Measuring Ocean Waves from Space

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Overview

• Measuring ocean waves with satellites
  o What do we measure, how and how well?

• Some recent developments

• Some new missions coming soon

• Drivers for new mission concepts

• Conclusions
Measuring ocean waves with satellites

- **Main focus on microwave techniques**
  - EM frequency: 1.2-35 GHz (wavelength 1-25 cm)
  - Effective day and night => 24/7 operation
  - Lower frequencies less affected by precipitation => “all weather”
- **Reflected signals are sensitive to surface roughness**

- Also sense range (time) and surface motion (Doppler)
  - Remote sensing of waves is closely linked to sensing of surface winds and currents
Satellite Altimetry

- Mainly for high-accuracy sea surface height (range)
  - but also significant wave height (SWH) and wind speed
  - Very short transmitted pulse; Rise time of the echo changes with SWH

Credits: Val Byfield (NOC/ESA LearnEO!)

Diagram showing the process of satellite altimetry, including diagrams of reflected pulses and their timing.
Satellite Altimetry

- Well-established with over 20 years of continuous data
- Altimeter SWH as good as/better than buoys
- Used for climatology and statistical analyses (e.g. marine renewable resource assessments)
Satellite Altimetry

- Map shows typical 1 day sampling with currently available altimeters
  - Narrow swath ~ 5-7 km wide
  - 10, 17, 35 day repeat orbits
- SWH widely assimilated in wave models
  - but benefits of SWH in wave models are localised and of limited duration
- Provide altimeter wave data within 200km of any location every 6 hours would require a constellation of 12 altimeters
Synthetic Aperture Radar

- Side-looking
- High resolution or wide-swath (not both)
- Non-linear SAR imaging of waves
Synthetic Aperture Radar

• Directional spectrum of swell waves
  o Wave period, direction and SWH for waves > 150-200 m
  o Use of phase eliminates directional ambiguity and remove the need for prior information

From Vachon et al., 2004
Synthetic Aperture Radar

- Methods established since ERS-1 (1990s) but systematic acquisition and processing only since Envisat (2004-2012)
- Sentinel-1A (April 2014) and 1B (April 2016) aim for complete coverage in six days
Surface Winds

- Scatterometry (active)
- Radiometry (passive)
  - Wide-swath, 25km resolution, global daily
  - Used for assimilation

QuikScat 25km
18 April 2008

WindSat 25km
18 April 2016

ASCAT-A 25km
18 April 2016

Ended Nov 2009
Some recent developments
Altimetry

Better precision & finer spatial resolution with Delay Doppler Altimetry
Delay Doppler Altimetry

- Demonstrated in-orbit with Cryosat-2 over oceans
- Adopted for Sentinel-3 series and Sentinel-6/Jason-CS series
Conventional altimetry vs Delay Doppler altimetry

- More “looks” => reduced noise
- Finer spatial resolution along track (~250-300 m)
- Less contamination near land
Delay Doppler altimetry on Cryosat-2
Cryosat-2 DDA SWH v. Met Office buoys

<table>
<thead>
<tr>
<th>Run reference</th>
<th>1Hz Noise @ 2m</th>
<th>SWH v buoy Hs</th>
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<tr>
<td></td>
<td>SSH (cm)</td>
<td>SWH (cm)</td>
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<tr>
<td>CNES</td>
<td>1.254</td>
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<td>ESRIN R5</td>
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<td>8.42</td>
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<tr>
<td>Jason-2</td>
<td>1.566</td>
<td>11.09</td>
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</tbody>
</table>

Notes:
- Open-ocean
- No misfit threshold

Validation of Cryosat-2 SAR Significant Wave Height against Met Office buoys (50km, 30min)
Winds and Waves

Improved measurements at high winds with SMOS L-band radiometry
L-band radiometry for extreme winds

- Wind speed in hurricanes from SMOS mission
  - SMOS = Soil Moisture and Ocean Salinity
  - Example shows Haiyan Super Typhoon on 4-9 Nov'13 2013
- Wide-swath, unaffected by rain, no saturation at high winds
  - Higher quality winds up to 50 m/s
  - New insight into structure of hurricanes
Winds and Waves

Improved space-time sampling with GNSS-Reflectometry
GNSS-Reflectometry

• Based on signals of opportunity from Global Navigation Satellite Systems
  o e.g GPS, Galileo…

• Global, ubiquitous signals

• Small low-cost receivers
  o Suitable for small satellites or satellites of opportunity to build constellations of GNSS-R receivers
  o Huge improvement in space-time sampling
  o L-band (weakly affected by precipitation)

Measurements of ocean height and ocean surface roughness (wind)
GNSS-R missions

2003
Proof-of-concept on UK-DMC with Surrey Satellite Technology Ltd

8 July 2014
UK TechDemoSat-1 with SGR-ReSI GPS-R payload

Oct 2016
NASA Cyclone Global Navigation Satellite System (CYGNSS) mission

Collected ~ 50 data points over ocean

Aims for mean revisit time ~ 4 hours
TechDemoSat-1 GNSS-R and ASCAT-A/B
(TDS-1 / ASCAT-A or B over the ocean within 1h, 1°)

Foti et al., GRL, 2015

TDS1 GNSS-R collocated with 27.9 m/s ASCAT wind speed

- Collocated wind speed from ASCAT A or B
- Collocation: within 1x1° space, 1h time
- A or B whichever gives shortest time-offset with TDS1
- ASCAT swath L1b quality flags ON (rain, land, ice)
- TDS-1 data retained=67.4%
Inversion algorithms for GNSS-R winds

- Even in uncalibrated mode, TDS-1 GNSS-R delivers unbiased winds with RMS Error ~ 2 m/s

Foti et al., GRL, 2015
Some new missions coming soon

CYGNSS, CFOSat, SWOT
The CYGNSS mission

- NASA Cyclone Global Navigation Satellite System
- PI: Chris Ruf, University of Michigan

- Aim: to monitor ocean surface winds throughout the life cycle of tropical storms and hurricanes
  - 5-50km spatial resolution
  - 4 hour mean revisit time
  - Precision goal: 2 m/s or 10% of wind speed

- Constellation of 8 GNSS-R microsatellites in one orbital plane
  - 35 degree inclination

- Launch: October 2016
The CFOSat mission

• Chinese-French Oceanography Satellite

• SWIM instrument
  o nadir and near-nadir rotating real aperture radar
  o modulation of backscatter by long waves

• Directional wave spectra (70-500m) every 70km
  o Polar orbit; Global coverage
  o 13 days repeat

• Launch: 2018
The SWOT mission

- Surface Water & Ocean Topography mission
  - Joint mission between France/US/Canada/UK
- Aim: to determine ocean variability at small scales
  - Across-track interferometry at Ka-band (~0.9 cm)
- 2D high-resolution maps of sea surface height
  - Precision goal: 1cm @ 1km
  - Also, some wind and wave data from swath and/or nadir altimeter
- Launch: 2020
Some new missions concepts
Drivers for new mission concepts

• Better accuracy & precision
• Finer spatial resolution
  o E.g. for ocean sub-mesoscale dynamics (1-10km) and coastal applications
• More frequent sampling
  o E.g. wide-swath technology or constellations of small satellites
• Better performance in challenging/extreme situations
  o E.g. ice-covered oceans; hurricanes; close to land
• Ensuring continuity & sustainability
  o Compatibility with past satellite data record
  o Low-cost missions
Some example mission concepts

• GEROS-ISS
  o A GNSS-Reflectometry mission on the International Space Station for wide swath altimetry and scatterometry

• CYGNSS-2
  o CYGNSS follow-on at high-inclination for wind/sea state monitoring at high latitudes

• DopScatt
  o Next generation scatterometers with Doppler capability for global ocean surface current monitoring

• SEASTAR/Wavemill
  o Along-track SAR interferometry for high-resolution current and wind vector mapping
The SEASTAR mission concept

• High-resolution 2D maps of total ocean surface current and wind vectors
  o 1 km resolution; 0.1m/s accuracy
  o Collocated with directional swell spectra

• Objective: to characterise and parameterise the effect of ocean submesoscale dynamics on ocean circulation, air-sea coupling and vertical transports

• In preparation for submission as an ESA Earth Explorer mission
Conclusions

• Satellites provide a wealth of ocean wave measurements on a global scale
  o Well-established validated methods
  o A growing data record spanning multiple decades
  o Strong synergy with surface winds and currents

• Significant recent developments leading to new and improved measurements from satellites
  o Improved performance in coastal zone and hurricanes
  o Better time/space sampling
Conclusions

• Many new satellite missions coming up relevant to ocean waves
  o New instruments, increasingly exotic
  o New missions e.g. low-cost constellations

• Strong drivers for more and higher-resolution data
  o Many mission concepts in development

• Satellite measurements are well-suited to study processes, interactions and exchanges at the air-sea interface
  o Useful for assimilation but also to improve understanding
Thank you

Any questions?

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