Coastal Engineering 167 (2021) 103919

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Short communication

Satellite optical imagery in Coastal Engineering

Ian L. Turner [a,*], Mitchell D. Harley [a], Rafael Almar [b], Erwin W.J. Bergsma [c]

[a] Water Research Laboratory, School of Civil & Environmental Engineering, UNSW Sydney, NSW, 2052, Australia
[b] IRD-LEGOS, 14 Avenue Edouard Belin, 31400, Toulouse, France
[c] Earth Observation Laboratory, French Space Agency (CNES – Centre National d'Études Spatiales), 18 Avenue Edouard Belin, 31400, Toulouse, France

ARTICLE INFO

Keywords:
Remote sensing
Satellite optical imagery
Satellite-derived shorelines (SDS)
Satellite-derived bathymetry (SDB)
Stereoscopy
Earth observation
Google earth engine

ABSTRACT

This Short Communication provides a Coastal Engineering perspective on present and emerging capabilities of satellite optical imagery, including real-world applications that can now be realistically implemented from the desktop. Significantly, at the vast majority of locations worldwide, satellite remote sensing is currently the only source of information to complement much more limited in-situ instrumentation for land and sea mapping, monitoring and measurement. Less well recognised is that publicly available, routinely sampled and now easily accessible optical imagery covering virtually every position along the world's coastlines already spans multiple decades. In the past five years the common obstacles of (1) limited access to high-performance computing and (2) specialist remote sensing technical expertise, have been largely removed. The emergence of several internet-accessible application programming interfaces (APIs) now enable applied users to access petabytes of satellite imagery along with the necessary tools and processing power to extract, manipulate and analyse information of practical interest. Following a brief overview and timeline of civilian Earth observations from space, satellite-derived shorelines (SDS) and satellite-derived bathymetry (SDB) are used to introduce and demonstrate some of the present real-world capabilities of satellite optical imagery most relevant to coastal professionals and researchers. These practical examples illustrate the use of satellite imagery to monitor and quantify both engineered and storm-induced coastline changes, as well as the emerging potential to obtain seamless topo/bathy surveys along coastal regions. Significantly, timescales of satellite-derived changes at the coast can range from decades to days, with spatial scales of interest extending from individual project sites up to unprecedented regional and global studies. While we foresee the uptake and routine use of satellite-derived information becoming quickly ubiquitous within the Coastal Engineering profession, on-ground observations are – and in our view will remain - fundamentally important. Compared to precision in-situ instrumentation, present intrinsic limitations of satellites are their relatively low rates of revisit and decimetre spatial accuracy. New satellite advances including 'video from space' and the potential to combine Earth observation with numerical and data-driven coastal models through assimilation and artificial intelligence are advances that we foresee will have future major impact in Coastal Engineering.

1. Overview and scope

Civilian and commercial satellites with Earth Observation capabilities are increasingly delivering new insights and real-world solutions to many professions. Our own discipline of Coastal Engineering is no exception. Significantly, the satellite era has now achieved a stage of maturity where previous discipline and technical barriers to the everyday use of satellite-derived information are rapidly disappearing (Benveniste et al., 2019; Melet et al., 2020). It is now realistic for coastal practitioners with access to a desktop PC or laptop to regard satellites as a routine component of their everyday toolkit.

At its core, satellite remote sensing can provide information to complement in-situ instrumentation for land and sea mapping, monitoring and measurement; and at the vast majority of global locations - including at the coast - it is currently the only source. Less well recognised in Coastal Engineering, but especially relevant to our field, is that publicly available, routinely sampled and now easily accessible satellite optical imagery covering virtually every position across the Earth's surface already spans multiple decades (Belward and Skoien, 2015). This contrasts markedly to the very limited availability of long-term

---

* Corresponding author.
E-mail address: ian.turner@unsw.edu.au (I.L. Turner).

https://doi.org/10.1016/j.coastaleng.2021.103919
Received 4 March 2021; Received in revised form 28 April 2021; Accepted 8 May 2021

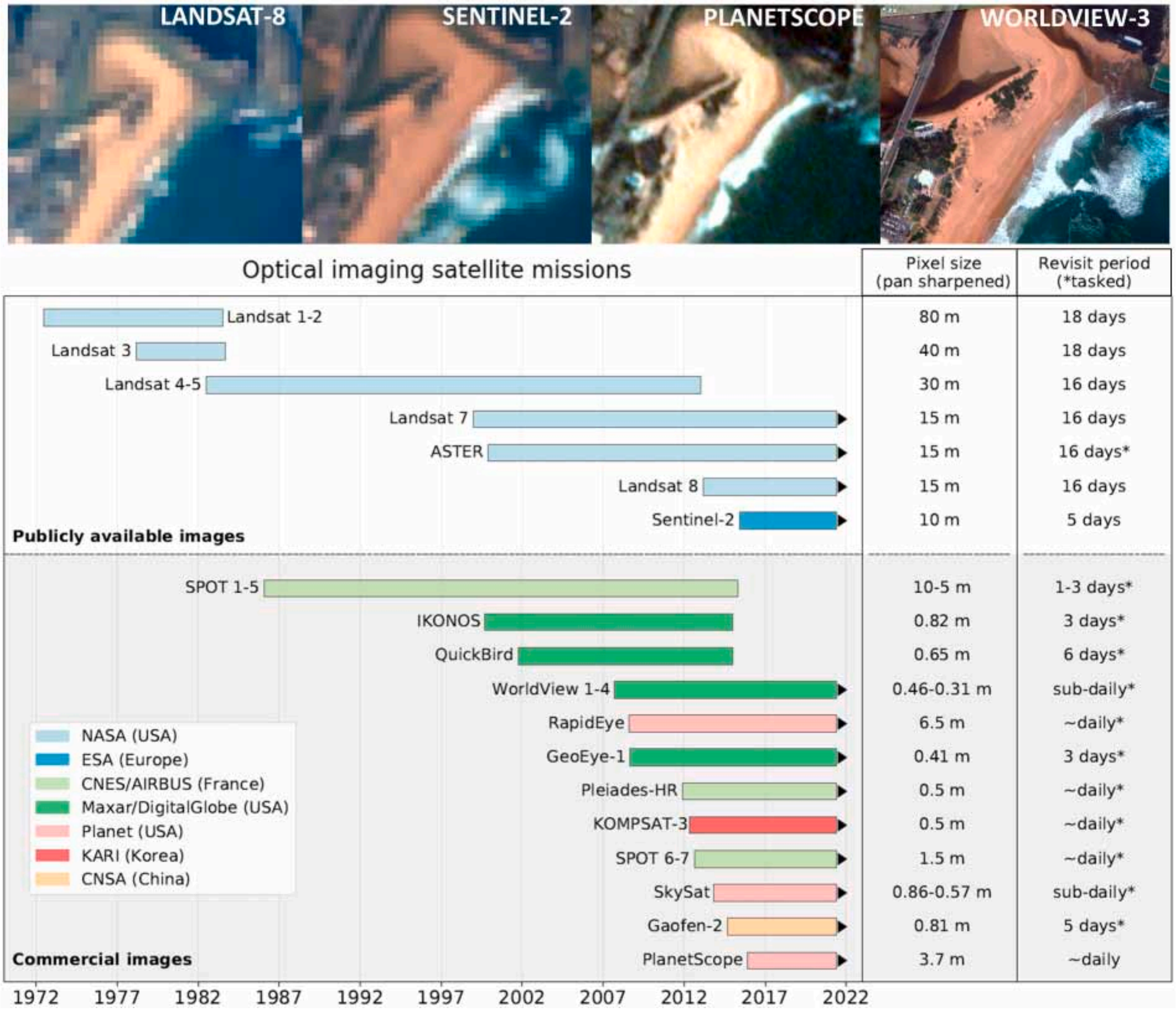

Fig. 1. The civilian era of optical earth-imaging satellites commenced in July 1972 with the launch of Landsat 1. From the partial list of satellites illustrated here (adapted from Vos et al., 2019a) it can be seen that the ensuing 40 years has seen the expansion and more recent very rapid acceleration in the growth of optical sensor satellite programs worldwide, accompanied by increasing image resolutions and decreasing time intervals between satellite revisits to the same position on the earth's surface. Note that image resolutions obtained from multi-spectral satellite sensors that capture a broad range of colour bands can be enhanced by combining with higher resolution panchromatic (single-band greyscale) imagery using a method called 'pan sharpening'. The resulting single colour image can have an image resolution several times greater than the original colour pixel size. Also note that the satellite revisit periods shown here are indicative, as these can vary with latitude. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in-situ coastline datasets worldwide (e.g., Turner et al., 2016; Ludka et al., 2019; Castelle et al., 2020).

High-performance computing resources and specialist remote sensing technical expertise are two of the primary barriers that, until now, have generally prevented the wider uptake of present and historical satellite optical imagery applied to real-world Coastal Engineering projects and applications. But in the past five years these obstacles have been largely removed, with the emergence of several internet-accessible application programming interfaces (APIs) that have transformed the applied remote sensing landscape. These cloud-based platforms now deliver to us non-experts the ability to access petabytes of data along with the necessary tools and processing power to extract, manipulate and analyse information of interest. At the time of writing, notable APIs include Google Earth Engine (Gorelick et al., 2017) that integrates a large repository of publicly available satellite optical imagery with supercomputer computation services at no-cost to most users; the free EO Browser tool by Sentinel Hub (www.sentinel-hub.com) that provides a very accessible interface to locate and download full resolution and customisable visualizations of a range of satellite imagery; and Planet Labs Inc. (www.planet.com) that is one of the current leaders in the more recent emergence of pay-for-use commercial providers who maintain their own and very rapidly growing constellations of earth imaging CubeSats.

Drawing from the authors' own experiences in Australia and Europe, the goal of this Short Communication is to provide coastal practitioners and researchers less familiar with satellite optical imaging capabilities a Coastal Engineering perspective and primer to real-world applications that can be realistically implemented from the desktop. Following a brief overview of the evolution of Earth optical imaging from space, practical illustrations focus on the implementation of shoreline detection and bathymetry estimation, representing two of the more robust and accessible Coastal Engineering applications that are presently available. We then introduce and illustrate recent developments that we foresee will soon further expand satellite optical imaging capabilities at the coast, including spatial and temporal resolutions that may begin to rivel some on-ground measurements, and the rapid progress towards 'video from space' that will open up new possibilities to examine underlying physical processes in the coastal zone. We do however conclude with a cautionary reality-check: although we foreshadow here that the routine use of satellite-derived information will quickly become ubiquitous

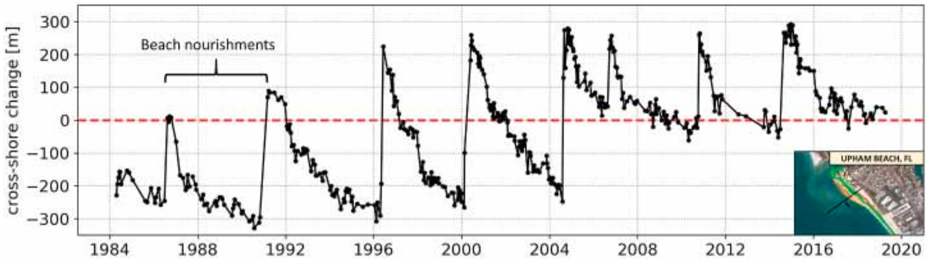

Fig. 2. Illustration of satellite-derived shorelines (SDS) to monitor and measure 35 years of engineered coastal changes at Upham Beach located on the west coast of Florida USA, the site of multiple beach nourishments.

within our profession, in-situ observations are - and will remain - fundamentally important. It is our perspective that satellites should not be perceived as a replacement to targeted on-ground measurement and monitoring at the coast, but instead can now be regarded as a valuable and practical adjunct to the everyday work of the practicing and research Coastal Engineer.

2. A brief timeline of civilian optical imaging satellites

For several decades now a growing list of fixed and airborne remote sensing tools and capabilities including cameras, video, Lidar, radar and UAV have been successfully deployed to compliment and extend in-situ monitoring and measurements in the field of Coastal Engineering, with a particular focus on sandy beaches (Splinter et al., 2018). The use of satellite altimetry (a precise measure of the time taken for a radar pulse to travel from a satellite to the sea surface and back) is very well established as the standard remote sensing tool to quantify changing global trends in ocean water levels (Nerem et al., 2018) and wave heights (Young et al., 2011). Importantly, the assimilation of atmospheric and ocean surface satellite measurements within global climate models now underpins a range of applications and products including the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 global reanalysis (Hersbach et al., 2020), delivering continuous timeseries of parameters that are of great interest to Coastal Engineers, including ocean temperature, water levels, waves and surface currents. Synthetic Aperture Radar (SAR) that exploits the motion of the satellite platform to increase radar resolution and map a three-dimensional surface irrespective of day/night or cloud-cover shows great potential for a range of applications in the coastal zone (Ottinger and Kuenzer, 2020). And in certain niche areas such as dredge plume monitoring, satellite optical imagery has already been used for a number of years (e.g., Islam et al., 2007) to observe engineering activities in the coastal zone, with a recent review identifying that there are presently of the order of 70 optical satellite ‘water quality’ algorithms that can be applied to this particular application (Fearns et al., 2017). But to the great majority of Coastal Engineers and Coastal Scientists, it is only in the past handful of years that the routine use of satellite optical imagery within our own work has emerged as a tangible possibility.

The civilian era of optical Earth-imaging satellites dates back to July 1972 when the joint NASA/USGS Landsat program was launched. For an excellent compendium of civilian Earth observation satellites in the ensuing 40 years the interested Reader is referred to Belward and Skoien (2015). Fig. 1 summarizes some of the more significant developments in the expansion and more recent very rapid acceleration in the growth of optical sensor satellite programs worldwide, accompanied by increasing image resolutions and decreasing time intervals between satellite revisits to the same position on the Earth’s surface. From an initial spatial resolution of 80 m and a revisit period of 18 days for the first Landsat missions (Landsat 1–2, 1972–1983), image resolution increased stepwise to 15 m with the launches of Landsat 7–8 (1999 – present, minimum revisit period = 8 days), and then 10 m resolution (minimum revisit period 5 days, Bergsma and Almar, 2020) with the launch of the European Space Agency’s Sentinel-2 in 2015. Notably, the number of commercial optical imaging satellite companies has grown substantially in the past decade, each with their own business model but generally based on the delivery of image-derived data products that are tailored to customer-defined needs.

Illustrated in Fig. 1 is the practical result of numerous technological improvements that have resulted in a two orders of magnitude increase in optical satellite image resolution during the past 4 decades. For illustration, contrasted are free and publicly-available Landsat 8 (15 m) and Sentinel-2 (10 m) imagery obtained at the very well-studied Narrabeen Beach located on Australia’s southeast coast. Alongside these are example images obtained by the PlanetScope constellation of commercial ‘Dove’ CubeSats (in 2021 consisting of 180+ individual satellites) that capture near daily with a resampled 3 m pixel resolution; and 31 cm resolution images obtained sub-daily by the WorldView-3 Earth observation satellite. As we will touch on later in the concluding ‘Future Directions’ section, this trend towards ever-increasing image resolutions accompanied by decreasing revisit periods will open up a new range of opportunities that the Coastal Engineering profession will no doubt exploit in the coming few years. But as has already been highlighted, there are already two substantive factors that now make it both attractive and realistic for coastal practitioners to regard satellite-derived information and analyses as an increasingly routine part of their everyday work practice. The first of these is the public availability of routinely sampled satellite optical imagery covering virtually every position across the Earth’s surface of a suitable on-ground resolution that now extends back almost 4 decades. And the second factor is the recent transformation of the applied remote sensing landscape such that, with no more than an internet connection, it is now very achievable for non-experts to easily access petabytes of imagery and the necessary tools and processing power to extract, manipulate and analyse satellite-derived information at the coast. The next section illustrates these capabilities applied to shorelines analyses and coastal bathymetry.

3. Practical applications – shorelines & coastal bathymetry

The practical use of satellite optical imagery to obtain and analyse shorelines along sandy coastlines builds upon several decades of well-established research and practice that has traditionally used fixed cameras and video for automated and routine image collection (e.g., Holman and Stanley, 2007). As shorelines provide a fundamental measure of coastline variability and change and the optical signature of this land-water feature is relatively distinct (Boak and Turner, 2005), there is a growing body of work that now reports the use of satellite-derived shorelines (SDS) applied to a range of shoreline mapping and monitoring applications around the world (e.g., Almonacid-Caballer et al., 2016; Xu, 2018; Hagenaars et al., 2018; Chu et al., 2020; Sánchez-García et al., 2020; Castelle et al., 2021). In parallel to this, the interpretation of colour image reflectance bands corresponding to varying water depths in the coastal zone has also seen the emergence of a range of tools and techniques that can now be applied to estimate shallow water bathymetry (Salameh et al., 2019). Extending from the pioneering work of

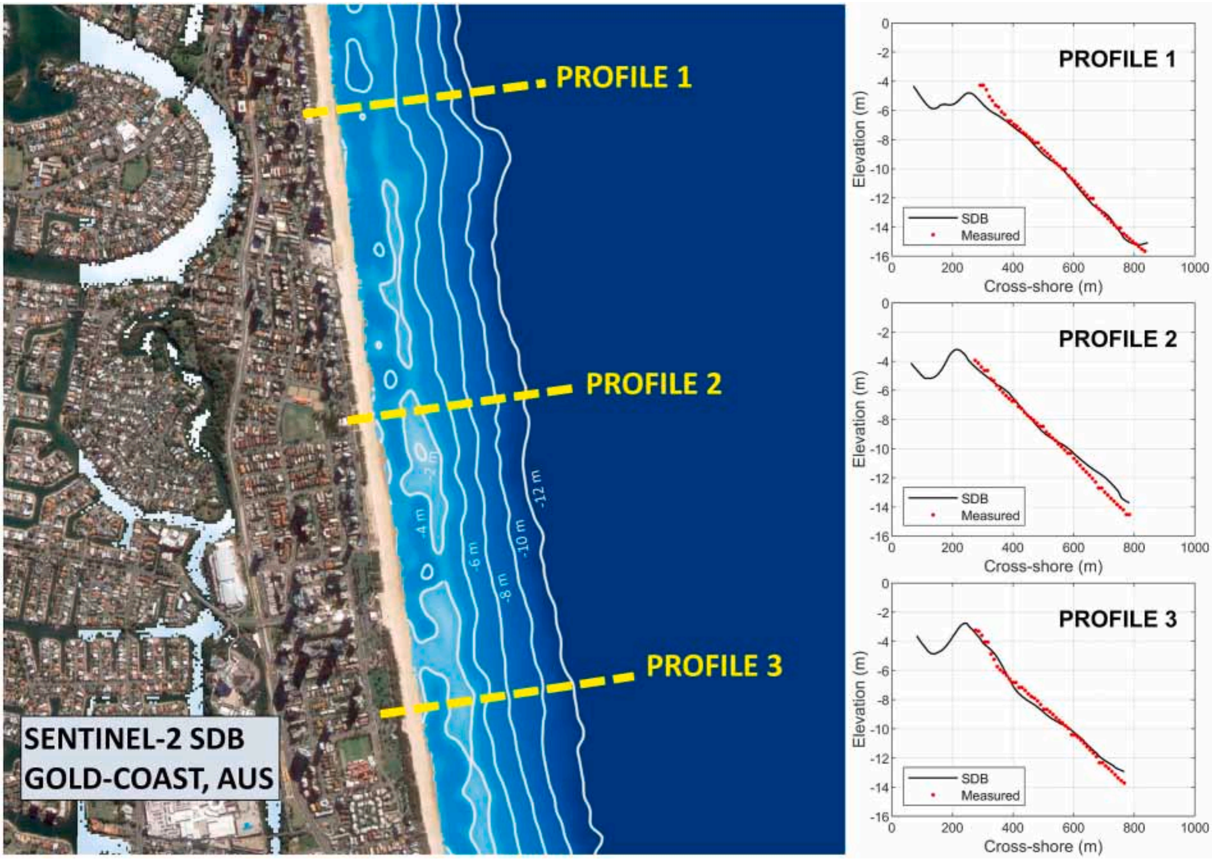

Fig. 3. Illustration of satellite-derived bathymetry (SDB) applied along approximately 4 km of the highly engineered Gold Coast, located in eastern Australia. For the three representative cross-shore profiles 1–3 where surveyed and SDB cross-sections are compared, vertical RMSE are 0.44 m, 0.53 m and 0.39 m, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Lysenga (1978), modern algorithms to calculate satellite-derived bathymetry (SDB) are broadly classified as either empirical models (e.g., Stumpf et al., 2003) or physics-based models (e.g., Lee et al., 1999). Key differences are that empirical regression methods still require in-situ survey data for colour-depth calibration, whereas physics-based approaches require sophisticated atmospheric and subsurface correction. The practical use of SDB in Coastal Engineering is beginning to emerge in the literature; for example, Misra and Ramakrishnan's (2020) recent use of Landsat 8 imagery to assess the impact of a beach restoration project along the coast of Puducherry in India.

A real-world illustration of satellite-derived shorelines (SDS) to monitor and measure engineered coastal changes is shown in Fig. 2. This depicts 35 years of beach width variability at Upham Beach located on the west coast of Florida USA, the site of multiple beach nourishments (refer Elko and Wang, 2007). To obtain this SDS time-series the open-source CoastSat toolkit (Vos et al., 2019a; Vos et al., 2019b) was used to repeatedly map the position of the shoreline at a frequency corresponding to the availability of Landsat 4–8 (1982-present) and Sentinel-2 (2015-present) imagery. Briefly, the automated workflow to create this shoreline timeseries includes 4 steps: (1) image retrieval from Google Earth Engine, (2) pre-processing that includes cloud masking and panchromatic image sharpening, (3) automated shoreline detection that combines an image classification and sub-pixel edge detection methodology to maximise accuracy, and (4) post-processing. This final step applies an individual tidal correction to every image and facilitates the automated generation of shoreline change time-series at any cross-shore transect(s) within the region of interest. The results shown in Fig. 2 are indicative of what can be realistically achieved along virtually any sandy coastline worldwide; i.e., a multi-decade record of shoreline variability, trends and change with a cross-shore accuracy of ~10 m (Vos et al., 2019a), obtained retrospectively using freely available satellite imagery. Notably, there are now several SDS timeseries and change-rate datasets that are publicly available to view and/or download, as well as open-source tools to automate the SDS mapping process. These include the Global Shoreline Database of multi-decadal shoreline trends (http://shorelinemonitor.deltares.nl/, Luijendijk et al., 2018); the web-based tool CASSIE to extract shoreline data at any coastal location worldwide (http://cassiengine.com/, Almeida et al., 2021); a growing database of high-frequency SDS shorelines and corresponding beach slopes obtained using CoastSat (http://coastsat.wrl.unsw.edu.au/, Vos et al., 2019b; 2020) and a national database and accompanying analyses tools of long-term shoreline trends and intertidal extent for the entire Australian coastline (https://maps.dea.ga.gov.au/, Bishop-Taylor et al., 2019a; 2019b).

A second practical illustration of the use of freely-available satellite optical imagery, in this example for the purpose of estimating surfzone and nearshore bathymetry along the highly engineered Gold Coast located in eastern Australia, is shown in Fig. 3. Again, imagery was sourced through Google Earth Engine and the workflow as described in Traganos et al. (2018) applied. A near concurrent multi-beam bathymetric survey that spanned a smaller subregion of the coastline, and with much more limited coverage landward of the breakpoint, was used for initial colour-depth calibration. The resulting bathymetry estimate spanning water depths from around −2 m to −12 m along this 4 km of partially surveyed coastline reveals a complex crescentic/bar-rip nearshore morphology that is characteristic of the Gold Coast region (van Enchevort et al., 2004). At this particular project site the core SDB algorithm that was applied (Stumph et al., 2003) successfully extends the empirically-based estimation of bathymetry to water depths of around −12 m, before significant divergence (depth underestimation at this

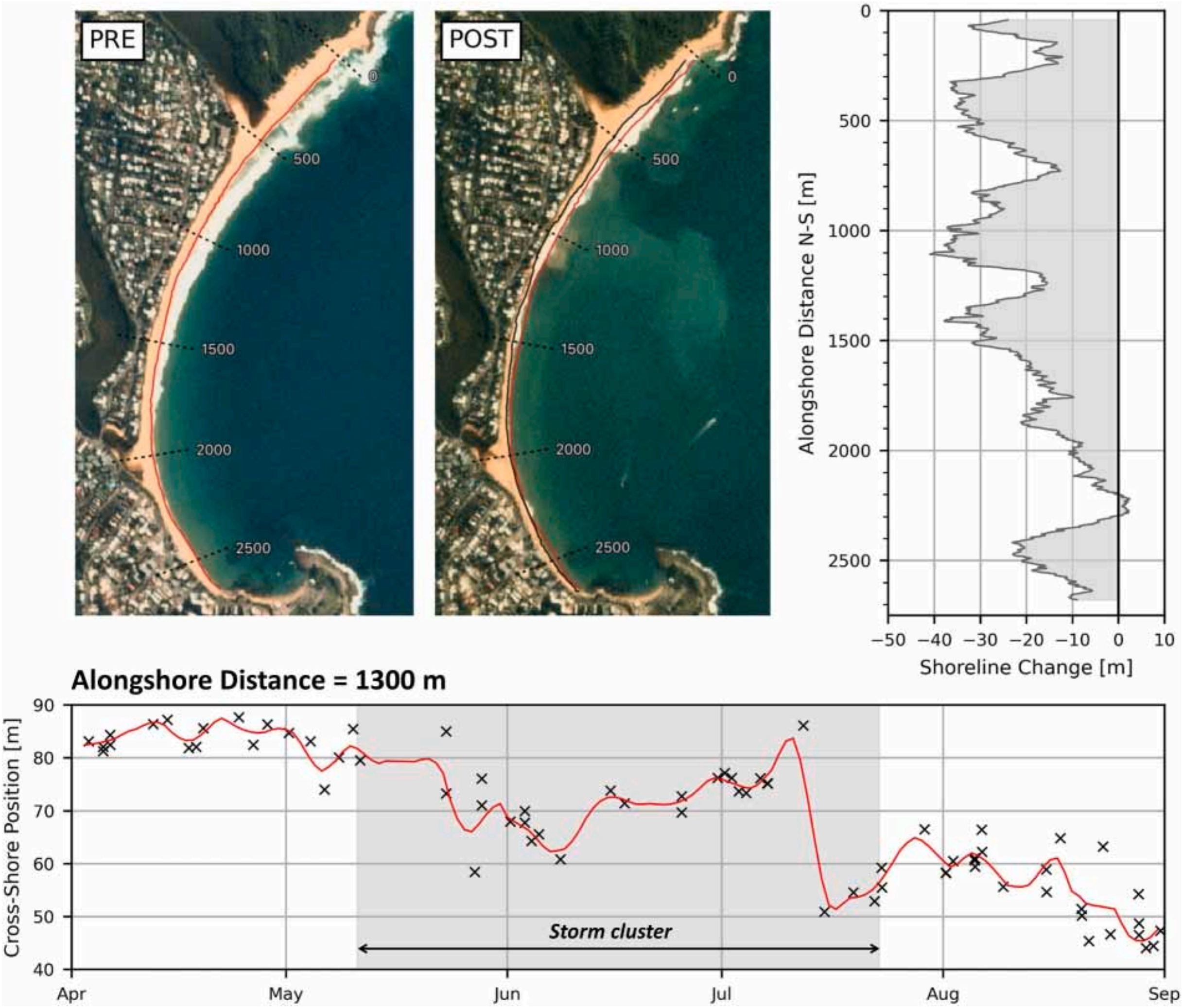

Fig. 4. Illustration of satellite-derived shorelines (SDS) using high resolution PlanetScope (a constellation of 'Dove' CubeSats) to quantify 'event-based' erosion that occurred at Wamberal Beach in southeast Australia, in response to a cluster of storm events that impacted this stretch of coastline from mid-May to mid-July 2020. Extensive damage to multiple beach-front homes was observed, and these data could provide rapid and repeated quantification of beach changes and their association with the evolving damage to individual properties.

particular location) was observed. For the three representative cross-shore profiles indicated, vertical RMSE is in the range of 0.39–0.53 m. This depth accuracy of decimeters to meters is typical for SDB results presently being reported by others (refer Bergsma and Almar, 2020), and notably, remains an order of magnitude greater error than the best in-situ hydrographic survey techniques. For practical Coastal Engineering applications such as the monitoring of beach nourishments and nearshore dredging, the expected SDB accuracy relative to the anticipated seabed changes must be carefully considered.

The growing availability of increasing resolution optical imagery with decreasing revisit periods (Fig. 1) can be anticipated to further expand SDB applications; for example, the use of large constellations of CubeSats to increase temporal resolution especially in areas of high cloud coverage (e.g., Poursandis et al., 2019) and new approaches to overcome present limitations in coastal regions that are characterised by turbid waters (e.g., Caballero and Stumpf, 2020). But at the present time, the rapidly growing availability of high spatiotemporal resolution satellite optical imagery is perhaps especially useful to Coastal Engineers in the context that it is now both feasible and practical to monitor and quantify shoreline changes down to the timescale of individual 'events' (e.g. a storm), at alongshore spatial scales corresponding to individual homes and other beachfront infrastructure. Illustrated in Fig. 4 is the application of the CoastSat toolbox applied to high resolution PlanetScope imagery to quantify the erosion that occurred at Wamberal Beach in southeast Australia spanning a cluster of storm events that impacted this stretch of coastline from May to July during 2020. Extensive damage to multiple beachfront properties occurred, and these data provided to Coastal Managers a source of rapid and repeated quantification of the alongshore variability in the evolving beach changes, as well as the associated impacts to individual homes.

4. Future directions

Since the launch of the first Sputnik satellite in October 1957, at the time of writing there are estimated to be approximately 6000 satellites orbiting the planet (60% of these are now defunct) of which around ~500 are used for observing the Earth's surface (see: http://stuffin.space/). It is our experience that - now the discipline and technical barriers to the practical use of satellites by Coastal Engineers are rapidly disappearing - three key factors will continue to drive the increasingly rapid uptake of optical imaging satellite capabilities by coastal professionals: (1) access to routine and repeated coastal measurements that already extend back several decades, (2) automated and 'always on' monitoring of present coastal conditions, and (3) universal coastline coverage. This latter factor is self-explanatory; the extent of in-situ instrumentation deployments in the coastal zone is (and will always

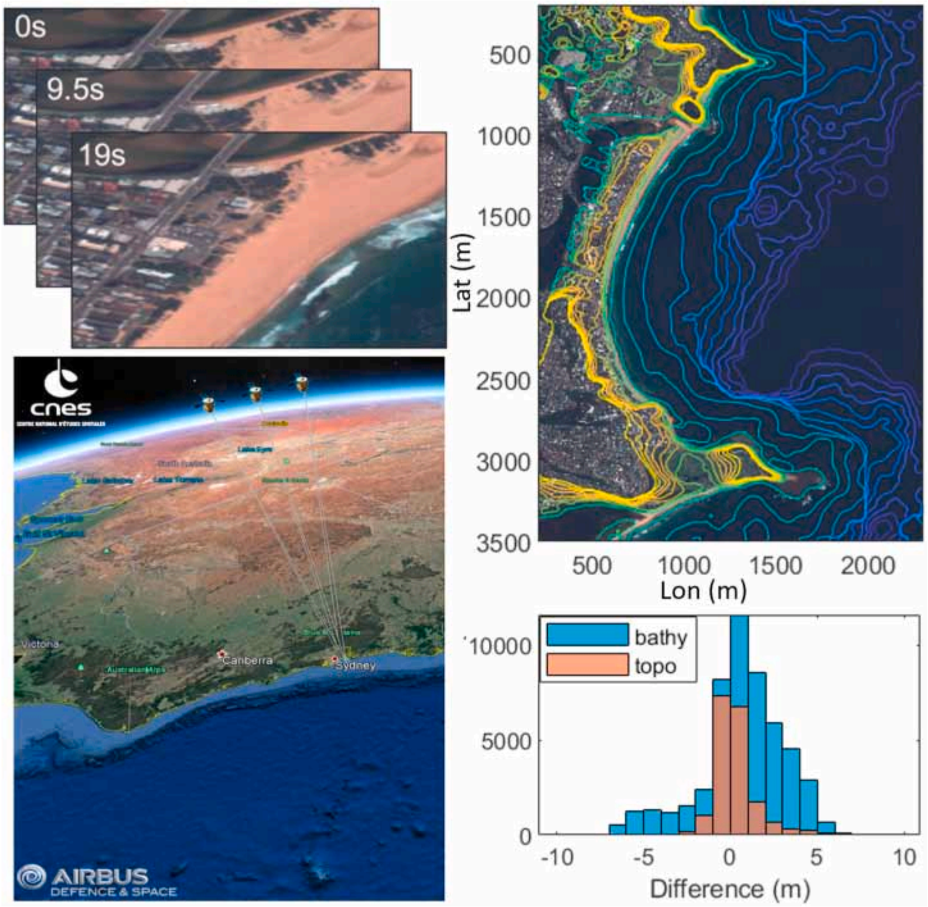

Fig. 5. Example of a seamless 3D topo-bathy derived from Pleiades-HR tri-stereo imagery obtained at Collaroy-Narrabeen Beach in southeast Australia. The acquisition of 3 images captured 9.5 s apart of the same location but from different positions along the satellite orbit enables the topography to be derived using stereoscopy, and simultaneously the bathymetry to be inferred based on the observed wave-kinematics in the nearshore zone. When compared to a combined airborne Lidar and hydrographic survey dataset obtained to coincide with the Pleiades-HR mission at Narrabeen, within the near-coast topographic region (0–15 above mean sea level) the satellite-derived RMSE = 0.83 m ($r^2 = 0.97$) and in the nearshore region (0 to −20 m below sea level) RMSE = 1.89 m ($r^2 = 0.76$). Though this figure correctly captures key coastal features such as the elevated headlands and their adjacent rock platforms, sand dunes, a steeper beachface and more gently sloping nearshore region interrupted by several rocky reefs, the present accuracy of this satellite-derived product is variable, and further refinement will be required for it to become a practical tool for Coastal Engineers. The next generation of 'video from space' satellites can be anticipated to significantly improve the accuracy of these and similar methods.

be) significantly limited by cost and resources. Satellite image-derived datasets provide a rich source of historical, contemporary and increasingly near real-time coastal measurements. And importantly, the spatial coverage can be readily tailorable to match specific project needs, ranging from localised to regional studies, and now extending to unprecedented and highly impactful 'big data' analyses at continental to global scales (e.g., Luijendijk et al., 2018; Mentaschi et al., 2018; Bishop-Taylor et al., 2019; Vos et al., 2020; Calkoen et al., 2021).

The continuing trajectory towards even greater spatial and temporal resolutions of 'next-gen' (so-called VHR or 'very high resolution') optical satellite missions such as Pleiades-HR and Worldview-3 are already opening up new opportunities to monitor an increasingly diverse range of coastal features. The combination of sub-meter pixel resolutions and multi-frame image acquisitions within a single satellite pass already provides new possibilities to exploit algorithms that are elsewhere considered 'routine', due to their existing widespread use in land-based nearshore remote sensing (video imaging, UAV, radar, etc). But now the possibility exists to radically upscale these approaches using satellites. And as satellite technology continues to advance, within the next handful of years, true 'video from space' will soon be a practical reality, further facilitating new possibilities for Coastal Engineers to investigate underlying physical processes in the coastal zone. Some practical examples of emerging optical satellite imaging opportunities that have or will evolve from existing land-based nearshore remote sensing approaches include:

- time-averaging of multi-frame satellite images to identify and track the evolution of nearshore morphology such as sandbars and rip channels;
- 3D stereoscopic and Structure-from-Motion (SfM) techniques to map coastal features above the waterline (e.g. coastal dunes, cliffs and coastal structures);
- wave-derived coastal bathymetry using physics-based depth-inversion methods from wave kinematics; and
- spatial and temporal variability of surface currents using wave dispersion relationships.

Used individually or in tandem, these and other techniques are likely to see a shift beyond instantaneous 'snapshots' of the shoreline and nearshore bathymetry (e.g. Figs. 2–4), towards seamless 3D monitoring of the entire and temporally-evolving coastal zone (Bergsma et al., 2021). Additional opportunities exist to combine satellite optical sensors with other space-borne sensors such as Synthetic Aperture Radar (SAR), with the potential to further expand coastal 3D mapping capabilities including night-time and all-weather conditions.

An exploratory example of these emerging capabilities is shown in Fig. 5, where multi-frame optical imagery obtained by a Pleiades-HR satellite is used to apply a stereo technique above the waterline (Almeida et al., 2019) with wave-derived bathymetry seawards of the shoreline (Almar et al., 2019), resulting in a simultaneous and seamless topo-bathy along Collaroy-Narrabeen Beach in southeast Australia. Compared to colour-based SDB methods, this use of multi-frame satellite images (and soon, true satellite video) can be expected to extend the practical use of satellites to measure coastal bathymetry into relatively deeper waters, as well as shallower, aerated surf zones and turbid coastal waters, where colour-based SDB methods are unsuitable. Analogous to the present use of UAV imagery to simultaneous map coastal topography and bathymetry (e.g., Brodie et al., 2019), the use of satellite optical imagery for this same purpose shows promise, but at the present time the accuracy achieved does yet match other remote sensing techniques such as drones and airborne Lidar.

Another key area of development is the potential use of satellite optical imagery as a routine data stream to support operational coastal management and decision-making. The 'always on' and near real-time availability of the latest satellite data (for example, public data portals such as the pan-European Sentinel Hub or national-based initiatives like Australia's Open Data Cube) can now provide critical information needed for short (days) to medium-range (seasons) hazard forecasting and early warning. This is particularly important for coastal applications where antecedent conditions, such as the extent of the existing sand buffer at a beach immediately prior to a storm, are known to exert a strong control on the magnitude of the resulting risk. Integrated with coastal modelling, 'real-time' satellite-derived data streams offer the very real potential through data assimilation to increase the forecast accuracy of rapidly evolving coastal hazards.

As satellite technology continue to develop, and the practical tools and techniques used to exploit these advances become increasingly accurate and accessible to the Coastal Engineering profession, it is important to recognise that in-situ observations in the coastal zone are - and in our opinion, will remain - fundamentally important. As the example illustrated here in Fig. 5 demonstrates, the accuracy of satellite-derived coastal topography and bathymetry remains a particular challenge, with present-day methods currently unable to consistently break the sub-decimeter level that is needed for key applications such as quantify sediment budgets, particularly on the shoreface (Anthony and Aagaard, 2020). Further practical limitations of optical satellites include cloud cover – particularly for tropical regions and during extreme cyclonic events – as well as the timing and duration of satellite passes. These limitations may be partially mitigated by the increasing prevalence of large constellations of a new generation of agile satellites such as the Airbus CO3D that are currently being developed for the French Space Agency (CNES), as well as the expanded use of complimentary sensors such as SAR. Nevertheless, instead of perceiving satellites as a likely replacement to targeted on-ground measurement and monitoring at the coast, satellite-derived information is rapidly becoming an increasingly valuable and practical adjunct to the everyday work of the practicing and research Coastal Engineer. New satellite advances including 'video from space' and the potential to combine Earth observation with numerical and data-driven models through assimilation and artificial intelligence are advances that we foresee will have future major impact within the Coastal Engineering profession.

Author statement

IT, MH, RA and EB jointly conceptualized this contribution. Drafting of Figures was undertaken by MD and RA. IT and MH prepared the original draft text with input from RA and EB. All authors contributed to review and editing of the final manuscript. Please refer to the 'Acknowledgements' section for the much-appreciated contributions of others.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The Authors acknowledge and thank our very many colleagues and collaborators – too many to mention here by name – who have assisted to shape our thoughts and ideas on the current status and future directions of satellite imagery applied to practical applications in the field of Coastal Engineering. Particular individuals who have significantly contributed to this publication include: Kilian Vos for providing the SDS analysis shown in Fig. 2; Chris Leaman for undertaking the SDB analysis included in Fig. 3; Yarran Doherty for undertaking the SDS analysis shown in Fig. 4; and Adelaide Taveneau for computing the satellite-based topography from tri-stereo Pleiades show in Fig. 5. We also thank Gold Coast City for providing the bathy survey dataset used for SDB calibration in Fig. 3.

References

Almar, R., Bergsma, E.W.J., Maisongrande, P., Almeida, L.P.M., 2019. Wave-derived coastal bathymetry from satellite video imagery: a showcase with Pleiades persistent mode. Rem. Sens. Environ. 231, 111263.

Almeida, L.P., Almar, R., Bergsma, E.W., Berthier, E., Baptista, P., Garel, E., Dada, O.A., Alves, B., 2019. Deriving high spatial-resolution coastal topography from sub-meter satellite stereo imagery. Rem. Sens. 11 (5), 590.

Almeida, L.P., de Oliveira, I.E., Lyra, R., Dazzi, R.L.S., Martins, V.G., da Fontoura Klein, A.H., 2021. Coastal analyst system from space imagery engine (CASSIE): shoreline management module. Environ. Model. Software 140, 105033.

Almonacid-Caballer, J., Sánchez-García, E., Pardo-Pascual, J.E., Balaguer-Beser, A.A., Palomar-Vázquez, J., 2016. Evaluation of annual mean shoreline position deduced from Landsat imagery as a mid-term coastal evolution indicator. Mar. Geol. 372, 79–88.

Anthony, E.J., Aagaard, T., 2020. The lower shoreface: morphodynamics and sediment connectivity with the upper shoreface and beach. Earth Sci. Rev., 103334

Belward, A.S., Skøien, J.O., 2015. Who launched what, when and why; trends in global land-cover observation capacity from civilian earth observation satellites. ISPRS J. Photogrammetry Remote Sens. 103, 115–128.

Benveniste, J., Cazenave, A., Vignudelli, S., Fenoglio-Marc, L., Shah, R., Almar, R., Andersen, O., Birol, F., Bonnefond, P., Bouffard, J., Calafat, J., Cardellach, E., Cipollini, P., Le Cozannet, G., Dufau, C., Fernandes, J., Frappart, F., Garrison, J., Gommenginger, C., Han, G., Høyer, J.L., Kourafalou, V., Leuliette, E., Li, Z., Loisel, H., Skovgaard Madsen, K., Marcos, M., Melet, A., Meyssignac, B., Pascual, A., Passaro, M., Ribó, S., Scharroo, R., Song, T., Speich, S., Wilkin, J., Woodworth, P., Wöppelmann, G., 2019. Requirements for a coastal zone observing system. Frontiers in Marine Science 6, 348.

Bergsma, E.W.J., Almar, R., 2020. Coastal coverage of ESA' Sentinel 2 mission. Adv. Space Res. 65, 2636–2644.

Bergsma, E.W.J., Almar, R., Rolland, A., Binet, R., Brodie, K.L., Bak, S., 2021. Coastal morphology from space: A showcase of monitoring the topography-bathymetry continuum. Rem. Sens. Env. 261, 112469.

Bishop-Taylor, R., Sagar, S., Lymburner, L., Alam, I., 2019a. Sub-pixel waterline extraction: characterising accuracy and sensitivity to indices and spectra. Rem. Sens. 11 (24), 2984.

Bishop-Taylor, R., Sagar, S., Lymburner, L., Beaman, R.J., 2019b. Between the tides: modelling the elevation of Australia's exposed intertidal zone at continental scale. Estuar. Coast Shelf Sci. 223, 115–128.

Boak, E.H., Turner, I.L., 2005. Shoreline definition and detection: a review. J. Coast Res. 21 (4), 688–703.

Brodie, K.J., Bruder, B.L., Slocum, R.K., Spore, N.J., 2019. Simultaneous mapping of coastal topography and bathymetry from a lightweight multicamera UAS. IEEE Trans. Geosci. Rem. Sens. 57 (9), 6844–6864.

Caballero, I., Stumpf, R.P., 2020. Towards routine mapping of shallow bathymetry in environmental with variable turbidity: contribution o Sentinel-2A/B Satellites <Mission. Rem. Sens. 12 (3), 451.

Calkoen, F., Luijendijk, A., Rivero, C.R., Kras, E., Baart, F., 2021. Traditional vs. Machine-learning methods for forecasting sandy shoreline evolution using historic satellite-derived shorelines. Rem. Sens. 13, 934.

Castelle, B., Bujan, S., Marieu, V., Ferreira, S., 2020. 16 years of topographic surveys of rip-channelled high-energy meso-macrotidal sandy beach. Scientific Data 7 (1), 1–9.

Castelle, B., Scott, T., Stokes, C., Konstantinou, A., Marieu, V., Bujan, S., 2021. Satellite-derived shoreline detection at a high-energy meso-macrotidal beach. Geomorphology 383, 107707.

Chu, L., Oloo, F., Sudmanns, M., Tiede, D., Hölbling, D., Blaschke, T., Teleoaca, I., 2020. Monitoring long-term shoreline dynamics and human activities in the Hangzhou Bay, China, combining daytime and nighttime EO data. Big Earth Data 1–23.

Elko, N.A., Wang, P., 2007. Immediate profile and planform evolution of a beach nourishment project with hurricane influences. Coast Eng. 54 (1), 49–66.

Fearns, P., Broomhall, M., Dorji, P., 2017. Optical Remote Sensing for Dredge Plume Monitoring: a Review. Western Australian Marine Science Institution, Perth, Western Australia, p. 46. Report of Theme 3 - Project 3.1.1, prepared for the Dredging Science Node.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google earth engine: planetary-scale geospatial analysis for everyone. Rem. Sens. Environ. 202, 18-17.

Hagenaars, G., de Vries, S., Luijendijk, A.P., de Boer, W.P., Reniers, A.J., 2018. On the accuracy of automated shoreline detection derived from satellite imagery: a case study of the sand motor mega-scale nourishment. Coast Eng. 133, 113–125.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146 (730), 1999–2049.

Holman, R.A., Stanley, J., 2007. The history and technical capabilities of Argus. Coast Eng. 54 (6–7), 477–491.

Islam, A., Wang, L., Smith, C., Reddy, R., Lewis, A., Smith, A., 2007. Evaluation of satellite remote sensing for operational monitoring of sediment plumes produced by dredging at Hay Point, Queensland, Australia. J. Appl. Remote Sens. 1 (1), 011506.

Lee, Zhongping, Carder, Kendall L., Mobley, Curtis D., Steward, Robert G., Patch, Jennifer S., 1999. Hyperspectral remote sensing for shallow waters: 2. Deriving bottom depths and water properties by optimization. Appl. Opt. 38 (18), 3831–3843.

Ludka, B.C., Guza, R.T., O'Reilly, W.C., Merrifield, M.A., Flick, R.E., Bak, A.S., Hesser, T., Bucciarelli, R., Olfe, C., Woodward, B., Boyd, W., Smith, K., Okihiro, M., Grenzeback, R., Parry, L., Boyd, G., 2019. Sixteen years of bathymetry and waves at San Diego beaches. Scientific Data 6, 161.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S., 2018. The state of the world's beaches. Sci. Rep. 8, 6641.

Lysenga, D.R., 1978. Passive remote sensing techniques for mapping water depth and bottom feature. Appl. Opt. 17 (3), 379–383.

Melet, A., Teatini, P., Le Cozannet, G., Jamet, C., Conversi, A., Benveniste, J., Almar, R., 2020. Earth observations for monitoring marine coastal hazards and their drivers. Surv. Geophys. 41, 1489–1534.

Mentaschi, L., Vousdoukas, M.I., Pekel, J.F., Voukouvalas, E., Feyen, L., 2018. Global long-term observations of coastal erosion and accretion. Sci. Rep. 8, 12876.

Misra, A., Ramakrishnan, B., 2020. Assessment of coastal geomorphological changes using multi-temporal Satellite-Derived Bathymetry. Continent. Shelf Res. 207, 104213.

Nerem, R.S., Beckley, B.D., Fasullo, J.T., Hamlington, B.D., Masters, D., Mitchum, G.T., 2018. Climate-change–driven accelerated sea-level rise detected in the altimeter era. Proc. Natl. Acad. Sci. Unit. States Am. 115 (9), 2022–2025.

Ottinger, M., Kuenzer, C., 2020. Spaceborne L-band synthetic aperture radar data for geoscience analyses in coastal land applications: a review. Rem. Sens. 12 (14), 2228.

Poursanidis, D., Traganos, D., Chrysoulakis, N., Reinartz, P., 2019. CubeSats allow high spatiotemporal estimates of satellite-derived bathymetry. Rem. Sens. 11 (11), 1299.

Salameh, E., Frappart, F., Almar, R., Baptista, P., Heygster, G., Lubac, B., Raucoules, D., Almeida, L.P., Bergsma, E.W.J., Capo, S., De Michele, M., Idier, D., Li, Z., Marieu, V., Poupardin, A., Silva, P.A., Turki, I., Laignel, B., 2019. Monitoring beach topography and nearshore bathymetry using spaceborne remote sensing: a review. Rem. Sens. 11 (19), 2212.

Sánchez-García, E., Palomar-Vázquez, J.M., Pardo-Pascual, J.E., Almonacid-Caballer, J., Cabezas-Rabadán, C., Gómez-Pujol, L., 2020. An efficient protocol for accurate and massive shoreline definition from mid-resolution satellite imagery. Coast Eng. 160, 103732.

Splinter, K.D., Harley, M.D., Turner, I.L., 2018. Remote sensing is changing our view of the coast: insights from 40 years of monitoring at Narrabeen-Collaroy, Australia. Rem. Sens. 10 (11), 1744.

Stumpf, R.P., Holderied, K., Sinclair, M., 2003. Determination of water depth with high-resolution satellite imagery over variable bottom types. Limnol. Oceanogr. 48 (1part2), 547–556.

Traganos, D., Poursanidis, D., Aggarwal, B., Chrysoulakis, N., Reinartz, P., 2018. Estimating satellite-derived bathymetry (SDB) with Google earth engine and seninel-2. Rem. Sens. 10 (6), 859.

Turner, I.L., Harley, M.D., Short, A.D., Simmons, J.A., Bracs, M.A., Phillips, M.S., Splinter, K.D., 2016. A multi-decade dataset of monthly beach profile surveys and inshore wave forcing at Narrabeen, Australia. Scientific Data 3 (1), 1–13.

van Enckevort, I.M.J., Ruessink, B.G., Coco, G., Suzuki, K., Turner, I.L., Plant, N.G., Holman, R.A., 2004. Observations of nearshore crescentic sandbars. J. Geophys. Res.: Oceans 109 (C6).

Vos, K., Harley, M.D., Splinter, K.D., Simmons, J.A., Turner, I.L., 2019a. Sub-annual to multi-decadal shoreline variability from publicly available satellite imagery. Coast Eng. 150, 160–174.

Vos, K., Splinter, K.D., Harley, M.D., Simmons, J.A., Turner, I.L., 2019b. CoastSat: a Google Earth Engine-enabled Python toolkit to extract shorelines from publicly available satellite imagery. Environ. Model. Software 122, 104528.

Vos, K., Harley, M.D., Splinter, K.D., Walker, A., Turner, I.L., 2020. Beach slopes from satellite-derived shorelines. Geophys. Res. Lett. 47 (14), e2020GL088365.

Xu, N., 2018. Detecting coastline change with all available Landsat data over 1986–2015: a case study for the state of Texas, USA. Atmosphere 9 (3), 107.

Young, I.R., Zieger, S., Babanin, A.V., 2011. Global trends in wind speed and wave height. Science 332 (6028), 451–455.