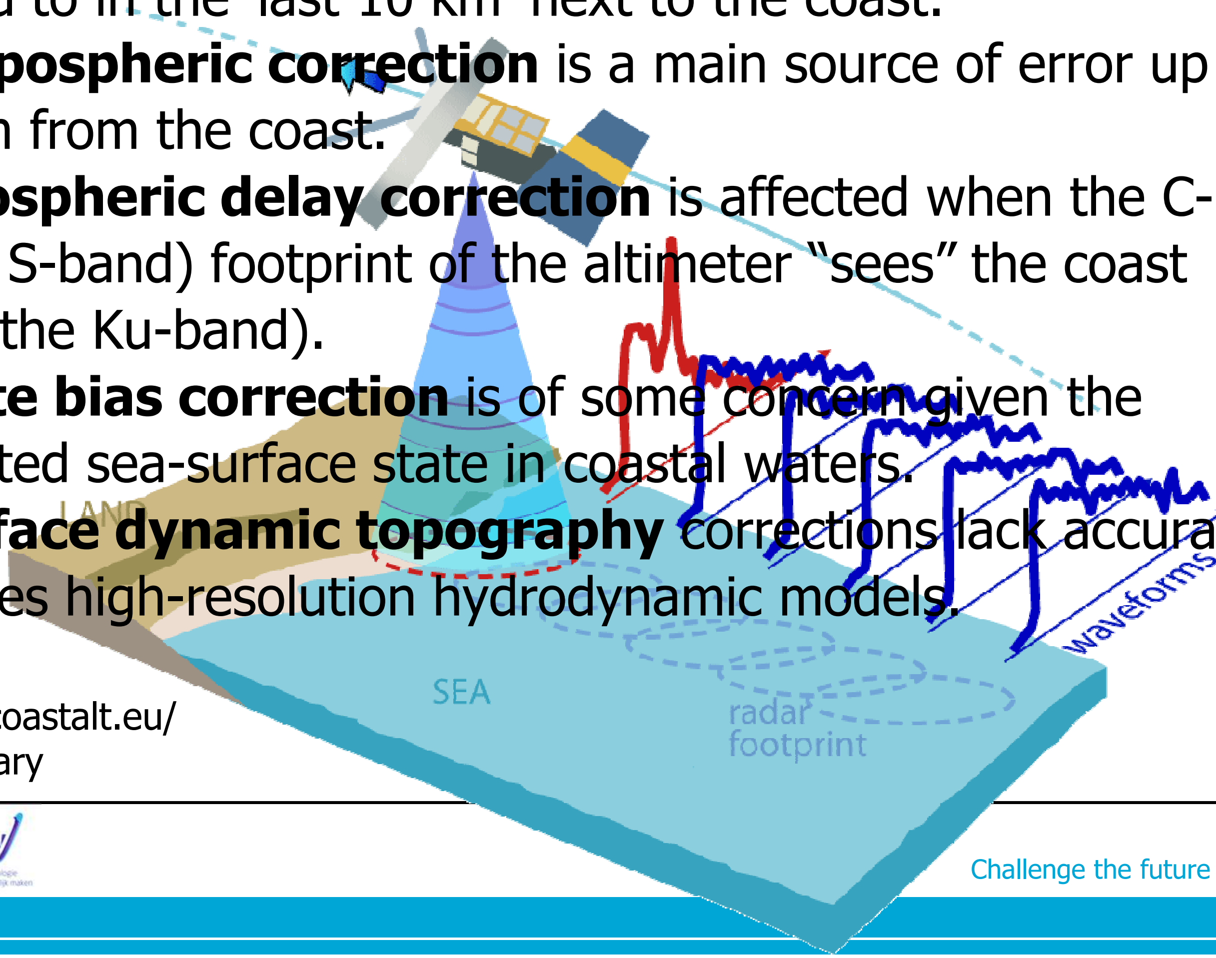
Estimated maximum errors

Signal or Error Source	Length (km)	Height (cm)	Slope (μrad)
Gravity signal	12–400	1–300	1–300
Orbit errors[a]	8000–20,000	400–1000	<0.5
Ionosphere[b,c]	>900	20	<0.22
Wet troposphere[d]	>100	3–6	<0.6
Sea-state bias[e]	>20	<0.6	<0.3
Inverse barometer[f]	>250	<5	<0.2
Basin-scale circulation (steady)[g]	>1000	100	<1
El Niño, interannual variability, planetary waves[h]	>1000	20	<0.2
Deep ocean tide model errors[d,i]	>1000	3	<0.03
Coastal tide model errors[c,i]	50–100	<13	<2.6
Eddys and mesoscale variability[j]	60–200	30–50	2.5–5
Meandering jet (Gulf Stream)[g]	100–300	30–100	3–10
Steady jet (Florida Current)[g]	100	50–100	5–10

Taken from: Sandwell and Smith, 2009

RA in coastal waters

- **Recorded waveform contaminated by land** → retracking is needed to in the 'last 10 km' next to the coast.
- **Wet tropospheric correction** is a main source of error up to 20-50 km from the coast.
- The **ionospheric delay correction** is affected when the C-band (or S-band) footprint of the altimeter "sees" the coast (prior to the Ku-band).
- **Sea state bias correction** is of some concern given the complicated sea-surface state in coastal waters.
- **Sea surface dynamic topography** corrections lack accuracy → requires high-resolution hydrodynamic models.

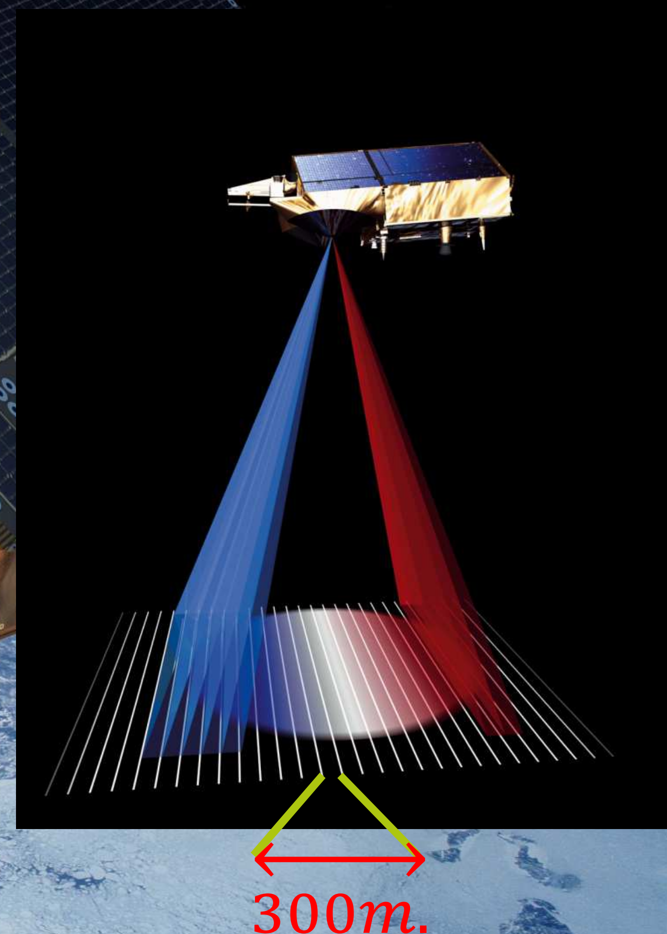


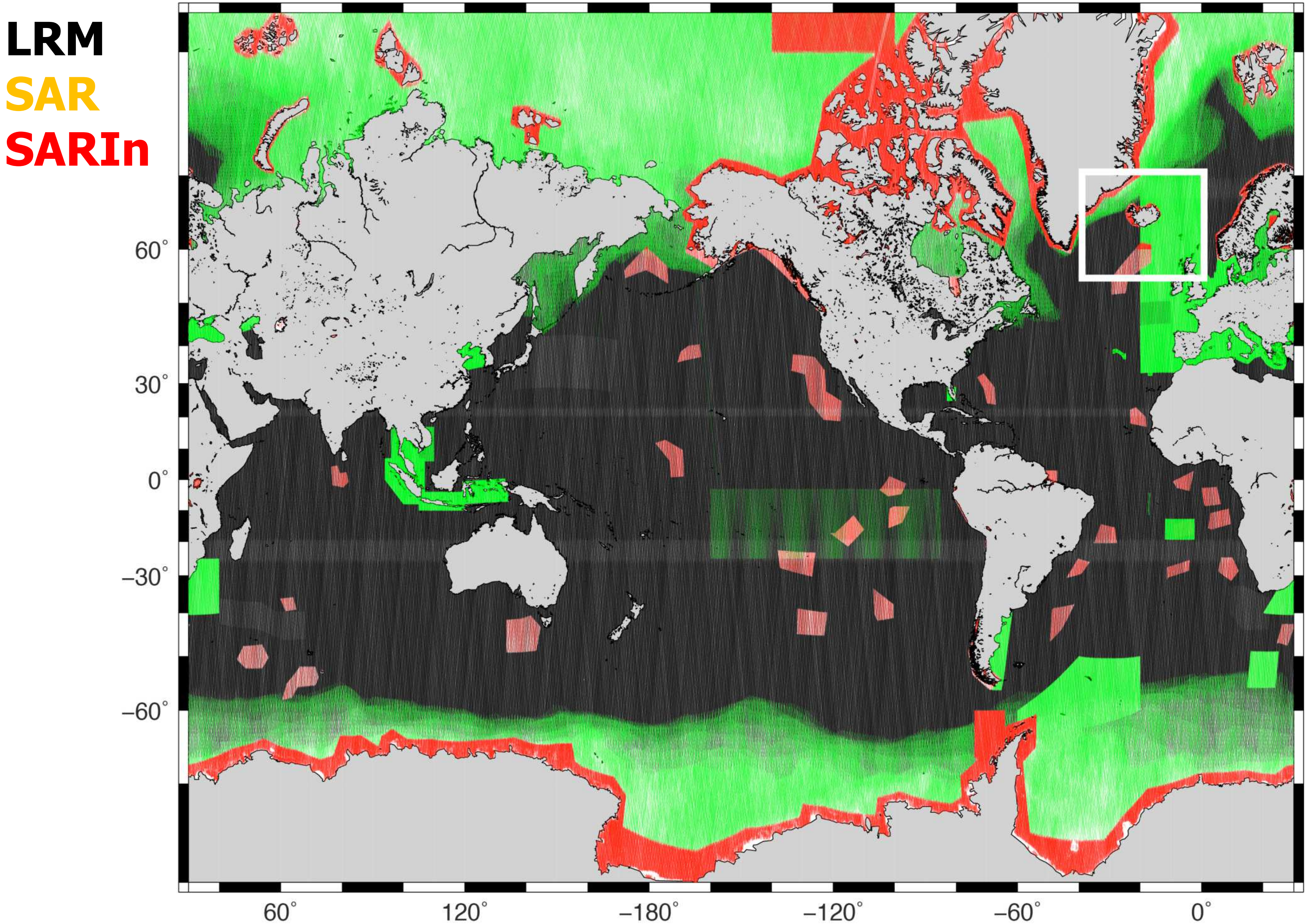
Taken from: http://www.coastalt.eu/coastalt-short-web-summary

NEVREF: Shipboard GNSS

New generation: CryoSat-2

- CryoSat-2
  - launched in Feb 2010;
  - 369-day repeat cycle → (average ground track spacing 3.8 km equator).
- 3 modes:
  - *Low Rate Mode* (ice-free ocean areas);
  - *Synthetic Aperture Radar* mode (ocean areas where sea ice is prevalent + some small test areas);
  - *SAR/Interferometric Radar Altimeter* mode (land ice surfaces where there is significant topographic slope)`.





Taken from: Garcia and Sandwell, 2013, Retracking CryoSat-2, Envisat, and Jason-1 Radar Altimetry Waveforms for Optimal Gravity Field Recovery

Range accuracies: double-retracked data

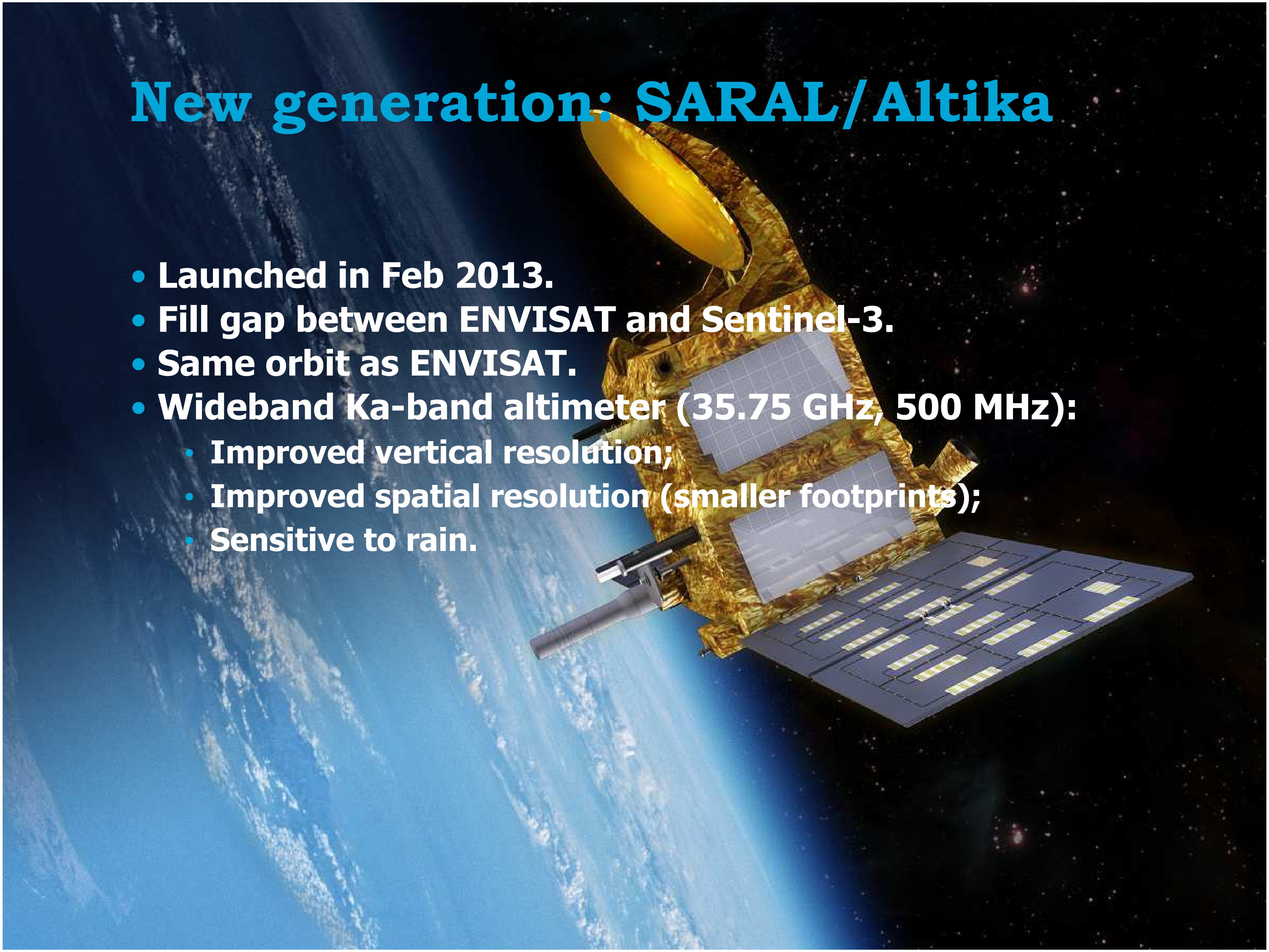
20-Hz altimeter noise in mm

Altimeter	2-PAR @ 2m	2-PAR @ 6m	3-PAR/2-PAR
Geosat	57.0	105.4	1.54
E[illegible]	[illegible]	[illegible]	[illegible]
E[illegible]	[illegible]	[illegible]	[illegible]
Jason-1	[illegible]	[illegible]	1.63
CryoSat[illegible]	[illegible]	[illegible]	1.51
CryoSat[illegible]	[illegible]	[illegible]9	.996
CryoSat[illegible]	[illegible]	[illegible]6	.998

Current accuracy: 1.7-3.75 mGal

$$\frac{42.7}{\sqrt{20}} = 9,5 \text{ mm}$$

Taken from: Sandwell and Garcia, 2013

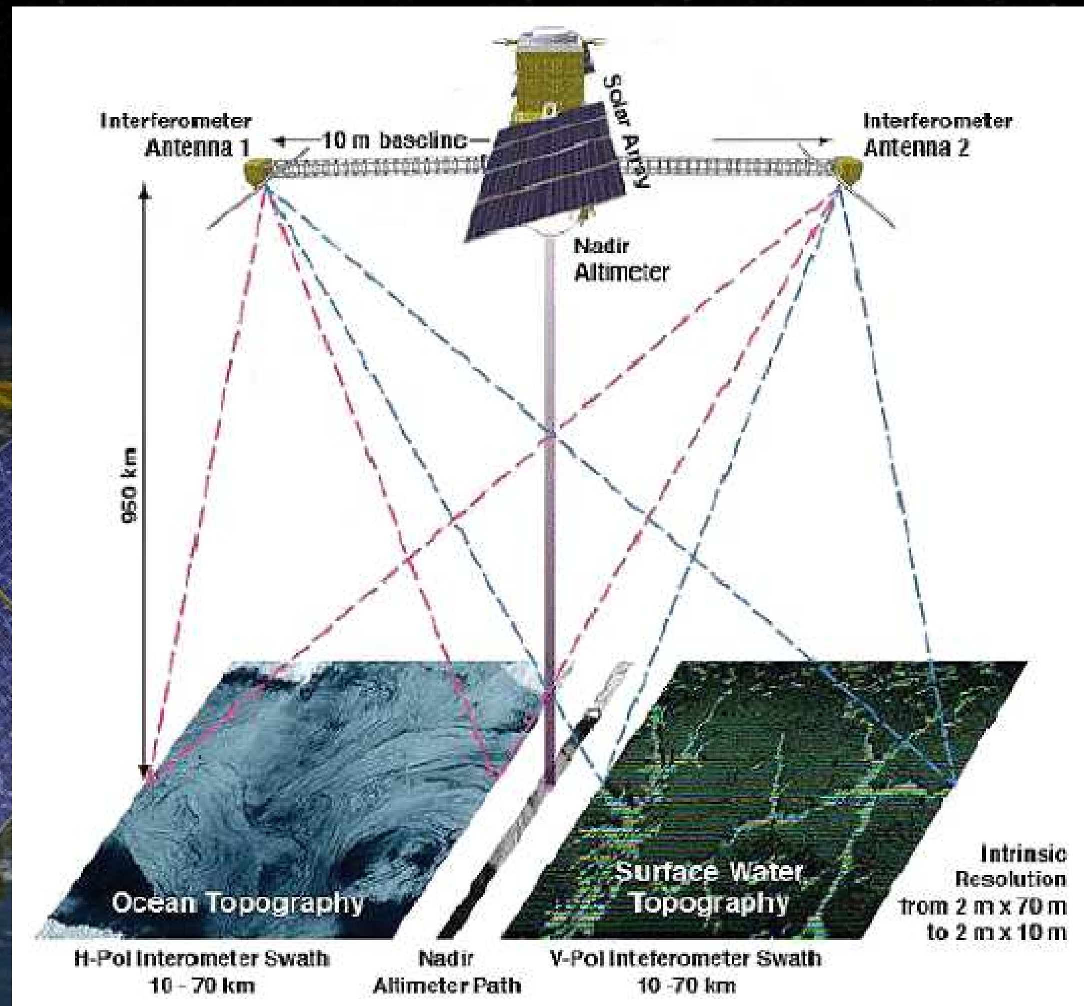


New generation: SARAL/Altika

- Launched in Feb 2013.
- Fill gap between ENVISAT and Sentinel-3.
- Same orbit as ENVISAT.
- Wideband Ka-band altimeter (35.75 GHz, 500 MHz):
  - Improved vertical resolution;
  - Improved spatial resolution (smaller footprints);
  - Sensitive to rain.

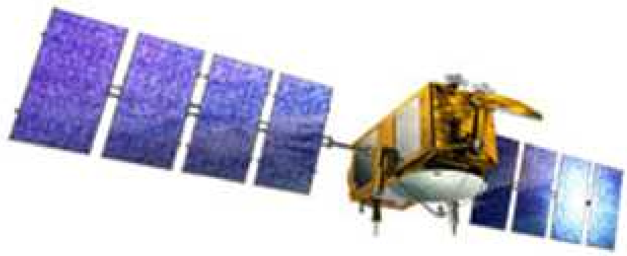
New generation: SWOT

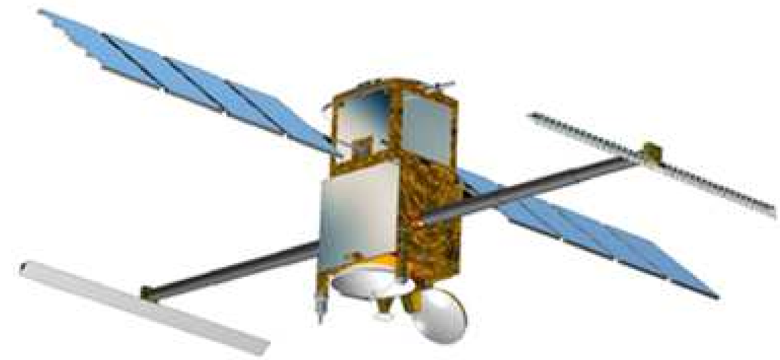
- Surface Water Ocean Topography
- Scheduled for launch in 2019.
- Wide-swath altimeter:
  - 2 Ka-band SAR antennas

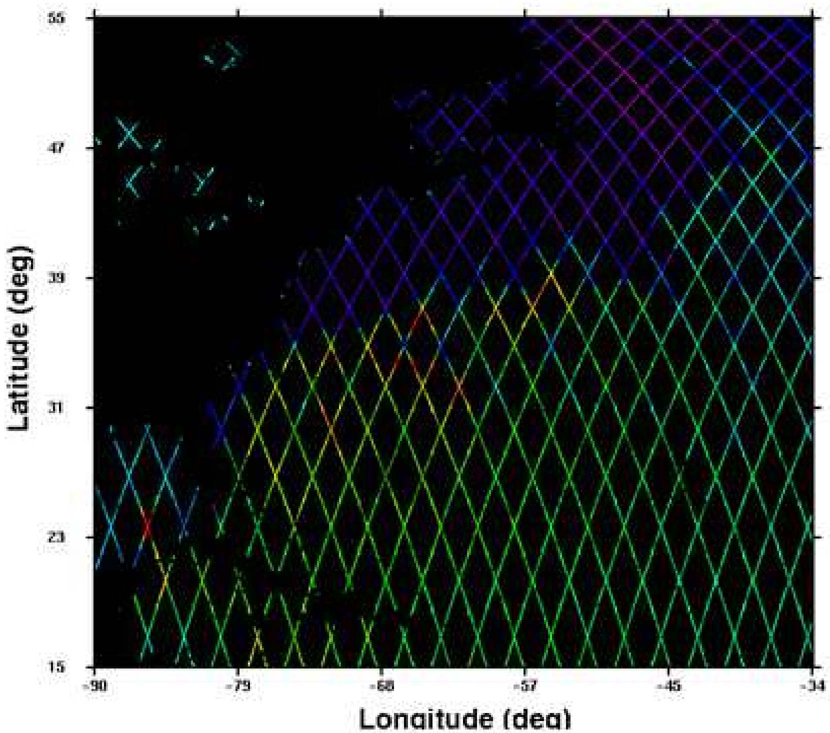


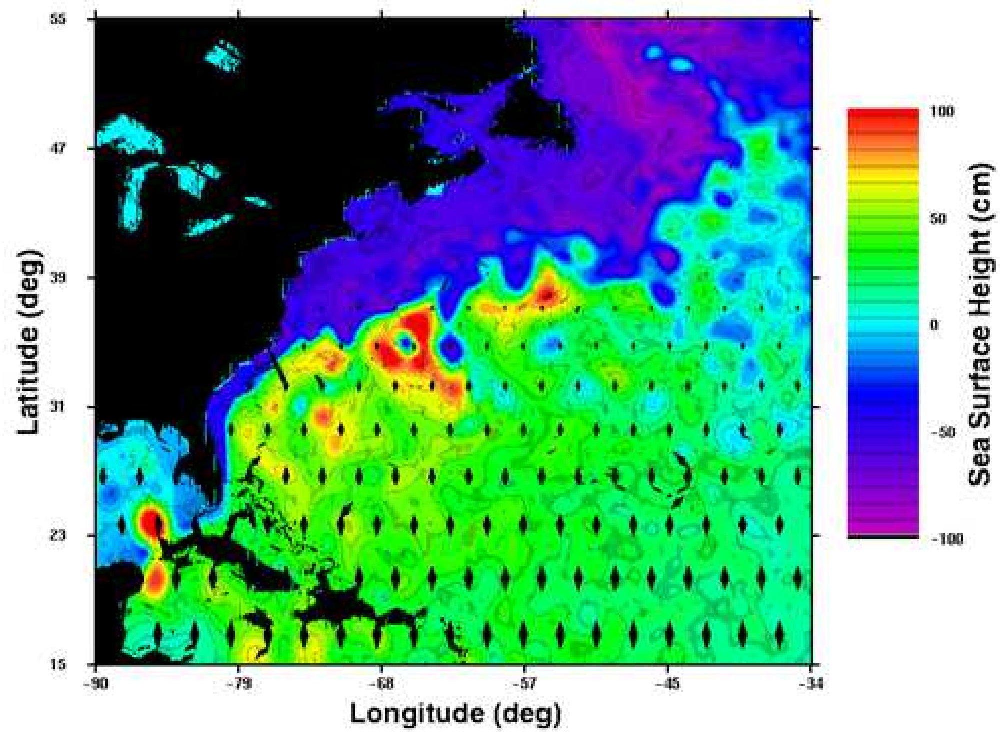
Traditional altimeter

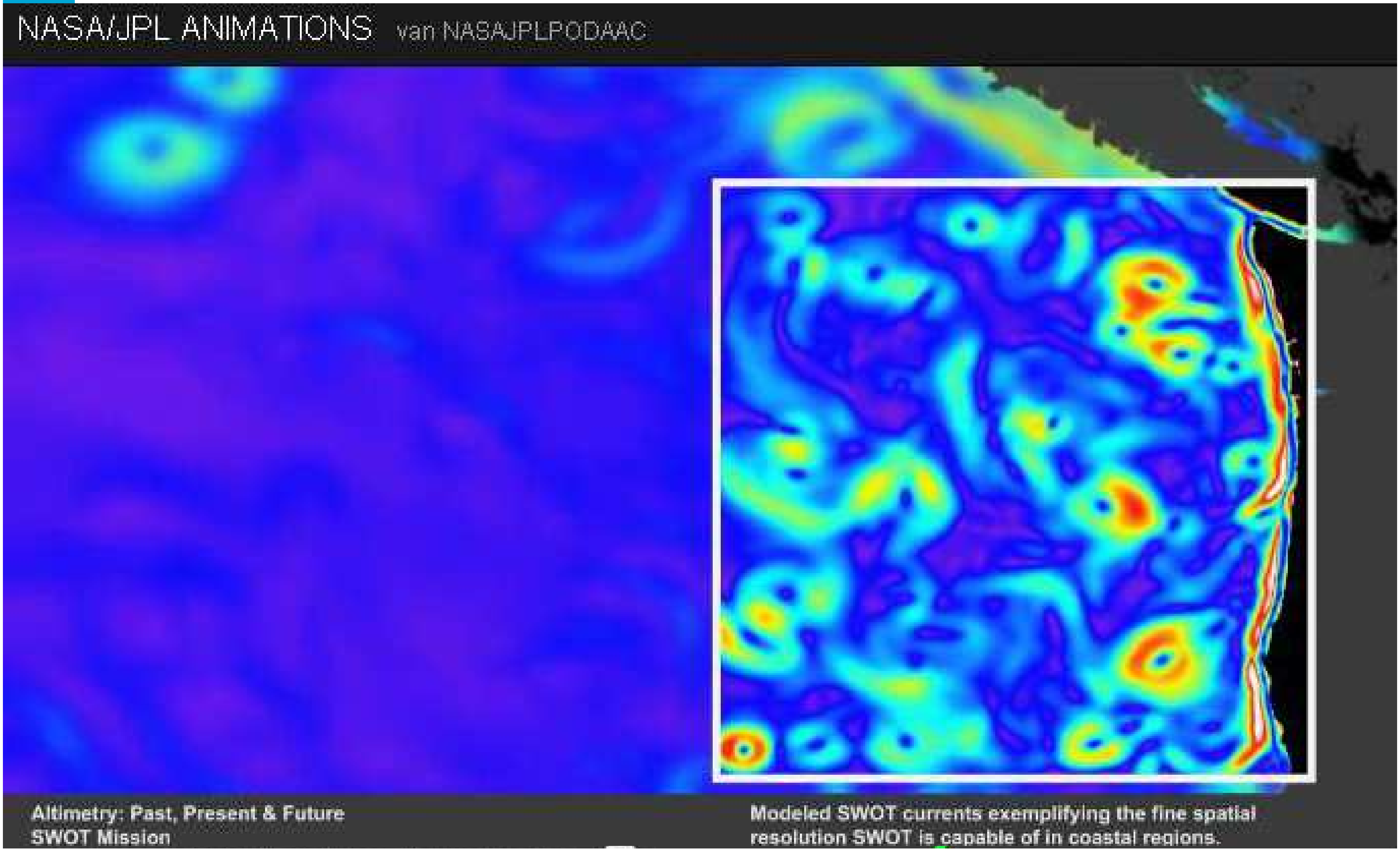
SWOT





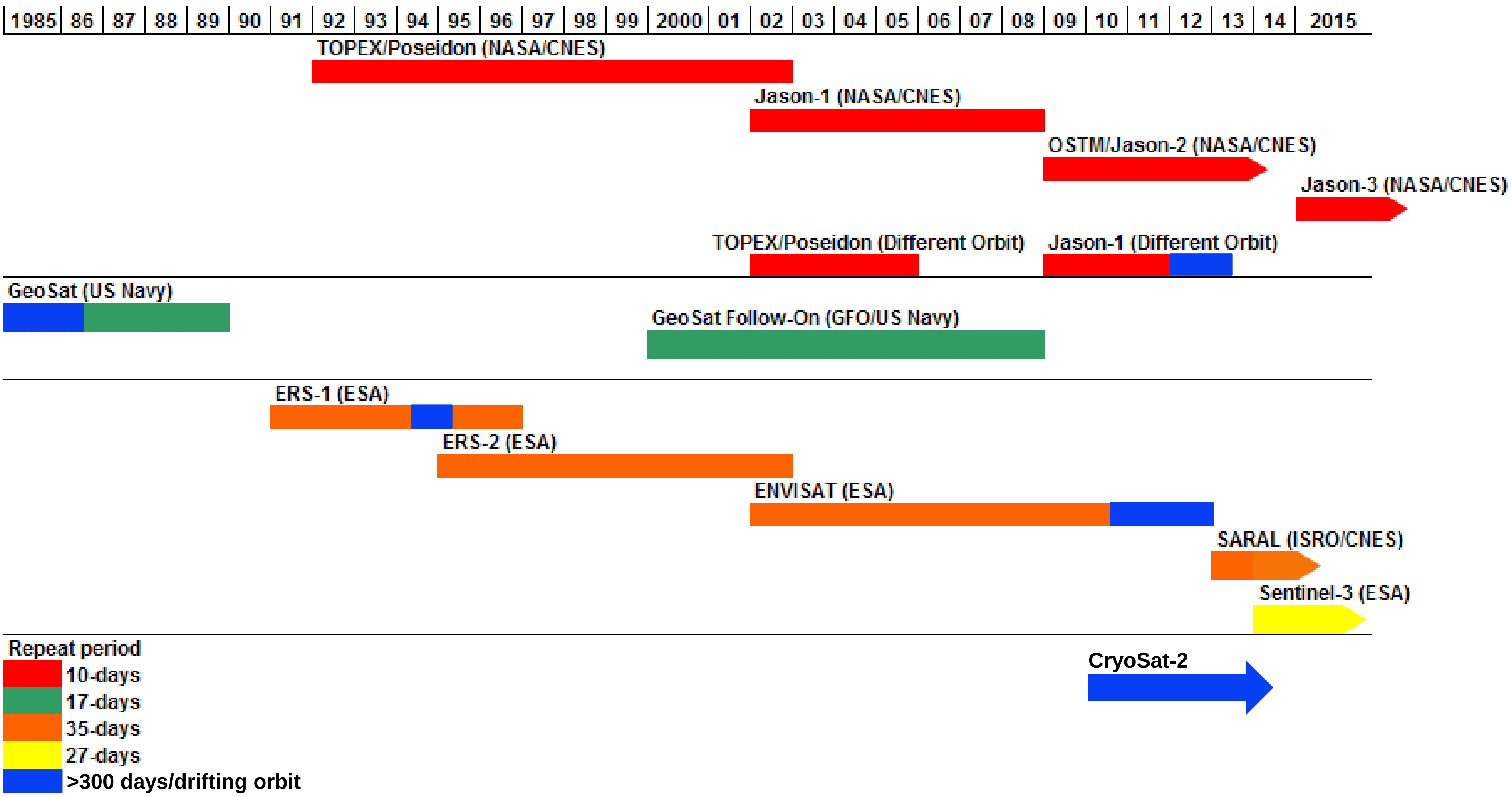




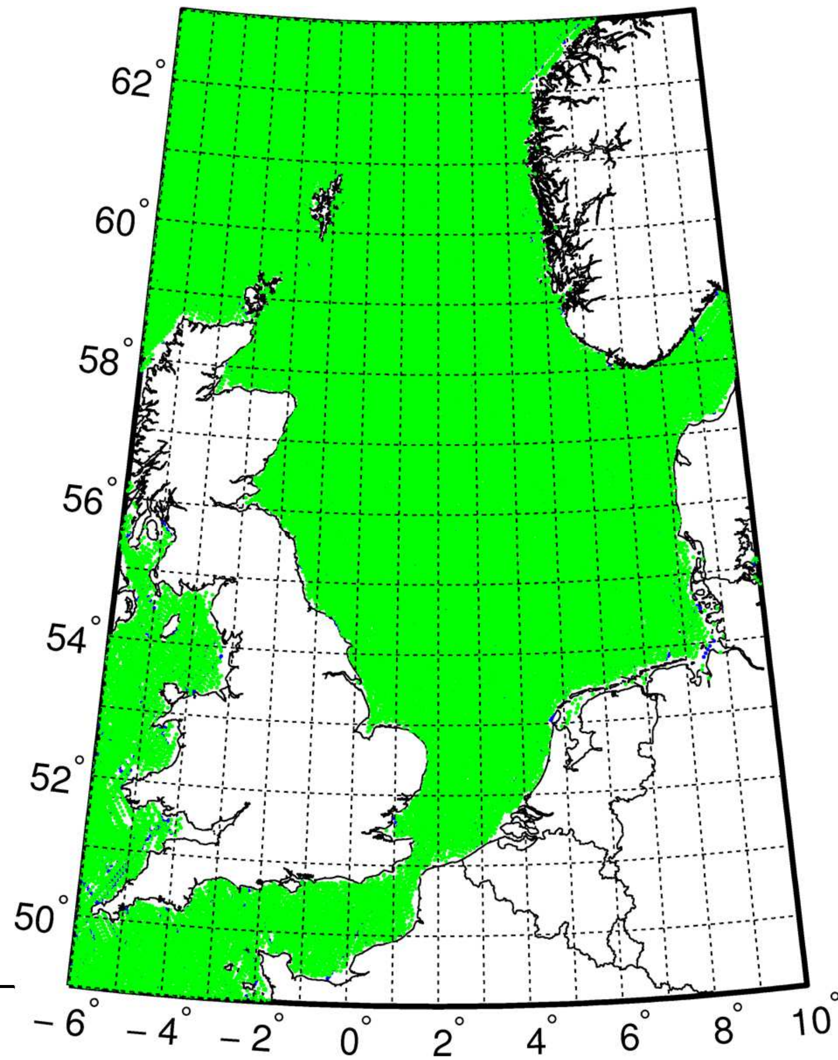

NASA/JPL ANIMATIONS van NASAJPLPODAAC
Altimetry: Past, Present & Future
SWOT Mission
Modeled SWOT currents exemplifying the fine spatial resolution SWOT is capable of in coastal regions.

Spatial track density

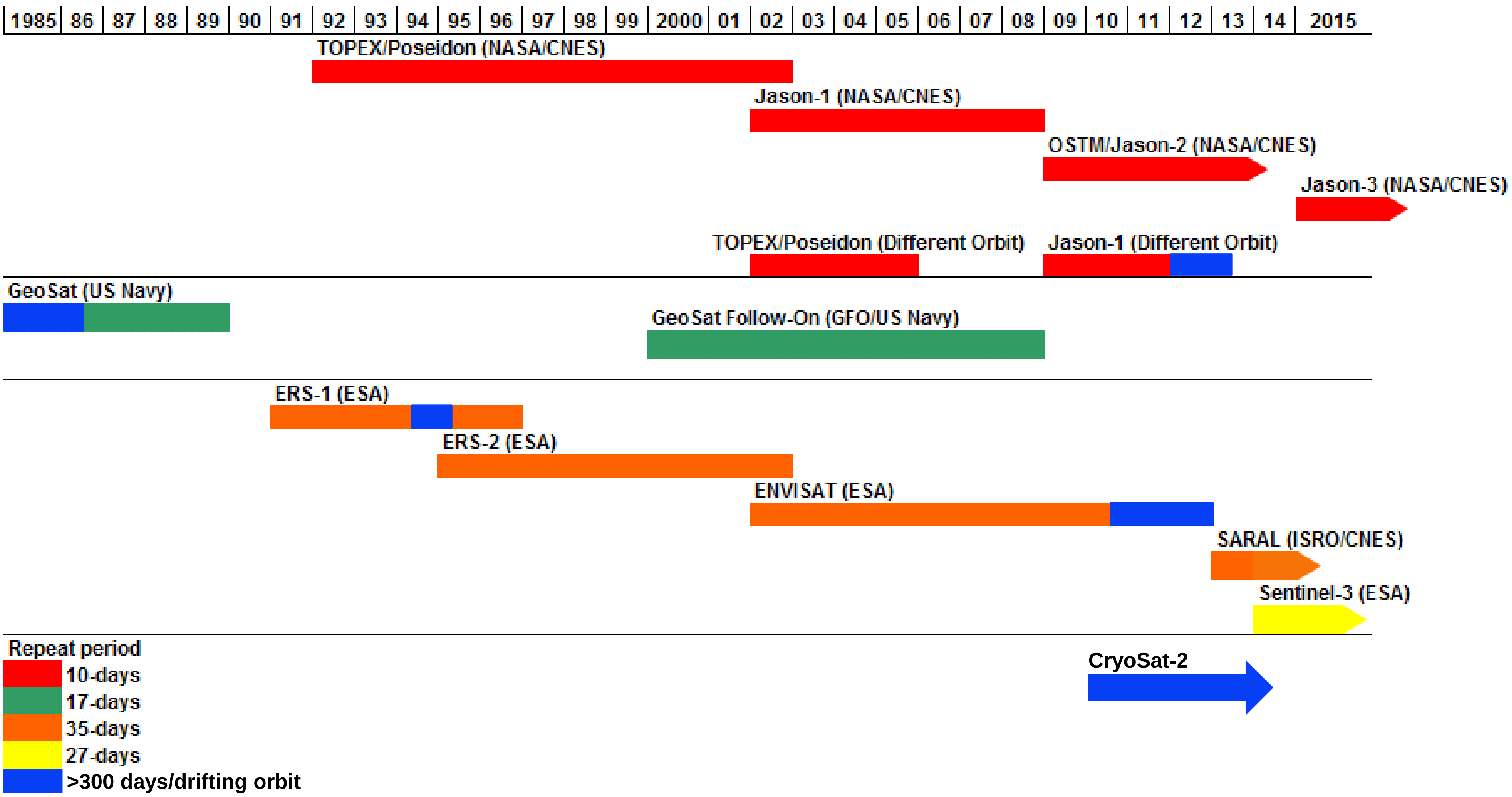
Available data



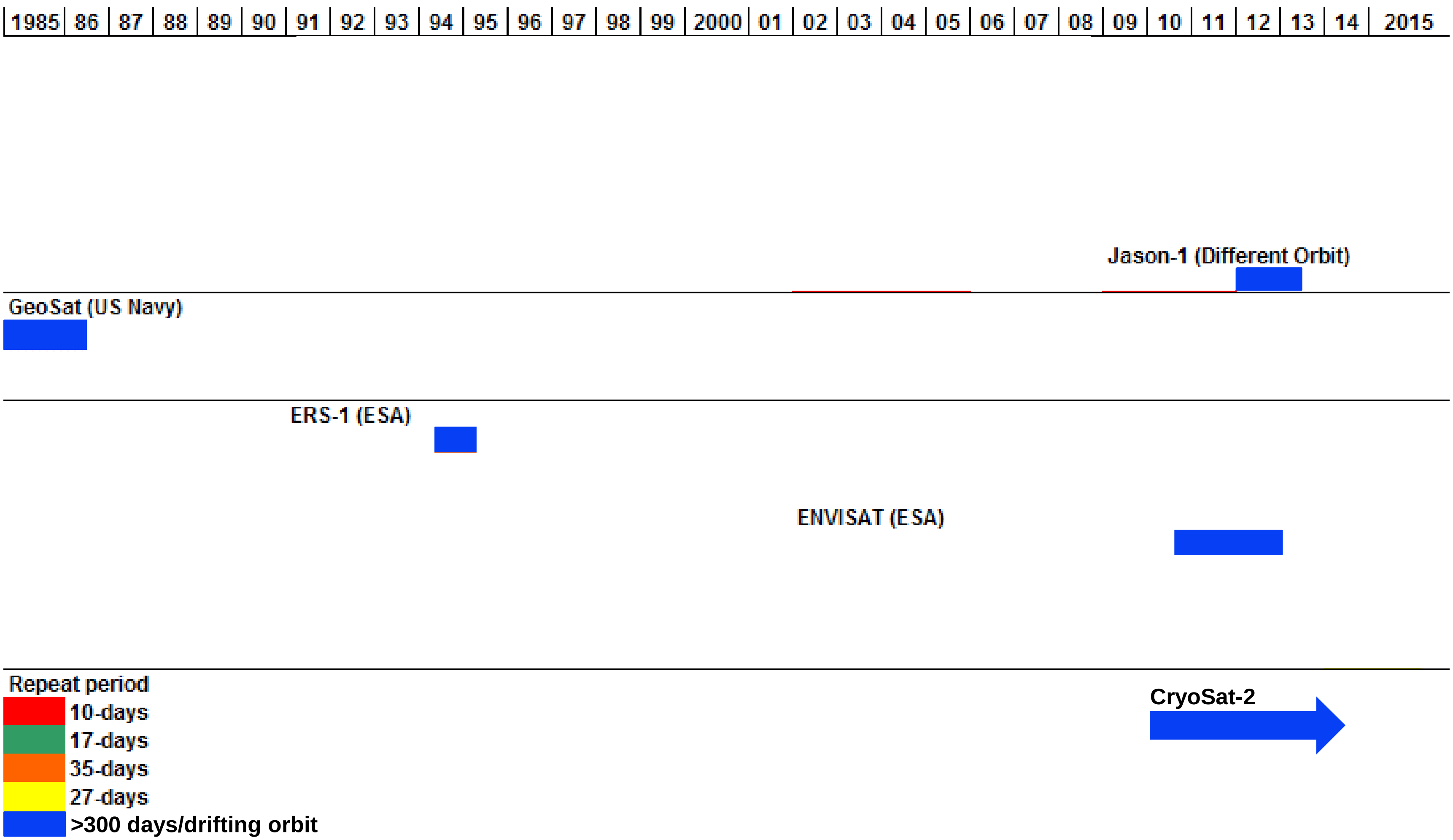
Exact Repeat versus Geodetic Missions



Available data



Useful data


1985 86 87 88 89 90 91 92 93 94 95 96 97 98 99 2000 01 02 03 04 05 06 07 08 09 10 11 12 13 14 2015
Jason-1 (Different Orbit)
GeoSat (US Navy)
ERS-1 (ESA)
ENVISAT (ESA)
Repeat period
10-days
17-days
35-days
27-days
>300 days/drifting orbit
CryoSat-2

Accuracy of the coastal tide models

Background & Motivation

- In (quasi-)geoid computations we use geoid slopes
- Dynamic topography (DT) corrections to altimeter-derived sea surface slopes:

$$\text{slope}_{\text{DT}} = f(\text{tide,surge,baroclinic})$$

- Practice

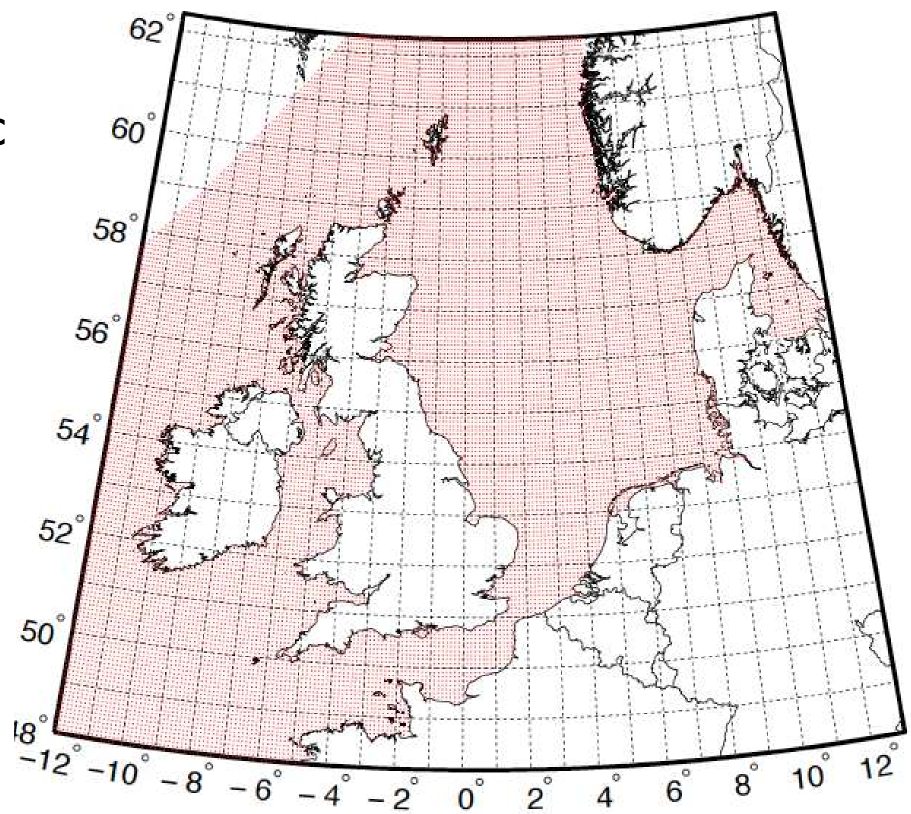
$$\text{slope}_{\text{DT}} \approx f_1(\text{tide}) + f_2(\text{surge})$$

- Shelf and shallow seas and coastal water
  - DT is one integral phenomenon
  - provided by a shallow water hydrodynamic model (DCSMv5)

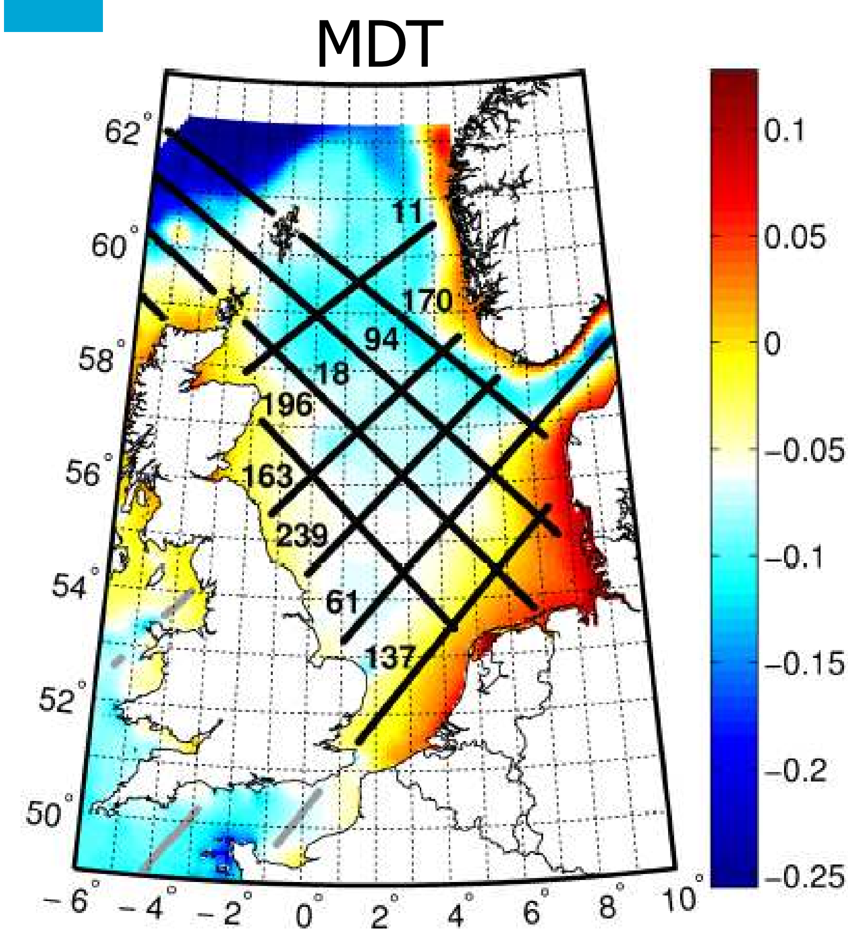
Hydrodynamic model and forcing data

- 8x9 km spatial resolution
- **Baroclinic forcing** explicitly added by treating the water density as a diagnostic variable computed from temperature and salinity values obtained from the Atlantic - European North West Shelf - Ocean Physics Hindcast provided by POL
- **ERA-Interim** wind and air pressure fields
- Vertically referenced to a quasi-geoid by prescribing water levels at the open sea boundaries relative to this quasi-geoid (EGG08)
- Run over **20 years**

DCSMv5

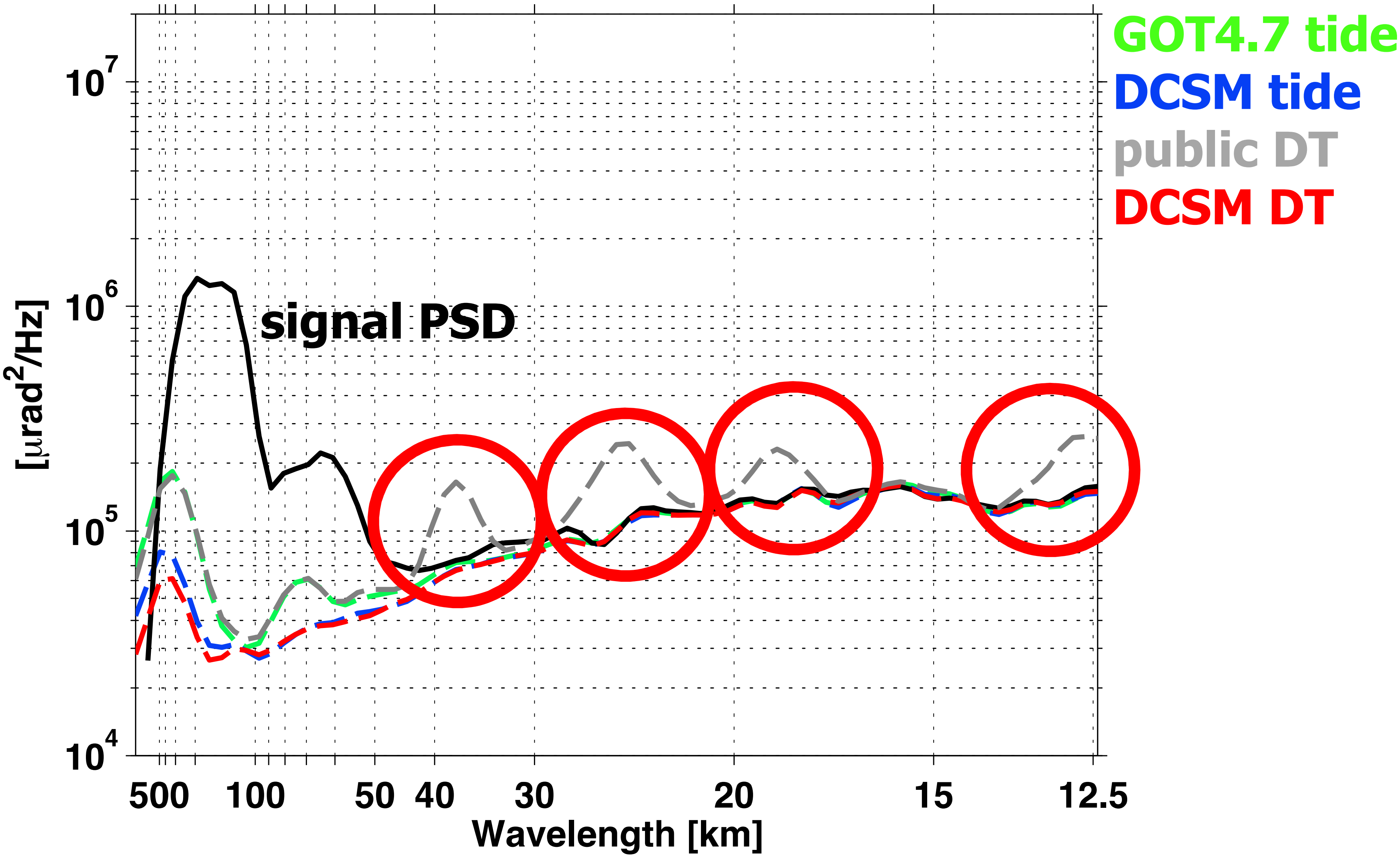


Noise PSDs of altimeter-derived (residual) geoid slopes



- 9 passes of T/P data from 10-day repeat mission cycles 10-365 (Dec 1992 - Aug 2002)
- 4 DT corrections are compared:
  - DT 1: global ocean tide model GOT4.7 (Ray 1999)
  - DT 2: DCSM tide model
  - DT 3: linear superposition of tide, surge, and baroclinic contr. computed separately from available models (GOT4.7, MOG2D, DTU10 MSS, EGG08)
  - DT 4: DCSM full DT corrections

Noise PSDs of altimeter-derived (residual) geoid slopes pass 137 (southern North Sea)



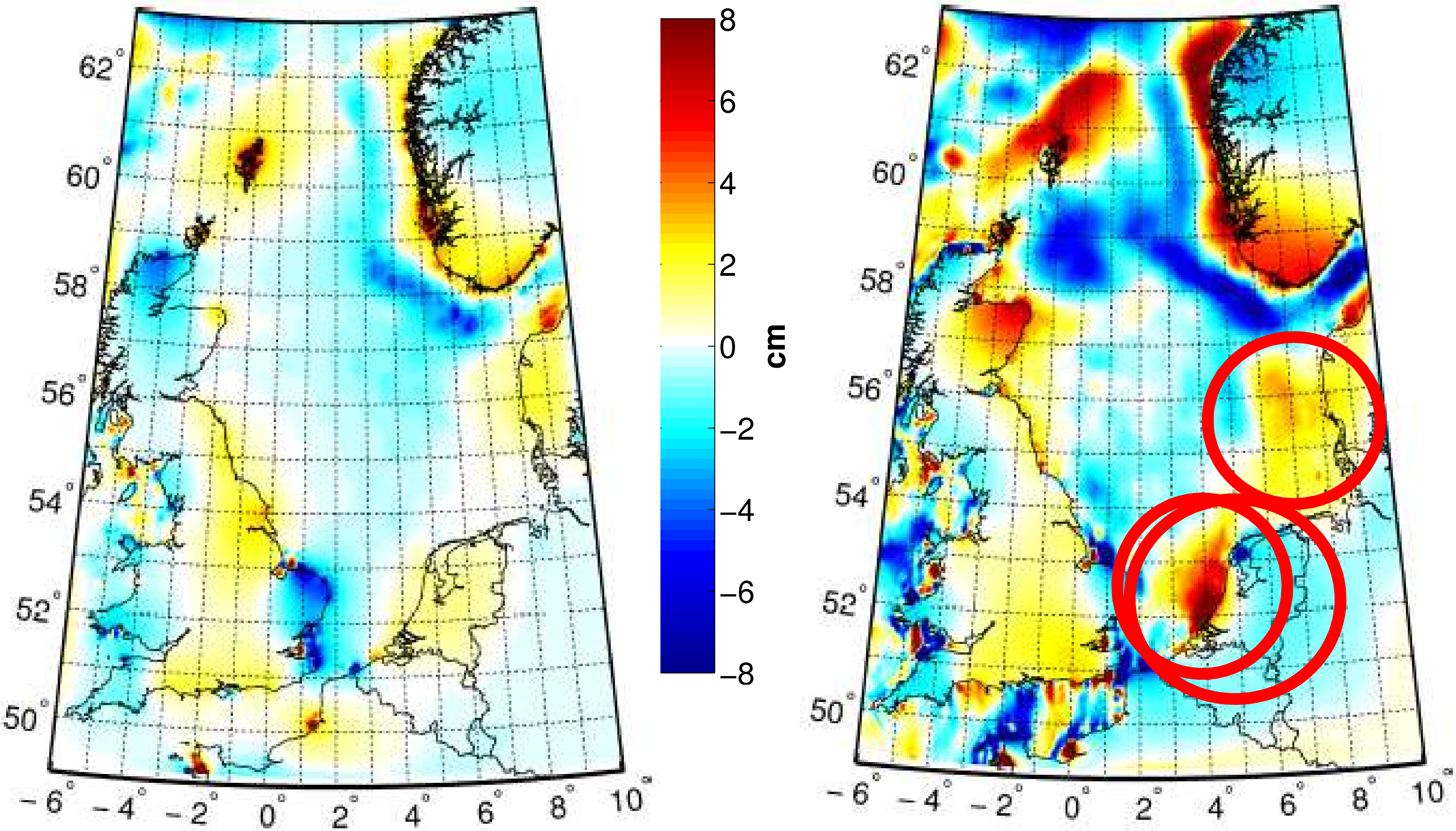
Impact of DT corrections on the quasi-geoid

- Remove-compute-restore
  - DGM-1S **GRACE/GOCE** model removed
- Terrestrial/shipboard/airborne gravity data sets
- **Altimetry** data from GEOSAT, ERS-1/2, Envisat, GFO-1, Jason-1/2, and T/P (1985 – 2003); ERM and GM data;
  - 4 different DT corrections applied to sea surface slopes
  - → 4 different sets of altimeter-derived geoid slopes
- → 4 different quasi-geoids, each uses a different set of altimeter-derived geoid slopes
- Mutual **weights** estimated using variance component estimation.

Difference between two quasi-geoid solutions (GOT4.7 vs DCSM DT corrections)

incl shipboard gravity data

excl shipboard gravity data

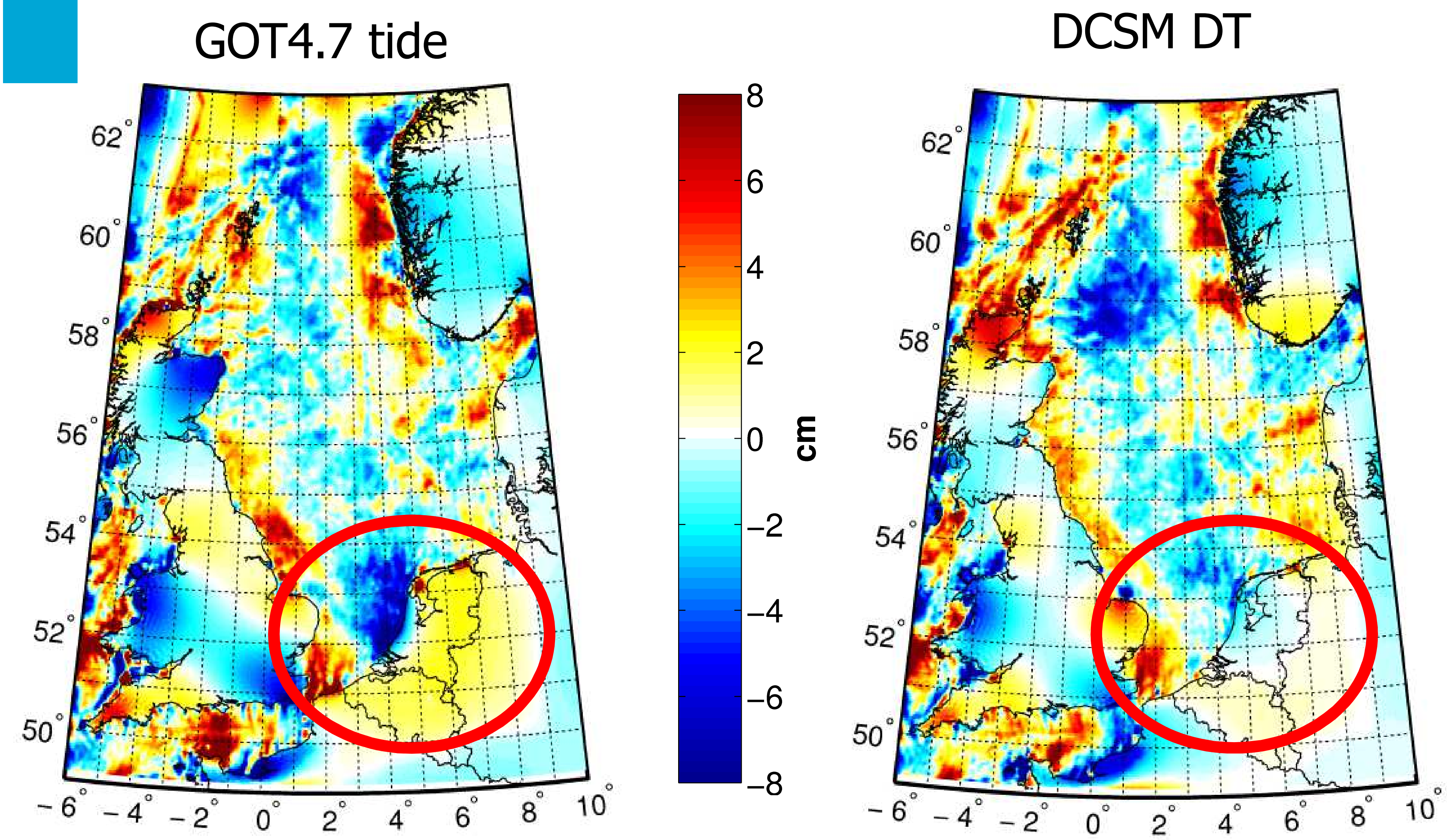


Validation against GPS/leveling data on the Dutch mainland
(solution without shipboard gravity data)

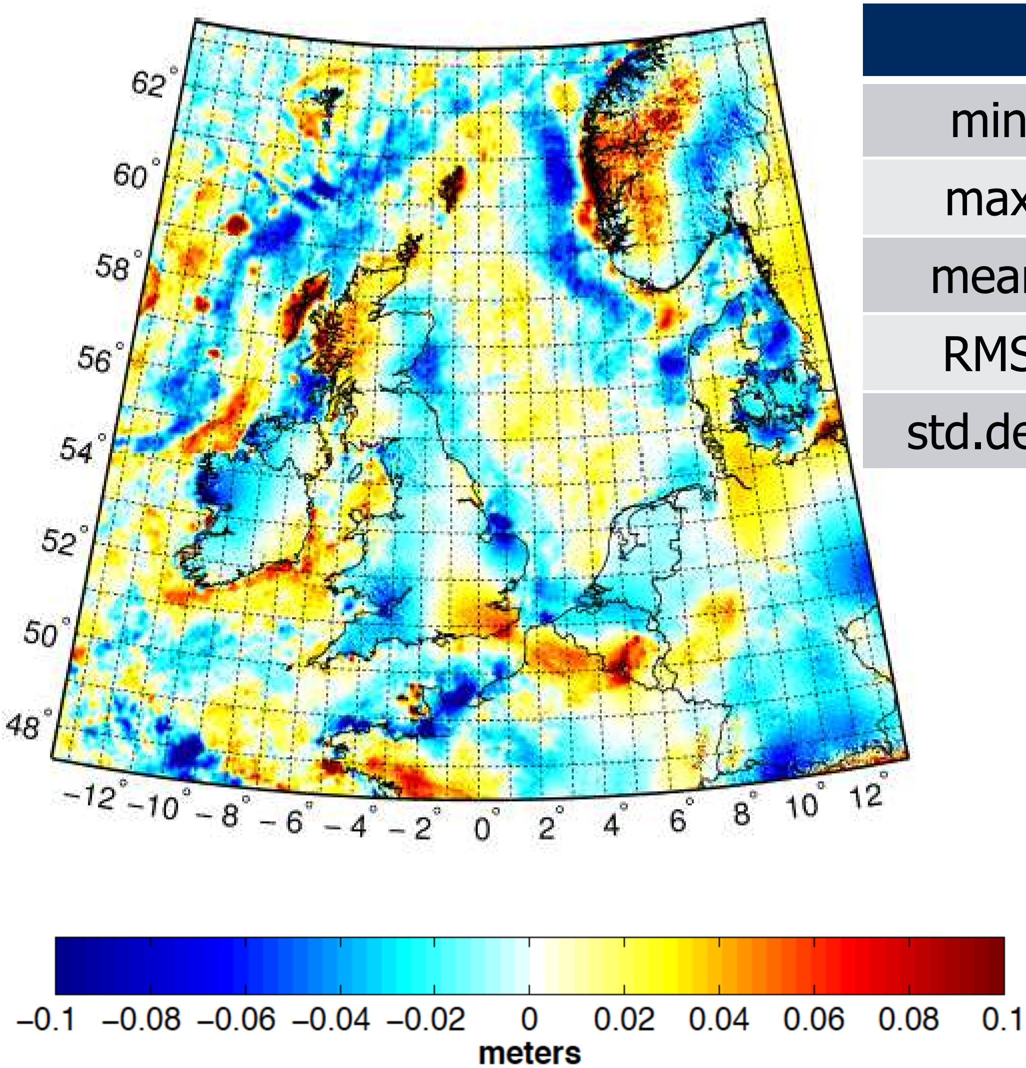
	range [cm]	mean [cm]	std.dev. [cm]
GOT4.7 tide	**11.5**	**1.9**	**2.2**
DCSM tide	**8.1**	**1.7**	**1.4**
DCSM DT	**7.2**	**1.4**	**1.2**
Public DT	**13.0**	**2.5**	**2.2**

Difference between two quasi-geoid solutions

excl altimeter data vs excl shipboard gravity data

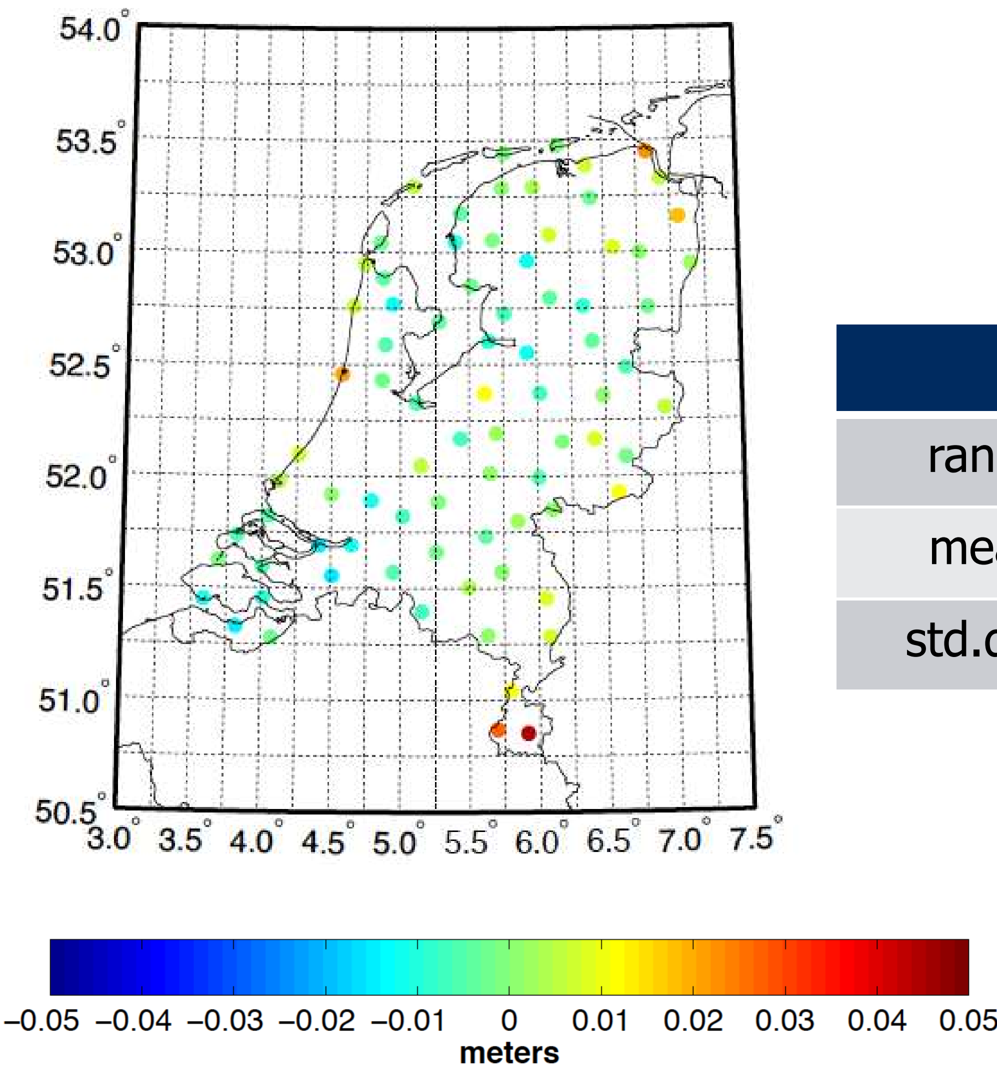


Differences between NLGEO2013 and EGG08



	oceans	land	NL
min	- 19.0 cm	- 13.9 cm	- 4.2 cm
max	28.1	19.7	1.1
mean	0.0	0.2	- 1.1
RMS	2.7	2.7	1.4
std.dev.	2.7	2.7	0.9

Comparison with GPS/levelling data



	NLGEO2013	EGG08
range	6.0 cm	6.3 cm
mean	0.9 cm	2.0 cm
std.dev.	1.0 cm	1.1 cm

Summary

- Benefit of full DT corrections has been demonstrated
  - Better modelling the (shallow water) tides is most important
  - Significance of surge & steric corrections demonstrated for wavelengths > 100-200 km, but still unknown @ shorter scales
  - Southern North sea benefits the most
- Errors in DT corrections → systematic errors in the quasi-geoid
- No corrector surface needed over the Dutch mainland