Coastal Erosion from Space

Coastal Erosion events:

in Nerja (Spain) *in Kilkee (Ireland)* *in St Laurent mouth (Canada)*

Requirement Baseline Document

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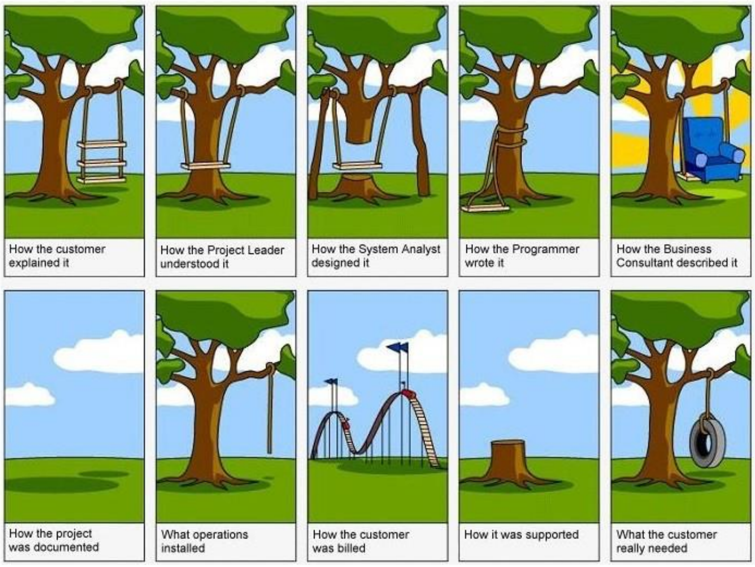
A self-explanatory cartoon to justify the publication of a Requirement Baseline



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Applicable and reference documents

Id	Description	Reference
AD-1	User Requirement Document	To be supplied by BGS

Contents

1 Introduction

1.1 Statement of Intent

This document, called the **Requirement Baseline Document** (RBD), presents the requirement baseline for the "Coastal Erosion [monitoring] from Space" project and fulfils the requirement for Milestone 1 of the first phase of the contract with ESA.

As required by ESA it gives "*a detailed requirement analysis and synthesis* […] *with the consolidated* **User Requirement Documents** (URDs) *collected during the proposal preparation and consolidated during the initial phase of the project* [thus including] *reviewing with the end-user organisations and obtaining their formal acceptance* [as demonstrated by the publication of the URD under their own brand —an official document of the British Geological Survey (BGS) on behalf of all governmental bodies involved]".

The finalised URD is annexed to this RBD for ease, however it will also be forwarded as a separate document under its own authority as a specific task assigned to the "Authoritative End User Group". The URD provides the latest/ revised requirements of these authoritative end-users who are partners of Argans Ltd for this contractual project —they include the British Geological Survey (BGS) and Geological Survey Ireland (GSI), which are the national agencies acting on coastal erosion monitoring in their respective countries, the Instituto de Hidráulica Ambiental de la Universidad de Cantabria (IHC) on behalf of the Subdirección General para la Protección de la Costa (SGPC)[1] of the Ministerio para la Transición Ecológica of the Spanish government, and the Canadian company Arctus, on behalf of the Chaire de Recherche en Géosciences Côtières of the Université du Québec à Rimouski (UQAR) which is funded by the Government of Quebec in the 2013-2020 loss prevention framework; these organisations act as representatives of coastal authorities for UK, Ireland, Spain and Quebec region of Canada respectively. The revised URD has synthetized the needs of these institutional users in

[1] Dirección General de Sostenibilidad de la Costa y del Mar

order to facilitate the design of common products with minimal adjustments to local conditions and goals.

This document describes the Requirement Engineering, the User Requirement Documents (URD) produced by each of the end-users, in the framework of the ESA requirements. These requirements can be found in AD-1 (submitted separately).

The Requirement Engineering process shall define, document and maintain the requirements: one not only gathers the requests & requirements but also defines the service that should be provided, the products. The steps are the following: - requirement specification (ESA SOW and URD), - requirement specifications (Section 2), - requirements verification (Section 3), - requirements validation (Section 4), and – requirements management (Section 5).

The techniques used for requirements specification by ARGANS Ltd and the end-users were threefold: reviews of available documents, interviews of the end-users' work beneficiaries, and brainstorming that was concluded by a workshop in Santander by July 2019. The requirements specifications were drawn concomitantly by the end-users and by ARGANS Ltd, the latter working from the URD versions. The requirements verification was made of a pre-feasibility study with the goals of coastal geomorphologists in mind, as the URD, on the ESA template, contains quantified specifications of EO products to sketch the thematic specifications. Requirements validation, i.e. the set of tasks that ensure that the system and the EO-products has been built is traceable to end-users' requirements, is a document which will be finalized at the end of phase 1, when the aforesaid system and products will be definitively prototyped. With request to the Requirements management, i.e. collecting, analyzing, documenting, tracking, prioritizing and agreeing on the requirements, it shall be performed by versioning the RBD.

Table 1.1: Requirements for compliance during phase 1 of the project. These shall be delivered in specific documents (X). (RBD = Requirement Baseline Document, TSD= Technical Specifications Document, PVP= Product Validation Plan, N/A= Not Applicable)

Phase 1 -activities		reports		
		RBD	TSD	PVP
Req_Ph1-1	Consolidating, with an active contribution of the end-user organisations, the user requirements, and documenting the individual user requirements with the use of User Requirement Documents (URD) that shall follow the URD template provided in the Annex A to the present Statement of Work;	x	N /A	N/A
Req_Ph1-2	Performing a detailed requirement analysis and synthesis that shall be documented in the Requirements Baseline (RB);	X	N/A	N/A
Req_Ph1-3	Reviewing the Requirements Baseline with the end-user organisations and obtaining their formal acceptance	X	x	x
Req_Ph1-4/1	Describing in detail the requested service;	TSD	x	N/A
Req_Ph1-4/2	Describing in detail the ensuing products;	TSD	x	N/A
Req_Ph1-4/3	Specifying in detail the requested service and the ensuing products;	N/A	x	N/A
Req_Ph1-5	Assessing different implementation schemes for the service and products;	TSD	x	N/A
Req_Ph1-6/1	Investigating and documenting alternative methodological approaches and algorithms for generating the products	N/A	x	N/A
Req_Ph1-6/2	Investigating and documenting alternative methodological approaches and algorithms for validating the products	N/A	N/A	x
Req_Ph1-7	Assessing and testing the feasibility of the proposed end-to-end service processes through a Proof of Concept that shall be based on a solid and well-selected set of EO Test Data Sets (TDS) and prototyped products;	N/A	x	x
Req_Ph1-8	Establishing a sound and scientifically meaningful validation methodology that shall be implemented in the second phase of the project;	N/A	N/A	x

		reports		
RB		RBD	TSD	PVP
Req_RB-1/1	The Requirement Baseline Document shall contain a detailed specification of the user requirements;	x	N/A	N/A
Req_RB-1/2	The Requirement Baseline Document shall be considered as the primary input for all engineering tasks of the project;	TSD	x	x
Req_RB-2/1	The RB shall be written in close collaboration with the end-user organisations;	x	N/A	N/A
Req_RB-2/2	The RB shall include a synthesis and critical analysis of all user requirements;	x	N/A	N/A
Req_RB-3	The user requirements collected from each end-user organisation shall be attached to the Requirement Baseline as individual URDs;	AD - 1	N/A	N/A
TS				

Req_TS-1	the TS Document shall include a detailed description of the service and its products in response to the URDs outlined in the RB;	TSD	x	N/A
Req_TS-2/1	a detailed technical description of the service as seen from the end-user side;	None	x	x*
Req_TS-2/2	an assessment of different implementation schemes for the service, and a well-documented justification of the selected implementation scheme;	TSD		
Req_TS-2/3	an architectural design of the service;	TSD	x	N/A
Req_TS-3/1/1	a detailed description of each product, including the supporting documentation such as the Algorithm Theoretical Basis Document (ATBD);	TSD	x	N/A
Req_TS-3/1/2	the corresponding metadata;	X	x	N/A
Req_TS-3/1/3	the supporting ancillary information;	X	x	N/A
Req_TS-3/1/4	the particular tailoring to certain areas or to certain users;	None	x	N/A
Req_TS-3/2	an assessment of the alternative methodological approaches and algorithms for each product, a well-documented justification of the selected methodology and algorithms;	None	x	N/A
Req_TS-3/3	a product generation workflow (input data, end-to-end-processes, output);	None	x	N/A
Req_TS-4/1	a summary of all experimental and critical analysis done during the requirement and system engineering;	TSD	x	N/A
Req_TS-4/2	all trade-off, design choice justifications, feasibility analysis and technical assessments;	X	x	None
Req_TS-4/3	results of the Proof-of-Concept done at the end of this first phase;	None	x	None
Req_TS-4/4	final justification of the methodological and algorithmic choices;	N/A	x	x**
Req_TS-5	update of the data procurement plan (for the production and validation of the products) related to the second phase of the project;	N/A	x	x***
PV				
Req_PV-1	the PVP shall contain a scientifically-sound validation protocol;	N/A	x	x
Req_PV-2/1	description of all the activities planned by the Contractor to obtain the best acceptance of the EO products;	N/A	N/A	x
Req_PV-2/2	description of all the activities planned by the Contractor to obtain the best acceptance of the service by the end-user organisations;	N/A	N/A	x
Req_PV-3/1	detailed specification and justification of the validation methods	None	x	x
Req_PV-3/2	detailed specification and justification of the validation metrics	None	x	x
Req_PV-4	complete and unambiguous list of the validation input and reference data	N/A	N/A	x

(*) the service comprises the information of the users about the validation of the EO products

(**) the methodological and algorithmic choices depend on the results of the validation

(***) the procurement plan includes data needed for the validation

1.2 Review of the project's objectives

Coastal erosion is recognized worldwide as a great threat for human establishment, and the number of academic publications in scientific journals about the use of remote sensing from satellite (EO) has soared in the last decades.

However, surveys by EO have not yet been considered as core professional components of marine & land sites' characterization services[2] by the big geotechnical & survey companies and by the national agencies working on assets' integrity, though they all have EO offices aside their marine, ground & aerial survey departments, these latter adopting the use of LIDAR, SONAR, seismic systems, gravimeters, ground penetrating RADAR, magnetometers, resistivity tomographers, wireline logging, self-potential measurement devices, etc.

Remote Sensing laboratories departments in public research institutions, including universities and start-ups from these laboratories have long since expected that EO would supplement or replace the "old" techniques supporting geotechnics and geographic tools which would be of the same value and providing even greater utility at a lower price; yet, despite the investment in academic research and in education of students, EO still remains an under utilised technology and start-ups struggle to break the barrier to SME growth. Either (i) there is no great technological progress, or (ii) adaptation to new technologies is innately slow as it requires great effort, with associated risk[3], or (iii) demand has yet to be correctly identified.

ESA's requirements address the first two issues, while the URDs address the third. This ESA project has its root in the belief that technological progress, demonstrated by the publication of so many scientific papers (see Section 2.2.1) exposed to professionals (in this specific case of monitoring coastal erosion) by EO, is core to introducing EO and breaking the barriers. The excitement is

[2] marine geotechnics, hydrographic and geophysical surveys, metocean surveys and marine environmental services, geological & geotechnical ground investigations…

[3] innovation resistance is possible due to a negative feedback in the economic system; and social groups, socio-professional groups, as well as any other systems, are characterized by negation of innovation changes $\Rightarrow$ the adaptation of social groups to new ideas and innovation takes quite a long time…

nonetheless soothed by the recognition that economic systems resist innovative changes due to the inertial nature of their development. Accordingly, due to the challenges of reorganizing such large institutions, the risk of adopting innovative/new technological trends (a path–dependent process) is far greater, leading to a reliance on incumbent and proven technologies (discounting the potential value of the former).

For these reasons ESA has assigned great value to the implication of "authoritative" end-users; **Therefore, this project has been conducted with world leading institutions who have partnered to from an Authoritative End User Group**.

These institutions which comprise this group which sustain the public services are de facto, due to the necessity of social stability. The scale of these organizations mean that adoption of new technologies requires great effort, creating a limiting factor in the speed of deployment. Accordingly, these public services would use any assistance in justifying the necessity and credibility for these technologies. Furthermore, endorsement of EO technologies by the authoritative end-user group is invaluable in accelerating wide-scale adoption of EO by coastal management stakeholders.

We are therefore especially grateful and thank our partners who have accepted the challenge of assessing the value of EO for fulfilling their needs. Of course, they represent the institutional pillars of 'coastal erosion monitoring', which remain a topic managed at regional, national or supra-national level, rather than local levels. These institutions benefit from national investment and have an overarching policy, authoritative and strategic role and as such have provided that viewpoint.

Argans [4], however recognises that the organisations who conduct local level surveys and those who deliver engineering projects (including new entrants, and often supported by independent academic and research institutions[5]) which serve local communities are often distant from this strategic level, have a slightly differing requirement and by us combining these two user views will ensure a closer link and deliver much more effective and efficient products and services.

[4] Argans Ltd benefits from the experience of one such company, ACRI-IN which belongs to its corporate group

[5] ESA considers the new entrants to be represented by the second consortium which was allocated a // contract with same objectives

Does EO compete with other technologies to fulfill needs which are already satisfied with varying levels of success or does it fulfill needs that have never been satisfied?

The answer to the former question is positive for this project, as demonstrated by the End User Requirements (URD) that are published in appendix 1[6].

The COPERNICUS program, with a lifetime roughly similar to a career should facilitate users' uptake, as long as the value (In its own right or as a complementary technology to existing methods) of the EO is higher than the value of the other existing technologies, whether traditional such as surveys from planes or the newer technologies such as drone surveys, crowdsourcing etc. The attached URD validates the demand; yet, the performances which are specified in the URD are far from being achievable, except by aerial surveys —which is therefore the reference standard.

The cost, with free public EO data, are advertised as being so negligible that the economic value of surveys looks like collapsing.

However, for EO, the direct costs for users are on expensive VHR commercially supplied data acquisition if needed, cheap Public HR and Commercial VHR data processing, very low exchange costs due to handling low-priced digital data/ products in small number (even if global), and high transaction costs[7] due to:

- search & information (too many players on the market, too many data & product sources, no standard, lack of specialists to specify information needed),
- bargaining (the spread of prices, owing to lots of new entrants and R&D subsidies, which puzzles the end-users and increase the 'bargaining cost', i.e. delay of orders/purchases),
- policing & enforcement (possibility to act when a party does not satisfy its commitment),

[6] but other users may privilege the second case, though we don't know of any revolutionary EO-product which could give birth to a new market

[7] Also termed 'institutional costs' and defined as "any costs that are not conceivable in a "Robinson Crusoe economy"—in other words, any costs that arise due to the existence of institutions"

- confused rationality and opportunism when acting on the market (e.g. using EO to get grants rather than exploiting/ selling, or valorizing downstream services for the mere sake of getting space segments' funding),
- lack of protection of expertise (e.g. specification) and property rights (e.g. open source),
- unstructured suppliers (a dispersion of players not justified by local tropism, and jack-of-all-trade activities).

Important, the above conditions hamper EO uptake by surveyors or their customer.

Our priority is to design services that are of high value in the range of survey services, while reducing the transaction costs.

It is common-place to highlight that the stand-out factor of EO compared to the other technologies is the supply of instantaneous synoptic views with a very large Field of View (FOV), a differentiating attribute which is mitigated by the degradations due to the height of the satellites at some 100s of km above the Earth. Surveyors have drawn shorelines by hand on EO data for decades with the intention of using remote sensing techniques to map and predict the beach erosion patterns and beach sediment responses to coastal dynamics for management purposes. This attribute of EO satellites has existed for decades, and the question remains "why isn't EO core to coastal geomorphology studies?".

A partial answer is that EO identified coastal geomorphological features and shoreline changes, but further processing was not applied to delineate zones based on their sand & silt budget, although erosion rates were supplied[8]. Another answer is that uncertainties were seldom analysed despite

[8] not only are the 1D products not systematically representatives of the 3D fields, but the transformation of the proxy-based 1D shoreline indicators in datum-based 1D shoreline indicators bears more uncertainties than the delineation of the proxy-based 1D shorelines

scientific validation[9], with aliasing effects due to random sampling in an environment which moves at the sea waves' scale, tidal scale, storms scale that put in question the erosion rates' significance[10].

Drawing shorelines on optical-VNIR[11] and SAR EOs is traditionally performed by photo-interpreters seamlessly. The photo-interpreters combining bands to enhance the contrasts of the features against the background according to their experience of surveyors; the automatization of shoreline indicators' drawing was not a priority, except for the geolocation of the EOs and the stacking of EOs in time-series whose components could be compared one against the other, and the context can only change if the demand targets long-term analysis on large areas, and related customers exist, i.e. regional organizations with mandates (accountability and responsibility) and budgets for coastal erosion management.

Rather than improving efficiency of automatic shoreline extraction on EOs by image classification, artificial intelligence, morphological operations, etc., the **top priorities are;**

- the delivery of **uncertainty budgets** whatever the method
- the **pre-processing of the EOs** incl. colocation to get spatial accuracies of the same order as the spatial resolution, inter-calibration and/or normalization for the extracted shorelines to be similarly reliable before calculating change rates that could contingently translate in erosion rates.
- the design of **terrain models** in order to assess the local imbalance in the supply and export of shore materials which make up for coastal erosion and to calculate erosion rate in volume/length/time, e.g. in m^3/m/year, rather than the coastline shift rate in m/year for the record, the mere shoreline extraction from EOs, the simplest being the waterline, i.e. the

[9] unfortunately, very limited and exclusively focused on the individual shoreline extractions

[10] erosion rates that, for instance, are calculated on a temporal set of extracted shorelines' positions with The Digital Shoreline Analysis System (DSAS) of ESRI ArcGIS v.10 that enables a user to calculate shoreline rate-of-change statistics from multiple historic shoreline positions but without taking care of the coastal geomorphology dynamics, thus delivering estimates of little value

[11] Visible & Near Infra-Red bands

instantaneous landward border of the water body[12], does not provide an unambiguous answer. These "shorelines" need be assimilated in models[13] to deliver the coastline shift rate or the erosion rate; the same is true for land and seabed features.

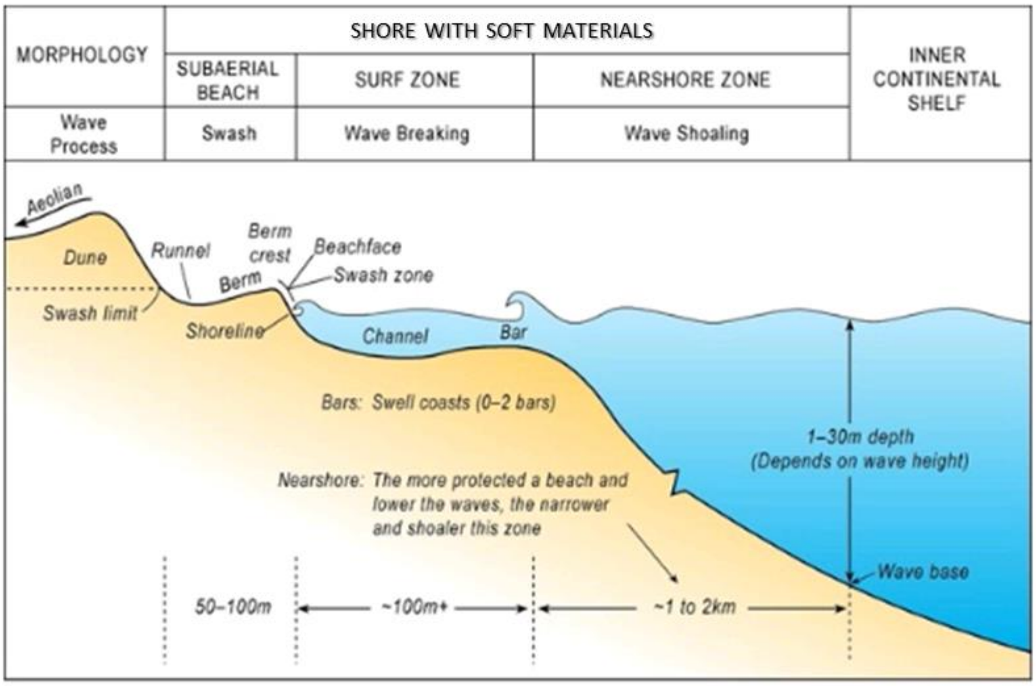


Figure 1.1: Description of the cross-shore profile, defining the extent of multiple coastal zones and the associated coastal geomorphology. Source: Short, 2012

When we are successful in delivering EO products of value for assimilation in geomorphological models, even the simplest, and demonstrate this on a minimum of 1000 linear km of coast, split into 3 different ESA member states, with products "*suited to end user requirements over the past 25 years*", we would be fulfilling the requirements of ESA for the promotion of EO.

[12] difficult to define because of the wtare dynamics, the porosity of shore materials, and the sea-spray

[13] "it is essential to understand this geologic framework before attempting to model the large-scale behavior of [...] coastal systems" (Riggs et al., 1995), all the more than the systems have a behavior which is governed by hysteresis (dependence of the current state of a system on its history) and not Markov properties (memoryless)

We will be delivering valuable information to authoritative end-users which would then simulate the EO downstream sector, advocating the novel observational capabilities of the Sentinel-1 and Sentinel-2 constellations and the complementarity with the EO missions of the past, and making the best of the R&D projects funded under the major European EO application programs.

1.3 Abstract of the document

After updating the user requirements introduced in the contractual proposal 18 months ago, a new version is published in the URD at Annex 1. Initially a first list of 17 universal EO-products was derived. These products were considered in a pure academic manner without reference to specific EO missions and sensors. However, these EO-products (solutions) were specific to the countries involved (UK, Ireland, Spain and Canada), and to the sites chosen for demonstrations. A further analysis of commonalities and a pre-feasibility analysis was performed which led to the definition of **five basic EO products**:

- Four generic EO products at level 2, i.e.
  - two proxy-based shoreline indicators (waterlines, and MHWM-OHWM-vegetation lines-seafront),
  - one subsequent datum-based shoreline indicator (shorelines based on tidal datum and cross-shore profiles, calculated from waterlines), and
  - one plain shoreline indicator (bathy-topo morphology of the shore-bed),
- One statistical Level-3 product (mean MHWM-OHWM-vegetation lines-seafront).

In addition, three intermediary Level-2 and Level-3 products (the cross-shore profiles, the LU/LC maps based on a single EO or multiple EOs) which are used to deliver the previous products and will therefore not be validated.

Finally**, a time-series of the previous basic EO products will be defined.**

Time sampling is critical to assess the erosion status of the shores whose dynamics are complex with a quasi-equilibrium built on a series of erosion events and recovery periods superimposed on trends of erosion or accretion depending on the local availability of materials introduced in the ocean. Typically, shoreline retreat is a consequences of processes operating in two distinct scales: i) **Short-term large-scale** morphological change**,** due to extreme conditions (storm conditions, high impact waves / surges causing break-up of land barriers) that are not rebuilt by natural accretion/replenishment; ii**) Long-term small-scale** morphological change, including natural seasonal cycle of erosion and accretion. EO resolution (VHR) and spatial accuracy is core for coastline shift estimation accuracy in the latter case, whereas HR observations are deemed acceptable for the former. To complete a time-series, all EO missions shall be considered; the best approach being to use same algorithms for all optical EO missions' data and for all SAR EO missions.

This approach has led to the choice of standard EO products at Level-2, with common data processors that are parametrized according to the sensors.

All EO-products will be produced by automated processors, which can be parametrised according to the area of interest. These parameters will utilise a suite of multi-spectral indices (e.g. NDVI, NDWI, MNDWI, etc.) and represented in a mapping system / projections or geodetic systems, which are configured to the scale and conditions of region of interest. Furthermore, all data will be presented in a format that can be utilised by the Geographic Information Systems (GIS) of choice. These parameter selections need to be specified by the intended user and should consider the environmental conditions of the shoreline during the observation period (Beach morphological type, tide regime, geology and sea state). Future work will utilise the results of validation testing (planned for Phase 2 of this project), to generate algorithms that will automate this parameter selection process.

The EO-products will contain:

- files of shoreline indicators' location
- files of metadata which inform on the Eos
- the choice of the algorithms
- the selection of their parameters
- the Quality Controls, etc.,
- files or links to the auxiliary data,
- uncertainty budgets, either global or at scale.

Additional information on the system that should be developed to deliver the service, and some examples of the EO products which have been prototyped, including outputs of the pre-processing steps will be published in a separate Technical Specification Document (TSD). Version 1 of the TSD will be delivered at the beginning of October and the final version will be delivered at the beginning of December.

The list of all EOs, whether from ESA mission, COPERNICUS missions or TPM missions, that could be used for phase 1 of the project (Proof-of-Concept) is in Annex 2 as excel files.

2 Requirement Engineering: Specifications

The Requirements specifications are based on the URD by the authoritative institutional end-users. These specifications have reviewed and interpreted from the perspective of the service providers. These reviews cover both the ESA requirements and/or expectations (Section 2.1), and the end-users' requirements (Section 2.2). Importantly, the service providers have embraced these requirements while complimenting them with the coastal monitoring considerations of the scientific and coastal management industries[14].

2.1 ESA requirements

ESA requirements and/or expectations which are listed hereinbelow are extracted from the statement of work (SOW) and the minutes of negotiation & kick-off meetings. By definition, they summarize the view of the EO science community, and, when appropriate, they are spelled out using a technical terminology that might be more understandable to specialists of coastal morphology than EO scientists'. If some of them are prescriptions, while other are hopes and even opinions, they all translate an understanding of the needs of the users by public space agencies, and reveal surmises of success by introducing new EO downstream services with new EO products. As such, they weave the thread of the story.

Each ESA requirement is fitted with a numbered label to facilitate their matching with the requirements that are listed in the URD.

[14] companies specialised in surveys and the design of coastal defenses

2.1.1 Intent

The call by ESA, and the subsequent order/ award to two consortia for performing the work, is meant to enhance EO uptake by users, i.e. the promotion of EO, but also the valorization of "EO science" (a list of reference papers was published by ESA in the SOW – see Section 2.1.3).

As per the ITT, the project is an "application project", i.e. a programmatic element within the Science for Society slice of the 5th Earth Observation Envelope Programme (EOEP-5) of ESA for three ITTs (Table 2.1), which are designed to achieve two key objectives (Table 2.2).

Table 2.1: Description ITTs described in the Statement of Work (SOW).

ITT	Description
ITT.i	Bridging the gap between research activities and the sustainable provision of Earth Observation products at information level[1]
ITT.ii	Bringing EO capabilities accessible mainly to EO experts from the research and scientific community, towards much larger end-user communities[2], and, consequently
ITT.iii	Satisfying the needs of large user communities[3]

Table 2.2: Description of Objectives defined to comply with the ITTs (Table 2.1).

Objective	Description
OBJ_ESA.i.	**Developing innovative EO products and methods that**

[1] transfer scientifically proven EO research results into a pre-operational context by defining, developing, producing and validating high-quality EO information products and services

[2] who need to access such information at larger scales and without being necessarily experts in Earth Observations

[3] meet prioritized and authoritative observational needs from user organizations and public authorities, in and outside ESA Member States.

	OBJ_ESA.i.a.1	source of EO data used —including	
		OBJ_ESA.i.a.1	Sentinel 1
		OBJ_ESA.i.a.2	Sentinel 2 missions of the European Copernicus initiative[4]
		OBJ_ESA.i.a.3	ERS-1, ERS-2 and Envisat/SAR archives
		OBJ_ESA.i.a.4	Envisat/VNIR and SPOT archives
	OBJ_ESA.i.b	Describe novel EO derived products, incl. the innovating algorithm.	
	OBJ_ESA.i.c	Raise the awareness and readiness of the user community involved.	
OBJ_ESA.ii:	**Developing products and methods in response to authoritative end-user requirements.**		
	OBJ ESA.ii.a.	requirements expressed in the *URD*	
	OBJ_ESA.ii.b.	preparing, in particular, the ground for a long-term exploitation by large user communities, as it is expected to provide substantial and concrete benefits to the targeted user communities.	

[4] "the Sentinel 1 and 2 missions, used individually or jointly, significantly improve the quality and adequacy of High Resolution (HR) satellite observations in both radar and optical domains"

2.1.2 Details

According to the intents, the contractor shall develop innovative EO products and demonstrate its ability to provide a valuable and reliable service in a framework under the rules described in Table 2.3:

Table 2.3: Description of rules that the contractor must adhere to when completing the objectives (Table 2.2).

Rule	Description	
RUL.i.	**It is a R&D project[5],** that complements rather than overlap the R&D projects funded under the major European Earth Observation application programs[6].	
RUL.ii.	**EO products to be used by the user communities**.	
RUL.iii	**Aforesaid "user communities" being defined by those "responsible to monitor and control this process"**, (i.e. 3 champion user organizations that best represent the targeted/ their user communities and which are associated or integrated into the project).	
RUL.iv.	**Innovative products and services to be developed shall include**:	
	RUL.iv.1	a scientifically sound validation,
	RUL.iv.2	a comprehensive user assessment.
	RUL.iv.3	a representative service roll-out analysis.

[5] *"the Coastal Erosion project is expected to provide the ideal platform to undertake these R&D activities in close partnership with…"*

[6] such as the ESA EOEP Data User Element (DUE), ESA EOEP Value Adding Element (VAE), the ESA EOEP Support to Science Element (STSE), the ESA EOEP Scientific Exploitation of Operational Missions (SEOM), the ESA EW GMES Service Element (GSE), the ESA EW Climate Change Initiative (CCI), the EC Copernicus core and downstream services, the EC 7th research framework program, the EC Horizon 2020, the EU framework programme for research and innovation, and the national Earth Observation programmes of the ESA Member States

RUL.v.	**Project's innovation is tested against state-of-the-art R&D**, i.e. designing and mapping "shoreline indicators" which take into account the dynamics of the land–water interface that are categorized in 2 groups:	
	RUL.v.1.	tidal datum-based indicators determined by the intersection of the coastal profile with a specific vertical elevation, defined by the tidal parameters (e.g., mean high water [MHW])[7]
	RUL.v.1.	visible or non-visible (to the human eye) features/shoreline indicators based on the application of image-processing techniques to extract proxy shoreline features from digital coastal image. These are not necessarily visible to the human eye.
RUL.vi.	**Accuracies of shoreline mapping need be addressed;**	
	RUL.vi.1.	geometric accuracy (in the case of SAR data, the efforts concentrate on speckle reduction trying to limit the impact on pixel resolution);
	RUL.vi.2.	accounting for tidal variations
RUL.vii.	**Identify main steps for shoreline extraction and change detection** (e.g. coastal erosion):	
	RUL.vii.1	extraction of the shorelines/coastline/water line from satellite data, with potential methods being: ▪ image classification (e.g. thresholding, band indexing, supervised/ unsupervised classification, soft classification), ▪ Artificial Intelligence (e.g. neural networks, support vector machines), ▪ morphological operations (e.g. edge detection, tracing algorithms, segmentation), ▪ or various combinations of the above methods;

[7] *"Using tidal datum indicators is a more objective way to identify the shoreline, but this requires working with a digital elevation model derived by means of photogrammetry, LIDAR or ground survey data. This method has limited use for historical shoreline. The latest approach in digital elevation surfaces is based on the use of unmanned aerial vehicles (UAVs) in coastal environments"*

	RUL.vii.2	trace the shoreline erosion-accretion trends (e.g. vectors representing shorelines at different times).
RUL.viii.	**EO utilization must comply with the following principles:**	
	RUL.viii.1	use of different characteristics of SAR image data (polarimetry and coherence), to facilitate discrimination between land/water, exploiting c and x-band data at different resolutions (ERS, ENVISAT, RADARSAT-1 and SENTINEL-1 at 20-25m, RADARSAT-2, COSMOSKYMED and TERRASAR-X at 10 m or less).
	RUL.viii.2	use of different spectral properties of Optical data sets as reported for studies exploiting data at different resolutions (LANDSAT 5 and 8 at 20-30m, SENTINEL-2 at 10m, SPOT-5 at 5m or less, IKONOS, PLEIADES and Worldview-2 at 1m or less).
RUL.ix.	**Review of the 10 most cited papers on coastline/shoreline extraction from the last 10 years** (source SCOPUS);	
RUL.x.	**Analyse the erosion of a minimum of 1000 linear km of coast split into 3 different member states**	

2.1.3 Scientific papers of reference

To consolidate its requirements, ESA has referred to a list of the 10 most cited paper on coastline/ shoreline extraction in EOs from the last 10 years (source SCOPUS), whether SAR imagery or Optical Imagery. Here is a summary of the conclusions to be considered:

2.1.3.1 VNIR

W. Muttitanon & N. K. Tripathi (2005) Land use/land cover changes in the coastal zone of Ban Don Bay, Thailand using Landsat 5 TM data, International Journal of Remote Sensing, 26:11, 2311-2323

This paper presents application of several change processing operations of remotely sensed data for change detection to map land use/land cover patterns (LU/LC), the sea being a class by itself. One uses NDVI as the variable to perform the classifications, and, in particular, track the changes of the interface between mangroves and the sea.

Conclusions of the reader:

- NDVI is a good parameter for the classification, and
- the shoreline shall extend inland to embed the coastal areas incl. field, forests, etc.

Josep E. Pardo-Pascual et al. (2012) Automatic extraction of shorelines from Landsat TM and ETM+ multi-temporal images with subpixel precision, Remote Sensing of Environment 123, 1–11

This paper presents a methodology for sub-pixel shoreline extraction and geometric accuracy improvement that demonstrates HR imagery @ 30 m resolution can compete with VHR on artificially stabilized coastal segments on the Spanish Mediterranean coast, extending from the port of Castelló de la Plana to the port of Borriana, that have a constant and well-defined land-water boundary (mean error ~1.5 m, and RMSE of ~5 m), when traditional methods based on hard classification can't monitor small changes to the shoreline (<10 m). It emphasizes the use of co-registration of images in the Fourier domain (cross-correlation using Fast Fourier Transform) to determine the variation in position between successive images at a subpixel level. The analysis is structural: using the structure on neighborhoods of 7 x 7 pixels to get a shoreline at sub-pixel level by approximating the NIR signal with polynomial expression (sampled on the 7 x 7 pixels) then looking for the position of null Laplacian and maximum gradient of the function at sub-pixel level. In short, it makes the hypothesis that the HR pixel has a radiance which is a combination of the radiances of HR pixels around (land & sea).

Conclusions of the reader:

- it is a deconvolution method which works if the VHR radiance fields of the landside is smooth (e.g. large beaches), and, for time series, if the local radiance values and spatial structure are the same landward of the shoreline from one snapshot to the other (e.g. urban areas or industrialized areas with seawalls, roads…, but not rural areas where fields will have different spectra along the years); when there is little spectral difference between land and sea the position of the coastline is significantly deviated towards the sea, while when spectral differences are higher the bias is not as dramatic and it occurs towards land; in tidal areas, it should at low tide, but not at high tide
- generic applicability is not demonstrated, all the more than it does not take into account the wave set-up and the wave run-up.

Pasquale Maglione et al. (2014) Coastline extraction using high resolution WorldView-2 satellite imagery, European Journal of Remote Sensing, 47:1, 685-699.

This paper presents the use of WorldView-2 imagery for coastline extraction in the Campania Region (Italy) where shorelines include reefs interspersed with segments of sandy beach, using Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI), and pan-sharpening the related NDVI-NDWI images, and adopting 'optimal' thresholds to distinguish bare soil and sea water (thresholds calculated o, training sites). Because of geolocation errors of the ortho-ready Standard WV2 products (RMS of 37 m), some 130 Ground Control Points (GCPs) need be used (orthorectification method is based on Rational Polynomial Functions RPF) because of the variable coastal morphology to get a positioning accuracy similar to the spatial resolution of the images. Coastlines are smoothed with PAEK (Polynomial Approximation with Exponential Kernel) algorithm. It is validated by visual analysis of RGB true color compositions which are directly vectorized.

Conclusions of the reader:

- why is NDVI or NDWI variables used if RGB is used at last for the validation? It seems more sensible to design a data processor that mimics the operators' knowhow.
- refined ortho-rectification of images is a pre-requisite.

Manoj Kumer Ghosh et al. (2015) Monitoring the coastline change of Hatiya Island in Bangladesh using remote sensing techniques, ISPRS Journal of Photogrammetry and Remote Sensing, 137–144

This paper presents a study using Landsat/TM & ETM to monitor the spatiotemporal changes of coastal zones, using the modified normalized difference water index (MNDWI) to discriminate the land–water interface and infer the erosion/accretion sectors along the coast. Surprisingly, the images were ortho-rectified with no more than 21 GCPs. In this study the coastlines were not corrected for variations in tide levels, and it was assumed that these variations were low compared to the scale of coastline shifts.

Conclusions of the reader:

- the erosion/ accretion rates are so high in Bangladesh (0.4 km to 2.3 km in 20 years on the surveyed sites) that it was an easy job;
- this paper doesn't bring anything new in terms of methodology,

Virginie K.E. Duvat and Valentin Pillet (2017) Shoreline changes in reef islands of the Central Pacific: Takapoto Atoll, Northern Tuamotu, French Polynesia, Geomorphology 282, 96–118

This paper presents a study of the shoreline of an atoll using a combination of vertical aerial photographs (1969, 1981, 1984, 1995) and satellite imagery (Pleiades satellite image from 2013). Work was done by hand, not using the edge of the vegetation as a proxy for the seaward island boundary because in high-energy ocean coasts, the vegetation line does not necessarily correspond to it: where shingle or rubble ridges have formed and filled large embayments, the vegetation line may not correspond to the external limit of the stable part of islands; the non-vegetated surfaces made of blackish (i.e. weathered) shingle or rubble with structures that are stable at a multi-decadal timescale. The authors defined a "stability line" which corresponds to the outward limit of stabilized shingle or rubble deposits. Over the 1969–2013 period, the stability line predominantly advanced on the leeward (i.e. western) side of the atoll of > 12 m while it predominantly retreated on its windward (i.e. eastern) side, both on ocean and lagoon shores of -5 to -12 m.

Conclusions of the reader:

- it is a paper about the use of shorelines' change along the year, rather than the methodology of shoreline mapping;
- it demonstrates that the NDVI and vegetation indices are not systematically the best variables to draw a shoreline indicator

2.1.3.2 SAR

Margarida Silveira, Member, and Sandra Heleno (2009) Separation Between Water and Land in SAR Images Using Region-Based Level Sets, IEEE Geoscience and remote sensing letters, VOL. 6, N°. 3.

This paper presents method for the separation between land and water by SAR amplitude, using lognormal densities as the probabilistic model (histograms) for the pixel intensities in both water and land classes, and geometric ACM (active contour models) for the segmentation rather than Markov Random Fields (MRF) or mere thresholding, and apply it to riverbeds, flood extent areas, and shorelines. The image is partitioned into

two classes Ω_1 and Ω_2 separated by a curve C , also called a snake, classes Ω_1 and Ω_2 are modeled by pdfs p_1 and p_2 , respectively; the partition is obtained by minimizing the following energy function

$E(C,p_1,p_2)=\mu\cdot\mathrm{length}(C)-\lambda_1\int_{\Omega_1}\ln p_1 dx-\lambda_2\int_{\Omega_2}\ln p_2 dx$ where μ,λ_1,λ_2 are weighting parameters, and C is the zero level set of a higher dimensional level set function $\Phi(x,t)$: $C(t)=\{x|\Phi(x,t)=0\}$; one then need to chose the probability density functions: gamma, K, lognormal, Weibull, generalized Gaussian–Rayleigh distributions, etc. the authors adopted a finite-mixture model of gamma distributions which are approximated by lognormal distributions to obtain both the mean and variance of its components in closed form. The parameters of the models (mixing probabilities and lognormal parameters) are calculated with training data sets picked on the images using a maximum-likehood criterion.

Tests were performed on SAR amplitude precision images: Envisat ASAR IMP, ERS-2 SAR PRI, and Envisat ASAR Wide Swath images ASA_WSM_1P of coastal and river basin regions in Portugal and northwest Spain (Galicia), which were acquired between 1997 and 2008. Descending VV polarization mode. Variable incidence angles ranging from 18◦ to 45◦. Pixel sizes of 12.5 m × 12.5 m for IMP and PRI products (resolution of 30 m), and 75 m × 75 m for the WSM product (resolution of 150 m).

Conclusions by the reader

- nice semi-supervised algorithm for segmenting land and water if the classes are strongly spatially disconnected;
- an academic work which does not take into account the physics of backscattering of microwaves.

Yuanming Shu et al. (2010) Shoreline Extraction from RADARSAT-2 Intensity Imagery Using a Narrow Band Level Set Segmentation Approach, Marine Geodesy, 33:2-3, 187-203.

This paper presents a semi-automated method for shoreline extraction which is based on the traditional method of thresholding, but after enhancing the contrast of the SAR image (Gaussian filtering and histogram adjustment) and performing morphological filtering (shrinking features with a median filter to round off the large structures and to remove the small structures, then growing back the remaining structures by the same amount) rather than linear filtering, narrow band level set segmentation being carried out at last to refine the segmentation result + a last step of morphological filtering to eliminate any remaining spurious segments. It is recognized that one of major difficulties for this task is the speckle noises on SAR images which forces to use filters to smooth the original SAR images. E.g. gaussian or sigma filter, speckle reducing anisotropic diffusion (SRAD), etc. In fact the authors use the same “level set method” as the previous paper, but with the Narrow Band Method because the the computing time to apply the original level set method proposed by Osher and Sethian (1988) is unbearable though it is relatively simple and easy programming.

Adalsteinsson and Sethian (1995) introduced a method named narrow band method, which confine computation to a narrow band around the interface of interest.

Conclusion by the reader:

- a nice exercise in image processing, the robustness is questionable by lack of explicit mathematical model for “speckle noise” and “edge.”

A’kif Al Fugura et al. (2011) Semi-automated procedures for shoreline extraction using single RADARSAT-1 SAR image, Estuarine, Coastal and Shelf Science 95, 395-400

This paper presents a semi-automated technique and procedures for shoreline delineation using r speckles removal with a Lee sigma filter then an Sobel Edge detector.

Conclusion by the reader:

- basics in image processing.

Fabio Baselice and Giampaolo Ferraioli (2013) Unsupervised Coastal Line Extraction From SAR Images, IEEE Geoscience and remote sensing letters, Vol. 10, N°.6

This paper presents a technique for coastline extraction originally developed for the exploitation of COSMO-SkyMed (CSK) dual polarimetric (15 × 15 m) PingPong data, which does not require any speckle reduction preprocessing and is based on the estimation of the HH/VV correlation, now applied to CSK Stripmap SAR image stacks (images at full resolution). The method is developed in Bayesian stochastic estimation and Markov random field (MRF) frameworks and is based on the estimation of the spatial correlation among neighboring pixels (a Gaussian MRF with local hyperparameters / the local hyperparameters are seen as indicators of the spatial correlation of the pixels => the detection of edges is carried out by estimating the local hyperparameters = the knowledge of such correlation provides the extraction of the coastal line). In particular, the proposed detector exploits the joint a posteriori distribution of the real and imaginary components of the acquired data. The SAR images need to be properly co-registered, and the method assumes the coastline in the same position for each image.

The behaviour of each pixel is related only to the pixels belonging to its neighbourhood $\aleph$. An MRF can be conveniently analytically expressed in terms of joint distribution of all image pixels $p(l,\theta)=1/\left(Z(\theta)e^{U(l,\theta)}\right)$ where l is the vector of labels in neighbourhood pixels, U is an energy function, Z is the partition function, and θ is the so-called hyperparameter; the local gaussian Markov random field models U as $U(l,\theta)=\sum_{p=1}^{N}\sum_{q\in\aleph_p}\frac{\left(l_p-l_q\right)^2}{2\theta_{p,q}{}^2}$ where $\aleph_p$ is the neighbourhood of pixel labelled p.

The proposed edge detection is based on the estimation of these hyperparameters: given two neighboring pixels p and q, the local hyperparameter $\theta_{p,q}$ can be seen as an indicator of the spatial correlation of neighboring pixels; a high value of $\theta_{p,q}$ means that the probability that the two pixels p and q have very different labels (phase or reflectivity) is high; a low value of θp,q means that the probability that l_p and l_q are very different is small = for a high value of $\theta_{p,q}$ corresponds to a transition between different label values (an edge between p and q), and for a low value of $\theta_{p,q}$ no label transition (no edge between p and q).

Yet, $\theta_{p,q}$ has to be estimated starting from the available data; this is the edge detection. If we look at 8 pixels together, $\hat{\theta}_p{}^2=\sum_{q\in\aleph_p}\frac{\left(l_p-l_q\right)^2}{9}$ and $\hat{\theta}_{p,q}=\left\langle\hat{\theta}_p,\hat{\theta}_q\right\rangle$; however, in practice, the labels are not a priori known (incomplete data problem) and have to be estimated, using an expectation maximization (EM) algorithm -but it is not clear how.

Conclusions by the reader:

- a quite complex method without a theoretical proof that it is workable, even if coastal erosion processes probably behave as Markov variables (to be memoryless —the conditional probability distribution of future states of the process depends only upon the present state and not past states = the state of the coast is directly visible to the observer, but some of the parameters might be unknown, i.e. hidden), even if experimental demonstrations are convincing;

nota: by discarding Bayesian network representation in favor of Markov networks, the authors reject causal dependencies in favor of cyclic (and mutual) dependencies, which is also a more realistic way to represent coastal geomorphology processes;

- the Markov network is not explicitly described, and the name "hyperparameter" seems to hide the mathematical notion of "clique factor" (a clique of size k is a subset C of the Markov Random Field MRF, i.e. a graph, of k nodes of the MRF so that for each pair X, Y ∈ C with X ≠ Y holds that X and Y are connected by an edge): $p(l, Cliques) = \frac{1}{Z} \prod_{C \in Cliques} \varphi_C(C)$ where $\varphi_C(C)$ is a potential function (large values of indicate that the configuration of the random variable in the clique is more probable), and $Z(Cliques) = \int \prod_{C \in Cliques} \varphi_C(C) dl$; the authors have chosen to represent potential functions as Gibs-Boltzman distributions $\varphi_C(C) = e^{-E_C(C)}$ where E_C is an energy function (large energy mean low probability), hence $p(l, Cliques) = \frac{1}{Z} \mathrm{e}^{-\sum_{C \in Cliques} E_C(C)}$; the choice of $U(l, Cliques) = \sum_{p=1}^{N} \sum_{q \in \aleph_p} \frac{(l_p - l_q)^2}{2\theta_{p,q}{}^2}$ demonstrates a posteriori that that they use a Conditional Random Field (CRF) based on a Pott model whereby only 2 pixels are involved in forecasting the label value of a third one even if in a group of n pixels indexed by i and j: the cliques are of size 1 (a point) and 2 (pair of pixels), and $p(\{X_{i,j}\})$, where $X_{i,j}$ is the observation / measurements, depends only on $p(\{X_{i,j}\} | l_{i,j})$ where $l_{i,j}$ is the class label at the pixel (i,j), which is the classifier; in short, the joint distribution $p(\{X_{i,j}, l_{i,j}\})$, which cannot be fully specified because we do not know $p(\{l_{i,j}\})$; as such $p(l, Cliques)$ is a conditional probability $p((l, Cliques)|X) = \frac{1}{Z} \prod_{C \in Cliques} \varphi_C(C)$; the probabilities are those of a Boltzman machine whereby $E_l(x) = -\theta_l \cdot x$ and $E_{l,m}(x, y) = -\omega_{l,m} \cdot x \cdot y$ but the authors decided that $\theta_l = 0, \ \forall l$; their « hyperparameters » are the weight factors $\omega_{l,m}$; it seems that their hyperparameter of each label or class is an average of the $\hat{\theta}_l^2 = \left\langle \omega_{l,m}{}^2 \right\rangle_m$ and they approximate $\omega_{l,m|l\neq m}$ by $\left(\hat{\theta}_l + \hat{\theta}_m\right)/2$; by not referring to the mathematical framework that has been developed at length, and to the early developer of the method for SAR images (Lee and Jurkevitch, 1990, X. Descombes et al. 1995, among others) the authors mislead the readers and their formalism is more complex than the descriptions in mathematical textbooks;

- the hypothesis is not analysed within the framework of SAR physics and coastal morphological processes; it is an image segmentation exercise.

Andrea Buono et al. (2014) A Multipolarization Analysis of Coastline Extraction Using X-Band COSMO-SkyMed SAR Data, IEEE journal of selected topics in applied Earth observations and remote sensing, Vol.7, N°.7

This is a paper from the same group at the Università degli Studi di Napoli Parthenope which works using Markov Chain Networks. The paper presents a coastline extraction methodology applied to COSMO-SkyMed (CSK) data, collected in the single-polarization stripmap Himage mode, with a multipolarization analysis (HH and HV) of sea surface backscattering = it uses a conventional Sobel edge detector on the co- and cross-polarized Himage CSK SAR data. The originality is the threshold Constant False Alarm Rate (CFAR) detector based on an exponential sea clutter distribution providing the binary outputs prior to applying the Sobel edge detector to extract the continuous coastline. Experimentally they show that the is both effective and accurate when low-to-moderate wind conditions apply (no swell nor breaking waves). The authors recognize that i. SAR-based coastline extraction depending strongly on radar frequency (L-, P-, C- and X-band SAR) using higher frequencies is better for an accurate coastline detection; ii. HV Normalized Radar Cross-Section (NRCS) of the sea is significantly lower (from10 to 30 db) than the co-polarized ones, while HH and VV backscattering are very close to each other; iii. sandy areas or bare soils may be challenging to be discriminated from sea surface because of similar backscattering strength, reason why they use a CFAR detector based on an incomplete gamma function $P_{FA} = 1 - \Gamma\left(\frac{thr_g}{\sigma_g}, 1\right)$ where thr_g is a global threshold and σ_g is the distribution mean value of backscattering (as such $thr_g = \sigma_g \ln P_{FA}$).

Conclusions by the reader:

- A simple and nice algorithm: the detection itself is fairly straightforward as it compares the signal to a threshold T which is a function of both the probability of detection and the probability of false alarm; yet, it is not detailed how it performs, with a definite threshold for the whole image $T = thr_g$, or an adaptative threshold $T = \alpha\sigma$ where σ is the mean value of backscattering in the n neighboring cells and α is a scaling factor whereby $\alpha = n\left(1 - P_{FA}{}^{-1/n}\right)$
- it is not explained why it would give better result than a classical detector using Neyman-Pearson principle.

Ferdinando Nunziata et al. (2014) Coastline Extraction Using Dual-Polarimetric COSMO-SkyMed PingPong Mode SAR Data, IEEE Geoscience and remote sensing letters, Vol.11, n°.1.

This paper from the same group as the 2 previous papers' (reason why the introduction paragraph of the papers are very similar), develops a dual-polarization scattering model that relates the correlation r_c between the HH and VV CSK polarimetric channels against time τ (the difference between the zero Doppler azimuth first time related to the n^th^ burst of the two polarimetric channels, which increases with the increase of the incidence angle and range, vs. scene coherence time) and the coherence time of the observed scene τ_s ($\tau_s \to \infty$ for land, i.e. $\tau_s > \tau$, and finite for sea $\tau_s \approx 3\lambda/u$ where λ is the radar wavelength and u is the wind speed considering the sea surface spectrum follows the Pierson–Moskowitz distribution, and $\tau_s \ll \tau$). The authors used the CFAR method described in the previous paragraph except that the gamma function is complete: $1 - P_{FA} = \int_o^{thr_g} 1 - \Gamma^{(-1)}\left(r_c;\alpha,\beta\right) dr_c$, $\left(\alpha,\beta\right)$ being estimated from the data using a so-called second-kind-statistics method that involves the Mellin transform. As metallic ships generate high r_c, these outliers shall be discarded. For the coastline extraction from these outputs, it relies on simple image processing that consists of extracting intermediate frequency components using two Gaussian-shaped filters: the first one is a regularization filter that reduces the noise by means of a narrow Gaussian kernel to filter out high-frequency components, e.g. isolated points and small structures; the second filter is a broader Gaussian kernel to extract very low frequency components. Finally, the output of the low-pass filter is subtracted from that of the regularization one, and points of zero crossing are associated with the coastline.

Conclusions by the reader:

- it is a nice exercise in image processing based on the dynamic properties of the land and the ocean.

Zhongling Liu et al. (2016) A Novel Region-Merging Approach for Coastline Extraction from Sentinel-1A IW Mode SAR Imagery, IEEE Geoscience and remote sensing letters, Vol.13, n°.3

This paper presents the use of a combination of modified K-means method and adaptive object-based region-merging mechanism(MKAORM) to extract coastlines on Sentinel-1A (S1A) IW (Interferometric Wide-swath) mode SAR imagery: i. a modified K-means unsupervised classification method is used to produce initial oversegmentation for the following region-merging stage, which is ii. an adaptive and coarse–fine object-based region-merging scheme using subregion classification to extend the automatically selected “sea” seed and “land” seed, respectively. It is validated from coastline extraction by a photo-interpreter on the same images.

The differentiation between land and sea is nonetheless crude: the sea zone is visually darker than the land region in the SAR image due to the lower backscattering coefficient caused by scattering mechanisms —and that’s all.

Conclusions by the reader:

- this is fully different from previous papers because using a non-supervised classification method instead of supervised and object-based classification to refine it instead of edge-based schemes;
- the region-merging method is non-conventional with the use of a simple adaptive histogram homogeneity test (AHHT).

Mohammad Modava & Gholamreza Akbarizadeh (2017) Coastline extraction from SAR images using spatial fuzzy clustering and the active contour method, International Journal of Remote Sensing, 38:2, 355-370

This paper presents a method that overcome the drawback of the active contour method for the edge detection task which is considered as computer time-consuming with a first step of clustering for noise reduction, a second step of binarization by Otsu's method on the fuzzification results, a third step of morphological filtering on the binary images to eliminate spurious segments after binarization, and a last step of applying active contour level set method to re fine the segmentation..

Conclusions by the reader:

- despite statement by the authors that it extracts the coastline at full resolution of the input SAR image without degrading the resolution because not despeckling, it is not true because speckle is there although the proposed approach being based on an active contour model, it does not require preprocessing for SAR speckle reduction;
- the main advantage of the method is not requiring q manual initialization for the level set method.

2.2 Users/ Partners Requirements

The following section provides an overview of the URDs (Appendix B), identifying two key requirements to adhered to when designing EO products These themes include i) identification of Coastal State Indicators (CSI) and ii) delivery of EO products that describe coastal change across three spatial scales, namely 1D (boundary definition), 2D (area classification and extent) and 3D (surface altitude and sediment volume), and to monitor change across time (4D). Each of these are described more detail below and throughout the remainder of this document.

2.2.1 Coastline State Indicators (CSI)

The overall objective is to retrieve Coastal State Indicators (CSI), i.e. a reduced set of measurable parameters that can simply, adequately and quantitatively describe the dynamic-state and evolutionary trends of coastal systems, from Shoreline Indicators (SI), i.e. gauges, pointers or markers that are used as proxies to represent the shore (either visible discernible features, or tidal datum-based indicators to get isobaths and isohypses (contour lines).

For the record, the words coast, coastline, shore and shorelines are often confused, although the focus on the same geographical features:

- a shore or a shoreline is the fringe of land at the edge of a body of water (the ‘line’ is quite thick on a large scale map, e.g. 1:5,000, but very thin on a small scale map, e.g. 1:1,000,000, ⇒ a precise line that can be called a shoreline cannot be determined if it does not refer to a representation scale or spatial frequency cut),
- a coast, also called coastline or seashore, is a shore which borders the sea; however, coast often refers to an area far wider than the shore, often stretching miles into the hinterland

The focus is the assessment of the change of volumes of geologic materials (the rocks and sediments that make up the Earth) at the fringe of the sea, and volumes are measured by bathy-topometry.

2.2.2 EO products of scale

As “the coastal stakeholder community is on the agreement that any policy for coastal erosion should increase coastal resilience by restoring the sediment balance and providing space for coastal processes (EUROSION, 2004)", "all champion user organizations have expressed interest on [EO] products that represent the change over time of different observable geometries (1D, 2D and 3D) [to help deliver the CSIs, all the more than CSIs need Topo-Bathymetric Digital Elevation Model TBDEM]". In short, Coastal erosion is related to changes in earth materials' volumes in the coastal area, materials being taken out from land, brought in the sea, then staying on the seabed or coming back to land at the same position or in other areas15; yet, erosion processes are topography-controlled: it is the study of the varying elevation, also called 'hypsography' (the practice of determining elevation points being called 'hypsometry').

The context of these requirements should consider the following:

- The consulted champion user organizations agreed accordingly on limiting the spatial scope of the products requirements to the coastal area, i.e. an extended shore incl. not only the backshore and the beach face, the seaward nearshore/ shoreface (foreshore + inshore) down to the closure depth (thus excluding areas further offshore which are nonetheless of interest for the coastal stakeholder in charge of ICZM), but the coast landward of the coastline and some hinterland as necessary.
- Though datum-based shoreline indicators provide a more objective detection technique of materials' volume changes (erosion-accretion) than proxy-based shoreline indicators, both datum-based and proxy-based shoreline indicators are required from the champion user organizations because i. historical mapped shorelines were mapped using visually discernible features to produce proxy-based shorelines, ii. proxy-based shorelines are based on geographic features of interest to ICZManagers.

[15] Short description of coastal erosion: it is the process of wearing away material from the coastal zone due to imbalance in the supply and export of material from a certain section; it takes place in the form of scouring in the foot of the cliffs or in the foot of the dunes.

Coast erosion takes place mainly during strong winds, high waves and high tides and storm surge conditions, and results in coastline retreat (back-wearing) and or lowering of the bottom elevation (down-wearing);

→ the rate of erosion is correctly expressed in volume/length/time, e.g. in m3/m/year, but erosion rate is often used synonymously with coastline retreat, and thus expressed in m/year

- All champion user organization expressed a common interest on using the ca. 25 years EO historical database to obtain a time series as long as possible for each EO product, but ICZM and CFERM involves time horizons of 100 years and it is on the interest of all champion user organizations to be able to assess coastal change over a similar time span: as such, the EO-derived time series should be mended to the ancient time-series.

2.3 Contractor's provision EO-paradox (strengths and weaknesses)

When considering the requirements of coastal monitoring products, it is important to consider the capabilities of current and previous EO technology. Furthermore, considerations should be made of the erosion regime (scale over time) of the region of interest, and how this aligns with available EO data. This section accounts for these factors.

2.3.1 EO CSI challenges

Remote sensing from satellite provides snapshots of the Earth surface, which, on land, are images of radar backscatter or light reflection of the land surface [16] (soil, vegetation, and human-made structures) at various wavelengths, and, on water bodies, image of radar backscatter or light reflection but of the water volume[17], i.e. the water column (its constituents at various depths) and its interfaces (seabed and sea-surface). It is similar to remote sensing from planes (e.g. aerial photographs), and, as such, do not sense directly the topography of the backshore (emerged shore) and the foreshore (immerged shore), and, at first glance, is not so convenient to help assess coastal erosion. In addition, these snapshots are images of a rugged terrain, with points at different altitudes, and, unless "ortho-rectified" with information from terrain models, pixels cannot be accurately located in the reference mapping systems.

Could photogrammetry methods, commonly used by surveyors, be useful? (in particular i. the stereo-photogrammetric methods for optical snapshots, i.e. reconstruction of the terrain from multiple images taken from different viewpoints, using the variation of distances; and ii. interferometric methods for radar imaging sensors, which work on the variation of the signal phase instead of distance).

[16] because of small penetration of the incident signal in the floor

[17] though radar waves sent from satellite-borne sensors do not really penetrate the skin of the water bodies

The main issues include the following:

- the lack of strong radar scatterers on soft materials of the shoreline prevents performing a proper interferometric task to retrieve the altitudes of the backshore from SAR (same scatterers with enough S/N on different images);
- 3D-reconstruction with optical images is made on features (handling of focal points) which need be discernable, requesting images at same resolution as the aforesaid features, which also can't be soft materials.

As such, it is nearly impossible to develop methodologies solely based on the exploitation of EOs, except for:

- the retrieval of altitudes within the water, using
    - the attenuation of light as a measure of the depth —the so-called SDB (Satellite-Derived Bathymetry), if the water is clear enough; yet, one needs an a priori information on the reflectance of the seafloor and of the water optical properties;
    - the change of sea-waves' wavelength & direction in the shoaling area nearshore, which informs on the bathymetric changes at the scale of the sea-waves' wavelength; yet, if wave crests can be +/-viewed on radar and optical images, it requires a priori information on the sea-wave spectrum offshore and scraping all diffraction effects due to bathy-topographic obstacles;
- the detection of shoals & the assessment of depth where waves break, which can be spotted on optical and SAR images, which gives the inshore limit of the retrieval of altitude of the seabed by EO.

2.3.2 EO Waterlines

The only reliable use of EO is i. the drawing of the instantaneous interface between the water and +/- dry materials of the land, so-called "waterline" (WL) in the following paragraphs, and ii. the drawing of the "seafront" (SF), where marine ecosystems (sand, silt, encrusted rocks, algae, seaweed…) change to land ecosystems cliffs, seawalls, dunes, …); difficulties being:

- the mix-up of wet materials and still water on SAR images, which trigger errors near tidal flat, in estuaries…;
- the masking of the waterline by buildings on the shore or cliffs on SAR images;
- the confusion between land and sea in areas such as saltmarshes;
- the wave run-up on the beach which provides an instantaneous waterline which is different from one part of the beach to the other as EO sensors are scanners, and represent a WL at a temporal scale of a few seconds when we look at coastal erosion at the scale of months, years, nay decades;
- the errors due to the localization of immerged sand bars (and shoals) instead of the most shoreward waterline because of wave breaking, on optical images.

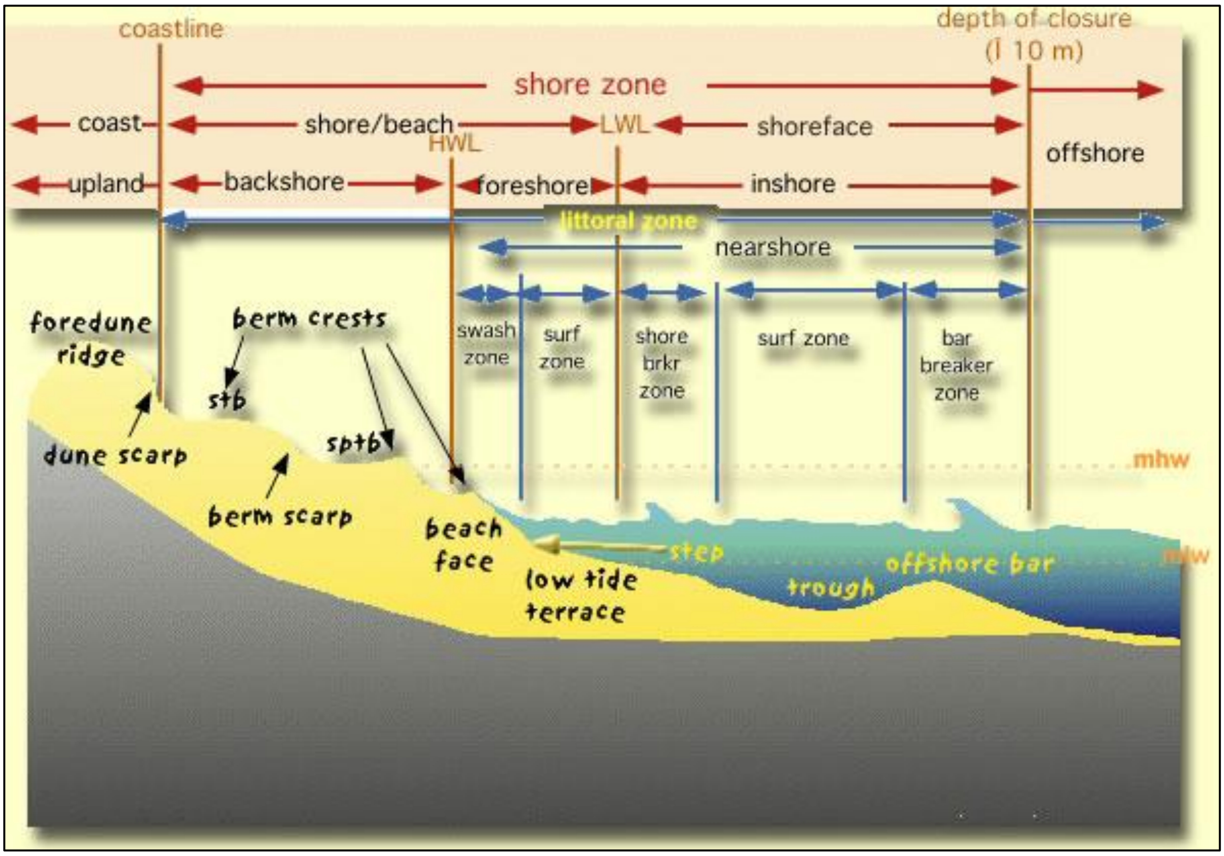


Figure 2.1: Description of cross-shore profile, defining multiple coastal features and the extent of multiple zones. Source: Lindley S. Hanson[18]

[18] http://w3.salemstate.edu/~lhanson/gls210/GLS210_coasts/beach1.htm

A waterline derived from EO is not only prone to observation errors, but cannot be considered as an isobath or a contour line (isohypse), due to a. the waves reaching different height on the shore at different points (wave set-up of the surf zone, wave run-up of the swash zone), and b. the tide height being different along the shore because of the shore morphology; as such it is critical to have an error/uncertainty budget.

To transform EO waterline information into geodetic and tidal datum ('contours' / isobaths or isohypses), these data need to be complimented with the following data/considerations:

- Sea state conditions (with reference to geodetic datum – from an official geodetic network):
  - tidal heights (usually from tide predictor as there is little chance to have a tide gauge nearby),
  - atmospheric pressure offshore, and onshore-offshore wind speeds;
- Sea state variability:
  - to correct from wave set-up, which depend on wave breaking fields on offshore bars or the low tide terraces, to be observed on EO or to be derived from wave forecast delivered by meteorological offices and 'expected' bathymetry of the offshore and nearshore areas)
  - to assess the wave run-up amplitude on the shoreface, which depends on wave swash or breaking on the beach face, to be calculated from LUTs supplied by surveyors or with models of the surf zone (knowledge of the position of the bars, the depths of the troughs, the slope of the terraces, the location, height and size of steps, the incident wave spectrum and the energy transferred by breaking waves to the shoreface)
  - to assess the shoreface slope m along the shore to derive the contour line at the nearest tidal datum from the waterline which has been drawn on EO: it relies anew on a priori knowledge of the foreshore bathymetry, which is supposed to change with coastal erosion, that occurs at timescales from minutes to decades!

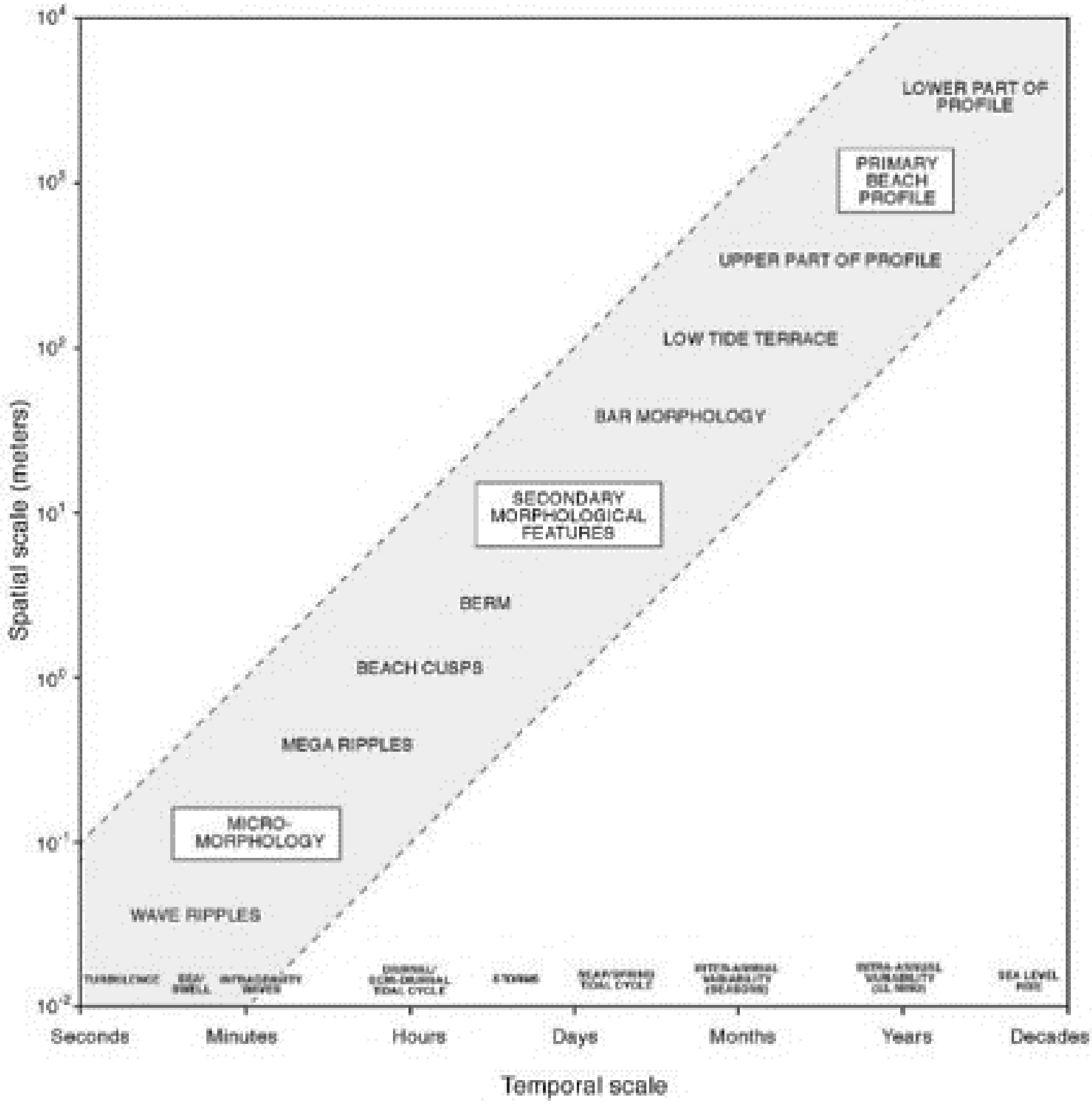


Figure 2.2: Relation between spatial and temporal scales of morphological features and fluid motions associated with sandy beaches. Source: © Masselink and Kroon[19]

[19] COASTAL ZONES AND ESTUARIES – Morphology and Morphodynamics of Sandy Beaches - G. Masselink, A. Kroon

2.3.3 *Cross-shore Profile*

Typically, the cross-shore profile depends on the following variables or parameters:

- the surf scaling parameter $\varepsilon = H_b\omega^2 / gm^2$ (or Irribaren number ξ) where H_b is the height of waves when breaking at the shore, $\omega = \frac{2\pi}{T}$ with T being the wave period, g is the gravity constant and m is the beach slope;
- the relative tide range $RTR = TR/H_b$, where TR is the tide range in height;
- the Dean parameter or dimensionless fall velocity $\Omega = (H_b/w_s T)$, where $w_s h$ is the stationary fall velocity of a grain of sediment in the water;
- the Embayment Scaling Parameter $\delta' = \frac{S_l^{\,2}}{100 C_l H_b}$ where C_l and S_l are planform geometry parameters (the shoreline length between the headlands, and the chord length directly between headlands);
- the incident breaking wave condition, and the wave obliquity β, i.e. angle of waves with the shoreline;
- the Longshore Variation Index $LVI = \frac{Q_{std}}{|Q_{mean}| + Q_{std}}$, where Q is the dissipated energy of waves at the shore, Q_{mean} the average, and Q_{std} the variability;
- the bar parameter $B^* = \frac{y|_{m\approx 0}}{gmT^2}$, where $y|_{m\approx 0}$ is the distance offshore where the slope is nearly 0;
- the mean beach face sediment size $\phi_{50}|_{\text{BeachFace}}$;
- the geological constraints TYPE *i.* which inform on the availability of sediments to move up-and-down a beach;
- the aerial accretion parameter $v_{wind} / (h_{berm}^{dune} / \Delta T_s)$ where v_{wind} is the wind speed, h_{berm}^{dune} the difference of altitude between the dunes foot and the land platform, and ΔT_s the duration of wind events;

- and the temporal lags τ_S between changing wave/ wind conditions and changing cross-shore profiles.

All parameters shall be introduced in the models i. to determine the altitude of a single waterline then ii. derive the position of the nearest tidal-datum shoreline ("nearest" in terms of altitude) in order to build-up time-series for inter-comparisons along time —it is expected that the cross-shore profile is +/- linear or abiding to a simple geometrical law when performing the extrapolation from i. to ii.

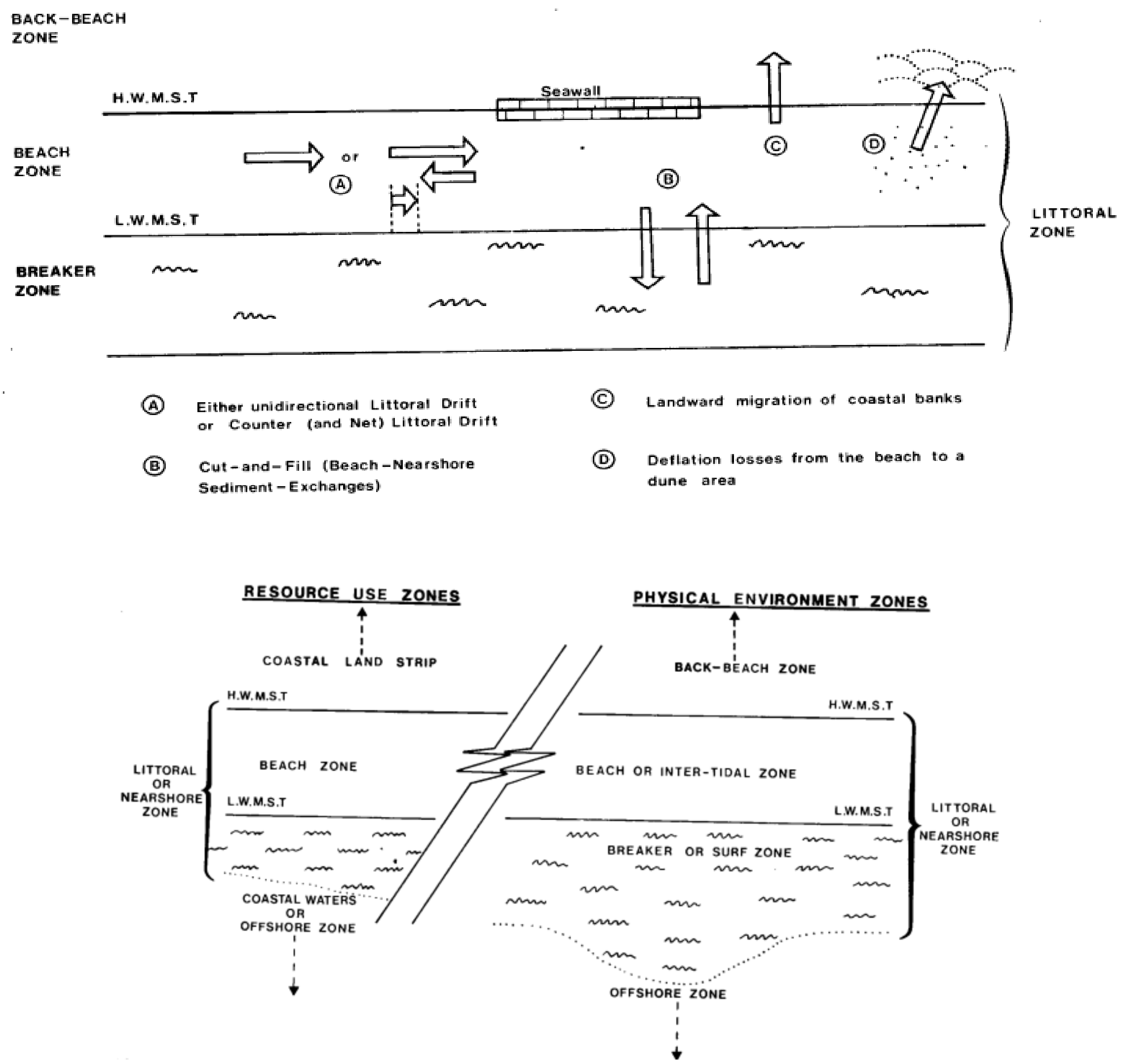


Figure 2.3: Modes of littoral and offshore sediment transport for multiple coastal zones. Source: *I.P. Jollliffe*

Nota: Coastal erosion that EO shall help assess is related to materials wearing (source and transformation of earth materials) and transport, whether hard materials falling from cliffs, or soft material on the seabed —transport being assessed by local sourcing rates and volume changes which are estimated by bathy-topometry (bathymetry of the foreshore and topography of the backshore); seafront retreat or summer beach shrinking are symptoms, but could be erroneous if due to events that "break" the shore but all materials remaining in the shoreline area, even if it impacts human activities; yet, to assess the bathy-topographic changes with EO we need to have an a-priori information on the first differential properties of the bathy-topography;

if we had enough waterlines, i.e. +/- contour lines, drawn from EO during a period of stationary/motionless behavior of the shore, we could infer the terrain altitude or seabed morphology from the contour lines at altitudes that are different owing to tides and meteorological conditions, but only between lower tide and higher tide during that period; by selecting two periods far apart in time we could then assess the volumetric changes; yet, these periods are short because even shorter that the interval between two storms (when the shore recovers from the assault of the sea) or a lunar month (when the shore profile adjusts to the drag of tidal currents in the period between new moon and full moon); = stationarity only exists during periods of calm weather, far from storm events, near Neap tides and for a few astronomical tide cycles (of the order of 5).

2.3.4 Summary EO paradox

Despite all the drawbacks described herein above, among others, ***EO from satellite is the only way to get a <u>regular</u> & <u>synoptic</u> view of the shore*** (contrary to ground surveys, whether on the backshore or the foreshore, and to aerial surveys, which are, both, too expensive), and to order/collect snapshots at wish in a few hours because of the availability of VHR satellites in current constellations, or in a few days because of the regular surveys by HR public satellites, for **investigations** and **monitoring**.

However, EO either provides <u>complementary means to ground & aerial surveys + models</u> with regards to investigations or delivers alerts when monitoring the shore dynamics at the temporal scale of the snapshot orders and the spatial scale of the sensors —it is not a full inclusive self-supporting & complete methodology.

2.4 Third Party Mission (TPM) Data Requirement

Phase 1 Requirement

2.4.1 For Phase 1 (Proof of Concept), the TPM requirement will initially look at a “from and to” date for Landsat, however the requirement will be further refined to very specific dates to be adopted to test the erosion process (and rate) thesis for each Phase I site. This approach, ie selecting specific sampling dates, will be supported by the current research/evidence/analysis from the authoritative users which will be used to determine those specific dates for sampling. This will enable the feasibility to demonstrate that EO has a significant part to play in understandings the processes of erosion, but in a limited test case sense.

Phase 2 Requirement

2.4.2 At phase 2 the consortium will want to push that envelope and look at a much larger sampling rate, perhaps every month over many years (25) to test whether the initial research on the erosion processes identified so far is valid. This approach will improve the knowledge of the specific processes on a range differing geo-morphological conditions across many sites. Phase 2 will not be limited to a feasibility/test sampling environment but will be a full comprehensive test. Adopting this approach will provide the authoritative users the opportunities to amend current thesis in phase 2 and make necessary adjustments (and publish) in order to provide accurate vulnerability and risk assessments and predict erosion rates more realistically.

Detailed List of EO input for Phase 1 (Proof of Concept) over five sites

2.4.3 The list (by site) of data from ESA and TPMs can be found at Annex 2 and is divided into the Optical requirement and the SAR requirement. For ease the Sentinel 1 and 2 requirements (time bracketed) have also been added as it is understood that the Long Term Archive system will be required to be used.

3 Requirements Engineering: Verification

3.1 High Level Review (User Specifications)

To our understanding, the URs are of four types:

- *UR_OBJ_i.* the extension of historical time-series of shorelines' by EO data, complementing previous shorelines derived by non-EO methods.
- *UR_OBJ_ii.* the monitoring of the fluxes of sediments to help mitigate the adverse effects (e.g. beach nourishment, dredging….), -
- *UR_OBJ_iii.* feeding shoreline change indicators or coastal state indicators (CSI) to monitor the change of status of the shoreline and the coastline, and
- *UR_OBJ_iv.* performing process studies that would help parametrize forecast models.

However, the URD mentions explicitly that "*detailed specifications of outputs are aspirational requirements needs for the future, and the champion organizations expect to know of the feasibility, considering results with; (i) available EOs of the last 25 years to assess an average erosion rate at the decadal time scales, (ii) COPERNICUS and commercial higher resolution EOs of last 5 years to monitor erosion and accretion for the management of the coastline by local authorities, (iii) using state of the art sub-pixel resolution techniques* [to reach the expected performances if not attainable at pixel resolution]".

The authoritative users which are members of the Coastal Change' Consortium expect that objectives (1, 2 and 4) will be fulfilled during the project, albeit with the following considerations:

UR_OBJ_i:

- Will be required at the decadal time scale, for the last 25 years (time-scale fixed by ESA) with 3 status reports for the period, i.e. one every 7 years;

UR_OBJ_ii and UR_OBJ_iv.

- Will be required to help coastline management by relevant public authorities, monitoring of the shoreline with demonstration over the last 5 years (time scale of storm recurrence)

UR_OBJ_iii.

- although of prime interest to the Spanish government and to BGS, this UR shall be tackled at a later stage.

Nota: by referring to "sub-pixel resolution techniques", the URD acknowledge that current EOs are likely not to poses the spatial accuracy required to meet their requirements.

3.2 EO products' nomenclature and file organization

The high-level EO products (Table 3.1), *i.e.* Level-3 (L3) and Level-4 (L4) products according to the NASA-ESA nomenclature, made of Level-2 (L2) products that have been listed in the previous paragraphs, have a temporal scale of meteorological events, seasons, years and decades.

Instead of a nomenclature of products that add the time dimension as if another dimension, e.g. 1D_DB/tide level-SL → 2D_DB/tide level-SL for time series of the former, we will now make use of the standard EO nomenclature that goes from L2 to L3 products (products designed with multiple L2 products of the same EO source) then L4 products (products designed with multiple L2 products of different EO sources).

Table 3.1: EO Product nomenclature

EO original generic product code	**EO product code according to standards** and for each EO mission referred to as [EO]	**Updating frequency of the L3 and L4** [Δt]
1D_FB_MHWM	[EO]-L2_1D_FB_MHWM_{area/date/hour}	yearly
1D_FB_OWHM-VL	[EO]-L2_1D_FB_OWHM-VL_{area/date/hour}	yearly
1D_DB/tide level-SL	[EO]-L2_1D_DB/[tide level]-SL_{area/date/hour} where [tide level] is a datum and there may be many	quarterly monthly few days before any storm surge
2D_ext-LULC	[EO]-L2_2D_[classification]-LULC_{area/date/hour} where [classification] is a set of classes and there may be many	quarterly monthly few days before any storm surge
3D_BTMc	[EO]-L2_3D_BTM_{area/date/hour}	yearly quarterly monthly few days before any storm surge, before and after works (such as dredging)

The L3 products would be catalogued as:

- [EO]-L3_1D_FB_MHWM_{area/date/hour-[Δt]},
- [EO]-L3_1D_FB_OWHM-VL_{area/date/hour-[Δt]},

- [EO]-L3_1D_DB/[tide level]-SL_{area/date/hour-[Δt]},
- [EO]-L3_2D_[classification]-LULC_{area/date/hour-[Δt]}, and
- [EO]-L3_3D_BTMc_{area/date-[Δt]}

Where [t, t+Δt] is the period during which L2 products are collected to produce the L3 products.

and would be made of two files, i. the data set of L2 products that are used as inputs to get an output (consider it as the time-series), and ii. the result of the calculation made with the aforesaid L2 products (e.g. a mean, a median, etc.):

for instance [EO]-L3_1D_FB_MHWM_{area/date/hour-[Δt]} =

{ [EO]-L2_1D_FB_MHWM_{area/date*/hour*} | $_{\text{date*/hour*} \in \text{[date/hour, date/hour + Δt]}}$ }

⊗ < [EO]-L3_1D_FB_MHWM_{area/date/hour-[Δt]} >

The L4 products would be catalogued as:

- L4_1D_FB_MHWM_{area/date/hour-[Δt]}—{[EO], [EO'], [EO'']-…},
- L4_1D_FB_OWHM-VL_{area/date/hour-[Δt]}—{[EO], [EO'], [EO'']-…},
- L4_1D_DB/[tide level]-SL_{area/date/hour-[Δt]}—{[EO], [EO'], [EO'']-…},
- L4_2D_[classification]-LULC_{area/date/hour-[Δt]}—{[EO], [EO'], [EO'']-…}, and
- L4_3D_BTMc_{area/date/hour-[Δt]}—{[EO], [EO'], [EO'']-…}

where {[EO], [EO'], [EO'']-…} is the list of sensors or EO missions whose L1 products are all used: {$[EO]_I|_{i=1,\dots,n}$}

and would also be made of two files, i. the data set of L2 products that are used as inputs to get an output (consider it as the time-series), and ii. the result of the calculation made with the aforesaid L2 products (e.g. a mean, a median, etc.):

for instance L4_1D_FB_MHWM_{area/date/hour-[Δt]}-{$[EO]_I|_{i=1,\dots,n}$} =

{ { $[EO]_i$-L2_1D_FB_MHWM_{area/date*/hour*} | $_{\text{date*/hour*} \in \text{[date/hour, date/hour + Δt]}}$ } $|_{i=1,\dots,n}$}

⊗ < L4_1D_FB_MHWM_{area/date/hour-[Δt]} >

The L2, L3 and L4 products' nomenclature should also refer to:

i. the algorithm and data processor that has been used, e.g. Alg (which represents the algorithm with its equations & process, as well as the parameters used to apply it).

ii. the auxiliary data used by the processor, e.g. ADF; best is to attach the auxiliary data file ADF in the delivered products;

for instance $\{[EO]\text{-}L3\_1D\_FB\_MHWM\_\{area/date/hour\text{-}[\Delta t]\}\}_{Alg}$ =

$$\{ [EO]\text{-}L2\_1D\_FB\_MHWM\_\{area/date^*/hour^*\}_{Alg(L2)} \mid {}_{date^*/hour^* \in [date/hour,\ date/hour + \Delta t]} \}$$

$$\otimes\ ADF\ (\ [EO]\text{-}L3\_1D\_FB\_MHWM\_\{area/date/hour\text{-}[\Delta t]\}\ )$$

$$\otimes\ <[EO]\text{-}L3\_1D\_FB\_MHWM\_\{area/date/hour\text{-}[\Delta t]\}>_{Alg(L3)}$$

3.3 EO Products Description (User Specifications)

Section 2 of the URD[20] (AD-1) has synthesized the expectations of the partners that are detailed in the templates of Appendix 1 for the objectives/ topic of interest of each, and of Appendix 2 for the area and EO products' specifications, while restricting the scope for practicality.

- [EO]-L3_2D_[classification]-LULC_{area/date/hour-[Δt]} $_{\mathrm{Alg(L2)}}$, and
- [EO]-L3_3D_BTMc_{area/date-[Δt]} $_{\mathrm{Alg(L2)}}$

3.3.1 1D: Waterlines and shorelines

	URD:	comments & implications
SUMMARY	End-users are interested in 1D products such as shoreline indicators (SI) for both legal interest and to monitor protection change standards over time.	[EO]-L2_1D_FB_MHWM_{area/date/hour-[Δt]} $_{\mathrm{Alg(L2)}}$, [EO]-L2_1D_FB_OWHM-VL_{area/date/hour-[Δt]} $_{\mathrm{Alg(L2)}}$, [EO]-L2_1D_DB/[tide level]-SL_{area/date/hour-[Δt]} $_{\mathrm{Alg(L2)}}$, and backshore edge in [EO]-L3_2D_[classification]-LULC_{area/date/hour-[Δt]} $_{\mathrm{Alg(L2)}}$, and related L3 and L4 products, shall be defined according to requirements that can be - either legal specifications (e.g. drawing the shore limit between private and public domain), - or requirements for shoreline monitoring to implement coastal defence policies, - or related to sovereignty, when dealing with the LAT baseline from which are calculated the breadth of the territorial sea and EEZ.

[20] which is the contractual reference

SUMMARY		
	These type includes; proxy-based (PSI) and datum-based (DSI) shoreline indicators	PSI: [EO]-L2_1D_FB_MHWM_{area/date/hour-[Δt]} $_{Alg(L2)}$, [EO]-L2_1D_FB_OWHM-VL_{area/date/hour-[Δt]} $_{Alg(L2)}$, and backshore edge in [EO]-L3_2D_[classification]-LULC_{area/date/hour-[Δt]} $_{Alg(L2)}$ DSI: [EO]-L2_1D_DB/[tide level]-SL_{area/date/hour-[Δt]} $_{Alg(L2)}$
	PSI has been used historically, i.e. before the advent of Satellites. It implies some restrictions to Shoreline Indicators proxies Proxies used for PSI varies within country partners and have changed over time	Historical PSI (before EO satellite era) and modern EO products consistency has to be assessed and uncertainty budgets of published time-series have to be studied
	Tidal level used for DSI also varies within country partners and has changed over time	The set of {tidal datum}, e.g. the current HAT, MHWS, HWST, MHW, MHHW, MHLW, MHWN, DTL, MTL, MSL, MLWN, MLW, MLLW, LWST, MLWS, LAT, Sounding Datum, and CD; or the old HWMOT, LWMOT, HWMMT, LWMMT, MHW, LHW, LWM, HWM, HWMOST, LWMOST, OHWS, etc. is wide; but the number of tide levels to be used can be reduced because each tide level shall only represent - Either a cadastre or EEZ legal limit, or - a reference for coastal defence engineering (scaling of hard structures, and inputs of models for soft schemes)
	Land-ward Extent of SI within estuarine environments varies with end users' requirements	In view of further industrialization of this production, we suggest using the limit published by EEA on behalf of the European Commission, and get more inland applications on request

	✓ All end-users have expressed interest on analysing the full historical ca. 25 years archive of Satellite data and also exploring what is feasible with higher accuracy satellite data	✓ The main issue in tidal areas is that the tidal Metonic cycle lasts 29 years; as per USGS and NOAA practices of good science, “average” for sea-level rise should then be calculated over 29 years, and the same should apply to coastal erosion; ✓ Users are interested in comparing High-Resolution observations, usually retrieved from uninterrupted historical series, and commercial VHR & HR EOs recorded ‘by chance’ on an irregular basis

	URD	comments & implications
BENEFITS	▪ SI is of legal interest and also used as an indicator of standard of protection from coastal flooding and coastal erosion threats. This product allows authorities in charge of managing flood and coastal erosion risks to set up a coastal erosion baseline policy from which decisions and priorities can be elaborated.	The users’ overall objective is (a) to draw the legal shorelines, and (b) design a “<u>coastal erosion policy</u>” based on Shoreline Indicators, whether PSI or DSI ➔ SI is to be defined by the user, and there may be several SIs, depending on the application envisaged. we suggest for a (legal shorelines): apply national laws and practices for b (coastal erosion): to use *i.* either the seafront, i.e. backshore edge in [EO]-L3_2D_[classification]-LULC_{area/date/hour-[Δt]} $_{Alg(L2)}$ *ii.* or the MHW and MLW shorelines, i.e. L2_1D_DB/MHW-SL_{area/date/hour-[Δt]} $_{Alg(L2)}$ and L2_1D_DB/MLW-SL_{area/date/hour-[Δt]} $_{Alg(L2)}$, as well as the HAT shoreline L2_1D_DB/HAT-SL_{area/date/hour-[Δt]} $_{Alg(L2)}$. It is reminded that HAT is the IHO recommended charted coastline,

	▪ This will allow coastal engineering practitioners and research community to understand better the change processes and validate the conceptual and numerical models used to assess coastal change and their options.	What is feasible in our opinion: i. deliver an average coastal erosion model providing geomorphology changes observed for 25 years periods or by decades based on historical archive. This would be compared to holistic models' outputs, and EO resolution permitting ii. study the possibility of carrying out the studies with free Sentinel data and commercial VHR snapshots.
	▪ To assess the effectiveness of sediments back-pass performed regularly by Port Authorities	cf.. previous paragraph, point ii.
	▪ To improve the understanding of coastal morphodynamics at two timescales: interannual evolution and short-term response to storms. This knowledge is the first step towards developing an action plan targeting both the coastal defences routine maintenance and mitigation actions in case of emergency.	cf. ante-previous paragraph, point ii.
	▪ To document coastal protection strategies	cf. points i. and ii. of ante-ante-previous paragraph
	▪ To inform monitoring bodies and help them design regular maintenance and emergency works	cf. last comment
	▪ To assess accretion rates	All previous comments are valid when replacing the word 'erosion' by 'accretion'

3.3.1.1 1D Products - Conclusions:

- Choice of tidal reference levels against selected DSI,
- Delivery of
  - i. decadal geomorphological changes over a 25 years' period based on EO-derived DSI and PSI.
  - ii. a feasibility study with regards to monitoring the shoreline (with DSI and PSI) with the Sentinel HR constellation, or other public satellites, and only with commercial VHR satellites for large scale observations as appropriate.

3.3.2 2D: Land use, land cover and habitats maps

SUMMARY	URD	comments & implications
	▪ End-users are interested in 2D products for land characterisation, land cover and habitat mapping	Such EO products are out of scope in this ESA contract; however, drawing the seafront, which is the local communities' main subject of interest with breadth of beaches, needs such products in at least 2 classes: - marine ecosystems, - land ecosystems. → [EO]-L3_2D_[classification]-LULC_{area/date/hour-[Δt]} $_{Alg(L2)}$ is to be delivered, at least as an intermediary product, to get the backshore edge which is none other than the common seafront
	▪ Land use and land cover maps are required to characterize the references used in standard coastal risk management practices	This is also out-of-scope of this ESA contract, but the intermediary EO seafront delineation product can be optimized to deliver this information short of classification uncertainty budget.
	Habitat mapping is required to monitor the implementation of wetland restoration projects. Wetland restoration is becoming a common adaptation option to reduce risk of coastal flooding and coastal erosion.	Wetlands/ saltmarshes edges are part of the seafront and will therefore be delivered
	▪ Habitat mapping and vegetation cover are also essential in sand dune restoration projects, such as the one in Maspalomas.	
	▪ Classes required for land use, land cover and habitat mapping vary among end-users.	An agreement should be reached between end-users to specify a ± generic EO-derived product.
	▪ The spatial scope also varies with end-users concerns and responsibilities	As mentioned already, such EO products are not in the scope of this ESA contract but the seafront mapping intermediary product [EO]-L3_2D_[classification]-LULC_{area/date/hour-[Δt]} $_{Alg(L2)}$ shall be delivered to end-users.

	URD	comments & implications
BENEFITS	▪ In UK, habitat initiatives achieved as part of coastal managed realignment schemes have been estimated to be worth between £680 and £2,500 per hectare in environmental benefits, including carbon storage subsidies . Furthermore, the Climate Change Committee (2013) advised that 6200 ha of coastal habitat created nationally by 2030 (costing £10-15M per annum) would save £180-£380M in capital and maintenance costs on coastal flood and erosion management over the long-term when compared to the cost of replacing/maintaining hard defences.	Argans Ltd is currently funded for a pre-feasibility study by the UKSA thanks to DEFRA interest.
	▪ Monitoring change of land cover and land use will help assessing coastal vulnerability and aggravation of flooding and coastal erosion phenomena.	This statement introduces the difference between *Hazards, Risks*, and **Vulnerability**; ➢ The shorelines time-series at the core of this ESA contract are a combination of stacked-up consequences but do not assess the hazards themselves which are not continuously surveyed; whereas risks are only related to occurrences of impacts; ➢ Vulnerability shall be assessed via the coastal indicators fed by EO-products.
	▪ To assess the efficacy of replacing hard structures by soft engineering and backshore revegetation in support of coastal risk management To inform decision-makers and define regular maintenance planning and ad-hoc emergency actions	This requirement introduces the concept of **Resilience** which complements the trio *Hazards, Risks*, and *Vulnerability*, i.e. passive or active actions to mitigate the risks or reduce the vulnerability when facing unpredictable circumstances.

3.3.2.1 Conclusions - 2D Products:

- to replace LU/LC classes in by ecosystem classes in the [EO]-L3_2D_[classification]-LULC_{area/date/hour-[Δt]} products
  - in the nomenclature, such a product should be now named as
    - [EO]-L3_2D_[classification]-ES_{area/date/hour-[Δt]}
    - instead of ~~[EO]-L3_2D_[classification]-LULC_{area/date/hour-[Δt]}~~

- to consider [EO]-L3_2D_[classification]-ES_{area/date/hour-[Δt]} as an intermediary EO product, which is delivered as such but the product that shall be distributed with an uncertainty budget is the inland edge of the backshore or seafront, which is a shoreline SL
  - in the nomenclature, such a product should be now named as
    - [EO]-L3_1D_SL/ES-[classification]_{area/date/hour-[Δt]}
    - Instead of ~~[EO]-L3_2D_[classification]-ES_{area/date/hour-[Δt]}~~
    - with an intermediary product [EO]-L3*_2D_ ES-[classification]_{area/date/hour-[Δt]}
    - (the asterix * representing the fact that the product is intermediary)

3.3.3 *3D: Topo bathymetric digital elevation models & coastal state indicators*

	URD	comments & implications
SUMMARY	▪ End-users are interested in 3D products such as Topo-Bathymetric Digital Elevation Models (TBDEM), elevation transects (ET) and Coastal State Indicators (CSI)	TBDEM are necessary to transform waterlines (WL) into shorelines (SL). Shorelines which belong to the category of contour lines (isohypses or isobaths), are 1D subsets of the 2D seabed dataset. - TBDEM and SLs could be derived from WLs if the WLs dataset span the whole seamless range of altitude and depths and the seabed does not change between WL observation, - TBDEM could be retrieved from ground & aerial surveys or from nautical charts/maps; It is possible to deliver [EO]-L2_3D_BTM_{area/date/hour} and related L3 and L4 products from SDB modellised with optical images and/or SAR and optical images wave fields analysis. i. [EO]-L2_3D_BTM/SDB_{area/date/hour} ii. [EO]-L2_3D_BTM/WF_{area/date/hour} → feasibility to fulfil the user requirement needs to be confirmed.

	▪ TBDEM is a raster product, ET is a vector product and CSI are a combination of vector and raster products	Although EO-based TBDEMs use raster products as inputs and are displayed on a regular grid, they are not proper raster products—yet they have a raster file format in Geographic Information Systems (GIS). Elevation Transects derived from EO-based TBDEMs are curves that use the TBDEMs grid to retrieve values and interpolate them on GISs transects, -they are formatted as shapefiles/vectors in GISs. The CSI, when calculated on a GIS platform, makes use of datasets in raster and vector formats → all SLs are delivered in vector format and all TBDEMs in raster format. Extraction of ETs and CSIs' calculations are the users' responsibility.
	▪ TBDEM are required to produce Datum Based Shoreline Indicators and also assess volumetric sediment change	cf. ante-previous comment for the first point; TBDEMs are core to any further analysis of coastal erosion, and shoreline defence failure assessment as one needs to check regularly whether materials are flushed away or stable.
	▪ ETs contain elevations along transects perpendicular to the coastline from Backshore to Foreshore	As mentioned above, EO services would deliver the TBDEMs so that users can then derive their ETs. Nota: to calculate erosion rates alongshore, a stable shore reference needs to be defined to draw transects perpendicular to the coastline/ reference shoreline
	▪ CSIs requirements varies among end users and can be derived from 1D, 2D and 3D products	NC

	URD	comments & implications
BENEFITS	▪ Assess geomorphic change and volumes of sediment eroded and deposited by subtraction of two independent DTM surfaces to produce a DTM of Difference (DoD), with each grid cell value representing a measure of the vertical elevation difference	To facilitate the delivery of uncertainty budgets, there is a need to set up a reference DTM (e.g. the first element of the time series) rather than applying the uncertainty budget to each DTM when performing the comparison.
	▪ Monitoring dredging activity and environmental awareness; Monitoring an active coastal erosion in a urban area; Monitoring estuary dynamics; Monitoring coastal erosion, sea level and submerged landscapes; For gas pipeline buried across beaches, replace monthly subaerial checks by a proactive management plan aiming at preventing the pipeline to be excavated; Assess the efficacy of sand dredging for navigational purposes and estimate beach silting rates in order to plan further mitigating actions.	This is a non-exhaustive list of applications (use of EO products to map the shoreline)

3.3.3.1 Conclusions – 3D Products:

The 3D products to be delivered are:

- One 3D intermediary product with the [EO]-L2_1D_DB/[tide level]-SL_{area/date/hour} because it is needed to transform waterlines into shorelines; if we were to use a linear approximation of the cross-shore profile near the waterline, the nomenclature should refer to the shore slope *m*; even if we were to use a more complex approximation of the shore profile (e.g. a Bruun profile type), let's call this intermediary product:
  - [EO]-L2_1D_BTM/m_{area/date/hour}

Nota: there is no reason to deliver L3 and L4 products from this L2 intermediary product, except for Quality Control purposes

- Two distinct 3D products:
  - [EO]-L2_3D_BTM/SDB_{area/date/hour} based on the reflectance of light by the seafloor and the attenuation of light in the water column

- [EO]-L2_3D_BTM/WF_{area/date/hour} based on the analysis of the wave fields with related L3 and L4 products.

3.3.4 Coastal State Indicators (CSI)

The URD refers to the coastal state indicators (CSI) (such as those in Table 3.2) that governmental agencies shall deliver to the national and local authorities. CSIs are not supposed to be delivered within this ESA contractual framework but having to specify them should provide information on the errors acceptable to EO products. Shorelines' positions are CSIs, coastlines positions too.

Table 3.2: Coastal State indicators as stated by industry.

CSI*	Quantity represented	Spatial separation	Time between measurements
Dune strength	SoP for storm	250 m	5 years
Barrier width	SoP for storm	180 m	1 month
Total barrier volume	SoP for storm	180 m	1 month
Backshore width	SoP for storm	Mean 1.75 km	1 year
Dune zone width	SoP for storm	Mean 1.75 km	1 year
Dune zone height	SoP for storm	Mean 1.75 km	1 year
Momentary coastline	Position & boundary condition for SoP	250 m	1 year
Beach width	Boundary condition for SoP of hard defence	100 m	6 months
Barrier crest position	Position	180 m	1 month
Shoreline position	Position	Few m	4 to 5 years
Coastline position	Perception of safety	Irregular	Event-driven
Coastal foundation	Rise with sea level	250m	Several years
Shoreface volume	Flood and coastal erosion risk	500m	4 years
Coastal slope	Flood and coastal erosion risk	Mean 1.75km	4 to 5 years

SoP: standard of protection

COASTAL STATE INDICATORS

- Coastal state indicators (CSIs) are a reduced set of measurable parameters used by coastal managers as benchmarks to support management processes.
- They are designed to provide evidence of trajectories of change and to inform timely management interventions [4].
- The coastal zone offers multiple benefits to local inhabitants, and depending on their responsibilities, Integrated Coastal Zone Managers (ICZM) will be interested in different CSIs sub-sets.
- CSIs are often framed within Source-Pathway-Receptor (SPR) or similar risk analysis frameworks [5] (Figure 3.1).
- Coastal geomorphology is a crucial component, representing the pathway that modifies the severity of marine hazards (e.g. surges, extreme waves) as they are experienced by coastal ‘receptors’.
- Next figure summarizes a list of CSIs that represent different coastal environments pathways and can be derived from the 1D, 2D and 3D products described in this document.

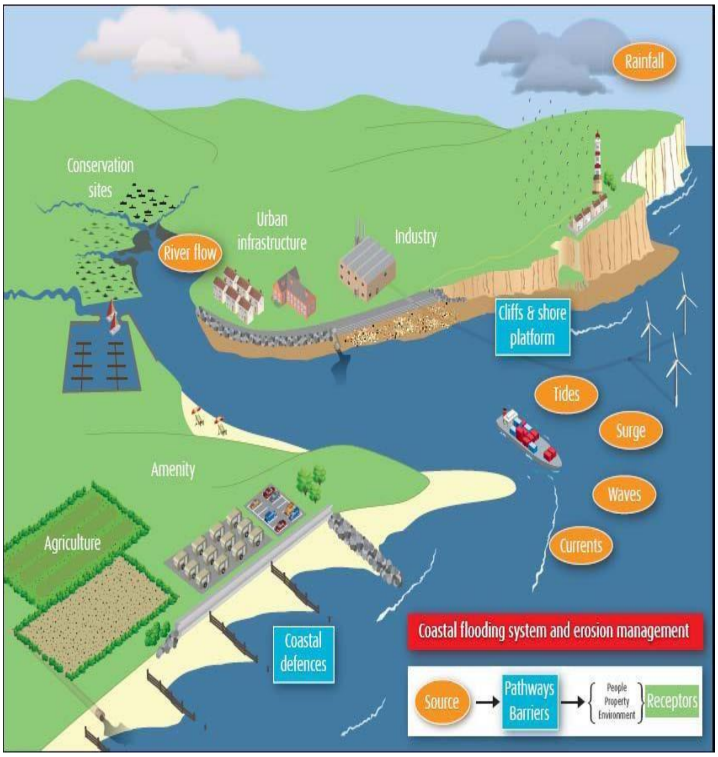


Figure 3.1: Illustrative example of the sources, pathways and receptors for coastal erosion and coastal flooding

3.3.5 What’s missing, if any?

The EO products interesting end-users are L3 and L4 outcomes designed/produced by using L2 results, but the ones that were defined in the previous paragraphs are all about ‘status’ (current situation/ L2 products, or significant, or average, situations delivered per time period/ L3 & L4 products). No EO product for mapping the erosion rates has been specified, this calculation being left to the end-users who will design their own shore reference to calculate changes.

However, we would deliver statistical analysis of the time series along the time-series by themselves.

Table 3.3: Final list of EO products from the URs

EO product code	Description
[EO]-L2_1D_FB_MHWM_{area/date/hour} [Alg(L2)]	: feature-based shoreline based on the mark of high tide
[EO]-L2_1D_FB_OWHM-VL_{area/date/hour} [Alg(L2)]	: feature-based shoreline based on the vegetation line or civil works (seafront)
[EO]-L2_1D_DB/WL _{area/date/hour} [Alg(L2)]	: wet/dry edges on the shore, i.e. waterlines (border between land and water at the time of a snapshot)
[EO]-L2*_1D_BTM/m_{area/date/hour}	: the cross-shore profiles, which is an intermediary product
[EO]-L2_1D_DB/[tide level]-SL_{area/date/hour} [Alg(L2)]	: shorelines based on tidal datum, waterlines, and cross-shore profiles
[EO]-L2_1D_SL/ES-classification_{area/date/hour} [Alg(L2)]	: seafront based on thematic classification of ecosystems = the interface between marine and land habitats
[EO]-L2*_2D_SL/ES-classification_{area/date/hour} [Alg(L2)]	: the map of the shore by land and marine ecosystems' classes, which is an intermediary product, used to get [EO]-L2_1D_SL/ES-classification_{area/date/hour} [Alg(L2)]
[EO]-L3_1D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L2)]	: seafront based on thematic classification of ecosystems but on a series of EOs from same satellite mission to smooth the seasonal effect
[EO]-L3*_2D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L2)]	: the map of the shore by land and marine ecosystems' classes using a series of EOs from same satellite mission, which is an intermediary product, used to get [EO]-L3_1D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L2)]
[EO]-L3t_..._{area/date/hour-[Δt]} [Alg(L3)]	: outputs of calculation on time series of previous shorelines derived from snapshots from same EO mission
L4t_..._{area/date/hour-[Δt]} -{[EO]$_i$ | $_{i=1,\dots,n}$} [Alg(L4)]	: outputs of calculation on time series of previous shorelines derived from snapshots from different EO missions

[EO]-L2_3D_BTM/SDB_{area/date/hour} [Alg(L2)]	: bathy-topo morphology changes based on SDB (vs. a reference DEM-DTM)
[EO]-L2_3D_BTM/WF_{area/date/hour} [Alg(L2)]	: bathy-topo morphology changes based on Wave Fields analysis (vs. a reference DEM-DTM)
[EO]-L3_3D_BTM/…_{area/date/hour -[Δt]} [Alg(L3)]	: result of data fusion of BTM/SDB or BTM/WF on a data sets of snapshots in the Δt time interval
[EO]-L3_3D_BTM_{area/date/hour -[Δt]} [Alg(L3)]	: result of data fusion BTM/SDB and BTM/WF on a data sets of snapshots in the Δt time interval
L4_3D_BTM_{area/date/hour -[Δt]} -{[EO]$_i$ $\vert_{i=1,\dots,n}$} [Alg(L4)]	: result of data fusion BTM/SDB and BTM/WF on a data sets of snapshots from different EO missions in the Δt time interval
L4t_3D_BTM_{area/date/hour -[Δt]} -{[EO]$_i$ $\vert_{i=1,\dots,n}$} [Alg(L4)]	: outputs of calculation on time series of previous BTMs

3.4 Pre-Feasibility analysis 1: EO Theory

This section aims to introduce the theory applied to deriving shoreline indicators from EO products. These are developed on the requirements described in Section 2.

The current paragraph will aim to:

- highlight the main issues with EO that need to be solved
- describe the reason for using certain solutions.

As mentioned in § 3.2, the specifications of the EO-products dedicated to the market of shoreline studies & status monitoring shall be compliant/ compatible with the EO dataset inputs, the relevance of which is prime to sustain attraction.

3.4.1 Background information and theory

EO's information content is characterized by:

- the dimension of the EO signal, made of ε-*m* waves' reflection coefficients, i.e. the number of bands for optical EO or the number of polarizations modes for SAR EO, to enhance the senses
- the spatial resolution to distinguish features by their sizes, their shapes and their ruggedness in addition to their radiometric properties.

From EO products we should be able to detect and map different indicators and shorelines characteristics whether landward or seaward features. Wet and dry line, debris line, cliffs and dunes, sea/land interface (instantaneous waterline), see Figure 3.2, are discernible on Figure 3.3.

EO times series are built to extract statistics of (quasi-)stationary phenomena and predict future values based on previous observations. They are characterized by:

- Time-sampling resolution to apply frequency-domain methods or time-domain methods
- Observations similarity, i.e. relative spatial accuracy (same position for motionless & unaltered features) and recognition reliability (same radiometric characteristics) of the observations to match features from different EO products to fit curves/ function approximations to series at a data point. EOs may need transformations before stacking them

in a time-series for analysis for example when the positioning accuracy of the EOs is not correct and the snapshot conditions are different, or sensors are different.

Relative spatial accuracy from EOs co-registration, further to precise geodetic localization of Ground Control Points (GCP) and orthorectification of the EOs so as to measure shifts of shore features.

Normalization of EOs[21] if observations conditions are different from one to the other. It ensures a reliable matching between features of the different EOs

Out of the 5 characteristics: *i.* the dimension of the EO signal, *ii.* the spatial resolution of EO, *iii.* the density of time-sampling by EO, *iv.* the relative spatial accuracy, and *v.* the similarity of EOs, the most important in terms of EO data sets choice is (ii.) the spatial resolution of EO, then (i.) the dimension of the EO signal, which, if higher can mitigate a lower spatial resolution if applying super-resolution methods; a lack of (iv.) positioning accuracy and (v.) similarity of views between the EOs may be corrected; (iii.) the time-density of EOs is unknown until digging in archives or ordering new snapshots. Point ii., part of i. (components of EO signals that are usable) and part of iv. (absolute spatial accuracy) will be discussed in the following paragraphs; complement to points i. & iv., as well as points v. and iii. will be dealt with in the chapter related to *System Engineering*.

[21] for the usable components of the EO signal

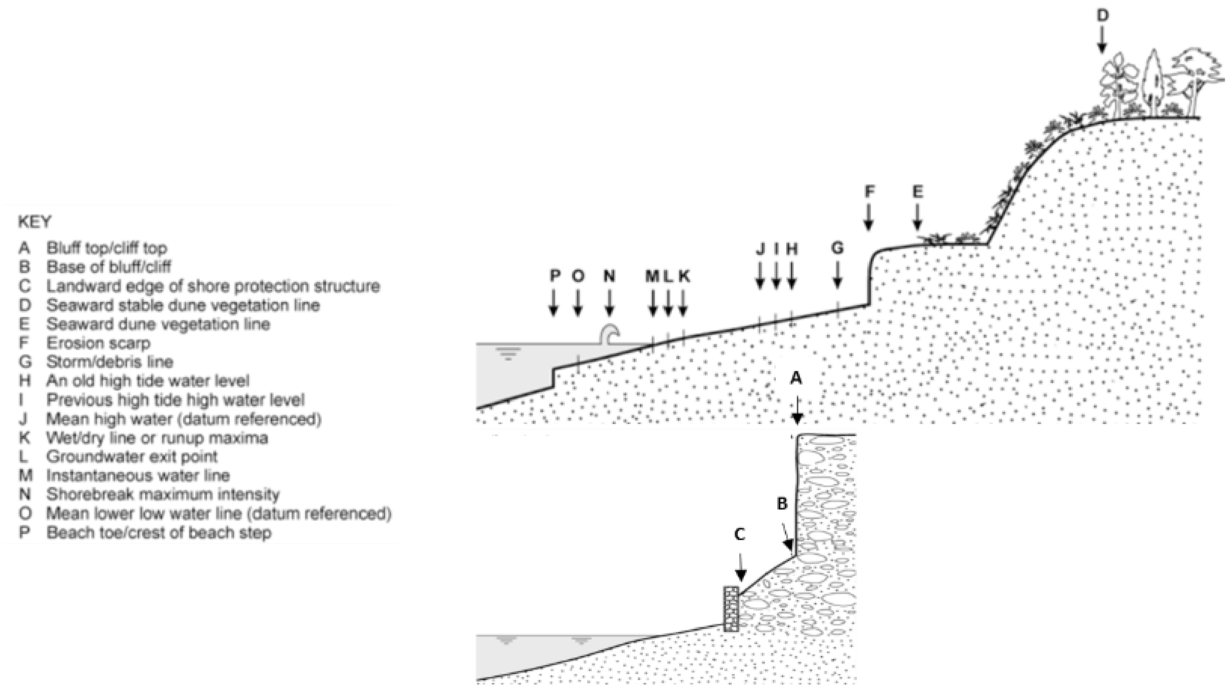


Figure 3.2: Sketch of the spatial relationship between many of the commonly used shoreline indicators, © Boak & Turner, 2005

Figure 3.3: An example of a range of visibly discernible shoreline indicator features, Duranbah Beach, New South Wales, Australia, © Boak & Turner, 2005

The value of EOs for coastal erosion studies relies on their suitability, i.e. the amount of information an observer would expect to gain about the observed system that is consistent with human perception of information present in a given image. Given the events E and E_t, respectively the existence, or occurrence, of a feature of the shoreline and a change of its shape (property or localization), with the probability $P=\Pr(E)$ and $P_t=\Pr(E_t)$, the information content is a mix of $\mathrm{I}(E)=-\log(P)$ and $\mathrm{I}(E_t)=-\log(P_t)$, those averages are the Shannon entropy if the events or change of events are random variables X with discrete values, or the continuous entropy if the random variables are endowed with a probability density function $f(x)$;

- $H(X)=\mathrm{E}\left[I_X(x)\right]=-\int_X f(x)\log(f(x))dx$ is the expected value of the information content of the random variable, i.e. the diversity in the image, which is constrained by its spatial resolution (it bounds the performance of the theoretical strongest lossless data compression possible. In practice, compression algorithms deliberately include some judicious redundancy in the form of checksums to protect against errors
- $H(X_t)=\mathrm{E}\left[I_X(x_t)\right]$ is the entropy rate of the stochastic process

From an image, humans can assess its quality in term of sharpness, colour and noise as well as the amount of interesting structural details. At the opposite, an automatic process, looking at multiple data set indexed by location would work similarly but in a space of higher dimension. It performs its assessment independently of any reference image or prior knowledge of ground truth[22].

Following the theory of Solomonoff-Kolmogorov-Chaitin's complexity[23], information content grows with higher spatial resolution, greater dimension of the multivariable signal, and higher dynamics of the signal (Signal/Noise ratio). Yet, descriptors creation must start with a depiction of the most general and abstracted data structure that can be distinguished within an image.

[22] the spatial arrangement of the pixels to be taken into account in the evaluation of these measures.

[23] Solmonooff, 1964, Kolmogorov, 1965 and Chaitin 1966; Kolmogorov complexity = inductive inference theory also known as Kolomogorov-Chaitin randomness;

If the image information content cannot make any difference between true information and fake information, or between truly located information and badly located information or distortions which are concepts out of the image scope, it is not the case for series of images when features deform and move: there is a high risk of errors when pairing features or pixels and $H(X_t)$ should account for the noise that is generated by the pairing function.

Nota: the exploitable information content of an image depends on the viewpoint, in particular when 3D occlusion occurs or in the presence of shadows.

The related EO attribute that assesses the capacity to describe the physical complexity of objects including their organizations, is the logical depth[24] which is built on i. the EO definite spatial resolution, ii. the pixels' positioning accuracy & time-sampling, and iii. the signals' dimension and dynamics: logical depth assigns a low complexity to both random and trivial objects, in keeping with our intuitive sense of the complexity of physical objects because trivial and random objects are intuitively easy to produce, have no long history and unfold quickly. It is the time connecting the current state of an object with its plausible origin that is the appropriate measure of its complexity in physical terms, but it depends on our understanding of the view or the series of views (recognition of features).

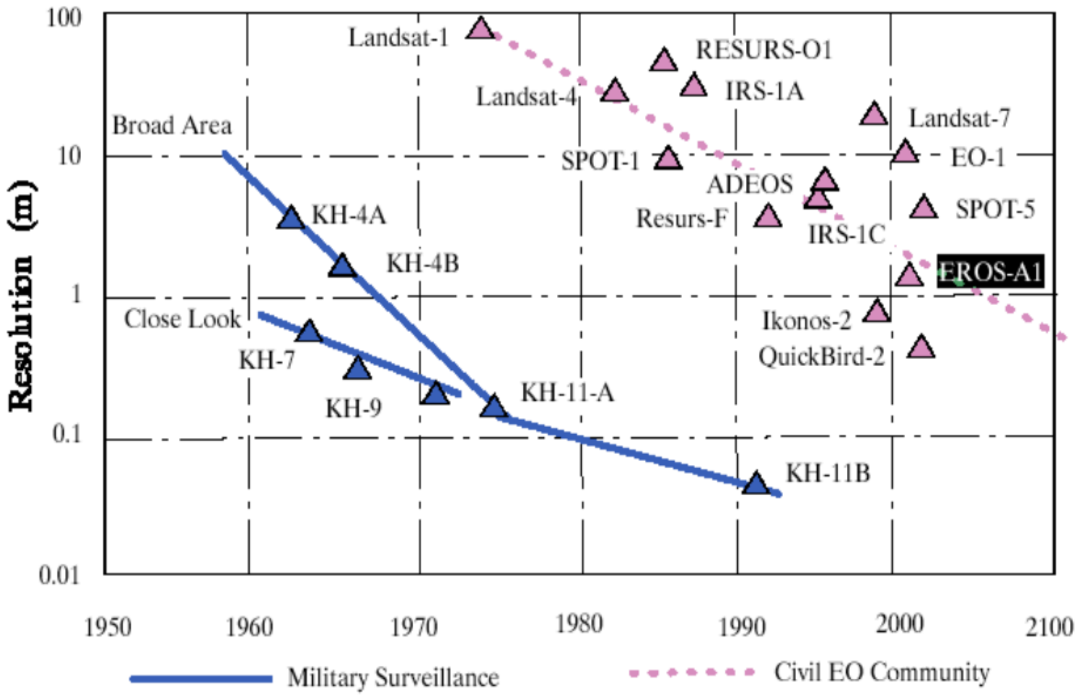
The information content of an EO or a series of EOs for coastal erosion studies depend on the EO definite spatial resolution, the pixels' positioning accuracy & time-sampling, the dimension of the

3.4.2 EO data inputs' and EO products' spatial resolutions

Image resolution describes the details contained in an image, the higher the resolution, the more image details.

[24] concept by Charles Bennett, 1988 & 1990: - Logical Depth and Physical Complexity in Rolf Herken (ed) The Universal Turing Machine–a Half-Century Survey, Oxford University Press 227-257, 1988, - How to define complexity in physics and why. In Complexity, entropy and the physics of information. Zurek, W. H., Addison-Wesley, Eds. SFI studies in the sciences of complexity, p 137-148, 1990

This is the reason why the URD refers to resolutions (and positioning accuracy of the same order) which are sub-metric, with some confusion between what's feasible technically, but restricted to defense & security use, and what's available publicly for free (through e.g. USGS & NOA or EC programs) or commercially (by e.g. Maxar, Airbus, Planet).



Note: KH=Keyhole [designates several DoD reconnaissance satellite series, such as CORONA, ARGON, LANYARD, and LACROSSE - as well as the principal camera system of the S/C]

Figure 3.4: Resolution evolution for different sensor between 1950 and 2000

While image sensors, including the optics, limit the spatial resolution of the image, the image details (high frequency bands) are also limited by the transmission of the signal in the atmosphere which spreads it geometrically (e.g. light dispersion by aerosols, and earth adjacent effect). Either one accepts image degradations, or one uses signal processing to post process the captured images.

For shoreline monitoring, mainly based on handling contours (i.e. interfaces between water and land, isobaths & isohypses, seafront, etc.), the EO resolution impacts their thickness, which represent the precision of the contour measurement —not to confuse with the accuracy of positioning the contour, and with the reliability of the segmentation between land and sea.

Hereinbelow some information, with differentiation between optics (observations similar to eyes', but hampered by clouds and observations need be in daylight) and radar (all-weather conditions with cloud cover penetration, day/night Imaging). It is not an exhaustive list, but a list of significant satellite missions. It refers to the geometric ground resolution of the sensors, the resolution of images that are delivered by the satellite operators, and the point spread function (PSF) which is the "true" resolution of an image; these 3 parameters are seldom supplied concurrently, and images are the result of a gridding of the measurements, with pixels that may be smaller than the resolution of the sensors; as such the resolution of the image does not inform exactly on the information content scale of the image. This list does not distinguish between satellites which have a systematic global cover and the satellites which take snapshots on-request.

Table 3.4: EO missions and their specifications

Satellite constellation	sensor & bands (optical or SAR)	geometric ground resolution	pixel resolution of L1 products	PSF
VNIR				
Landsat Landsat 7 (ETM+)	0.52 - 0.90 µm		15 m	
	0.45 - 0.52 µm, 0.52 - 0.60 µm, 0.63 - 0.69 µm, 0.77 - 0.90 µm		30 m	
Landsat 8 (OLI)	0.503 - 0.676 µm		15 m	
	0.435 - 0.451µm, 0.452 - 0.512µm, 0.533 - 0.590 µm, 0.636 - 0.673 µm, 0.851 - 0.879 µm		30 m	
Sentinel-2 A & B /MSI	448-546 nm, 537-583 nm, 645-683 nm, 762-908 nm		10 m	
	604-723 nm, 731-749 nm, 768-796 nm		20 m	
	430-467 nm, 932-958 nm		60 m	

Planet Lab RapidEye 1,2,3	440–510 nm, 520–590 nm, 630–685 nm, 690–730 nm, 760–850 nm	> 6.5 m	5 m	
Skysat 1,…7	Panchro	90 cm	0.8 m	
	450-900 nm, 450-515 nm, 515-595 nm, 605-695 nm, 740-900 nm	2 m	0.8 m	
	Video (panchro)	> 1.1m	?	
Planetscope	610 - 700 nm, 500 - 590 nm, 420 - 530 nm, 770 - 900 nm	~ 3.70-4.90 m	3 m	
SPOT SPOT 1-2-3-4	0,50–0,73 µm	10 m		
	0,50–0,59 µm, 0,61–0,68 µm, 0,78–0,89 µm	20 m		
SPOT5	480 – 710 nm	2.5 m		
	500 – 590 nm, 610 – 680 nm, 780 – 890 nm, 1580 – 1750 nm	10 m		
SPOT6-7	panchro		1.5 m	
	0.455–0.525 µm, 0.530–0.590 µm, 0.625– 0.695 µm, 0.760– 0.890 µm		6 m	
Pleiades	480-830 nm	50 cm		
	430-550 nm, 490-610, 600-720 nm, 750-950 nm	2 m		
Ikonos	450-900 nm	1 m		
	450 – 530 nm, 520 – 610 nm, 640 – 720 nm, 760 – 880 nm	4 m		
Quickbird	450 – 900 nm	0.61 – 0.72 m		
	450 – 520 nm, 520 – 600 nm, 630 – 690 nm, 760 – 900 nm	2.44 – 2.88 m		

GeoEye-1	450 – 900 nm	0.41 m		
	450 – 520 nm, 520 – 600 nm, 625 – 695 nm, 760 – 900 nm	1.65 m		
WorldView WV-1	400 – 900 nm	0.50 – 0.55 m		
	450-510 nm, 510-580 nm, 630-690nm, 770-895 nm			
WV-2	450-800	0.46 – 0.52 m		
	400-450nm, 450-510 nm, 510-580 nm, 585-625 nm, 630-690nm, 705-745 nm, 770-895 nm, 860-1040 nm	1.84 – 2.4 m		
WV-3	450-800 nm	31-34 cm		
	400-450nm, 450-510 nm, 510-580 nm, 585-625 nm, 630-690nm, 705-745 nm, 770-895 nm, 860-1040 nm	1.24-1.38 m		
	405 - 420 nm, 459 - 509 nm, 525 – 585 nm, 620 - 670 nm, 845 - 885 nm, 897 - 927 nm, 930 - 965 nm,	30 m		
WV-4	450-800 nm	0.31-0.34-1 m		
	655 - 690 nm, 510 - 580 nm, 450 - 510 nm, 780 - 920 nm	1.24-1.38-4 m		
Cartosat-1	500-850 nm	2.5 m		
Eros	A1/500-900 nm	1;8 m		
	B/	65 cm		
	NG/450-900 nm	30 cm		

Runner & Sprinter	400-670 nm	70 cm – 1 m		
PRISM & AVNIR-2	520 – 770 nm	2.5 m		
	420 – 500 nm, 520 – 600 nm, 610 – 690 nm, 760 – 890 nm	10 m		
Formosat	F-2/ 450 – 900 nm	2 m		
	F-2/ 450 – 520 nm, 520 – 600 nm, 630 – 690 nm, 760 – 900 nm	8 m		
Kompsat K2	500-900 nm		1 m	
	520nm - 600nm, 450nm - 520nm, 760nm - 900nm, 630nm - 690nm		4 m	
K3	450-900 nm	>0.7 m		
	450-520 nm, 520-600 nm, 630-690 nm, 760-900 nm	>2.8 m		
K3A	450-900 nm	>0.55 m		
	450-520 nm, 520-600 nm, 630-690 nm, 760-900 nm	>2.2 m		
Triplesat	450-650 nm	0.8-1 m		
	440-510 nm, 510-590 nm, 600-670 nm, 760-910 nm	3.2-4 m		
DMC Bilsat	panchro	4 m		
	Red, green, Blue, infra-red	26 m		
NigeriaSAT1	3 spectral bands	32 m		
NigeriaSat2	panchro	2.5 m		
	B, G, R, NIR	5 m		
UK-DMC1	3 spectral bands	32 m		

UK-DMC2	3 spectral bands	22 m		
Beijing-1				
Deimos-1	3 spectral bands	22 m		
Deimos-2	450-900 nm	0.75 m		
	420-510 nm, 510-580 nm, 600-720 nm, 760-890 nm	4 m		
SAR				
ERS ERS1 & ERS2	AMI	<30 m x <26.3 m		
Envisat/ASAR	Image Mode Wide Swath Mode Alternating/Cross Polarization Wave Mode Global Monitoring	28 m x 28 m 150 m x 150 m 29 m x 30 m 28 m x 30 m 950 m x 980 m		
Radarsat R1 (C-band)	Standard Wide (1) Wide (2) Fine Resolution ScanSAR (N) ScanSAR (W) Extended (H) Extended (L)	25 x 28 m² 48-30 x 28 m² 32-45 x 28 m² 11-9 x 9 m² 50 x 50 m² 100 x 100 m² 22-19 x 28 m² 63-28 x 28 m²	25 x 28 40 x 28 40 x 28 10 x 9 50 x 50 100x100	
R2 (C-band)	Wide ultra fine Wide multi-look fine Wide fine Wide fine Quad-Pol Wide standard Quad-Pol	1.6 - 3.3 x 2.8 m² 3.1-10.4 x 4.6-7.6 m² 5.2-15.2 x 7.7 m² 5.2-17.3 x 7.6 m² 9-30.0 x7.6 m²		
RCM (C-band)	Low Res Med Res 50		100 x 100 50 x 50	

	Med Res 16 Med Res 30 High Res 5 Very High Res Low Noise Spotlight		30 x 5 3 x 3 4 x 2 1 x 3	
Sentinel-1 (C-band)	SM IWS EWS WM		5 m x 5 m 5 m x 20 m 25 m x 80 m 20 m x 5 m	
TerraSAR-X & Tandem X (X-band)	ScanSAR Wide (SCW) ScanSAR (SC) StripMap (SM) Spotlight (SL) High-Resolution Spotlight (HS) Sliding Spotlight (HS) Staring Spotlight (ST)	40 m 18 m 3 m 1.7 m - 3.5 m 1.4 m - 3.5 m 1.1 m – 1.8 m 0.9 m – 1.8 m		
Cosmos-SkyMed CSK (X-band)	Spotlight ("Frame") HIMAGE (Stripmap) WideRegion (ScanSAR) HugeRegion (ScanSAR) Ping Pong (Stripmap)		< 1m 3-15 m 30 m 100 m 15 m	
CSG	Spotlight-2A Spotlight-2B Stripmap Pingpong Quadpol ScanSAR-1 ScanSAR-2	0.35 x 0.48/0.55 m^2 0.63 x 0.63 m^2 3 x 3 m^2 12 x 5 m^2 3 x 3 m^2 20 x 4 m^2 40 x 6 m^2		
PAZ (X-band)	Stripmap	3 m x 3 m		

	ScanSAR Spotlight HR Spotlight	6 m x 6 m 16 m x 6 m 1 m x 1 m 2 m x 2 m < (1 m x 1 m) < (2 m x 2 m)		
SAOCOM (L-band)	Stripmap TopSAR narrow TopSAR wide	< 10 m < 30-50 m < 50-100		
NovaSAR	Stripmap Stripmap (wide swath) Stripmap x-polarization Maritime (scanSAR) ScanSAR Dual polarization Tri polarization		6 x 6 m² 6 x 6 m² 6 x 10 m² 6 x 14 m² 20 x 20 m² 20 x 20 m² 30 x 35 m²	
ICEYE X1	Stripmap Stripmap Hig ScanSAR Spotlight		3 m x 3 m 1.5 m x 1.5 m 20 m x 20 m 1 m x 1 m	

Very-high Resolution products, in particular for SAR satellites, are usually screened off the civilian customers.

It is noticeable that the satellite operators seldom deliver the PSF, reason of their absence in the table, geometric ground resolution, pixel resolution of L1 products, and PSF of L1 products being confused.

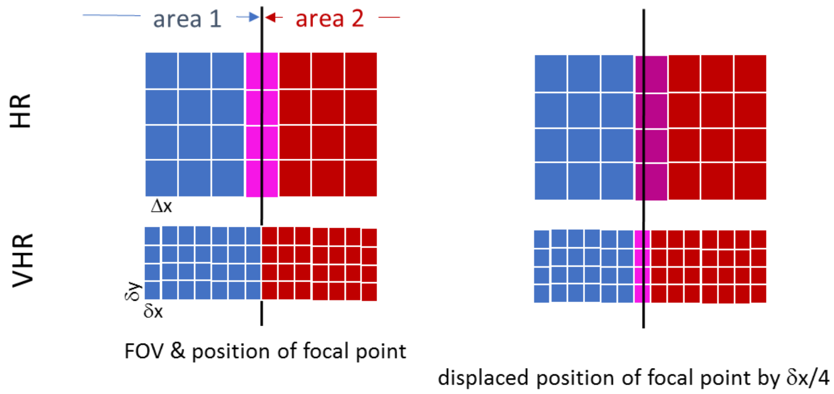
3.4.3 1D EO products

1D EO products, i.e. shorelines from waterlines, are designed by identifying points in the digital images at which the image characteristics change sharply when coming landward from the sea, or, more formally, have discontinuities —usually in the brightness, but one also uses chromatic parameters such as NDVI or NDWI. The variety of mathematical methods based on gradient operators falls under the name “edge detection”. The result of applying an edge detector leads to a set of +/- connected curves that indicate the boundaries of the sea. However, it is not always possible to obtain an ideal continuous edge from EOs, even with moderate complexity, i.e. taken in calm weather, because of shoals, cusps, etc.: extracted edges are often hampered by fragmentation, when the edge curves are not connected, missing edge segments as well as introducing false edges not corresponding to the interesting phenomena in the image, i.e. the most landward discontinuity – thus complicating the subsequent task of interpreting the image data.

In the following paragraphs, we would address the issue of edges not being ideal step edges because of the finite size of the point spread function (PSF) represented by a pixel in L1 products delivered by EO satellite operators that are used as inputs.

3.4.3.1 Standard EO resolution

E.g. to draw a line or linear mark $L_{1\text{-}2}$ which impersonates the divide of a surface between two areas of different properties S_1 and S_2, one needs at least 2 pixels; but, in practice the line's thickness is of 0 to 1 pixel which could give 2 lines across one pixel for a single mark: as such the line is effectively of 1 pixel thickness:



and, if the signal is too noisy and the image needs to be un-speckled or smoothed on *n* pixels before looking for edges, the true thickness of the line is in-between 1 and *n* pixels, something like 2*n*+3. It is summarized by the following formula:

$$L_{1-2} = \Lambda_{1-2}\left(EO\_scale, EO\_S/N, \vec{\nabla}properties\left(S_1, S_2\right)\right)$$

which words that the line depends on the spatial resolution of the snapshot $(\Delta x, \Delta y)$, and the difference of optical or SAR reflective properties between S_1 and S_2 compared to the signal/noise ratio of the sensor;

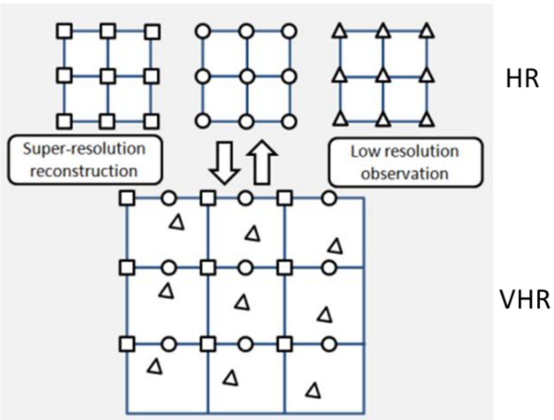
as such the thickness of the line $\|L_{1-2}\|$ depends on the same parameters

$$\|L_{1-2}\| = \mathrm{T}\left(EO\_scale, EO\_S/N, \vec{\nabla}_{local}\, properties\left(S_1, S_2\right)\right)$$

3.4.3.2 Super-resolution

There are two main methods to mitigate a lack of spatial resolution, the use of super-resolution imaging reconstruction methods (SR), and the demixing methods (also identified by the acronym SR unfortunately);

- in the first case, one constructs high-resolution (VHR) images from several observed high-resolution (HR) images, thereby increasing the high frequency components —the basic idea behind SR is to combine the non-redundant information contained in multiple HR frames to generate a VHR image, this non-redundant information being typically introduced by subpixel shifts between them, i.e. snapshots taken in different geometries;



: the basic idea for super-resolution reconstruction from multiple HR frames: subpixel motion provides the complementary information among the HR frames that makes SR reconstruction at VHR possible.

while the sensors capture several HR frames, which are downsampled from the VHR scene with subpixel shifts between each other, SR construction reverses the process by aligning the HR observations to subpixel accuracy and combining them into a VHR image grid;

nota: it is a similar method that is used to co-register HR scenes with a VHR image (cf. following paragraph §2.2….)

tests have been performed with Sentinel-2 images, showing that it is possible to get from a 10 m resolution to some 5 m resolution at temperate latitudes, when different tracks allow capture snapshots of the earth in different geometries;

➔ it works when 2D features exist at scales between HR and VHR, but there is no reason to improve the resolution of features' edges

- pixel demixing methods, such as those used for SDB, which are based on the presence of various materials, whose optical/ scattering properties are known, and in different concentrations;

  it is the method requested by the end-users in the URD: with regards to the waterlines, the intermediary pixel which is made of S_1 (land) and S_2 (sea) properties

  $$properties(\mathrm{pixel}_{\mathrm{int}}) = \alpha \cdot properties(S_1) + (1-\alpha) \cdot properties(S_2) \text{ where } \alpha \in [0,1]$$

  it is possible to reduce the thickness of the line to zero, and locate it within the intermediary pixel at $\alpha \cdot \Delta x$ in the geometrical configuration considered in the figure hereinabove; yet, the accuracy depends on the accuracy of the $properties(S_1)$ and $properties(S_2)$ as

  $$\alpha = \frac{properties(\mathrm{pixel}_{\mathrm{int}}) - properties(S_2)}{properties(S_1) - properties(S_2)}$$

  $$\left\| L_{1-2}^{\mathrm{demix}} \right\| = \delta\alpha \cdot \Delta x$$

  where $\delta\alpha = \dfrac{N + \sigma_{properties_S}}{\left|\Delta properties_{1,2}\right|} + 2\dfrac{\left|\Delta properties_{int,2}\right| \cdot \sigma_{properties_S}}{\left|\Delta Properties_{1,2}\right|^2}$,

  with N being the measurement's noise, incl. the sensor's noise and all errors of the L1 data processor, $\sigma_{properties_S}$ is the error on the assessment of the adjacent values, which is usually the variability of the properties in each surface, and $\left|\Delta properties_{1,2}\right|$ is the contrast between the two surfaces;

  as $\delta\alpha \cong \dfrac{N + 3\sigma_{properties_S}}{\left|\Delta properties_{1,2}\right|}$ also noted $\delta\alpha \cong \dfrac{N + 3\sigma_{properties_S}}{\sigma_{properties_{\Delta S}}}$ where $\sigma_{properties_{\Delta S}} = \left|\Delta properties_{1,2}\right|$, we can write it using the gradient of properties or $contrast_{1,2}$: $\delta\alpha \cong \dfrac{N + 3\sigma_{properties_S}}{contrast_{1,2} \cdot \Delta x}$,

  leading to an estimate of the line thickness of $\left\| L_{1-2}^{\mathrm{demix}} \right\| \simeq \frac{N+3\sigma_{properties_S}}{contrast_{1,2}}$ which can be even simplified in $\left\| L_{1-2}^{\mathrm{demix}} \right\| \approx \dfrac{3\sigma_{properties_S}}{contrast_{1,2}}$ or $3\dfrac{\sigma_{properties_S}}{\sigma_{properties_{\Delta S}}}\Delta x$: to reduce the thickness of the line, one needs $\sigma_{properties_{\Delta S}} > 3\sigma_{properties_S}$

→ application to drawing waterlines:

- with optical data,

  - the reflectance of a water column of infinite depth in calm weather is some 5% and the reflectance of land features is between 20 and 50%: the ratio of 4 to 10 is higher than the threshold of 3 to justify the use of demixing, as long as the water is not too shallow —in this case, as materials lose some 10-to-30% of reflectance when wet on the seafloor and the seabed reflectance would decrease of some 100% per Secchi depth, the ratio would fall to ratio of 3-to-4 if the pixel contains only shallow waters and not deep waters

    in short, demixing is valid for calm weather images where pixel size Δx is much larger than the nearshore; as the slope of the shore is in-between 0.02 and 0.2, this optical nearshore width is of the order 10-to-100m;

  - in choppy seas, the water properties are rather characterized by whitecaps from wave breaking in the surf zone, hence a reflectance of the water which is of the same magnitude as the reflectance of land features by a factor 2; demixing does not help;
  - The choice of this method would depend on the shoreline types, a priori reflective coasts characterized by surging breakers, in non-tidal areas and with no offshore bar.

- (pan-)sharpening: when the satellite-borne sensors have a band at a higher resolution than the others, e.g. the panchromatic band of Landsat or the 10m resolution bands of Sentinel-2 vs. the 20m & 60 m resolution bands, one can apply correlations between the highest resolution band and the lower resolution bands to increase the resolution of the latters;

  however it does not really decrease the thickness of the interface line between two surfaces, except when looking at the shoreline with the band of highest resolution (without sharpening the others)

In conclusion, only the demixing method could easily work, but in specific cases, i.e. for shore type that have a narrow surf zone.

3.4.4 2D EO products

The 2D EO products are the outcome of a transformation of images with continuous dynamics (e.g. light or radar reflectance) to images with discrete dynamics (e.g. labels of classes, in finite numbers for the taxinomy, usually 10 to 20) or quasi-discrete dynamics (e.g. probability that the input is a particular class, each class being a 2D feature) —a transformation, called a partition, which, if not based on edge detection as for 1D products, is based on similar principle, i.e. looking at discontinuities yet getting rid of most of them vide an optimal smoothing filter when clustering the data[25] while segmenting the images.

The result of image segmentation is a set of segments that collectively cover the entire image, each of the pixels in a region being similar with respect to some properties, and adjacent regions being significantly different with respect to the same characteristic(s). The interfaces between segments, i.e. the contours, build-up 1D products, and we are mostly interested in the contour that represents the border between land ecosystems and sea ecosystems.

Whereas edge detection, which is usually applied to retrieve waterlines, is mainly based on thresholding, segmentation is based on thresholding + a further step of data clustering that takes care of the spatial continuity of expected segments. As such, 2D EO products increase the contextual of the image, i.e. the size of the neighborhood of each pixel in which we look for a single class, and the contours are smoother, but also thicker because one accepts more variability of properties on one side or the other.

Contours’ thickness is not related to contours’ positioning, whose accuracy is translated in the scale of a map. It manifests the scale of observation of objects. 2D EO products’ observation scale, and the related 1D EO products that are derived from them, is lower than the scale of the 1D EO products which are directly computed on EOs.

[25] given the criteria of detection, localization and minimizing multiple responses to a single edge

3.4.5 3D EO products

3D EO products' resolution is also dependent on the EO resolution, but there is no transformation of scale if the EO data inversion that delivers the products is pixel-based. It is currently the case for SDB, even if some attempts have been performed to consider the differences between the variability scales of the atmosphere's, the ocean surfaces', the land surfaces' and the seabed's optical properties. For SAR interferometry or optical photogrammetry, the situation differs by the use of multiple images, and localization accuracy of each image or inter-localization of the images used is more important than the image resolution.

3.4.6 Existing shoreline indicators

Most shoreline indicators have been defined by measurements on ground or aerial photographs, and they are identified "by eye", using details of the ruggedness of the shoreline bed and their radiometric properties. As such, they use at most 5 independent characteristics, 3 radiometric ones and 2 topographic ones (altitude/bathymetry and gradient).

Table 3.5 lists examples of shoreline indicators that are currently in use, and that provide the reference accuracy to which the URDs request. Importantly, the definition of these indicators is not always consistent, and the observations do not always match the process or geographic feature that it targets. These indicators are based on physical, morphological or biological changes with the waterline as a reference.

Table 3.5: Features to be identified and mapped (proxy-based shoreline indicators)

shoreline indicator	identification of feature	generic name	comment
bluff top/cliff top or bluff line/ line/crest of slope	landward edge of the bluff top or cliff top	bluff top/cliff top	Good erosion indicator, but will not show accretion; morphology specific (hard coast)
	break in slope resulting directly from wave erosion or from mass movements triggered by wave erosion		

Landslide headwall	top of the headwall; only used on bluffed shorelines with zones of mass movement, e.g., earth flows, landslides, lumps, or transitional slide blocks	idem	morphologic specific
Base of bluff/cliff	base of bluff or cliff; used when bluff/cliff top is rounded, and it is not easy to determine the landward edge	idem	not clearly defined; base position may be distorted due to rubble, etc; morphology specific (hard coasts)
Landward edge of shore protection structure	Landward edge of shore protection structures and development	idem	case specific: only where the coastline has been protected; a properly designed structure is designed not to move/fail within its design life, so the indicator is unlikely to relocate
Seaward edge of dune vegetation	seaward edge of stable, long-term vegetation	seaward stable dune vegetation line	case specific: only where dune vegetation is present; good erosion indicator, but may not show acretion or will show it with a significant time lag (what defines stable and long term?)
	seaward edge of dune vegetation	seaward dune vegetation line	same
Dune vegetation line	seaward edge of dune vegetation	seaward dune vegetation line	same
Vegetation line	distinct edge in image based on tonal differences (brightness) between the vegetated and non-vegetated beach areas	seaward dune vegetation line	same
Dune line	appears as a topographic break or scarp between the wind- or wave-deposited dunes and the seaward-sloping beach	erosion scarp	good erosion indicator, but will not show accretion; not always present, both spatially and temporally
Foredune foot	upper level of the highest spring tide, a sharp break in slope from the gentle upper beach to the steep dune front, or a dune erosion scarp	erosion scarp	same

Berm crest	accretionary morphologic feature interpreted as HWL	berm	good erosion indicator, but will not show accretion. Not always present, both spatially and temporally
High Water Line (HWL)	seaward line of two lines of slight discoloration; the more landward line is the storm/debris line	previous high tide HWL	may not be clearly visible; affected by wind/wave/tide conditions at the time
	a change in color or gray tone caused by differences in water content of the sand on either side of the high-water line		same
	approximation of MHW: marking on beach from last high tide, not last storm/debris line; visually detected in the field	T-sheet HWL	may not be clearly visible; not MHW; affected by wind/wave/tide conditions at the time
	on a rising tide = maximum runup limit; on a falling tide = part of beach that is still wet, but it may be beyond the instantaneous run-up limit	wet/dry line	clearly visible on all photos but variation due to sand drying is not quantified/ affected by wind/wave/tide conditions at the time; Dolan et al (1978) inferred that the wet/dry line is a stable shoreline indicator and is less sensitive to tidal stage than the instantaneous runup limit
	the location of the wet and dry beach contact or the high-water debris line	previous high-tide HWL; or storm/debris line	may not be clearly visible; affected by wind/wave/tide conditions at the time; or represents only elevated water conditions during storms
	zone of high-pixel brightness variance	near-shorebreak	NOC
	change in color or shade of the beach sand, or a line of seaweed and debris	previous high-tide HWL; or storm/debris line	may not be clearly visible; affected by wind/wave conditions at the time; or represents only elevated water conditions during storms

	wet/dry boundary on a beach, recognized by an abrupt or subtle change in contrast; may be obscured by shell deposits, debris along the beach, or vegetation; or the outer limits of emergent marsh vegetation as seen in lagoons and estuaries	previous high-tide HWL; or seaward estuarine vegetation line	may not be clearly visible; affected by wind/wave conditions at the time; marsh vegetation may not die off rapidly in erosion or accretion conditions, so a time lag may be present
Usual (or mean) high-water line	seaward edge of vegetation; or high-water line left by last storm; identified by residuals such as sticks, branches, weed clumps; or water line of last high tide identified by points of darker tone, an identifiable edge after drying and receedance of the tide	seaward vegetation line; or storm/debris line; or previous high-tide HWL	vegetation not always present —good erosion indicator, but may not show accretion or will show it with a significant time lag; or only represents elevated water conditions during storms; or may not be clearly visible; affected by wind/wave conditions at the time
Mean high-water line	changes in color or gray tone	previous high-tide HWL	NOC
Average high-water line	boundary between where an average high tide often reaches and where higher high water reaches less frequently; landward of the smooth sand (high reflectance) caused by recent swash; seaward of wind-rippled sand that represents longer aerial exposure; a line of driftwood or seaweed deposits was often the landward edge; dewatering line also used for identification during a falling tide; sparse seaward edge of vegetation used when changes in beach reflectivity (tonal contrast) allowed for two possible choices; if insufficient variation existed, then operator selected a point equidistant from instantaneous water line and seaward edge of vegetation	between instantaneous water line and seaward edge of vegetation	not consistent

Wet/dry line	on a rising tide = maximum runup limit; on a falling tide = part of beach that is still wet, but it may be beyond the instantaneous run-up limit	wet/dry line	cf. previous comment on wet/dry lines
	distinct edge in image based on tonal differences (brightness) between the dry and wet beach areas	same	NOC
Water Line	Land/water boundary	instantaneous waterline	
Beach toe	change in slope at the transition between nearshore and foreshore: natural feature that marks the seaward edge of the beach; crest of beach step, marked by a distinct tonal contrast by the change in water depth over the feature	beach toe/crest of beach step	not visible in many locations

3.5 Pre-Feasibility analysis 2: EO exploited by Surveyors

This section describes the use of EO data to determine CSI.

3.5.1 Extracting morphological variable: altitude (z)

With EOs available to the contractor, it is impossible to get the altitude of the shore by stereo-imaging, even if technically feasible, or by SAR interferometry. Yet, results would not fulfill the users' expectations because i. the stereo-mapping error with optical data sets would be of some 0.5 m which is too much for coastal materials' volume assessment, and ii. typically, the beach surface lacks significant roughness required to produce a strong backscatter signal, thus preventing effective interferometry (i.e. information with errors less than 1 m). Accordingly, only the depth could be retrieved by EO.

3.5.2 EO Data: Optical

Surveyors only use optical data to identify the shoreline features despite numerous studies being carried out for shoreline extraction from SAR images since the launch of the first SAR satellite SEASAT in 1978[26].

- ➔ Out of the 5 characteristics that are used by surveyors to map the shoreline (up to 5 equations, 1 unknown variable), only 3-to-4 could eventually be used with EOs if applying the same concepts: the sole consistent indicators, that operators can eventually see on EOs are

[26] the sea surface has a weaker return signal due to larger specular reflection and absorption by water compared to the land surface, allowing to draw a shoreline based on the difference in the return signals, with segmentation algorithm based on histograms & thresholds, edge detection and regional detection

- in optics: the indicators A & B (top and base of bluffs/cliffs[27]), C (landward edge of coastal defense structures[28]), M (water line[29]), F (seasonal erosion scarp[30]), E (seaward vegetation line[31]), D (seaward stable dune vegetation line[32]), N (shore-break maximum intensity[33]), and eventually G (storm/debris line[34]), of the last figure;
- with SAR: the indicators A (top of bluffs/cliffs[35]), M (water line[36]), K (wet/dry line[37]), N (shore-break maximum intensity[38]), and eventually G (storm/debris line[39])

➔ Automats shall, in a first stage, use methods derived from those used by operators, with 4 bands from optical data sets, and at least one polarimetry from SAR data sets. However, it is fashionable to use a NIR band, not available to the operators' eyes, to map Earth features (e.g. use of the NDVI) —the validation on it being only on-ground surveys.

➔ Water lines M, which need 3 bands to be drawn and to avoid confusion with indicators N and K, are consistent indicators in terms of observations by EOs, reason why datum-based shoreline indicators, i.e. waterlines related to standard tidal heights, provide a more objective detection technique than proxy-based shoreline indicators, and are the preferred shoreline indicators. However, historical mapped shorelines were mapped using visually discernible features to produce proxy-based shorelines, and continuity shall be provided: we suggest inferring the proxy-based shorelines from datum-based shorelines, and using EO-based proxy shorelines (the proxy-based shorelines), except for indicators A-B, C and D.

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[27] which are brown

[28] which are grey

[29] interface between blue and …

[30] If there' is a shadow, or change of materials (coarser in the top) translated in change of reflectance

[31] border of green area

[32] detected by the green + a shadow

[33] which is white

[34] line of brown and green materials

[35] higher reflectance than sand and water

[36] absorption of microwaves by water

[37] maybe confused with M, because of the absorption of signal by interstitial water

[38] Bragg diffraction on breakers

[39] higher scattering on debris than on sand

3.5.3 EO Data: SAR

With regards to SAR images, it is not fully understood to what extent the signal returned from the sea surface differs from that from the neighbouring land surface to find the land-sea boundary, and most of shoreline detection technique relies on threshold methodologies, applied to smoothed images (to get rid of the speckle) with histograms that are empirical and local because the contrast between the land and the sea is significantly affected by polarization method, sea surface conditions, and incident angle of the radar. Yet the following conclusions have been reached in the last decades:

- the HH polarization mode (horizontal transmit and horizontal receive) has been found to be the best mode for shoreline detection due to the contrast of the backscattering coefficient between the land and sea. Backscattering of active microwave relies on surface roughness, dielectric constant on land and on Bragg scattering on water i.e. ripples on the nearshore sea surface[40]. Most of the electromagnetic energy of the microwaves is scattered in the same propagation direction and thus the sensor receives relatively stronger backscattering signals in the like-polarization modes. In terms of contrast, land backscattering σ_l is higher that the backscattering of the sea σ_S in HH mode whereas σ_S is nearly equal or greater than σ_l in VV mode. σ_l is not sensitive to polarization on bare soils such as silt, sand and gravel, and σ_S(VV) > σ_S (HH), therefore, HH polarization usually generates a larger difference in backscattering between a beach and the sea than VV polarization.
- SAR scenes, with incident angle from 30° to 50° under sea-to-land observation direction, are recommended for shoreline detection. Preferential incident angles for shoreline detection should be either small or large depending on the roughness of the land surface, with shoreline +/- undetectable if the incident angle is out of the range of these two critical incident angles.
- distance measurements between the sensor and the Earth are converted in angles and location on a representation of the earth surface, hence the distortion of the waterline and

[40] without any clear correlation between the significant wave height and the backscattering coefficient of the sea surface; but wave breaking in the nearshore leads to a complex backscattering process and an increase in backscattering coefficient

the masked of low proxy-based shoreline indicators by the tall features of the backshore and hinterland.

- large waves have a significant effect on shoreline detection (wave height shall be small); same for moisture (wet sand vs. dry sand —the dielectric constant of dry soil is around 3, while it increases to 20 for the wet soil) which depends on wave run-up and rains; and
- X-band SAR scenes may be preferred to C band, and obviously, L-band SAR scenes for shoreline detection where the grain size of the beach material is relatively fine. Yet, according to the Rayleigh criterion, beach grain size smaller than 0.5 cm is considered as the criteria of smooth surface under the incident angle of 40.0° in the case of COSMO-SkyMed SAR which has 3.1 cm microwave length, 0.7 cm for Sentinel-1 SAR at 5.4 cm wavelength, and 3.7 cm for ALOS SAR microwave length of 24 cm in the same conditions of observations = the bed roughness of sandy beaches is categorized as smooth surface with small scattering power. Radars with shorter wavelength also deliver better shoreline mapping over gently sloping beaches because the Bragg waves resonant with different frequencies reside in different regions but are badly affected by wave breaking.

Nota: ESA recently published a news brief[41] by Deltares of results obtained in the H2020 project ECOPOTENTIAL on the use of a simple threshold value on Sentinel-1 data sets/ Ground Range Detected (GRD) products for defining the contour of the detected edge on the Torre Canne Apulian beach in Southern Italy and the intertidal mudflats and flood-tidal channels of the Wadden Islands in The Netherlands, could be considered as reliable shorelines to assess coastal erosion. However, the uncertainty budgets on EO-waterline locations have not been published despite a promising statement that "satellite data can be used to aid in the monitoring of similar beaches […] which do not currently have the benefit of video monitoring systems to track changes" and "many […] coastlines do not have the resources to implement active high frequency monitoring programmes; the ability of open and free satellite data to track developments in such areas is a boon to research and

[41] https://sentinel.esa.int/web/sentinel/news/-/article/copernicus-sentinel-1-supports-detection-of-shoreline-positions

management" —the authors recognize that, if "Copernicus Sentinel-1 provides useful data in such a region", however, "additional correlation of the tidal cycle to the image acquisition is required as the wetting and drying of broad shallow beaches impacts the results from such an approach" to get shorelines that may be used to assess coastal erosion.

The use of SAR interferometry coherence maps based on a couple of SAR snapshots at roughly the same time, had been advocated by DLR to add information to a single image because of the missing contrast between the beach and the sea: interferometry coherence map describes the degree of stability of the complex scatterers between the two acquisitions. Since the ocean surface is highly nonstationary as opposed to land surfaces, coherence information is exploited to determine the land/sea boundary.

Main issue is the concurrence of the "snapshots" to avoid tidal effects (SAR EOs from one day to the other observe different waterlines).

3.5.4 EO information extraction

All traditional methods, whether performed by operators or by automats, rely on classification, which is based on either:

- Single pixel value of dimension n, i.e. the finite/discrete dimension of the observation space.
- Object recognition based on shapes with a dimension of the observation space which can be infinite $n = \infty$ without a finite taxonomy.

The simpler is the former, whether with radar scattering for various polarimetry or optical bands, but the spectral multi-variable information provided by the pixel does not consider the spatial organization of these pixels (e.g. the waterline is continuous, whether a cliff top is not). The simplest of the simpler is to use supervised classification with thresholds on specific variables such as spectral indices NDVI[42], NDWI[43], NDSI[44], SWI[45] which work on shoreline, or band ratios, and even textures. Although unsupervised methods or clustering, such as the Iterative Self-Organizing Data Analysis (ISODATA) model, an improved version of K-means, or fuzzy C-mean classification, even non-fuzzy classification methods based on ANN models (the feed forward network) made of multi-layer perceptron MLP, probabilistic neural network PNN, radial basis function RBF, generalized regression neural networks GRNN, deep learning algorithms in convolutional neural networks (CNN), have been used to perform land/sea segmentation.

In fact, the second step for most coastline/shoreline indicators' drawing is always an object classification with the objective to link all the pixels of interest to be in-line: search for 1D objects.

The two steps a. and b. can be combined in segmentation methods, e.g. the ISRG and watershed WS transforms, which define regions by their variable gradients, or the simple Canny or Sobel edge detectors.

In order to distinguish the land from the sea, remote sensing labs have used indices that mix various optical bands from EO satellite sensors, including bands not accessible to the eyes of ground surveyors or photo-interpreters, and backscattering channels from SAR sensors. These indices copy the information content of the EOs and are all the more precise that one uses the full relevant information content, with all its complexity. Yet, the simplest algorithms that replicate photo-interpreters' knowhow in mapping the shoreline should do the work, as most end-users are ground surveyors and the shoreline representation concepts derive from observation by eye.

[42] Normalized Difference Vegetation Index

[43] Normalized Difference Water Index

[44] Normalized Difference Snow Index

[45] Superfine Water Index

3.6 Pre-Feasibility analysis 3: EO data accuracy assessment

The accuracy of localization of each pixel in an image depends on *i.* the accuracy of: the satellites' position measurement (orbit determination), the satellites' attitude measurement, the sensors' position and orientation measurement within the frame of the satellite, and then *ii.* the quality of the processes for all pixels to be in an accurate (x,y) position on the ground, i.e. *ii.1* corrections for optical distortions from the sensor system, and *ii.2* apparent changes in the position of ground objects caused by the perspective of the sensor view angle and ground terrain (orthorectification).

The first sets of requirements (*i.* and *ii.1*) mainly depend on the satellite operators, who translate the errors in a proxy value of Δx (=Δy) as if the earth was flat Δx_{L1_b} yet using crude Earth Elevation Models and applying *ii.2* step to deliver their L1c products then informing users of Δx_{L1_c} —we have used the notation for optical products, but it is not different for SAR products as the distances measured by the sensors need to be transformed in geometric information with a Terrain Model before the delivery of L1 products: L1/SLC or Single Look Complex products are provided in zero-Doppler slant-range geometry (slant range is the natural radar range observation coordinate, defined as the line-of-sight from the radar to each reflecting object), and L1/GRD or Ground Range Detected products are provided further to a projection to ground range using an Earth ellipsoid model[46] corrected by using terrain heights which vary in azimuth but is constant in range[47].

The second set of requirements (*ii.2*) is either tackled by the users when producing by themselves the L2a optical products from L1b products or their own L2/GRD products, or by the satellite ground segment operators when they deliver L1 & L2 products.

If the positioning error Δx of a pixel of an EO on a map is the sum $\Delta x_{sat-sens} + \Delta x_{ortho-rect}$, the satellite operators usually deliver only one value for all their L1 and L2 products plus the $\Delta x_{sat-sens}$ sensitivity.

[46] ground range coordinates are the slant range coordinates projected onto the ellipsoid of the earth

[47] thus introducing an error

3.6.1 EO Accuracy: Specifications of EO products

The figures are taken from leaflets edited by the satellite operators or various publications. The information is not really standardized, and it is difficult to know if the accuracy is the CE90 or a RMSE, reason why there may be a discrepancy of 3 (1σ to 3σ). Also the RMSE is given without the use Ground Control Point (GCP[48]) or with the use of GCPs but not knowing their density and the accuracy of external positioning of the GCPs.

Positioning accuracy do not have the same meaning for optical EOs and SAR Eos. In the former case one builds the image from a geometric projection knowing the position of the satellite, the sensor in the frame, and the attitude of the satellite, and intersecting rays with a reference Earth surface model whereas in the latter case one builds the image from measures of distance across-track, knowing the position of the satellite, and from beam forming along track, knowing the speed and direction of the satellite to set-up a synthetic aperture —the distances are then converted in position by intersecting a cone with the reference Earth surface.

In the two cases the errors in the positioning of the satellite add up to the errors in the reference of the Earth surface (reason why the Data Elevation model DME of the Earth or the DTM shall be at much coarser scale than the EOs), and the sole solution to overcome this issue is to use couples of EOs for stereo-restitution of the Earth surface, i.e. calculating simultaneously the local altitude and the reflectance of the Earth.

The sources of errors for optical EO positioning are purely geometric.

For SAR, the most significant uncorrected perturbation is currently the atmospheric path delay, which can introduce cross-track (slant range) sample shifts of typically ~3.5 m; the second most important source of error is the clutter contribution to the standard deviation of target locations. Beyond applications such as interferometric SAR (InSAR), an improved geolocation accuracy enables the establishment of a "blind" connection between the radar images and, e.g. a Digital Elevation Model (DEM), which is essential for applications such as radiometric terrain flattening.

[48] A ground control point (GCP) is a feature which is clearly identified in the raw image for which ground coordinates are known

Table 3.6: High and Very High resolution EO platforms considered for coastal monitoring.

Satellite constellation	ground resolution	σ-to-3σ (~CE90)	RMSE without GCP	RMSE with GCP
VNIR				
Landsat 8 (OLI)	0.3-4m	12 m	22-50 m	
Sentinel-2 A & B /MSI	10-20-60 m	11-12 m		
Planetscope	3-4.9 m	5-8 m		
Pleiades	0.5-2 m	7 m		
Quckbird	0.6-3 m	24 m	17 m	3-5 m
GeoEye-1	0.4-1.7 m			2-3 m
WorldView-1	0.5 m	4-6.5 m	5.3-7.6 m	2 m
WorldView-2	0.5-2.5 m	3.5-6.5 m		
WorldView-3	0.3-1.4 m / 30 m		3.5 m	
WorldView-4	0.3-4 m		4 m	
Kompsat-2	1-4 m		25 m	4-4.6 m
Triplesat	0.8-4 m	50 m		
NigeriaSat1	32 m	300 m		
UK-DMC2	22 m	25-35 m		
SAR				
ERS1 & ERS2	<30 m x <26.3 m	10 m (slant range)		2 m
Sentinel-1	5-80 m	SM: 2.5m, IW: 7.m, EW: 14.4 m		
TerraSAR-X & Tandem X	0.9-40 m	1-16m		

Overall, EO positioning accuracy is lower than the resolution of the EOs by a factor of 1 to 10.

The accuracy of localization of features on our 1D, 2D and 3D products is solely the accuracy of the input Eos, either “raw” from the satellite operators or pre-processed by the end-users. It is expected by end-users that the accuracy values are similar to the resolution values, which is the reason why some processing is needed.

3.6.2 Pre-processing accuracy enhancement techniques

To improve the positioning accuracy of EOs received from space agencies or commercial operators, the solutions are the following:

- to match the location of specific features in the images with geodetic points that are recognizable on the optical and SAR images, i.e. additional GCPs;
- to perform orthorectification with Digital Elevation Model (DEM or DTM, i.e. Digital Terrain Model, or DSM Digital Surface Model) which have the same positioning accuracy and resolution as the original EOs; or
- to co-register the images at the highest resolution available and to relocate only the reference image when building time-series, in order to reduce the number of GCPs matching and orthorectification[49].

GCPs are needed for the orthorectification of images to locate the images on the DEM at the resolution/accuracy of the DEM, which are usually lower than the resolution of the images. Yet, the lower resolution of the DEM creates positioning errors.

For optical images, error of the order $\Delta x = \delta_{HR} h \cdot \sin\theta$, where $\delta_{HR} h = \vec{\nabla}_{HR} h \cdot \Delta_{DEM}^{res} \vec{x}$ is the error of altitude in the DEM model due to sampling at lower resolution as $\vec{\nabla}_{HR} h$ is the error in relief gradients restitution and $\Delta_{DEM}^{res} \vec{x}$ is the resolution of the DEM, and θ the zenith viewing angle from the satellite. Then $\Delta x = \alpha\ \Delta_{DEM}^{res} \vec{x}$ with $\alpha = \vec{\nabla}_{HR} h \cdot \sin\theta$. Knowing that $\vec{\nabla}_{HR} h$ can be very high in rough terrains with slopes more than 35%, giving value $\alpha = 10\%$ in side views of $\theta = 20°$ (views are in between 0° and 40° for HR and VHR optical sensors); for instance, using SRTM60 as DEM (60 m resolution) as the case for L1c products of Sentinel-2 would deliver an error of 10%*10m. For SAR images $\sin\theta$ must be replaced by $\cos\theta$ in the previous formula, incident angles being usually between 15° and 55° (e.g. 18.3-46.8° for Sentinel1, and 20°-50° for TerraSAR-X). These leads to values of $\alpha = 7 \div 35\%$ which, using SRTM60 as DEM, as the case for Sentinel-1 GRD products, would deliver an error of 4-to-20 m. The orthorectification spans the two steps of GCP matching and raw orthorectification, i.e. the

[49] The co-registration of two images is a process similar to GCP matching using all pixels of the reference image as GCPs. The higher the spatial resolution of the image the more options are available for identifying good targets on the image. It is then easier to identify them on the field. The better the target discrimination capability the more accurate the GCP coordinates must be which means that the reference image shall have the highest resolution.

process of removing the image distortion (effects of image perspective and relief), to create a planimetrically correct image.

3.6.2.1 Orthorectification

Ortho-ready satellite images are provided with approximate geo-reference information computed from the satellite's orbital position and the imaging geometry. Most satellite operators supply a Rational Polynomial Coefficient (RPC) sensor model or Replacement Sensor Model (RSM) to remove distortions that occur during image capture, thus avoiding delivery of satellite/sensor information, i.e. the sensor model with the image, and use their own non-open DEMs or public DEMs.

Ground Control Points

As a rule of thumb, the number of control points for a resolution r in m is $n = \left(10 + Area_{km^2}/25\right)/res_m$ with a minimum of 4 points. The best GCPs are corners and intersections of sidewalks, corners of pavement and parking lots, parking space lines or their intersection, edge of bridges, sides of roads and paths or their intersection, telephone poles and/or electrical towers, fences, livestock pens, stream intersections, small shrubs, distinct clearings in trees… which are fine for VHR data sets/ images.

For HR images, the lack of details to spot features leads to the use of VHR thumbnails, i.e. orthorectified aerial images or VHR satellite images, for GCPs, GCPs being then replaced by Ground Control Regions (GCRs) which are matched to the HR images using the simplest co-registration methods such as least squares.

Matching algorithm or fast normalized cross correlation (FNCC) techniques might be used to co-register the images against the thumbnails. However, it is a heavy burdened task, not fit for automatization except in a Payload Data Ground Segment (PDGS) of satellite operators.

Digital Elevation Models

Most high-resolution/high accuracy DEMs are built for military purposes, at least national ones, and are not free and open for civil use such as coastal erosion monitoring, except if performed by national Ordnance Survey agencies according to their public mandates.

Conclusion: Orthorectification

Whatever the approaches of orthorectification, i.e. the correction of images to reflect the physical reality of the viewing geometry, it is out of scope of this work to extract GCPs or GCRs and to manage databases of aforesaid information. Even if the end-users had been committed to deliver high resolution DEMs, coastal change mapping would not be facilitated as DEMs of the shoreline should change from one snapshot to the other and be retrieved from the EOs simultaneously to the shoreline indicators.

3.6.2.2 Co-registration images

The cheap and effective solution to feature-based orthorectification, i.e. detection of the image positions of geolocated ground objects or tie-points based on distinct recognition features which are still such as crossroads, borders of agricultural parcels, mountain ridges or other sharply delineated objects, is to use a VHR image or a mosaic as a mapping reference and to co-register all the other images of the same area to the it. Methods abound, called "intensity-based image registration techniques", whereby similar value patterns are recognized and matched; algorithms developed for image matching and used in remote sensing applications include Harris corner detection and RandomSample Consensus (RANSAC) outlier rejection model, Template Matching, Speeded Up Robust Features (SURF), Scale Invariant Feature Transform (SIFT), and Uniform-Robust SIFT (UR-SIFT). Two of them are in use with the contractor: i. the SIFT-based method, also called SIFT based automated orthorectification, and ii. phase correlation.

SIFT based co-registration on areas outside the shorelines:

SIFT is used for the identification of common GCPs or GCRs in a set of images and replaces manual approaches with already collected GCPs or GCRs; it is applied after removal of outliers with RANSAC (Figure 3.5).

SIFT extracts features that are invariant to image rotation and scale: 1) the rotation invariance is ensured using the gradient orientations and magnitudes of the pixels around the key points; 2) the scale invariance is ensured using the scale space approach (convolving the input images using Gaussian Convolution); 3) the steps of the algorithm are then a difference of Gaussian models (DOG), finding local maximum and minimum, i.e. key points, by comparing neighbour pixels with the target pixels in the current and adjacent DOG images, excluding bad points which lie on the edges and have low contrast, assigning orientation to key points (calculating gradient orientations and magnitudes of the neighbour pixels around the key points), assigning a 128 dimensional vector to related key points, and matching process via a distance comparison between two key point datasets —key points, i.e. relative GCPs which satisfy predefined threshold values for the distance comparison process are saved as matching points. These matching points can then be identified on maps, geolocated and the orthorectification refined.

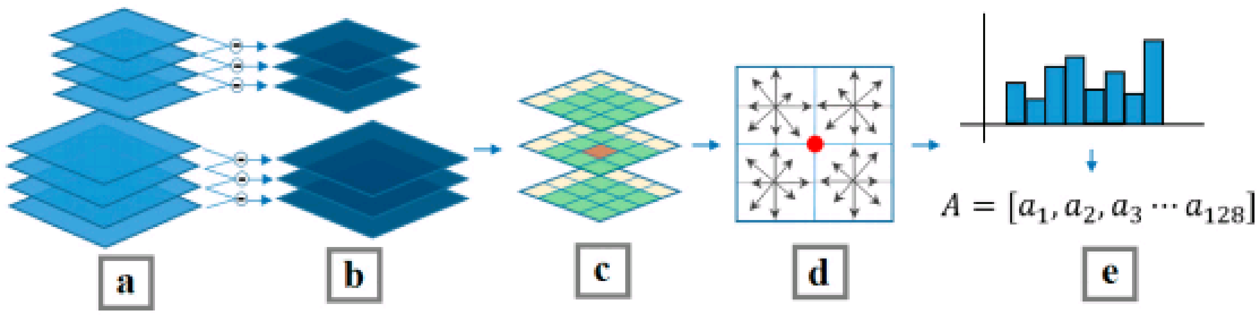


Figure 3.5: The steps of SIFT feature extraction: (a) scale space generation; (b) DOG image generation; (c) detection of local maximum and minimum; (d) gradient calculation; (e) histogram calculation and generation of 128 dimensional vectors.

Phase correlation-based co-registration on areas outside the shorelines:

Phase correlation provides an improvement of the classic cross-correlation of images. It relies on deriving image displacements in the frequency (Fourier) domain to calculate relative and local translational offsets between two images for the same scale owing to distinct peak in the cross-power spectra which indicate the points of registration. By increasing drastically, the GCPs or GCRs, it delivers excellent co-registration results, even in the case of poor signal-to-noise ratios and albedo differences, e.g. substantial ground cover changes between different images due to seasonal vegetation dynamics and absence or bad atmospheric corrections for optical images.

Phase Correlation requires several data preparation steps and data inputs, including:

1. selection of the variables (spectral bands or polarimetries) in target and reference image to be used for co-registration;
2. user-provided masks (e.g. clouds, cloud shadows, offshore, inland) for reference and target image;

3. calculation of the respective footprint polygons and corresponding overlap area;
4. pixel coordinate grid equalization; and
5. adjustment of matching window positions and sizes;

Fundamentally, Phase Correlation provides a detection of geometric shifts in a moving-window manner for each point of a dense grid (local co-registration approach). This technique produces a correction of displacements by warping the target image under the use of a list of tie points, using a cubic resampling technique with the ability to align the pixel grid of the target image to the one of the reference images or to change target spatial resolution.

Conclusion: Co-Registration

In the case of co-registration, respecting local distortions is pursued. It is expected that the distortions calculated inland apply to the shoreline, which may not be true if the shoreline is affected by a change of altitude, e.g. cliff/top & toe, dune/ top & toe —in this case, the shoreline indicator that is positioned should be the shoreward one, e.g. cliff/top. For waterlines the local co-registration shift in the nearest flat land area should be applied, not the shift at the nearest grid point. Use of low incidence angle optical images and high incident angle SAR images provides better accuracy than high incidence angle optical images and low incident angle SAR images. Automated co-registration can employ two different techniques, including SIFT-based and Phase-based co-registration.

SIFT-based co-registration has been used for SDB with multiple images at different spatial resolution (from Landsat, Sentinel-2, Rapid Eye, and Pleiades missions) but it is not robust enough. To be fully automated, ocean beacons as GCPs should be manually introduced in order to avoid a lack of correction of image tilt around the shoreline.

Phase Correlation has been used for shoreline mapping being more generic and suited to multisensor remote sensing datasets—provided that the geometric displacements follow a relatively polynomial pattern which would limit this approach if using L1b data sets. Indeed, since remote sensing data are usually distributed as georeferenced L1c datasets, it can be reasonably assumed that the input datasets are already roughly matching and do not show any severe geometric artefacts. They are only corrupted by global co-registration shifts mainly due to i. satellite position & attitude biases, ii.

unequal map projections of the input images, and iii. DEM errors incl. inadequate DEM resolution. The optimal size of the sliding window is twice the resolution of the DEM.

3.6.3 EO products reliability

As previously mentioned, the EO product reliability for coastal erosion is related to the proper identification of the shoreline features and the uncertainty on features' calculated location (accuracy and precision). For the choice of features, only the instantaneous waterlines, the storm/debris line, the borders between silt/sand/cobble areas, the seaward vegetation border, the seaward coastal man-made structures' border, the cliffs and dunes tops, and the seaward limit of the instantaneous surf zone can be easily distinguished from one another if the EO resolution allows it, i.e. they are far apart according the scale of the EO view and the size of artefacts (e.g. shadows or mapping inversion & shifts in SAR). Otherwise they would contribute together to a proxy-based shoreline indicator.

The EO L2 products/proxy-based shoreline indicators contain instantaneous information. As such, they are not exploitable for coastal erosion studies except if representative of longer period of time[50]. Only the L3 and L4 products are valuable to the end-users.

3.6.4 Error budgets: Shore-line Indicators (Optical)

The error budget for a shore-line indicator which has been drawn from a proxy-based shoreline indicator, then contingently transformed in a datum-based shoreline indicator, is made of 3 main components:

- **Accuracy of EO Detection:** the probability that the EO-drawn proxy-based shoreline indicator is the right one (probabilities of detection P_D , miss-detection $1-P_D$ and false alarm P_{FA}) and the probability of good positioning of the EO-drawn proxy-based shoreline indicator (according to a reference geodetic network and a given projection system, or to a reference image), in terms of non-errors, i.e. accuracy and precision of the observations $\left(\Delta_{\mathrm{obs}}^{\mathrm{abs}}x, \Delta_{\mathrm{obs}}^{\mathrm{abs}}y\right)$

[50] L2 products can be labelled L3 products if distributed with a time period of validity and an uncertainty budget for that period.

or $\left(\Delta_{\text{obs}}^{\text{rel}}x, \Delta_{\text{obs}}^{\text{rel}}y\right)$, and uncertainties , i.e. resolution of the observations $\left(\Delta_{\text{res,obs}}x, \Delta_{\text{res,obs}}y\right)$; as a rule of thumb, $O\left(\Delta_{\text{obs}}^{\text{abs}}x\right) = O\left(\Delta_{\text{res,obs}}x\right)$ and $O\left(\Delta_{\text{obs}}^{\text{abs}}y\right) = O\left(\Delta_{\text{res,obs}}y\right)$ by choice of the satellite operators but after a refined absolute or relative orthorectification, $\Delta_{\text{obs}}^{\text{rel}}x \simeq 2\Delta_{\text{res,ref}}x$ and $\Delta_{\text{obs}}^{\text{rel}}y \simeq 2\Delta_{\text{res}}^{\text{ref}}y$ where $\Delta_{\text{res,ref}}$ is the resolution of the reference image; for 1D products: $\Delta_{\text{obs,proxy-SL}}^{\text{rel}}s_{\perp} \approx 2\Delta_{\text{res,ref}}s_{\perp} + \Delta_{\text{res,obs}}s_{\perp}$ and $\Delta_{\text{obs,proxy-SL}}^{\text{abs}}s_{\perp} \approx 2\Delta_{\text{res,obs}}s_{\perp}$, where $s_{\perp}$ is the coordinate perpendicular to the shoreline which would be parametrized by a curvilinear coordinate s [51].

- **Scale of variability:** the potential that the location of the EO-drawn proxy is at a different spatial scale to natural variability of L alongshore and l across-shore waterline position, due to external parameters, e.g. tides differences, wave set-up or runup, etc.: $\delta_{\text{obs,proxy-SL}}^{\text{rel}}\left(s_{\perp}, L\right)$, $\delta_{\text{obs,proxy-SL}}^{\text{abs}}\left(s_{\perp}, L\right)$, $\delta_{\text{obs,proxy-SL}}^{\text{rel}}\left(s, l\right)$, and $\delta_{\text{obs,proxy-SL}}^{\text{abs}}\left(s, l\right)$

- **Proxy transformation to datum:** the errors due to the transformation $\text{TF}_{\text{proxy}}^{\text{datum}}$ of a proxy-based shoreline indicator into a datum-based shoreline indicator, whether the propagation of the previous errors $\text{TF}_{\text{proxy}}^{\text{datum}}\left(\Delta_{\text{obs,proxy-SL}}^{\text{rel}}s\right)$, $\text{TF}_{\text{proxy}}^{\text{datum}}\left(\Delta_{\text{obs,proxy-SL}}^{\text{rel}}s_{\perp}\right)$, $\text{TF}_{\text{proxy}}^{\text{datum}}\left(\Delta_{\text{obs,proxy-SL}}^{\text{abs}}s\right)$, $\text{TF}_{\text{proxy}}^{\text{datum}}\left(\Delta_{\text{obs,proxy-SL}}^{\text{abs}}s_{\perp}\right)$, $\text{TF}_{\text{proxy}}^{\text{datum}}\left(\delta_{\text{obs,proxy-SL}}^{\text{rel}}\left(s, L\right)\right)$ and $\text{TF}_{\text{proxy}}^{\text{datum}}\left(\delta_{\text{obs,proxy-SL}}^{\text{abs}}\left(s, L\right)\right) \forall L$, or $\text{TF}_{\text{proxy}}^{\text{datum}}\left(\delta_{\text{obs,proxy-SL}}^{\text{rel}}\left(s_{\perp}, l\right)\right)$ and $\text{TF}_{\text{proxy}}^{\text{datum}}\left(\delta_{\text{obs,proxy-SL}}^{\text{rel}}\left(s_{\perp}, L\right)\right) \forall L$ or the introduction of new errors due to uncertainties on the parameters of the transformation or the inherent non-completeness of the model of the transformation, e.g. from an instantaneous waterline to a HSWM line considering the tide and the METOC conditions: $\Delta\text{TF}_{\text{proxy}}^{\text{datum}}\left(s, L_{TF}, \Delta t\right)$ and $\Delta\text{TF}_{\text{proxy}}^{\text{datum}}\left(s_{\perp}, L_{TF}, \Delta t\right)$ where L_{TF} is the spatial scale of the transformation or rather its parameters, and Δt is the temporal scale or period of validity.

[51] a representation chosen because of the inability to distinguish one point from another on the 1D shoreline indicator

A description of how one calculates the error budget of shore-line indicators due to the accuracy of the EO detection algorithm have been given in previous sections (see Section 3.6.1).

The following sections give examples of how errors due to the scale of variability caused by longshore and cross shore change in waterline position during EO observation period. These sections also describe potential errors created in the transformation of proxy based shoreline indicators to datum based indicators. These cases describe 1D products, 2D and 3D products will be tackled in the System Engineering section of the Technical Specifications Document (TSD).

3.6.4.1 *Error Budget Example: Proxy-based shoreline indicators against datum-based shoreline indicators*

A waterline is the border between water and land at a given time t in a given area. An instantaneous border can be defined as:

$$WL(t)=\left\{\vec{X}_{\mathrm{WL}}(t,s)\middle|s\in\left[s_0(t),s_1(t)\right]\right\}$$

where s is a curvilinear coordinate, $\vec{X}=\left(\vec{X}_{\mathrm{h}},z\right)\middle|\vec{X}_{\mathrm{h}}=(x,y)$. z can't be derived from an image or EO, except if we were to perform stereo-plotting with a couple of EOs with proper accuracy, contrary to $\vec{X}_h$; as such $WL^{\mathrm{EO}}(t)=\left\{\vec{X}^{\mathrm{EO}}_{\mathrm{WL,h}}(t,s)\middle|s\in\left[s_0(t),s_1(t)\right]\right\}$ and $z_{WL}(t,s)$ is an external/ independent parameter which will be noted $z^{ext}_{WL}(t,s)$; $z^{\mathrm{ext}}_{\mathrm{WL}}(t,s)=z^{\mathrm{ext}}_{\mathrm{WL}}\left(\vec{X}^{\mathrm{EO}}_{\mathrm{WL,h}}(t,s)\right)$ is not a constant if an altitude, as the altitude of the sea level changes from one place to the other because of the astronomical tides, the generic meteorology (atmospheric pressure), and the consequences of meteorological events at the coast such as wind waves and swells that break when reaching the shore.

However, the wave-filtered sea-surface away from the shore is a relative reference, its altitude to the geoid or a reference ellipsoid or reference points ashore being known as astronomical tides are deterministic $z^{\mathrm{ext}}_{0,\mathrm{ocean}}(\hat{s})+z^{\mathrm{ext}}_{\mathrm{ocean\_as\text{-}tide}}\left(t,\widehat{\vec{X}_h}\,|scale\right)$ where $\widehat{\ }$ represents spatial scales of the astronomical tides, i.e. a few 1000s km. They need to be modulated by the ocean border geomorphological scales $\delta z^{\mathrm{ext}}_{\mathrm{costal\_as\text{-}tide}}\left(t,\widehat{\vec{X}_h}\,|scale*\right)$ such as those of the English Channel, leading to

$$z^{\text{ext}}_{0,\text{ocean}}(\hat{s}) + z^{\text{ext}}_{\text{ocean\_tide}}\left(t, \widehat{\vec{X}_h}\,|scale\right) + \delta z^{\text{ext}}_{\text{costal\_tide}}\left(t, \widehat{\vec{X}_h}\,|scale *\right)$$

As one expects an EO tile to be smaller than the length scale of the astronomical tide components, it becomes independent from the position of the waterline: $z^{\text{ext}}_{0,\text{ocean}} + z^{\text{ext}}_{\text{ocean\_tide}}(t) + \delta z^{\text{ext}}_{\text{costal\_tide}}(t)$.

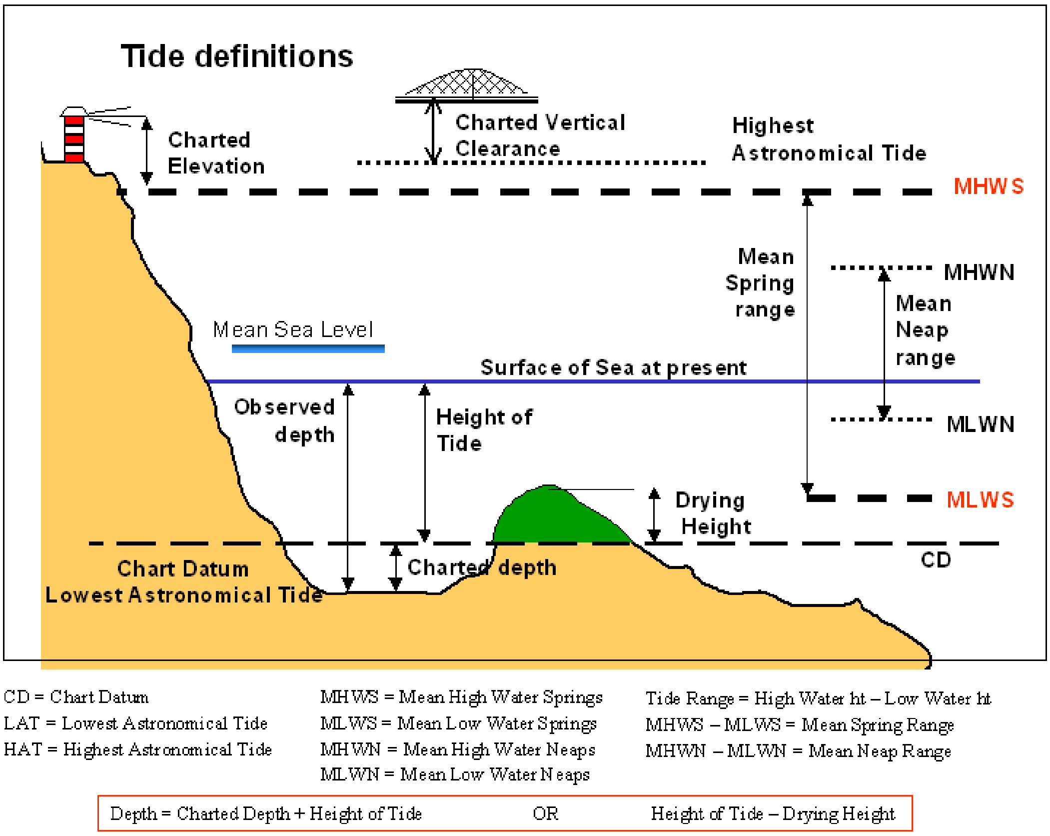


Figure 3.6: Tide definitions. Source: http://www.skysailtraining.co.uk/tide_definitions_causes.htm

Yet, one should add the meteorological effects, whether atmospheric ones, at length scales of a few hundreds of km ($\sim 100\ km$), which is larger than an EO tile, i.e. $\delta z^{\text{ext}}_{\text{atm}}(t)$, but that include wind-driven currents that may pile up water on a coast, or ocean waves' ones at scales from a few cm to hundreds of km, i.e. $\delta z^{\text{ext}}_{\text{waves}}(t)$. The latter term has 3 components: the Stokes drift induced by waves, i.e. $\delta z^{\text{ext}}_{\text{waves,Stokes}}(s,t)$ which is considered small enough to be discarded; the wave set-up or local elevation in the mean water level on the foreshore caused by the reduction in wave height through the surf-zone, i.e. $\delta z^{\text{ext}}_{\text{waves,set-up}}(s,t)$; the wave swash or alternate rise and fall of the waterline on the shore slope due the propagation and reflection of waves, i.e. $\delta z^{\text{ext}}_{\text{waves,swash}}(s,t)$ [52].

In the end:

$$z^{ext}_{WL}(t,s) = z^{\text{ext}}_{\text{0,ocean}} + z^{\text{ext}}_{\text{ocean\_tide}}\left(t\middle|_{\text{10mn}}\right) + \delta z^{\text{ext}}_{\text{costal\_tide}}\left(t\middle|_{\text{few-mn}}\right) + \delta z^{\text{ext}}_{\text{atm}}\left(t\middle|_{\text{1h}}\right) + \delta z^{\text{ext}}_{\text{waves,set-up}}\left(s\middle|_{\text{10m}}, t\middle|_{\text{few-mn}}\right) + \delta z^{\text{ext}}_{\text{waves,swash}}\left(s\middle|_{\text{1m}}, t\middle|_{\text{few-s}}\right)$$

We are only interested in the variations:

$$\delta z^{ext}_{WL}(t,s) = z^{\text{ext}}_{\text{ocean\_tide}}\left(t\middle|_{\text{10mn}}\right) + \delta z^{\text{ext}}_{\text{costal\_tide}}\left(t\middle|_{\text{few-mn}}\right) + \delta z^{\text{ext}}_{\text{atm}}\left(t\middle|_{\text{1h}}\right) + \delta z^{\text{ext}}_{\text{waves,set-up}}\left(s\middle|_{\text{10m}}, t\middle|_{\text{few-mn}}\right) + \delta z^{\text{ext}}_{\text{waves,swash}}\left(s\middle|_{\text{1m}}, t\middle|_{\text{few-s}}\right)$$

- A waterline $WL^{\text{EO}}(t)$ is defined by $WL^{\text{EO}}(t) = \left\{ \left(\vec{X}^{\text{EO}}_{\text{WL,h}}, \delta z^{ext}_{WL} \right)(t,s) \middle| s \in \left[s_0(t), s_1(t) \right] \right\}$

The reader will notice that, if t is the instantaneous time of the snapshot, then:

- the satellite sensor may take a few seconds to pick-up the datasets that build up an image, e.g. Sentinel-2/MSI has three arrays of sensors that are not in the same focal plane, and look at different areas of the earth, leading to a temporal adjustment from one array to the other in order to deliver a consistent image,
- waterline variability occurs continuously with the boundary between the land and sea defined by multiple factors, including sea state, tidal regime and local morphology.

The reader will also notice that, if the length-scale of the observations is given by the EO sensor resolutions (10 m for S2/MSI, but fewer than 2 m for VHR snapshots from commercial satellites), the length-scales of the phenomenon which build-up the variability of the waterlines are i. the geomorphological length scales, but also ii. the hydrodynamic length scales / or combined hydro-morph length scales which go down to a few decimetres.

[52] Sum-up of the last two terms leads to the wave run-up or maximum level the waves reach on the beach relative to the still water level.

Geo-morphodynamical processes' studies require full 3D terrain model of the shore/shoreline (DME & DMT, i.e. 2D fields, land & seafloor characteristics, i.e. 2D fields, and currents & winds, i.e. 3D fields) along time $\Rightarrow$ 4D fields.

What could be done with 1D fields, i.e. waterlines or shorelines, within a time-series?

I. Build-up time-series of 2D and 3D fields by combining the 1D fields during a short period while the fields are 'fixed', and looking at changes over time scales that are higher, or
II. Using lines that are edges of 'objects' or area segments, i.e. features, to delineate/ define the aforesaid features and monitor their changes along time, else
III. Using lines as proxies of the features' characteristics.

3.6.4.2 Error Budget calculation: Stationary cross-shore profiles

If t is considered as a sampling index and the shore is supposed to be of roughly constant characteristics during a period, for snapshots at times t_i such that $t_i \in \left[t_0, t_0 + \Delta t\right]$ the data set is made of:

$$\left\{\vec{X}^{\mathrm{EO}}_{\mathrm{WL,h}}\left(\delta z^{ext}_{WL}\left(t_i\right), s^i_l\right) \middle| s^i_l \in \left[s^i_0\left(t\right), s^i_1\left(t\right)\right],\ i = 0,1,\ldots,n\right\}$$

which is the sampling of a surface $S_{ns\&fs}$: $\widetilde{S_{ns\&fs}} = \left\{\vec{X}\left(\delta z_i, s^i_l\right) \middle| s^i_l \in \left[s^i_0(t), s^i_1(t)\right], i = 0,1,\ldots,n\right\}$

If 3 points $\vec{X}\left(\delta z_i, s^i_l\right)$ that are different exist, then the approximation of $S_{ns\&fs}$ is made by triangulation. Parametrizations for the purpose of smooth surface fitting are then made using solutions of linear systems based on convex combinations to lead to visually smooth surface approximations.

The surface shall be regular, avoiding abnormal gravitational anomalies (e.g. no overhang in soft sediments) but may be vitiated by errors due to bad delineation of the waterlines and bad corrections of the altitude of the waterlines.

A shoreline for a specific δz_0 can be drawn by intersecting the surface $S_{ns\&fs}$ and the surface $\left\{\left(\vec{X}_h, z\right) \middle| z = \delta z_0\right\}$

Sampling period Δt should be during a calm period while the system is in equilibrium, i.e. in-between storms or heavy sea events, covering a 1 month lunar period if under tidal conditions, and far away from the storm events to give the system time to recover. Most of the times 1 to n storm events occur per months, which makes it impractical even if snapshots are taken daily and allow sample a tidal cycle. This sampling mode is therefore not feasible.

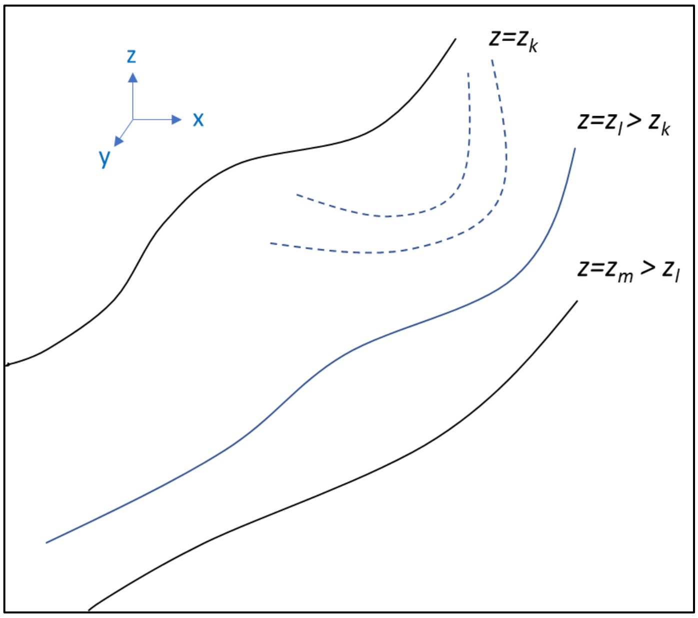


Figure 3.7: Network of isobaths from various waterlines.

3.6.4.3 *Error Budget calculation:* Shore segmentation

Apart from the HAT (seafront), the ordinary high water mark (OHWM) defines the boundaries of aquatic/non-aquatic features. It may be considered similar to the MHHW or MHWS (OHWM is a bit higher on the shore) and from MLWS or MLLW which is marked by a cross-shore step. There is no tidal datum in the OHMW which is generic and accurately correlated to world-wide biotopes.

3.6.4.4 *Error Budget calculation*: *Tide-based shorelines*

If the shorelines are hypothetical waterlines of average conditions and specific tidal level indexed by l, one should first calculate $z_{astr,l} = z^{\text{ext}}_{\text{ocean\_tide}}\left(\text{tidal\_st}(l)\right) + \delta z^{\text{ext}}_{\text{costal\_tide}}\left(\text{tidal\_st}(l)\right)$ for standard atmospheric and ocean situation, usually calm weather, then extrapolate the waterlines $WL^{\text{EO}}(t) = \left\{\vec{X}^{\text{EO}}_{\text{WL,h}}(t,s) \middle| s \in \left[s_0(t), s_1(t)\right]\right\}$ at these conditions:

$$WL^{\text{EO}}(t) \xrightarrow{T_l} SL_{z_{astr,l}}$$

where $SL_{z_{\text{astr},l}} = \left\{\vec{X}^{\text{EO},t}_{\text{SL}_{z_{\text{astr},l}},\text{h}}(s^*) \middle| s^* \in \left[s^{\text{EO},t}_{z_{\text{astr},l},0}, s^{\text{EO},t}_{z_{\text{astr},l},1}\right]\right\}$ with $\vec{X}^{\text{EO},t}_{\text{SL}_{z_{\text{astr},l}},\text{h}}(s) = \vec{X}^{\text{EO}}_{\text{WL,h}}(t,s) + \overrightarrow{\delta X^{\text{EO},t}_{\text{SL}_{z_{\text{astr},l}},\text{h}}}(t,s)$

We will now write $\vec{X}_{\text{SL}} = \vec{X}^{\text{EO}}_{\text{WL}}(t,s) + \overrightarrow{\delta X}(t,s) = \left\{x_{\text{WL}} + \delta_{\text{wl}}x, y_{\text{WL}} + \delta_{\text{wl}}y\right\}_t(s)$ to simplify the notation.

Corrections of waterlines to standard meteorological conditions

First the waterline $\vec{X}^{\text{EO}}_{\text{WL}}(t,s)$ must be brought to the standard/still waterline s.l.w. if there was no wave in fair weather.

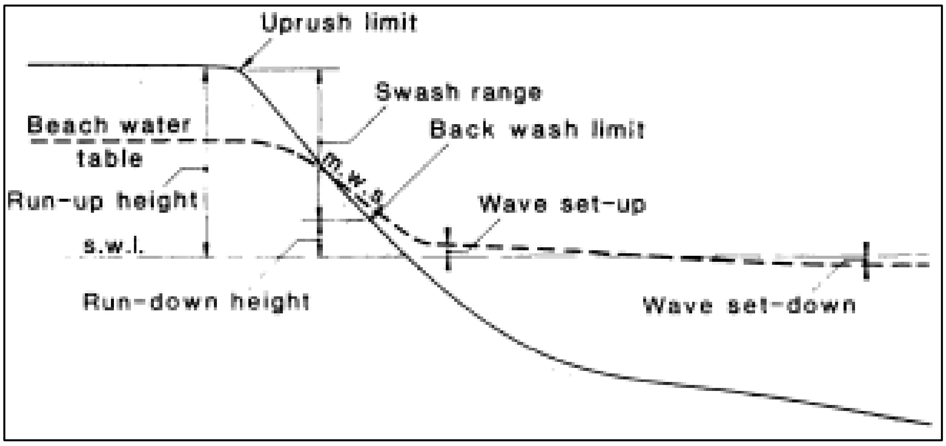


Figure 3.8: Waterline characteristics relative to coastal and meteorological parameters.

$$\vec{X}^{\text{EO}}_{\text{WL}}(s) \xrightarrow{metoc} \vec{X}^{\text{EO}}_{\text{WL,s.l.w.}}(s) = \vec{X}^{\text{EO}}_{\text{WL,fair-weather}}(s)$$

We shall lower the line according to the cross-shore profile whose slope is m_{WL} at the waterline. Unfortunately it is not derived from the EO but it is possible to get it from the run-down height or the mid-swash height $\overline{\eta}$, which is made of the wave set-up (increase in mean water level due to the presence of breaking waves), and the lift till the lower limit of the swash zone, also called the dynamic set-up. Again, we have formula for the calculation of the maximum runup level, i.e. set-up + max swash incl. incident swash at T<20s and infragravity swash at T>20s, e.g.

- $H_0 \xi_0$ for regular waves on smooth, impermeable and straight slopes according to Hunt, 1959, where ξ_0 is the surf similarity parameter SSP or Irribaren number $\xi_0 = m_{fs} \big/ \sqrt{H_0 / L_0}$, and m_{fs} is the slope on the foreshore
- $2.32 H_0 \xi_0^{\,0.77}$ for irregular waves according to Mase, 1989, but $\overline{\eta} = \left[0.27 - 0.38\right] H_{0s} \xi_0^{\,0.4}$ where H_{0s} is the wave height in shallow water, according to Yanagishima and Katoh,…;
- even Stokdon et al.[53], 2006,

$$R_{2\%} = 1.1 \left\{ 0.35 \beta_f (H_0 L_o)^{1/2} + \frac{\left[H_o L_o \left(0.563 \beta_f^2 + 0.004 \right) \right]^{1/2})]}{2} \right\} \; for \; \xi_0 \geq 0.3$$

$$R_{2\%} = 0.043 (H_0 L_0)^{1/2} \; for \; \xi_0 < 0.3$$

where $R_{2\%}$ is the runup at the 2% exceedance probability, β_f is the slope m_{fs} and $\bar{\eta} = [0.35 - 0.385] m_{fs} \sqrt{H_0 L_0} = [0.35 - 0.385] H_0 \xi_0$. But $\bar{\eta} = 0.043 \sqrt{H_0 L_0}$ for very dissipative beaches.

[53] Stockdon, H.F., Holman, R.A., Howd, P.A., and A.H. Sallenger, Jr. 2006. Empirical parameterization of setup, swash, and runup, Coastal Engineering, 53(7), pp. 573-588

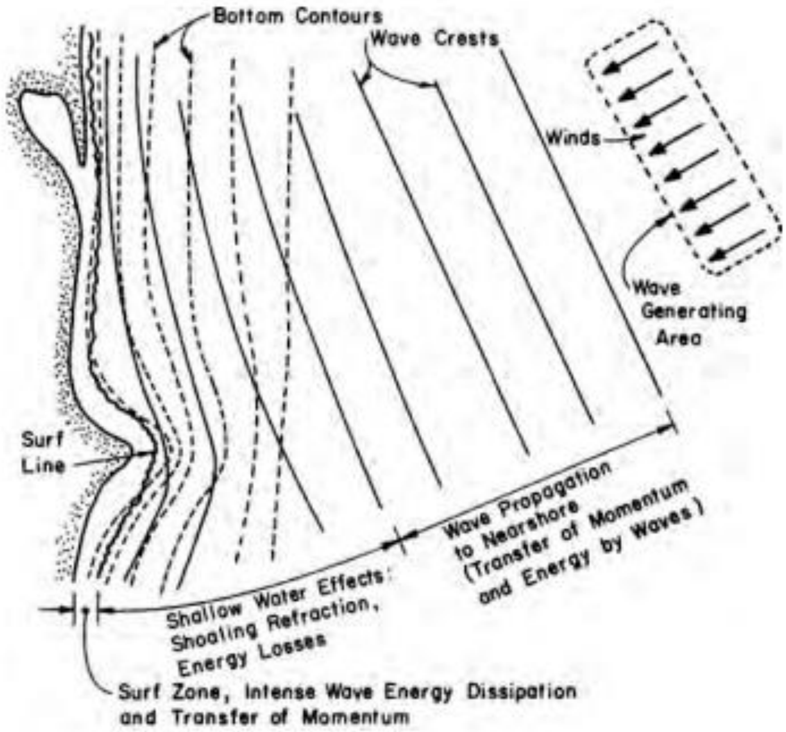


Figure 3.9: Orientation of waves according to nearshore morphology. Source: Dean and Walton, 2017

As shown by Figure 3.9, energy and momentum are transferred from winds to waves in the generating area. The waves convey energy and momentum to the surf zone where the waves break. Upon the breaking point the energy is dissipated, and the momentum is transferred to the water column resulting in longshore and onshore forces exerted on the water column. Wave setup is the additional water level that is due to the transfer of wave-related momentum to the water column during the wave-breaking process. Upon breaking, the wave energy is dissipated, as it is evident from the turbulence generated. However, momentum is never dissipated but rather transferred to the water column resulting in a slope of the water surface to balance the onshore component of the flux of momentum; if waves are irregular, in addition to a steady wave setup, a dynamic component that oscillates with the wave group period will be included.

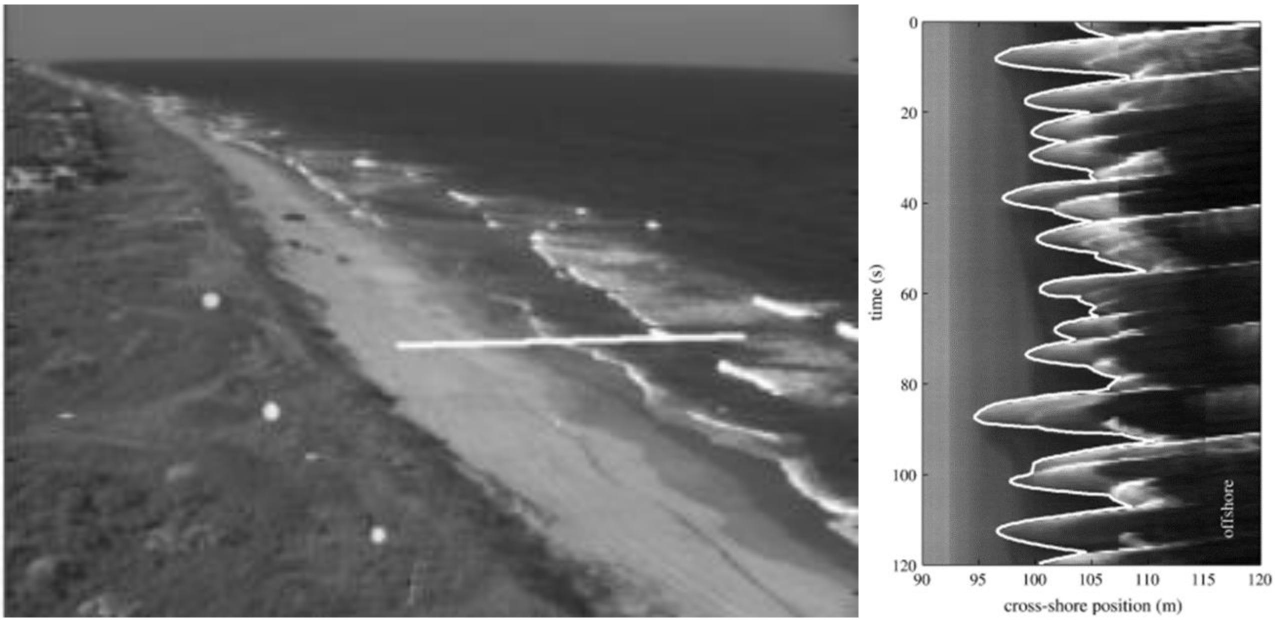


Figure 3.10: A view of the runup on a beach and a runup timestack on the white cross-shore transect of the image (Stokdon et al., 2006)

Dean, 1985, has confirmed the method of Lo[54] (1981), which is to augment the static setup associated with the significant wave height by 50%. Considering 20% instead of 50%, we will use a difference from the average atmospheric pressure of 1 hPa that can cause a difference in height of 1 cm (a low barometer will allow the sea level to rise and a high barometer will tend to depress it = inverted barometer effect): $\delta z_{\mathrm{atm}}^{\mathrm{ext}} = -\alpha\left(P_{atm} - P_{atm,0}\right)$[55].

Consequently, $\vec{X}_{\mathrm{WL,s.l.w.}}^{\mathrm{EO}}(s) = {}_{\mathrm{WL}}^{\mathrm{EO}}\ (s) + \overrightarrow{\delta X}(s)$ where $\overrightarrow{\delta X}(s)$is perpendicular to the waterline in $\vec{X}(s)$ towards the sea, and $\left\|\overrightarrow{\delta X}^{(1)}(s)\right\| = \frac{\delta z_{\mathrm{waves,set\text{-}up}}^{\mathrm{ext}} + \delta z_{\mathrm{waves,swash}}^{\mathrm{ext}} + \delta z_{\mathrm{atm}}^{\mathrm{ext}}}{m_{WL}}$.

In addition, we need auxiliary data Aux_t^{SL} which are:

[54] Lo, J.M. 1981. Surf Beat: Numerical and Theoretical Analyses. Ph.D. dissertation, Department of Civil Engineering, University of Delaware

[55] Changes in sea level due to barometric pressure alone seldom exceed 30 cm; the water level does not adjust itself immediately to a change of pressure. Instead, it responds to the average change over a considerable area.

- the slope m_{WL} of the beach face in $\vec{X}(s)$ and the slope m_{fs} of the foreshore of $\vec{X}(s)$ at the time of the snapshot t;
- the significant wave height for H_0 offshore $\vec{X}(s)$, and the related peak period T_p to calculate $L_0 = \frac{g}{2\pi} T_p^{\ 2}$;
- the atmospheric pressure P_{atm} offshore.

How to get them will be developed in another chapter.

The approximation of the cross-shore profile by a segment/line, which will depend of the seafloor altitude is not very accurate, but it is difficult to get an approximation of the profile that will be better because of the scarcity of information as cross-shore profiles change with time, even in a tide period.

Offshore wave patterns when shoaling in the coastal area might modify their energy distribution and the waves' steepness accordingly, and longshore currents might also modify the amplitude distribution — not to mention that the morphology of the coastline and the geology, e.g. shore materials porosity and density, or the thickness of soft materials on rocky substratum, as well as storm surges.

Corrections of the waterlines for astronomical tides

To extrapolate $\vec{X}^{\mathrm{EO},t}_{\mathrm{SL}_{z_{\mathrm{astr},l}},\mathrm{h}}(s)$ from $\vec{X}^{\mathrm{EO}}_{\mathrm{WL,fair\text{-}weather}}(s)$, i.e. adjusting the hypothetical waterline in fair weather at time t to hypothetical waterlines related to depth = tide datum $z_{\mathrm{astr},l}$, one needs to know the astronomical tide effect in each $\vec{X}_{WL}(t,s)$, i.e. $z^{\mathrm{ext}}_{\mathrm{ocean\_tide}}\left(\vec{X}_{WL}(t,s)\right)+\delta z^{\mathrm{ext}}_{\mathrm{costal\_tide}}\left(\vec{X}_{WL}(t,s)\right)$ which is considered as roughly constant in the area for $z^{\mathrm{ext}}_{\mathrm{ocean\_tide}}\left(\vec{X}_{WL}(t,s)\right)$, i.e. $z^{\mathrm{ext}}_{\mathrm{ocean\_tide}}(t)$, but may differ for the coastal effects.

A tide predictor from national Hydrographic Offices can be used to get the necessary values, then the shift is calculated by:

$$\left\|\overrightarrow{\delta X}^{(2)}(s)\right\| = \frac{z^{\text{ext}}_{\text{ocean\_tide}}(t) + \delta z^{\text{ext}}_{\text{costal\_tide}}\left(\vec{X}_{WL}(t,s)\right)}{m_{fs}}$$

$$\vec{X}^{\text{EO},t}_{\text{WL}} \xrightarrow{metoc} \vec{X}^{\text{EO},t}_{\text{WL,s.l.w.}} \xrightarrow{astr\_tide} \vec{X}^{\text{EO},t}_{\text{SL}_{z_{\text{astr},l}}}$$

whereby $\vec{X}^{\text{EO},t}_{\text{SL}_{z_{\text{astr},l}}} = \vec{X}^{\text{EO},t}_{\text{WL}} + \frac{\bar{\eta}_{\xi_0}\left(\vec{X}^{\text{EO},t}_{\text{WL}}\right) - \alpha\left(P_{atm} - P_{atm,0}\right)}{m_{WL}}\vec{u}_1 + \frac{z^{\text{ext}}_{\text{astr\_tide}}\left(\vec{X}^{\text{EO},t}_{\text{WL}}\right)}{m_{fs}}\vec{u}_2$

with $\vec{u}_1 \simeq \vec{u}_2$except near headlands, canyons…

If one chose mid high water (MHW), mean low water (MLW) and mean tide level (MTD) to get the shorelines, m_{fs} can be considered the same for all.

Uncertainty budget

The errors can be calculated for all the transformation that are described in the previous paragraphs, considering linear transformation for easiness. The errors' assessment will depend on our capacity to do all the corrections and to collect the parameters' values with an assessment of errors. This will be described/developed in the ATBDs.

3.6.5 Error budgets: Shore-line Indicators (SAR)

SAR observations are complementary to optical/VNIR observations, and they have been performed by surveyors for centuries to get shoreline indicators, because weather independent and day-night imaging capacity;

Why "complementary" and not a replacement of VNIR observations? This is defined by three points and described in detail in the following section:

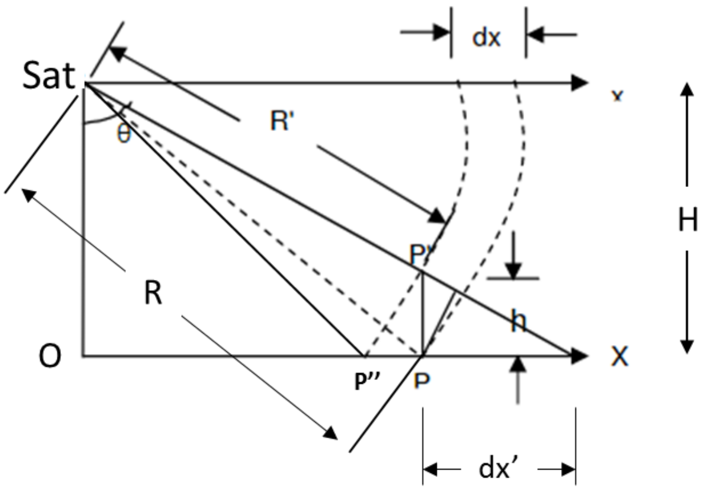
1. **Geometric distortion:** the mapping distortions when looking at "objects" like the seafront (an edge at the border of between the land platform and the sea-or-the beach). Furthermore, the drastic differences between the views of from different satellite tracks (e.g. ascending track (S→N) of the satellite and a descending track (N→S) of Sentinel-1) because of different geometries.
2. **Signal Return:** the lack of strong scatterers on the beach, which prevents viewing the waterline.
3. **Signal Noise:** the speckle which is inherent to SAR views.

3.6.5.1 Geometric Distortion

SAR active systems measure distance between the satellite-borne sensor and the ground (a side-looking imaging sensor). Accordingly, it is not possible to have a direct angular geometry as one gets when looking with the eyes or with a passive Optical sensor on a plane or a satellite. Instead, we measure a signal vs. a distance in SAR and not a signal vs. an angle as in VNIR passive sensing. In SAR data, the geometry is retrieved by integration of a terrain model and therefore the geometric correction process or ortho-rectification is much more critical for SAR than it is for Optical sensors. The side-looking methodology of SAR data (Figure 3.11) creates certain characteristics, including:

- Varying geometric distortion due to changes in viewing angle across swath;
- Data dropouts due to topographic shadow.

Figure 3.11 provides an example with a flat terrain (e.g. the sea) with a quay or a dock: the water surface intersects the quay at P, and the upper part of the quay is in P' at a height h. On a SAR image from a satellite at an height H, represented by the line O→X in the figure herein below, the edge of the quay P' will be on P'', at dx in front of the quay.



$$dx = -h(H-h)/R \cong h/\cos\theta$$

Figure 3.11: Geometries of side-looking SAR active sensors.

The ground resolution given by the time-size of the radar pulse, i.e. half of a pulse length (two objects can be distinguished if the leading edge of the pulse echo from the more distant object arrives at the antenna later than the trailing edge of the pulse echo from the nearer object, thus if their distances to the antenna are different by at least half of the pulse length, or the distance the pulse travels in the time p during which the transmitter is turned on, then the objects are resolvable); in the case of Sentinel-1 it is 25 m at the middle of the swath when working in Strip-Map mode (reaching 30m at the edge of the swath); and $1/\cos\theta = 1.06\text{-to-}1.4$

In real-life examples, this can have a dramatic effect on the output information:

- **A pier** which is 5 m above the water will be 5 to 7 m in front of the real location on the SAR image;
- **A crane** on the pier, with a typical height of 65m, produces a signal between 70-to-90 m in front of its geographical location.
- **A seawall** and looks from landward, typical seawalls height is non-tidal environment is about 7 m (case of the med sea), and more than 10 m in tidal areas, we get a shadow of dx' on the

images behind the sea wall (i.e. some 10-to-29 m that forbid to see the toe of the wall). $dx' = h/\sin\theta = 1.4\text{-to-}2.9 \cdot h$

- **A cliff** (defined here as a seafront) with a beach below, oriented SW-NE with the sea to the east and a height of around 30m.
- If the satellite is west of the cliff, the beach will be omitted due to radar shadow. Accordingly, the shoreline will represent the edge of the cliff (not the obscured beach below), generating high uncertainty on its geographic location.
- If the satellite is east of the cliff the beach will be seen on the image, but it will be behind the cliff and confused with the cliff plateau the location will be rather out at sea.

3.6.5.2 Signal Return

As previously mentioned, sandy beaches provided limited backscatter return in SAR imagery. Only where the beach surface contains pebbles or rocks will there be a significant representation in SAR analysis. However, during storms, the surf areas (shoaling zone) and the wave wash-up on the beach will also be visible. Turbulence in surface water, caused by wave breaking shall increase small-scale roughness for Bragg scattering, but we don't know if it will deliver a higher signal than the pure RCS (radar cross-section) on the 'dry' beach. It is probably true for some polarization of the radar signal.

3.6.5.3 Signal Noise

Beach surfaces are poor radar retroreflectors except when the viewing angle from the satellite is minimal (<20°). In these conditions, the speckle/noise generated due to the poor reflectivity of the sand or the water surface is quite high. This signal noise can be removed through filtering, whereas groups of speckled pixels are removed by re-sampling techniques.

3.6.5.4 Conclusion: Shore-line Indicators (SAR)

SAR provides a seafront line rather than a waterline. The difficulties that must be faced consists of i. orthorectifying properly the image, which needs knowledge of altitudes (not only the ground but all 'objects' on the ground) and of ii. differentiating between the seafront and tall objects in the backshore areas (roofs of the buildings/ trees/ hills/ etc.).

The stacking of seafront lines from different SAR image, i.e. co-registration, can become particularly complicated due to SAR-intrinsic artefacts created by varying side-looking geometries. Indeed the features derived in SAR data from ascending orbits will appear differently in descending orbit data. Accordingly, co-registration based on these targets will cause significant errors in waterline comparison.

Lastly, the poor signal return of beach surfaces generates issues with speckle, whereby high frequency noise dominates the ‘shoreline’ signal.

While SAR imagery can penetrate cloud and is independent of solar illumination, the limitations noted above mean that it cannot be used in isolation and should be used in conjunction with optical/VNIR images to prevent misinformation in shoreline assessment.

3.7 Pre-Feasibility analysis: Summary

Prior to delivering EO products, a feasibility analysis must be carried out. Sections 3.4 – 3.6 have demonstrated the challenges and potential solutions to creating EO products as shoreline indicators in line with the requirements specified by the end-users. In the following section, some of the conclusions were not discussed in these previous sections, but their inclusion is nevertheless vital. Importantly, the feasibility study carried out here is not concerned with the development of automatic processors, which systematically detect and delineate lines on a map - this will be covered by and ATBD in the TSD. The purpose of this feasibility study is to determine the spatial and temporal capability of EO in observation/ sensing geometric properties.

3.7.1 Recap: EO-products defined from user requirements

Tables 3.7 describes the EO products as considered outcomes of requirements of the End-Users (URDs). These have been consolidated with regards to their temporal (Table 3.8) and spatial requirements (Table 3.9).

Importantly, it is considered that sampling rate shall be higher than the update rate, as the outputs are filtered values at the time update scale, but this sampling rate not only depends on the availability of EOs in archive/ availability of the satellites for snapshots/ cloud cover, as well as the acceptable errors and the dynamics of the shorelines which depend on climatological METOC conditions ⇒ application of the Nyquist-Shannon sampling theorem, to keep the aliasing effect below the acceptable error level.

Table 3.7: Final list of EO products from the URs.

EO product code	Description
[EO]-L2_1D_FB_MHWM_{area/date/hour} [Alg(L2)]	: feature-based shoreline based on the mark of high tide
[EO]-L2_1D_FB_OWHM-VL_{area/date/hour} [Alg(L2)]	: feature-based shoreline based on the vegetation line or civil works (seafront)
[EO]-L2_1D_DB/WL _{area/date/hour} [Alg(L2)]	: wet/dry edges on the shore, i.e. waterlines (border between land and water at the time of a snapshot)
[EO]-L2*_1D_BTM/m_{area/date/hour}	: the cross-shore profiles, which is an intermediary product
[EO]-L2_1D_DB/[tide level]-SL_{area/date/hour} [Alg(L2)]	: shorelines based on tidal datum, waterlines, and cross-shore profiles
[EO]-L2_1D_SL/ES-classification_{area/date/hour} [Alg(L2)]	: seafront based on thematic classification of ecosystems = the interface between marine and land habitats
[EO]-L2*_2D_SL/ES-classification_{area/date/hour} [Alg(L2)]	: the map of the shore by land and marine ecosystems' classes, which is an intermediary product, used to get [EO]-L2_1D_SL/ES-classification_{area/date/hour} [Alg(L2)]
[EO]-L3_1D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L2)]	: seafront based on thematic classification of ecosystems but on a series of EOs from same satellite mission to smooth the seasonal effect
[EO]-L3*_2D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L2)]	: the map of the shore by land and marine ecosystems' classes using a series of EOs from same satellite mission, which is an intermediary product, used to get [EO]-L3_1D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L2)]
[EO]-L3t_..._{area/date/hour-[Δt]} [Alg(L3)]	: outputs of calculation on time series of previous shorelines derived from snapshots from same EO mission
L4t_..._{area/date/hour-[Δt]} -{[EO]$_i$ | $_{i=1,...,n}$} [Alg(L4)]	: outputs of calculation on time series of previous shorelines derived from snapshots from different EO missions
[EO]-L2_3D_BTM/SDB_{area/date/hour} [Alg(L2)]	: bathy-topo morphology changes based on SDB (vs. a reference DEM-DTM)
[EO]-L2_3D_BTM/WF_{area/date/hour} [Alg(L2)]	: bathy-topo morphology changes based on Wave Fields analysis (vs. a reference DEM-DTM)
[EO]-L3_3D_BTM/..._{area/date/hour -[Δt]} [Alg(L3)]	: result of data fusion of BTM/SDB or BTM/WF on a data sets of snapshots in the Δt time interval

[EO]-L3_3D_BTM_{area/date/hour -[Δt]} [Alg(L3)]	: result of data fusion BTM/SDB and BTM/WF on a data sets of snapshots in the Δt time interval
L4_3D_BTM_{area/date/hour -[Δt]} -{[EO]$_i$ $\|_{i=1,\dots,n}$} [Alg(L4)]	: result of data fusion BTM/SDB and BTM/WF on a data sets of snapshots from different EO missions in the Δt time interval
L4t_3D_BTM_{area/date/hour -[Δt]} -{[EO]$_i$ $\|_{i=1,\dots,n}$} [Alg(L4)]	: outputs of calculation on time series of previous BTMs

Table 3.8: Consolidated list of EO products, grouped into spatial requirements.

EO product code	scale	spatial res.	position acc.	altitude acc.
[EO]-L2_1D_FB_MHWM_{area/date/hour} [Alg(L2)]	1:1,250 i.e. mu=25cm 1:2,500 i.e. mu=50cm 1:10,000 i.e. mu=2m	δx=50cm δx=1m δx=4m	Δx=50cm, σ_x=50cm Δx=1.1m, σ_x=1m Δx=4.1m, σ_x=4m	? ? ?
[EO]-L2_1D_FB_OWHM-VL_{area/date/hour} [Alg(L2)]	1:5,000 i.e. mu=1m	δx=1m	Δx=1m	Δz=50cm
[EO]-L2_1D_DB/WL _{area/date/hour} [Alg(L2)] [EO]-L2_1D_DB/[tide level]-SL_{area/date/hour} [Alg(L2)]	1:1,250 i.e. mu=25cm 1:2,500 i.e. mu=50cm 1:5,000 i.e. mu=1m 1:10,000 i.e. mu=2m	δx=50cm δx=1m δx=4m	Δx=50cm, σ_x=50cm Δx=1.1m, σ_x=1m Δx=20cm or 1m Δx=4.1m, σ_x=4m or Δx=1m	? ? Δz=25cm ?
[EO]-L2_1D_SL/ES-classification_{area/date/hour} [Alg(L2)]	1:5,000 i.e. mu=1m 1:10,000 i.e. mu=2m	δx=1m or 10m ?	Δx=1m or 5m ?	
[EO]-L2_3D_BTM/SDB_{area/date/hour} [Alg(L2)] [EO]-L2_3D_BTM/WF_{area/date/hour} [Alg(L2)] [EO]-L3_3D_BTM/…_{area/date/hour -[Δt]} [Alg(L3)] [EO]-L3_3D_BTM_{area/date/hour -[Δt]} [Alg(L3)]	1:5,000 i.e. mu=1m 1:25,000 i.e. mu=5m 1:50,000 i.e. mu=10m	δx=1m or 5m ? ?	Δx=20cm or 1m ? ?	Δz=10 or 20cm Δz=15cm Δz=15cm

Table 3.9: Consolidated list of EO products, grouped into temporal requirements.

EO product code	Updating frequency
[EO]-L3t_1D_FB_MHWM _{area/date/hour-[Δt]} [Alg(L3)] L4t_1D_FB_MHWM _{area/date/hour-[Δt]} [Alg(L3)]	yearly
[EO]-L3t_1D_FB_ OWHM-VL _{area/date/hour-[Δt]} [Alg(L3)] L4t_1D_FB_ OWHM-VL _{area/date/hour-[Δt]} [Alg(L3)]	yearly
[EO]-L3t_1D_1D_DB/SL _{area/date/hour-[Δt]} [Alg(L3)] L4t_1D_1D_DB/SL _{area/date/hour-[Δt]} [Alg(L3)]	every 6 months every 3 months every month few days after storm surges
[EO]-L3t_1D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L3)] L4t_1D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L3)]	every 6 months every 3 months every month few days after storm surges
[EO]-L3t_3D_BTM/SDB_{area/date/hour} [Alg(L3)] [EO]-L3t_3D_BTM/SDB_{area/date/hour-[Δt]} [Alg(L3)] [EO]-L3t_3D_BTM/WF_{area/date/hour} [Alg(L2)] [EO]-L3t_3D_BTM/WF_{area/date/hour-[Δt]} [Alg(L3)] [EO]-L3_3D_BTM_{area/date/hour -[Δt]} [Alg(L3)] L4t_3D_BTM_{area/date/hour -[Δt]} -{[EO]$_i$ | $_{i=1,\ldots,n}$} [Alg(L4)]	yearly monthly before and after dredging

3.7.2 Content of products

A product shall contain not only i.a the proxy-based or datum-based shoreline indicators, but i.b the metadata that inform the users on the EO data inputs' identification, the data processor's version, the nomenclature, the results of the Quality Control of the product, the validation tests that were performed, the geodetic system, the projection type… and ii.a the auxiliary data or the link to the auxiliary data that have been used to process the EO, as well as ii.b the related metadata —auxiliary data are all data used in addition to the EOs, whether the parameters of the data processors or additional data (e.g. the atmospheric pressure, tide height, cross-shore slope, the typical reflectance of features, significant wave height, etc.), and iii. error budget, either at pixel level or with a formula.

[EO]-L3 products are either i. time-series of [EO]-L2 products which have been normalized accordingly, i.e. [EO]-L2$_{norm}$ products which could be made available as individual products —with reference to the [EO]-L3 product of reference— so as to reduce the size of files to download when users prefer the normalized L2 products to the L2 products, or ii. statistics on the data sets of the components of the time series. The type of statistics, in particular the coastal erosion assessment from the time-series of indicators, shall be defined with the users.

3.7.3 Production workability

[EO]-L2_1D_FB_MHWM_{area/date/hour} [Alg(L2)] is based on the detection of lines of debris, or on the change of materials, with coarse materials upward-landward; nota: the size of the debris is such that it would be impossible to detect them with HR and even VHR EOs, as demonstrated through another ESA contract (closed Oct 2019) and a project for the UKSA (closed Nov 2018).

[EO]-L2_1D_FB_OWHM-VL_{area/date/hour} [Alg(L2)] is based on the detection of changes between Land Use/ Land Classes, and should be similar to the [EO]-L2_1D_SL/ES-classification_{area/date/hour} [Alg(L2)] if it were to include a higher number of classes. Same if we use classification methods for the production of [EO]-L2_1D_FB_MHWM_{area/date/hour} [Alg(L2)].

As such these product can be included in a [EO]-L2_1D_SL/ES-classification_{area/date/hour} [Alg(L2)] product that would contain multiple shoreline indicators, then noted [EO]-L2_1.5D_SL/ES-classification_{area/date/hour} [Alg(L2)]. Same for a [EO]-L3_1.5D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L2)] products.

With regards to the [EO]-L2_3D_BTM products, there is no reason to make a difference between the SDB and wave fields' indicators, as a particular SAR EO, identified by [EO], will only provide wave fields' indicators, whereas a particular VNIR/optical EO, identified by [EO] would contain two files, one with SDB and the other with wave fields' indicators. [EO]-L2_3D_BTM/SDB_{area/date/hour} [Alg(L2)] and [EO]-L2_3D_BTM/WF_{area/date/hour} [Alg(L2)] shall be put together in a [EO]-L2_3D_BTM _{area/date/hour} [Alg(L2)] product. It is the metadata that will inform the users on the precise content of the products.

Same for [EO]-L3_3D_BTM_{area/date/hour -[Δt]} [Alg(L3)] products.

We suggest to get rid of the L4_3D_BTM_{area/date/hour -[Δt]} -{[EO]$_I$ |$_{i=1,\dots,n}$} [Alg(L4)] because EO-products fusion is the users' role rather than an EO service provider, taking into account the users' knowledge of the shore's dynamics. Same for [EO]-L3_3D_BTM/…_{area/date/hour -[Δt]} [Alg(L3)]. It is not true for time-series L3t,

3.7.4 *Mapping accuracy and resolution*

As a rule of thumb, the positioning accuracy and resolution of the [EO] products which are proxy-based coastline indicators are similar to the positioning accuracy and resolution of the EOs, and super-resolution methods may improve the resolution, but not the accuracy, yet i. increasing the false alarms, and ii. decreasing the reliability of the improvement.

The positioning accuracy and resolution of the [EO] products which are datum-based coastline indicators is much lower and mainly depends on properly modelling the dynamics of the sea and its impacts on the shore materials; as such, the [EO]-L2_1D_DB/[tide level]-SL_{area/date/hour} [Alg(L2)] are not L2 products but L4 products, and should be renamed [EO]-L4_1D_DB/[tide level]-SL_{area/date/hour} [Alg(L4)].

Nota: the same is true, but for the thematic classification between land and sea, which is based on training classifiers, the information brought in the training set being as important as EOs.

Accordingly, the following product names should be changed:

- *[EO]-L2_1.5D_SL/ES-classification_{area/date/hour} [Alg(L2)]*
    - *should be renamed* ***[EO]-L4_1.5D_SL/ES-classification_{area/date/hour} [Alg(L2)]***
- *[EO]-L3_1.5D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L2)],*
    - *should be renamed* ***[EO]-L4_1D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L4)].***

.

Table 3.10: Final list of EO products (EO-derived proxy-&-datum shoreline indicators)

EO product code	Description
[EO]-L2_1D_DB/WL _{area/date/hour} [Alg(L2),par]	: wet/dry edges on the shore, i.e. waterlines (border between land and water at the time of a snapshot)
[EO]-L2*_1D_BTM/m_{area/date/hour}	: the cross-shore profiles, which is an intermediary product
[EO]-L2_1D_DB/[tide level]-SL_{area/date/hour} [Alg(L2),par]	: shorelines based on tidal datum, waterlines, and cross-shore profiles
[EO]-L2_1.5D_SL/ES-classification_{area/date/hour} [Alg(L2),par]	: feature-based shoreline based on the mark of high tide (MHWM), feature-based shoreline based on the vegetation line or civil works (OHWM), seafront based on thematic classification of ecosystems (interfaces between marine and land habitats)
[EO]-L2*_2D_SL/ES-classification_{area/date/hour} [Alg(L2),par]	: the map of the shore by land and marine ecosystems' classes, which is an intermediary product, used to get [EO]-L2_1.5D_SL/ES-classification_{area/date/hour} [Alg(L2)]
[EO]-L3_1.5D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L3,par)]	: seafront, MHWM & OHWM based on thematic classification of ecosystems but on a series of EOs from same satellite mission to smooth the lunar, solar & seasonal cycles' effect
[EO]-L3*_2D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L3),par]	: the map of the shore by land and marine ecosystems' classes using a series of EOs from same satellite mission, which is an intermediary product, used to get [EO]-L3_1.5D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L2)]
[EO]-L3t_..._{area/date/hour-[Δt]} [Alg(L3),par]	: outputs of normalization & calculation on time series of previous shorelines derived from snapshots from same EO mission
[EO]-L2_3D_BTM_{area/date/hour} [Alg(L2),par,Ref(DEM-DTM)]	: bathy-topo morphology changes based on SDB (vs. a reference DEM-DTM) and/or on Wave Fields analysis (vs. a reference DEM-DTM)

4 Requirements Engineering: Validation

In the frame of the contractual requirements drawn by ESA, a translation of the user requirements to broad & generic specifications of EO-derived proxy-and-datum based shoreline indicators has been described in Section 3. This resulted in a list of generic L2 and L3 products, whose algorithms may need an adaptative parametrization depending on the coast types. Importantly, these requirements need to be validated against the phenomena that they are aimed at measuring. Fundamentally, case-by-case assessments should be made to determine if the specifications of the developed EO products, (spatial resolution and positioning accuracy) compare to the scale (spatial and temporal) of local coastal change. This section describes how that assessment (requirement validation) can be made, by looking at the theoretical accuracy of the EO shoreline products, in terms of spatial resolution (Section 4.1), temporal resolution (Section 4.2), object recognition (Section 4.3), change representation and assessment (Section 4.4). Finally, Section 4.5 summarises the Requirement Validation by referencing the context of the URDs from both the authoritative end-users perspective and that of ESA.

4.1 Confidence in EO derived shorelines: Spatial resolution

There are two groups of spatial scales, the **cross-shore** scales Δl_c , which scale the changes in shoreline position, and the **along-shore** scales l_l which scale the changes of Δl_c alongshore.

With regards to the **cross-shore** profiles: the system behaviour depends on the variability of the following shoreline metrics.

1- **the swash length** Δl_{swash} of the order $\frac{H_0\xi_0}{m_{ns}}$where $\xi_0$is the Irribaren number$\xi_0 = \frac{m_{fs}}{\sqrt{\gamma_0}}$ where H_0 and L_0 are resp. the height and wavelength of the offshore wave that break, γ_0 is the offshore steepness of the waves $\gamma_0 = \frac{H_0}{L_0}$, m_{fs} is the beach/foreshore slope and m_{ns} is the beach/nearshore slope where $m_{ns} \geq m_{fs}$ $\Delta l_{swash} = O\left(\frac{\left(\frac{m_{fs}}{m_{ns}}\right)H_0}{\sqrt{\gamma_0}}\right)$

2- **the length of the surf zone** Δl_{surf}which depends on the position of bars, whose depth is 5 to 10 times the mean annual significant wave height $\langle H_s\rangle_{year}$or on the depth of a sloping seabed by a relation of the order $d_b \simeq 1.5L_0\frac{m_{fs}}{\sqrt{\gamma_0}}$, $\Delta l_{surf} = O\left(min\left\{5\frac{\langle H_s\rangle_{year}}{m_{fs}}, 1.5\frac{L_0}{\sqrt{\gamma_0}}\right\}\right)$

3- **the length of the tidal zone** Δl_{tide}, knowing the tide range in height TR $\Delta l_{tide} = \frac{TR}{m_{fs}}$

4- **the length of morphological structures** such as mega ripples, cusps and berms, which, for the formers can be approximated by $1.5\Delta l_{swash}$ if $\Delta l_{swash}$is truly the horizontal swash excursion (the horizontal distance between the limits of runup and rundown, and for the latter, berm elevation coincides with wave runup height but the size to the accumulation of sand before a destroying event[56] with a dimensional analysis one can envision a scale of $\frac{(H_0+TR_{neap})}{m_{ns}}$with TR_{neap} being the tide range in height at neap tide $\Delta l_{morph} = O\left(\left\langle 1.5l_{swash}, \frac{(H_0+TR_{neap})}{m_{ns}}\right\rangle\right)$ which can be also represented by $\Delta l_{morph} =$

[56] s two different modes of berm development: (1) vertical growth at spring tides or following significant beach cut due to substantial swash overtopping, and (2) horizontal progradation at neap tides through the formation of a proto-berm located lower and further seaward of the principal berm

$\frac{\sigma(m)}{m_{mean}}\frac{m}{\gamma_0}O(\{l_{swash}, l_{surf}, l_{tide}\}) \simeq \frac{\sigma(m)}{\gamma_0}O(\{l_{swash}, l_{surf}, l_{tide}\})$ where m_{mean} is an average slope, and $\sigma(m)$ the variation of slope, of the order $m_{ns} - m_{fs}$;

5- **the distance offshore** $\Delta l_{bar} = y|m \approx 0$, i.e. where the slope is nearly 0, which constrains the bar parameter $B* = \frac{y|_{m\approx 0}}{gmT^2}$

All depend mainly on the shore slopes, which themselves depend on the Dean parameter or dimensionless fall velocity $\Omega = (H_b/w_s T)$, where w_s is the stationary fall velocity of a grain of sediment in the water which depends on the mean beach face sediment size $\phi_{50}|_{\text{BeachFace}}$;

nota: the reader will notice that the main parameter is the ratio of wave steepness to the slope, whereas geomorphologist usually refer to the Ursel number[57] which normalizes the wave steepness $N_U = \gamma_0 \left(\frac{L_0}{d}\right)^3$ *with d being the depth —a formula which is probably valid in shoaling areas until wave breaking.*

With regards to the **long-shore** scales, there are five main scales

1- **the traditional geographic scales** $l_g = C_l$ and $l_{g*} = S_l$ which are the planform geometry parameters (the shoreline length between the headlands, and the chord length directly between headlands), with processes that depend on the Embayment Scaling Parameter $\delta' = \frac{S_l^{\ 2}}{100 C_l H_b}$ where H_b is the height of waves at breaking which depend on H_0, m and γ_0 ;

2- **the scales related to changes incident breaking wave condition**, and the wave obliquity β, i.e. angle of waves with the shoreline; probably of the kind $l_i = l_{g*}/\cos\beta$;

[57] indicating the nonlinearity of long surface gravity waves on a fluid layer

3- **the scales related to the Longshore Variation Index** $LVI = \frac{Q_{std}}{|Q_{mean}| + Q_{std}}$, where Q is the dissipated energy of waves at the shore (the loss of wave energy, with consequent decrease in wave height, due to wave breaking, turbulence, and viscous effects, and, in shallow water, due to the effects of bottom friction = 3 regimes A. Bottom friction dominated B. Shoaling dominated C. Depth breaking dominated), Q_{mean} the average, and Q_{std} the variability; as the value of Q is of the order $\frac{3\sqrt{16}}{\pi} B\rho g \frac{H_{rms}{}^3}{d} \frac{r_b}{T_{av}}$[58] where r_b is the rate of breaking in s^{-1}, ρ the seawater density, g the gravity, and $B \approx 1$, i.e. $Q \approx 20 \frac{H_0{}^3}{dT_0} \simeq 20\gamma^3 \frac{L_0{}^{\frac{5}{2}}}{d\sqrt{\frac{2\pi}{g}}}$, i.e. $\Rightarrow l_d = O\left(\frac{d}{\frac{\partial d}{\partial s}}, \frac{\gamma}{\frac{\partial \gamma}{\partial s}}\right) | f s$ in the foreshore where s is a curvilinear coordinate of the waterline, and γ is the wave steepness when approaching the shore which decreases with β ;

4- **the scales** l_{geol} **related to the geological constraints** TYPE *i.* which inform on the availability of sediments to move up-and-down a beach;

5- **the scale of change of shore materials**, including the variability of the aerial accretion parameter $v_{wind} / \left(h_{berm}^{dune} / \Delta T_s \right)$ where v_{wind} is the wind speed, h_{berm}^{dune} the difference of altitude between the dunes foot and the land platform, and ΔT_s the duration of wind events.

The generic specification introduced in the URD for the spatial resolution of EO products, which describe shoreline features and their positioning accuracy at each site, will be further refined to optimize the monitoring of coastal erosion that will be of interest to both scientists and engineers as well as enabling a better understanding of the overall erosion processes at work, which impact the land and human activities . The availability of EO data will define the spatial scale and temporal frequency of the coastal erosion processes that can be addressed.

[58] model commonly used in SWAN

4.2 Confidence in EO derived shorelines: Temporal resolution

Temporal resolution and related sampling schemes are of the utmost importance to avoid that reconstructed signals, i.e. location of shoreline indicators, are too different from the continuous signal, leading to artefacts, i.e. false conclusions on erosion rates. The phenomenon would be due to 'aliasing' or "repliement de spectre" due to the confusion between a low frequency signal, e.g. erosion rate at the Metonic cycle, and a high frequency signal, e.g. erosion further to a single storm or accretion in the following weeks.

Nota: for the record, all 'means' or "averages" should be on a 19 year period because of the 18.6 years of Metonic Cycle of the moon's nodes, and sea-level rise can only be based on these averages, e.g. the US national tidal datum epoch using 32 stations along the east and west coast out of the 210 NWLON stations:

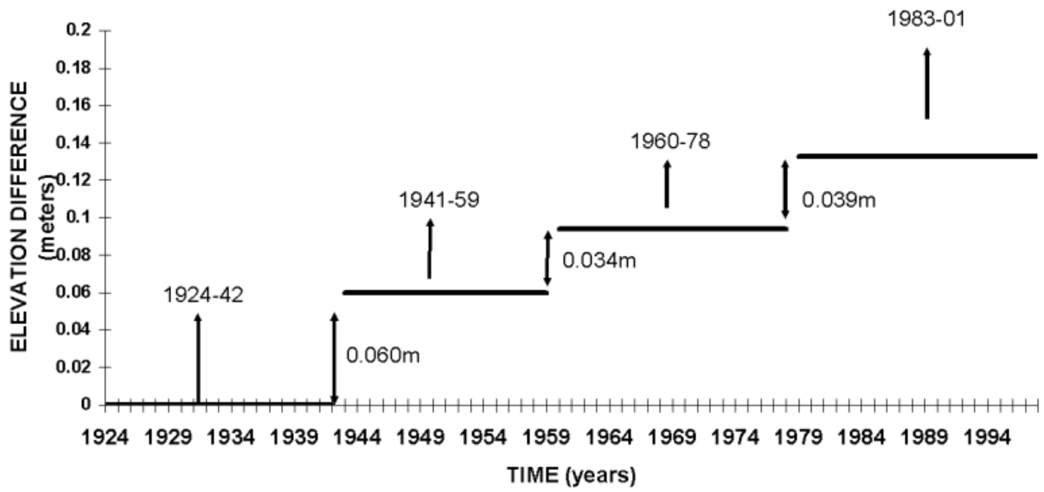


Figure 4.1: Schematic depiction of bi-decadal elevation change as a result of sediment transfer.

The main events that shape the shore are the wind episodes (for immerged/foreshore materials' transport by wind waves, and aerial transport of materials of the backshore), the waves/swell episodes (out of the fetch —for immerged/foreshore materials' transport by the swell), the recovery periods between the episodes when the shore forego an hysteresis-type track, the whole being modulated by tides, whether astronomics or meteorological, and superimposed on hydrological phenomena such as outflows at river mouths or ocen currents.

E.g. a shore is eroded in winter, and accretion occurs during the summer, but it can add to a general accretion due to an influx of sediment giving a systematic accretion trend which is seasonnaly modulated. If this long-term, also called low-frequency, process is stronger than the seasonal process built-up by meteorological events modulated by tides, then samples taken 10 years apart whatever the season would deliver an acceptable assessment of the erosion or accretion. On the contrary, false conclusions would be drawn: characteristic samplings shall be done seasonally, or accurate statistics from samplings shall be performed seasonally.

If erosion, i.e. definite loss of materials without extraordinary events (incl. human intervention), is the main topic of interest, one has to average on numerous hysteresis cycles, i.e. many storms, yet considering seasons which center on neap tide and spring tide periods (meteorological events have a solar cycle, whereas tidal events have rather a lunar cycle). Seasonal statistics shall be performed with an aprior knowledge of the intra-seasonal shoreline dynamics.

The URD in Annex 1 currently considers a standardised statistical assessment period (a year, a quarter, etc.). In order to achieve a greater understanding of the erosion processes the assessment period will need to be refined to account for significant, seasonal and local events (accounting for high frequency and low frequency dynamic movement). This will better inform the accuracy and prescision required to deliver assessment of coastal erosion/accretion.

Further discussions with the end-users to take place for deciding how sampling rate will be specified

It should be noted that the EO products currently specified (cf. §2) are time series of normalized shoreline indicators, discrepancy assessments which 'measure' shifts, i.e. coastal erosion/accretion indicators, but not statistics.

4.3 Confidence in EO derived shorelines: Distinguishing shoreline features

Users have requested the mapping of debris lines, vegetation lines and waterlines, as well as terrain altitudes where the features are the seabed and the land (bathymetry and hypsometry).

The lines are surfaces of manifold whose definitions shall be clarified:

- the line of debris is an area, whose width is not constant, made of litter and beached rafts of natural materials (drifting wood, unrooted seaweed and algae, etc.); it has to be detected, and mapped as a surface or as a line, but which line if the surface is wider than a pixel?
- the line of vegetation at the toe of the dune can also be a line of vegetation on an ancient berm depending on the season, or a line of vegetation up the dune or behind a seawall; accordingly it is not an indicator of the terrain (height), but of ecosystems' health and condition; the waterline is a fuzzy concept because of wave breaking and water swash: when wave breaks, it spreads water in the atmosphere (bubbles, mist…) and aerially on the beach; when waves swash the beach face, it runs-up a mass of water which, when flowing back, may leave pools of water, or wet material (porous material filled with water) which can even form water skins depending on the flowing properties of the porous material
- <u>Depending on the sensor, one or the other, or all will be identified, but what will an automated processor pinpoint?</u>

For the terrain altitude, the features that help assess the altitude shall be classified and identified, even recognized. E.g. SDB assesses depth at the scale of a pixel, whereas seafloor morphology derived from wave fields assesses depth at the scale of the wave sizes and the surf zone width.

The URD will be further refined to clearly identify which shoreline indicators will be adopted to define coastal change and how this change will be represented.

4.4 Confidence in EO derived shorelines: Shoreline representation

The URD has specified mapping scales. Because of probabilities of detections >1 and probabilities of false alarms $\neq 0$, some shoreline features are missing, or they are duplicated, triplicated…: mapping consists in cleaning and linking when possible, under a constraint of continuity and constraints of differentiability (curves +/- smooth).

The fractal dimension of the shoreline indicators will need to be further defined to enable mapping consistently according to the spatial scales of variability of change of the shorelines.

4.5 Requirement Validation: Summary

This paragraph about the 'Requirement Validation' does not deal with *i.* either the validation of the URD goals in terms of coastal erosion/accretion assessment's needs in the various selected sites, which would be obviously out of the mandate of the contractor, or *ii.* the validation of the ESA requirements which were published in the ITT and are contractual except if a waiver is raised. It covers the technical requirements which were missing in the URD about the EO-products, and the amendments that may be brought.

4.5.1 URD requirements

The requirements which have been published are about Coastal Erosion & Coastal Flooding, which are respectively defined by:

- the process of wearing away material from the coastal zone due to imbalance in the supply and export of material from a certain section;
- the process of flooding normally dry, low-lying land by seawater due to a sea level rise or wave overtopping the barriers.

Coastal erosions occurs in the form of scouring in the foot of the cliffs or in the foot of the dunes, hence coastline retreat (back-wearing) and/or lowering of the bottom elevation (down-wearing), the former being quantified by an erosion rate $r_\perp$ in m/year perpendicular to the coastline, the latter by an erosion rate in m^3/m/year, the difficulty being to define the reference surface for which the volume & volume changes are calculated —an erosion rate can also be calculated locally by the conservation of mass: $\vec{r} = \frac{\partial d}{\partial t} \vec{\nabla} d \bigg/ \left\| \vec{\nabla} d \right\|^2$ where d is the depth (positive when below the *zéro hydrographique*). At the landward limit of the backshore $\vec{r} = \left(r_{\perp}, r_{\parallel} \right)$.

The EO products [EO]-L2_1.5D_SL/ES-classification_{area/date/hour} [Alg(L2)] and [EO]-L3_1.5D_SL/ES-classification_{area/date/hour-[Δt]} [Alg(L3)] would allow to monitor the coastline retreat, this coastline being the seafront according to an extensive definition that does not restrict its use to towns .

The EO product [EO]-L2_3D_BTM_{area/date/hour} [Alg(L2)] shall fulfill the needs for assessing the removal of materials ; if the SDB gives very crude terrain altitudes in very shallow waters ($d \leq 5m$) of the surf zone, i.e. non reliable values, whereas the accuracy is some 50 cm in intermediate water (offshore but in depth lower than the closure depth, i.e. the most landward depth seaward of which there is no significant net sediment exchange between the nearshore and the offshore); in the surf zone, the assessment of depth by wave breaking informs on the location of the bars, but the depth assessment is cruder than SDB's; and the depths calculated with wave fields (waves refraction when reaching the shore) are of little interest because offshore. As such, it is the datum-based waterlines or shorelines [EO]-L2_1D_DB/[tide level]-SL_{area/date/hour} [Alg(L2)] which can mitigate the issue as they give contours, but contours which can't be staked to build-up a terrain model if the EOs are too far apart, and certainly not across a storm episode.

The EO-products L2_1D_DB/[tide level]-SL_{area/date/hour} [Alg(L2)] partially fulfill the need of coastal flooding monitoring, in particular near saltmarshes, but we do not provide any altitude of the border between the backshore and the hinterland except in low-lying areas, when coastal flooding is a function of the elevation when flood waters penetrate inland, i.e. it is controlled by the topography of the coastal land exposed to flooding.

In terms of objectives, the URD reminded that the Shoreline Indicators (SI) were meant to fulfill legal requirements in terms of ownership, i.e. separation between the public and private coastal domains, and in terms of coastal risk management references. The choice of the tidal datum for the datum-based shoreline indicators (DSI) [EO]-L2_1D_DB/[tide level]-SL_{area/date/hour} [Alg(L2)] shall be done according to the national and international legal obligations.

4.5.2 ESA requirements

By refering more extensively to SAR than optical EO mission in the ITT, and through the questions of the ESA technical officer at the KO meeting, more emphasis was given to the use of SAR EO missions than optical EO missions. We do not rank them in terms of effectiveness to fulfill the User Requirements, but it should be noted that the effective resolution of SAR images overall (all EO missions included.) is lower than the effective resolution of optical images overall (all EO missions included.) because of speckle and geometric characteristics. In addition, the contrast between the dry/wet shore and the water seems lower, and the observation of reflectance/distances rather than reflectance/ angle triggers issues when high structures (cliffs, buildings, etc.) hide the shore or distort the location of its features. Not to mention that the physics involved is not obvious for surveyors, which define shoreline indicators ‘by eye’, and most of the research of the last decade is about the application of complex optical image processing algorithm to SAR images when the physics is not . However, SAR is an all-weather sensor, this characteristic being critical to complement the job with optical data sets. But there is no algorithm currently to perform SAR and optical data fusion, reason why the [EO] products have been kept separate currently.

4.5.3 Comments by the end-users of the “Coastal Change” partnership

We, the authoriative user’s organization (BGS, GSI, IHC and ARCTUS) have been working closely with the service providers (ARGANS Ltd, IsardSat and adwäisEO) on the URD and this RB document. We are content with how the initial URD submitted with the tender has evolved to URD version 1 and we are pleased to see how the feasibility of our requirements has been seriously considered on this first version of the RB document. As highlighted throughout this document, there are still many details that need clarification and we will continue working with the service providers and the wider end user community on each country to make these clear by the end of phase 1 of this project.

5 Requirements Engineering: Management

The requirements of the End Users (BGS, GSI, IHCantabria and Arctus) has been managed, consolidated and communicated to the industrial partners by the British Geological Survey. ARGANS as prime and on behalf of the industrial partners (including isardSAT and adwaisEO) has led the interaction with the End Users from the development of the proposal, through a number of meetings and discussions, to the refinement and delivery of the URD. The current URD represents the requirements of the End-Users responsible for coastal erosion in their respective countries (UK, Ireland, Spain and Quebec, Canada). Through future engagement with the wider community, each of these End-Users will provide an updated account of the requirements by the end of Phase 1.

As the project has progressed the requirements have been developed, fine-tuned, updated and consolidated as the consortium worked together. The outcome being the URD. Thus far, numerous outreach actions have been conducted by ARGANS and the End Users. These include:

- **"Coastal Erosion project within the Science for Society slice of the 5th Earth Observation Envelope Programme of the European Space Agency: end users' requirements"** presented by Mike Ellis and Andres Payo of BGS at ESA Infrastructure Conference in Frascati, Italy
- **"LPS2019 ESA's Coastal Erosion Project"** presented by Mark Hennen on behalf of the Coastal Change from Space Consortium at the Living Planet Symposium in Milan, Italy
- **"Coastal Change from Space"** presented by Mark Hennen at ENGAGE in Barcelona Spain
- **"Coastal Erosion"** presented by Anne Valette at SIMHYDRO2019 in Sophia Antipolis France
- **"Coastal Erosion User Requirements**" presented by Andres Payo at Coastal Management 2019 conference, in La Rochelle, France at the end of September.

In addition, a meeting in was hosted by IHCantabria in Spain for the Coastal Change from Space Consortium End Users to prepare the URD.

Key to the successful delivery of products and services that fulfil the User Requirements is the establishment of a process, as the products are developed, that ensures a robust feedback loop, facilitates continuous improvement and manages expectations within the constraints and clear advantages of using EO data. In addition, user validation, feedback and acceptance play a vital role to ensure that the industrial partners and the End Users are aligned in their understanding of the products and services required by the market.

During the first part of Phase 1 the URD has been developed by the Coastal Change for Space Consortium. We are now at the stage where the End Users have communicated their requirements, the industrial partners have responded to the URD, identified deliverable products and are developing services. During the remainder of Phase 1 and during Phase 2 engagement will be with two User Groups:

- the project End Users and
- the broader community of Coastal Management stakeholders

Regular meetings and correspondence will take place between the industrial partners and the End Users to:

- validate the products and services
- to supply feedback and suggest improvements
- to refine and enhance the products and services
- to achieve End User Acceptance
- to collect and analyse new requirements
- to assess that they are line with the expectations of the users, add value and are deliverable
- if accepted to deliver the solutions required

In addition, now that the URD has been delivered an increasingly active outreach programme will be put in place for the wider Coastal Management stakeholder community to:

- explain and promote the Products and Services being developed
- to collect their feedback and suggestions
- to submit these to the End Users for assessment
- to agree whether to change or adjust the products and services planned

As customer expectations are lightly to change as development and the project progress it is key that a robust management system is in place with regular customer interactions and trials. This is essential in order to avoid misunderstanding and ensure that the products and services add value for the customers. In order to do so the Coastal Change from Space Consortium will[59]:

- meet and review the status of the development of the products and services monthly
- agree and adjust the products and services according to potential customer needs
- update and communicate adjustments to the community through websites, social media and outreach presentations

[59] via BGS (consolidating the views of the End Users BGS, GSI, IHCantabria and Arctus) take care of the wider costal community requirements

6 Conclusion

This Requirements Baseline Document is a fundamental and definitive component of the projects delivery as it establishes what would be required by the authoritative end users who are the national institutions that deliver the real effects on the ground and then matches these needs in the context of the EO capabilities that exist. In particular, it draws out the significant value that EO can deliver (set against more traditional methods) and optimizes the potential product types with this in mind. In effect this RDB sets the agenda for the remainder of phase but in a way that also enables freedoms to push the boundaries of research and exploitation ready for the project to approach phase 2.

The key findings can be characterized in the following bullets;

- A team of expert and authoritative users (Our partners) were set the task of identifying the problem sets and requirements that they considered need to be addressed.
- These experts were not constrained by the current capabilities that Earth Observation systems currently deliver.
- The URD is attached as an Annex to this document for ease, however as this document is the official “statement” of the Authoritative End User Group, it will be also be forwarded in its own right.
- The analysis process then refined these “pure” academic user requirements to “fit” the current capabilities of EO, heavily focusing of the unique attributes of EO exploiting the significant value that EO provides over traditional and currently adopted expensive and labour-intensive methods.
- This analysis has led to five basic product types and the requirement to additionally design and operate these products within a time series, optimising automated processes and processors.
- The approach to the Technical Specifications, the System Engineering (both service and system architecture, concept of operations and product specification), the Value Engineering and the detailed Technical Specifications of the products will be covered in the following Technical Specification Documentation due at the end of September.

The five product types that have been identified will shape the work moving forward as the project refines their definition and designs automated process to seamlessly deliver them. By adding the additional time series component, the project will demonstrate a unique way to observe coastal change and enable traditional modelled approaches to be better understand and re-evaluated. This level of production is only practical and achievable due to the exceptional properties of the Sentinel satellites under the Copernicus programme due to the considerable effort that is placed on the quality control, validation and verification procedures that have been established. Without these procedures being in place the ability to compare over time would be almost impossible. The ability to "blend" these attributes with the high definition that commercial VHR satellite data provides optimises the "best of both" approach and will enable revolutionary insight and understanding of the coastal change processes to be delivered that would be hitherto unrecognised based on current traditional survey procedures.

7 Appendix

Annex 1 User Requirement Document (URD)

	Name	Company or Institute	Date
Prepared by	Andres Garcia	British Geological Survey	11/09/2019
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Authorised by	Mike Ellis	British Geological Survey	11/09/2019

(published as a separate document)

Annex 2 Third Party Mission (TPM) Data Requirement for Phase 1 Proof of Concept Sites

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