A High resolution, accurate, seamless coastal model of 950+ linear km of the northern coastal of France

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Key words: hydrography, coastal monitoring, geoid model, Airborne LiDAR Bathymetry (ALB), Mean Sea Surface (MSS)

SUMMARY

Fugro, a key player in coastal monitoring geo-solutions enabling resilient coastal communities, infrastructure, and natural capital, is currently undertaking the ALB (Airborne LiDAR Bathymetry) survey of the northern French coastline from the famous Mont-Saint-Michel to the Belgium border. The challenging environmental conditions available within this project area which includes high tidal range (>10m), strong tidal streams, highly variable weather conditions combined with a mostly sedimentary type of seabed is making this area particularly complex to survey with ALB technology.

In this paper, we show case how the Fugro ALB solution eco-system which includes the Fugro satellite analytic tools for pre-planning, the Fugro RAMMS (Rapid Airborne Multibeam Mapping System) for data acquisition and data processing leveraging from machine learning algorithm as well as the Fugro Virgeo® WebGIS platform for client engagement and delivery is enabling the production of an accurate, high resolution coastal morphological model of this area.

This model, combined hydro-dynamic information, enables coastal hazard identification in terms of coastal erosion, submersion and flooding for example, streamline the production of adaptation response strategy and participate to the evaluation of the adaptation strategy outcome.

Finally, to solve for the uncertainty of the geoid model at sea, we show how it is possible to rely on airborne LiDAR data and a combination of tide gauge data, GNSS data and hydrographic modelling data to estimate dynamic sea topography and finally validate the application of the geoid model nearshore ensuring the most accurate connection between the sea level and the land.

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1. UNDERSTANDING THE SURVEY AREA

Over the last decades, coastal areas have seen substantial growth in population and urban expansion putting them at the heart of prosperous economic and societal development all over the globe. However, in today's reality of global warming and climate change, the increasing frequency of extreme weather event and scale of natural disasters, such as floods and storm surges, have led coastal zones to experience severe environmental degradation, asset losses, disruption, and even casualties.

Processes of coastal erosion and sedimentation have always existed all over the world and have contributed throughout history to shape the great diversity of coastal landscapes with which we are familiar today. A combination of several factors, of both natural and human origins, are behind coastal erosion. Winds, coastal currents, sea level rise, freeze-thaw alternations and heavy rainfall are the main components of the natural erosion phenomena. Coastal works, dredging operations as well as the extraction of gas and water constitute the main human causes contributing of erosion.

Part of the survey area is characterized by a rocky massif in the form of Cliffs. With the intensifying erosion phenomena, the hazard of landslides and the risk of falling rock blocks is increasingly important. The changes in the coastline depend greatly on the sediment intake and loss experienced by a hydro-sedimentary cell. Therefore, any changes in sediment circulation or coastal currents could deprive beaches of their sediment budget. Areas with large tidal ranges are particularly vulnerable, due to their exposition to tidal currents, waves, and storm surges.

1.1 What problems do people suffer from?

With the rising intensity of coastal erosion, several coastal hazards are also on the rise such as the loss of valuable land (with economic, ecological, and societal value), and the breakdown of natural defenses leading to submersion, storm surges, and coastal flooding. In France, 20% of the coastline is receding due to coastal erosion causing 30 km² of land to disappear over the last 50 years.

The Xynthia Storm, which hit the French Atlantic coast in spring 2010, has caused fatalities and large-scale flooding damages (+50 000 ha). This disaster has demonstrated the critical need to tracking the coastline evolution, to help improve flood prevention, land use planning, and disaster preparedness, while informing a sustainable and balanced development of coastal urbanisation and economic expansion.

Facing important coastal risks, local and national authorities require reliable and up-to-date scientific data. The acceleration in the occurrence of extreme weather events in coastal areas in recent years has indeed placed public authorities under the obligation to monitor the constantly evolving coastal areas and inform the various coastal stakeholders. Hence, the goal of the project led by the Normandy & Hauts-de-France coastal observation network (ROL) who has contracted Fugro to undertake and deliver an accurate, up to date and homogeneous Digital Terrain Model of the land-sea continuum on the coastline from The bay of Mont St Michel to the Belgian border.

The challenging environmental conditions encountered in the project area, including high tidal ranges (>10 m), strong tidal streams, and highly variable weather conditions combined with a mostly sedimentary seabed type, make this area very complex to survey with ALB technology.

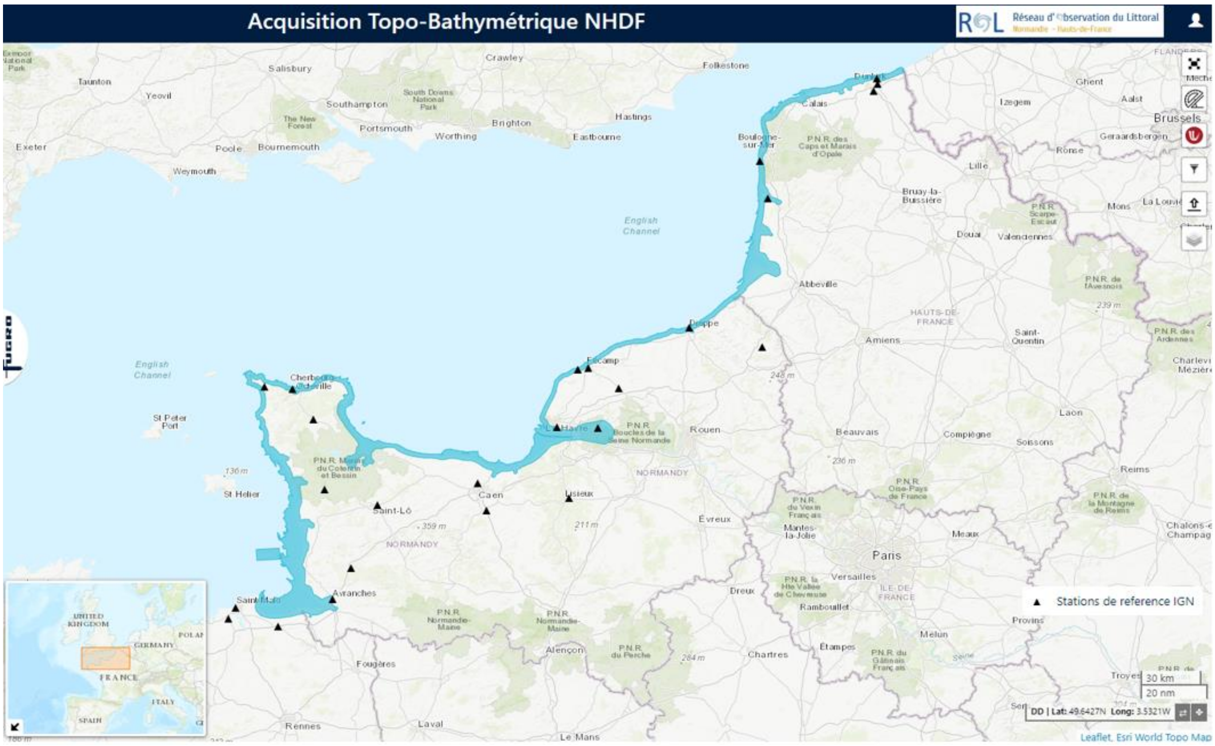

Figure 1: CORS distribution along survey area

1.2 Environmental conditions (morphology and turbidity)

The survey area, located along the English Channel, covers some of the most important estuary ecosystems in France, with UNESCO's world heritage site of the bay of Mont Saint Michel, home of the largest tidal range in Europe (~14 m), and the bay of the Seine where France's second-longest river (777 km) meets the Channel. The area is characterized by a wide variability of seabed morphological components, from sand and soft sediments in the eastern part to rocky units of different morphology outcrops in the west around the Cotentin peninsula.

Some sedimentary structures as shoals and dunes are subject to relatively rapid changes caused by the force of tidal current, wind, and swell. In addition to metocean forcing, the transport of sediment bodies is accentuated with river outflows and heavy shipping traffic in shallow waters.

Using traditional shipborne-based acoustic methods, monitoring morphological changes over the long coastal strip would be quite challenging. Therefore, the use of airborne LiDAR topo-bathymetry is the best-suited solution to map, model and monitor the land-sea interface over a widespread dynamic area, even though the variable clarity of the water column poses a challenge to this light-based measuring technology.

Turbidity is a physical parameter that describes the water column. It is an indicator of water column clarity that could refer to the obstruction of light transmittance through the water due to the presence of solid particles in the water column. Thus, turbidity impacts the performance of the airborne LiDAR bathymetric signal. The higher the value of turbidity, the higher the attenuated or scattered LiDAR light intensity. The mass concentration of the suspended particles is mainly driven by the contribution of organic elements (nutrients, bacteria, etc.) or the resuspension of sediments (silt, clay, etc.) through waves and currents.

River discharges (Seine, Somme, etc.), resulting in several river plumes, and the widespread coastal erosion, account for most of the sediment imports into the water bodies of the project area. A predominant influence of the neap-waters spring-waters cycle with intense tidal mixing, combined with dynamic currents and continuous wave action, is consequently driving the sediments distribution and the turbidity increase in the coastal survey area.

2. SURVEY PREPARATION AND PLANNING

2.1 Informed planning

Fugro apprehended the environmental conditions of the survey area by conducting a metocean desktop study to assess seasonal and extreme metocean conditions that may influence the marine operations, hence optimizing the ALB survey acquisition strategy. The project area was divided into three sub-marine zones, with each presenting coherent characteristic. The metocean study relied on a 10-year period of site-specific measured data of marine conditions including water level, currents, waves, and sea state in addition to atmospheric and weather conditions covering wind characteristics (e.g., wind speed, direction) and precipitations (Figure1).

Tide, with its semi-diurnal regime, is the dominant physical process in the English Channel. Its tidal range varies from 5 m in the west of the survey area to 14 m at medium spring tide in the Bay of Mont-Saint-Michel. The strong tidal currents play a decisive role in the vertical mixing and the transport of water masses in the area, with tidal currents amplitude, reaching 5 m/s, being modulated by a 14-day period spring tide cycle. In addition to tidal currents, surface wind action and fluvial freshwater inflows are the second important processes that alter the tide-induced current structures and lead to residual eddies or current reversals, hence resulting in increased turbidity.

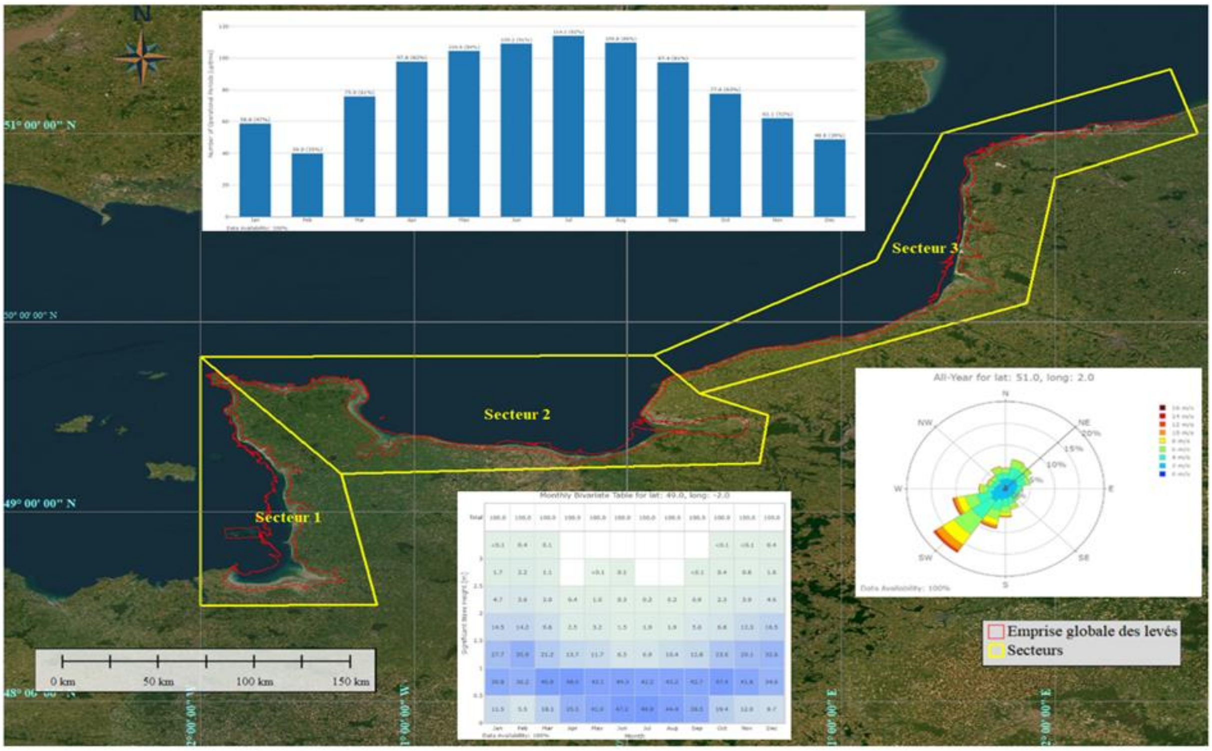

Figure 2: Metocean conditions in survey area

To complement its metocean analysis, Fugro implemented its SatAnalytics desktop solution. This solution, based on satellite analytic capabilities, leverages Fugro’s processing algorithms and expertise in satellite-derived data analysis to enable reconstructing the historical changes of the water column turbidity in the area, hence deriving an effective spatial indicator of water clarity changes over time. This indicator was used in combination with the ALB characteristics of Fugro’s Rapid Airborne Multibeam Mapping System (RAMMS®) to predict the anticipated water depth penetration over the entire survey area. The computed results were analyzed on seasonal and multi-year scales (~20 years), and then consolidated into a spatiotemporal model within Fugro’s web-based GIS platform Virgeo®.

The water depth penetration estimates are essential for informing the planning of the ALB acquisition strategy in all the marine subregions of interest. For instance, penetration prediction provides estimates for the optimum survey acquisition windows and helps to map the anticipated ALB effectiveness depending on sub-area characteristics (tidal range, human activities, natural streams, and water bodies dynamics). Fugro’s water depth penetration estimates, at planning stage, are proven reliable and consistent with the achieved effective survey coverage at the survey acquisition stage (Figure 3).

The correlation of the metocean observation data, recorded between 2012 and 2022, with ALB operational conditions allowed for computing the ALB operability period which provides the optimum survey conditions. For instance, in the West of the survey area around the Cotentin peninsula, the period between May and September appears best for ALB operations to benefit from maximum suitable flight sessions, estimated to 82% of all available ALB survey windows.

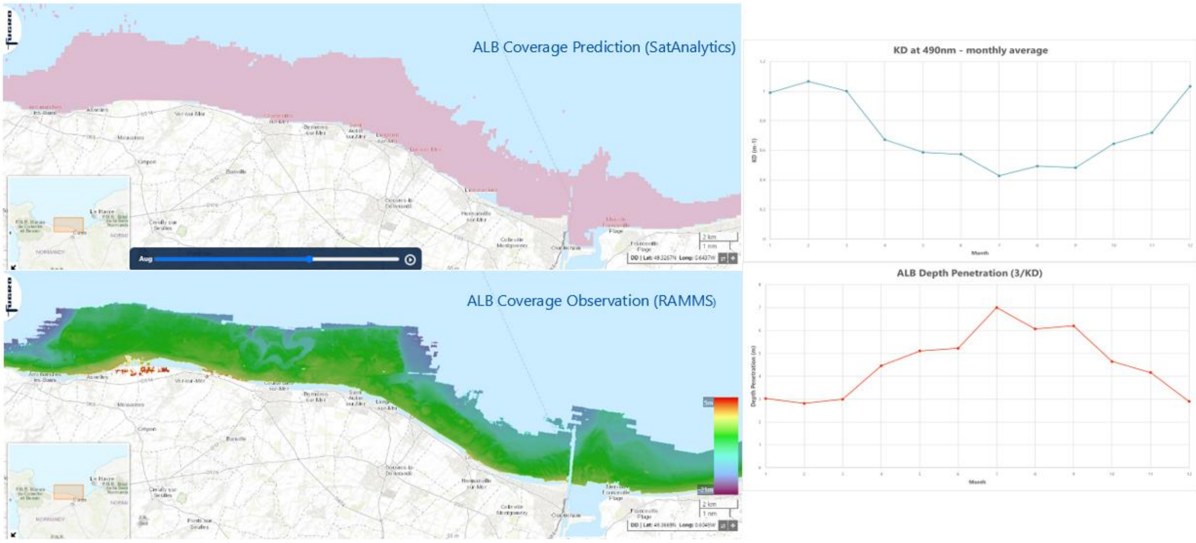

Figure 3: A Virgeo display with SatAnalytics depth estimates and effective ALB coverage

2.2 Fugro's ALB survey technology

The project has seen Fugro adopt a holistic approach that focuses on addressing client needs by selecting the right expertise and cutting-edge technologies in its coastal portfolio solutions (e.g., SatAnalytics, RAMMS®, Virgeo®).

The survey was undertaken utilizing Fugro's proprietary Rapid Airborne Multibeam Mapping System (RAMMS®) technology. This is a best-in-class technology that provides timely and cost-effective capabilities for hydrographic surveying, it achieves a water depth penetration of nominally 3x Secchi depth with a nominal point density of 2.8 point/m^2. The flights were carried at 325 m altitude above sea level with a Pilatus Porter PC-6. To allow for a fully detailed characterisation of the land-sea interface, Fugro partnered with Altoa to allow pairing the Fugro RAMMS with a high-density topographic LiDAR sensor (Riegl VQ-780) and high-resolution cameras (VEXCEL UltraCam Eagle M3 and Phase One).
So far, 49% of the survey acquisition has been performed, and the data is being processed to create project deliverables that include a 3D point cloud and seamless topographic and bathymetric digital elevation models (DEMs) and high-resolution imagery (5 cm).

Figure 4: The RAMMS onboard the survey aircraft

RAMMS data is processed using Fugro proprietary RAMMS Processing Module (RPM). RPM primary function is to generate bathymetric depths and topographic elevations based on algorithms that leverage machine learning to analyze RAMMS imagery and waveforms. The machine learning algorithm acts as an advanced tracking and filtering mechanism that classifies seabed, land, target, and water surface signal returns to produce point clouds in LAS 1.4 format output files.

With its advanced RPM software, Fugro managed to compute preliminary bathymetric LiDAR data within 5 hours from the end of each 6-hour LiDAR survey flight. The bathymetric quality assurance that follows, in the post-processing stage, consists of reviewing the automatic data classifications, and most importantly, ensuring that every accepted depth and elevation meet the survey accuracy requirements of the project. Some mid-water targets are analyzed with surrounding points and aerial high-resolution imagery (10 cm) to determine whether a seabed feature is real or false. In the Normandy survey area, some mid-water targets matched oyster cages or wrecks.

The absolute accuracy of ALB data varies with depth due to the physical properties of light transmission through a water column and quality of the positioning solution mainly. Fugro has used uncertainty models as a basis for the total propagated uncertainty of ALB. This model is constructed from actual measurements made over a smooth and gently sloping seafloor that covers depths at the shoreline to maximum depth detection. The collected RAMMS data is fully compliant with IHO S-44 Order 1 specifications, with the achieved total horizontal uncertainty of $\pm\sqrt{(3.52+(0.05*d)^2)}$ and total vertical uncertainty of $\pm\sqrt{(0.322+(0.013*d)^2)}$.

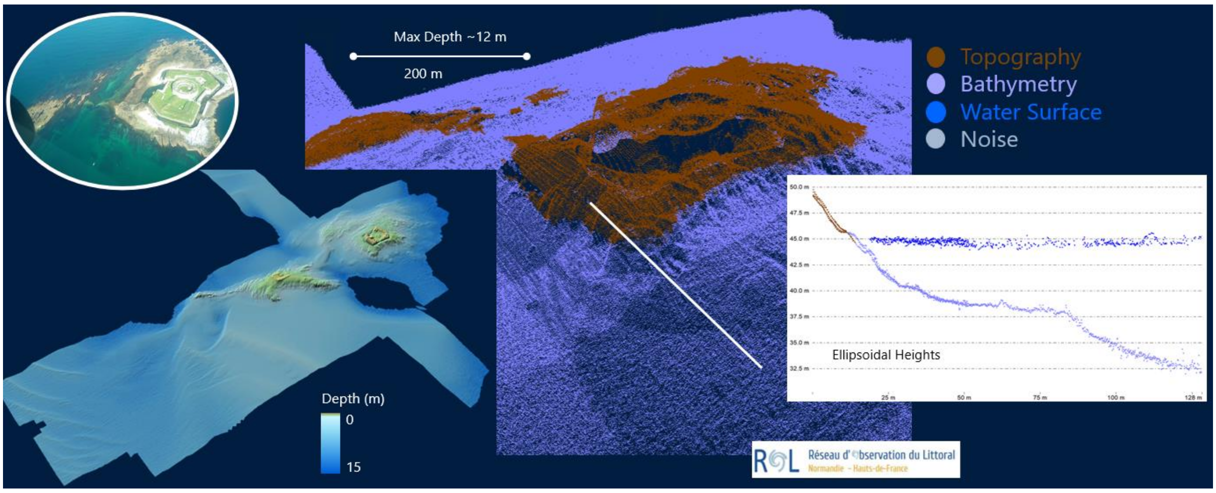

Figure 5: Preliminary survey data

Information sharing about the project execution is key for Fugro stakeholders. So, whether for planning works (e.g., LiDAR survey lines, SatAnalytics depth estimates, airspace restricted zones) or delivering preliminary bathymetric results (e.g., daily bathymetric coverage), all geodata are managed through Virgeo®, Fugro's collaborative cloud-based platform that provides project stakeholders a singular source of project data, maps, and reporting documents integrated with previous site-specific project data.

Through its web custom applications, Virgeo® organizes project data and reporting deliverables into one location accessed via secure web browsers through a unique user login. It integrates interactive web maps and applications, operational dashboards, a document management system, and a data deliverable portal to download key data in one convenient location.

3. GEODETIC REFERENCING AND VALIDATION

3.1 Geodetic referencing

Ensuring that project geodata deliverables will meet the geodetic specifications of a country is the foundation of an effective use of any type of geodata, especially in the coastal areas where the land meets the sea, also considering that each business sector has its own historical approach in reducing depth or elevation into a suitable vertical reference level. Obtaining seamless land sea interface data requires, therefore, bathymetric, and topographic heights to be aligned to the same homogeneous reference level.

For the Normandy and Hauts-de-France survey project, the geodetic requirements consisted of using the geodetic reference frame RGF93v2b, the French realization of the European datum ETRS89, in association with the Lambert conformal conic projection Lambert 93. The French heigh system NGF-IGN1969, defined by a normal height type and a fundamental benchmark next to the historical tide gauge in Marseilles, is set as the project vertical datum. NGF-IGN69 is consistent with French quasi-geoid QGF96 and modelled through RAF20 quasi-geoid separation grid to RGF93v2b reference ellipsoid GRS80.

The LiDAR data georeferencing in RGF93v2b is performed by post-processing flight trajectories using two approaches. The first one relies on raw GNSS observations collected from local CORS, available along the survey area (Figure 1), which allow computing the aircraft horizontal and vertical positions in post-processed kinematic double differencing mode, accurate to a few centimetres. The second approach consisted in computing the aircraft trajectories using precise point positioning mode. This dual approach provides quality control of the aircraft positioning.
Regarding heights, the LiDAR point cloud is first referenced to the ellipsoid GRS1980 then converted to NGF-IGN69 normal heights using RAF20 conversion grid.
For quality control purpose, Fugro has established ground control grids prior to LiDAR acquisition. Control grids are georeferenced in RGF93v2b and NGF-IGN69 to allow checking the effective vertical and horizontal accuracy of the LiDAR point cloud.

In countries lacking reliable geoid or quasi-geoid model, survey practice consists in relying on a Global Geoid Model (GGM) fitted to a balanced network of GNSS/levelling benchmarks, but in many cases, this latter solution fails to deliver accurate vertical referencing.
Much preferable, when no accurate geoid or quasi-geoid model is available, Fugro implements concurrent LiDAR and airborne gravimetry, which enables computing an accurate gravimetric geoid model and finally allows delivering a digital terrain model referenced in both ellipsoidal and orthometric – or normal – heights with high accuracy, so compliant to water-related applications requirements.

In the nearshore-inshore interface, referencing LiDAR GNSS-derived ellipsoidal heights into a reliable common land and sea vertical reference surface may be challenging, and often leads to discrepancies when attempting land and marine data reconciliation.

For this project, it is possible to use the reliable RAF20 quasi-geoid model conversion grid, but this solution raises two questions: (i) what's the accuracy of this model at sea ? and (ii) since the mean sea surface does not coincide with the quasi-geoid (or the geoid) but differs by a metocean component – the Topography of the Sea Surface –, is the quasi-geoid close enough to the mean sea surface throughout the area of interest ?

3.2 Validation of the vertical referencing

Whereas, on land, GNSS/Levelling benchmarks provide a robust way to assess and validate a geoid or quasi-geoid model, there are no such reference control points at sea. However, in the marine domain, ALB can provide a reliable tool to validate the geoid model, providing that hydrodynamic data are available. In that respect, the area of interest is covered by BathyElli hydrographic mean sea surface and a few tide gauges delivering water level observations. In addition, local Mean Sea Level relative to the ellipsoid is known for every tide gauge.

BathyElli project (standing for "bathymetry relative to the ellipsoid"), developed by SHOM (French Naval Hydrographic and Oceanographic Service), includes several products, notably a Hydrographic Mean Sea Surface (HMSS), developed by combining the global MSS derived from satellite radar altimetry, a coastal MSS based on shipborne GNSS profiles (in the ~15 nm nearshore strip), and coastal tide gauge data. Satellite altimetry-based water levels were not corrected for inverse barometer effects to maintain consistency with tide gauge processing. FinallyBathyElli HMSS differs up to 25 cm from the global MSS. Unlike RAF20 whose uncertainty at sea is unknown, BathyElli HMSS can be considered as fairly accurate.
ALB provides not only topo-bathymetric data but also Sea Surface Heights (SSH) (Figure 6).

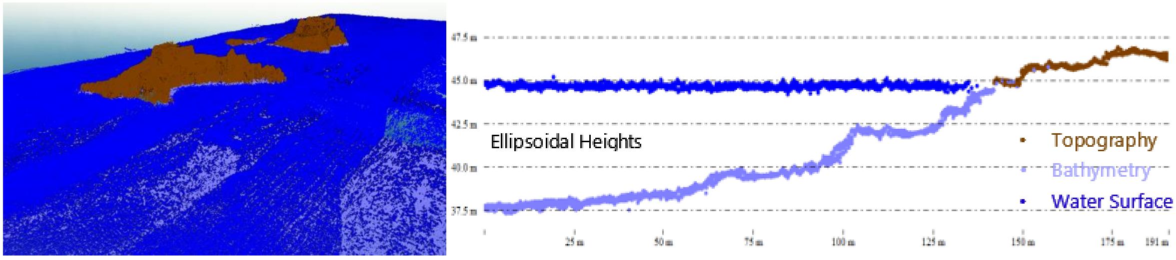

Figure 6: Slice view of sea surface dataset captured with RAMMS

At sea, the geoid model corresponds to the long-wavelength (or low-frequency) component of the ALB-derived SSH (SSH_{ALB}). To determine this component, several sub areas are selected in the vicinity of the existing tide gauges. The selected ALB lines are filtered using a 2D low-pass filter, with the filtering window size and inline overlap being fitted to the geoid model resolution (0.025 x 0.033 deg), the ALB line swath width (respectively in along- and across-track directions) and the aircraft speed, respectively. This filtering yields window-averaged SSH_{ALB} from instantaneous SSH_{ALB}.

To compute ALB-derived geoid undulations (N_{ALB}), the window-averaged SSH_{ALB} are corrected for Dynamic Bias (DB), consisting of the sum of the Topography of the Sea Surface Height (H_{TSS}), the Topography of the Sea Surface Datum Bias (DB_{TSS}), and the filtering window Mean Tide Height, as derived from the nearest tide gauges real time water levels using the concordance method implemented by least squares collocation (LSC) gridding. Each H_{TSS} is derived by subtracting RAF20 quasi-geoid separation from BathyElli HMSS, and each DB_{TSS} is inferred from the discrepancy computed on the related tide gauges between its known MSL and BathyElli-derived MSL.

In the Gulf of St. Malo, the differences between RAF20 geoidal undulations and ALB-derived quasi-geoid undulations reach 3.4 cm (Standard Deviation), which is considered as an acceptable validation of RAF20 quasi-geoid separation model in the marine areas.

3.3 Additional evaluation

Even though RAF20 validation below 5 cm in the Gulf of St Malo can be deemed acceptable, it may be questioned whether a finer validation is possible, including over a larger area.

Especially, BathyElli's HMSS is based on a global MSS that was released about 2 decades ago. Several MSS have been developed since that time, including the recently released CNES CLS 2022 MSS (whose errors are displayed in Figure 7), which can be corrected for mean tide to tide-free MSS for handling with GNSS.

To check its suitability in the area of interest, CNES CLS 2022 MSS differences with respect to in-situ data were computed in a few locations of the Gulf of St Malo. Indeed, in addition to its intrinsic improvements, this MSS was completed with the EIGEN 6C4 geoid model over the continent and over an area not covered by altimetric observations considered as valid, which typically encompass marine areas close to the shore. In that respect, the Gulf of St. Malo is bordered by five tide gauges for which local MSL is known relative to the reference ellipsoid.

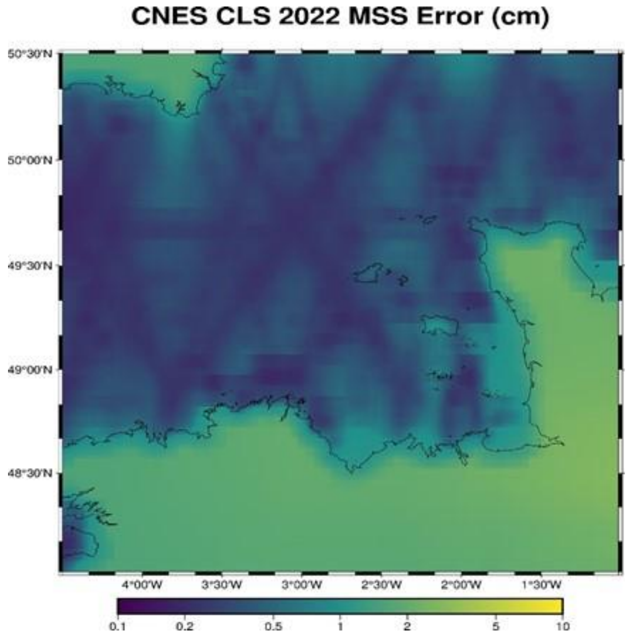

Figure 7: CNES CLS 2022 MSS errors

CNES CLS 2022 MSS is fitted by Adaptative Least Squares Collocation (ALSC) onto the five available tide gauges. Compared to conventional LSC, this modified collocation method, combining the interpolation of deterministic and stochastic fields, is based on the empirical estimation of an anisotropic and inhomogeneous covariance function of the interpolated field, suitable for the Gulf of St. Malo tide gauges whose distribution is not regular (Figure 8).

The raw MSS, once corrected for the tidal datum bias, appears to be quite consistent to three of the five available tide gauges, with raw discrepancies showing a standard deviation of 7.4 cm. Once fitted by ALSC, tide gauge residual discrepancies to the resulting local MSS are reduced to a standard deviation of 3.3 cm.
One may notice that, not surprisingly, the largest adjustments to global MSS induced by adaptative LSC occur around the southeasternmost end of the St. Malo Gulf, where tidal range exceeds 14 m.

As a result, CNES CLS 2022 MSS appears matching quite well in-situ data. Assuming that these good results are also found in other areas, this new MSS could be a good candidate to upgrade BathyElli's HMSS by swapping the previous MSS by this new one in the computation, which would allow refining the computation of the Topography of the Sea Surface in the area of interest and possibly improving the accuracy of RAF20 validation at sea.

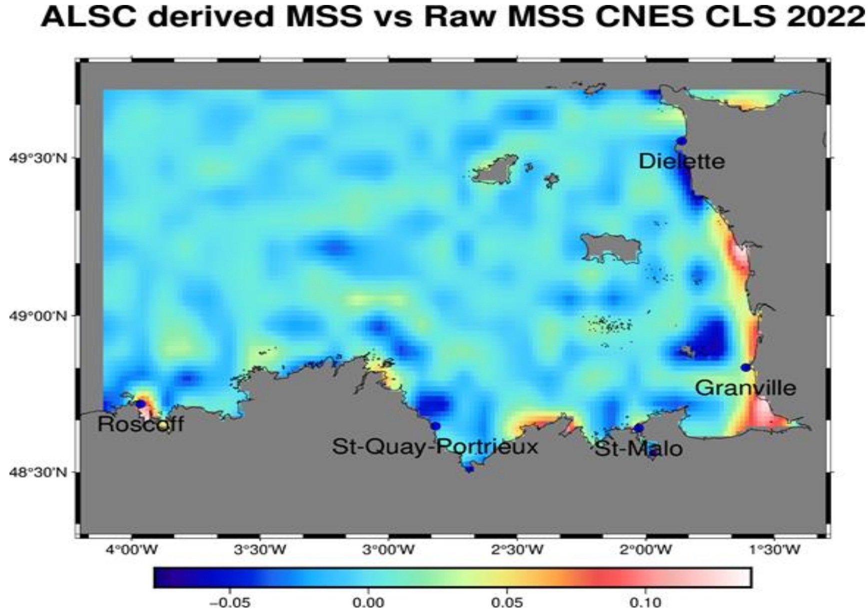

Figure 8: Residuals of Adaptative Least Squares Collocation

4. GEODATA DRIVEN VALUE

With global warming impacts and climate change effects, the difficulty of ensuring both the security of goods and people while preserving natural coastal areas is consistently on the rise. Addressing such difficulty requires informed investments and a sound knowledge of the land and sea interface, especially in regions with variable climate and low adaptation capacities. For instance, in Small Island Developing States (SIDS), where a few centimeters sea level rise would increase the frequency of flooding and drive the intensification of severe and life-threatening environmental degradation. Thus, relying on bathymetric and topographic heights accurately aligned to sea level, lie the foundation for translating sea-level rise projections into potential exposure of population and assets, hence allow for reliable hazard identification and efficient adaption planning.

Unlocking insights from Geo-data across the land and marine environments is, therefore, critical for providing improved knowledge of coastal areas and climate impacts, which is paramount to protect population and assets, including risk assessment, disaster preparedness, and implementation of adaptation and resilience measures.

The communities of the Normandy and Hauts-de-France regions, under the leadership of the Coastal Observation Network (ROL), will utilize Fugro's integrated land to sea digital terrain model to assess the intrinsic characteristics of the coastline which makes it possible to:
– Monitor sedimentary stocks in a coastal area where inflows and outflows of sedimentary materials are observed. Tracking these changes over a relevant period allows building a model of the coastal budget or sediment balance of the observed coastal compartment. The coastal budget is paramount for understanding the mechanisms occurring within each hydro-sedimentary cell, which determine the evolution trend of the shoreline processes of erosion or accumulation.

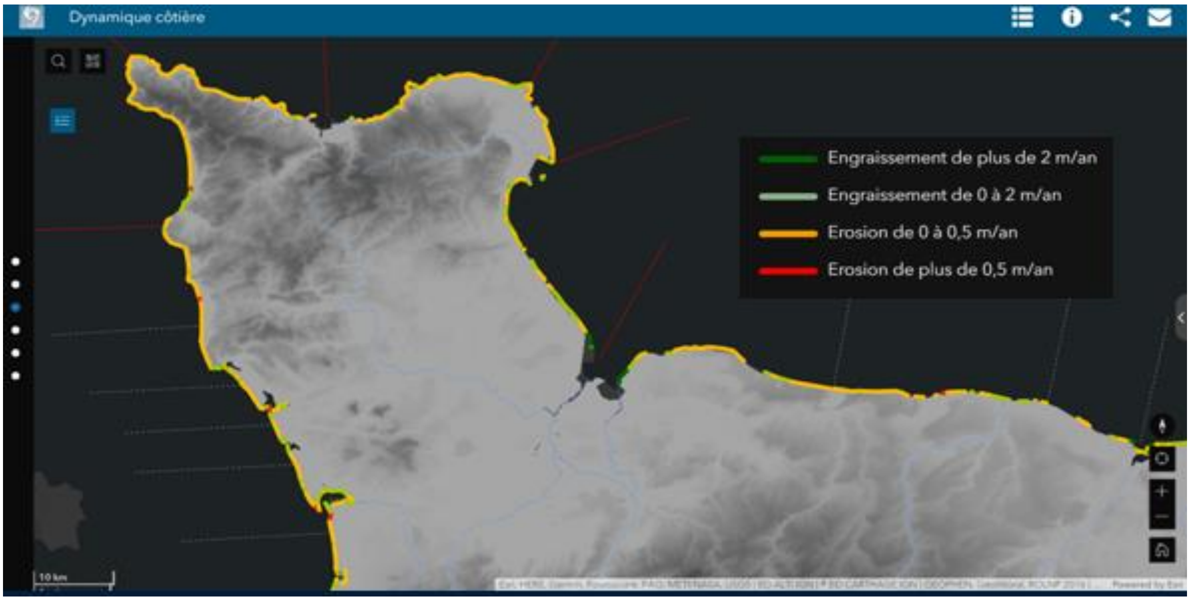

Figure 9: observed erosion and accumulation annual rates, Cotentin Peninsula (source: ROL)

– Update, by ROL, coastal erosion indicator for the coast of Normandy and Hauts-de-France. This erosion indicator, which measures the coastline evolution trend, was developed as part of the France National Strategy for Integrated Coastal Management, to support recommendations for coastal management, development choices, and prioritization of public actions.
– Build up time series to feed models and, ultimately, forecasts and scenario planning of natural disasters for resilient infrastructure and effective emergency response management. This allows communities for instance to anticipate the impacts of sea level rise and floods in their territories, by translating sea-level projections into potential exposure of population and assets. Hence, program and act resilient strategies in flood-prone areas.

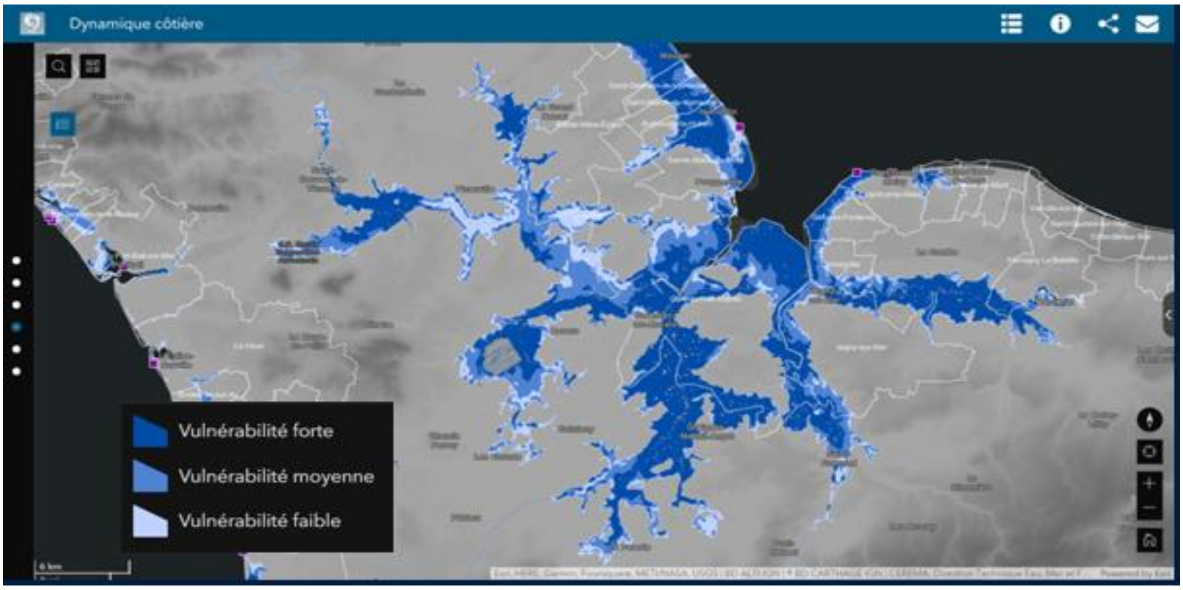

Figure 10: Identification of exposed areas based on different flooding scenarios (source: ROL)

Fugro's geo-data is the backbone of both costal hazard identification and the development of the attractiveness and the resilience of the studied territories.

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BIOGRAPHICAL NOTES

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Benoit Cajelot is Coastal Resilience Manager for the Europe and Africa region at Fugro. He holds a M.Eng in Surveying from INSA Strasbourg, France, and gained advanced knowledge in coastal zone monitoring and nautical charting over almost 20 years in the Europe and Asia-Pacific regions leading large programs and business & organizational development.

Laurent Pronier holds a M.Eng from ENSG, Champs-sur-Marne, France. He has been a commercial director at Fugro Geoid since 2006. Prior to joining Fugro, Laurent held various positions from special works party chief at IGN to Regional Manager at IGN international.

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