A new airborne instrument to image ocean-atmosphere dynamics at the sub-mesoscale: OSCAR instrument capabilities and the SEASTARex airborne campaign

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SeaSTAR motivation

High-resolution satellite images often show small ocean eddies, swirls and filaments at scales below 10 km.
- Frequent near jets, large eddies, in coastal and polar seas
- Fingerprints of dynamic processes at the sea surface
- Few observations of surface dynamics at these scales
  - Challenging & expensive

Numerical models indicate small-scale ocean phenomena have major impact on global ocean circulation and climate.
- Key role of ageostrophic circulation and interactions with surface winds and waves
- Impact on vertical exchanges e.g. heat, CO2, nutrients…
- Impact on horizontal dispersion & pathways e.g. debris, oil…

No existing or planned mission with the necessary performance and space-time sampling to observe these small and fast processes.
SeaSTAR Primary science objectives

to measure, for the first time, 2D images of Total Surface Current Vectors and Ocean Surface Vector Winds at 1 km resolution with high accuracy, over all coastal seas, shelf seas and Marginal Ice Zones.

to characterise their magnitude, 2D spatial variability and temporal variability on daily, seasonal to multi-annual time scales.

to deliver, for the first time, high-order derivative products like gradients, vorticity, strain and divergence to explore the relations between small-scale phenomena and vertical exchanges between the atmosphere and the ocean interior.

to investigate the relations between small-scale surface dynamics and marine productivity using synergy with in situ data and high-resolution optical, thermal and microwave satellite data.

to validate high-resolution and coupled models and support the development of new parameterisations to improve operational forecasts and reduce uncertainties in climate projections.
SeaSTAR Secondary science objectives

to measure **instantaneous sea ice drift vectors** with high-accuracy to observe the sea ice and ice floes response at small scales for different wind, waves & current forcing.

to develop new experimental products for **full directional ocean wave spectra** (including wind waves) to study localised surface phenomena, including fronts, wave breaking, Langmuir cells…

to examine ocean current and wind fields **close to major estuaries** to investigate the **dispersion of major river plumes** in coastal zones and the fate of terrestrial inputs to the ocean.
## SeaSTAR Primary Products & Requirements

### SeaSTAR Primary Products (Level 2)

#### Total Surface Current Vector (L2-TSCV)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>One continuous swath</td>
<td>≥ 100-150 km</td>
</tr>
<tr>
<td>Horizontal posting (resolution)</td>
<td>≤ 1 km</td>
</tr>
<tr>
<td>TSCV Uncertainty @ 1km resolution</td>
<td>≤ 0.1 m/s or 10%</td>
</tr>
</tbody>
</table>

#### Ocean Surface Vector Wind (L2-OSVW)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same swath as TSCV</td>
<td></td>
</tr>
<tr>
<td>Same horizontal posting as TSCV</td>
<td></td>
</tr>
<tr>
<td>OSVW Uncertainty @ 5km resolution</td>
<td>≤ 1 m/s or 10%</td>
</tr>
</tbody>
</table>
SeaSTAR measurement principle

Squinted SAR Along-track Interferometry (ATI), Ku-band

Backscatter & Doppler in 3 azimuth directions

Simultaneous measurements of total current vector, wind vectors and directional wave spectrum

- one pair looking forward (+45°)(VV)
- one pair looking backward (-45°)(VV)
- one broadside DCA or ATI (VV, HH)

Heritage

Scatterometry
SAR Doppler Anomaly

*Envisat ASAR, Tandem-X, Sentinel-1*

Dual-Beam Interferometer
Wavemill

© NOC
SeaSTAR Space-time sampling

Focus on Coastal, Shelf-seas & Marginal Ice Zones + Open-ocean Regions of Special Interest

As an independent dedicated mission, SeaSTAR can tailor its space-sampling to its science needs.

Two mission phases:

Fast-repeat phase (6 months)
- 1 day repeat
- 150 scenes every day, each 250 km long

Drifting orbit (4 years)
- ~30-day repeat, 1-day sub-cycle
- 50% swath overlap at the Equator

Aircraft certification
Feb 2022
SEASTARex campaign Iroise Sea May 2022

Trefle mooring site is indicated in red square with a T and La Jument site with a J.
Data Production Updates

We have focused all 17, 22, 25, 26 days (besides the **circular tracks**).
Star-pattern tracks

The star-pattern was flown so each channel effectively gives look directions at 45° intervals around the compass.

Assuming environmental homogeneity we can then group data by incidence angle and look azimuth.

Wind (AROME) 5.75 m/s, 42°

Current (ADCP) 0.92 m/s, 185°

Swell (Buoy) 1.12m, 9.3s, 250°
1. Filter the OSCAR land data using the GSHHG land-sea mask;
2. Collocate ASCAT winds with OSCAR observation (<1 h);
3. Interpolate ASCAT u/v wind components bi-linearly to OSCAR grids;
4. Simulate sigma0_ASCAT;
5. Calculate the difference between measured and simulated sigma0 (binning@0.2 m/s and 1°);
6. Average the sigma0 difference over all the wind speed bins.

\[ \Delta \sigma = \sum_i (\sigma_i^A - \sigma_i^{NWP}) \]
Ocean Calibration results

Using the collocated ECMWF winds as calibration reference. The discrepancy is assumed to be due to wind variability effect.

8 tracks on May 22nd
New Ocean Calibration algorithm

Assumptions:
1. The radar instrument is stable over the whole particular day;
2. The wind vector is constant for one particular flight leg. However, the wind vector may vary with the flight leg.
3. The calibration factor only depends on the incidence angle.
4. The wind speed variability is smaller than 3 m/s, and the wind direction variability is smaller than $30^\circ$.

\[ f_{c,i} = \frac{\sigma_{s,i}^0}{\sigma_{m,i}^0} \]

\[ f_{c} = \frac{\text{max}\{\text{min}\{f_{c,i}\}\} + \text{min}\{\text{max}\{f_{c,i}\}\}}{2} \]

Initial calibration

Iterative Calibration

Output leg-mean wind vectors and calibration factors
Ocean Calibration results

8 tracks on May 22nd

Using the collocated ECMWF winds
Compared with the above 'retrieved' calibration curve (black)
Ocean Calibration results (using May 25th data)

Beam 00 (mid)  
Beam 33 (fore)

Color curves: calibration using ECMWF wind vectors  
Black curves: calibration using the new method

Black curves: ECMWF wind vectors  
Red curves: Retrieved by the new method
Ocean Calibration results (using May 25th data)

Color curves: calibration using ASCAT wind vectors
Black curves: calibration using the new method

Beam 00 (mid)  
Beam 33 (fore)

Black curves: ASCAT wind vectors
Red curves: Retrieved by the new method
Calibration factors for May 22\textsuperscript{nd} & May 25\textsuperscript{th}

For a given beam (Mid or Fore), the calibration factors are of similar shapes on different days, but with a bias of 3-4 dB.
Calibration factors for May 22\textsuperscript{nd} & May 25\textsuperscript{th}

For a given beam (Mid or Fore), the calibration factors are of similar shapes on different days, but with a bias of 3-4 dB.
L2 simultaneous retrieval results

OSCAR retrieved Current Velocity
2022-05-17T09:32

OSCAR retrieved Wind Speed
2022-05-17T09:32
Comparison with X-band

OSCAR retrieved Current Velocity
2022-05-17T09:32

X-band derived surface current velocity
20220517T093545

Current Velocity (m/s)
Comparison with X-band
NovaSAR-1 & MARS2D comparison

OSCAR Retrieved surface current velocity
2022-05-17T09:32

MARS2D Current Velocity
20220517T0930

17 May 2022
10:30 am

La Jun

NovaSAR-1 image (S-band) courtesy of SSTL & Martin Cohen, Airbus UK
Comparison with HF Radar
Comparison with AROME

OSCAR retrieved Wind Speed
2022-05-17T09:32

AROME predicted U10 wind speed
2022-05-17T09:00
Star pattern

- OSCAR
- MARS2D
- AROME
Validation

Assumption of temporal and spatial homogeneity allows us to take the mean retrieved parameter for each track of the pattern.

No wind buoy (FLAME), so interpolated AROME to 200m grid, comparing at retrieved pixel level for RMSE.

<table>
<thead>
<tr>
<th></th>
<th>OSCAR</th>
<th>ADCP</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Currents</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>0.64</td>
<td>0.62</td>
<td>0.08</td>
</tr>
<tr>
<td>Direction (degrees N)</td>
<td>14.4</td>
<td>8.4</td>
<td>8.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>OSCAR</th>
<th>AROME</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Winds</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed (m/s)</td>
<td>5.54</td>
<td>5.86</td>
<td>0.44</td>
</tr>
<tr>
<td>Direction (degrees N)</td>
<td>49.08</td>
<td>45.75</td>
<td>5.43</td>
</tr>
</tbody>
</table>
Radial Surface Current

‘Star-pattern’ analysis of grouping data by incidence angle and azimuth

GMF = Mouche (2012)

RSC data (points) with fitted curves (lines) for Fore and Aft channels

Black line is ADCP
From SEASTARex to OSCAR-Med

The SEASTARex campaign focused on demonstrating the OSCAR instrument capabilities regarding SEASTAR primary objective:

- To measure, for the first time, 2D images of Total Surface Current Vectors and Ocean Surface Vector Winds at 1 km resolution with high accuracy, over all coastal seas, shelf seas and Marginal Ice Zones.
- Target: a strong tidal current region, i.e., the Iroise Sea

The next objective is to prove the OSCAR capabilities on

- Delivering, for the first time, high-order derivative products like gradients, vorticity, strain and divergence to explore the relations between small-scale phenomena and vertical exchanges between the atmosphere and the ocean interior.
- Target: a region with mesoscale and submesoscale features associated with strong vorticity and divergence fields and vertical exchanges between the ocean interior and the atmosphere, i.e., the Western Mediterranean

The OSCAR-Med campaign aims at flying OSCAR over the Western Mediterranean Sea to complement in situ research activities taking place in the context of the SWOT mission
BIOSWOT-Med
PIs A.M.Doglioli and G.Grégori

The BioSWOT-AdAC cruise in the SW Mediterranean Sea
Track 6 (Marseille):
91, 2023-04-21 20:36:00
92, 2023-04-22 20:26:37
93, 2023-04-23 20:17:14
94, 2023-04-24 20:07:51
95, 2023-04-25 19:58:28
96, 2023-04-26 19:49:05
97, 2023-04-27 19:39:42
98, 2023-04-28 19:30:19
99, 2023-04-29 19:20:56
100, 2023-04-30 19:11:33
101, 2023-05-01 19:02:10
102, 2023-05-02 18:52:47
103, 2023-05-03 18:43:24
104, 2023-05-04 18:34:01
105, 2023-05-05 18:24:38
106, 2023-05-06 18:15:15
107, 2023-05-07 18:05:52
108, 2023-05-08 17:56:29
109, 2023-05-09 17:47:06
110, 2023-05-10 17:37:43
111, 2023-05-11 17:28:20
112, 2023-05-12 17:18:57
113, 2023-05-13 17:09:34
114, 2023-05-14 17:00:11

Track 19 (Baleares)
90,, 2023-04-21 07:25:53
91,, 2023-04-22 07:16:30
92,, 2023-04-23 07:07:07
93,, 2023-04-24 06:57:44
94,, 2023-04-25 06:48:21
95,, 2023-04-26 06:38:58
96,, 2023-04-27 06:29:35
97,, 2023-04-28 06:20:12
98,, 2023-04-29 06:10:49
99,, 2023-04-30 06:01:26
100,, 2023-05-01 05:52:03
101,, 2023-05-02 05:42:40
102,, 2023-05-03 05:33:17
103,, 2023-05-04 05:23:54
104,, 2023-05-05 05:14:31
105,, 2023-05-06 05:05:08
106,, 2023-05-07 04:55:45
107,, 2023-05-08 04:46:22
108,, 2023-05-09 04:36:59
109,, 2023-05-10 04:27:36
110,, 2023-05-11 04:18:13
111,, 2023-05-12 04:08:50
112,, 2023-05-13 03:59:27
113,, 2023-05-14 03:50:04

R/V l’Atalante
21 April 2023 – 14 May 2023
Strategy and methodology

adaptive Lagrangian sampling strategies & Innovative instrumentation

SPASSO & MVP, gliders, AUV, drifters & floats, FFADCP, VVP, Cytometry, zooplankton and omics

« back and forth » strategy for the horizontal continuous sampling

<table>
<thead>
<tr>
<th>Day D</th>
<th>Water mass A</th>
<th>Water mass B</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16:00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day D+1 08:00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day D+2 00:00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

« Lagrangian stations» strategy for the vertical sampling

MVP - Moving Vessel Profiler

The resulting multi-variable sampling

MVP - Moving Vessel Profiler

Water mass A  Front F  Water mass B

SVP drifter  BIO-ARGO float  CTD+O2 ARGO float  VVP  pumping system

Zoecon  Floats

ADCP  CTD

WEIGH

ADCP  CTD  WEIGH
Unfortunately, SEASTAR was not selected! EE13 candidate mission?

SeaSTAR community

ESA team
Alejandro Egido (Mission Scientist)
Tania Casal (Airborne Campaigns scientist)
Kevin Hall (System Study Manager)
Petronilo Martin-Iglesias (Payload & Performance)
Valeria Gracheva (Payload & Performance)
Dulce Lajas (E2E Simulators)
+ Lorenzo Iannini, Mauro Federici, Gunther March, Paolo Cipollini, Craig Donlon

Science Consolidation team
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Fabrice Collard, Clément Ubelmann (Ocean Data Lab, France)
Anis Elouyuncha, Leif Eriksson (Chalmers University Of Technology, Sweden)
Joanna Staneva, Benjamin Jacob, Johannes Schulz-Stellenfleth (Helmholtz-Zentrum Hereon, Germany)
Louis Marié, Fabrice Arduhin (Ifremer, France)

SeaSTARex airborne team
Adrien Martin, Christine Gommenginger (NOC, UK)
David McCann (NOC, UK)
Christian Trampuz, Adriano Meta (MetaSensing, NL)
Karlos Macedo (MetaSensing, NL)
Louís Marié (Ifremer, FR)
Jean-François Filliot (France Energies Marines, FR)
Jose Marquez (RadarMetrics, SP)
Jochen Horstmann (Helmholtz-Zentrum Hereon, DL)
Wenming Lin (NUIST, CN)
Giuseppe Grieco (ISMAR, IT)
Marcos Portabella (ICM-CSIC, SP)

And more...

Aida Alvera-Azcárate (University of Liege, Belgium)
Ole Balltazar Andersen (DTU Space, Denmark)
Fabrice Arduhin (CNRS / LOPS, France)
Antonio Bonaduce (NERSC, Norway)
Øyvind Breivik (Norwegian Meteo Institute, Norway)
Fabrice Collard (OceanDataLab, France)
Mohammed Daboor (Environment and Climate Change, Canada)
Robert King (Met Office, United Kingdom)
Joanna Staneva (Helmholtz-Zentrum Hereon, Germany)
Ad Stoffelen (KNMI, The Netherlands)
David Woolf (Heriot Watt University, United Kingdom)
Synergy with other missions

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>EE11 Call</td>
</tr>
<tr>
<td>2019</td>
<td>Copernicus Sentinel-1-NPC</td>
</tr>
<tr>
<td>2020</td>
<td>Copernicus Sentinel-2-NG</td>
</tr>
<tr>
<td>2021</td>
<td>Copernicus Sentinel-3-NG OPT &amp; TOPO</td>
</tr>
<tr>
<td>2022</td>
<td>Copernicus Sentinel-6 Michael Freilich</td>
</tr>
<tr>
<td>2023</td>
<td>HPCM CRISTAL</td>
</tr>
<tr>
<td>2024</td>
<td>HPCM CMIR</td>
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<tr>
<td>2025</td>
<td>SWOT</td>
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<tr>
<td>2026</td>
<td>PACE</td>
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<tr>
<td>2027</td>
<td>EE11 SEASTAR</td>
</tr>
<tr>
<td>2028</td>
<td>MetOp-SG-B</td>
</tr>
<tr>
<td>2029</td>
<td>EE10 HARMONY</td>
</tr>
<tr>
<td>2030</td>
<td>SeaSTAR launch</td>
</tr>
<tr>
<td>2031</td>
<td>You are here</td>
</tr>
</tbody>
</table>

National Oceanography Centre
Star-pattern on May 22nd
Calibration (Sigma-0)

![Graphs showing Sigma0 (dB) vs Azimuth (deg) for different Incidence angles from 25 to 65 degrees with different wind directions and incidence angles.](image-url)
Interferograms (uncalibrated)
Interferogram – land calibrated (L1c)

Incidence angle = 25

Incidence angle = 30

Incidence angle = 35

Incidence angle = 40

Incidence angle = 45

Incidence angle = 50

Incidence angle = 55

Incidence angle = 60

Incidence angle = 65

Azimuth (deg)

Interferogram (rad)
Wind-wave Artefact Surface Velocity (WASV)

‘Star-pattern’ analysis of grouping data by incidence angle and azimuth

RSV data (points) with fitted curves (lines) for Fore and Aft channels

\[ \text{WASV} = \text{RSV} - \text{ADCP} \]
What about extremes?

Over hurricanes (sampling permitting)

- SeaSTAR instrument operates in Ku-band, thus limited by rain contamination effects
- But at high spatial resolution!
- +heritage from Ku-band scatterometer QC

Before and after hurricanes, we could study

- The formation and temporal evolution of cold wakes
- The response of the ocean meso- and submesoscale to intense atmospheric events
1) vertical advection

From altimetry to \( \mathbf{w} \)

Numerous works (e.g. Lapeyre, G., & Klein, Qiu et al, 2016, 2020, Pietri et al 2021) show a need of:

**in situ direct** measurement of the balanced (Med Sea ideal conditions with no tide) in particular in the surface layer associated with

- Mixing microstructure measurement
- High resolution ctd cast
- Horizontal vorticity

---

Our strategy:

**BIOSWOT-Med**

**Innovative methods:**
- 5-beams acoustic (FFADCP)
- & buoyancy profiler (VVP)

**Turbulence profiler (VMP)**

**Towed fish (MVP/SeaSoar)**
- Argo drifting profilers gliders

**hull mounted ADCP and surface drifters**
Data Production Updates

We have focused all 17, 22, 25, 26 days (besides the circular tracks)

17 (cal + 1 available)

22 (cal + all available)

25 (cal + 1)

26 (cal)
Pierre Garreau (IFREMER), Frank Dumas (LOPS-SHOM)

C-SWOT 2023
A TWO SHIPS STRATEGY FOR MORE SYNOPTICITY

TETHYS II + SWOT + ATALANTE

March - April 2023
N-W Mediterranean Sea

- High resolution
- Parallel transects and synoptic observations (MVP/Seasat/S-ADCP/Drifting buoys)
- Exploring the variability of the North-Current
- Revisiting mesoscales and sub-mesoscales dynamics in the North Balearic Front
- Participating in Calibration/validation
- Evaluate the 2-ship strategy
C-SWOT 2023
TOOLS TO BE DEPLOYED DURING THE CRUISES

High resolution transects
- MVP (0-400m)
- SEASOAR (0-400m)
- U-CTD (0-400m)
- VMADCP (0-400m)

Lagrangian approach
- Carthe drifters
- GDP drifters
- Spotter buoys (sea state)
- "Flame" buoys (Air-Sea exchanges)

Classical hydrology using CTD and LADCP

DRIX USV Unmanned surface vehicle

ADCP Moorings
SWOT orbits during the Cal/Val phase over the Mediterranean Sea

Location of the BioSWOT ship campaign in 2018. The BioSWOT-Med campaign in May 2023 would take place in the same area (currently waiting for authorisation by Spanish authorities).
SeaSTAR Summary

SeaSTAR is a dedicated ocean mission to address clear and urgent scientific needs for new synoptic imaging of ocean current and wind vectors at fine resolution ~ 1km.

SeaSTAR focuses on key interfaces of the Earth system and is relevant to a large and growing community of ocean, atmosphere, cryosphere, coastal and climate scientists and operators.

A ‘quantum leap in knowledge’ for Earth Observation and Earth Science

The first mission of its kind, with some ambitious elements, that builds on high levels of scientific and technological readiness in Europe.

https://projects.noc.ac.uk/seastar/