SPIE Remote Sensing, Edinburgh 26-29 Sept 2016

Advances in Satellite Altimetry and GNSS-Reflectometry for monitoring world's oceans and coasts

Paolo Cipollini (1), Francisco M. Calafat (1), Maria Paola Clarizia (2), Christine Gommenginger (1), Marcello Passaro (3), Helen Snaith (4)

(1) National Oceanography Centre, UK, cipo@noc.ac.uk
(2) University of Michigan, USA
(3) Technischen Universität München, Germany
(4) British Oceanographic Data Centre, UK

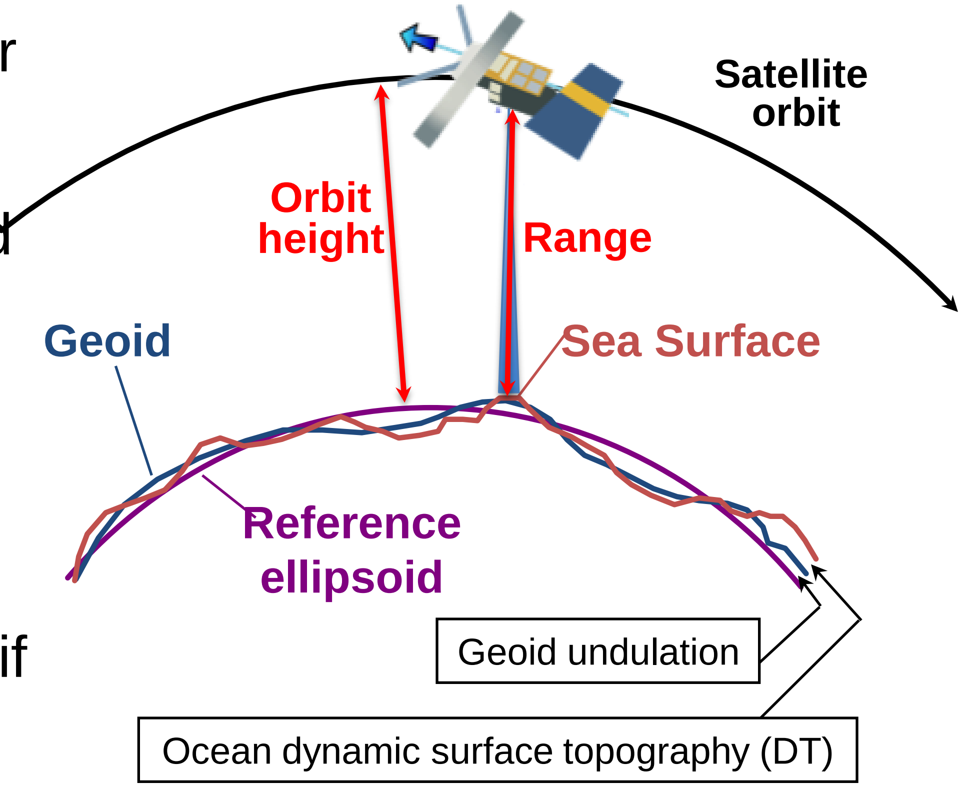
Outline

- Ocean Altimetry: from basics to mature results
- Advances in ocean altimetry
  - New domains: coastal altimetry
  - New technologies: Ka-band altimetry, SAR altimetry
- GNSS-Reflectometry
  - for scatterometry (winds)
  - for altimetry

Basic Principles of Altimetry

- The altimeter is a radar at vertical incidence
- The signal returning to the satellite is from quasi-specular reflection by the sea surface
- By timing it, we measure the distance between satellite and sea (**range**)
- We know the position of satellite (precise **orbit**) from models and measurements
- Hence determine **height** of sea surface w.r.t. reference ellipsoid (or even w.r.t. **geoid** if that is known with good accuracy)
- altimeters also measure **waves** and **wind**

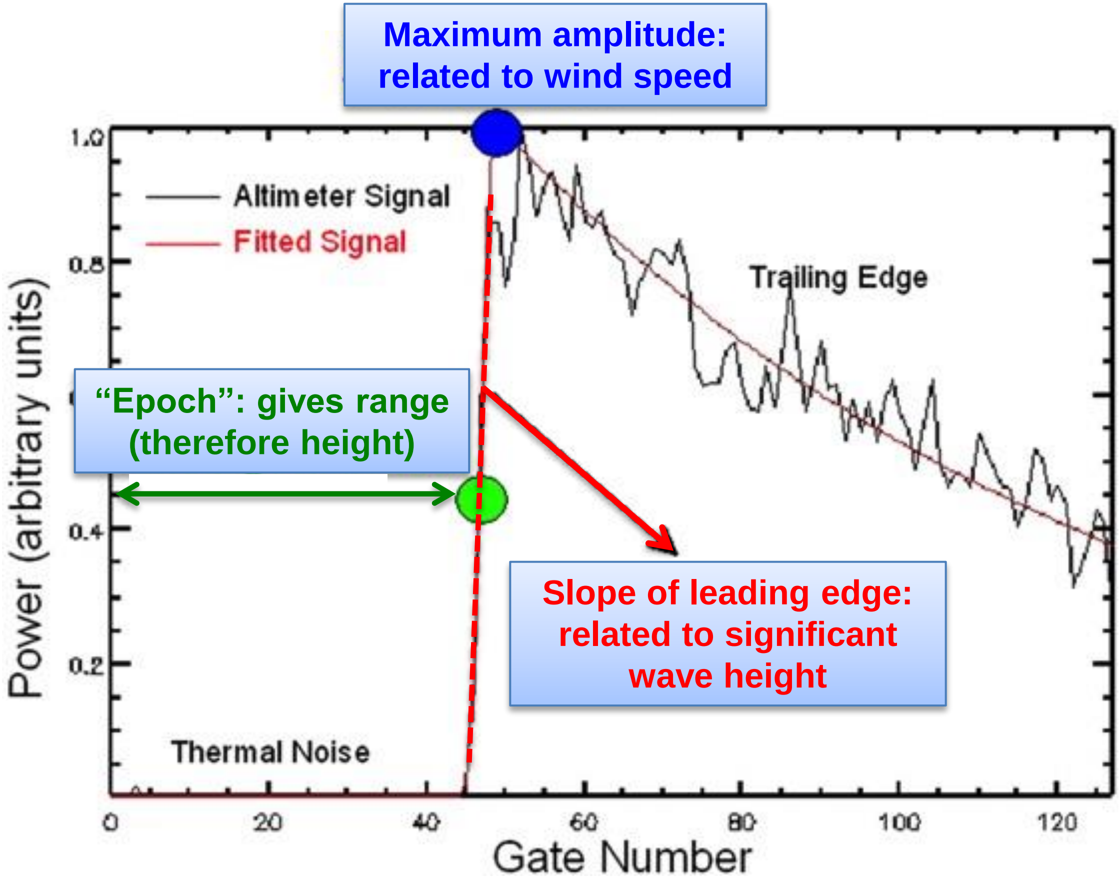
Conceptually simple
Technically challenging!!
(required accuracy ~1 cm from ~1000km)



DT= Orbit - Range - Geoid

“Retracking” of the radar waveforms

= fitting the radar echoes (waveforms) with a waveform model,
→ we estimate the three fundamental parameters

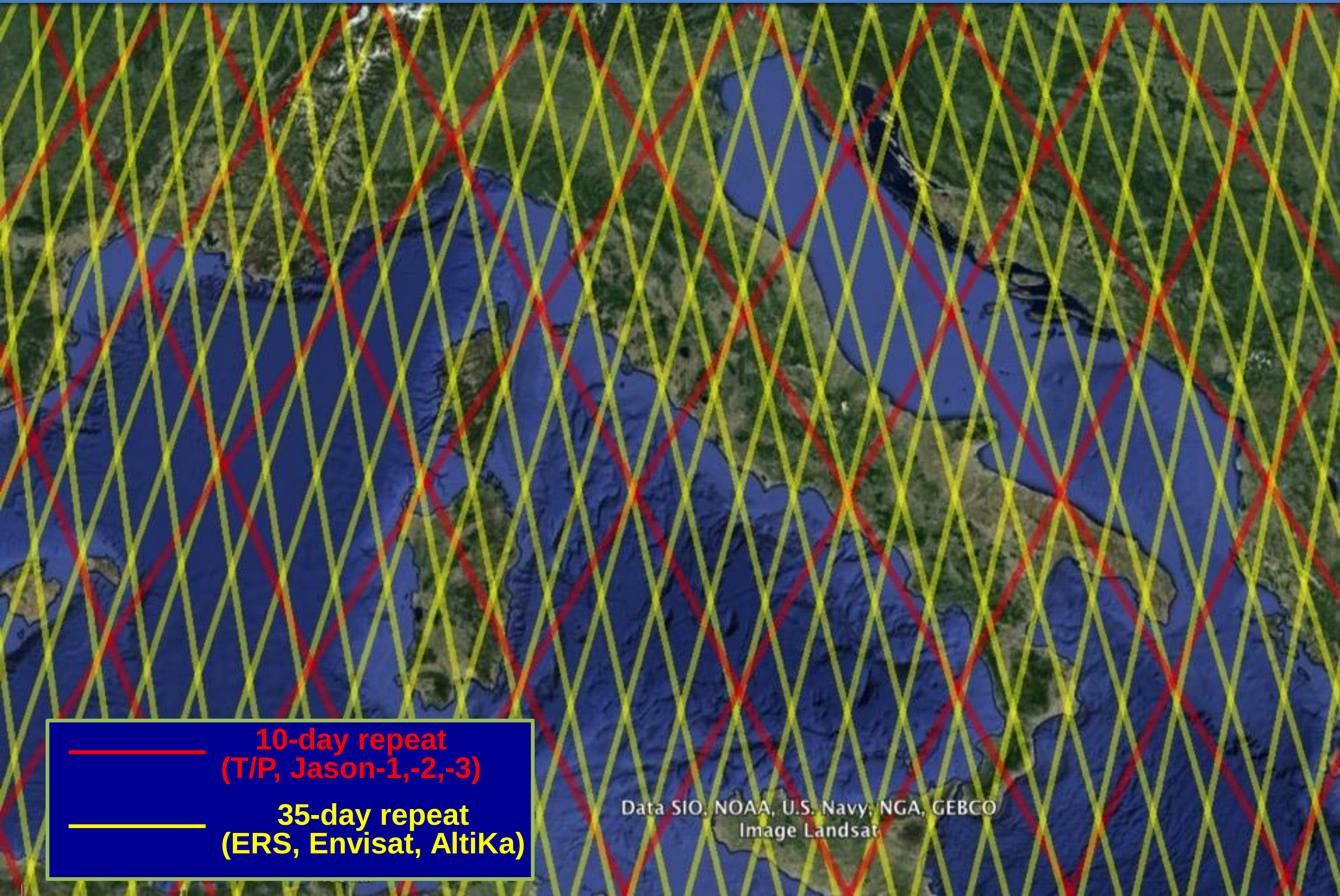


Normally done at 18-20 Hz (~350 m along-track) and then averaged at 1-Hz (~7km) to improve precision

Figure from J Gomez-Enri et al. (2009)

Open-ocean waveform model: Brown, 1977

Altimetry is "along-track"



Satellite Altimetry Instruments/Missions

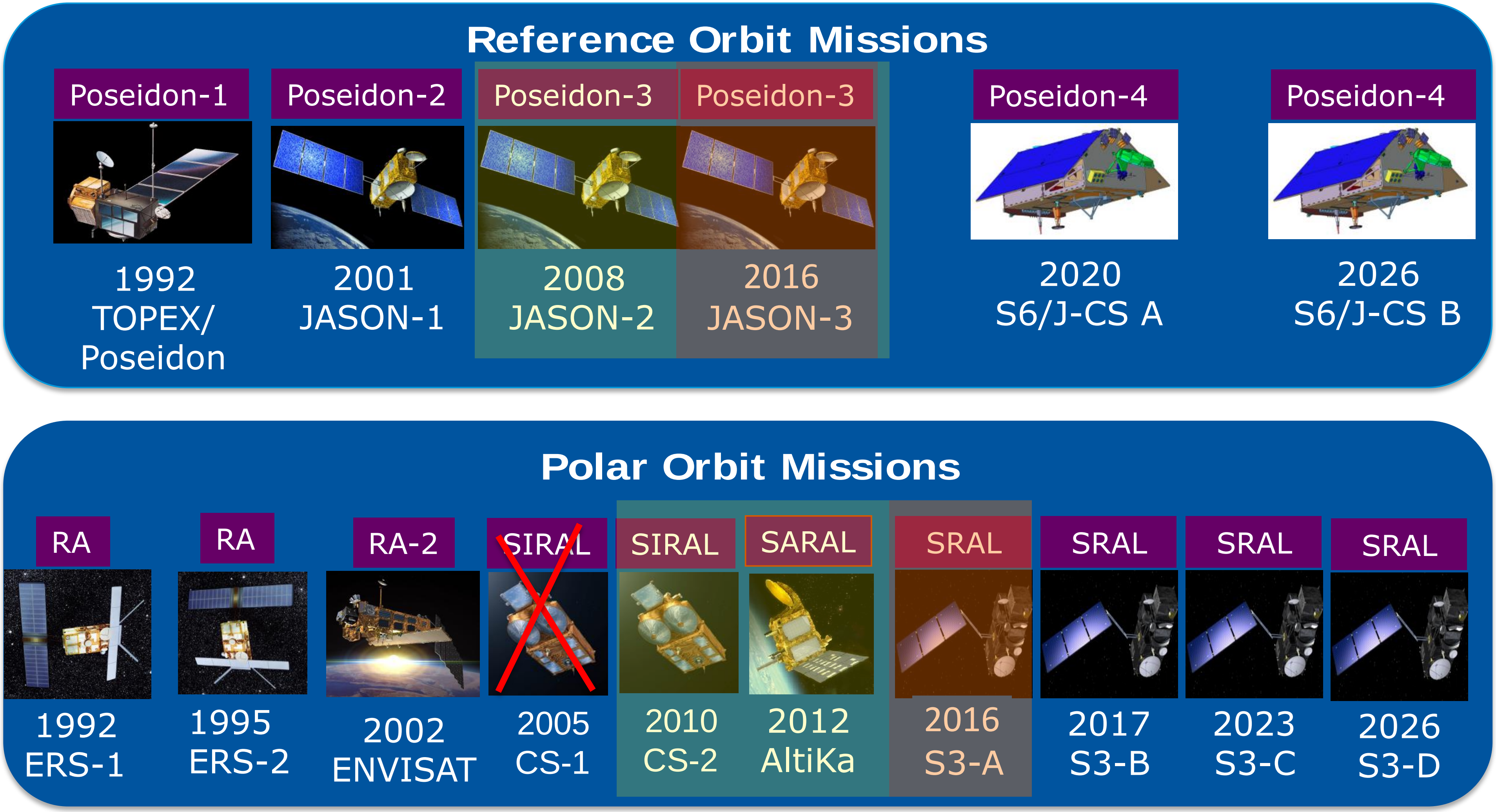
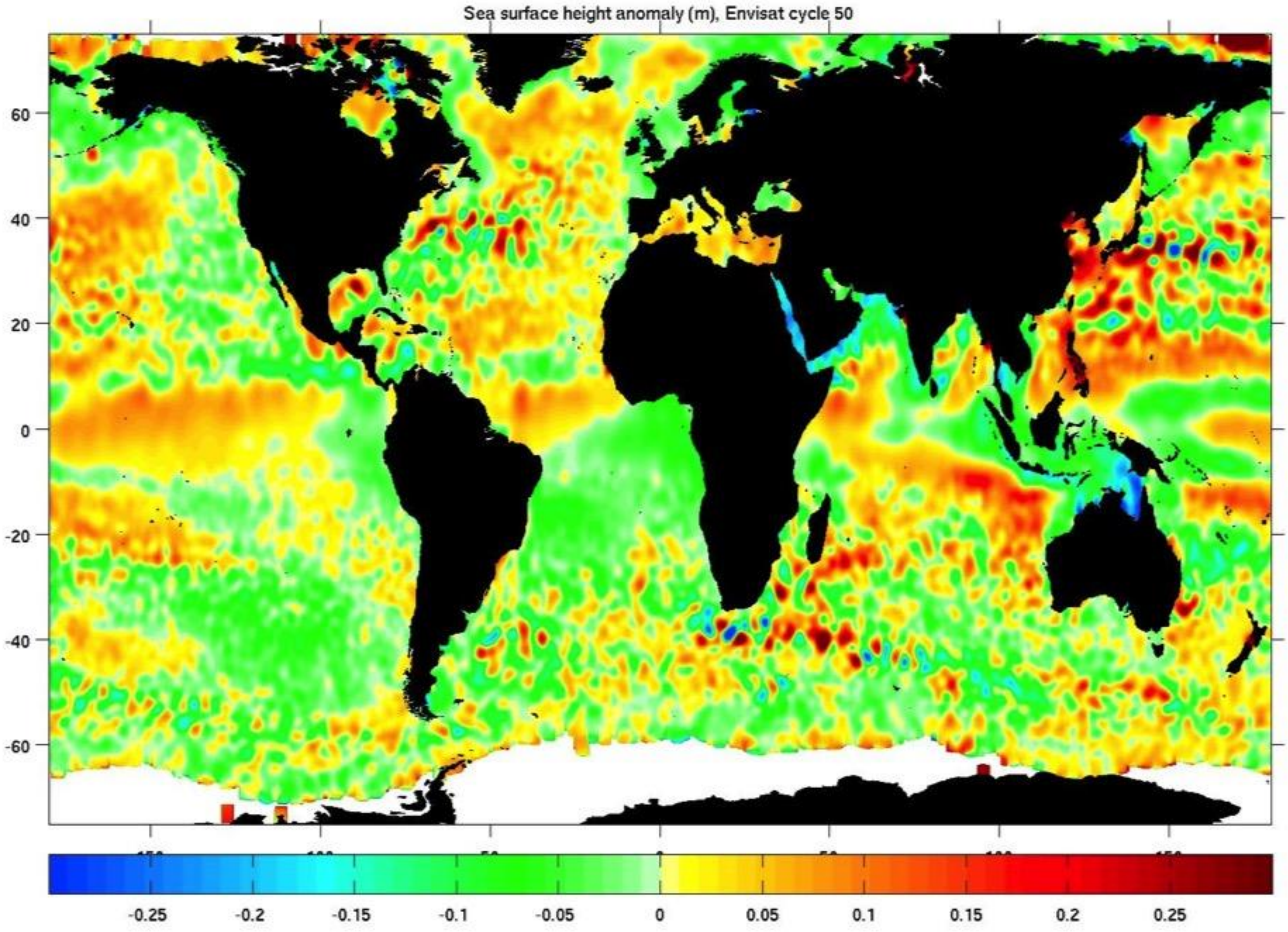


Figure from Craig Donlon, ESA

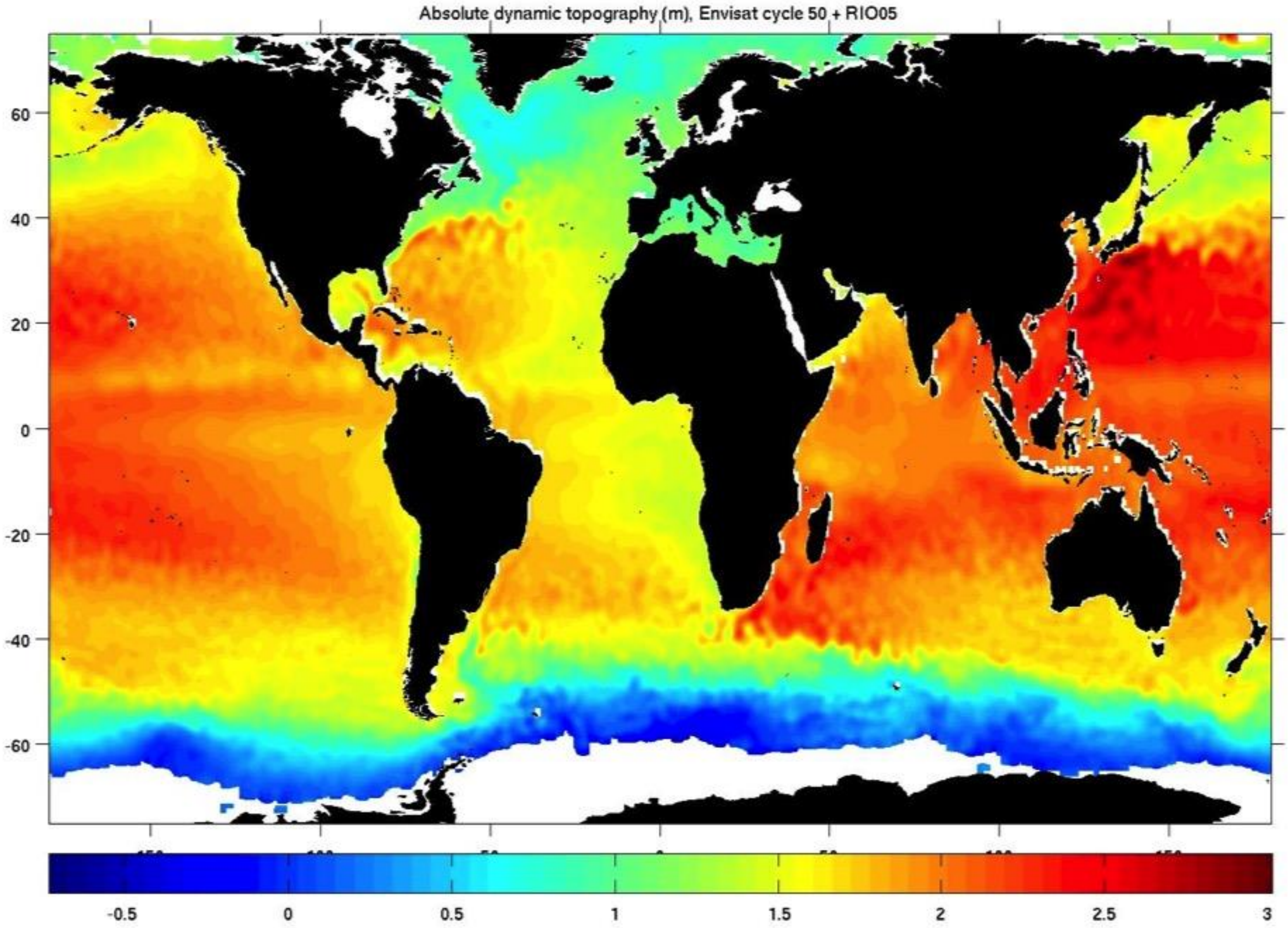
Satellite Altimetry: a mature technique

- workhorse of operational forecasting systems – extensively used in FOAM/NEMO, ECMWF, Mercator,…
  - synergy with SST, ARGO
  - also wind, waves
  - (some research issues still to be resolved for the assimilation)
- 24 years (and counting) of good quality data, continuity of service secured
- use for climate studies (long-term **sea level rise**): ESA Climate Change Initiative
- precise (i.e. repeatable) and accurate (i.e. small biases)
- even more impetus from technological advances:
  - **SAR altimetry from CryoSat-2 (2010–), Sentinel-3 A(2016–)/B/C/D, Sentinel-6 (2020)**
  - **Ka-band altimetry from AltiKa (2013–)**

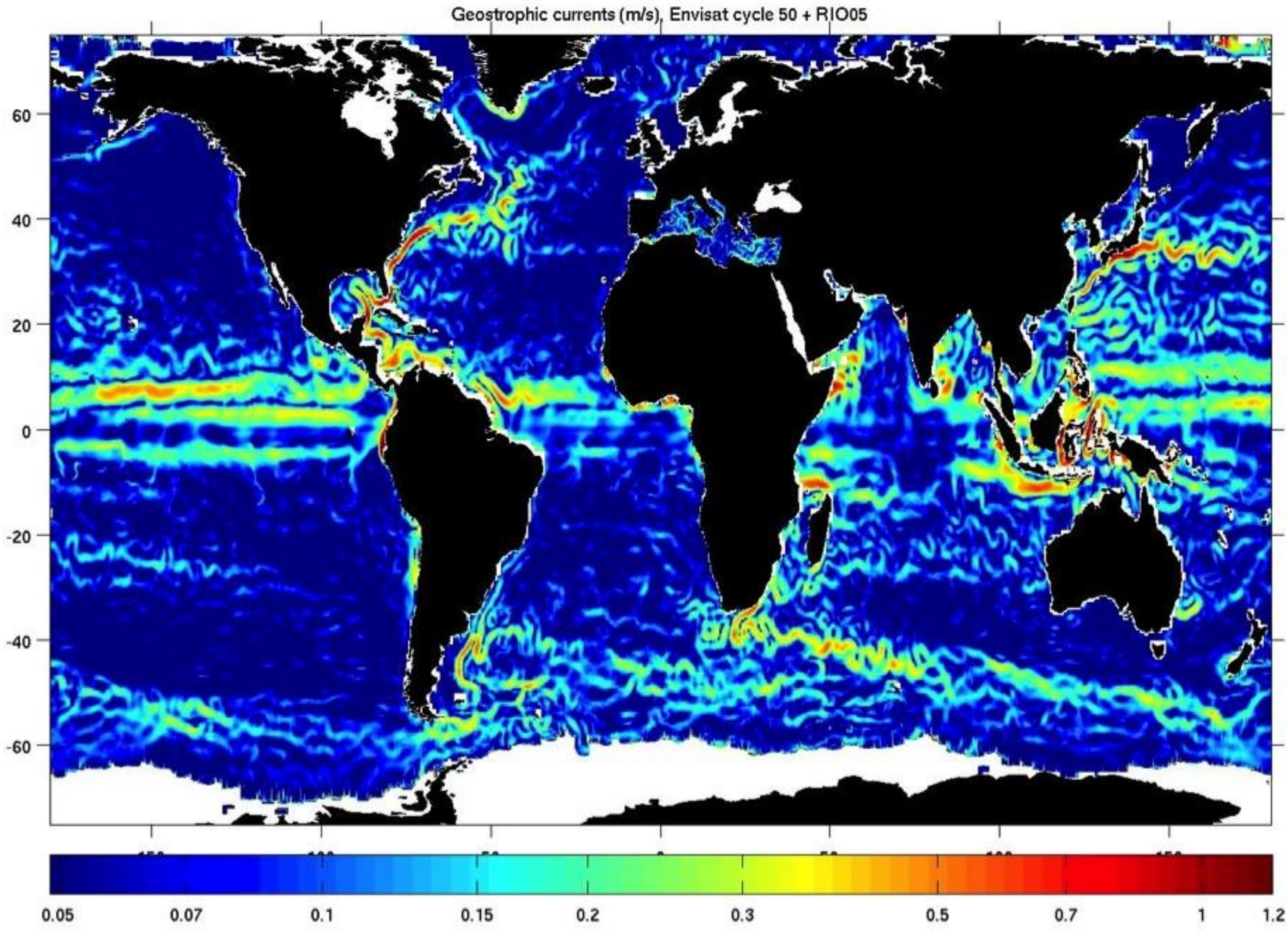
SEA LEVEL ANOMALY



ABSOLUTE DYN TOPO



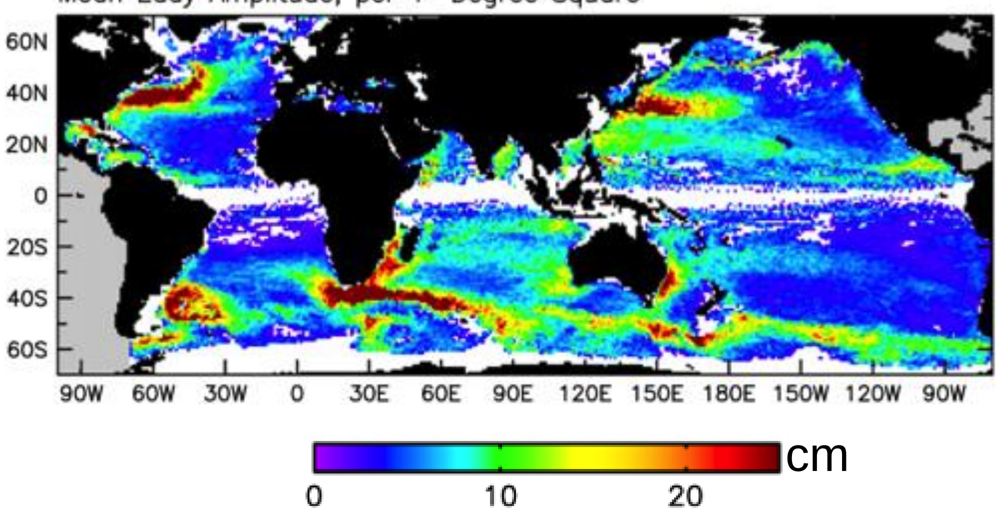
SURFACE CURRENTS

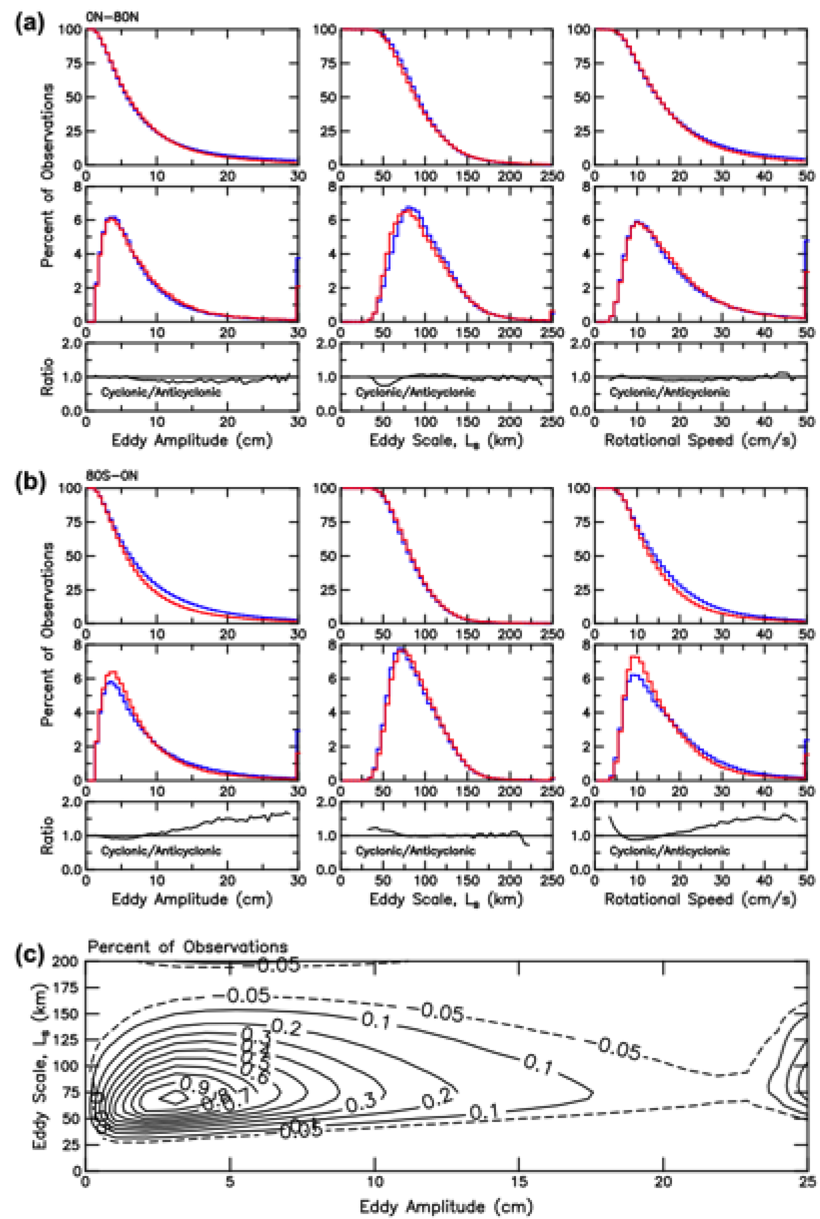


MESOSCALE FEATURES

- Chelton et al., 2011, have identified **35891 eddies** (with lifetimes >=16 wks) in 16 years of two-mission altimeter data
- averages:
  - lifetime 32 weeks
  - propagation distance 550 km
  - amplitude 8 cm
  - radius 90 km

Mean Eddy Amplitude, per 1° Degree Square

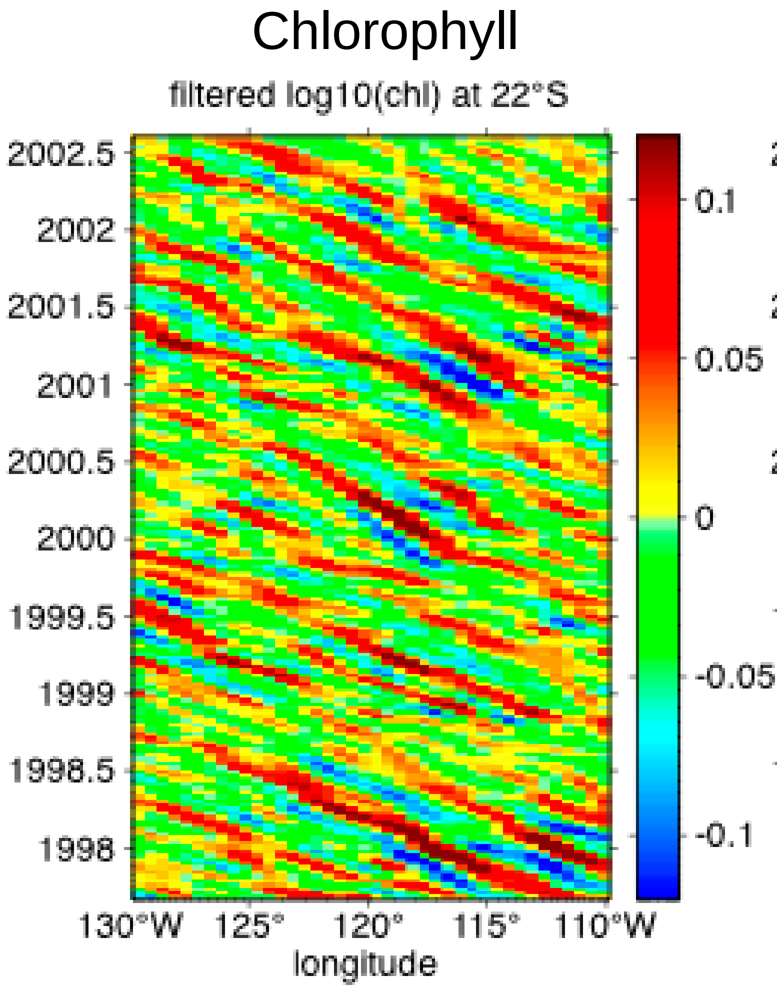


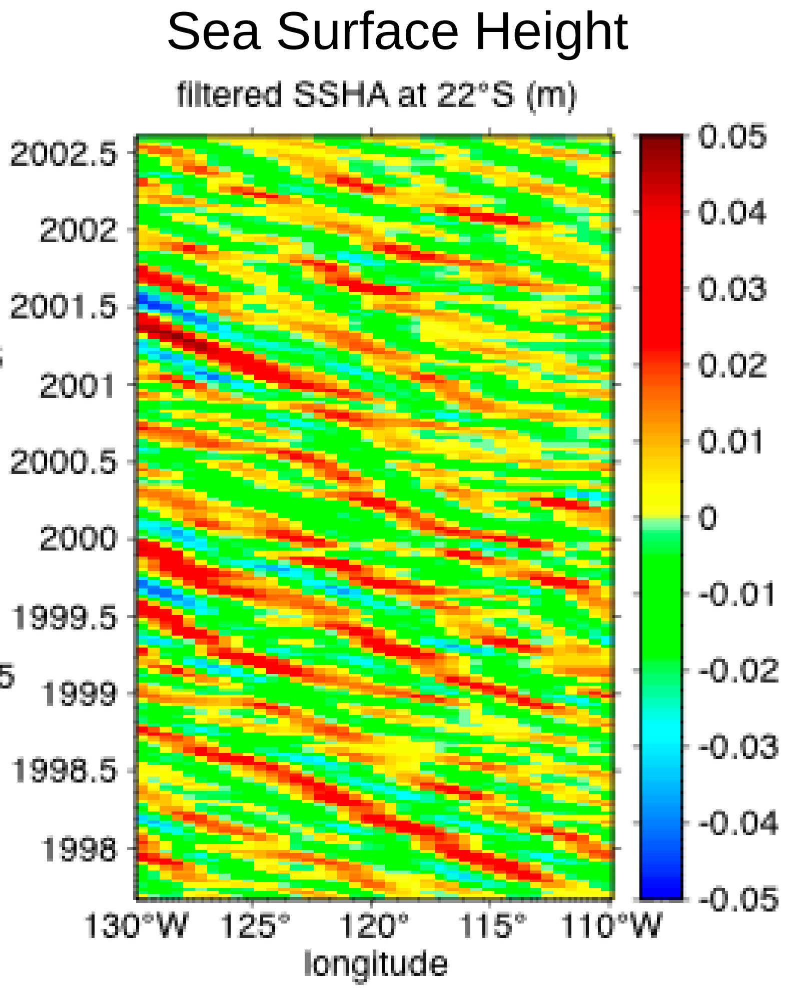


D. Chelton et al., 2011

ROSSBY WAVES AND EDDIES

Cipollini et al, 2001; Uz et al, 2001; Siegel, 2001; Charria et al., 2003; Killworth et al, 2004; Dandonneau et al., 2004; Charria et al, 2006, various papers by Chelton and co-authors



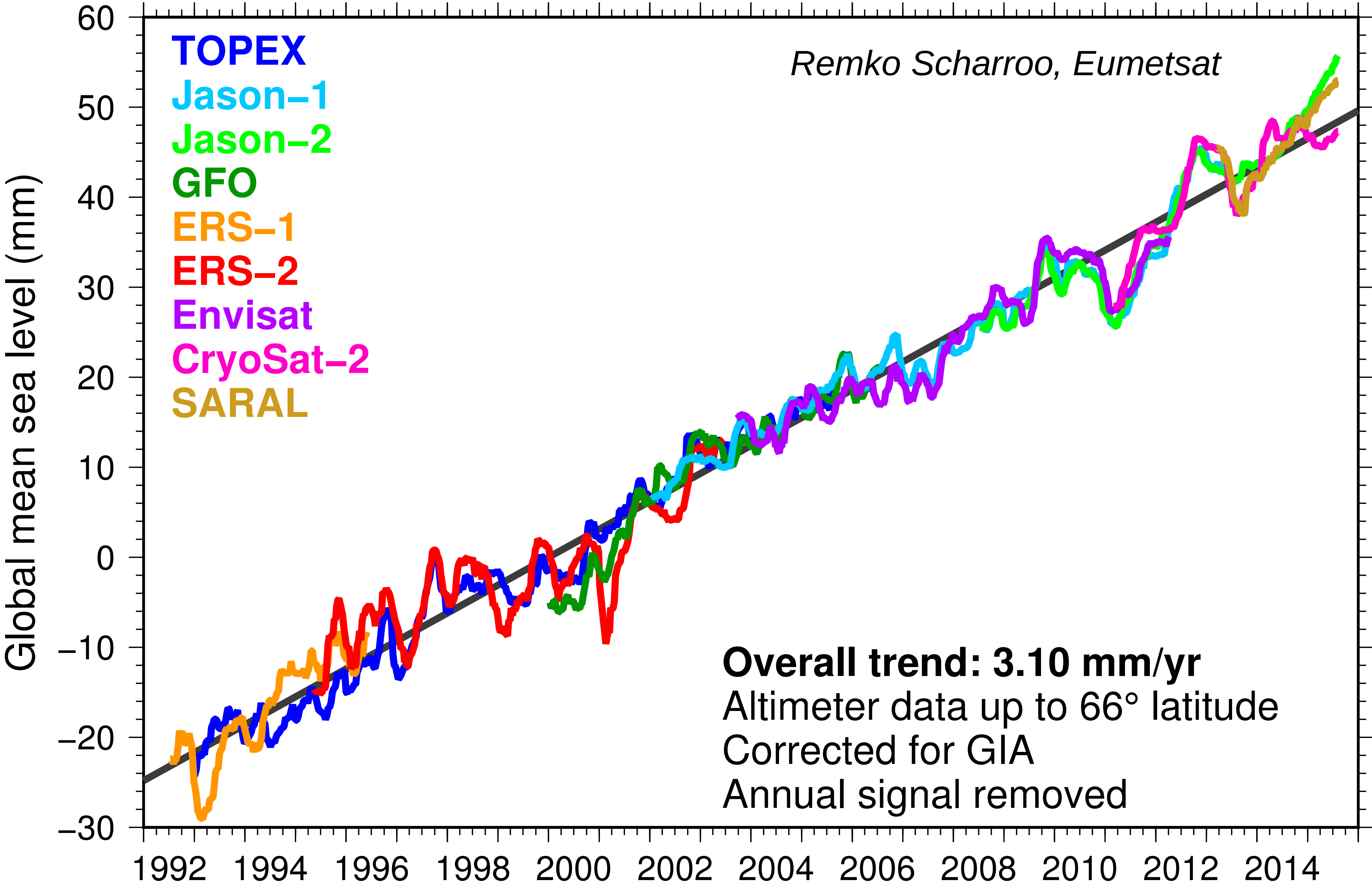


Great synergy possible in all studies of bio-physical interactions when altimetry is combined with SST, ocean colour

Sea Level Rise!

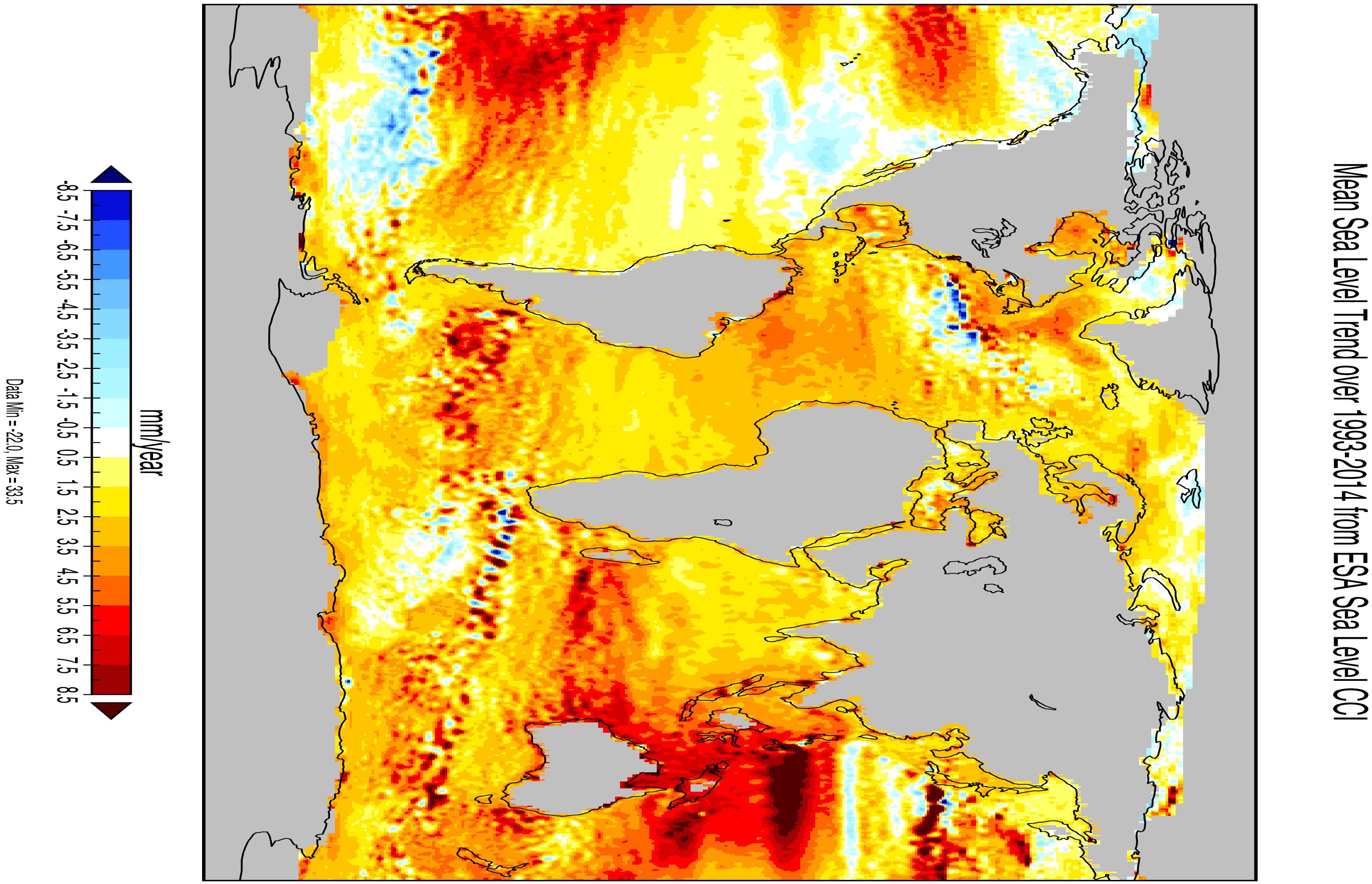
- 1.5 billion people at the coast, 20+ "megacities" are at sea level
- Coastal infrastructure, transports, shipping, power plants, leisure….
- Many very vulnerable regions (think Bangladesh, or low-lying Islands)
- Sea level rise makes coastal flooding more frequent and its impacts worse

SEA LEVEL RISE - global



SEA LEVEL TRENDS - regional

→ Sea Level component on dedicated ESA programme, the “Climate Change Initiative”

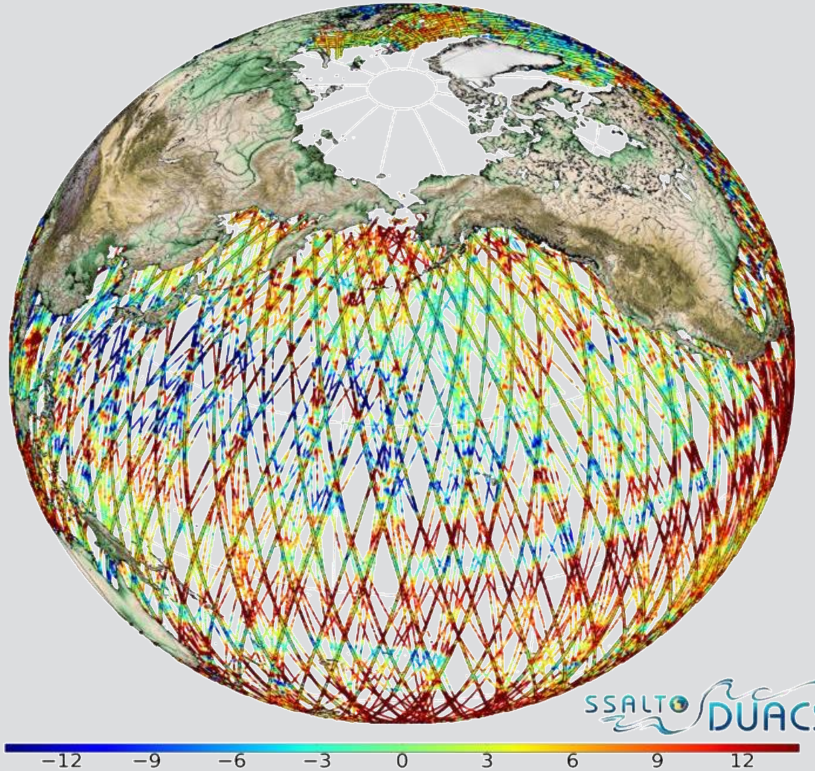


SL_cci ECV products

- 7 altimeter missions: TOPEX/Poseidon, Jason-1/2, ERS-1/2; Envisat, Geosat-Follow On
- 60 cumulated years of data reprocessed
- Based on SSALTO/DUACS infra-structure (CNES)

- SL_cci ECV release V1.1 :

→ Period: 1993-2014
→ Available via : http://www.esa-sealevel-cci.org/
→ Request at info-sealevel@esa-sealevel-cci.org



from: JF. Legeais et al., ESA LPS 2016

Year 2016 : on going …

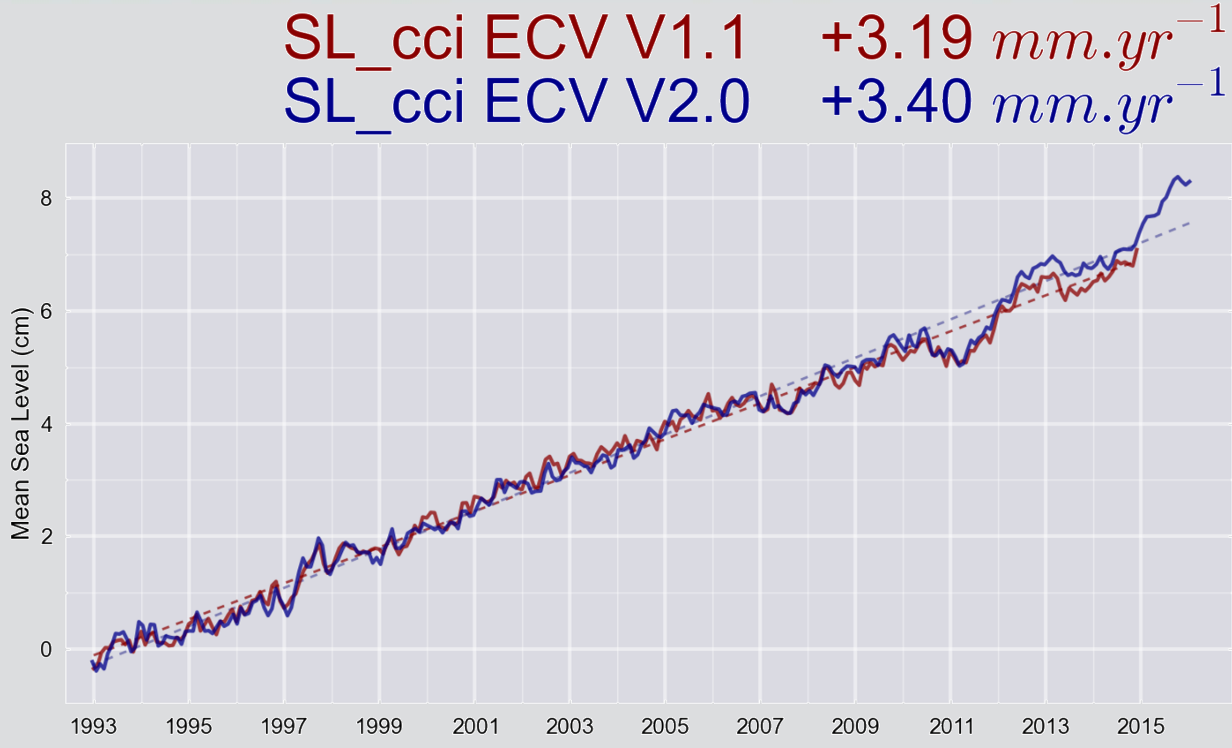
- SL_cci ECV release V2.0:

→ 9 altimeter missions: Cryosat 2 and SARAL/Altika added

→ Period: 1993-2015

→ Improved altimeter standards : new wet troposphere correction (GPD+), new ocean tide model (FES 2014), new orbit solution (POE CNES);…

→ Available by the end of 2016



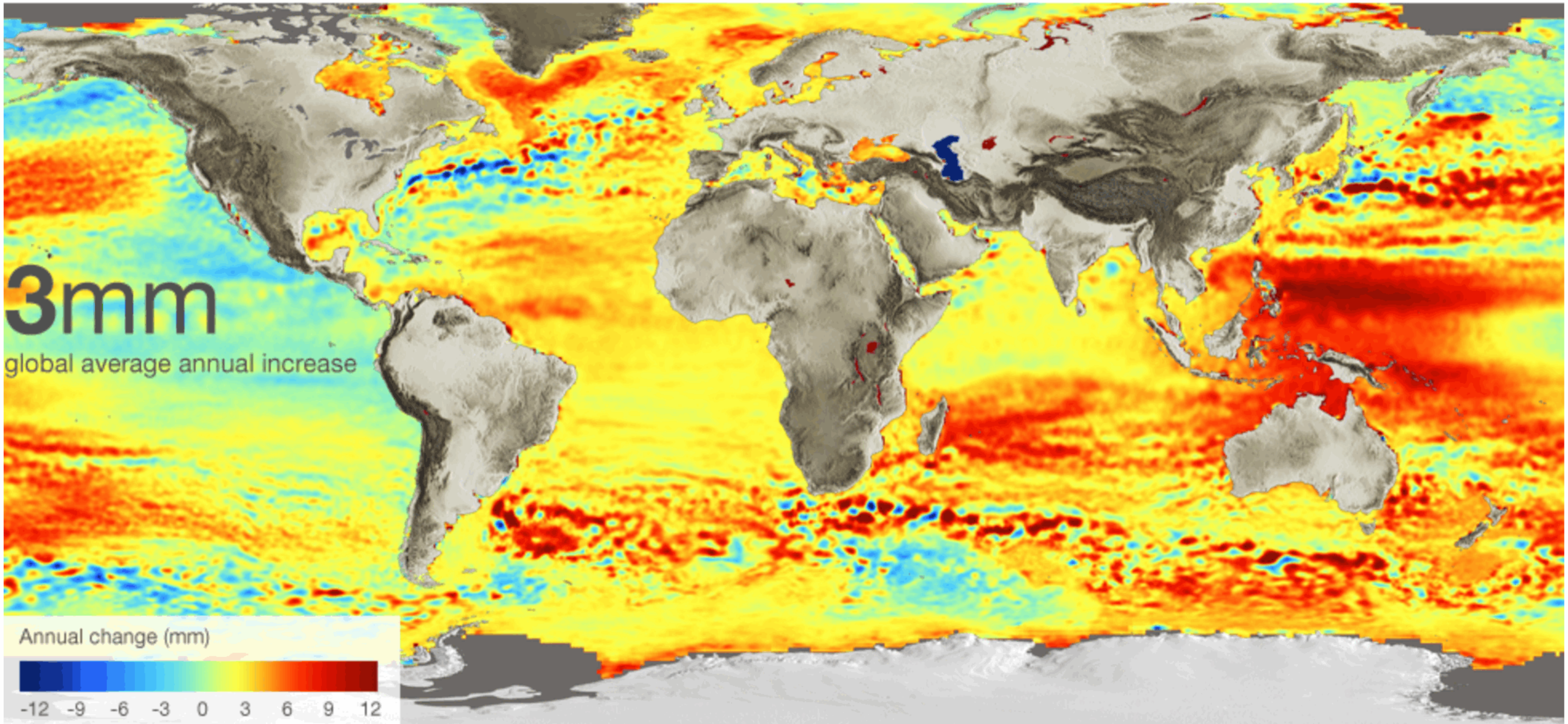
from: JF. Legeais et al., ESA LPS 2016

24 September 2012 Last updated at 17:19

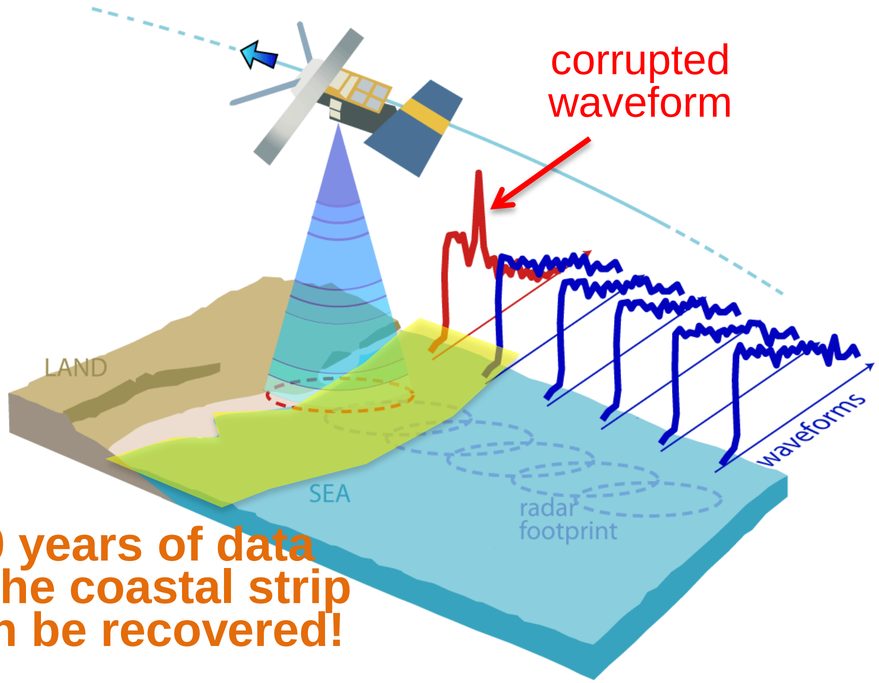
Satellites trace sea level change

Scientists have reviewed almost two decades of satellite data to build a new map showing the trend in sea levels. Globally, the oceans are rising, but there have been major regional differences over the period.

Annual average sea-level rise, 1993-2010



The new frontier - coastal altimetry



20 years of data in the coastal strip can be recovered!

Traditionally, data in the **coastal zone** are flagged as bad and left unused

(coastal zone: as a rule of thumb 0-50 km from coastline, but in practice, **any place where standard altimetry gets into trouble** as waveforms are non-Brown and/or corrections become inaccurate)

In recent years a vibrant community of researchers has started to believe that most of those coastal data can be recovered

http://www.coastalt.eu/community

Also important for **SAR & Ka-band altimetry, having good coastal performance - and for coastal wave field**

AND – to link open-ocean sea level rise with observations done by tide gauges at the coast!

The Coastal Altimetry Community

- Coastal Altimetry Workshops (CAW) since 2008 (CAW-1 in Silver Spring was promoted by NOAA, then ESA has been main supporter)
  - large community: 100+, COASTALT-SWT mailing list
  - a big ‘splinter’ of Ocean Surface Topography Science Team (OSTST)
- A Community Science Review
  - **techniques, new datasets, applications**
  - **recommendations** (internal / external)

CAW-5 San Diego, 2011

CAW-10: Florence, Italy 21-24 Feb 2017

Coastal altimetry continues to improve

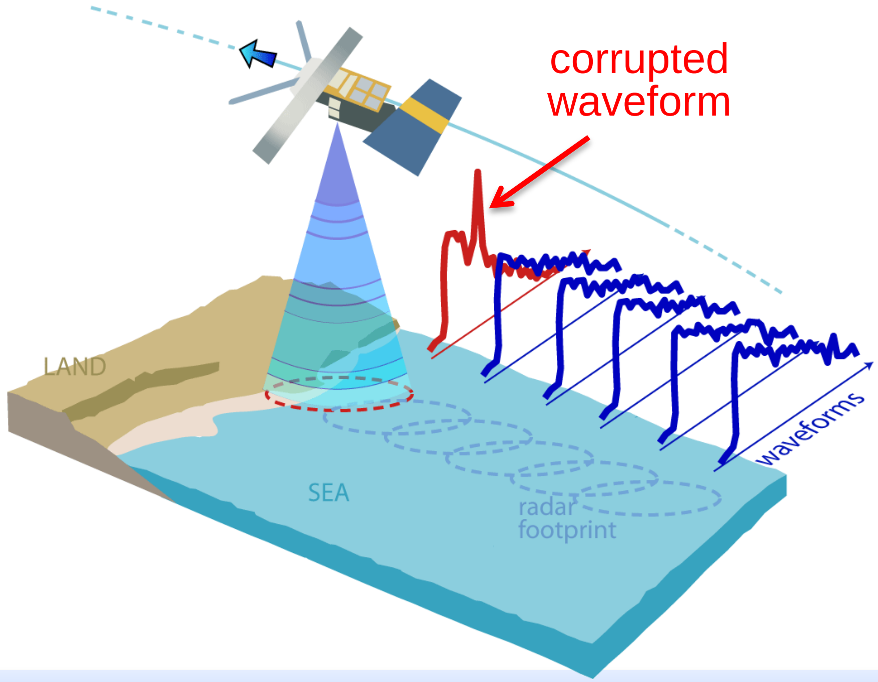
- Processing advances
- Continuing improvement in corrections
- **Many datasets are now available…**
- … and applications have high impact
  - coastal dynamics
  - storm surges
  - regional sea level rise
- Takes advantage from new technologies: SAR, Ka-band altimetry

Datasets for coastal altimetry

ID	Produced by	Missions	Product level	Posting rate	Coverage	Download from
AVISO	CLS CNES	e1,tx,e2, en, j1, j2, c2 (LRM/PRLM), sa	L2, L3 also L4	1 Hz	Global + european regions	AVISO+
CMEMS	CLS CNES	e1,tx,e2, en, j1, j2, c2 (LRM/PRLM), sa	L3 L3 for assim	1 Hz	Global + european regions	marine.copernicus.eu
PISTACH	CLS CNES	j2	L2	20 Hz	Global	AVISO+
PEACHI	CLS CNES	sa	L2	40 Hz	Global	AVISO+
XTRACK	LEGOS-CTOH	tx, j1, j2, gfo, en	L2, L3	1 Hz 20Hz (test)	23 regions	CTOH AVISO+
RADS	EUMETSAT, NOAA, TUDelft	gs, e1, tx, pn, e2, gfo, j1, n1, j2, c2, sa		1 Hz	Global	TUDelft
ALES	NOC	j2, n1 (coming)		20 Hz	Global, <50 km from coast	PODAAC
SARvatore	ESA-ESRIN	c2 (SAR only)		20 Hz	SAR mode regions	ESA GPOD

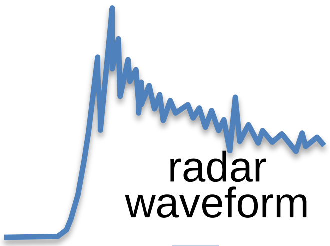
Coastal altimetry continues to improve

- **Processing advances**
- Continuing improvement in corrections
- Many datasets are now available…
- … and applications have high impact
  - coastal dynamics
  - storm surges
  - regional sea level rise
- Takes advantage from new technologies: SAR, Ka-band altimetry



NOC's ALES retracker

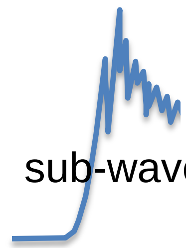
Adaptive Leading-Edge Subwaveform (ALES) retracker
Passaro et al., Rem Sens Env., 2014



Pass 1: identification of leading edge and initial estimate of SWH

$h_{s(1)}$

ALES algorithm for width of sub-waveform window
(from Monte Carlo Simulations)



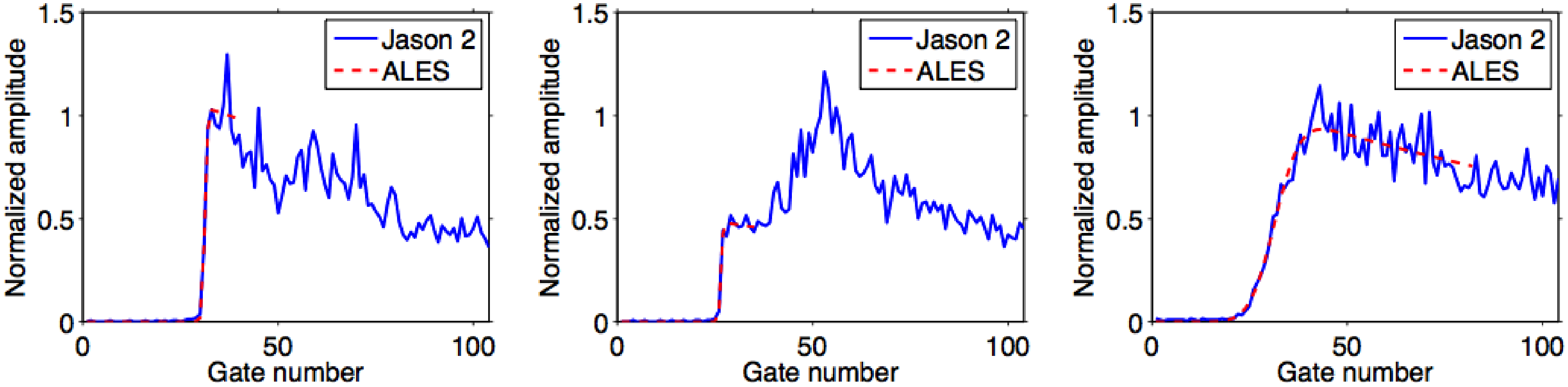
Pass-2: subwaveform retracking (Brown Model)

range, σ^0, h_s

The sub-waveform approach keeps the measurement focused on the pulse-limited footprint of the instrument → prevents any non-homogeneities in the far-view field from degrading its accuracy.

→ very good for **coastal zone and fine scales**

Examples of Jason-2 retracking by ALES



Open ocean
SWH = 0.75 m

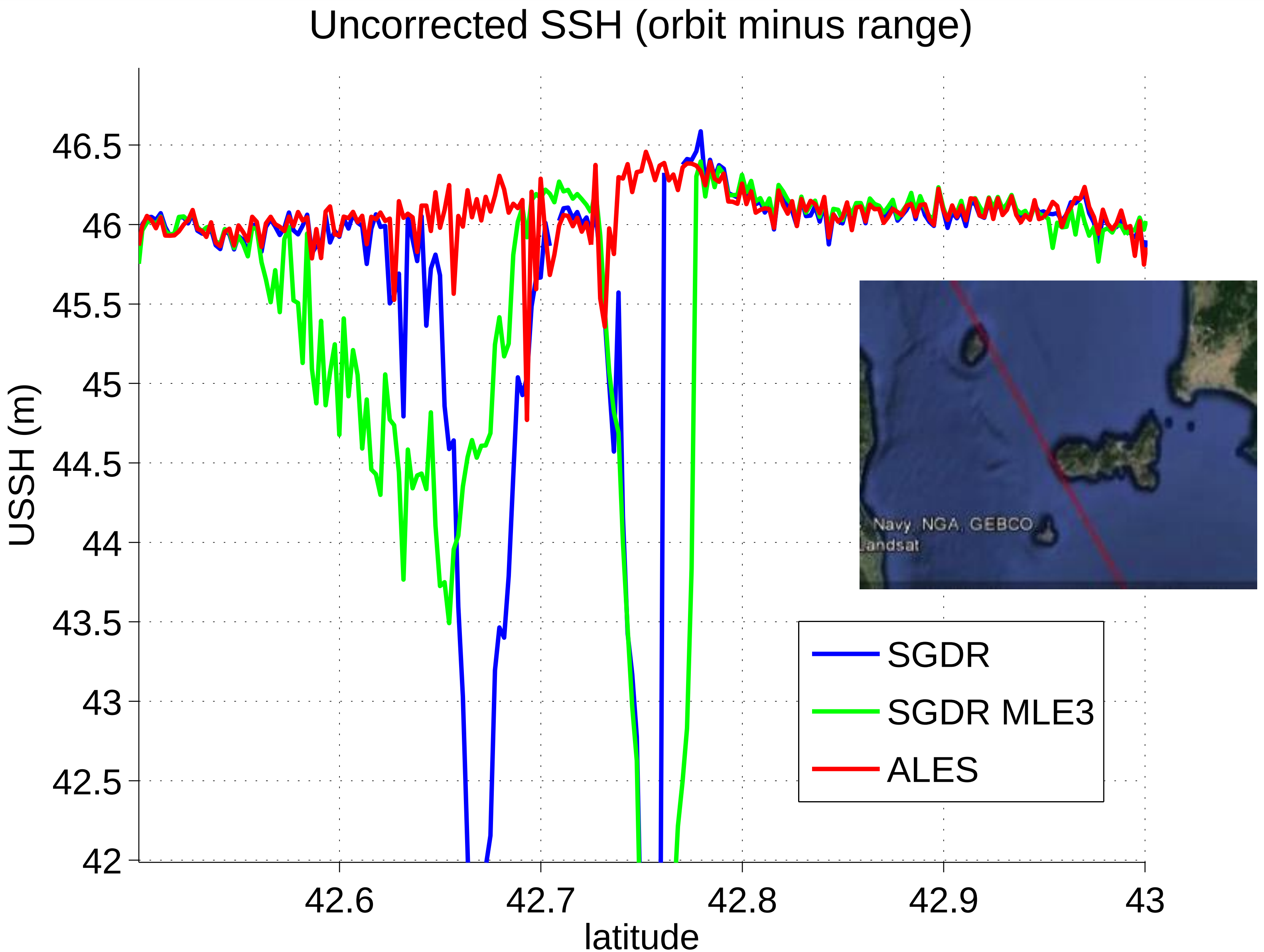
Coastal ocean
SWH = 1.65 m

Open ocean
SWH = 9.5 m

- Validated for SSH for Envisat, J-1, J-2, AltiKa
- Validated for SWH for Envisat, J-1/2 (Passaro et al 2015)
- J-2 data available now from PODAAC, Envisat coming

ftp://podaac.jpl.nasa.gov/allData/coastal_alt/L2/ALES/

J2 p0044 cycle 252 - 7 May 2015 around Elba



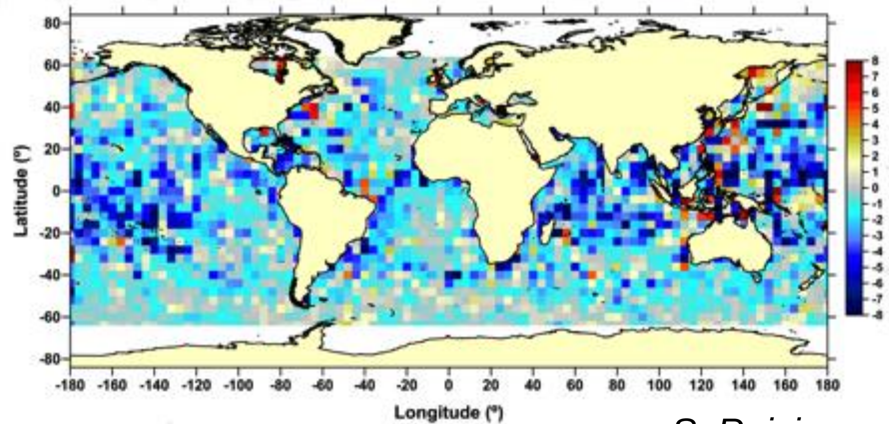
Continuing improvement in corrections

- DComb Wet Tropo
- High-res MWR on the horizon
- MSS – and tides!!
  - in coastal regions data editing for MSS determination is critical
  - SarIN! Example
- Significant differences shown between the GDR-Global DAC prediction and local models within several regions.
  - do not apply the global DAC to the altimeter SSHA, or do so after evaluation against wind-forced HF signals along your coastline.

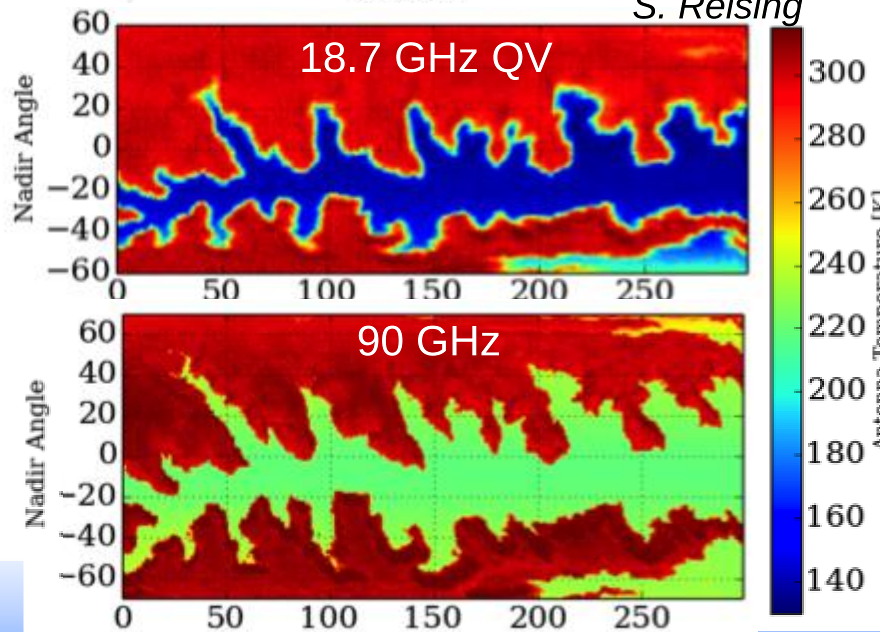
Variance difference at Xovers: DComb-ECMWF

SLA variance difference at crossovers (cm2) between **DComb and ECMWF Operational Model.**

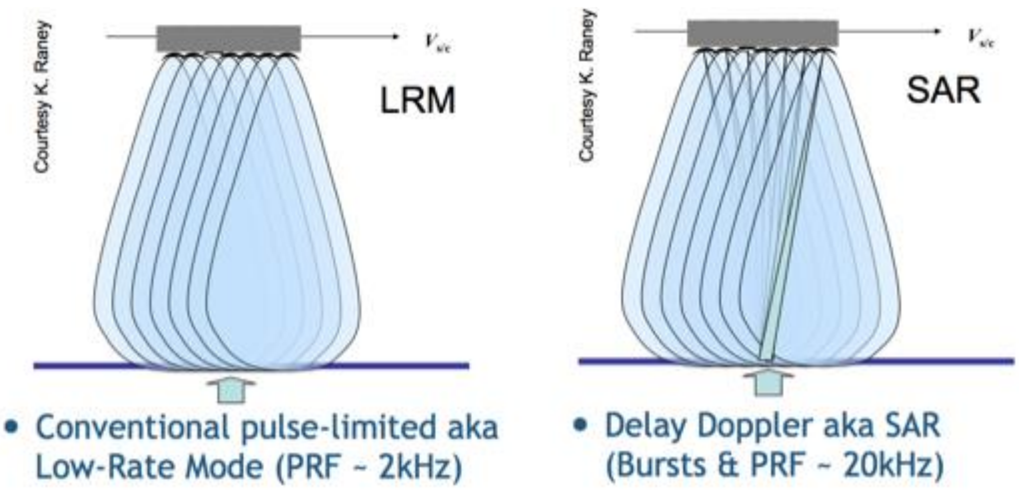
J. Fernandes



S. Reising

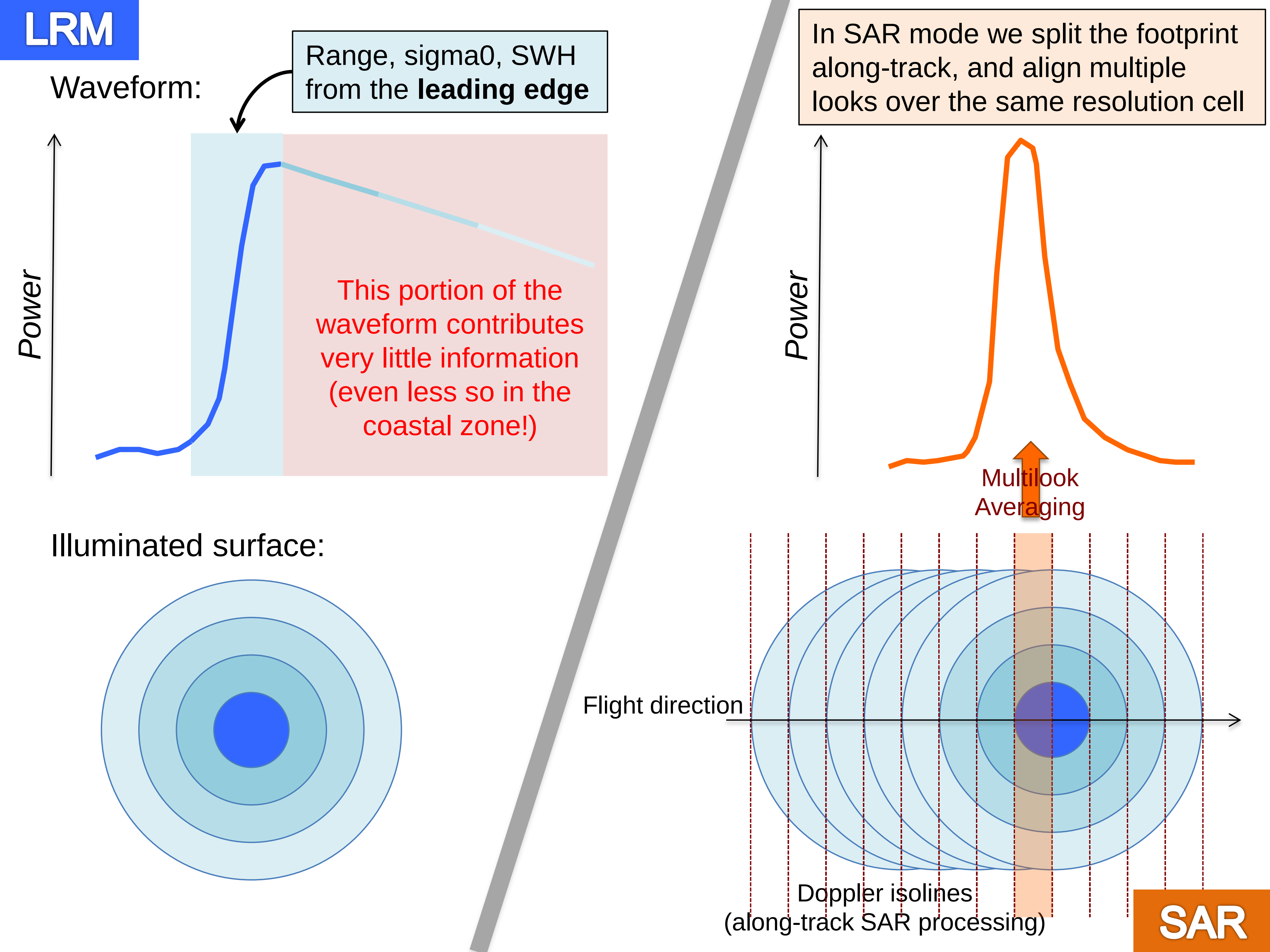


SAR Altimetry – quantum leap



- More "looks" = improved SSH retrieval accuracy
- Finer spatial resolution along track
  - ~ 300 meters along-track
- Less contamination close to land
  - Very well suited for coastal altimetry

- Sentinel-3 and -6 in SAR mode over the whole ocean!
- The improvements w.r.t. conventional (pulse-limited or 'LRM' – Low Rate Mode) altimetry:
  - higher along-track resolution
  - better signal to noise ratio
  - explained with simple energy considerations in the next slide


LRM
Waveform:
Range, sigma0, SWH from the **leading edge**
Power
This portion of the waveform contributes very little information (even less so in the coastal zone!)
Illuminated surface:
In SAR mode we split the footprint along-track, and align multiple looks over the same resolution cell
Power
Multilook Averaging
Flight direction
Doppler isolines (along-track SAR processing)
SAR

S-3 Error budget

Table 7
Estimated Sea Surface Height (SSH) error budget for the Sentinel-3 topography mission.

Source	ENVISAT error [cm]	S-3 error [cm]	Contributor
Altimeter noise	1.8	1.4 **for LRM**	SRAL
Sea state bias	2	2	SRAL
Ionosphere	0.5	0.5	SRAL
Dry troposphere	0.7	0.7	SRAL
Wet troposphere	1.4	1.4	MWR
Total range error	3.1	2.9	
Radial orbit error	1.9	1.9	POD
Sea Surface height error	3.6	3.4	

from Donlon et al., 2012

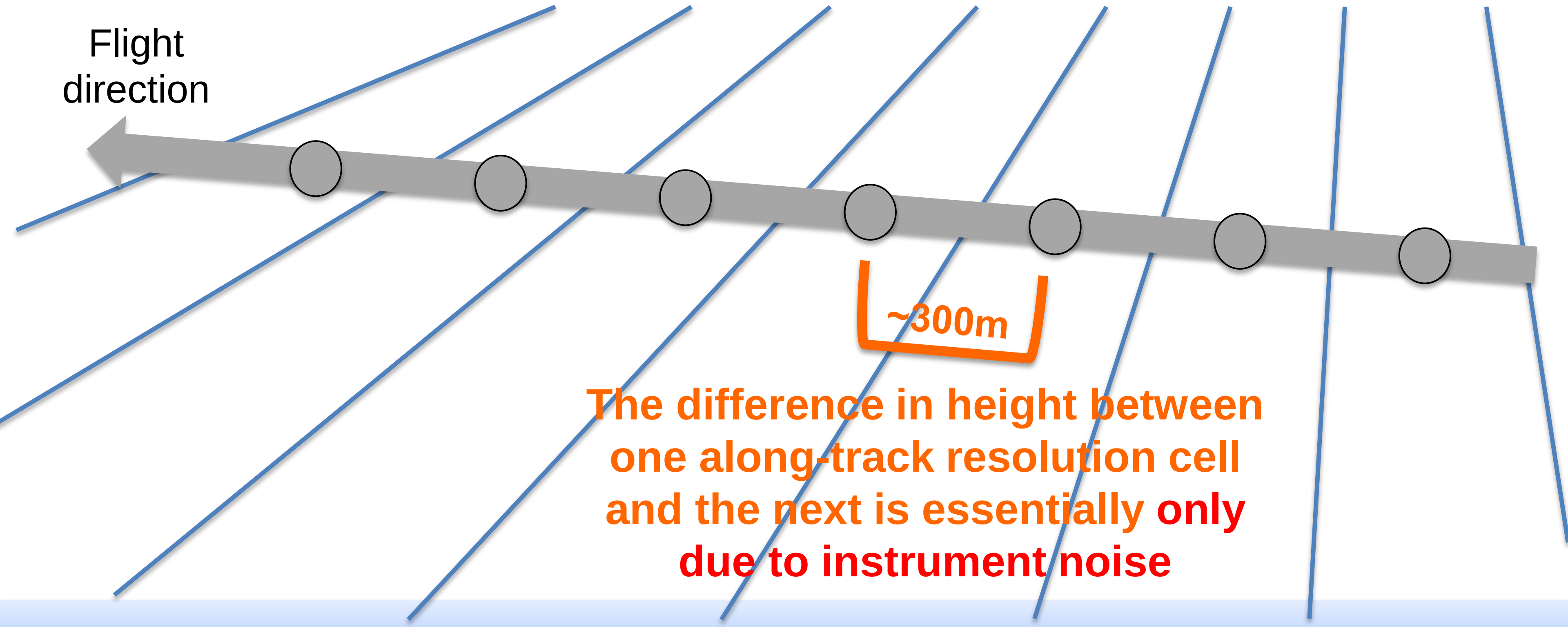
Altimeter noise expected in SAR mode < 1 cm (@ 1 Hz, 2m SWH)

Coastal zone benefits from SAR mode

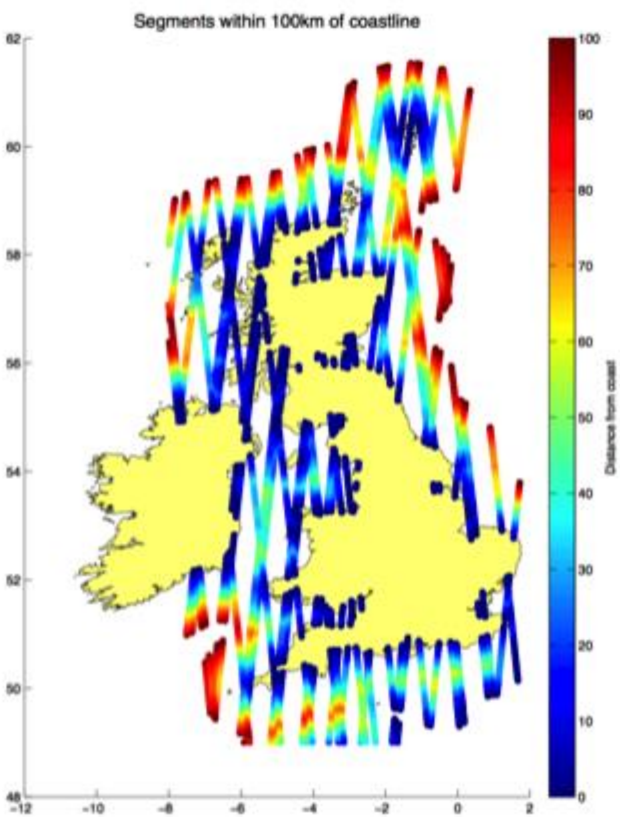
- Higher SNR – can detect small signals in ‘noisy’ (from the point of view of altimetry observables) coastal environment
- Much higher along-track resolution
  - part of it can be traded off, if not needed, in change for further noise reduction
- Reduced contamination by land and coastal targets (depending on their position relative to satellite track)
- Individual echoes — allows editing out affected echoes or Doppler bins

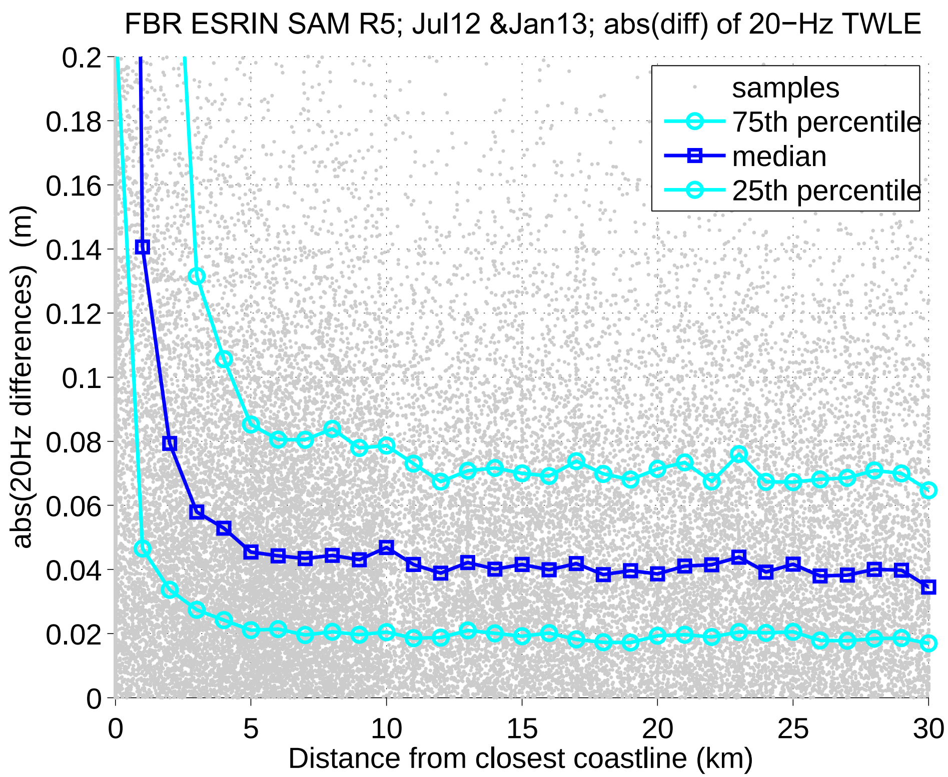
Cryosat-2 the first SAR altimeter in orbit

Assessing SAR mode performance in the coastal zone



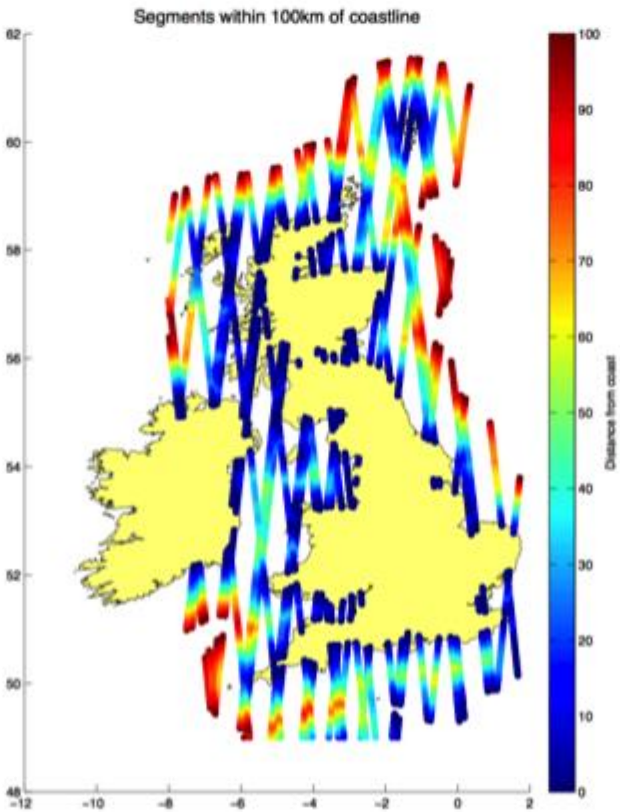
Assessment around the UK coast



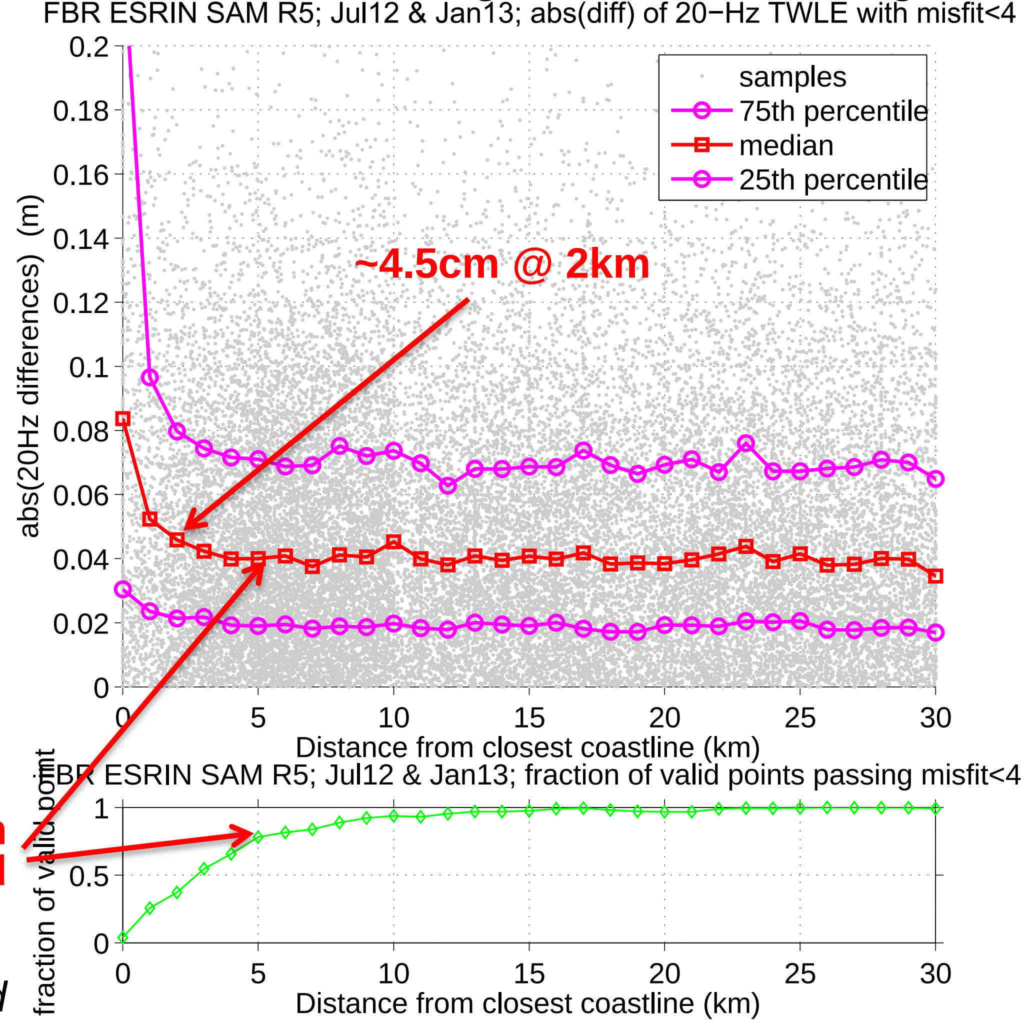


CP4O - CryoSat Plus for Oceans Project
C2 data from SAMOSA processor, provided by S. Dinardo, ESA/ESRIN

Assessment around the UK coast



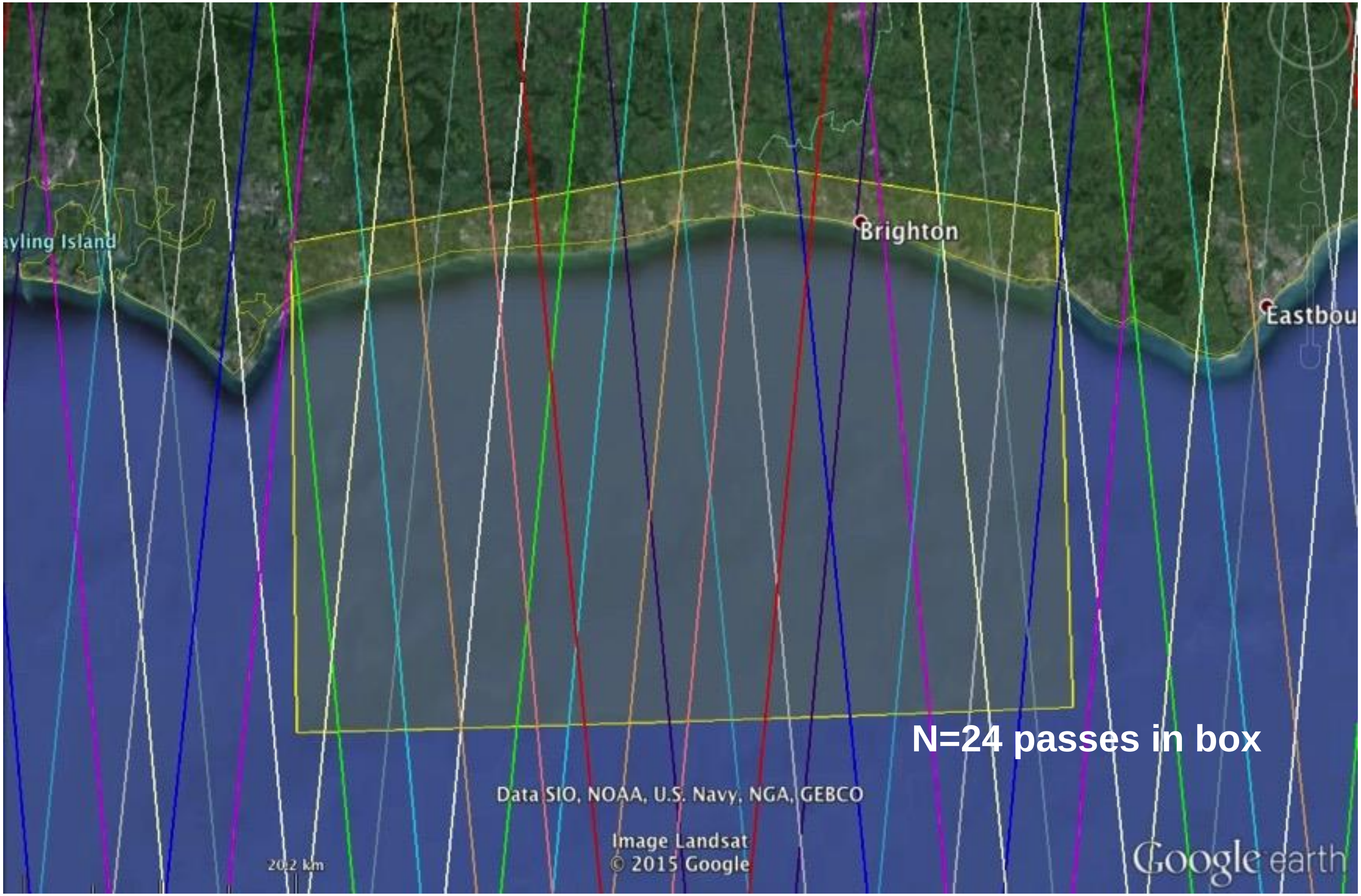
With additional screening based on retracking misfit



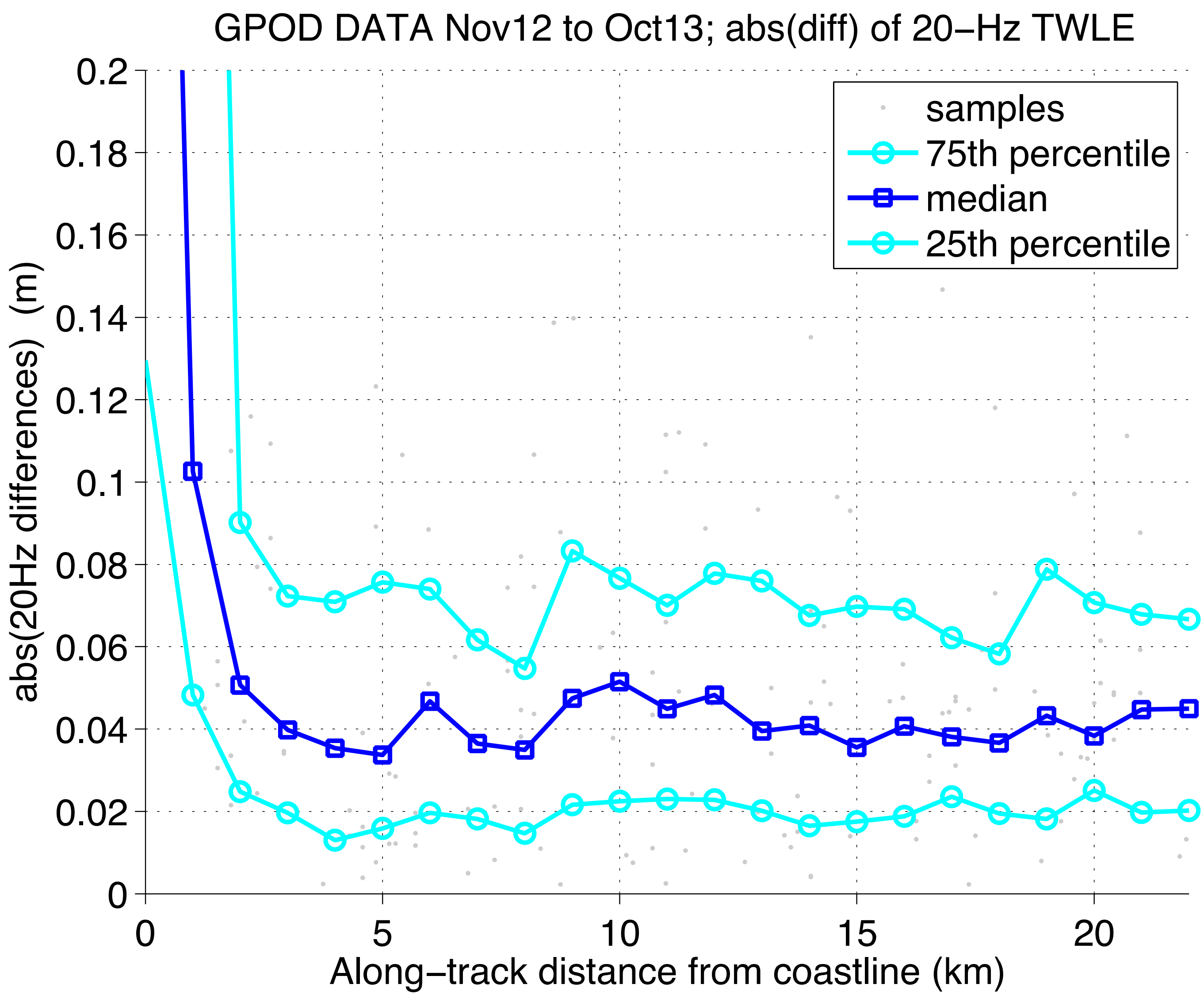
~4.0cm @ 5km
with ~80% valid

CP4O - CryoSat Plus for Oceans Project
C2 data from SAMOSA processor, provided by S. Dinardo, ESA/ESRIN

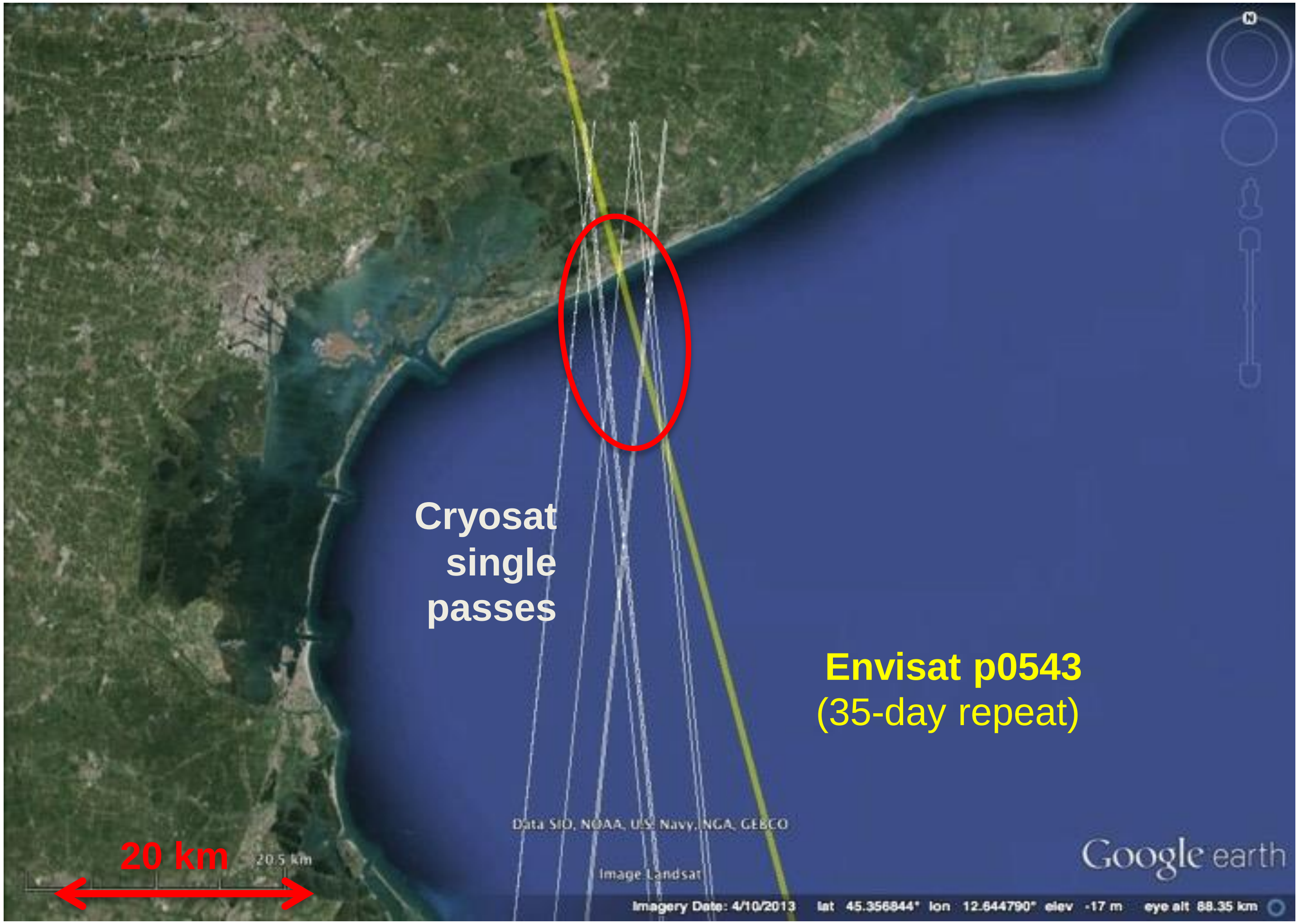
A good case study: Brighton Box



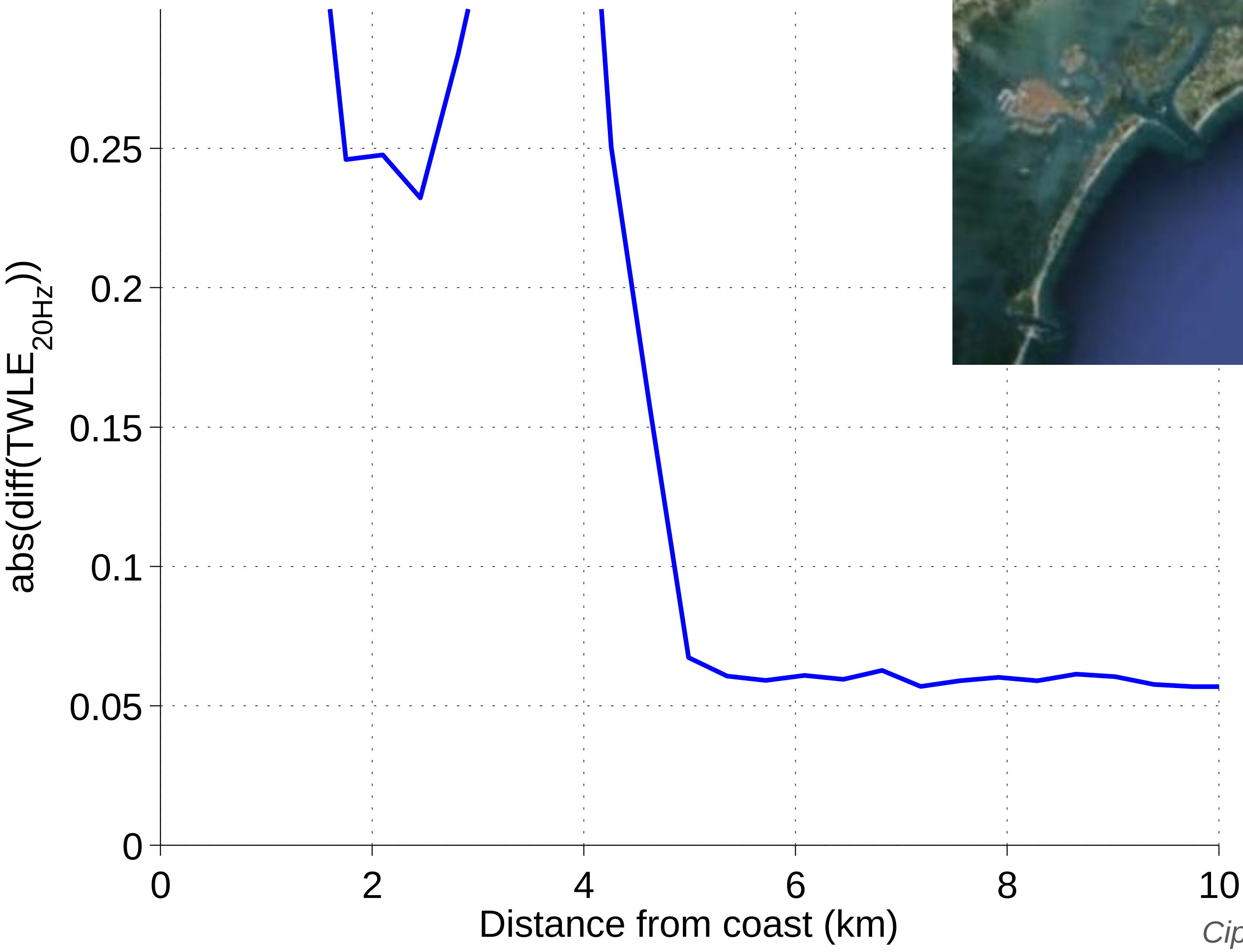
GPOD on Brighton Box vs along-track d

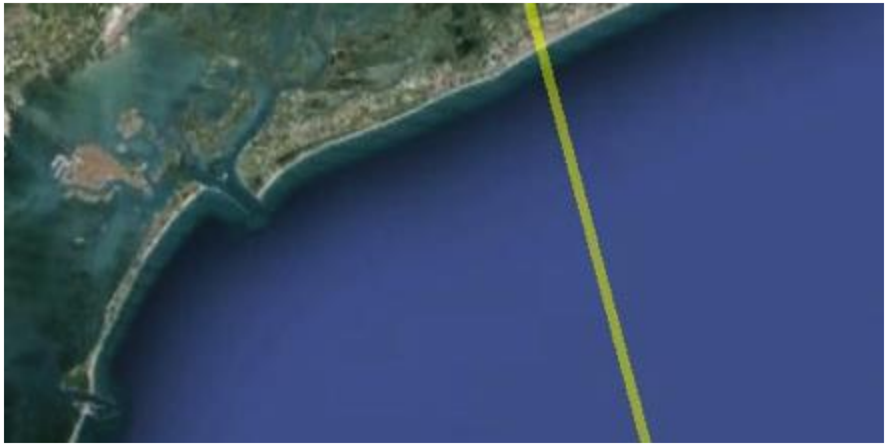


Another good case study



Another good case study

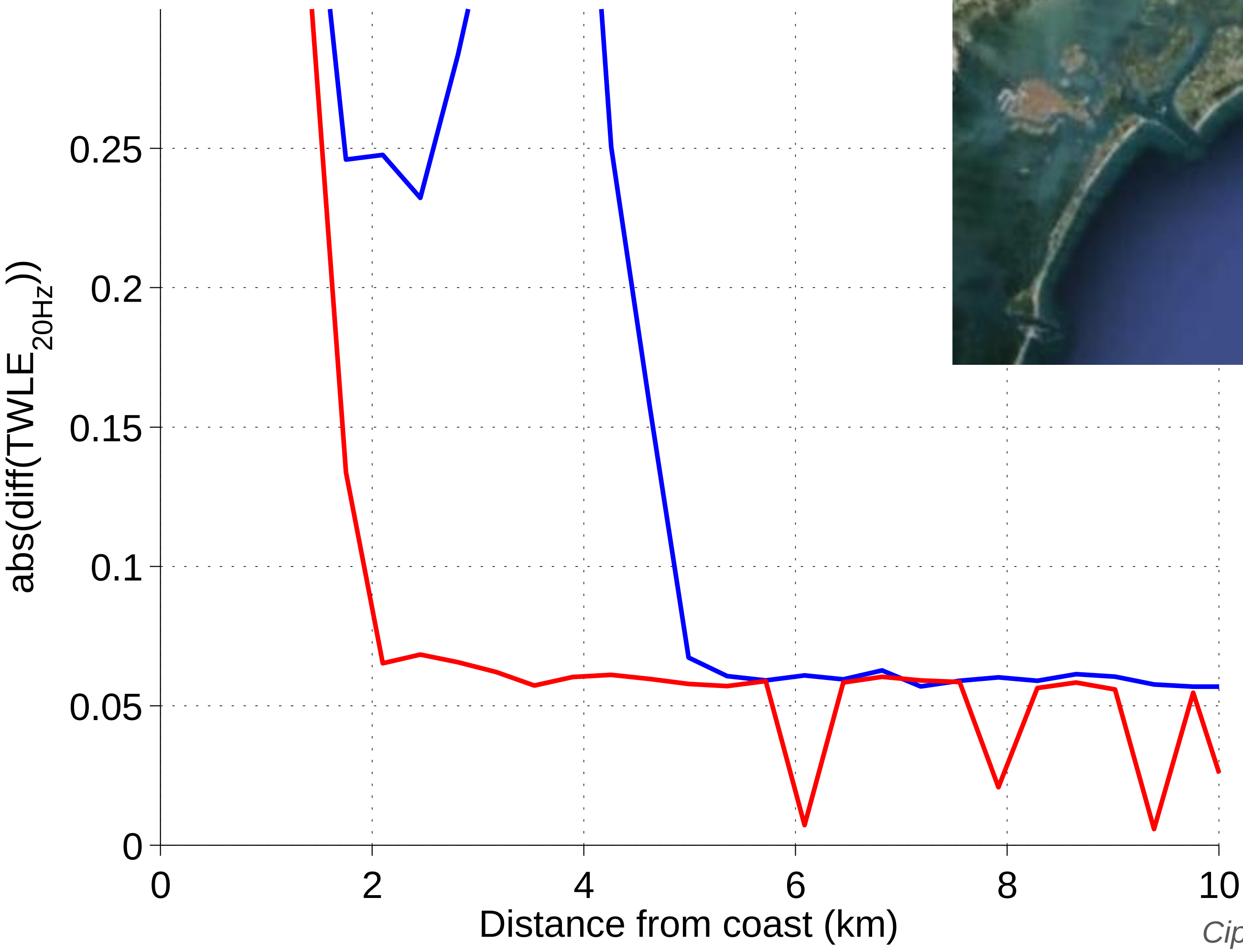


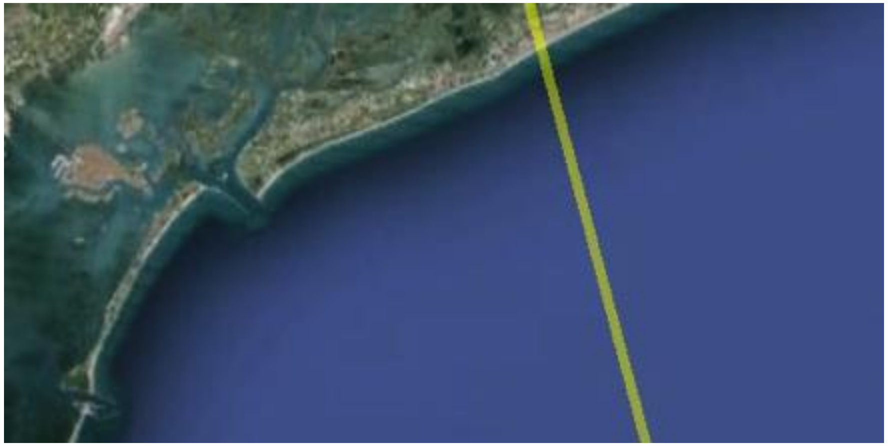


Envisat p0543 SGDR (median of 76 passes)

Cipollini, Passaro & Vignudelli, paper in prep.

Another good case study



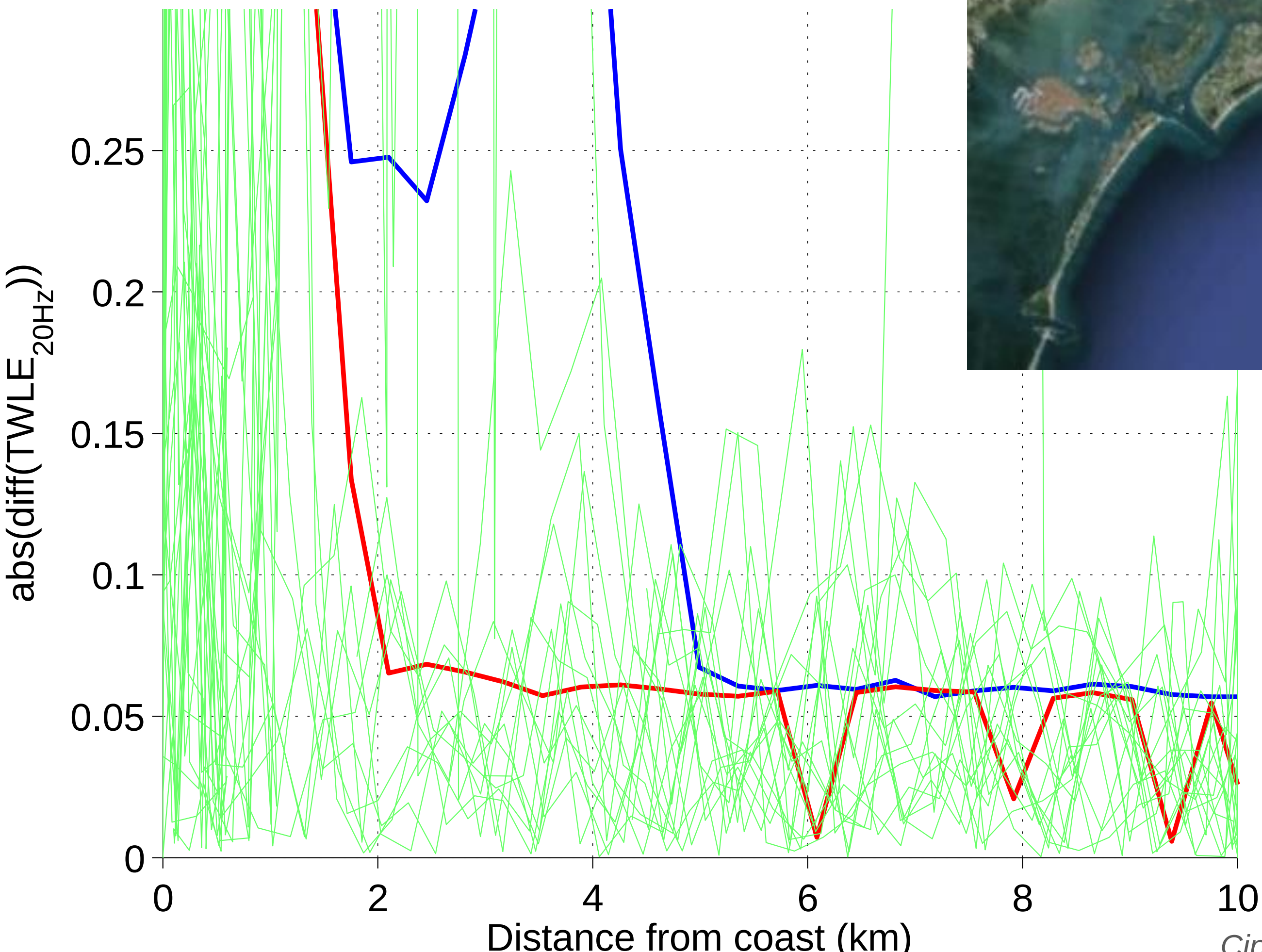


Envisat p0543 SGDR (median of 76 passes)

Envisat p0543 ALES (median of 76 passes)

Cipollini, Passaro & Vignudelli, paper in prep.

Another good case study



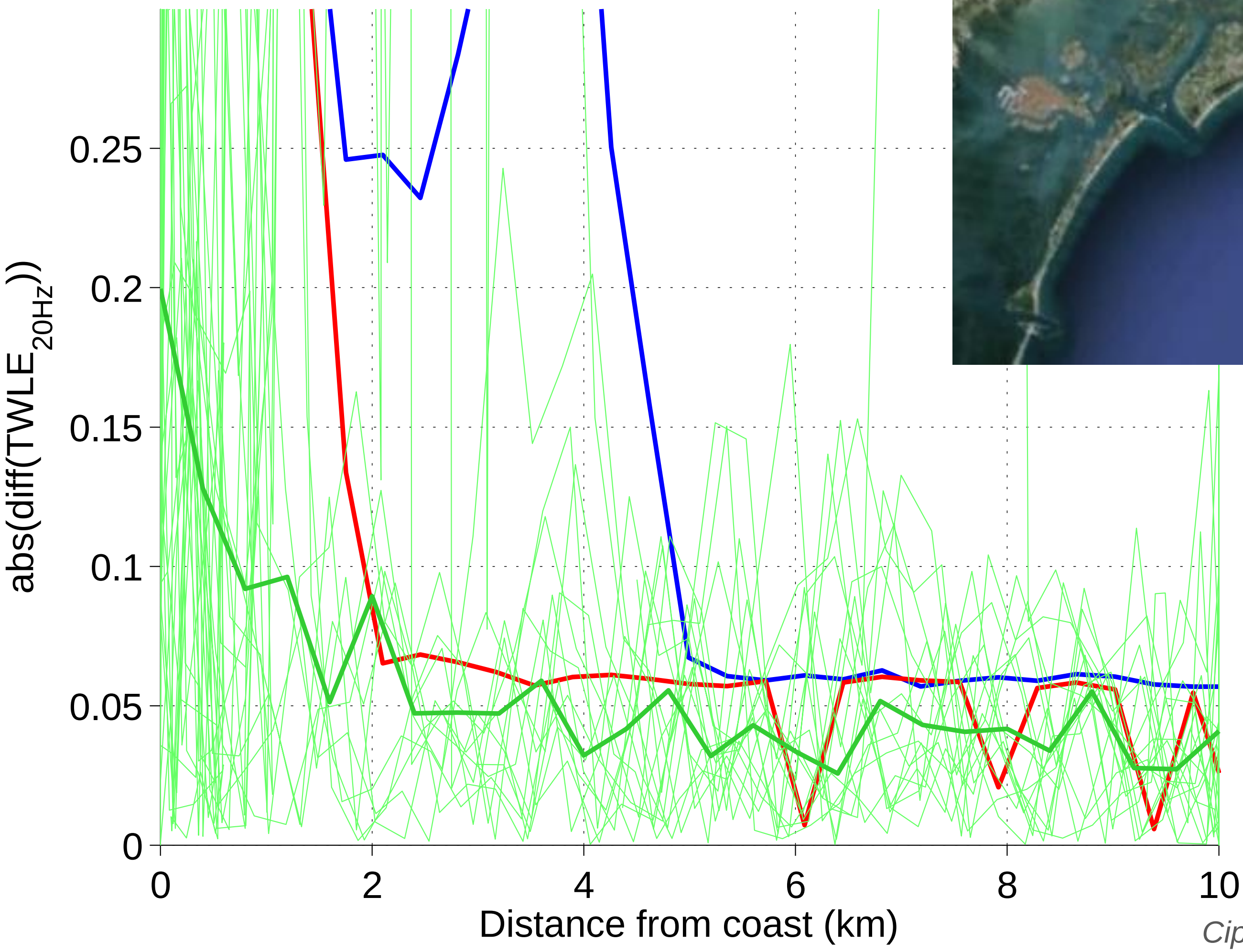
Envisat p0543 SGDR (median of 76 passes)

Envisat p0543 ALES (median of 76 passes)

CryoSat–2 SAMOSA (single passes)

Cipollini, Passaro & Vignudelli, paper in prep.

Another good case study



Envisat p0543 SGDR (median of 76 passes)

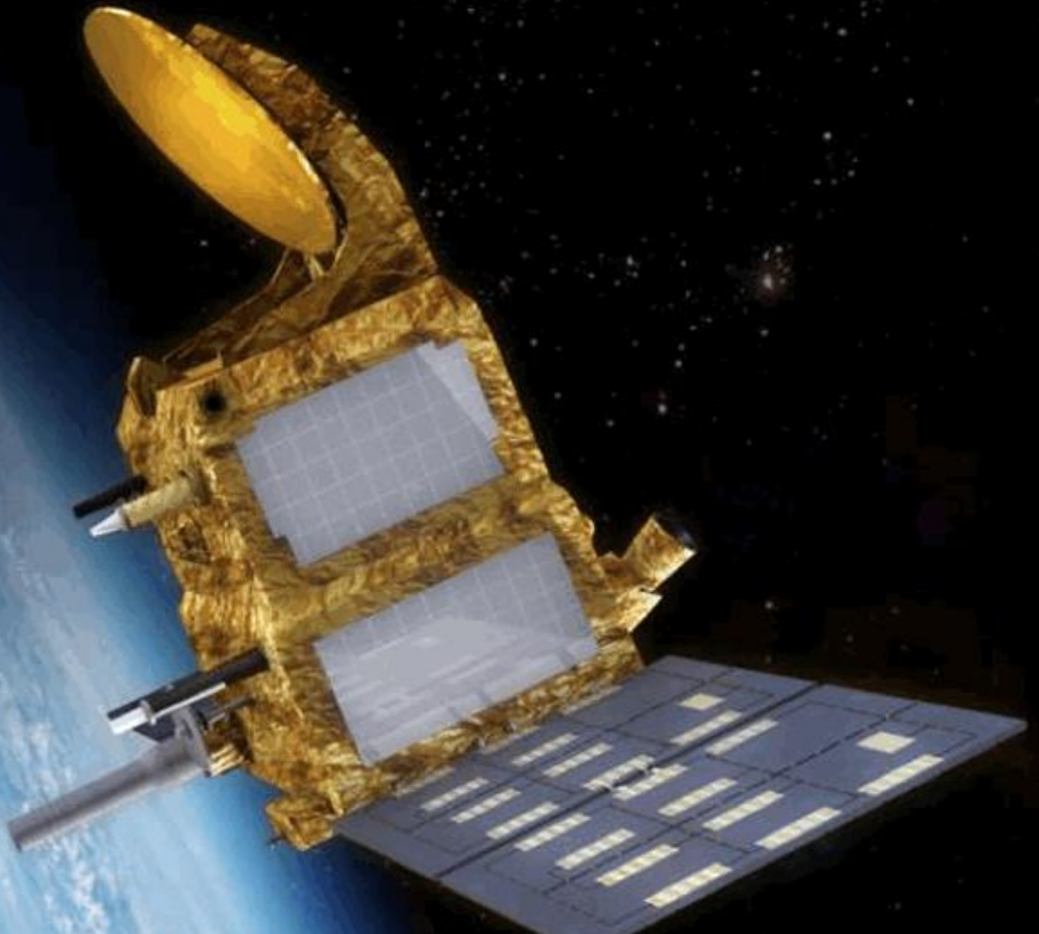
Envisat p0543 ALES (median of 76 passes)

CryoSat–2 SAMOSA (single passes)

CryoSat–2 SAMOSA (median of 11 passes)

Cipollini, Passaro & Vignudelli, paper in prep.

Altimetry in Ka-band: AltiKa

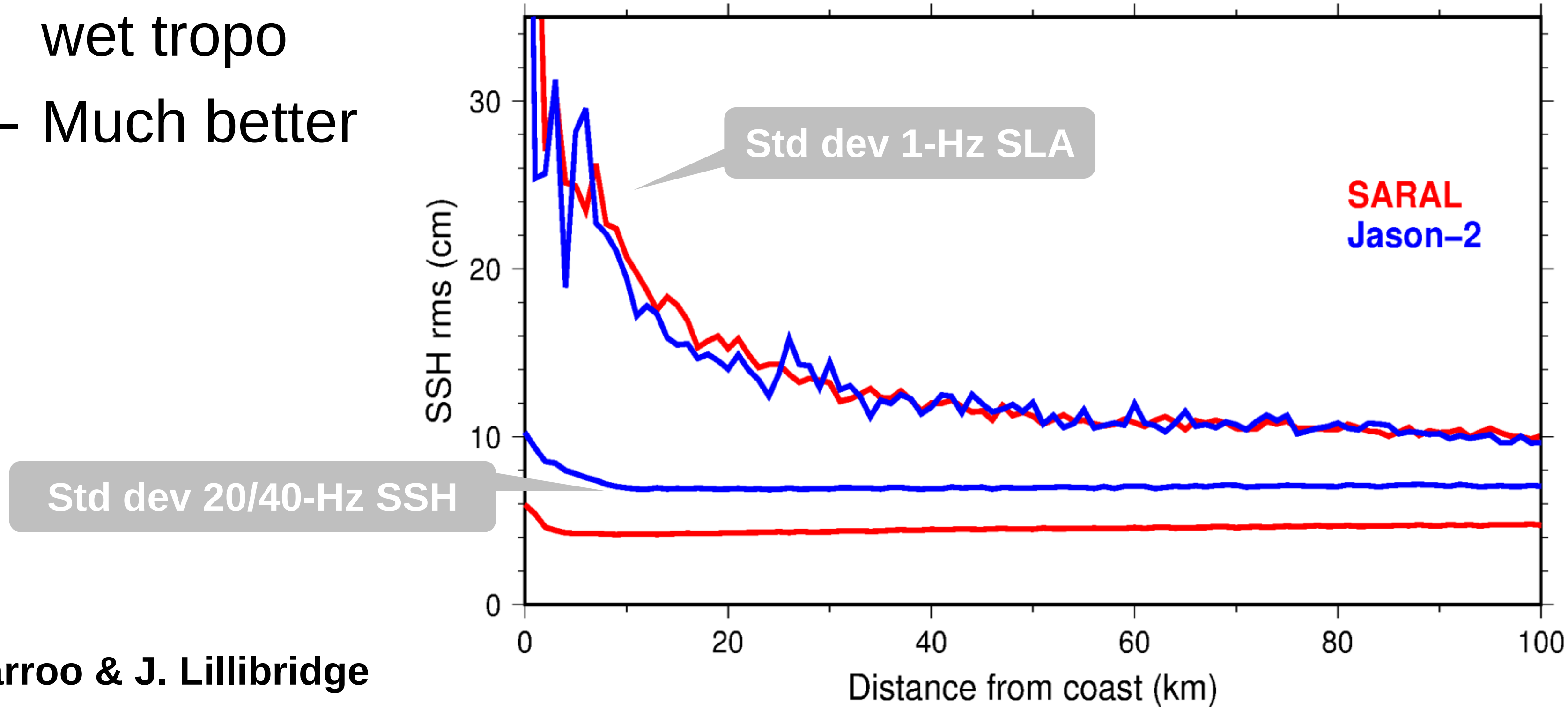


Ka-band much shorter wavelength than conventional Ku → higher precision (~8mm), smaller footprint (~2km), more affected by rain

SARAL/AltiKa (35.75 Ghz) launched Feb 2013 by CNES/ISRO -- **works very well**

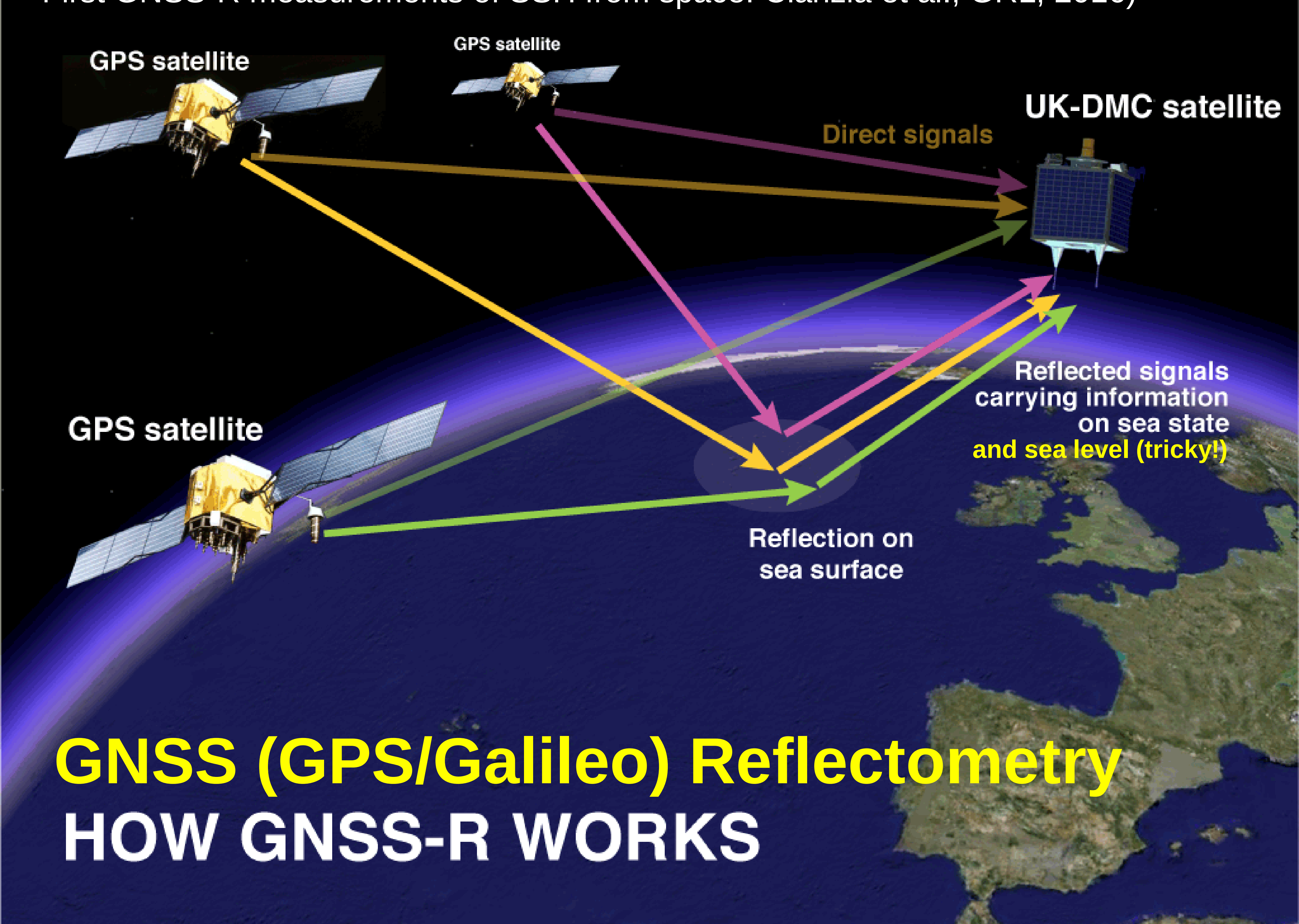
Sea level anomaly near the coast with AltiKa

- Std dev of 20/40-Hz SSH
  - Much lower for SARAL, particularly nearing coast
- Std dev of 1-Hz SLA
  - Now with ECMWF wet tropo
  - Much better

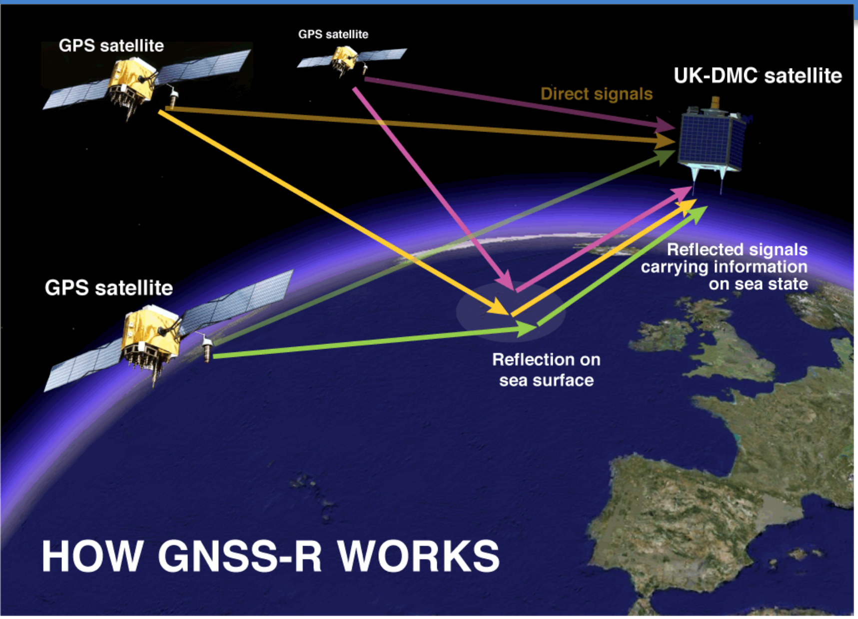


R. Scharroo & J. Lillibridge

First GNSS-R measurements of SSH from space: Clarizia et al., GRL, 2016)



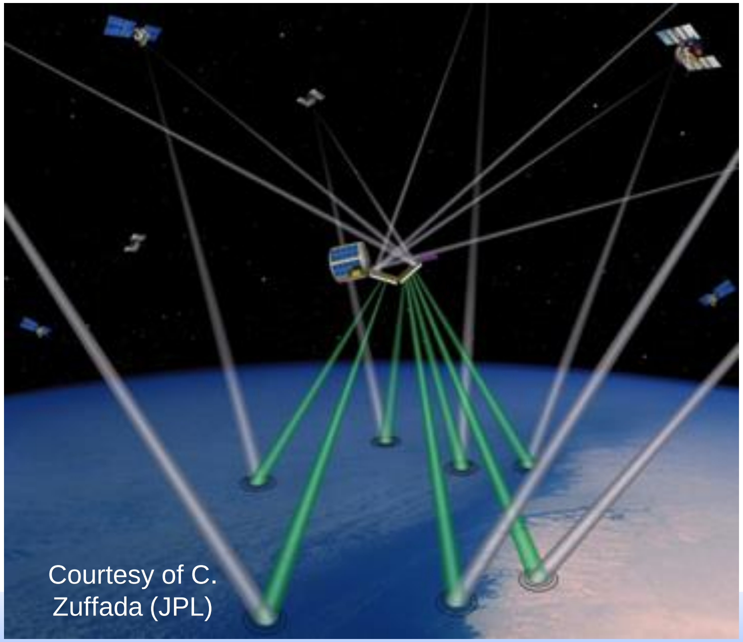
Global Navigation Satellite System-Reflectometry (GNSS-R



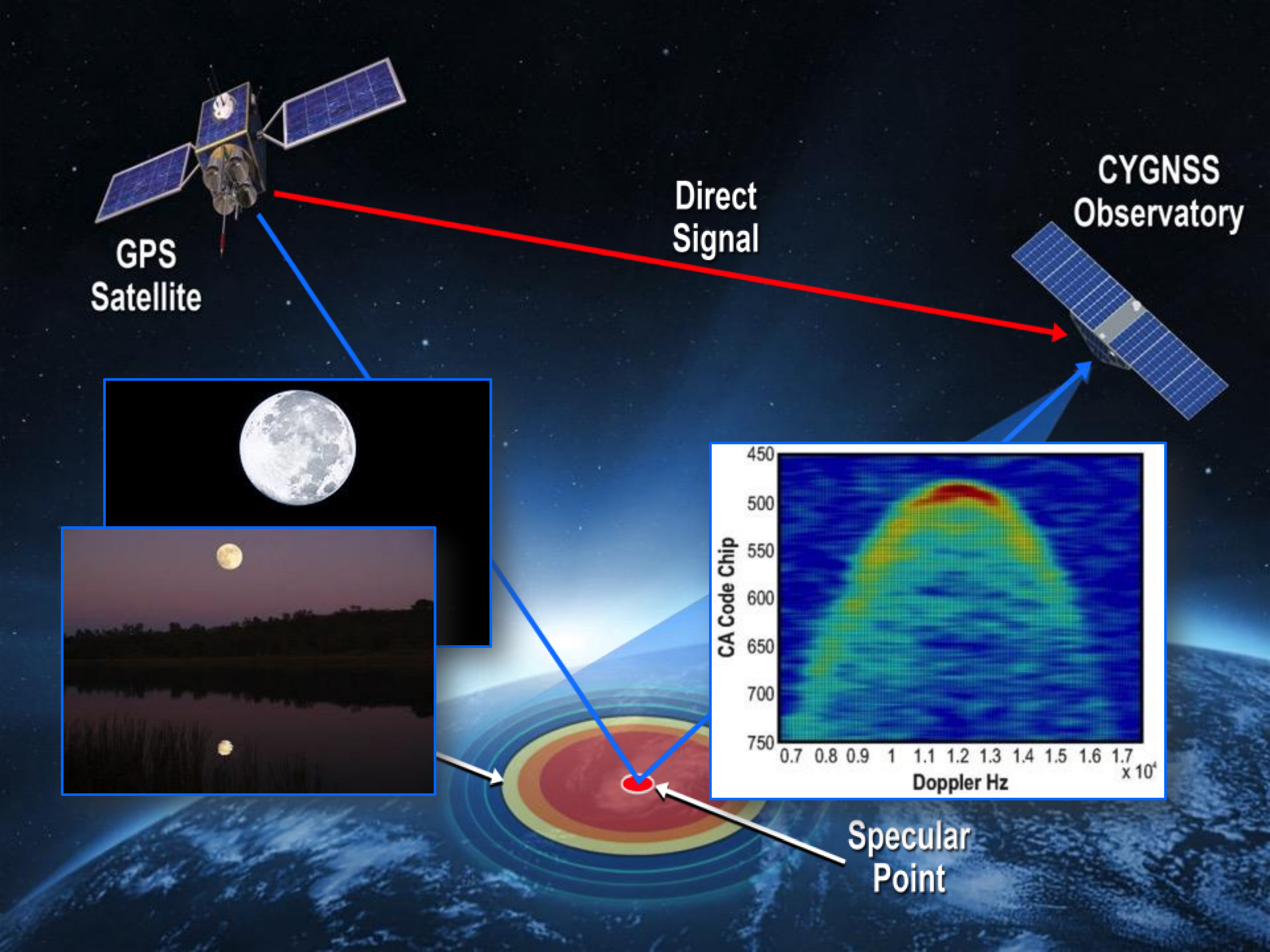
- GNSS-R exploits **signals of opportunity** from navigation constellations (i.e. GPS, Glonass, Galileo etc.)

- The **time delay**, **amplitude** and **shape** of the reflected signal are used to estimate **waves/wind speed, sea surface height, soil moisture, sea-ice…**

- Multistatic Radar System **with many pros:**
    - Multiple, simultaneous measurements
    - Dense spatial/ rapid temporal coverage
    - Leverages existing GNSS signals
    - Growing number of GNSS transmitters
    - Transmitters operate at L-band: all weather
    - Modified, lightweight, cheap and low-power GPS Receivers
    - Good characteristics for a constellation!



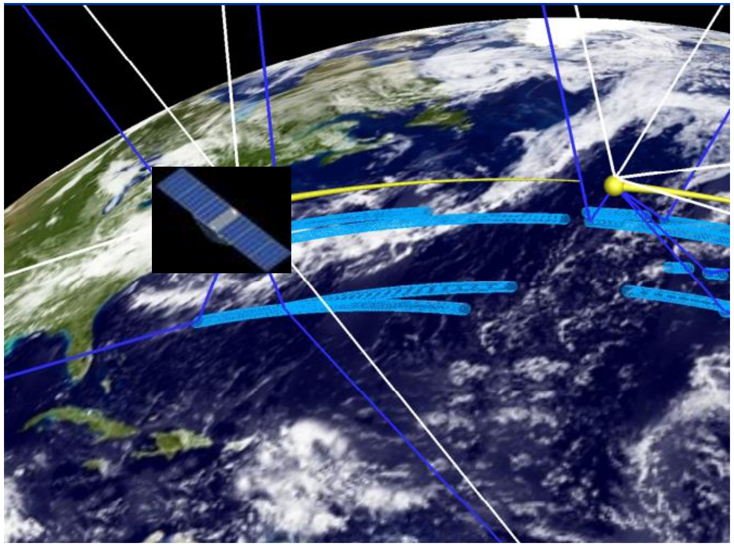
Courtesy of C. Zuffada (JPL)

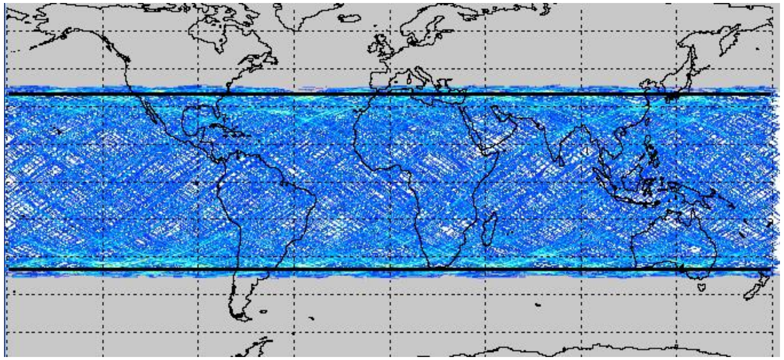

GPS Satellite
Direct Signal
CYGNSS Observatory
450
500
550
600
650
700
750
CA Code Chip
0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7
x 10⁴
Doppler Hz
Specular Point

CYclone Global Navigation Satellite System (CYGNSS)

A constellation of 8 micro satellites for the study of the inner core of tropical cyclones (TC)

- Selected by NASA in EV-2 competition
- Scheduled for **launch on Nov. 21, 2016**
- 8 LEO microsatellites at 500 km altitude, 35 deg inclination
- One sat will collect 4 simultaneous DDMs per second from 4 different locations;
- CYGNSS objectives:
  - Measure ocean surface wind speed in all precipitating conditions, including those experienced in the TC eyewall
  - Measure ocean surface wind speed in the TC inner core with sufficient frequency to resolve genesis and rapid intensification

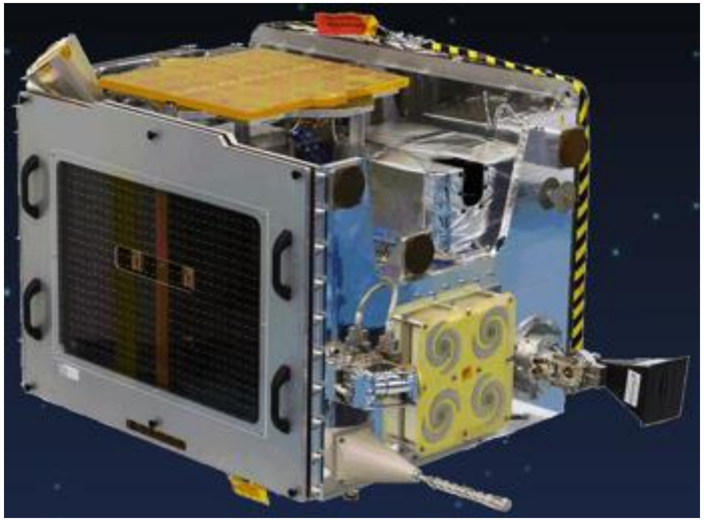


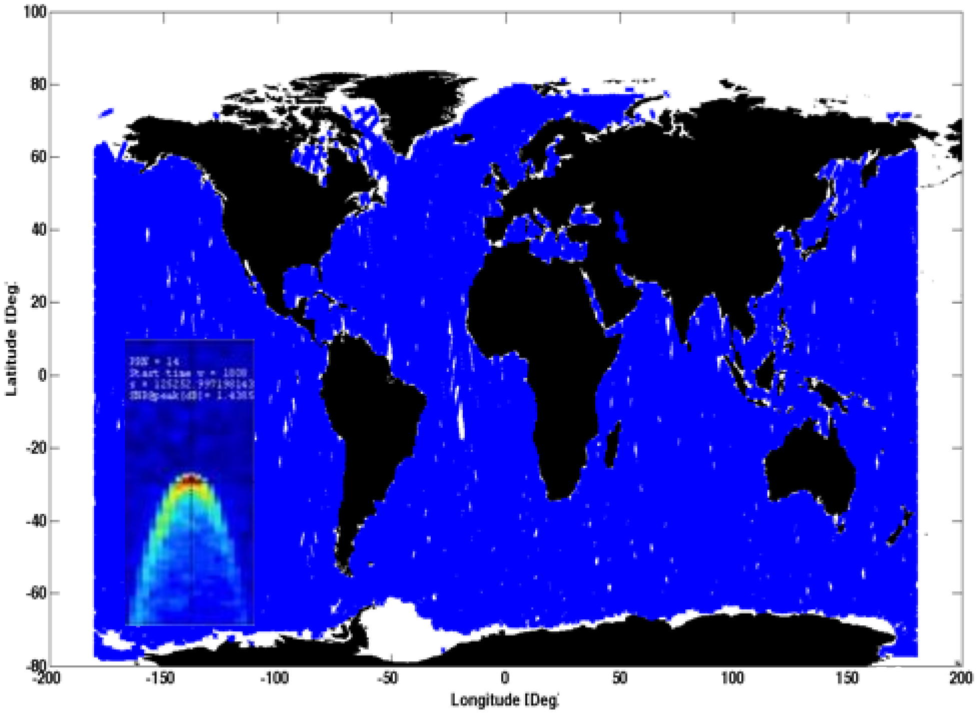


CYGNSS 24-hr coverage

UK SSTL TechDemoSat-1 (TDS-1)

- **SSTL GPS-Reflectometry Experiment (2014 – present)**
  - Altitude of 635 km, collecting data for 2 days out of an 8-day cycle (more than 1 million DDMs so far)
  - DDMs generated onboard, wide geographical coverage
  - Data acquired from September 2014 to April 2015 are available to users at ***www.merrbys.org***

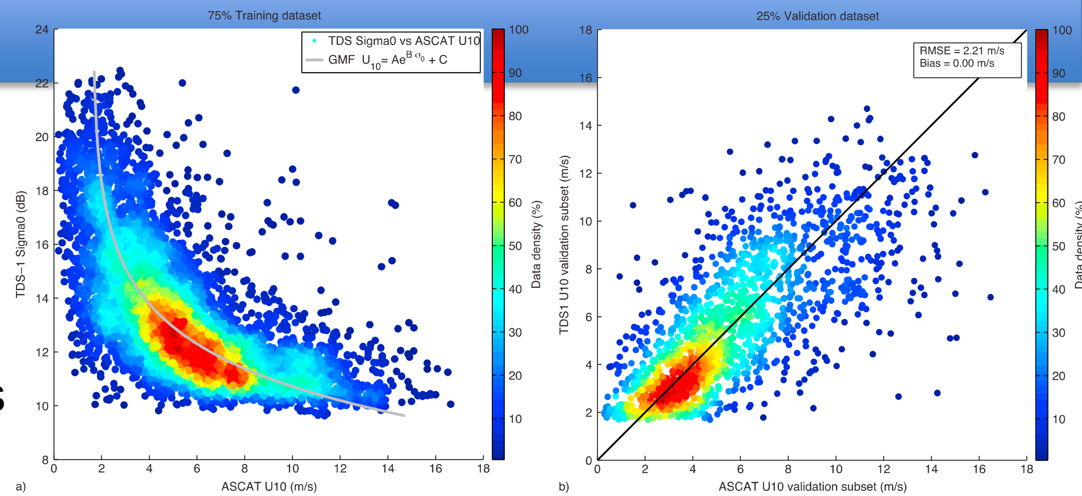


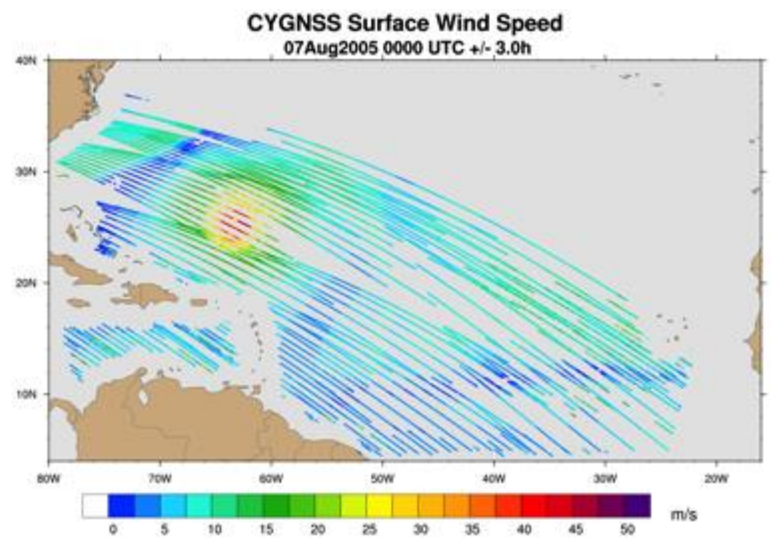


Wind Speed Retrieval

- Wind Speed estimation based on the use of DDM observables and the development of a Geophysical Model Function (GMF);
- Wind Speed uncertainty is ~ 2 m/s from UK-DMC data (*Gleason, 2013, Clarizia et al., 2014*) and from TechDemoSat-1 data (*Foti et al., 2015*);

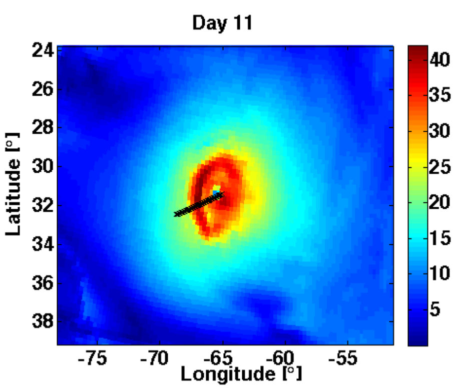
From Foti, Gommenginger et al., 2015

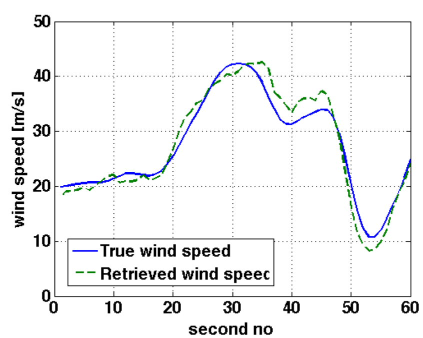




Predicted wind speed uncertainty for CYGNSS is 2 m/s or 10% of measured wind (*Clarizia & Ruf, 2016*);

Example of true vs retrieved wind speed for CYGNSS Transect crossing the hurricane eye (from Clarizia and Ruf, 2016)





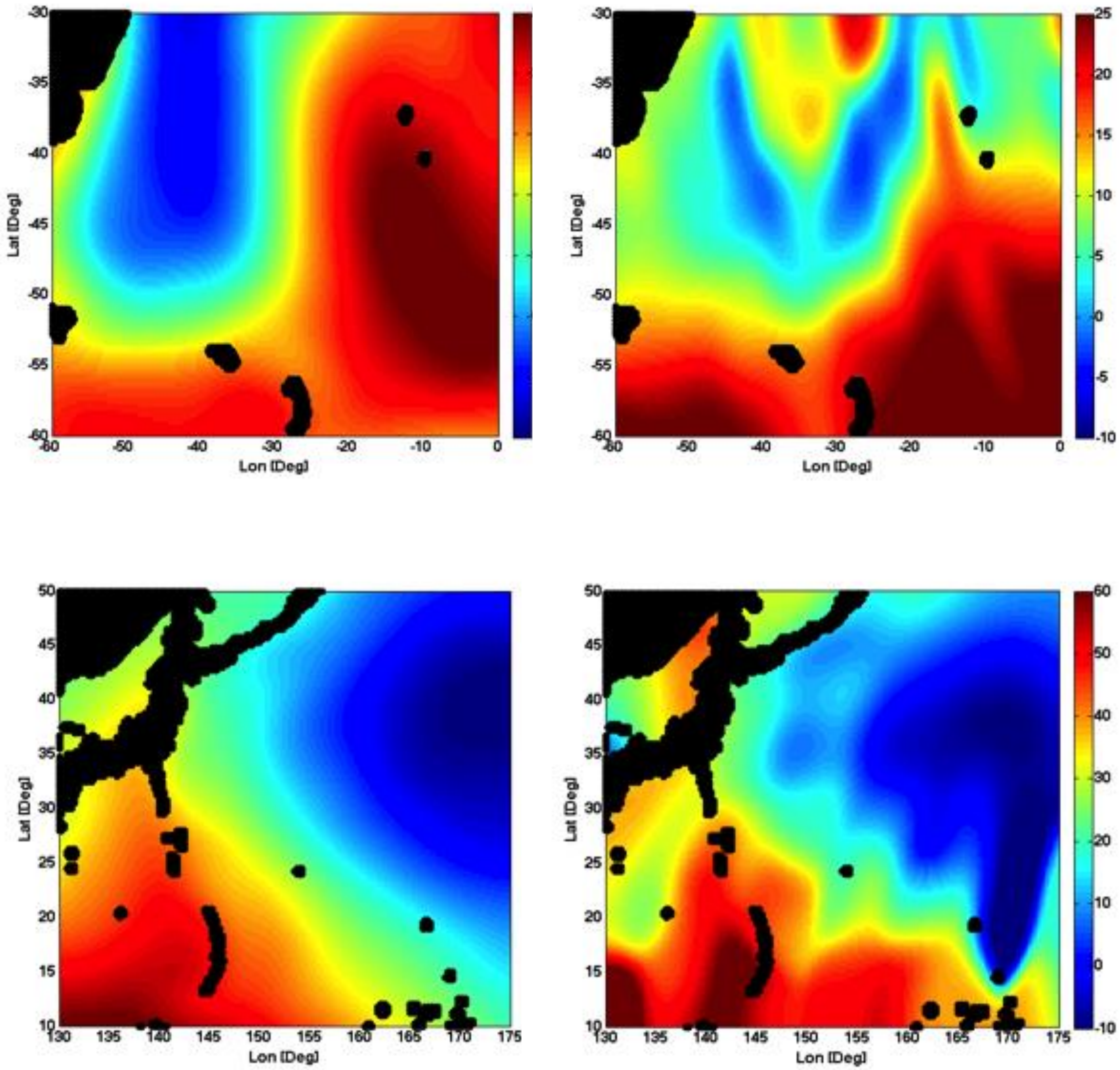
Sea Surface Height Retrieval

Ground Truth MSSH

Smoothed SSH estimated from TDS-1

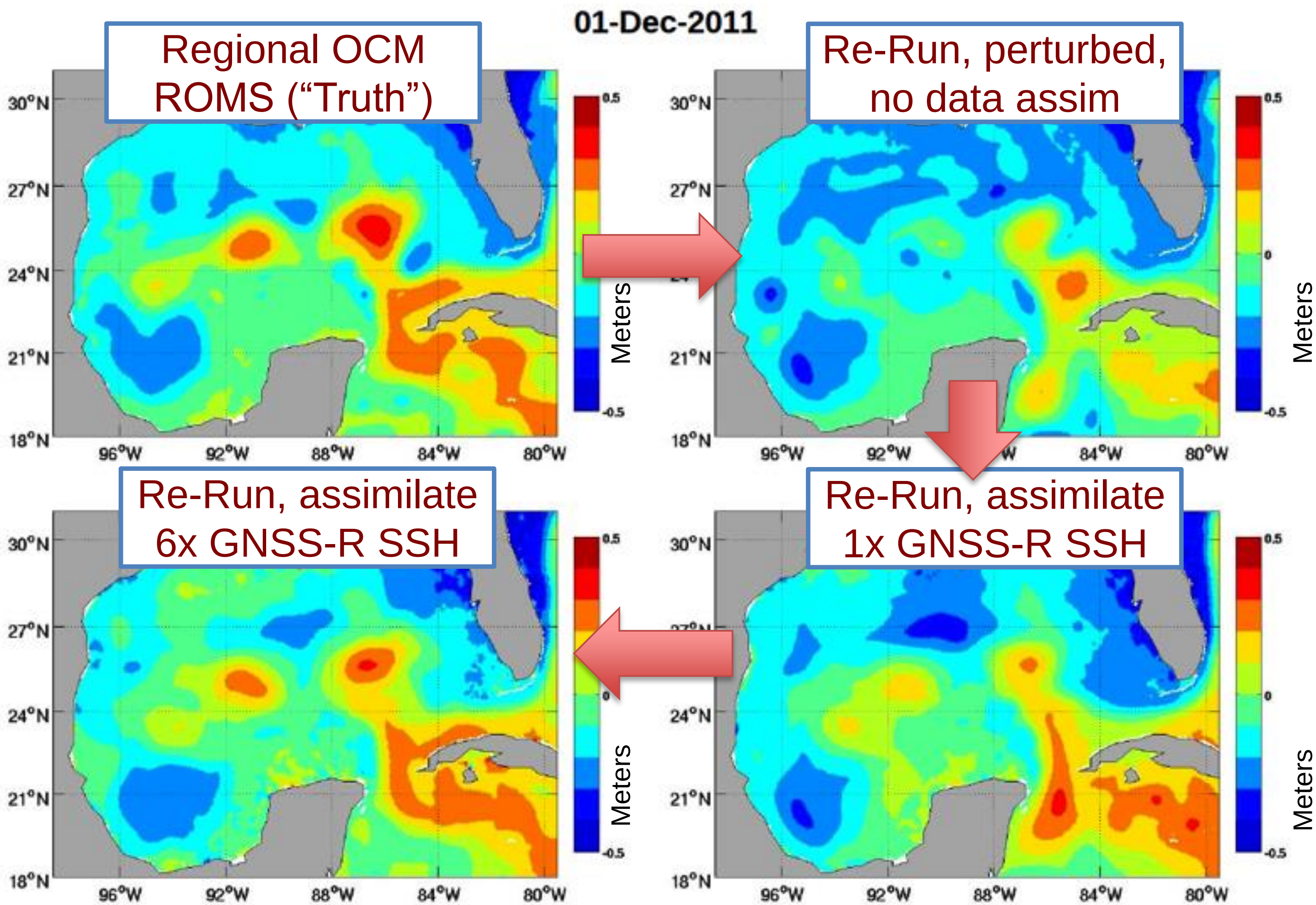
South Atlantic

North Pacific



RMS difference between TDS-1 and DTU10 MSS is 8.1 m for the South Atlantic Region and 7.4 m for the North Pacific Region *(Clarizia et al., 2016)*

Using SSH info from GNSS-R



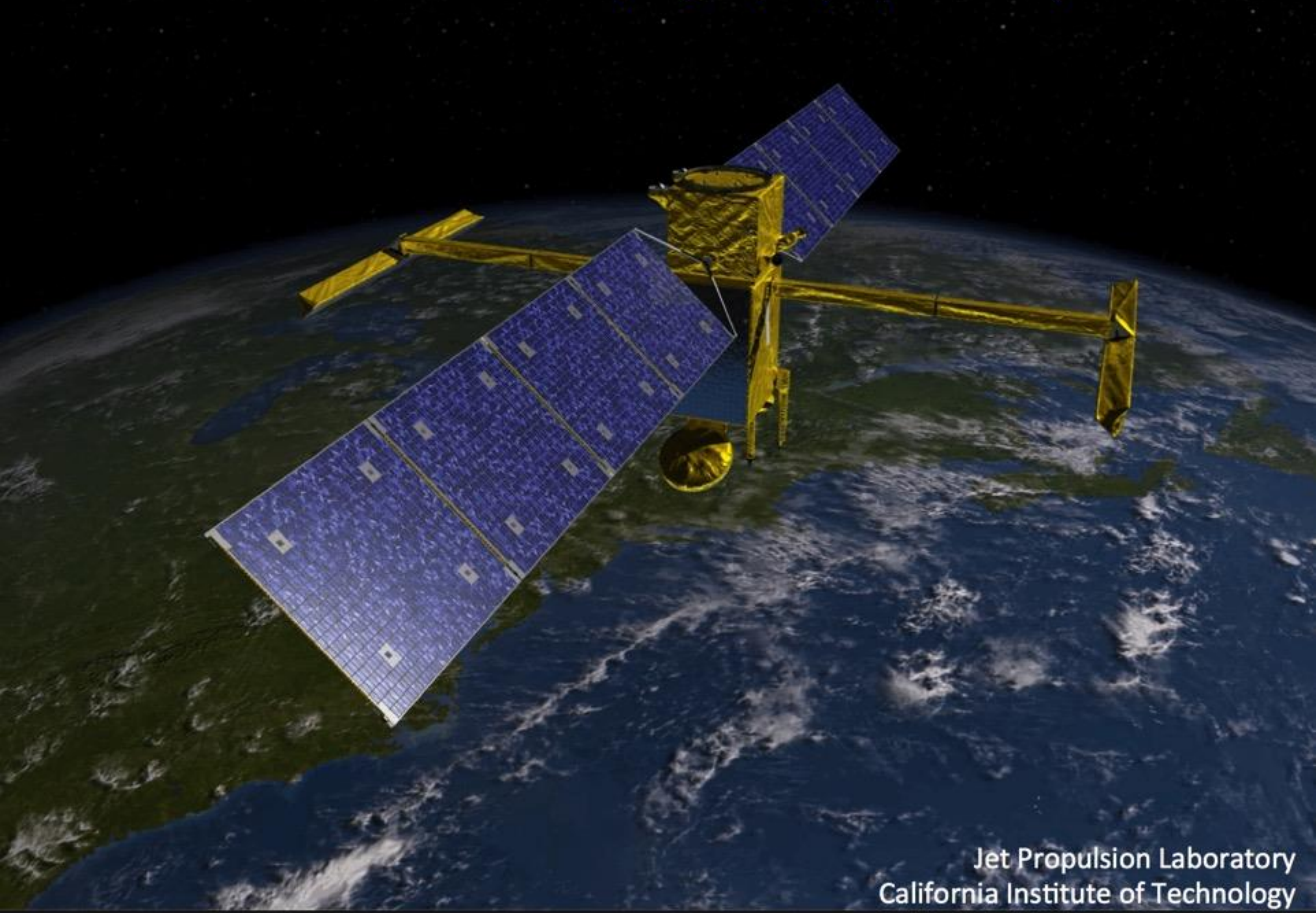
*OSSE experiment with 1 day of GNSS-R data, with 50 cm noise on derived heights - **Courtesy of JPL***

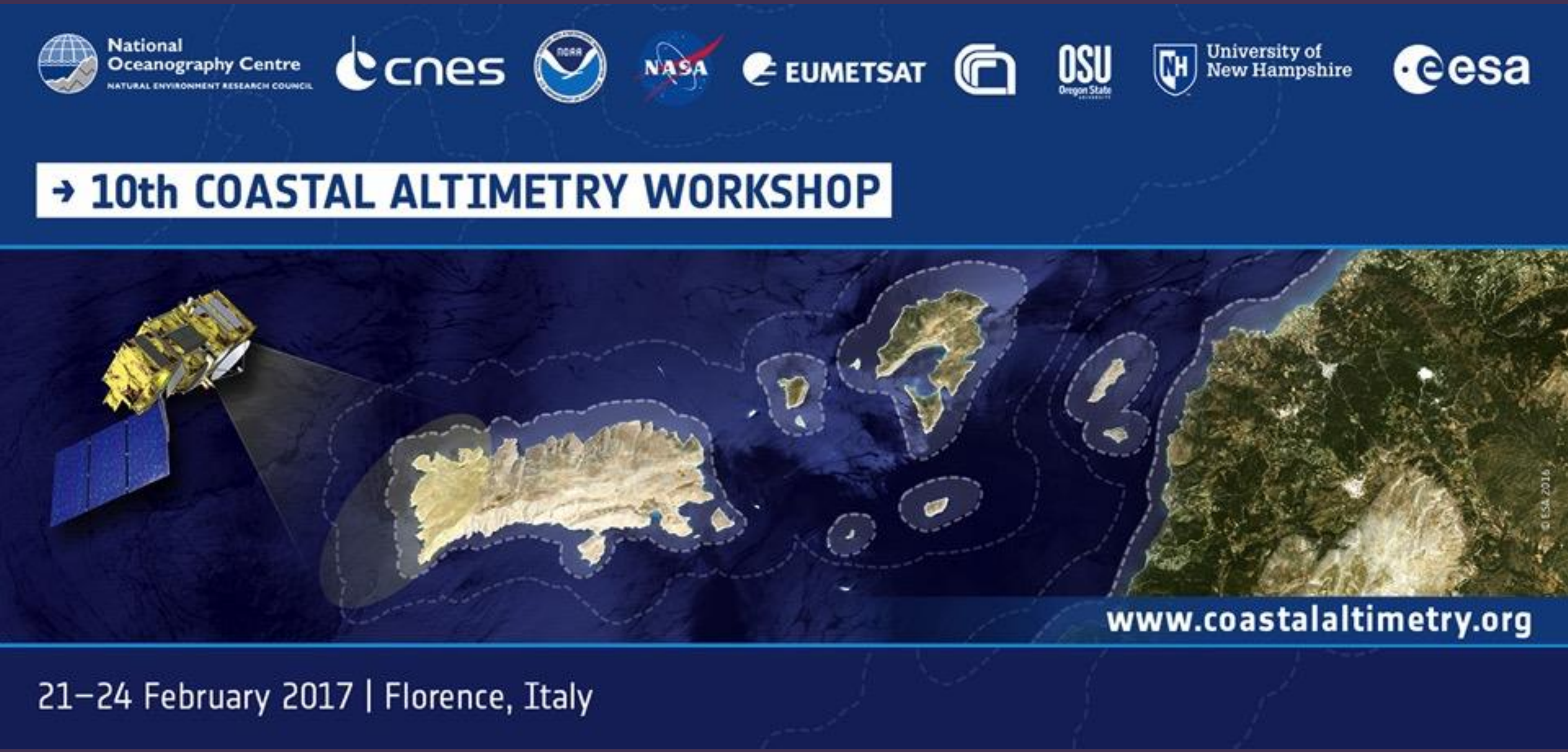
→ GNSS-R can help improve mesoscale mapping

Take home message

- Sampling of the ocean from altimetry is improving steadily:
  - we get better data – in **precision and resolution** – from the technical evolution (Ka-band, SAR altimetry)
  - we are extending the domain of application of altimetry and conquering the coastal zone (the “1-km challenge”)
- The use of GNSS-R for altimetry (in addition to scatterometry) can dramatically improve the spatio-temporal sampling
- **the combination of the two techniques prepares the community to ingest high-resolution data from SWOT**

Surface Water Ocean Topography (SWOT*) Mission





cipo@noc.ac.uk