The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLIII-B3-2022
XXIV ISPRS Congress (2022 edition), 6–11 June 2022, Nice, France

SATELLITE-BASED LAND/SEA CONTINUUM: AN APPLICATION TO MONITOR THE SAINT LOUIS COAST (SENEGAL, WEST AFRICA)

A. Taveneau[1,*], R. Almar[1], E.W.J. Bergsma[2], B. Sy[3], A. Ndour[4]

[1] Institut de Recherche pour le Développement, LEGOS (IRD/CNRS/CNES/Université de Toulouse), 31400, Toulouse, France - (adelaide.taveneau, rafael.almar)@ird.fr
[2] Earth Observation Lab, Centre National d'Etudes Spatiales (CNES), 31400, Toulouse, France - erwin.bergsma@cnes.fr
[3] Leidi Laboratory, Université Gaston Berger (UGB), 46024, Saint Louis, Senegal - boubou-aldiouma@ugb.edu.sn
[4] Laboratory of Sedimentology, Cheikh Anta Diop University (UCAD), 12500, Dakar, Senegal - abdoulaye17.ndour@ucad.edu.sn

Commission III, WG III/10

KEY WORDS: Remote Sensing, Coastal monitoring, Topography, Bathymetry, Continuum, Tri-Stereogrammetry, Pleiades.

ABSTRACT:

The historical city of Saint Louis in Senegal is situated on the *Langue de Barbarie* sand spit and is particularly prone to erosion: buildings have collapsed and population relocated due to shoreline retreat. At Saint Louis understanding the beach-morphodynamics is essential, and relies on the monitoring of nearshore topography and bathymetry. Remote sensing techniques relying on very high resolution (sub metric) satellites such as the Pleiades constellation and Planet now offer new perspectives in coastal monitoring and engineering. Digital Elevation Models (DEMs) of the emerged part of the beach, topography, and the submerged nearshore bathymetry can be obtained using respectively (tri-)stereogrammetry, and depth inversion through wave kinematics or/and colour based methods. These methods offered promising results (Almeida et al., 2019, Taveneau et al., 2021, Almar et al., 2019a) in previous studies when applied to Pleiades satellite. This work showcases a DEM derived from a 3-images ($dT \simeq 9.5s$) Pleiades acquisition in March 2020 and covering the key topography/bathymetry morphological continuum. Root mean squared errors of about 5 m for bathymetry and 0.9 m for topography are obtained. To limit erosion at Saint Louis urban beaches, the construction of a protection structure has begun in late 2020. Here, satellite DEM is used to monitor the efficiency of the structure and its downstream impact along the sand spit.

1. INTRODUCTION

Sandy beaches represent a non-negligible portion of the world's coastline (31% of the shores) and are ecosystems with a very complex dynamic. Among these coasts, 24% are severely eroding with alarming erosion rates of about -0.5 m/year (Luijendijk et al., 2018). The African continent contains 66% of the sandy coasts, which makes it particularly exposed to marine-associated risks (Pradhan et al., 2015), and human interactions. Combining the effects of the climate-change that will increase the sea level rise and sea hazards, these shores are at high-risks (Temmerman et al., 2013, Sinay and Carter, 2020). Coastal management of such areas must be done through the arrangement of sustainable infrastructures that are part of the complexity of coastline dynamics (Cicin-Sain, 1993). But even before considering the implementation of a shore-protection strategy, it is fundamental to understand the beach morphodynamics. Accessing high-resolution parameters – such as nearshore topography and bathymetry – on a wide area allows the comprehension of the beach's natural behaviour and variability (Gesch et al., 2016).

In this context, remote sensing observations are well-indicated to better adapt the coastal management as they provide and cover regional areas with high-frequency acquisitions (Cazenave et al., 2017, Almeida et al., 2019, Bergsma and Almar, 2020, Turner et al., 2021, Taveneau et al., 2021). So far, state-of-the-art methods for coastal monitoring are limited to local scale and offer a high degree of accuracy (in-situ measurements that are expensive and thus often performed several months apart) or less precise estimates (camera that is affordable and with a high-frequency acquisition (Bergsma et al., 2019b)), or LiDAR (Light Detection And Ranging) acquisitions that cover regional areas with a centimetric-precision but at a high-cost (Kidner et al., 2004). A tool that combines the advantages of each of these methods is the satellite: low-cost (or open-access), covers regional areas, and provides high-resolution (sub-)metric images with a high acquisition frequency. In previous studies that used Pleiades imagery, satellite derived-topography and bathymetry showed promising results with root mean squared errors around 1 m (Almeida et al., 2019, Taveneau et al., 2021) for topography estimated from (tri-)stereogrammetry techniques and of about 2 m (Almar et al., 2019a) for bathymetry estimated with depth inversion through wave kinematics or/and colour based methods (Salameh et al., 2019).

In West Africa, considering changes in the coastal system, anticipating the impacts and thus adapting the protection strategy is key (Alves et al., 2020, Dada et al., 2021). Saint Louis (Senegal) is a site that suffers from severe erosion (Sadio et al., 2017): build on a sand spit named the *Langue de Barbarie*, this city faces large erosion rates of -4.2 m/year (Ndour et al., 2018), buildings are collapsing, and the population is relocated. Its inhabitants, as well as its cultural heritage, are threatened by sea-hazards. In this work, Pleiades derived-topography and bathymetry are merged to analyze a land/sea spatial continuum at a regional scale to better understand the sand spit dynam-

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[1] * corresponding author

https://doi.org/10.5194/isprs-archives-XLIII-B3-2022-1005-2022 | © Author(s) 2022. CC BY 4.0 License.

ics (Anthony and Aagaard, 2020). This study will enable the implementation of sustainable coastal protection in the future. A protective riprap - which construction has begun in December 2020 - is under construction (Figure 6) to insure short-term protection of the urban area (for a few years) while the morphodynamics study is conducted. The use of Pleiades imagery will permit us to see its direct impact on the shoreline position.

2. MATERIALS

2.1 Study site

Saint Louis city is located in Northern Senegal (West Africa, Figure 1.a.b) and built on a sand-spit named the *Langue de Barbarie*. Build between the Senegal River and the Atlantic Ocean (Figure 1.c), this city is a site with one of the most powerful coastal sediment transport world-wild generated by strong oblique waves (coming from the North-West (Sadio et al., 2017, Almar et al., 2019b)) and resulting in a very dynamic wave-dominated sand spit (Taveneau et al., 2021, Bergsma et al., 2020, Sadio et al., 2017, E.J., 2015). The tidal regime is micro-tidal and semi-diurnal: 0.5 m at neap tides and 1.6 m at spring tides (Sadio et al., 2017).

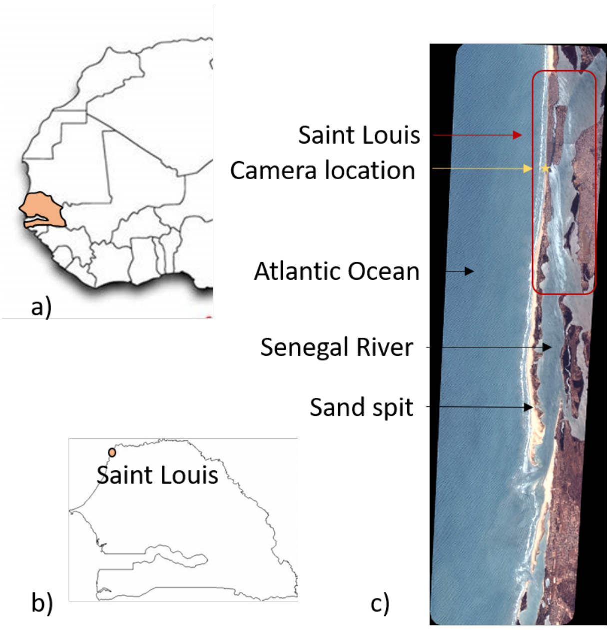

Figure 1. **(a)** Location of Senegal on Africa's map. **(b)** Location of the city of Saint Louis. **(c)** Overview of the *Langue de Barbarie* – from Pleiades imagery (acquisition of 03/2020)

The Senegal River has a very irregular hydrological regime that highly depends on the monsoon rains (Sall, 2006). Regular rises in the level of the river during the monsoon season lead to flooding in the city of Saint Louis. To alleviate the water level in Saint Louis due to a significant flood that occurred in October 2003, an artificial breach was initiated in the sand spit. The length of the sand spit has always largely fluctuated over the last century but as the 2003-breach rapidly became the new river-mouth, it has led to an erosion pattern up-drift ($-3.72 m/year$ (Ndour et al., 2018)) and the sand spit is progressively migrating southwards since then (Bergsma et al., 2020, Taveneau et al., 2021). The spit lengthening and narrowing are part of a stochastic cyclicity hypothesis shown in (Taveneau et al., 2021). According to that study, the cycle of the spit is T=35 years meaning that if the spit continues to stretch southwards, the river mouth will probably close around 2040. To deal with the societal issues generated by the beach erosion, the construction of a protection riprap started in December 2020 to prevent the poorest and most populated area of the *Langue de Barbarie* from destruction. A camera was installed in January 2021 to monitor the coastal evolution of that neighbourhood (Figure 1 ; yellow point). Snapshots extracted from that camera - that are 5 months apart - show the local accretion of the beach (Figure 2).

2.2 Pleiades satellite imagery

The Pleiades constellation (CNES/Airbus) orbits out-of-phase at 694 km and was launched in the early 2010s. It provides on-demand very high-resolution optical imagery (pixel-resolution of 0.5 m and 2 m for panchromatic and multi-spectral imagery respectively) and has the capability of acquiring a burst of up to 12 images during a single overpass. At Saint Louis, there is an every-6 months data-set of at least 3 images that started in March 2019. Here, the study focuses on the acquisition of March 2020. The tri-stereo images were collected at the across-orbit angle -17° with a timelapse in between the images of dT $\simeq$ 9.5 s resulting in a base to height ration of $\frac{B}{H} = 0.12$. This satellite acquisition was made at a tidal elevation of $+0.8$ m (low tide).

3. METHODS

3.1 Topography

To derive a topography (DEM at 2 m-resolution) from the Pleiades imagery sequence, the software AMES Stereo Pipelines (Shean et al., n.d.) (ASP) developed by NASA was used. The topography is estimated through a tri-stereogrammetry approach using the panchromatic images (0.5 m resolution). The resulting topography is post-processed following the procedure elaborated in (Taveneau et al., 2021). The obtained-DEM was vertically corrected using Ground Control Points (GCPs) that were collected in March 2019 with a Real-Time Kinematic-GPS.

3.2 Bathymetry

The bathymetry is derived from Pleiades satellite imagery. From successive images, a set of wave parameters is required to invert the water depth using the linear dispersion relation for free surface waves (Almar et al., 2014, Bergsma et al., 2019a, Bergsma et al., 2021a) are extracted. Satellite images are first ortho-rectified with the AMES Stereo Pipelines software (Shean et al., n.d.) and the Radon Transform is then applied to squared sub-tiles. The sub-tiles size is 300 × 300 m to ensure that at least one wavelength can be detected (Figure 3). The Radon Transform projects a two-dimensional Cartesian image onto the polar space after which undular wave signals can be identified. The wave signal is picked from a forced direction - which was determined from the sinogram (Figure 3 ; right panel *red line*) - and used to estimate a corresponding wavelength by detecting the distance between two intensity-peaks (Figure 3 ; right panel **L**).

Figure 2. Images acquired with the camera (see Figure 1 for location) on the indicated time. A small picture (bottom panel, on the left) shows the on-going construction of the riprap.

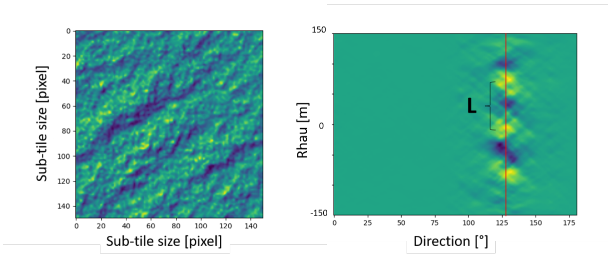

Figure 3. Raw offshore sub-tile from 03/2020 Pleiades imagery (2 m resolution pixel) **(left)** and its associated sinogram calculated with Radon Transform **(right)**. The signal picked to estimate the waves parameters along the forced direction is in red, and the wavelength **L** corresponds to the distance between two intensity peaks.

Once the wavelength of the sub-tile is determined, the celerity is derived from the correlation between two time-successive wave-signals: as the satellite dT is known (9.5 s), one can calculate the distance travelled by the wave between two images. Finally, the linear dispersion equation 1 is applied to the couple (wavelength L, celerity c) to inverse the water-depth point-by-point.

$$c = \frac{L}{T} = \sqrt{\frac{g}{k} tanh(kH)} \qquad (1)$$

where c = the wave celerity
L = the wavelength
T = the wave period
g = the acceleration of gravity (here 9.81 m.s²)
k = the wave number (1/L)

3.3 Land-sea continuum

The topo- bathymetry DEM is computed by merging satellite-derived topo- bathymetry (Figure 4). The continuum DEM is compared to in-situ acquisition collected around the same time as the Pleiades acquisition in 2020 for the topography, and in January 2019 for the bathymetry from DPGS and echo-sounder surveys respectively. The satellite-derived estimates have an output resolution of 2 m for the topography, and 100 m for the bathymetry.

4. RESULTS

The satellite estimates are map-projected on an ortho-rectified raw satellite image (Figure 4) with elevation information added by transparency which is represented by the color bar - ranging from $-20m$ to $0m$ for bathymetry, and -0 to $10m$ for topography. The satellite borders introduce an error for the offshore-estimate of the bathymetry (Figure 4 ; for X UTM $\simeq 3.34 \times 10^5$). The bathymetry trend is well-captured by using the Pleiades satellite imagery: cross-shore, the depth values go from low values ($-15m$) to values that tend to $0m$ near-shore. Also, the topography estimate reveals that the sand spit is a very flat area - values do not $2m$ above sea level when not on the urbanized area.

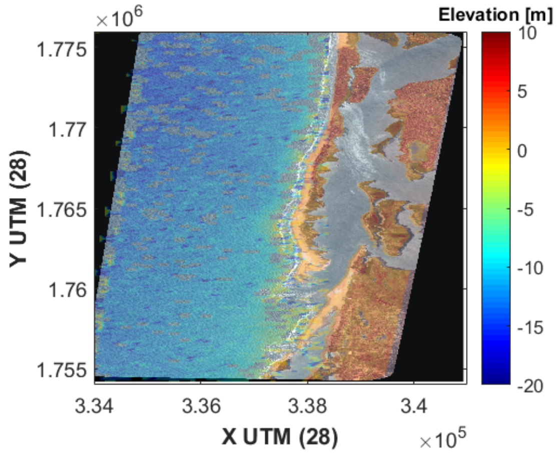

Figure 4. Spatial land/sea continuum derived from Pleiades 03/2020 acquisition, the vertical height (in meter) is represented with the color shades.

To better see the topo-bathymetry trend, an alongshore-median transect (in red) is calculated and compared to in-situ measurements (in black; Figure 5). The derived root-mean-squared errors (RMSE) are sub-metric for the topography, and metric for the bathymetry (Figure 5). The bathymetry is well captured in the deep and intermediate-water, but the intertidal zone is largely underestimated.

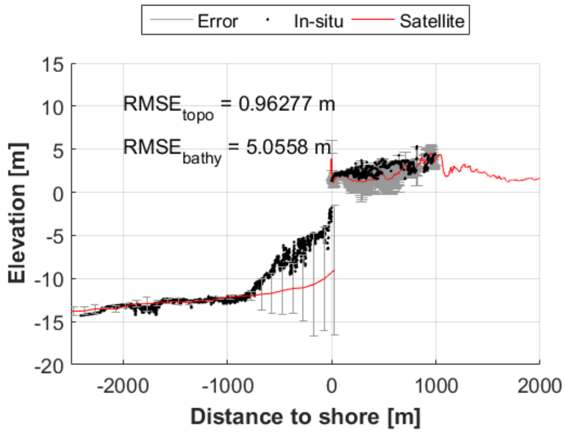

Figure 5. Comparison of in situ (black) and satellite-derived data (red) on a longshore median transect. The alongshore error between in-situ measurements and satellite estimate is represented as error bars (gray)

Regarding the emerged part (Figure 5), the topography trend is correctly estimated through Pleiades imagery. But it appears that the stereogrammetry technique underperforms at the land/sea interface where a local error in the estimate can be observed at position 0 m (Figure 5).

5. DISCUSSION

The high-resolution satellite imagery approach offers numerous advantages (profusion of data over a long period, wide observable scale, easy access to data in developing countries) and enables a regional understanding of coastal morphodynamics for low-costs (Benveniste et al., 2019, Melet et al., 2020). With only one acquisition, it is possible to estimate several parameters such as topography and bathymetry that are presented in that study, but also quantify spatial and temporal volumetric beach evolution (Taveneau et al., 2021). But the errors range found in Section 4 are too important - especially for the bathymetry - to only rely on these tools for coastal engineering. State-of-the-art methods are not to be replaced yet.

Morphological changes in shallow waters are the most interesting area to understand for implementing a protective structure, and the depth of the submerged nearshore area is largely underestimated. The ongoing work is focused on how to improve the results of inter-tidal bathymetry. Two ideas are investigated. Firstly, the wave direction changes when approaching the shore so that they arrive parallel to the coast. Not forcing the wave direction in the nearshore area could improve the bathymetry estimate. Second, working on a smaller sub-tile (less than 300 m) could also improve the estimate of the wavelength, and thus the estimate of celerity and depth. The ultimate goal would be to reach a sufficiently fine precision allowing the detection of the submerged sand bar. Knowing its dynamics would enable the quantification of the sand volume exchanged between the lower-beach and the inter-tidal area, which is crucial to fully understand the *Langue de Barbarie* morphodynamics.

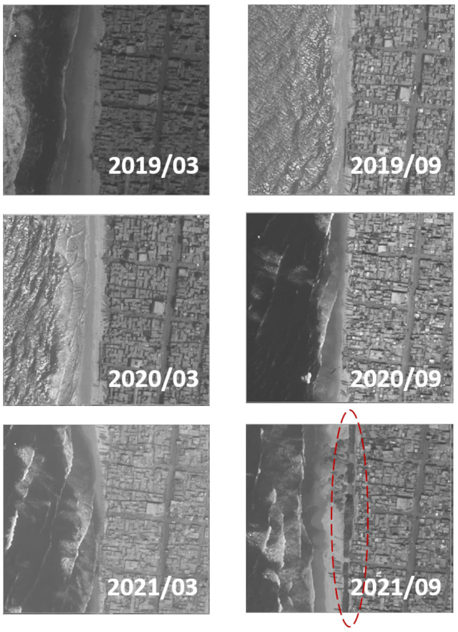

Figure 6. Ortho-rectified panchromatic images from Pleiades constellation to keep track of the construction of the protection structure (in red).

In the coming years, the every-6 months Pleiades acquisition will allow the monitoring of the protection riprap and the beach response to its implementation – its construction started in late 2020 (circled in red Figure 6). Doing a continuum analysis for each data-set will help to understand the spatio-temporal morphological changes of the sand spit at a regional scale.

6. CONCLUSION

The offshore bathymetry does not evolve much as its changes are independent of the wave conditions: the comparison of the two data-sets (that are one year apart) is relevant and is well-captured by the satellite depth-inversion method - which gives confidence in the method. However, the bathymetry in intermediate and shallow water constantly evolves and highly relies on the waves climate through the linear dispersion relation (Equation 1). Though, the satellite completely misses the inter-tidal trend - which is a challenging area for remote sensing methods (Almar et al., 2022, Bergsma et al., 2021b) and where shoreline approaches such as (Vos et al., 2019) are preferable. However, these results will improve in time with the launch of new satellites with even higher resolution than imagery from the Pleiades constellation such as Pleiades Neo (CNES).

The same observation can be done for tri-stereo derived topography: the lower-beach area is the most arduous to estimate (Section 4). As the tri-stereogrammetry method (with 3 images) used to estimate the elevation relies on the correlation in between the satellite images, it encounters difficulty when estimating a flat area so the estimation of the land/sea interface introduces errors in the lower-beach elevation calculation.

ACKNOWLEDGEMENTS

The authors would like to thank the SHOM for the topographic in-situ measurements, the UCAD, and UGB for their time and help in Senegal, and the CNES for the Pleiades imagery.

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