CYMS2 – FR

Final Report

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[SOP] - CLS-ENV-NT-20-0226 - Standard Operating Procedure (SOP) for SHOC in 2020-2021 - v1.2 - 30/11/2020

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[CCD] – CCD CONTRACT 4000129822 - CONTRACT CLOSURE DOCUMENTATION - v1.0 – 11/04/2023

1 Introduction

This document aims at presenting an overview of the activities performed at the end of the CCN for CYclone Monitoring Service (CYMS) with Sentinel-1 project.

As a stand-alone document, the proposed development, the technical and scientific objectives, and the overall work logic are synthetized in the first section.

In the second section, the status of the technical and scientific objectives of the project is given over the entire project.

Finally, the list of the deliverables due at T0+12 is given.

2 Reminder of CYMS CCN proposal context

This CCN inherits from the CYMS project initiated by CLS and IFREMER, a one-year project that started in February 2020 and ended in June 2021. It aimed at scaling up an operational service for Tropical Cyclone (TC) monitoring, in view of its potential integration as part of a Copernicus Service. In 2020, the demonstration of such a service has been successfully operated and user's requirements refined thanks to a consultation of numerous new end-users among which regional meteorological centers specialized in TC monitoring. More than 90 scenes of TC and 30 over major ones have been acquired worldwide with Sentinel-1A, Sentinel-1B and Radarsat-2 thanks to the late programming acquisitions. These images were processed into ocean surface wind field and disseminated to the user community.

Three main gaps were identified in the Final Report of this initial project in 2021:

- The user feedback on CYMS data confirms that the capabilities of SAR to probe ocean surface winds at high resolution is unique and offers potential for operational TC monitoring (NRT or re-analysis) as well as Science applications related to the analysis of the TC inner core structure. In particular, those observations are crucial over regions lacking any aircraft observation or ground-based meteorological Radars for monitoring and validating the TC forecasts. Another crucial user feedback is the importance of having access to **additional prototypes products and parameters** (e.g. wind radii, independent wind direction, rain filtering).
- The demonstrated capability to observe ocean surface winds at high-resolution has also opened applications to **other intense phenomena** (e.g. Extra-Tropical Cyclones (ETC), Polar Lows (PL), Medicanes or Cold Air Outbreaks (CAO)), and thus to new users and new regions located in European waters. Adapting CYMS to produce and deliver wind products for these cases was thus identified as a major interest.
- Simultaneously, the activity aiming at engaging new users has also allowed the identification **of new user types** with respect to those initially targeted at the beginning of the project (e.g. insurance, maritime transport, private meteorological forecasting companies) and are key users to further motivate CYMS integration as part of a Copernicus Service.

In agreement with these main project outcomes, the following objectives for a CYMS follow-on were identified and a CCN activity was proposed to address them with an extended consortium including METNO on top of CLS and IFREMER.

- Obj. 1 - New end-users and new applications
- Obj. 2 - New products and new parameters
- Obj. 3 - New extreme phenomena

The following section details the content of this objective and their status by the end of the CYMS CCN project.

3 Status of technical and scientific objectives

In this section, we remind the objectives as written in our CYMS CCN proposal. For each one, its status is provided as of end Dec. 2022. Some details of the conducted activities are provided.

A color code is provided:

- Green: this sub-objective is completed
- Orange: this sub-objective has not been fully completed by the end of the project.

3.1 Status of [OBJ 1] - New end-users and new applications

This objective was identified by the European Commission. The objective is to involve new end-users and develop new applications:

- New applications: Assimilating CYMS products over TC and new phenomena (e.g., Polar lows, Medicanes, ETC, cold-air outbreaks…) - new partner (MetNo), project leader in the European consortium of atmospheric modelling (ACCORD) in data assimilation
- New end-users: Maritime transport, insurance, private meteorology…

This objective is articulated along the following steps:

- Illustrate through Use Cases, CYMS service contribution to "the efficient management of emergency situations and the improvement of the security of every citizen" and for "Mitigation and Adaptation".

  ✓ **New applications:**

  - Assimilation exercise of CYMS products by MET Norway, as developed in [ASM]. This short study is meant to investigate the potential of CYMS products for automated assimilation in NWP models. This approach well complements the use of CYMS data by meteorological forecasters in helping them to refine their TC NRT- or re-analysis.
    This short study shows that we can assimilate SAR winds and that the Data Assimilation (DA) system can handle the information as the cost function minimizes smoothly. A number of quality control problems in the screening were not looked into due to time constraints. The small impact in the storm case is actually quite normal even when established observation types are studied, especially when the reference performance is quite good which was the case here, i.e., the Copernicus Arctic Regional ReAnalysis (CARRA) system performed well in representing this storm. With that in mind, it is a good indicator that the SAR wind assimilation only gave minor impact. On top of this, several ideas for future assimilation studies are detailed in the [ASS] document in the recommendations section to improve the assimilation impact. They are based on data selection, aggregation of NETCDF files, quality control and finally use of ambiguous wind components.

  - Model validation: CYMS products also enable better assessing storm events for validation purposes. Bidlot from ECMWF (MAXSS international workshop, 3rd-5th May 2023) showed the usefulness of CYMS products for the validation of ECMWF model in research versions able to better represent extreme winds thanks to a major update in Drag coefficient parameterization.

  - Cloud processing: The ability to process massive datasets on cloud-based environment is becoming a compulsory step, urged by the growing SHOC archive and the increasing need to

process data from L1 SLC products. The capability to process CYMS products on various clouds was successfully tested (Datarmor, Creodia, HAL) using GRD products. Massive processing is still under investigation, major questions questions left being related to the job scheduler of jobs.

✓ **New end-users:** As complement to the first phase of CYMS, several initiatives were performed to approach new end-users and provide them with most exhaustive knowledge to handle CYMS products:

- A first questionnaire was sent to 8000 people and 300 answers gathered to identify their sector, their needs, their application, Region of Interest..

- A webinar was held, reaching 70 registrations and 39 attendees to present CYMS project (objectives, data processing & perspectives), demonstrate accessing data and visualization tools and finally present 3 different use cases with different partners (LACy, Météo-France La Réunion and METNO)

  On top of this general presentation, several individual CYMS presentations were performed throughout the 2nd phase. The following entities were contacted individually and a full CYMS presentation and demonstration was performed. In total, 27 new end-users were contacted individually and 9 visio-conference presentation were performed.
- The Twitter account was regularly updated with real-time wind events covering both Tropical Cyclones but also European based extreme wind events. Its audience raised from 78 up to 169 followers. Best impression tweets are very widely seen with more than 13200 views for TC Danielle.

- The ESA-CYMS website has reached 1682 users while it was only equal to 125 by 2021, which indicates a huge increase of the website audience.

- Similarly, the CyclObs website audience is also constantly increasing and recently reached a maximum number of 430 unique visitors per month during high tropical cyclone season (Feb. 2023).

- Interested end-users are both showing a wider range of industrial sectors and showing a more experienced knowledge of CYMS products. This is illustrated by the two recent publications from JTWC and NOAA which add to the publication from MF la Réunion on their operational use of CYMS products.

  - On the usefulness of CYMS data for JTWC meteorological forecasters: Howell, B., Egan, S., & Fine, C. (2022). Application of Microwave Space-Based Environmental Monitoring (SBEM) Data for Operational Tropical Cyclone Intensity Estimation at the Joint Typhoon Warning Center, Bulletin of the American Meteorological Society, 103(10), E2315-E2322. https://doi.org/10.1175/BAMS-D-21-0180.1

  - On the usefulness of CYMS data for NOAA meteorological forecasters: Jackson, C. R., T. W. Ruff, J. A. Knaff, A. Mouche, and C. R. Sampson (2021), Chasing cyclones from space, Eos, 102, https://doi.org/10.1029/2021EO159148.

- The use of SAR for TC monitoring is now also widely recommended at WMO level, as presented at International Workshop on Tropical Cyclone IWTC-10: “Many IWTC-X attendees commented

on the usefulness of and/or otherwise expressed interest in synthetic aperture radar (SAR) observations with some concern expressed over loss of SAR from Sentinel."

- Raise concern of national delegates from several European countries, to present the service at a Copernicus User Forum.

Following the first meeting with Copernicus representatives on 2020-10-07 during the first phase of CYMS project, the need was identified to raise the concern of national delegates to make CYMS become an operational Copernicus service or at least product. More generally of Copernicus entities that could potentially help in that objective were contacted.

- First contact with **Copernicus/CEMS** team on 20/12/2021 to introduce CYMS.

- Attempt to get in touch with the national delegates of other European countries through our French national delegate to raise the need for monitoring following extreme events via CYMS:
  - polar-lows: Norway and Sweden
  - medicanes: Italy, Greece, Croatia / Ex: Apollo end of October
  - Extra tropical cyclones: Ireland, UK, France, Spain, Portugal, Netherlands, Denmark, Germany / Ex: Barra, Arwen
  - Tropical Storms: France, Netherlands, Spain, Portugal

  ==> Very few feedbacks

- Meeting with Peter Salamon, leader of Emergency Management Service and DG of Disaster Risk management Unit at JRC:
  - Peter recalls that EMS addresses emergency services on land even if he recognizes that CYMS products could be useful as an input for EMS services such as flood forecasting.
  - He has had discussions with Mercator and internally at JRC but there is currently no short-term solution he can provide to ensure CYMS service continuation after July 2022.
  - Peter indicates that the more Copernicus services/products can benefit from CYMS, the easier its integration in Copernicus products, and potentially services after, will be.

- Participation to the French preparation of the **5th CUF** (Copernicus User Forum on June 3rd 2022):
  - Organised by Copernicus & GEO interministerial coordinator (MESR DGRI)
  - Phillipe Caroff (Meteo France), Alexis Mouche & Emina Mamaca (ifremer) were connected
  - Remind that as a user all the interest we have in SAR data on cyclones (reminding the European islands in the various tropical oceans via the French and Dutch islands - the British are now excluded ...), and insisting on the small volume of data that represents the cyclone acquisitions.
  - The French national delegation was pleased to know our cyclone folder well and to have updated the HLOP with the cyclone component.
  - We are not "forgotten", but the current unfavourable context (750 million euros of budget reduction for Copernicus; loss of Sentinel 1B - waiting for the launch of the new Sentinel next year) make it impossible to consider it in the immediate future.

- Discussion with MOi (CMEMS) to present CYMS project and several potential scenarii for uptake of the service (March & April 2022).

This objective is judged not fully met since, after the end of the project, CYMS is not becoming a project funded by Copernicus services such as EMS for TC and extreme wind monitoring by the end of its second phase.

3.2 Status of [OBJ 2] - New products and new parameters

This objective was expressed by CYMS end-users. The objective is to enrich CYMS processing chain with new products/parameters: wind radii, directions estimated from SAR, rain impact (validation, processing chain update, new product documentation).

- ✓ Extensive validation of the L2P (wind maps) products

  The L2P wind products provided within CYMS have been extensively validated. This is all part of the [VAL-1] deliverable: "Validation report - Part 1: Main report", with case study in [VAL-2] deliverable: "Validation report - Part 2: Case study". In the first report, SAR products are successively validated against SFMR, SMAP and other SAR acquisitions. The analysis of this validation reveals inconsistencies between different satellites acquisitions, attributed due to different Sigma0 calibration strategies (e.g. between S-1 from ESA and RS-2 from MDA/CSA)

- ✓ A new candidate GMF

  The identified inconsistencies highlight the fact that identical wind conditions do not lead to identical Sigma0. Since all calibration strategies cannot be aligned among space agencies (at least in the short term), these facts plead for new candidate GMFs, specific to the different SAR missions, to deliver consistent wind maps. This estimation is also made possible thanks to the high number of TC products acquired during the successive SHOC campaigns thanks to ESA and the use of RS-2 acquisitions. New candidate GMFs are still being estimated to provide the most consistent set of CYMS products among the different satellites.

- ✓ New FIX products

  Similarly to the wind maps, the FIX products have also encountered extensive validation, including from meteorological forecasters (as shown in the project bibliography). The products are described in the [VAL-3] deliverable: "TC Vortex Analysis Product" including the algorithm description, the product format and the quality flag available.

- ✓ New wind streaks parameters

  Previously in CYMS products, only Sentinel-1 products could be provided with a wind streaks orientation and an associated estimated error with respect to the ECMWF wind direction. The availability of a larger dataset of TC SAR acquisitions over more SAR missions has now enabled to estimate the associated error for RadarSat-2 mission on top of Sentinel-1 acquisitions. This error is a good indicator of the wind streaks quality, for potential use in assimilation or Bayesian wind inversion.

  The wind streaks estimation chain has also been largely optimized in order to improve the processing efficiency. The overall calculation is now avoiding cumbersome "FOR" loops in two dimensions and using convolutions in complex space. This is making the overall process much faster.

- ✓ New format

  The analysis of feedbacks from CYMS phase 1 end-users has revealed that the L2P products format could be improved to be more compatible with common tools. The product format was accordingly adjusted with the second version of the document and of the products.

Among the various changes, the fill values were harmonized, some variable names are now fully in agreement with CF convention (e.g. latitude and longitude), the product dimensions are changed to allow products' concatenation.

3.3 Status of [OBJ 3] - New extreme phenomena

This objective logically results from the two previous ones. The objective is to operate the CYMS service with new products/parameters for tropical cyclones but also other intense phenomena that affect the new targeted end users: Extra-Tropical Cyclones (ETC), Polar Lows (PL), Medicanes or Cold Air Outbreaks (CAO). The service operation will tackle Sentinel-1A and -1B missions for both NRT and reprocessing activities. Access to RS-2 catalog will be granted to ensure at least the reprocessing activity. No dedicated acquisitions can be made with RS-2. Product access timeliness does not ensure NRT processing (to be confirmed).

- ✓ Identifying and (re-)processing new extreme phenomena into CYMS products: In order to focus on additional extreme phenomena, it is needed to identify them before being able to process them.
  - Polar lows (Reprocessed data): The polar lows from [Rojo et al. 2019] were co-located with Sentinel-1 products to process all the identified products. They are available at: https://cyclobs.ifremer.fr/app/polar
  - Mediterranean storms (Reprocessed and NRT data): Storms identified by the group in charge of the COST action: "European network for Mediterranean cyclones in weather and climate (MEDCYCLONES) https://www.cost.eu/actions/CA19109/. They were co-localized with Sentinel-1 and RS-2 and are available at: https://cyclobs.ifremer.fr/app/extra_tropical and on the NRT platforms (EODA and ftp).
  - Extreme windstorms catalogue (over Europe): The XWS (eXtreme Wind Storms, http://www.europeanwindstorms.org/) catalogue is a freely available database of storm tracks and model-generated maximum 3 second gust storm footprints (both raw and re-calibrated) at ~25km resolution for 50 of the most extreme windstorms to hit Europe in recent times. The catalogue currently covers the period **October 1979 - March 2013**. This catalogue could be used in the future is extended in time.
  - Generic wind extremes (NRT data): In order to provide CYMS products from S1 acquisitions over Europe in a NRT process, a dedicated processing chain was developed:
    - A processing mask is used to select the S1 data of interest (corresponding to European waters),
    - The maximum wind speed provided by ECMWF model over selected S1 slices is used as a threshold to process all S1 products with high winds, for which the CYMS processing is particularly well suited,
    - Detected slices are extended if a single slice is selected in order to provide longer S1 acquisitions, with more contextual information.
- ✓ Identification of forecast tracks to use in the future to extend the service to NRT monitoring with European Extremes. Similarly to TC forecast tracks, there is a clear need to identify forecast track for European Extreme tracks in order to potentially plan acquisition with S1 over region not systematically imaged or using Contributing Collaborative Mission (CCM) to increase the chances to catch such rare events with other SAR missions (e.g. RS-2 or RCM).
  - MedCyclone COST Action: [Flaounas et al. 2023]: This article presents a composite approach to produce reference datasets for extratropical cyclone tracks. It is applied over the Mediterranean cyclones and provides a dataset over time period 1979–2020 but a NRT capability should be made available by the end of 2023.
  - ECMWF internal products: These products have been identified in previous meetings with ECMWF. They consist in forecast tracks of cyclonic features that could be shared in order to feed potential SAR satellites acquisition plan updates.

- Successfully tested: The concept of tasking RS-2 images was successfully tested in late October 2021 with medicane Apollo.

4 CYMS recommendations

This last section is a copy from the [ASS] document in the recommendation section. It summarizes the recommendations from the CYMS consortium based on the analysis of CYMS service as a whole. This also takes into account feedbacks gathered from the [AR] document. As a reminder, feedbacks from end-users and WMO and other Regional Specialized Meteorological Centers (RSMC) are provided in the [AR] document.

The main identified recommendations are the following and are further detailed in the next sub-sections:

1. S1 acquisitions over TC: Review and automatize the overall procedure for updating S1 acquisition plan over TC,
2. SAR acquisitions over European waters: Increase the monitoring of extreme winds over European waters using Copernicus contributing missions,
3. SAR inter-calibration: Monitor and ensure the inter-calibration among SAR-derived geophysical products from the various sensors.
4. S1 radiometric calibration: Monitor with new metrics and improve S1 radiometric calibration,
5. CYMS products geophysical content: Improve the geophysical content of the current CYMS products and enrich them with additional parameters on data quality,
6. Service timeliness: Increase the overall processing efficiency so that all CYMS products can be made available within 3h after acquisition.
7. Tutorials/discussions with end-users: Organize regular meetings with end-users in order to present the content, possibilities and limitations of CYMS products, discuss use-cases with end-users and identify requirements to drive future evolutions.
8. Assimilation studies: The assimilation exercise performed by MetNo has enabled identifying many points to improve the assimilation impact in the NWP model.

4.1 S1 acquisitions over TC

Extensive analysis of SHOC efficiency, i.e., Sentinel-1 performances in catching TC eye were performed. They reveal that the use of Sentinel-1 datatake could be improved by reducing the time between the release of ECMWF forecast track and the update of S1 acquisition plan.

Several discussions have been (and are) performed with S1 mission planning team and are expected to lead to a revision of the CYMS Standard Operation Procedure [SOP] setup with ESA. **The objective is to review and improve the overall process with more automatized procedures** including automated identification of potential S1 passes of interest before modifying S1 acquisition plan and automatized distribution of information to the mission planners.

4.2 SAR acquisitions over European waters

Despite the global effort from the various space agencies to monitor TC worldwide, extreme winds phenomena met over European waters are not as well captured. Even though Europe is systematically imaged by Sentinel-1, it is composed of only 1 satellite (or 2 with the full S1 constellation). In comparison, 5 times more satellites are used for TC monitoring to capture extreme winds. **This results in seldom acquisitions over mid-latitudes phenomena** such as medicanes or extra-tropical storms. Polar lows would also greatly benefit from additional acquisitions as these systems have a small spatial extent and are short-lasting.

In that matter**, the ability to use contributing missions within the framework of Copernicus services would greatly benefit to the monitoring of extreme winds over Europe**, otherwise poorly sampled.

On top of this, the possibility to access to storms database over Europe for both Archive data or NRT is currently being discussed with various entities. It is of high interest for various purposes:

- For NRT activities, it would enable scheduling other SAR missions such as RS-2 using forecast tracks, similarly to what is being done today with Sentinel-1 over TC. Identified sources are:
    - ECMWF: Some sample internal products have been identified in previous meetings with ECMWF. They consist in forecast tracks of cyclonic features that could be shared in order to feed potential SAR satellites acquisition plan updates.

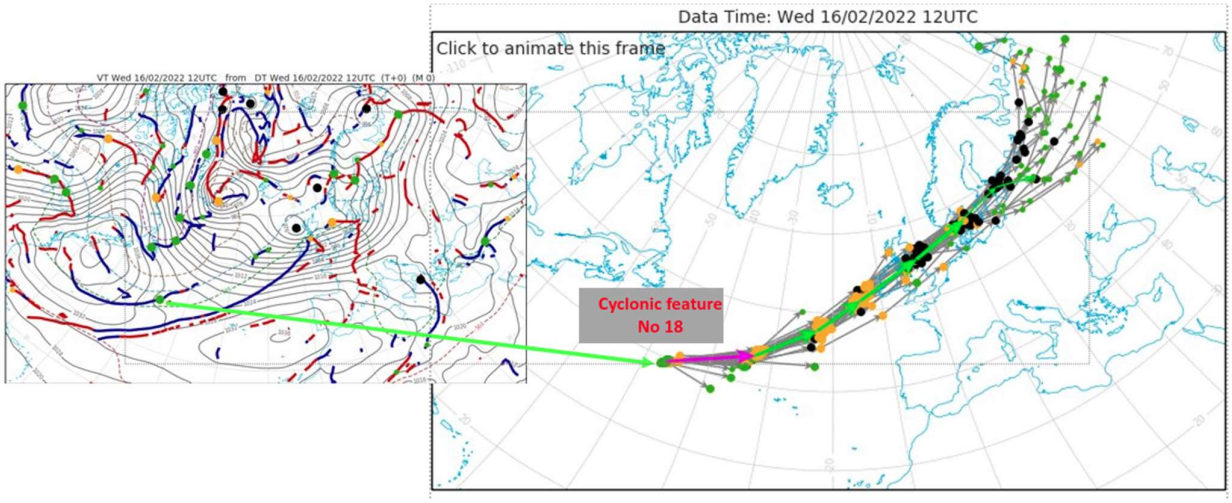

Figure 1: Caption of ECMWF Extra-tropical Cyclone Database (CDB) products illustrated over storm Eunice based on a forecast started on 16th Feb 12Z

    - MedCyclone COST Action: [Flaounas et al. 2023]: This article presents a composite approach to produce reference datasets for extratropical cyclone tracks. It is applied over the Mediterranean cyclones and provides a dataset over time period 1979–2020 but a NRT capability should be made available by the end of 2023.

- For archive activities: They enable better assessing storm events for validation purposes (Bidlot et al. 2023 - MAXSS international workshop, 3rd-5th May 2023) and for their overall effect, at a larger scale that just for a single SAR observation. They also provide possibilities to characterize the event using other sensors and parameters (e.g., SST, SSS anomalies):
    - ECMWF presentation from Jean Bidlot at MAXSS show the usefulness of CYMS products for the validation of ECMWF model research versions able to better represent extreme winds.
    - Extreme windstorms catalogue (over Europe): The XWS (eXtreme Wind Storms) catalogue is a freely available database of storm tracks and model-generated maximum 3 second gust storm footprints (both raw and re-calibrated) at ~25km resolution for 50 of the most extreme windstorms to hit Europe in recent times. The catalogue currently covers the period **October 1979 - March 2013**. An estimate of the uncertainty of the gusts for each re-calibrated storm footprint is also provided. http://www.europeanwindstorms.org/
    - MedCyclone COST Action: [Flaounas et al. 2023]: Similarly to the archive dataset presented in the paper, a NRT capability should be made available by the end of 2023.

4.3 SAR inter-calibration

Today, several initiatives from ESA, CSA, MDA Space and JAXA are contributing to the monitoring of TC worldwide with SAR acquisitions from S1, RS-2, RCM-1, -2, and -3 and ALOS-2.

This leads to an unprecedent frequency of TC acquisitions with SAR:

- Over the past years: S1A, S1B and RS-2 each contribute approximately equally to nearly 30 acquisitions over TC eyes per year, each satellite bringing new co-location opportunities with the TC track.
- Recently with TC Freddy, the impact of the additional 3 RCM satellites in the TC monitoring has particularly well illustrated the new capabilities with more than two SAR acquisitions over TC eyes per day.

Despite this wealth of TC SAR acquisitions, significant differences exist between 1- the acquisition strategy (e.g. the ocean basins monitored for acquisitions over TC) and 2- the SAR sensors' calibration.

- For the first point, it is relevant to ensure that, at global scale, the TC monitoring requirements from all regional centers are met. Therefore, it is first important identify, for each SAR mission, which ocean basins are TC-monitored and how, and then to possibly adapt it, if not satisfactory. For instance, in the past years, TC occurring in the North Indian Ocean were not as frequently monitored with S1 and RS-2 as in the Southern Indian Ocean.

- For the second point, differences in SAR calibration are partly attributed to varying NRCS calibration strategies among the space agencies (e.g., C-band missions from ESA, CSA and MDA Space). This results in discrepancies between the different missions of the downstream CYMS products (L2P and L3) if they are processed with the same algorithms**. A dedicated activity is therefore needed to make sure that all L2P and L3 products are consistent by proposing a common calibration and validation chain of either the Level-1 or the downstream products**. This work has already started for RS-2 and S1-A and S-1B comparisons, enabling correcting for large wind speed discrepancies, sometimes reaching 20 m/s for RS-2 and 7m/s for S1-A acquisitions. Yet, this work remains to be done for RCM and ALOS-2 before including them into CYMS framework.

4.4 S1 radiometric calibration

Sentinel-1 radiometric calibration is well assessed and known thanks to the joint activities performed as part of the Sentinel-1 Mission Performance Center project (MPC-S1). The Sigma0 quality is regularly improving over time with new IPF releases (Instrument Processing Facility). Yet, some issues can still be mentioned:

- The quality of the newly acquired products or old S1 data provides the best possible S1 data quality whenever processed with the latest IPF version. However, **preparing Cal/Val activities require a homogenous and the highest data quality over the largest possible dataset**. Possible ways to prepare this are:
    - Reprocessing from Level-0 with the IPF via the MPC-S1 facility,
    - Reprocessing from Level-1 with the latest retro-calibration possible (Schmidt et al. 2023) and then a Level-2 Wind processor.

  Depending on the number of products to process, the first solution may not possibly be applied. The second solution can therefore prove particularly useful for a more flexible way to process S1 data to the highest data quality level.

- Even with the latest IPF version, some large radiometric calibration inconsistencies can exist, particularly visible at subswath edges (reaching ~0.5dB) for both co- and cross-pol, including for winds > 20 m/s. This is illustrated in Figure 2 where a Beta0 discontinuity is visible at IW1-IW2 subswath change with differences larger than 0.5dB for both noise-corrected and noise-uncorrected data. Such products are manually detected via the daily processings performed by CYMS over both TC and European extremes. Such detected issues are typically passed to the MPC-S1 and discussed together with the L1 and L2 teams. However, **a more**

systematic monitoring of such inconsistencies should be implemented within the MPC-S1 by adding new metrics S1 radiometric calibration process.

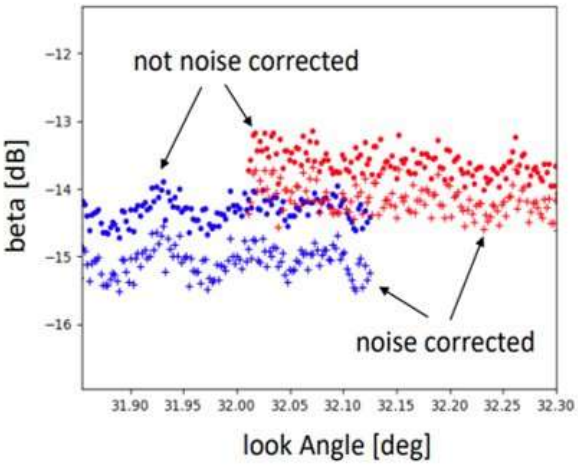

Figure 2: Analysis from Kersten Schmidt (DLR) on a S1 IW SLC data presenting large subswath jumps between IW1-IW2. For the current case, difference between sub-swaths even increases with noise correction (S1A_IW_SLC__1SDV_20220502T172608_20220502T172635_043035_052376_F155.SAFE)

4.5 CYMS products geophysical content

Feedbacks from the end-users, mainly meteorological forecasters, indicate that the currently provided products can be misleading and confusing. On top of the aforementioned issues (S1 radiometric calibration and consistency among SAR sensors), two main issues have been identified and are presented below.

4.5.1 Rain contamination and data quality

As mentioned in the [AR] deliverable, the quality of the SAR data can sometimes be very questionable for isolated situations. E.g., of Freddy on 08/03/2023 at 15:42 UTC indicates largely over-estimated Vmax (reaching 55 m/s) with respect to the Best Track data. This is seen on different sensors (RCM and Sentinel-1) thereby suggesting that this is not sensor-specific but rather attributed to the atmospheric conditions. In the present case, we suspect the rain contamination to be responsible for this overestimation. One issue with the current contamination is that it could not be detected based on the currently implemented heterogeneous filter. Additionally, undergoing research based on the texture analysis using DNN (Deep Neural Network) methodologies are not foreseen to identify such effects due to their rare occurrence and co-location with coastal rain radars. Other methodologies described in the literature based on the agreement between SAR observables are expected to be more promising (Zhao et al. 2023).

In a more general approach, it is a high priority to better identify all non-wind related processes expected to affect the SAR measurements and the downstream wind products. Some specific methodologies, applied as pre-processing modules ahead of the wind-inversion and based on the Sigma0 texture analysis, are already in place to filter bright targets and rain-related signatures inducing large heterogeneous features. Yet, they cannot answer this general issue alone.

To address this issue, it can be useful to take advantage of the wide range of observables provided by SAR measurements:

- Co- and Cross-polarized Sigma0 [Mouche et al. 2017 - Combot et al 2020],
- CCPC (Co- Cross- Polarization Coherence) [Longepe et al 2021],

- Doppler shift [Moiseev et al 2020],
- MACS (MeAn Cross-Spectra) [Li et al. 2019],
- wind streaks direction [Husson et al. 2021 – Zanchetta and Zecchetto 2020],

Their dependency on wind conditions is documented in the literature and their common agreement can be a very good approach to better quantify the SAR-derived wind quality. Besides, this topic is highly related to the following one.

4.5.2 Wind field estimation

The current wind inversion scheme is implemented based on [Mouche et al. 2017]. The downstream L3 (FIX) product is based on this L2P product. **The wind inversion methodology does not take advantage of all the possibilities that S1 can offer and that could greatly improve the quality of SAR-derived wind**:

- The wind direction currently estimated in the Bayesian process is strongly influenced by the model which often differs significantly from the actual situation observed by SAR close to the storm center. Wind streaks information is provided in the product as a separate variable but not included in the Bayesian scheme. Other SAR observables impacted by the wind direction should be included to provide a more model-independent wind retrieval: the Doppler Shift and the CCPC altogether provide a complementary wind vector estimation as shown in [Longepe et al. 2021], the estimated error on the wind direction error based on the wind streaks can facilitate the inclusion of this variable in the Bayesian scheme. Finally, MACS parameter can also be used to further constrain the wind inversion if an associated GMF was also developed and integrated in the Bayesian scheme.

- The current wind inversion is performed from the GRD products and such developments thus involve a re-architecture of the wind inversion process as some of the previously mentioned variables need to be estimated from the SLC products.

- More globally, this evolution of the Level-1 to Level-2 wind processing will also benefit to other geophysical variables which are closely nested with the sea surface wind estimation: the radial sea surface current and the wave parameters such as the total, the wind sea and the swell Hs.

4.6 Service timeliness

Currently, the service analysis in the previous sub-section **Error! Reference source not found.** has revealed that about 50% of the data was processed within 3 hours after acquisition time. Yet, in order to be used for forecasting but also potentially for assimilation purposes, it is mandatory to increase the service efficiency so that 100% of the data is made available in the time useful for NRT constraints.

This would require increased processing capabilities to improve the service timeliness and operational processing facilities to ensure a better Service Level Agreement (SLA).

4.7 Tutorials/discussions with end-users

The complexity of certain SAR acquisitions can require in-depth analysis of the situation by meteorological forecasters who are not necessarily well formed to fully understand the reliability, the quality and the content of the SAR-derived measurements. It is therefore important to setup a long-term loop of SAR tutorials and discussions allowing for in-depth discussions on CYMS products content, measurements possibilities and limitations to describe meteorological situations of interest and to keep including end-users needs for the development of future products. The end-users' practices are also a topic of interest as mentioned in the [AR] deliverable and they should be discussed in terms of data format, data access to keep improving end-users experience with CYMS products.

Past meetings with end-users within the framework of various projects (e.g., CYMS, RenovRisk, WMO Tropical Cyclones meetings) have proven very useful in better understanding their needs and identifying their reference sources and their practices.

It is therefore important to maintain a framework to **organize regular meetings with end-users** in order to present the content, possibilities and limitations of CYMS products, discuss use-cases with end-users and identify requirements to drive future evolutions.

4.8 Assimilation studies

The assimilation exercise of CYMS products by MET Norway, further developed in [ASM] document, shows that we can assimilate SAR winds and that the Data Assimilation (DA) system can handle the information as the cost function minimizes smoothly.

A number of quality control problems in the screening were not looked into due to time constraints. The small impact in the storm case is actually quite normal even when established observation types are studied, especially when the reference performance is quite good which was the case here, i.e., the Copernicus Arctic Regional ReAnalysis (CARRA) system performed well in representing this storm. With that in mind, it is a good indicator that the SAR wind assimilation only gave minor impact.

We outline below some points to be further considered:

- Data *selection*: Several impact studies would be needed to better identify the useful of all parameters provided in CYMS products. E.g., the **wind streak orientation** may be better to use for wind direction (mainly model driven) in some cases. This was already illustrated in [Duong et al. 2021]. Additionally, it would be useful to test the impact of using the **heterogeneity mask** to decipher between valid vs. non-valid pixels.
- Aggregating NETCDF files: If SAR data is available from **different satellite passages** withing the same assimilation window then they would be in different NETCDF files. There is already a solution to this. In later HARMONIEAROME versions this can be handled by the system in the BATOR script.
- Quality control: There should be more time spent on developing a more mature handling of SAR winds especially in the screening. E.g., making sure the **first guess check** is done and tuned properly. Also, making sure that SAR winds can be used together with other scatterometer data such as ASCAT.
- Use of ambiguous wind components: Overall, we think that since other scatterometer products are assimilated with the ambiguous wind components that DA methodology is more mature. It would therefore be better if the ambiguities were kept in the data provided to NWP. Then a SAR **DA methodology with ambiguities** can and should be developed.

5 List of deliverables

List of deliverables due at T0+3:

- Standard Operation Procedure
  - Updated technical note with standard operation procedure defined between end-users and ESA mission planners

    [SOP] delivered.
- Collected end-user requirements
  - Technical note with collected end-user requirements

    [EUR] delivered.

List of deliverables due at T0+9:

- Product user Manual
  - Product user Manual: draft @ T0+6 and final version @ T0+9. This document is available on the project website here.

    [PUM] delivered.
- User guide for online catalogues
  - User guides for online catalogues (EODA + CyclObs): draft @ T0+6 and final version @ T0+9
  - The user guide for Cyclobs is already integrated on the website (see here). It is provided with python notebook and API tutorials. This document is available on the project website here.

    [UG] for EODA delivered.

List of deliverables due at T0+12:

- CYMS products assimilation
  - Technical note or draft publication on the results from testing the assimilation of CYMS products in numerical atmospheric model

    [ASM] delivered
- Technical note or scientific paper on product validation

  [VAL-1, 2 and 3] delivered.
- Presentation of service evaluation, potential evolution, recommendations
  - Technical note on service technical evaluation and potential evolution, recommendations

    [ASS] delivered
- In the Monthly reports, all the activities performed are described.

  [MR] delivered
- Contract Closure Document

  [CCD] delivered
- Final Report (this document)

  [FR] delivered
- All presentations used during the project meetings are also available in the CYMS Sharepoint directory.

Appendix A - Acronyms

BOM	Bureau Of Meteorology
BUFR	Binary Universal Form for the Representation of. meteorological data
CEMS	Copernicus Emergency Management Service
CMEMS	Copernicus Marine Environment Monitoring Service
CPHC	Central Pacific Hurricane Center
CYMS	CYclone Monitoring with Sentinel-1
EC	European Commission
ECEPS	ECMWF Global Ensemble Prediction System
ECMWF	European Centre for Medium-Range Weather Forecasts
FTP	File Transfer Protocol
GMS	Geostationary Meteorological Satellite
HK	Hong-Kong
HKO	Hong-Kong Observatory
HNPW	Humanitarian Networks and Partnerships Weeks
IMD	India Meteorological Department
JMA	Japan Meteorological Agency
KMA	Korean Meteorological Administration
LACy	Laboratoire de l'Atmosphere et des CYclones
MF	Météo-France
NASA	National Aeronautics and Space Administration
NCEP	National Center for Environmental Prediction
NetCDF	Network Common Data Form
NMS	National Meteorological Services
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
RSMC	Regional Specialized Meteorological Centres
RMW	Radius of Maximum Wind
SAR	Synthetic Aperture Radar
SWIO	South West Indian Ocean
TCWC	Tropical Cyclone Warning Centres
TC	Tropical Cyclone
UKMO	United Kingdom Meteorological Office
WMO	World Meteorological Organization
WWMIWS	Worldwide Met-Ocean Information and Warning Service