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Coastal zone mapping with the world's first airborne multibeam bathymetric lidar mapping system

An article by DON VENTURA

Coastal zone mapping is becoming more and more important due to the magnified impacts on coastal communities due to climate change and the gradual but inexorable rise in global mean sea level. Accurate determination of the nearshore bathymetry and low-lying coastal terrain is vital for providing better modelling of the likely impact to areas due to storm surges and flooding. With this new concept in airborne lidar bathymetry (ALB) technology, mapping this challenging domain is now more possible to achieve in an efficient and effective way.

ALB | lidar | coastal zone mapping | RAMMS | UAV
ALB | Lidar | Küstenzonenkartierung | RAMMS | UAV

Die Kartierung der Küstenzonen wird immer wichtiger, da sich der Klimawandel und der allmählich, aber unaufhaltsam ansteigende globale mittlere Meeresspiegel sich spürbarer auf die an den Küsten liegenden Gemeinden auswirkt. Eine genaue Bestimmung der küstennahen Bathymetrie und des tiefliegenden Küstengeländes ermöglicht es, die wahrscheinlichen Auswirkungen von Sturmfluten und Überflutungen besser zu modellieren. Mit einem neuen Ansatz der luftgestützten Lidar-Bathymetrie-Technologie ist es einfacher geworden, die Kartierung effizient und effektiv durchzuführen.

Author
Don Ventura is Hydrographic Business Development Manager at Fugro in Hillcroft, Houston, Texas, USA.

dventura@fugro.com

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M. Filippone, M. Stender, M. MacDonald, J. Martinez, T. Mitchell – Fugro
S. Anderson, E. Korpie – Areté

For more information:
m.stender@fugro.com

Introduction

To map the coastal and nearshore environments, contemporary airborne lidar bathymetry (ALB) technology has always faced a serious challenge regarding data density and point accuracy sufficient to satisfy many agencies' requirements. The focus on coastal zone mapping is becoming even more important due to the magnified impacts on coastal communities due to climate change and the gradual but inexorable rise in global mean sea level. Accurate determination of the nearshore bathymetry and low-lying coastal terrain is vital for providing better modelling of the likely impact to areas due to storm surges and flooding. Relatively high-energy output ALB systems have sought to penetrate the water column sufficiently to create usable coverage to a depth where traditional acoustic technology can achieve parity in terms of efficiency (swath width) and cost per unit area. This design template typically creates data densities that do not meet International Hydrographic Organization (IHO) standards for target detection and therefore fail the IHO Order 1a criteria. The advent of lightweight »topo-bathy« systems, combining the 532 nm green laser of a bathy system with a topographic lidar design approach partially addresses some of the limitations of »deep« systems but at the expense of water penetration and consistent coverage, limiting their use in areas of marginal water clarity and variable bathymetry. To address these limitations, Fugro has, in partnership with system manufacturer Areté, adopted a new design paradigm and created the world's first multibeam bathymetric lidar, the Fugro Rapid Airborne Multibeam Mapping System (RAMMS). RAMMS is now operational and realising the design goals which were set: to attain accurate, fully attributed bathymetric data, at a data density exceeding that required to achieve IHO Order 1a and the associated seabed coverage and target detection criteria. This article describes the benefits of this technical approach, how it differs from contemporary bathymetric lidar technology and the considerable advantages it provides to the end user.

Depth penetration versus data resolution – yesterday's dilemma and the case for something new

In the 1990s, Fugro helped commercialise the use of airborne lidar bathymetry for regional mapping of the world's coastal zones in favourable bathymetric conditions. Due to the properties of laser light, »favourable« conditions require low water turbidity and a reasonably reflective seabed against which the light will be reflected in sufficient energy levels (photon count) to be detected back at the receiver. All bathymetric lidar systems require the same environmental conditions; some are better at overcoming water clarity and seabed reflectance to a degree, whilst some provide very good data resolution but at the expanse of depth penetration and coverage. However, before RAMMS, all systems used a pulsed diode to create discrete, individual parcels of energy. In these legacy systems, moving mirrors are used to divert the individual laser pulses from side-to-side or in an elliptical pattern, collecting data over a specific swath. As the light energy returns to the receiver, each point provides an independent water depth measurement.

Over the last several years, the world's leading hydrographic agencies have consistently challenged the industry to provide higher standards of quality in data collection and deliverables, most specifically to meet their requirements in airborne lidar bathymetry suitable for nautical charting. This precondition includes the underlying impositions on the data used; namely that it must support both safety of navigation (SoN) and, by inference, safety of life at sea (SOLAS). Great trust is put upon official nautical charts by the world's maritime community and, in turn, hydrographic charting agencies' need to have trust in the data used to compile their products as meeting the accuracy and resolution standards mandated for the safe navigation of surface vessels. As these standards have been raised in recognition of the advancement in hydrographic survey technology capability and fidelity, it was recognised that, in the case of ALB, Fugro could not wait for industry and manufacturers to solve this challenge and that affirmative action to meet the needs of our primary clients had to be taken. By identifying and leveraging decades of defence department technology for shallow-water littoral mapping, which utilised a completely different design and technology concept, and then refining it for hydrographic surveying, Fugro's RAMMS was born.

As mentioned earlier, the global hydrographic market includes a variety of stakeholder client groups, all with a varying need for hydrographic data. Although chief amongst these stakeholders is the nautical charting agencies group, other significant users of the data include the coastal zone management groups and agencies, whose main requirements are not limited to bathymetry but also the capture of the land-sea interface. Obtaining this seamless data, across the realm where the greatest interaction between land and water creates the scenario and extent of storm surge and coastal inundation, is most efficiently and successfully captured using airborne sensors. It also provides an abundance of baseline survey data depicting current sea level along the world's coastlines and therefore the basis for any subsequent sea-level change monitoring and assessment. Many of the world's coastlines, particularly those of low-lying, remote and often developing nations, where current mapping and charting is inadequate, are the very areas where better determination of the land-sea interface is critical to the safety of nearshore communities and critical infrastructure.

RAMMS system description and contemporary system comparison

Fugro RAMMS is a modular design concept featuring a new bathymetric lidar sensor from Fugro and technology partner Areté, based on Areté's earlier Airborne Laser Mine Detection System (ALMDS) and the Pushbroom Imaging Littoral Lidar System (PILLS) technology. These technologies are a result of over two decades of design and evolution for defence activities.

RAMMS was designed to advance bathymetric mapping quality and efficiency beyond current airborne mapping systems in the coastal and nearshore environments. Modular components can be added to provide the client with a tailored product delivery for the hydrographic, coastal zone management, marine engineering and environmental market sectors. Fugro's heritage and expertise in ALB has been leveraged to ensure that the evolved system has been designed with the future in mind; cost efficiency and improved data quality are major considerations, so access to this vital data by an increasing number of stakeholders is possible.

The RAMMS' integrated lidar system is used for simultaneously acquiring high-resolution bathymetry and topographic data, together with the required situational (processing) imagery and associated position and attitude sensory information. Further, the intensity of the returning imagery is a measure of the reflectance of the seabed materials; the processing of this intensity data can in turn generate a reflectance imagery product akin to (but different from) acoustic backscatter that is used extensively by today's contemporary acoustic hydrographic sonar technology providers to assist in determining the surface material composition of the seabed.

The RAMMS system provides timely and cost-effective capabilities for hydrographic surveying. Operational efficiencies translate into significant improvements in data quality and/or costs when compared to current methods, allowing for optimised value for collection of necessary data. The primary sensor weighs approximately 14 kg; this grows to a still very modest 35 kg as a system, which includes the main lidar sensor, the power distribution unit (PDU), a highly accurate inertial motion unit (IMU) and a multispectral (4-band) camera, all integrated within a protective housing, making it extremely portable and a viable option for working on smaller aircraft and uncrewed platforms. This allows not only more sensor combinations per cubic metre of space in the aircraft, it means that a much greater number of suitable platforms can be used to support survey operations. Other advantages include:

- Solid-state electronics creates more ruggedised, low-maintenance design;
- Greatly minimised shipping logistics;
- Greatly minimised mobilisation and check calibration procedures;
- Modularity and small overall size provide ease of installation;
- Laser ranging absolute accuracy is sub-decimetre;
- Compact metadata architecture;
- Real-time data processing results in rapid QC estimates in the field and onward processing routines by integrating and leveraging Fugro Back-2-Base technology;
- Point cloud data generation faster than actual acquisition;
- Point cloud data can be brought into any third-party mapping software (e.g. CARIS, QINSy).

Design concept and development

RAMMS, as the acronym suggests, represents a paradigm shift in conceptualising the airborne bathymetry approach. In summary, the sensor differs from other sensors on the market today in the following fundamental aspects:

- No mirrors;
- No scanner;
- No moving parts;
- No energy-hungry componentry;
- Very lightweight and portable;
- Already mission-proven as suitable for uncrewed autonomous vehicle (UAV) operations.

The original sensor was developed from a US Office of Naval Research (ONR) requirement for a »lightweight topo/bathy charting system for UAVs«. The original system (Fig. 1) was intended to map shallow littoral waters; initial designs were matured in 2010 and research and development continued throughout 2015. These designs from the outset required the system to operate from UAVs, which gives RAMMS its earliest design parameters. In other words, it is not a miniaturisation of an earlier, bulkier predecessor, but the evolution of an already very lightweight, portable design.

Focus on a commercially viable bathymetric system occurred from 2015 onwards with continued collaboration between Areté and Fugro. While most lidar systems use moving mirrors to divert laser pulses from side-to-side or in an elliptical pattern, the RAMMS unique push broom sensor fires pulses of laser energy that undergo divergence at the sensor and are spread outward laterally, perpendicular to the direction of flight. This creates a »fan« of energy, and in so doing, produces a true swath coverage. The laser energy returns to the receiver and is digitised into individual returns resembling a 2D cross section (~900 observations across-track with elevation/depth for each swath return). RAMMS single laser pulse thus achieves what a traditional lidar system would need hundreds of pulses to collect. These »2D returns« are collected every time the laser is fired along-track, to create representations of the ground or seafloor. Such a technique is not only unique in the bathymetric lidar realm, it is very analogous with multibeam sonar conceptualisation, and this has additional advantages in utilising processing software and practices.

Swath characteristics

As RAMMS has no moving parts, the scan characteristics are dependent upon beam divergence at the transceiver, altitude, speed and pulse rate frequency (PRF). The current configuration has the swath width approximately 83 % the altitude, with nominal operational altitude at 325 m above ground level (AGL).

Physical characteristics

As the primary sensor is extremely compact and light, platform suitability is considerably expanded over heavier, more power-hungry conventional systems with adoption of a much lighter, power-efficient system. The main design characteristics of RAMMS include two main templates, depending on whether a manned aircraft or UAV is the platform of choice: for aircraft, a vertically aligned (»stack«) frame allows a small physical footprint for the sensor above a standard photogrammetric port in the aircraft fuselage (which in turn also allows other sensors to occupy the same port), whilst for the fixed-wing UAV option, a longitudinal »pod« design is more in keeping for that platform profile. The outline characteristics of RAMMS are as follows:

- Current sensor contained in a 10 cm × 23 cm × 99 cm housing (0.023 m^3) (longitudinal »pod« design, Fig. 1) or a 76 cm × 42 cm × 37 cm housing (0.118 m^3) (upright »stack« design, Fig. 2);

Fig. 1: PILLS onboard a SeaHunter UAV – this represents the »pod« configuration of RAMMS

- Sensor weight < 14 kg in UAV »pod« mode; 35 kg in aircraft »stack« mode;
- Power draw is < 10 A @ 28 V DC;
- No chiller or air conditioner (unlike all other contemporary ALB systems);
- Low-power = low-heat generation – operable over a wider environmental window;
- 532 nm output (green);
- 30 Hz PRF, each producing equating to 0.33 m spacing across-track and 1 m to 2 m along-track (speed dependent).

By combining the core fundamentals of this defence-based technology with Fugro's decades of multibeam and bathymetric lidar surveying, RAMMS capabilities have been developed with new and higher standards in mind. In addition, one of the foundations and vision of this technology was our focus on how to assimilate the features and abilities to multibeam, but from an airborne collection perspective. After three years of development and testing, this new technology has been field-proven on multiple projects since 2017.

Fugro conducted a technical evaluation of various contemporary ALB systems and then compared these to RAMMS to confirm that the new system performance not only exceeds the capabilities of competing systems but also fulfils the specifications outlined in modern international hydrographic specifications. Specifically, Fugro evaluated various contemporary systems on the requirements as they relate to the systems being capable of achieving IHO Order 1 accuracies to a depth of 40 m in optimum water conditions and providing a density in-line with typical requirements of at least two points in a 2 m × 2 m bin size throughout.

Moreover, the Fugro RAMMS system's unique push broom technology, coupled with the water column processing algorithms at its core, make it the first and only system to allow for water column volume analysis and increased data density by utilising this feature. This water column insight from the push broom technology allows for detailed analysis of wreck investigations unlike any other airborne sensor, all by taking full advantage of its technology roots for littoral mapping activities.

In assessing the utility of RAMMS, Fugro conducted comparisons with the Optech CZMIL NOVA and Titan systems, and Leica's Chiroptera II/HawkEye III. These sensors provide different capabilities based on laser power, laser repetition rates and scanning type, which ultimately impact results in terms of point density and depth of bottom detection. It was determined that while all sensors are capable of meeting the outline specifications to some degree, it came down to which would cover all requirements of the specifications in the most holistic and efficient way. Specifically, the requirement for a sounding density of two unique data points in a bin with sides of 2 m and the potential to deliver sounding density of up to nine data points in a 2 m bin for significantly large areas (no less than two points per bin) dictated which sensors were capable of achieving specification. These density requirements dictated two variables that needed to be assessed for use of either system configuration (sounding spacing and number of line passes), all while balancing the swath width and operational efficiency of the technology under consideration.

It must be noted, however, that even by recording the base requirement of two data points per 2 m bin, this does not ensure points are not lost to uncontrollable environmental issues such as sea foam, mist, turbidity, whitecaps or similar. The statistical metric of 90 % attainment in data density was assumed, and Fugro evaluated what could be expected from each configuration. It was

Fig. 2: RAMMS in »stack« configuration for use in manned aircraft missions

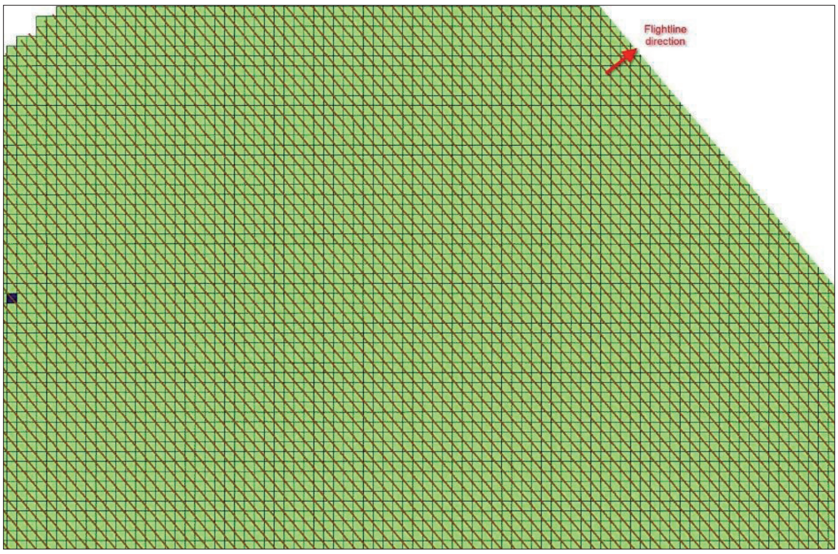

Fig. 3: Fugro RAMMS point density over 2 m bins (single pass)

anticipated that there would likely be six or more unique soundings in each 2 m bin, with side lap areas excluded from each primary waveform pulse alone. Fig. 3 illustrates actual RAMMS point pattern when flown at 120 kts and 325 m of altitude. The 2 m bins are coloured green, which indicated all of them (100 % coverage) have two or more points; the inset illustration shows a zoomed-in view of the point pattern.

In addition to an average six points per 2 m bin from each individual pulse, RAMMS can capture the full push broom water column returns to allow for potentially doubling the primary density, from six to twelve points per 2 m bin in the along-track direction. By capturing the water column, a 3D representation of areas with multiple overlapping coverage, in excess of the original single return, can be combined and evaluated independently from the stand-alone primary returns. This method, leveraging the shallow water littoral mapping techniques of the core technology, takes the multiple views outside the single return and combines them to allow for a deeper and separate standalone analysis algorithm. The overlapping illuminated coverage of the area is scanned using all common excess coverage across the multiple views of the same location, covered by the stand-alone single returns shown in Fig. 3. This allows the algorithms to detect potential returns that would not be detected in a single return. In addition, any detections that were weak or dark, have a better chance of being captured in this additional analysis, due to the redundant views and separate analysis. While this unique RAMMS feature is available at all water depths, it does lose effectiveness as water clarity degrades due to turbidity noise influencing the detections. However, in optimal conditions, it is anticipated the feature will produce up to twelve points per 2 m bin to 40 m water depth (localised environmental conditions permitting).

This method of combining water column views of additional areas allows for both an increase in density due to multiple views of the seafloor and also a more in-depth and intelligent method of performing wreck analysis from lidar. As shown in Fig. 4, weaker returns in a single pulse return are not strong enough to be picked by the detection algorithm. When combining multiple views and analysing the water column of that multiple view, even weaker returns can be identified, as well as new points common to the multiple views with strong returns in all the samples.

In comparison to all other systems that derive all information form a single spot return, more logical and valuable information is collected via this water column method. In Fig. 5, the potential returns could not be visualised with a »spot« system, as they would simply be consumed within the single waveform pulse of that one location that has a strong bottom return attached. Any possible object in the water column of the single spot return would only be detectible somewhere between the two large amplitude wave returns (which represent the water surface and seabed returns). Visualisation of any water column noise is virtually impossible to spatially assess with the spot single location returns.

The study confirmed that contemporary solutions, while partially attaining some of the facets required to meet nautical charting-quality hydrographic data, still resulted in a compromise between data density and depth penetration capabilities, and that the efforts to develop RAMMS based on attaining all the appropriate standards – not just some – is well-founded.

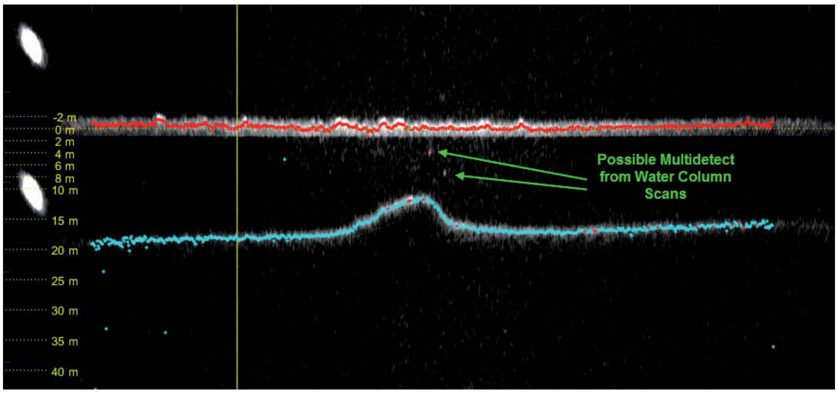

Fig. 4: Fugro RAMMS water column data example

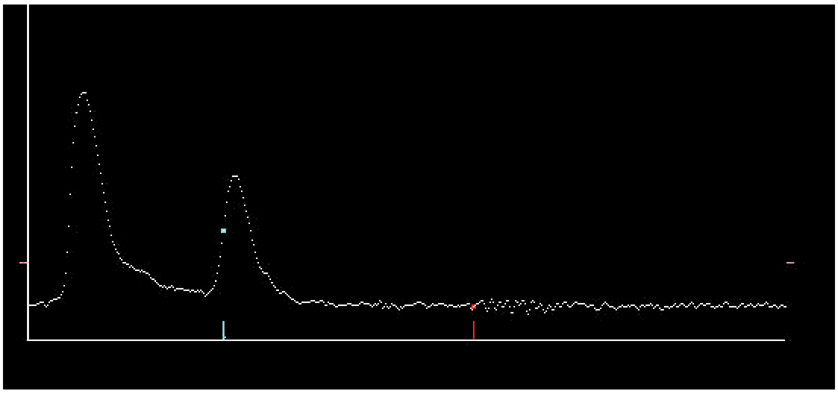

Fig. 5: Limited assessment from spot sensor

Advantages and applications

RAMMS' design and operational characteristics provide a number of clear advantages over contemporary systems. The key performance differentiators are summarised in the Table 1.

Although RAMMS and some shallow-water ALB systems are capable of being supported from UAV platforms as listed above, some integration effort would still be required to adapt system designs to fit the specific UAV selected (although the fact that RAMMS can be provided in a »pod« configuration already greatly simplifies this task).

In addition to the output data meeting or exceeding the requirements of current international

RAMMS	Current deep-water ALB	Current shallow-water ALB
3 Secchi depth-capable	2 to 3 Secchi depth-capable	1 to 1.5 Secchi depth-capable
~1:1 swath:flying altitude	0.7:1 swath:flying altitude	0.7:1 swath:flying altitude
25,000 observations/second	10,000 observations/second	Up to 550,000 observations/second (1 Secchi depth) Up to 70,000 observations/second (1.5 Secchi depth)
1.6 points/m^2 @ 300 m altitude @ 140 knots	0.49 points/m^2 @ 400 m altitude @ 140 knots	Up to 18 points/m^2 @ 600 m altitude @ 140 knots
Continuous cross-track acquisition	Individual observations	Individual observations
< 10 A current draw	> 70 A current draw	~17 A current draw
UAV-capable (now)	Non-UAV-capable	UAV-capable (now)
Large platform flexibility	Manned aircraft types only	Large platform flexibility

Table 1: Key performance differentiators of RAMMS in comparison with other ALB systems

hydrographic data standards, a number of other advantages result from RAMMS' design:

- Compact designs, low mass and very modest power requirements widen the number of suitable aircraft platforms, including UAVs, that can accommodate the system. This includes single- and piston-engine aircraft, from which contemporary ALB systems cannot be adequately supported.
- The small system size and solid-state componentry makes physical installation and mobilisation both more rapid and simple to conduct. This also allows for more flexible »bundling« with other sensors deployed in the same aircraft such as dedicated topographic lasers, hyperspectral cameras and the new generation of mini-imagers, micro synthetic aperture radars, etc.
- The smaller, lighter aircraft suitable to accommodate the system allow, in turn, more operational flexibility in the type of airfields and associated services necessary for the aircraft type. Many smaller airports and/or those with non-asphalt runways which cannot support larger turbo-prop aircraft can now be factored into mission planning.
- Increased endurance is possible compared to that achieved with previous systems using the same aircraft type, resulting in more effective flight planning.
- A smaller operational field crew is required for both mobilisation and field operations, reducing the HSE level of risk of any operation.
- Logistical overheads such as shipping are hugely reduced in scope and expense.
- The carbon footprint of hydrographic data acquisition is markedly reduced through the use of smaller aircraft, more airfield accessibility, less or no shipping, etc.
- More rapid deployment is possible due to the low shipping volume and smaller team of personnel required for data acquisition: in many cases the selected aircraft can mobilise with the system already installed, omitting entirely the need for shipping freight.
- The exciting use of UAVs is »now« rather than some future goal, further expanding the operational and geographic envelope in the use of the technology.

Regarding the extent to which RAMMS and ALB can be utilised, various stakeholder groups requiring nearshore and land-sea interface data represent a host of applications to which the data can provide useful input. The following list is not definitive but illustrates the breadth and diversity of possible clients over and above those involved in traditional nautical charting and terrestrial mapping markets:

- Cadastral (land usage and ownership) surveyors;
- Nearshore oil and gas industry;
- Tourism;
- Aquaculture;
- Cultural agencies;
- Conservation and natural resource groups;
- Renewable energy industry;
- National security and defence agencies;
- Cable route surveys for oil and gas, telecommunications and power;
- Fishing agencies;
- Recreation industry;
- Nearshore mineral extraction activities (e.g. beach renourishment, sediment mining);
- Coastal engineering (construction, etc.).

Summary

Fugro RAMMS continues to be refined, with further development of various advantageous workflows and updated software solutions constantly underway. Nonetheless, the system today is already fully operational and functional, heralding a new efficient, cost-effective and higher-resolution ALB solution on the marketplace. As the world's only 3-Secchi capable multibeam bathymetric lidar, Fugro RAMMS sets the standard for ALB systems by attaining the data quality and density standards demanded by an ever-growing customer base, who want quality data in challenging nearshore and coastal environments where flooding, tidal storm surges and undeniable sea-level rise require measuring and mitigation. //