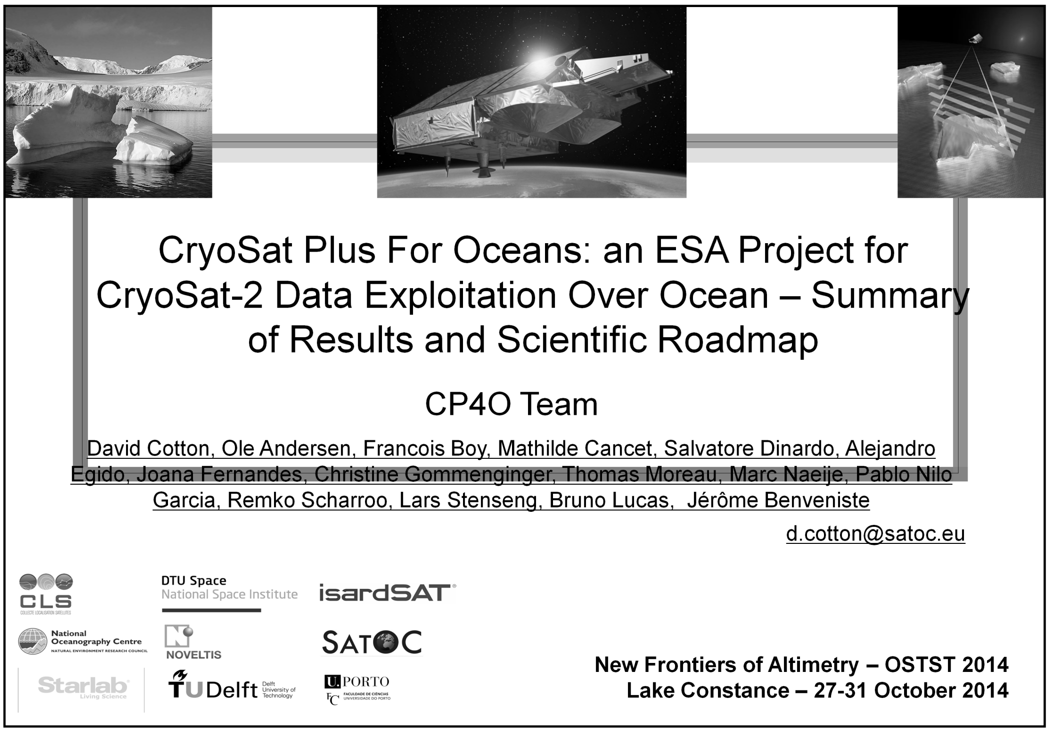

I'm going to give you a quick overview of the Cryosat Plus for Oceans – CP4O - project, and summarise the results.

This will just be a high level summary, as other presentations this week will provide details on individual aspects

CP4O is a project initiated in response to an ITT issued by ESA under its Support to Science Element programme. It was supported financially by ESA and by CNES. There were 9 partners as listed,

CryoSat Plus for Oceans (CP4O)

Objectives:

- Build a sound scientific basis for new applications of CryoSat-2 data over the *open ocean*, *polar ocean*, *coastal seas* and for *sea-floor mapping*.
- Generate and evaluate new methods and products that will enable the full exploitation of the capabilities of the CryoSat-2 SIRAL altimeter, and extend their application beyond the initial mission objectives.
- Ensure that the scientific return of the CryoSat-2 mission is maximised. Preparation for Sentinel-3, Jason C-S.

Themes:

- **Open Ocean:** (sub)meso-scale, SAR retrackers, RDSAR processing.
- **Coastal Ocean:** Coastal features, land contamination, SARIN mode.
- **Polar Ocean:** Sea-ice effects, new mean sea surface, MDT models.
- **Sea Floor Topography:** Can SAR data resolve new features?
- **Geophysical Corrections:** Wet Troposphere, Ionosphere, regional tides

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2

Basic premise for CP4O is that Cryosat-2 is the first spaceborne altimeter which offers SAR mode.

Primary mission for CryoSat was the Cryosphere – but of course SAR altimetry offers great potential for providing enhanced ocean measurements

The purpose of CP4O was to look at ocean applications of Cryosat data and to (first three bullets)

Work divided into Five main scientific themes

Open Ocean

Coastal Ocean

Polar Ocean:

Geophysical Corrections

CP4O Project Outline

1. SAR Altimetry “State of the Art” Review
2. CP4O Products: Development and Validation
   (RDSAR, SAR, SARin, geophysical corrections)
3. Impact Assessment
4. Scientific Road Map and Recommendations

CP4O project had four main aspects:

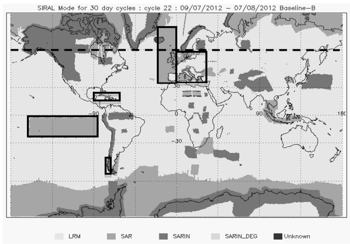
State of the Art Scientific and Technical Review – which included a thorough literature Review and a SAR Altimetry Expert Group meeting at Southampton in June 2013. This has been written up as a stand alone document which is available through the project website

Development and Validation of CP4O products

Impact Assessment – What benefits / improvements do the new products offer

Scientific Road Map and Recommendations

CryoSat Products Development and Validation



CP4O Data Sets Coverage

	Product	Who?	Coverage
1	**RDSAR** for **Open Ocean**	RADS (TU Delft), CPP (CNES/CLS)	Pac. & N Atl. SAR boxes, July 2012, Jan 2013
2	**SAR** for **Open Ocean**	SAMOSA (Starlab, ESA), CPP (CNES,CLS)	Pac. & N Atl. SAR boxes, July 2012, Jan 2013
3	**SAR** for **Coastal Ocean**	SAMOSA (Starlab, ESA), CPP (CNES,CLS)	NE Atlantic SAR boxes July 2012, Jan 2013
4	**SARIn** for **Coastal Ocean**	isardSAT	Cuba, Chilean Coast (few selected orbits)
5	**SAR** for **Polar Ocean**	DTU Space	Arctic, Lats > 60° N July 2010->
6	**SAR** for **Sea Floor** Mapping	DTU Space	Pacific SAR Boxes: 1 x 369 day cycle, starting 01/10/2012
7	Improved **wet trop correction**	U Porto	Global, July 2012, Jan 2013
8	Improved **iono correction**	Noveltis	Med, Europe cont. shelf Jan 2011- Jan 2013
9	Improved **regional tides**	Noveltis	North East Atlantic (coastal) Jan 2011- Jan 2013

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So we'll skip straight to the main focus of the project, which was to generate higher level ocean products from Cryosat data, validate them, and then subject them to an independent assessment (by CLS).

Nine sets of products under the five scientific themes

RDSAR for open ocean

SAR for open and coastal ocean

SAR for Polar Ocean, and SAR for Sea Floor Mapping

And Geophysical Corrections: Wet Troposphere, Ionosphere and Regional Tide Models.

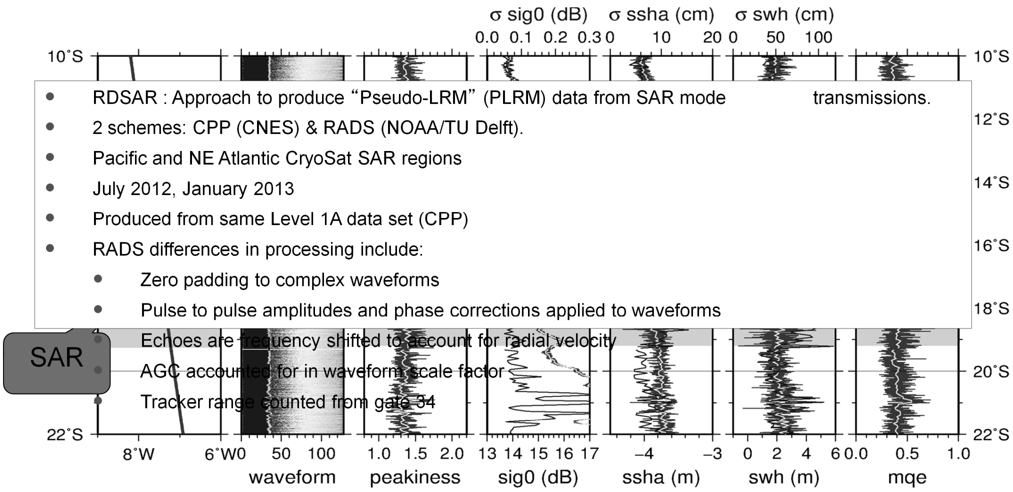
Who was responsible, and the coverage are given in the table and on the map.

The red boxes on the map, plus the area to the North of the dashed red line, show the areas we considered.

Products are available for download via ftp (details on the project website)

No time to go into detail.

CP4O Products - RDSAR



- RDSAR : Approach to produce "Pseudo-LRM" (PLRM) data from SAR mode transmissions.
- 2 schemes: CPP (CNES) & RADS (NOAA/TU Delft).
- Pacific and NE Atlantic CryoSat SAR regions
- July 2012, January 2013
- Produced from same Level 1A data set (CPP)
- RADS differences in processing include:
  - Zero padding to complex waveforms
  - Pulse to pulse amplitudes and phase corrections applied to waveforms
  - Echoes are frequency shifted to account for radial velocity
  - AGC accounted for in waveform scale factor
  - Tracker range counted from gate 34

RDSAR

Processing SAR mode data to generate an LRM like - or Pseudo LRM - product

Looked at RADS and CPP RDSAR product

Pacific and NE Atlantic CryoSat SAR regions

July 2012, January 2013

Produced from same Level 1A data set (CPP) – CPP Cryosat Processing Prototype

Some differences in the processing scheme listed

This figure from RADS RDSAR product close to St Helena. Focus on 5 and 6 figures from left. Good continuity across mode change boundary but note higher "noise" in SSH and SWH RDSAR, though the retrieved parameters are continuous and consistent.

Higher 1HZ standard deviation in RDSAR is a consequence of transmission pulse timing scheme in SAR mode – which has a burst of transmission, then a gap, then the next burst

Global stats also show consistency. Don't have time to go through CLS analysis, but Thomas Moreau is making a separate presentation on their findings.

RDSAR Assessment

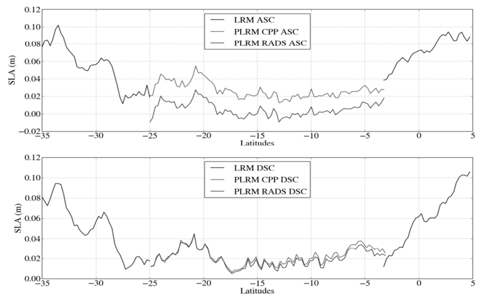
Findings of Independent Assessment being finalised, key points

- Seamless transition between LRM and PLRM data for SWH. Some steps in SLA in some tracks, some discrepancies between ascending descending tracks (figure below)
- 1Hz noise on RDSAR higher than the LRM.
- Time Tag bias differences to resolve.

Continuity of SLA from LRM – RDSAR – LRM

Ascending (top) and descending (bottom)

LRM (blue), RDSAR-RADS(red), RDSAR-CPP(green)



RDSAR assessment report still being finalised - main conclusions are:

Seamless transition for SWH, still some discrepancies in SLA between ascending and descending tracks (see figure below)

Larger value for 1 HZ std on RDSAR than LRM – can be reduced by along track averaging.

This assessment just being finalised.

There were still ongoing discussions around the CPP/RADS comparison last week, mainly to chase down some issues in time tag bias. Think there were signs of convergence.

CP4O SAR Open and Coastal Ocean Products

- Two approaches to model and re-track the SAR echo from CPP L1B: Numerical (CPP) and Analytical (SAMOSA).
- Data sets for SAR regions in NE Atlantic and Pacific: July 2012 and Jan 2013
- Along/cross off-nadir angles (star-tracker) input to retrackers
- Instrumental corrections: no timing-bias, no internal-path delay correction, constant bias applied to 20-Hz range and $\sigma 0$)
- Atm/Geo Corrections: same corrections, same MSS, same altitude

SAMOSA Model retracker	CPP CNES SAR retracker
Analytical retracker	*Numerical retracker*
3-parameters estimated (range, SWH, amplitude)	3-parameters estimated (range, SWH, amplitude)
SAMOSA 2: Full Analytical Model SAMOSA 3 (**Sentinel-3 DPM**): S2 simplified for computational efficiency SAMOSA 3+: "Enhanced" Sentinel-3	pre-computed multi-looked waveform models
Levenberg-Marquardt least square estimator	unweighted least square estimator (MLE3)
LUT applied to correct PTR approximations	No LUT

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Next set of products that were evaluated:

Open and Coastal SAR products: Data sets for two months in each of the CryoSat SAR regions in the open ocean in the Pacific and North East Atlantic

Two approaches to model and retrack SAR Level 1B waveforms: Numerical (CPP) and analytical (SAMOSA) – Latter is approach implemented in Sentinel-3 DPM.

Only difference is in retracker, all other inputs and corrections the same, as listed.

Table lists characteristics of the re-trackers

Note that different versions of the SAMOSA model were applied and evaluated (three listed here: "S2", "S3" and "S3+")

SAMOSA2 - Full analytical model

SAMOSA3 is simplified version of S2, to improve computational efficiency

Updates to the SAMOSA 3 model ("S3+") included:

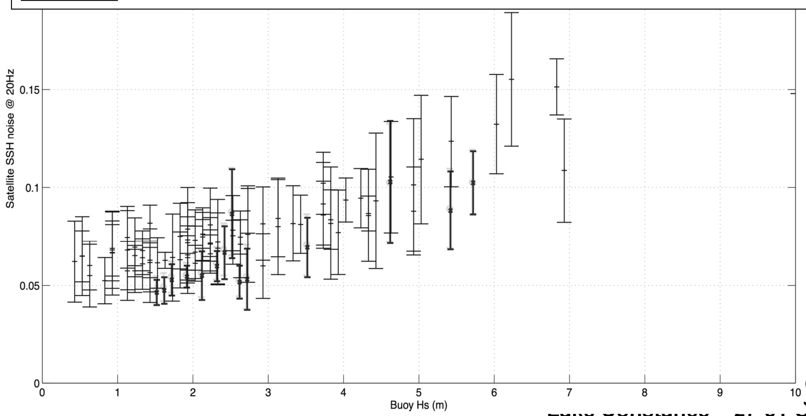
> RCMC Zero-padding effect, PTR with as a function of SWH, re-inclusion of some terms, Thermal noise calculation

CP4O SAR Open Ocean

SSH and SWH std dev v SWH

C-2 SAR (Hs = 2m)

(S2 full)	SSH std **1Hz: 1.223 cm**	SWH std **1Hz: 8.62 cm**
(S3 +)	SSH std **1Hz: 1.246 cm**	SWH std **1Hz: 8.58 cm**
(CPP)	SSH std **1Hz: 1.254 cm**	SWH std **1Hz: 8.74 cm**
J-2 LRM	SSH std **1Hz: 1.566 cm**	SWH std **1Hz: 11.09 cm**



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NOC Analysis of “Noise” (precision) in SAR products. Christine has presented an earlier version of this to OSTST last year this before, so I’ll be brief:

Data from NE Atlantic for same two months (July 2012 and Jan 2013)

Also extracted Jason-2 data for the same location and period.

Calculated standard deviation in Sea Surface Height and SWH over 1 Hz

Figure is for SSH: Red is for full SAMOSA 2 analytical mode, green is CPP, blue is Jason-2

V little difference to be seen between two SAR solutions (Green and Red), both lower than J-2

Note limited range in SWH for SAR data

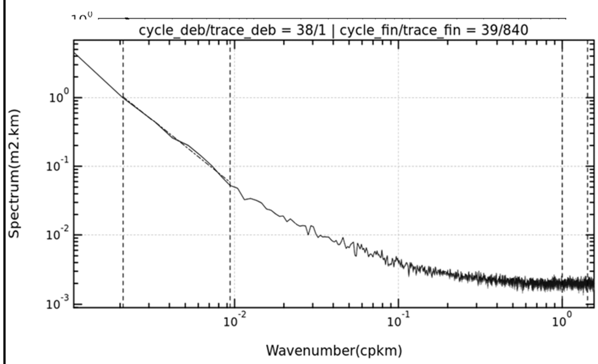
– limited data set but results significant reduction in SSH noise for SAR mode (factor of 1.5) .

Similar figure for SWH

Click gives more detailed numbers for SSH and SWH. Not a lot in it, but best performing on this analysis for SSH is the full SAMOSA2 model.

CP4O SAR Open Ocean

SSH SLA Analysis



- Sea level spectrum performed at all spatial scales:
  - Same oceanic signal content measured by both retrackers
  - Both perfectly follow the slope of the oceanic signal up to 50 km whereas the RDSAR SLA spectrum breaks off the signal at around 100 km
  - No correlated errors for scales between 10 and 80 km with the SAR retrackers whereas a « spectral hump » is detected with the LRM
  - SAR noise level ~5.5 cm at 20-Hz

➔ Both SAR retrackers allows 1-Hz product users to recover smaller wavelengths (10-80 km) of interest for oceanography

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Some points from (CLS) evaluation of SAR products over the open ocean

1st click compares C2 SAR, RDSAR and Jason2 SLA spectrum

Shows SAR recovers SLA signals not seen by LRM (or RDSAR) 10-100km

2nd click shows no difference between the two SAR retrackers (numerical or analytic)

CPP blue, SAMOSA 3 (Sentinel-3 DPM version) red

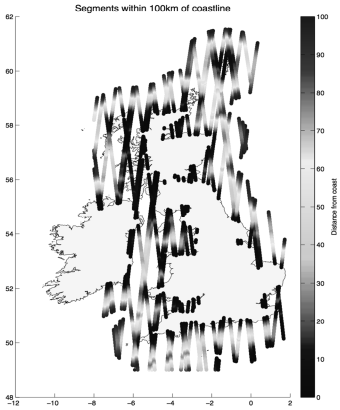
3rd click brings text

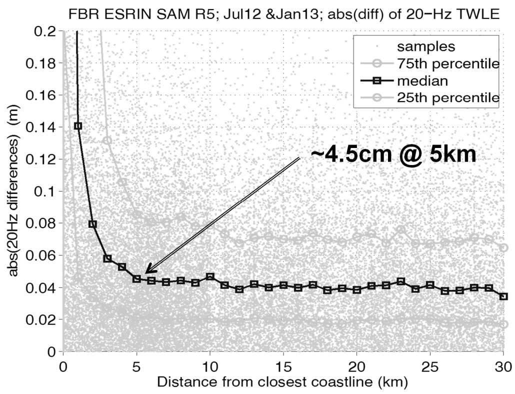
Global statistical analysis also carried out (Thomas' s presentation – again!)

CP4O SAR Coastal Ocean

Performance wrt distance from Coast

(proxy for
20-Hz noise)





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Recent NOC analysis of Coastal SAR products

All CryoSat-2 passes around UK in July 2012 and January 2013 – colour scale is distance from closest coastline.

Data from ESRIN SARvatore run ‘R5’ – which is improvement on the version of SAMOSA3 that is the Sentinel-3 DPM

We estimate this “noise” using the absolute value of first-order differences (difference between two consecutive points)

We show the 25th, 50th (median) and 75th percentile of the distribution in each 1-Km distance bin

HIGHLIGHTED: the median is ~flat at ~4.5 cm until %km from the coast, and still <6 cm at 3km. Note these estimates refer to the highrate data, so an equivalent 1-Hz noise over open ocean would be 4.5/sqrt(20), i.e. approx 1 cm!

SAR Open Ocean Assessment

- Confirmation that SAR mode provides
- Improved precision in range and significant wave height,
- Better resolution along track capability and so measurements of ocean variability at scales below 100km
- Accurate measurements closer to the coast than previously achieved
- Numerical (CPP) and analytical (SAMOSA) approaches to modelling and retracking the SAR echo were assessed
- ~mm difference in range correlated to SWH
- SAMOSA 3 shows errors SWH at low wave heights, Improved SAMOSA implementation with corrections to PTR approximation performs better, as does full SAMOSA implementation
- ~0.1dB differences in $\sigma0$ correlated to roll angle

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Summary for SAR over Ocean:

Confirmation that SAR mode provides improved precision in range and significant wave height, better along track resolution.

Hence measurements of ocean variability at scales below 100km – and measurements closer to the coast than previously available.
1 Hz Sd Range for SAR < 1.25 cm cf > 1.5 cm for LRM
1 Hz sd SWH for SAR < 9 cm, cf > 11 xm for LRM

Considering the two approaches to SAR echo modelling and retracking

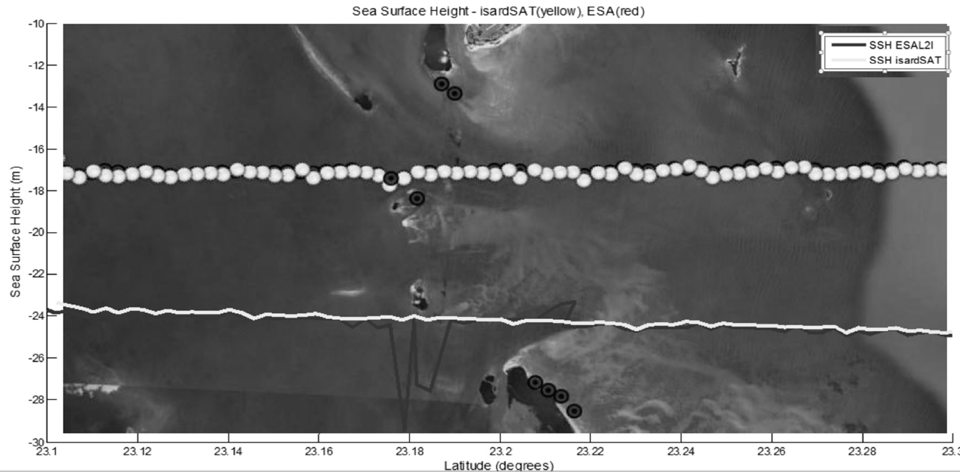
~mm difference in range correlated to SWH

SAMOSA 3 shows errors SWH at low wave heights, Improved SAMOSA implementation with corrections to PTR approximation performs better, as does full SAMOSA implementation

~0.1dB differences in s0 correlated to roll angle

SARin over Coastal Ocean

Example 1: CUBA, pass over North cays



SARin: Cryosat-2 specific mode for ice edge topography measurements. Provides insight to support improved approaches for processing SAR data close to coast

12

Coastal Signals are not like ocean waveforms, but are contaminated by reflections from land and calm water - thus the retracker processing needs some help.

Analysis of SARin data, carried out in CP4O by isardSAT, can help to develop techniques to identify and avoid "Non-ocean" (non nadir) contribution to waveform when retracking.

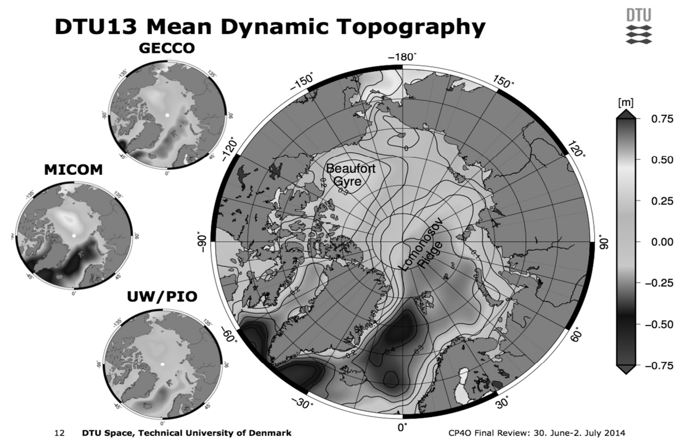
Can use phase echo to identify non-nadir land echo, then use that identification to "seed" the retracking of the ocean echo at the right point.

From this example of data close to the Cuban coast, the red and yellow points show the location of the echo along the Cryosat track. Red is the location of the echoing point tracked in the ESA L2 product. Can see how signals echoing from points to the left and right of the satellite track are selected. The yellow dots indicate the echoing points after the data are retracked when the ocean echo is located and tracked.

The solid lines show the SSH retrieved. Red for ESA L2, yellow after isardSAT retracking. It is clear the ESA product had errors of up to 6m, from the off nadir returns, whereas the isardSAT retracked data recovers an accurate SSH signal.

SAR over Polar Ocean

DTU13MSS and DTU13MDT ftp://ftp.space.dtu.dk/pub/DTU13/



Polar Ocean Conclusion:
Classification scheme and sea-ice re-trackers needed. C2 SAR data will support much improved representation of Arctic Ocean dynamics

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Next quickly look at the CP4O SAR product generated for the Arctic Polar Ocean – DTU carried out this work, based on retracked ESA Baseline B data

All C-2 data since July 2010, north of 60° N

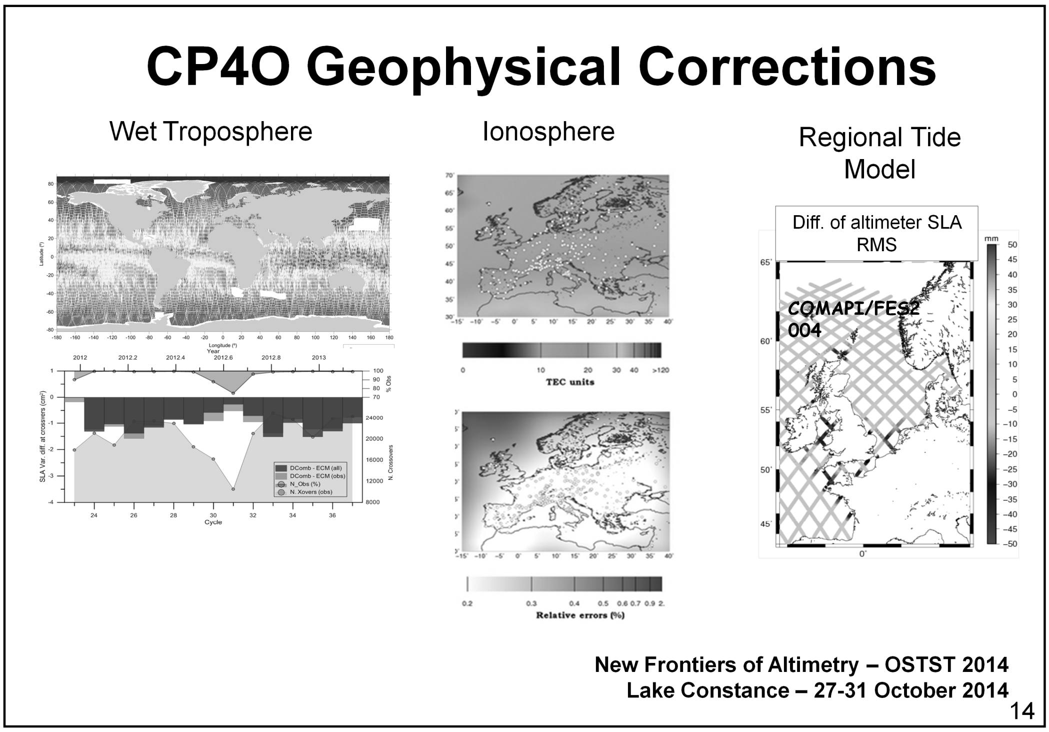
DTU Developed a new waveform classification scheme to distinguish between signals reflected from open ocean, sea ice leads and sea ice floes.

Developed and applied their own re-tracker for sea-ice lead echoes

From the SSH data thus retrieved generated new Arctic Mean Sea Surface and Mean Dynamic Topography – shown to perform better than existing models, and to provide improved characterisations of known arctic oceanographic features.

DTU13 MDT shown here, other existing models shown, and differences can be seen quite clearly.

Hope to also produce new tide model for Arctic



Final Set of products for Geophysical Corrections – needed for Cryosat because of the lack of Microwave Radiometer and a second frequency.

CP4O developed new models for Wet Troposphere and ionosphere corrections, and also an improved regional tide model for NW Europe, so supporting improved measurements near the European coastline.

These products were developed with coverage to coincide with that of the SAR products generated in CP4O, and then analysed by CLS in terms of the impact on SSH and SLA measurements.

Wet Troposphere:

Appreciable improvement (around 2cm²) for latitudes <50˚

Good improvement in coastal area

Some discontinuities recommended to be corrected for operational use

Ionosphere:

Diagnosis didn't identify any improvement, but Europe does not have an especially highly varying ionospheric signal.

Analysis should be repeated over region with bigger (ionospheric) signal

Regional Tides:

Models are equivalent in the open ocean (slight improvement with Comapi)

SAR Altimetry Open Issues

- Under-sampling of waveforms at low SWH
  - can be alleviated by zero padding?
- Optimising Doppler waveform processing
  - selection / weighting of waveforms
- Windowing: Purpose / recommendations.
- RDSAR processing. How to achieve equivalent performance to LRM
- Sensitivity to platform mispointing
- SAR mode Sea State Bias model
- Effects of swell (wavelength and direction)
- Investigations with FBR echoes and stack data

In the RoadMap we will provide recommendations for further Research and Development activities, needed to optimise the processing of SAR altimeter data, work needed to support scientific exploitation of SAR altimeter data, takes various forms but examples are the further development of coastal processors, sea-ice retrackers, and then finally actions needed so that SAR altimeter data are provided in a form so they can be integrated into operational use.

In this slide I have listed the major open issues for SAR altimetry that have been identified.

Undersampling: A number of analyses have identified that current schemes have a difficulty in retracking the more specular SAR waveforms and so in retrieving reliable geophysical parameters. These types of waveforms occur over smooth water, at low wave heights, in sea ice leads, and the problem arises particularly for SAR waveforms because of the peakier nature of these waveforms. The difficulty comes about because there are insufficient samples in the waveform to accurately recreate the full echo shape, in particular the leading edge.

Optimising Doppler Processing : The widely adopted process for processing the Doppler Waveforms is to include all 64 waveforms from each burst, and to give the contribution of each waveform equal weight. There is an argument that waveforms from the outer Doppler bins provide less useful information than those from the central bins and so should be given less weight in any processing approach.

Windowing: Some processing schemes apply windowing functions (e.g. Hamming) in order to reduce the sensitivity of waveforms to undesirable artefacts. It was recommended that a study be carried out to consider the purpose of windowing functions in waveform processing, to review and test alternatives and provide recommendations.

FBR echoes / stack data: The auto-covariance of FBR echoes (or stacks) can be expected to depend on different sea-states. Similarly it may be possible to derive further characterisation of the ocean surface from the stack data.

Summary

1) CryoSat is working well and providing, in SAR mode, improved precision and along track resolution, supporting better measurements of meso and sub mesoscale oceanographic features
2) CP40 provided significant improvement over the first SAMOSA model… There is still work to do in terms of optimising the processing of SAR altimeter data, at the Doppler stack stage and the re-tracking stage.
3) Lots of detail I haven't had time to go into, then next slide gives a list of relevant presentations (I hope I've got them all).

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Thank You ! For reports, deliverables, data sets go to:
www.satoc.eu/projects/CP4O

Also refer to the following presentations / posters:

➔ **DComb wet tropospheric correction for CryoSat-2 over open and coastal ocean**,
Fernandes et al. Instrument Processing: Corrections Tues 28th Oct 14:15
➔**SAR Processing on Demand Service for CryoSat-2 at ESA G-POD**,
Dinardo et al., Outreach, Education and Altimetric Data Services, Tues 28th Oct 17:00
➔**What Cryosat-2 revealed about existing MSS models in coastal regions**,
Andersen et al., the Geoid, Mean Sea Surfaces and Mean Dynamic Topography, Thurs 30th Oct, 10:15
➔**Recent Cryosat-2 and SARAL calibration and validation results**,
Naeije et al., Poster 35 (Regional and Global Cal/Val for Assembling a Climate Data Record)
➔**Validation of Open-Sea CryoSat-2 20 Hz Data in SAR Mode in the German Bight Area from 2010 to 2014**, Dinardo et al, Poster 106 (Instrument Processing: Measurement and retracking (SAR and LRM)
➔**A Fully Analytical SAR Altimetry Retracker for the Estimation of Geophysical Parameters**,
Egido et al., Poster 108 (Instrument Processing: Measurement and retracking (SAR and LRM).
➔**SAR altimetry over the ocean and the coastal zone: the new frontier**,
Gommenginger et al., Poster 110 (Instrument Processing: Measurement and retracking (SAR and LRM).
➔**Assessment of innovative algorithms for CryoSat-2 in the frame of the CP4O project**.
Moreau et al., , Poster 113 (Instrument Processing: Measurement and retracking (SAR and LRM).

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In Summary

1)CryoSat is working well and providing, in SAR mode, improved precision and along track resolution, supporting better measurements of meso and sub mesoscale oceanographic features

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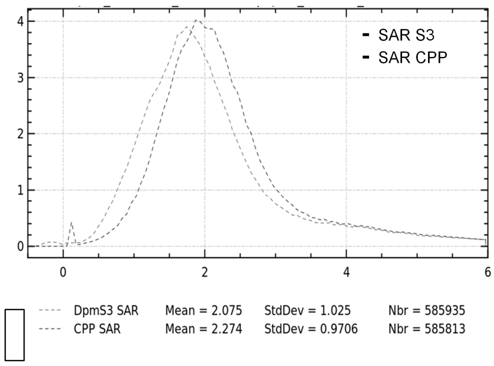
2.2 CP4O SAR Open Ocean

SAR SWH Analysis



- Significant SWH difference with a bias of around 20cm

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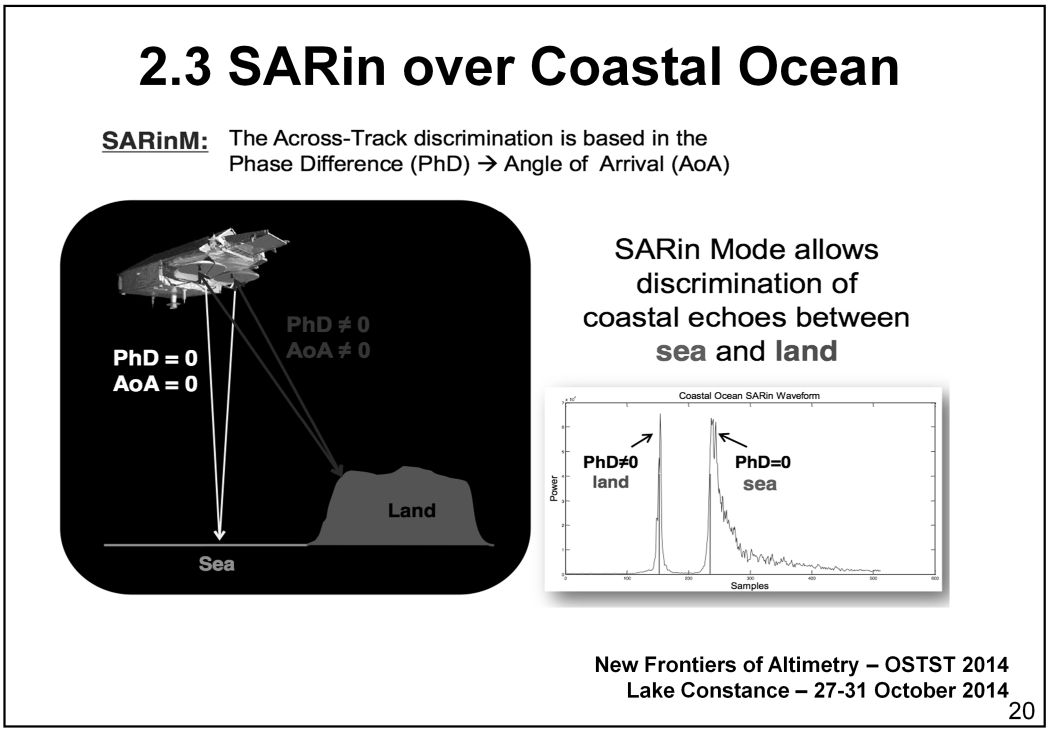
CLS figure

Range and range derived parameters (SSH, SLA) v similar in SAR products – main difference is in SWH at low wave heights – shown by this figure of distribution functions.

Bias between two approaches of ~20cm. Can of course be corrected – BUT there are consequent impacts on SWH related errors on the range.



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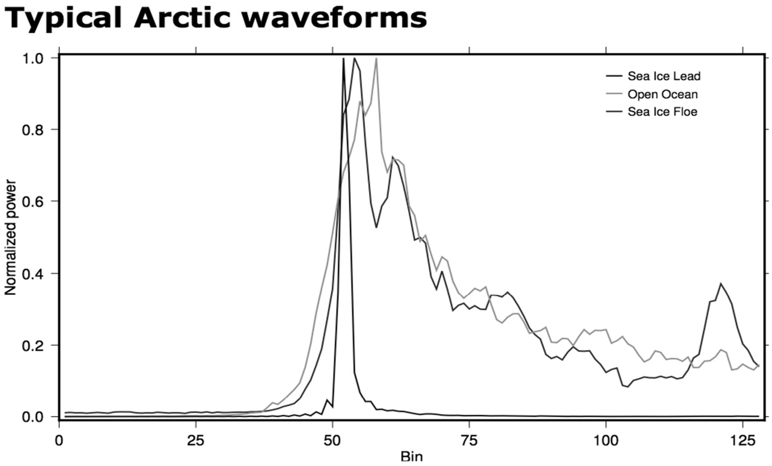
2.4 CP4O Products: SAR over Polar Ocean



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3.5 Geophysical Corrections Assessment

Wet Troposphere:

- Appreciable improvement (around 2cm²) for latitudes <50˚
- Good improvement in coastal area
- Some discontinuities recommended to be corrected for operational use

Ionosphere:

- Differences between SPECTRE and GIM evolve with the local time and with seasons but diagnosis do not highlight any improvement.
- Limited data set does not support crossover analysis.
- Analysis should be repeated over region with bigger (ionospheric) signal

Regional Tides:

- Models are equivalent in the open ocean (slight improvement with Comapi)
- Good improvement in the North East European shelf
- Spectral analysis confirms improvement for scales 50 – 200 km

- **Longer time series analysis recommended for all corrections**

The CLS analysis found:

Wet Troposphere:

Appreciable improvement (around 2cm²) for latitudes <50˚ ; Good improvement in coastal area; Some discontinuities recommended to be corrected for operational use

Ionosphere:

Differences between SPECTRE and GIM evolve with the local time and with seasons but diagnosis do not highlight any improvement; Limited data set does not support crossover analysis; Analysis should be repeated over region with bigger (ionospheric) signal

Regional Tides:

Models are equivalent in the open ocean (slight improvement with Comapi); Good improvement in the North East European shelf; Spectral analysis confirms improvement for scales 50 – 200 km

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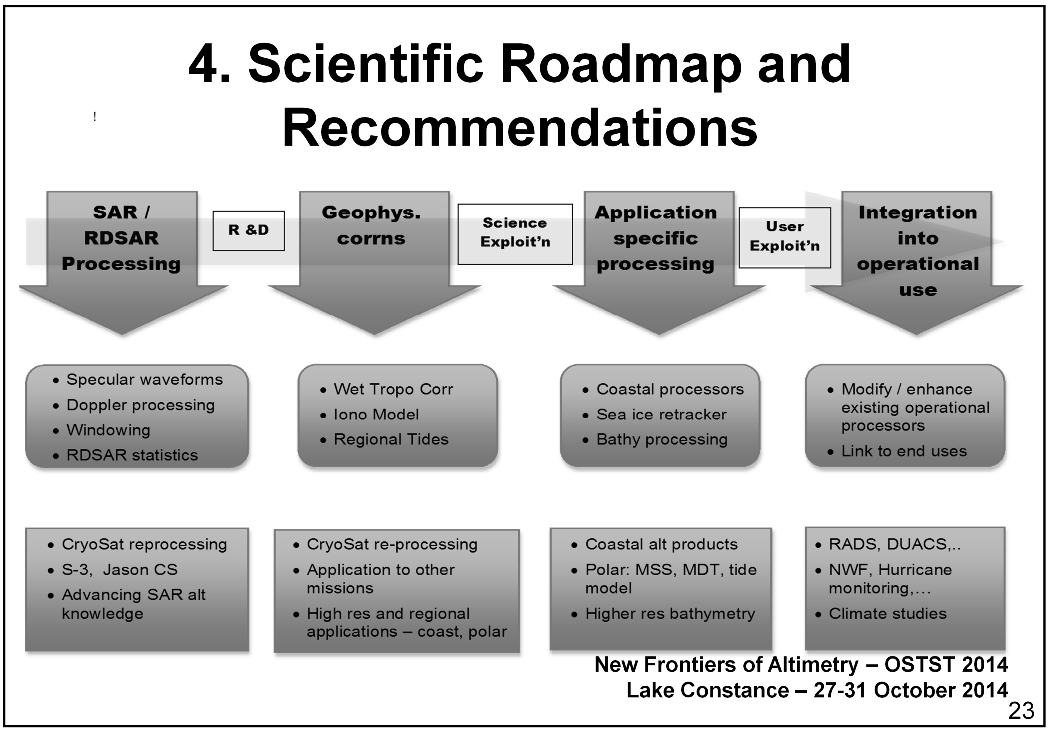

Final output from CP4O is a Scientific Roadmap, which includes recommendations for further Research and Development activities, needed to optimise the processing of SAR altimeter data, work needed to support scientific exploitation of SAR altimeter data, takes various forms but examples are the further development of coastal processors, sea-ice retrackers, and then finally actions needed so that SAR altimeter data are provided in a form so they can be integrated into operational use.

This slide provides a diagrammatic representation, moving from R&D activities (and objectives) on the left, to operational applications on the right.

A document is under preparation which details these.