TSUNAMI AND SURGE-RELATED COASTAL HAZARD MAPPING IN SRI LANKA, BY VERY-HIGH RESOLUTION, THREE-DIMENSIONAL, AIRBORNE AND SPACEBORNE REMOTE-SENSING

CARTOGRAPHIE A TRES HAUTE RESOLUTION DU RISQUE-TSUNAMIS AU SRI LANKA, PAR INTEGRATION DE TECHNIQUES TRIDIMENSIONNELLES DE TELEDETECTION AERIENNE ET SPATIALE

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ABSTRACT

Following an inter-Government agreement established between Italy and Sri Lanka in the aftermath of the great 2004 Indian Ocean tsunami, the operational project ‘HyperDEM’ was designed for mapping in 3-D the coastal areas of Sri Lanka, aimed to easing and speeding-up emergency mapping in tsunami-prone areas. The work, based on integration of airborne LiDAR and spaceborne RaDAR campaigns, started in autumn 2005 and was accomplished in summer 2006 after acquisition of the outstanding data volume of ca. 2.7 TeraBytes. Here, the synthesis of work carried out is reported, together with some examples of results and technical hints arising from methodological solutions adopted in solving operational problems. Upon completion of the work, the Government of Sri Lanka was provided with ca. 2’500 sq.km of Digital Elevation Models of the coastal areas, ca. 1’800 of which at the exceptional resolution of 1 metre and the elevation precision of 0.3 metres, and 700 at the resolution of 30 metres vs. an elevation precision of 2.6 metres.

RESUME

Suite aux accords intergouvernementaux intervenus entre l’Italie et le Sri Lanka après le grand tsunami du 26 Décembre 2004, un projet opérationnel de cartographie 3-D à trés-haute résolution – dénommé ‘HyperDEM’ - a été mis en oeuvre afin de simplifier et améliorer les travaux de cartographie d’urgence nécessaires à la reconstruction post-désastre. Le projet a été centré sur l’intégration des prospections MNT par LiDAR aéroporté et par interférométrie RaDAR satellitaire. La campagne s’est déroulée entre l’automne 2005 et le printemps 2006, donnant lieu à l’acquisition de presque 2,7 TéraOctets de données. Ici, les résultats techniques et scientifiques de la campagne sont synthétisés, avec une attention particulière aux solutions techniques qu’il a été nécessaire de trouver afin de résoudre des problèmes opérationnels, techniques et/ou méthodologiques. Le travail complet a permis de restituer un MNT sur presque 2’500 kilomètres carrées de zones côtières, dont 1’800 avec l’exceptionnelle résolution de 1 mètre (en planimétrie) et la précision de 30 centimètres (en élévation), et 700 avec une résolution de 30 mètres en planimétrie et une précision de 2,6 mètres en élévation.

PREAMBLE

Tsunamis are liquid gravitational waves that travel at speeds given by the square root of the sea bottom depth, times the gravity acceleration. Their velocity (even more than 700 Km/h in deep ocean vs. less than 70 Km/h in shallow waters) is much larger than humans can run for escaping them. This means that escape ways must be timely prepared for addressing people to the closest safe place, at any moment and wherever they are, independent of wether or not a regional *tsunami* alert system is available.

Following an official request of international aid issued by the Government of Sri Lanka - focused on urgent, *tsunami*-related emergency planning - the concepts outlined above were converted into an operational frame, founded on State-of-the-Art remote-sensing techniques.

The project, entitled “*The precise Digital Elevation Model of the Coastal Areas of Sri Lanka*” and nicknamed *HyperDEM*, was designed in a combined effort by Italian experts at the University of Calabria, the Polytechnic of Milan and the National Institute for Oceanography and Applied Geophysics of Trieste. Funded by the Italian Foreign Office, *HyperDEM* started in Autumn 2005. The handing over of final results between the Ambassador of Italy and the Srilankan Minister of Disaster Management and Humanitarian Affairs, took place in Colombo on December 7th, 2006.

RATIONALE

According to governmental agreements, *HyperDEM* aimed to mapping in 3-D and at high resolution, a portion of the coastal areas of the island hosting at least two-thirds of damage and casualties observed in 2004 (Fig.1).

Fig.1 Contour of coastal areas prospected by airborne LiDAR (dotted white lines, Southeast to West) and spaceborne RaDAR (grey continuous line, to the East), with ca. 20 km overlap. The inland extent of LiDAR strips ranges from 3 to slightly over 10 km, whereas RaDAR coverage extends from ca. 5 to over 20 km inland.

The overall impact of the 26th December 2004 event – probably the largest *tsunami* ever – was ca. 283’000 casualties and 14’000 missing persons, with nearly 1,100,000 displaced. In Sri Lanka, the death toll was definitely fixed at the level of ca. 34’000, with some 200,000 displaced. Still in Sri Lanka, the percentage of affected coastal populations ranged from 35% in the northern coastal districts to 80% in the eAstern districts, whereas southern districts displayed ca. 30% impact, albeit with scattered pockets of severe damage.

Notwithstanding the 2004 earthquake was obviously unpredicted, once it was felt in Sumatra it would have been possible to give a 2-3 hour advance notice of potential impact of the *tsunami* wavefield on distant countries as India, Maldives and Sri Lanka.

This did not happen, due to lack of a monitoring-and-alert system. However, the alert system alone would not have solved the problem, since major preparedness measures are required to timely move exposed populations to reachable and safe areas nearby, and to avoid blanket evacuation. In particular, damage maps demonstrate that unnoticeably elevated areas - even very close to the shoreline - can be good and sometimes unexpected escape places to single out and include in emergency plans, whereas the flat eAstern coasts of Sri-Lanka have undergone damage up to the outstanding distance of 8 km inland.

Since *tsunami* waves propagate at sea and create maximum damage on mainland, required knowledge is twofold. Accurate sea-bottom mapping allows modelling and forecasting (i) the wave pattern, (ii) the energy distribution and (iii) the run-up before impact: in brief, the “model *tsunami*”. In turn, high-resolution, accurate terrain mapping allows modelling and contouring precisely (iv) the limits of the impact zone, (v) the expected severity of impact, as well as (vi) the effect of manufacts on energy absorption and/or dispersion: in brief, the risk model and the scenarios.

The suitable combination of knowledge (i) to (vi) allows emergency deciders to plan evacuation and safety measures, and urban planners to protect citizens.

Project *HyperDEM* has dealt with items (iii), (iv) and (v). It was conceived bearing in mind the need for objective elevation mapping of the coastal areas, where “objective” stays for “precise” and “synoptic”. With respect to traditional topography missions, synoptic remote-sensing missions allow carrying out everywhere, fast and precise vertical measurements (from centimetres to metres) with unrivalled horizontal resolutions (from fractions of a square meter to a few tens of square meters).

THE AIR AND SPACE CAMPAIGNS

Over 1780 km^2 of coastal areas were prospected during the airborne campaign of February 2006. The survey, planned for integrated operation and combined acquisition of active and passive instruments at once, was designed on target ground resolutions of 1 m^2 for LiDAR, and 4 m^2 for hyperspectral.

The average inland extension of prospected area is ca. 3 km, with a maximum of over 10 km in the area of the artificial basin and the dam of Angunakolapelessa, in the south. Airborne LiDAR, orthophotos and hyperspectral data were acquired between February 11th and 21st, with a five-day interval (February 17th to 20th) devoted to processing and preliminary analysis of data acquired during the first leg.

The following payloads were installed on the airborne platform, a De Havilland Beaver DHC-3 flown by the Srilankan private operator Air Taxi :

- A LiDAR system Optech ALTM 3033. The instrument consists of a Near Infrared (λ=1064 nm) Laser beam with pulse repetition rate of 33KHz. A scanning mirror directs the Laser optical pulses across the flight path, providing coverage to either sides of the flight direction. The forward motion of the aircraft provides coverage in the direction of flight.
- ALTM incorporates a GPS receiver and an Inertial Measurement Unit (IMU). Roll, pitch and yaw (attitude) of the aircraft are measured by the Inertial Navigation System unit at a frequency of 200 Hz.
- A Hyperspectral Radiometer AISA Eagle 1K by the Finnish firm SPECIM. It is a pushbroom scanner made up of a V-NIR hyperspectral sensor, a GPS/INS Applanix sensor, and a laptop implemented data acquisition unit.

- AISA Eagle 1K operates at wavelengths between 400-970 nm; it is able to record up to 244 bands (with spectral sampling of 2.3 nm/pixel) and 1024 spatial pixels. The system is flexible enough to allow acquiring data in almost every band combination, simultaneously acting on the number of bands and the bandwidth by use of a computer assisted procedure.
- A semi-metric digital camera ROLLEI 6008 db45, with digital back Phase-One, model H2O. The camera presents a pixel spacing is 9 micrometers, in a scene composed of 4080 x 5440 pixel with 48-bit dynamics. Acquisition is assisted by a camera compensation system to adjust the roll and pitch variations due to aircraft position and flight attitude.

The flight zone (Fig. 1) spanned between Puttalam, in the West, and Pottuvil, in the Southeast. For security reasons, authorized flight plans did not include the capital, Colombo, nor damaged coastal zones in the East (Trincomalee, Batticaloa, Ampara, Pottuvil). Instead, EAstern areas were covered by spaceborne RaDAR, and qualified by high resolution spaceborne multispectral observation.

Aircraft flight paths were computed in realtime by Differential Kinematic GPS, using data simultaneously acquired by one GPS receiver onboard the aircraft and twin-frequency geodetic GPS receivers Ashtech at the fixed rate of 60 data/minute. Twin-frequency GPS receivers were operated only on the benchmarks of an ad-hoc geodetic frame created by OGS, starting from a re-calculated benchmark monumented at the Katunayake airport by the Sri Lanka Survey Department.

All benchmarks of the new geodetic frame were located both in Universal Transverse Mercator (UTM 44 North) on ellipsoid WGS84, and in Mercator Transverse on ellipsoid Everest 1830.

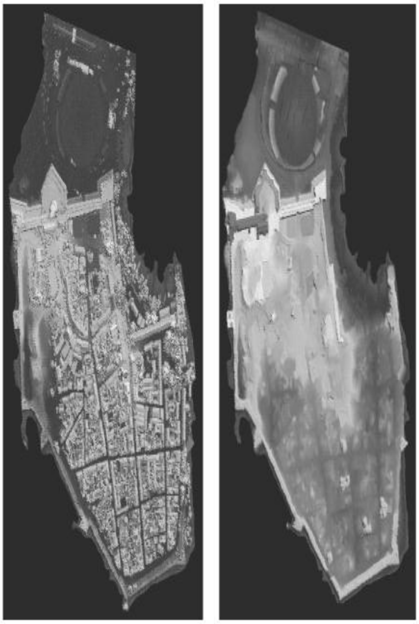

Fig.2 LiDAR-derived, Digital Surface Model (DSM, left) and Digital Ground Model (DGM, right). DSMs, obtained by mapping first LiDAR returns from terrain, including buildings and trees canopy, are not appropriate for traditional cartography. However, DSM are better suited than DGMs to *HyperDEM*-like applications in urban areas, since they allow 3-D mapping of buildings and infrastructures exposed to hydraulic impact. In the example above, removal of 3-D objects (right) is done by removing LiDAR reflections from the top of trees and solid objects, and mapping only late LiDAR returns from ground. The example relates to the XVII century Dutch fort in Galle, whose thick defence walls are singled out after removal of objects in the DGM (right).

Flight heights ranged between 900-2’700 metres, as a function of the desired ground resolution, the morphology and land-cover of surveyed areas, and the meteorological conditions.

GPS data were integrated to IMU data acquired at 200 Hz, giving rise to Best Estimated Trajectory of the aircraft composed of fixes spaced ca. 15 cm from each other, and characterized by residual r.m.s. errors better than 0.3 metres. Range data were georeferenced by use of spatial and orientation parameters; basic products are vectors of points, including the information on position, GPS time and backscattered LiDAR amplitude. All products are delivered in UTM (44 N) projection, on WGS84 ellipsoid. LiDAR data were also corrected by use of a geoidic model derived from the EGM96 model.

As for the space campaign, the dataset is composed of both RaDAR (28 ERS-2 and 8 ENVISAT) and Multispectral scenery (6 LANDSAT-7/ETM+, 4 ASTER, 21 QUICKBIRD)

To accomplish with the aim of *HyperDEM*, repeat-pass interferometry was carried out and provided two different products: Permanent Scatterers (PS) data and Digital Surface Model using ERS-1/ERS-2 ‘Tandem’ pair combinations.

The only available archived data source of any substance covering the region of interest and dating back to 1992, is that from the ERS-1 and ERS-2 satellites, belonging to the European Space Agency (ESA), with possible later refresh by combined use of ERS-2 (still active, in "gyroless" mode) and ENVISAT.

A search of this database revealed two catalogued data sets are available. The images were acquired along the descending orbits, since the number of acquired images during the ascending passes was too low for application of the Permenent Scatterers Interferometry (PS-InSAR) technique. Each ERS image covers an area of about 100x100 Km, and is identified by the date of acquisition, a Track number - corresponding to the satellite orbit – and a Frame number, that specifies the 100x100 Km 'tile' within the Track.

The data used for this project were ERS Track 33 - Frame 3465 and Track 33 - Frame 3447, acquired since 1992 and selected as a function of the baseline, with uneven time intervals between acquisitions. Later attempts to merge most recent ERS-2 and ENVISAT data acquired 2005-2006, did not reveal successful.

DATA AND MODELS

Raw data coming from the LiDAR airborne acquisition are in dual form, "first pulse" and "last pulse". Post-processing is required to transform clouds of points in a standard format suitable for immediate and straightforward utilization by the End User. Post-processing allows removing errors, or filling void data normally resulting from acquisition.

The generic definition of "DEM" (Digital Elevation Model), applies to elevation of terrain referred to bare-Earth without vegetation and/or manufacts. "DEM" is synonymous of "DTM", Digital Terrain Model. To avoid confusion in definitions, post-processed data are called *Digital Ground Model* (DGM) and *Digital Surface Model* (DSM) , respectively.

DGM represents the bare-Earth elevation cleaned of vegetation and manufacts, whereas DSM represent the elevation of LIDAR first pulses, including manufacts (Fig.2). Although including vegetation, DSM is indicated for detailed inundation mapping in urban areas: conversely, DGM is suitable for mapping the water penetration in vegetated areas with little presence, or absence of manufacts.

Considering that quality and reliability of elevation measurements strictly depend on the actual land-cover, and that LiDAR radiation may penetrate the canopy - thus providing a good measure of ground elevation even beneath the trees in the tropical rainforest - hyperspectral and multispectral observation from air and space were used for pixel-by-pixel terrain qualification.

In particular, Digital Elevation Models obtained by airborne LiDAR, were associated to co-registered airborne Hyperspectral data that underwent unsupervised, level-two classification for automatically discriminating bare soil from vegetation. Finally, unvegetated pixels were weighted 1, vegetated pixels weighted 0, and vegetated pixels for which two LiDAR returns are available (an early reflection from the top of canopy, and a late reflection from the underlying ground) were marked 0.5.

This procedure allowed automatically creating (i) a mask including all points whose elevation is fully reliable within the nominal error range, and (ii) a three-dimensional, level-two land-cover of subsets weighted 0.5 and 1.

Same procedure was followed for qualifying decametric Digital Surface Models – obtained by spaceborne RaDAR interferometry on data acquired by satellites ERS and ENVISAT of the European Space Agency – by means of multispectral ASTER and LANDSAT-7/ETM+ scenes provided with comparable ground resolution. In this case, however, three-dimensional landcover was not obtained because of the lack of Digital Ground Modelling capacity in C-band RaDAR operation on vegetation.

The information was completed by carrying out same bare soil classification on multispectral, very high-resolution, pre-/post-*tsunami* QUICKBIRD data. In spite of the comparable pixel footprint, however, the 4-band Visible-Near Infrared spectral content of QUICKBIRD provided much poorer information than the airborne 64-band Hyperspectral radiometer.

Unlike airborne LiDAR, spaceborne RaDAR data do not allow creating dual products because of the pixel size (ca. 10 to 30 metres) and the illumination frequency (6 GHz, C-band, that does not allow penetrating the canopy) and can lead to creation of DSM only. However, in spite of limitations related to looser ground resolution, our spaceborne DSMs present a nine-fold resolution improvement with respect to standard SRTM (Shuttle Radar Topographic Mission), and are good enough to realistically approximate the bare Earth envelope in areas with sparse or nil vegetation.

Both post-processed LiDAR products keep a horizontal resolution of 1 meter, and a vertical resolution better than 30 cm. Conversely, RaDAR DSMs present a (resampled) horizontal resolution of 30 metres, a measured vertical accuracy of 2.6 metres and a theoretical vertical resolution in the order of 0.01 metres (in differential mode).

Aimed to estimate the accuracy of PS-InSAR DSMs, a comparison with LiDAR was done over the RaDAR-LiDAR overlap area of Arugam Bay, in the southeast (see Fig.1).

It is worth noting that these products display a one-order of magnitude difference in ground resolution (1 m x 1 m pixel footprint or LiDAR vs. 30 m x 30 m for InSAR Digitam Surface Model), so the standard deviation was evaluated accounting for all possible Easting/Northing shifts.

Computed standard deviations present a least value equal to 2.56 m,, that can be assumed as the most reliable estimate of best PS-InSAR topography accuracy in height.

As expected, largest elevation differences between LiDAR and RaDAR digital surface models are raised at, or close to flat, near-perfect reflectors (rivers and lakes) that favour RaDAR forward reflections while minimizing Signal-to-Noise ratios in backscattered returns. Accounting for the huge data volume, the process of map generation required the development of an automated procedure to process the data set, preserve correctly the surface information, and minimize the time consumption.

In conclusion, LiDAR models were arranged in tiles of 1000 x 1000 x 1 metre (excepting those along the shoreline), for as much as 4'600 Billion gridpoints measured in elevation.

Spaceborne RaDAR Digital Surface Models were arranged in two frames of 1811x3497 and 894x3202 (columns x rows) respectively, with 30-metre spacing of points, allowing for total. 2.4 Million gridpoints measured in elevation.

RESULTS

According to the inter-Government agreement, the Disaster Management Center in Colombo (acting End User of *HyperDEM*), was provided also with a few inundation examples as in Fig.3, aimed to demonstrate the procedures for *tsunami* scenario building. For the sake of simplicity, simulation was conducted not accounting for the dynamic component of the *tsunami* wavefront.

Surprisingly, this "static" procedure – that does not allow calculating the energy budget, nor its distribution on obstacles on land – provided a very satisfactory fit with observed inland penetration of waters on December 26, 2004.

In conclusion of this short note, it is therefore worth observing that static inundation simulation on HyperDEM generated high-resolution 3-D digital Earth, are perfectly suited to build scenarios of inland propagation of *storm surges* that are - by far - the most important threat to the srilankan coasts.

Indeed, while only a handful of significant *tsunamis* is reported for the Central Indian Ocean in the last four centuries before 2004, *storm surges* associated to extreme, seasonal cyclogenesis in the Bay of Bengal have repeated frequently, with a worldwide unequalled edge (500'000 casualties) in Bangladesh, 1970.

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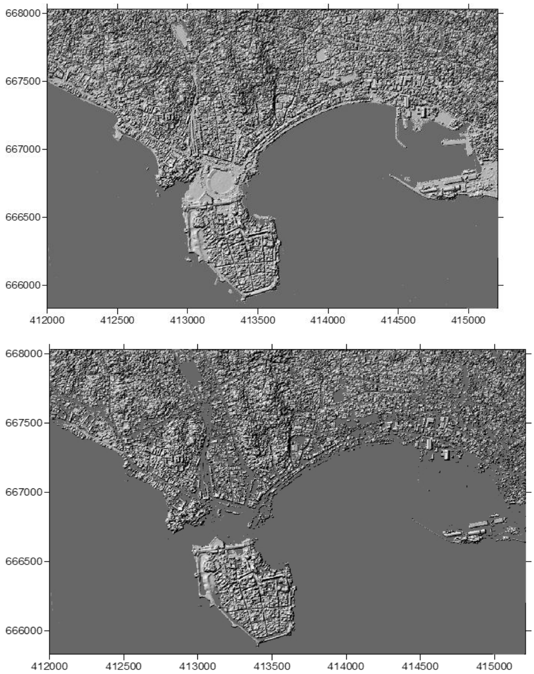

Fig.3 Digital Surface Model of the town of Galle (top), and inundation simulation by a 4-metre model *surge* (bottom). The synthetic scenario is satisfactorily consistent with the real case *tsunami* of December 26, 2004.

Complementary, pre/post-*tsunami* very high-resolution multispectral QUICKBIRD scenes were granted by the USGS-Pacific Disaster Center (Maui, Hawaii) that is gratefully acknowledged. The whole work was effectively backed by round-the-clock logistic and operational support provided by the Srilankan Air Force, the Disaster Management Centre, the Ministry for Science and Technology, Srilankan Airlines and the pilots of Air Taxi, and the personnel of the Italian Embassy in Colombo.

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