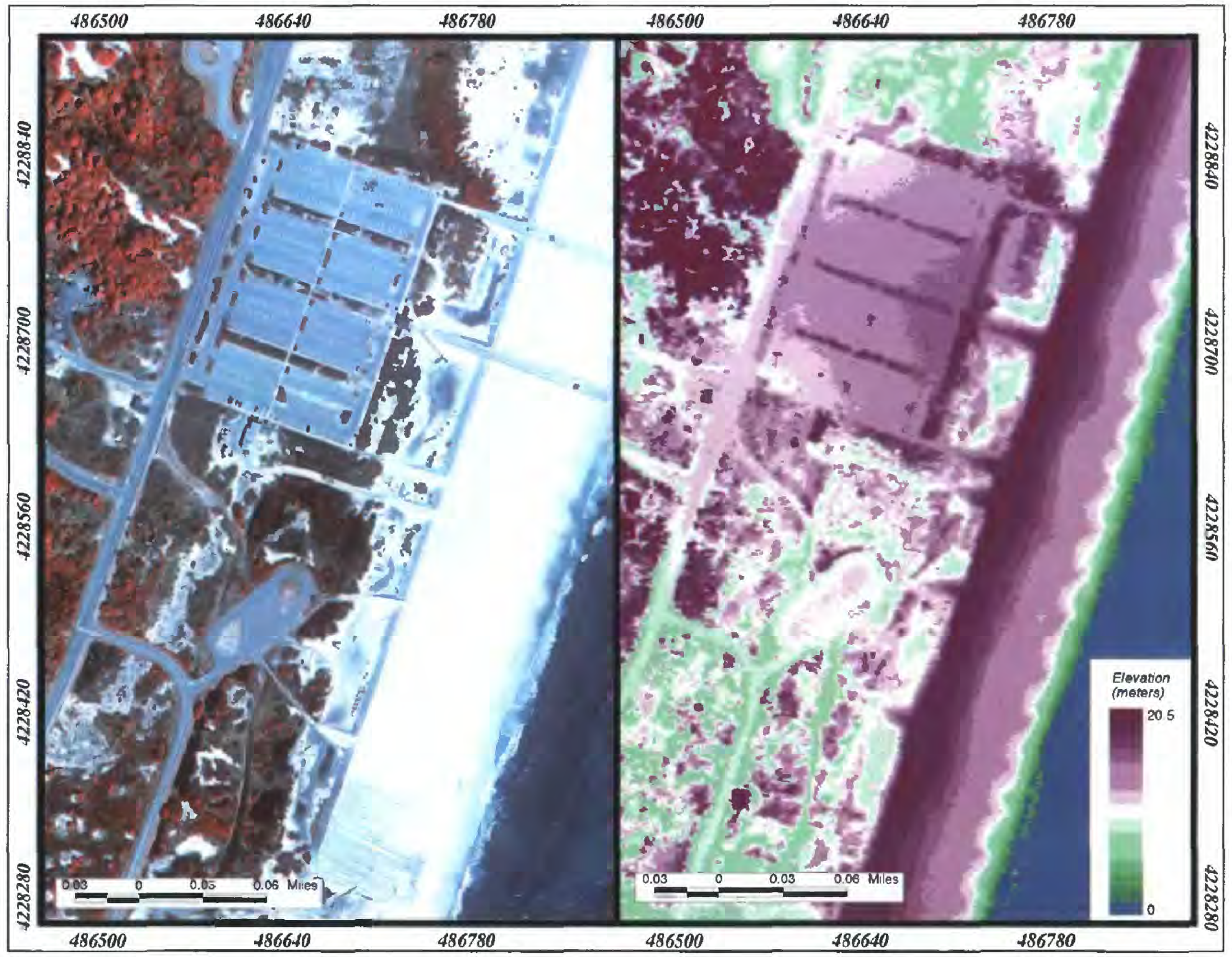

Figure 5b. Aerial photograph (left) and topographic lidar elevation map (right) covering a parking lot at Assateague Island National Seashore.

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Airborne Topographic Lidar Mapping for Coastal Science and Resource Management *by John Brock and Asbury Sallenger*

Airborne Topographic Lidar Mapping, also known as airborne laser surveying (ALS) *(Fig. 1) may now be applied to a wide range of coastal science questions and resource management issues at relatively low cost. Examples include the mapping of "bald earth" land surfaces below even moderately dense vegetation in studies of geologic framework and hydrology, and determination of the vertical distribution of vegetation material for improved habitat mapping. ALS has also proven to be an excellent method for the regional mapping of geomorphic change along barrier island beaches and other sandy coasts due to storms or long-term sedimentary processes (Sallenger et al., 1999). Similarly, bathymetric lidars are of great value in the analysis of shallow benthic environments. Coastal scientists are also adopting ALS in the prediction, modeling, and assessment of landslides along sea cliffs and headlands, examination of subsidence causing coastal land loss, improved storm surge and tsunami prediction, and for topographic monitoring of active volcanoes (Brock et al., 2000).*

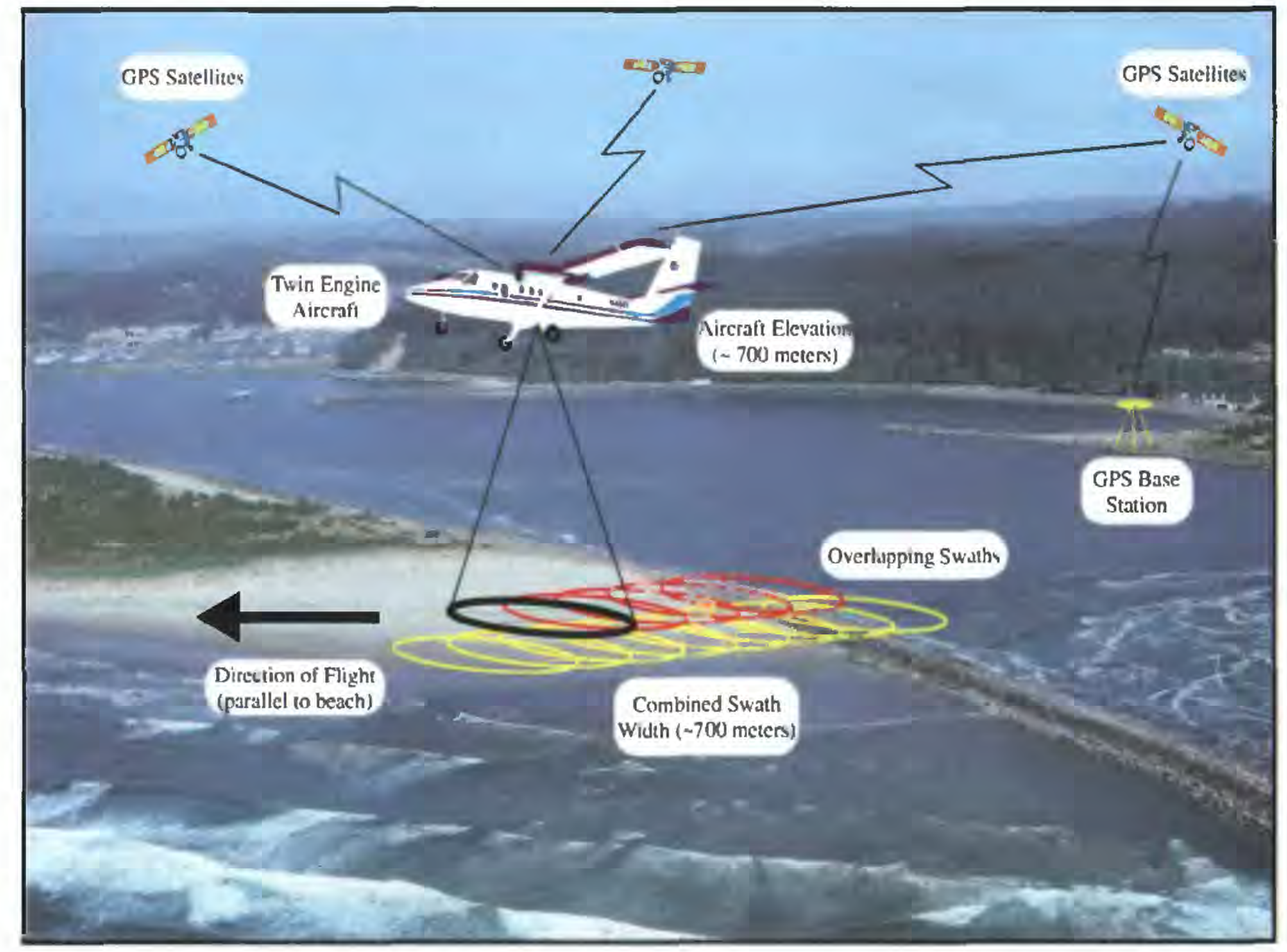

Figure 1. Airborne lidar mapping system in operation.

Introduction

Topographic information, a basic element in studies of geomorphology, hydrology and sedimentary processes can now be rapidly and accurately acquired at various spatial scales by ALS (Ackermann, 1999). Airborne laser surveying, inclusive of both topographic and hydrographic surveying, is a type of remote sensing generally known as ***"Light Detection and Ranging" (lidar)*** that has undergone rapid development during the last two decades. Numerous recent studies have verified that current ALS systems have potential to contribute to a wide range of additional coastal scientific investigations (Krabill *et al.*, 2000).

The advent of laser scanning as a new method for the direct, high density measurement of high vertical accuracy elevations from aircraft has been enabled by the parallel development of several techniques. Kinematic differential GPS methods now enable the positioning of light aircraft to within several centimeters (Krabill and Martin, 1987). Inertial Navigation Systems (INS) or Inertial Measuring Units (IMU) can provide three-dimensional aircraft orientation at 64-Hz with errors less than 0.005 degrees (Fig. 2), rendering aerotriangulation based on ground data points largely obsolete. Lightweight solid-state laser transmitters can provide elevation measurements at 2,000 to greater than 20,0000 points per second from a nominal 1000 meter altitude with an accuracy of 15 centimeters or better.

Coastal Applications

Combined within contemporary airborne laser mapping systems, these newly emerged technologies now enable low cost geomorphic surveys at near 10 centimeter vertical accuracy and at spatial densities greater than 1 elevation measurement per square meter. Researchers and resource managers are now pursuing various coastal resource applications for this remarkable capability. As much recent work has demonstrated, ALS is an excellent means of mapping change along barrier island beaches and other sandy coasts (Gutierrez *et al.*, 1998; Krabill *et al.*, 2000; Sallenger *et al.*, 1999). The ability of ALS to rapidly survey long, narrow strips of terrain is very valuable in this application, as beaches are elongate, highly dynamic sedimentary environments that undergo seasonal and long-term erosion or accretion, and are also impacted by severe storms. Closely related applications are airborne laser mapping of flood-prone coastal fluvial zones, and the use of

Figure 2. Inertial Navigation System used in topographic lidar mapping.

Figure 3. The NASA Airborne Topographic Mapper installed in a light aircraft.

laser bathymeters to survey benthic change caused by hurricanes. Wave effects on nearshore circulation, sediment transport, and littoral zone topography may be investigated through ALS coverage of sea state and surface wave displacement over continental shelves.

The most advanced airborne laser altimeters can record multiple reflections from a single laser pulse. This "multiple reflection" ALS is uniquely well suited to the mapping of land surfaces below even moderately dense vegetation, and enables the creation of "bald earth" digital elevation models in forested areas that can reveal fault scarps and stream channels. In addition to sub-canopy topography, laser altimeters that capture the entire time amplitude history of the return pulse can acquire the height and vertical structure of vegetation (Blair *et al.*, 1999).

Laser Mapping Systems

The typical ALS aircraft mapping configuration includes a twin- or single-engine light aircraft equipped with a lidar instrument, INS, and GPS, which is operated in tandem with a GPS base station, usually sited at the airport used to stage the flights (Fig. 1). In coastal applications, the aircraft flies along the coast at a height of about 700 meters, surveying a ground swath directly below the aircraft. The aircraft position throughout the survey flight is recorded by an onboard geodetic grade GPS receiver. The aircraft GPS signals are later combined with signals concurrently collected by a nearby GPS base station for differential kinematic GPS post-processing to determine the aircraft flight trajectory to within approximately 5 centimeters.

Although airborne laser mapping may be carried out at night, for flight safety, coastal ALS operations are normally confined to daylight hours, and timed to coincide with low tide to maximize coverage of the beach face. Use of lasers with sufficient pulse power minimizes the importance of atmospheric effects on laser signal intensity. However, where present, fog and heavy precipitation can cause inaccurate elevation measurement due to early reflection of pulses within the atmosphere. A variety of light aircraft are suitable for ALS, given installation of a port in the base of the fuselage and modification of the power supply to match the lidar instrument. The twin-engine aircraft used by USGS/NASA/NOAA beach mapping projects was selected based on maneuverability, high payload capacity, long range, ability to cruise at airspeeds near 100 knots, and safety considerations associated with flights over water. The bulk of topographic lidar data collected over US coasts has been acquired by use of the elliptically scanning ***NASA Airborne Topographic Mapper (ATM)*** (Fig. 3). This data set covers much of the Atlantic, Gulf, and West Coasts of the contiguous United States, and typically extends from the shoreline at least 700 meters inland.

Processing of Lidar Surveys

Specialized processing of ALS elevation data sets is necessary to enable their use in scientific analyses and Geographical Information Systems (GIS) without loss of essential information. The approach adopted by NASA (Level 1 processing) and the USGS (Level 2, Level 3, and Level 4 processing) is a multi-tiered system that is incorporated into the LaserMap software package (Fig. 4).

Aircraft Position → Laser Range ↓
Convert to Ellipsoid Elevations
Level 1 ↓
Convert to Common Reference system and Integrate Individual Swaths
Level 2 ↓
Generate the Digital Elevation Model
Level 3 ↓
Convert to Derivative Products (Images, Shorelines, Profiles, and Change Maps)
Level 4

Figure 4. Processing for topographic lidar observations.

The 3 lower levels (Level 1, Level 2, and Level 3) are common to virtually all applications of laser altimetry observations, and the fourth level (Level 4) allows easy entry of lidar topography and other derived information into a GIS. Determination of the spot elevation of a location on the earth's surface through aircraft laser altimetry requires that the laser range information be combined with the instantaneous location of the aircraft. Given laser range errors of several centimeters, the aircraft location must be known at all times throughout a survey flight to within approximately 5 centimeters in order to measure topography to the desired accuracy of 10 centimeters. This accuracy is achieved through the use of kinematic GPS techniques that rely upon comparison of the dual-frequency carrier-phase-derived position data obtained at both a fixed base station receiver, and at a mobile receiver in the aircraft (Krabill *et al.*, 2000). The aircraft location is determined via differential kinematic GPS techniques (Krabill and Martin, 1987) that involve the differencing of ranges obtained through reception of the GPS signals at both a fixed base station receiver and a mobile aircraft receiver. Combination of the laser range date with the aircraft locations during the survey results in data expressed in IERS (International Earth Rotation Service) Terrestrial Reference Frame 1997 (ITRF97) coordinates, referenced to the WGS84 ellipsoid. Ten to 15 centimeter vertical accuracy and meter horizontal accuracy ALS survey elevation data are available at the completion of Level 1 processing. The laser ground spot size and point to point spacing are typically 0.5 meters and 1 to 2 meters, respectively.

Level 2 processing converts the Level 1 data into a merged and sorted data set referenced to common horizontal and vertical datums, thereby greatly simplifying further analysis. Depending on the general compass bearing of the coastline, the data set for each flight line is converted from it's original elliptical scan geometry by ranking to an order in which consecutive point locations progress in latitude (north-south trending coasts) or longitude (east-west trending coasts) order. The ITRF97/WGS84 coordinates for the spot locations for each individual flight line are converted to the NAD83 horizontal datum using the GRS80 ellipsoid. Next, geoid heights are calculated by use of the National Geodetic Survey's GEOID99 model, and the ellipsoid and geoid heights are summed to yield orthometeric elevations in NAVD88, a vertical sea level datum. The resulting Level 2 data sets have a north-south or east-west sorted pseudo-raster geometry, are referenced to the NAD83 horizontal datum and the NAVD88 vertical datum, and typically merge observations from multiple swaths captured during several hours on a single day into one common data set.

Although readily comparable to many topographic observations collected using more traditional surveying methods, Level 2 data sets are basically lists of point values, not graphic visualizations of geomorphology or terrain surfaces. Level 3 processing first converts the coordinates of each point from longitude-latitude to UTM eastings and northings. The second stage of Level 3 processing grids the point elevation values to create adjacent tiles that cover the survey area. Level 4 processing converts Level 3 data into a variety of interpretable products that may readily be entered into a common Geographic Information System. Typical Level 4 products include scaled elevation image maps (Fig. 5a, b), vertical elevation change maps, and barrier island ocean or bay shorelines. As this stage is intended for interpretation of natural processes, Level 4 processing is tailored to the needs of particular scientific investigations, and as such, may differ considerably between various coastal research efforts.

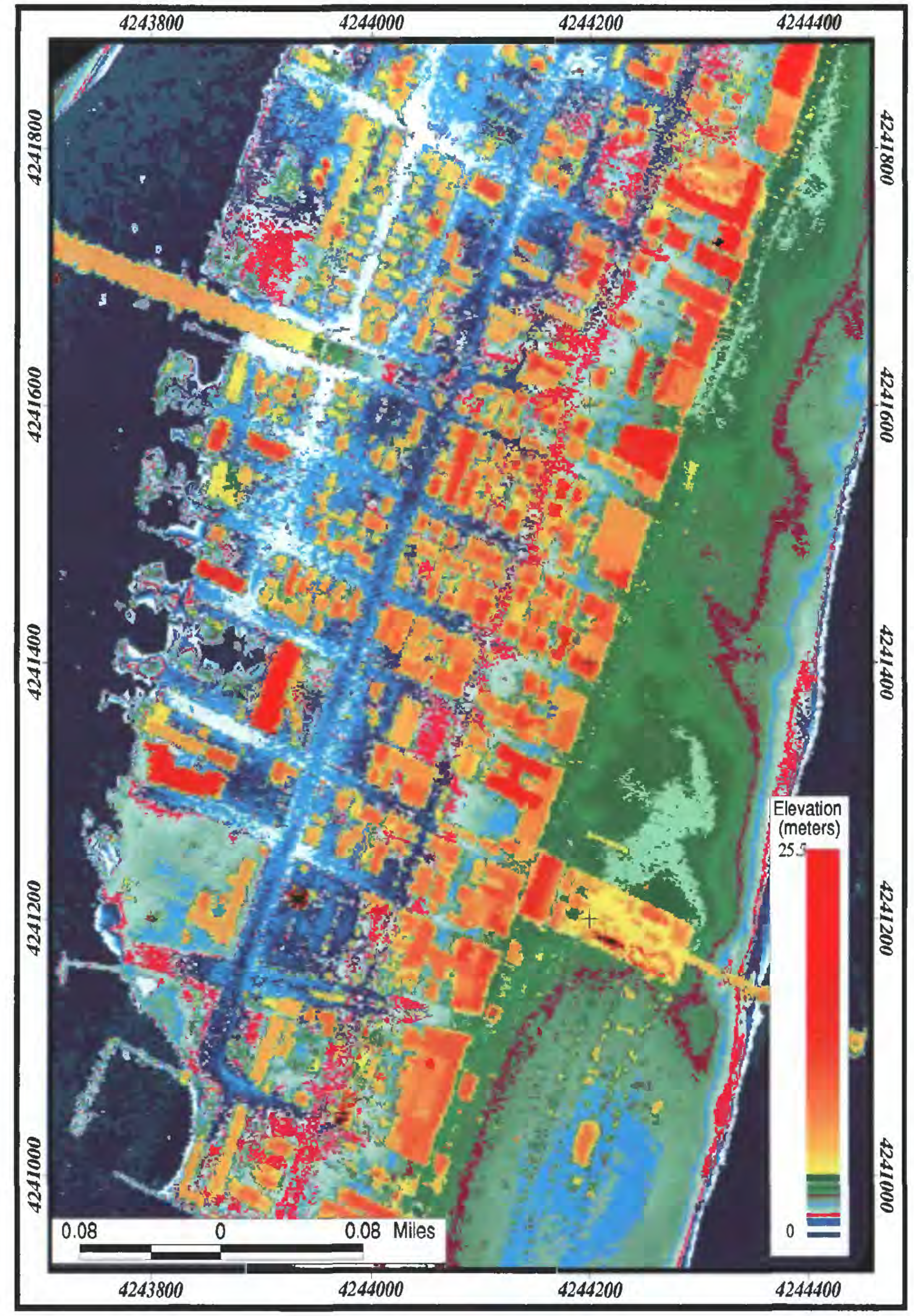

Figure 5a. Level 4 Topographic Lidar Elevation image map of a portion of Ocean City, MD. Colors correspond to ground height referenced to NAVD88.

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