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LIDAR as a Tool for Shoreline Mapping

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Abstract

Though the use of airborne lidar bathymetry (ALB) is not new, there is still a need for more reliable results using ALB in defining the shoreline. Previous algorithms for defining the land–water interface have used either the presence of a saturated peak in the infrared-channel waveforms, or a ratio between the green-channel, red-channel and infrared-channel waveforms to make a shoreline determination. Research and development for both algorithms were applied to older SHOALS-400 lidar data that varies in dynamic range and waveform record length from the current SHOALS-1000/3000 lidars. Observations of the red-channel waveforms show a strong dependence between the waveform and the presence of water. Different waveform characteristics are found from water and land returns (bare earth and vegetation coverage). We present here lidar observations from different land and water surfaces and an algorithm comparison for distinguishing land or water using the various lidar-channel waveforms. The results from the algorithms were compared with aerial imagery. The data for this study are from the 2000-2001 USGS surveys in Lake Michigan and Lake Tahoe, CA using the SHOALS-400 lidar system and the NOAA survey in the Isles of Shoals, NH-ME using the SHOALS-1000. The algorithm shows good preliminary results for both the older and the current SHOALS systems.

Introduction

The determination of the shoreline plays a major role in coastal management, where the land-water interface is a critical component. Accurate and consistent shoreline determinations are necessary for defining federal and state boundaries including marine territorial limits such as the Exclusive Economic Zone (EEZ). Hydrographic surveying and coastal management for storm modeling and damage assessment also relies heavily on demarcation of the coastal zone. Of the 95,000 miles of U.S. shoreline, to date only two-thirds are mapped and only a small portion were mapped using modern methods (Woolard et al., 2003).

There is a current need in the United States for efficient and cost effective ways to map the coast and near-shore areas (NOAA, 2007). The coastline is in a perpetual state of flux. The constant tidal influence interacts with topography and bathymetry to create a dynamic margin, and delineations along this margin vary with the stages of tide. The

National Ocean Service (NOS) of NOAA uses data from a 19-year tidal epoch to define Mean High Water (MHW) shoreline as a tidal datum derived statistically using the high-water heights and Mean Lower Low Water (MLLW) using the lower-low water recordings.

Aerial and satellite imagery can be used with modern stereographic techniques to derive digital elevation models (DEM). These DEMs allow for the delineation of shorelines such as MHW and MLLW (Parker et al., 2001). The limitations of this process arise from the variation introduced from individual operator interpretation imbedded in the current technique and correlation with the statistical definitions. There is a need for computerization of shoreline determination to combat these inconsistencies (Espey, 2003). The sensor technology used for shoreline mapping is passive imaging, which requires daytime acquisition and optimal weather conditions. As with other passive sensors, imagery relies on the collection of signals from the ambient scene and is therefore dependent on and affected by environmental factors such as haze, clouds, and illumination conditions (Molander, 2001). In contrast, active sensors produce, transmit to and receive from a remote location (Cracknell and Hayes, 1991). An active sensor may be designed and tuned for optimum remote sensing making it less sensitive to weather and lighting levels, although the effectiveness of the active sensor is dependent on outgoing source level and attenuation through the medium. The limitations of passive-sensors and the need for tide coordination limit the capacity for producing shoreline maps (NOAA, 2007).

Airborne lidar bathymetry (ALB) is an active sensor that is used for measuring bathymetry and topography in the coastal area. ALB is an airborne, scanning, pulsed laser that emits infrared and green wavelengths. The ALB technology is being explored by various groups worldwide in the coastal zone. Some examples of this research are: coastline mapping (Graham et al, 1999); rapid military reconnaissance (Lillycrop et al., 2000); and coastal monitoring and management (Irish, 2000 and Stockdon et al., 2002). An ongoing survey project of the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) is using ALB technology (SHOALS-1000 and SHOALS-3000 systems) to map the United States coastline. The project area includes the eastern seaboard, Great Lakes, and Hawaiian Islands (Wozencraft, 2007) (Figure 1).

The authors propose extending ALB capabilities from a bathymetric and topographic surveying tool into a shoreline mapping tool. This idea is not novel and was suggested in the past by Parker et al. (2001) and Woolard et al. (2003), however reliable results require careful interpretation of subtle features in the lidar data. A shoreline algorithm was developed based on observations from three generations of Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) lidar systems across the coastal profile (from water into the land). Preliminary results using this algorithm are presented here.

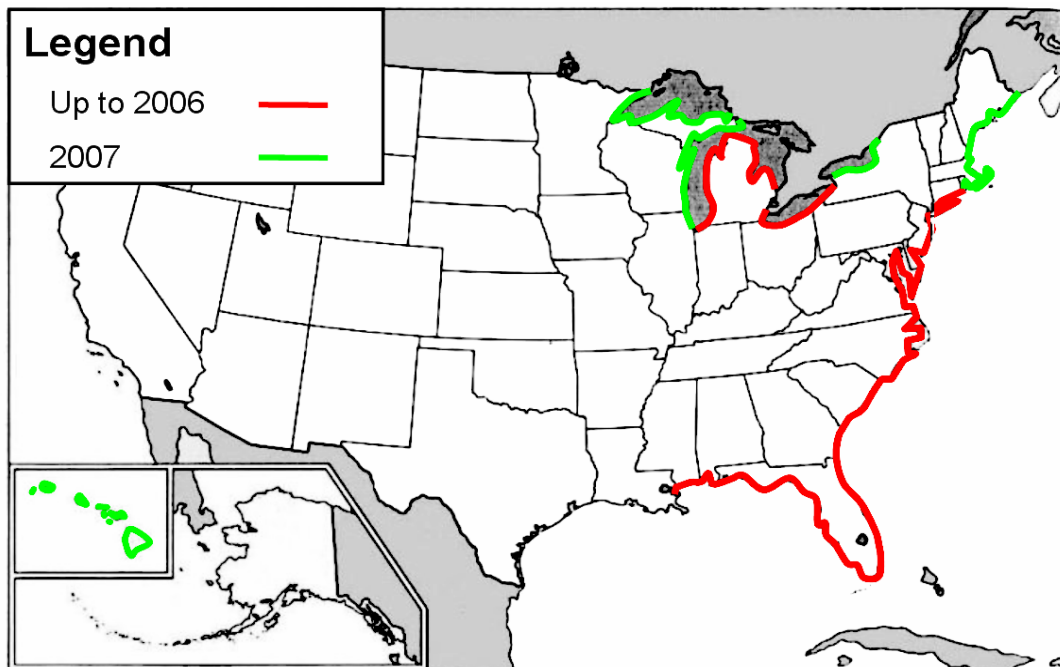


Figure 1. Current and planned lidar coverage area by JALBTCX. The red lines are the coastal zones that were surveyed up to 2006. The green lines are the coastal zones that are planned to be surveyed in 2007.

Airborne Lidar Bathymetry

ALB is a technique that traditionally has been used for measuring the depths of moderately clear, near shore coastal waters and lakes from a low-altitude aircraft using a scanning, pulsed laser beam (Hickman and Hogg, 1969; Guenther, 1985). The ALB systems uses a Nd:YAG laser that emits pulses at two wavelengths: (1) the natural wavelength of the Nd:YAG laser at 1064 nm in the infrared, and (2) frequency doubling of the Nd:YAG laser at 532 nm in the green (Penny et al., 1986; Guenther et al., 1994).

When the green laser pulse strikes the surface of a body of water, a fraction (less than 2%) is reflected back into the air and may be sensed by the receiver as the “surface return” (Guenther, 1985). The remaining portion of the green laser pulse is refracted into the water column, where scattering from entrained microscopic particulates cause it to spread out into a cone of continuously increasing angle. Once the laser beam has efficiently entered the water column, each individual photon may be scattered (elastically or inelastically) or absorbed (Exton et al., 1983). Elastic scattering is mainly due to Mie scattering from suspended particulates (Browell, 1977). Inelastic scattering is caused by two main processes: the Raman Effect and fluorescence. The first of these processes is when the high energy of the laser beam induces vibrational modes of the O-H stretch in the liquid water. The energy is re-emitted as photons at a different wavelength than was initially emitted by the laser. This effect is called the Raman Effect. The second inelastic process occurs when photons are absorbed by phytoplankton pigments found in the water column and re-emitted as fluorescence in a wavelength indicative of the host (Exton et

al., 1983). The water column backscatter for a 532 nm laser pulse is summarized in figure 2.

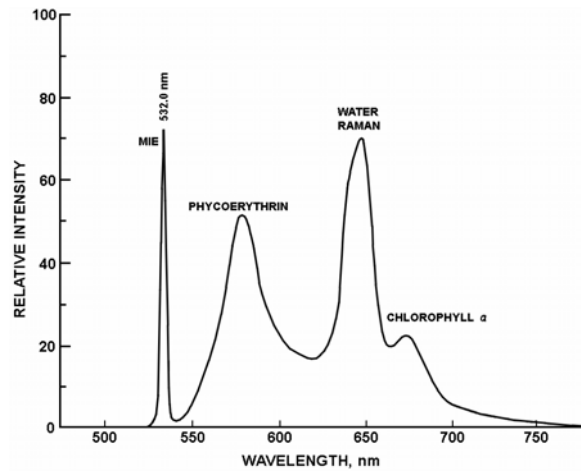


Figure 2. Backscattered spectra from natural water sample excited at 532.0 nm (based Exton et al., 1983).

Most bathymetric lidar-waveform research has been conducted by commercial lidar companies (LADS, SHOALS, HAWK-EYE) that use at least two channels to receive the returned pulses. Some systems, such as SHOALS use four channels: (1) an infrared channel (IR), (2) a green channel for shallow water using an Avalanche Photo Diode (APD), (3) a second green channel for deeper water using Photo Multiplier Tube (PMT), and (4) a red channel for receiving Raman-response pulse (RAMAN).

Methodology

In this study we investigate red-channel waveforms from three ALB systems: SHOALS-400, SHOALS-1000, and SHOALS-3000. The most obvious difference between the three systems is their scanning rates (400 Hz, 1000 Hz, and 3000 Hz, respectively). Also, the type of digitizer used in the SHOALS-400 system and the logging procedure is different than in the SHOALS-1000 and SHOALS-3000 systems.

The red-channel waveform observations were collected from four different lidar surveys that represent the three different generations of the SHOALS lidar system. Two USGS lidar surveys were conducted in Lake Tahoe, CA (2000) and Lake Michigan (2001) using the SHOALS-400 lidar system, one NOAA survey in the Isles of Shoals, NH-ME (2005) using the SHOALS-1000, and one USACE survey around Gerrish Island, ME and Portsmouth Harbor, NH (2005) using the SHOALS-3000 system.

Each study area was divided into land and water using aerial imagery that was collected during the time of the survey. The aerial imagery in the study was video data in the SHOALS-400 survey and digital images in the SHOALS-1000/3000 surveys. Based on aerial imagery, the red-channel waveforms from each lidar system were grouped according to land and water coverage. A subdivision of the land waveforms to vegetation coverage (grass, shrubs, and trees) or bare earth (sand, rock, asphalt, and concrete) was done also using the aerial imagery. This division is based on the possibility that the lidar

pulses may penetrate the vegetation coverage canopy, whereas the bare earth surface is opaque. The water red-channel waveforms were subdivided into water-depth groups. Depth values corresponding to each of the red-channel waveforms were assigned using the depths determined by the APD channel. The water red-channel waveform groups are 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m, 4.0 m, 5.0 m, 6.0 m, and 7.0 m. In depths shallower than 1 m, the waveforms were divided further according to their waveform shape into shallow and extremely shallow waveforms. An average digital value (8-bit and 10-bit for the SHOALS-400 and the SHOALS-1000/3000 systems, respectively) and a standard deviation were calculated for each time bin in the waveform group (Figure 3).

Observations

According to the observations of red-channel waveforms, it seems that the division should be of three types of red-channel waveform groups (“deep”, “shallow”, and land), rather than a division into two types of red-channel waveform groups (land and water). The characteristics of these three groups of red waveforms may be summarized as follows:

- “Deep” waters – These waveforms are also known as “basic” red waveforms (Pe’eri and Philpot, 2007). The common characteristic is that the waveform’s shape is not water-depth dependent and is the same for each sounding in the same survey line. The SHOALS-1000 and SHOALS-3000 waveforms are similar. The basic red-channel SHOALS-400 waveform has the same shape as the SHOALS-1000/3000 waveforms, but the digital value peak of the SHOALS-400 differs from the other two lidar systems.
- “Shallow” waters – These waveforms have also been called “shallow-water” and “extremely shallow-water” red waveforms (Pe’eri and Philpot, 2007). The shape of these waveforms is water-depth dependent. Also, the generation of a second peak that shifts to earlier time bins as the depth decreases was observed in the SHOALS-1000/3000 and the SHOALS-400 Lake Michigan waveforms. This second peak is attributed to fluorescence contribution (Wang, 2005).
- Land – The waveforms in all three lidar systems showed similar waveform characteristics. The bottom-return peak is weak and it is sometimes hard to distinguish the bottom-return peak from the other local returns present in the red channel-waveform. Also, no major difference in the waveform shape characteristics were noticed between the bare earth and vegetation groups.

The threshold between “shallow” and “deep” water varies between the lidar systems and the environment. In cases where aquatic vegetation is present, fluorescence occurs and may contribute to the red-channel waveforms (Wang, 2005; Pe’eri and Philpot, 2007). The fluorescence contribution generates a second peak that shifts to earlier time bins as the depth decreases. This second peak is noticed in water depths deeper than the Raman Effect. A schematic division of the waveform-group regions is presented in Figure 4.

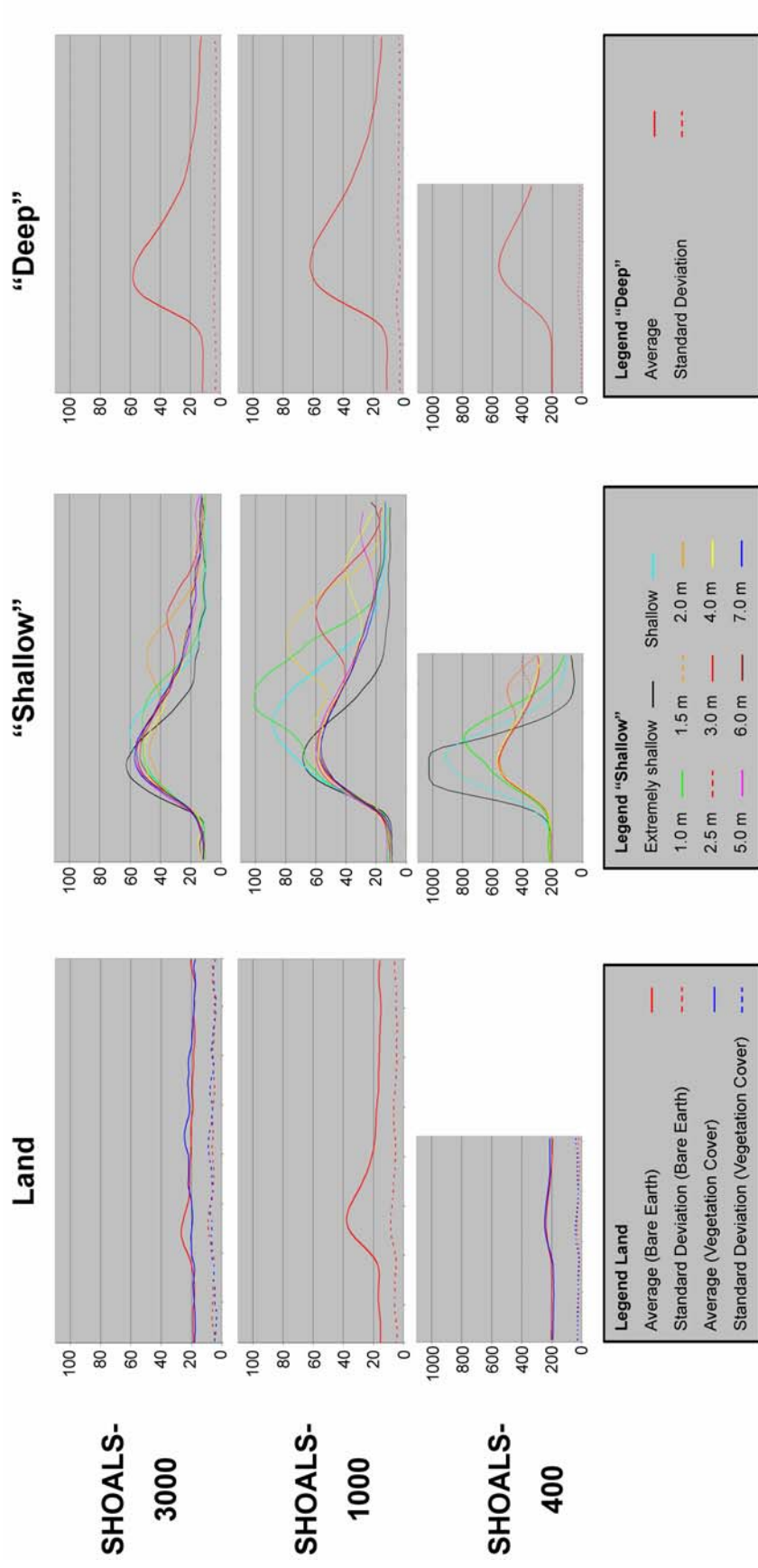


Figure 3. Red-channel waveforms from land, "shallow" and "deep" waters. Horizontal scale in 1 nsec bins; vertical scale in 8-bit digital number.

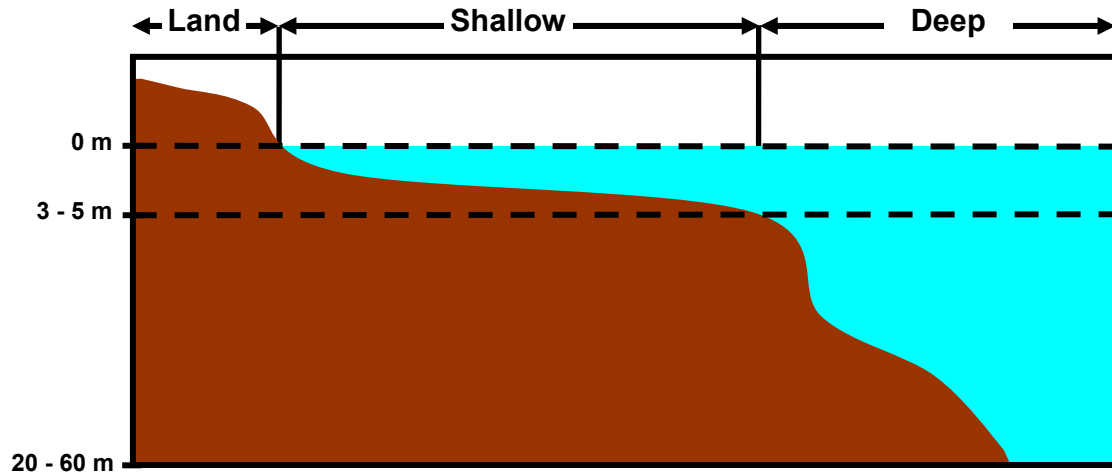


Figure 4. Coastal zones divided according to the lidar capabilities: Land – land topography to the water surface; Shallow – from the water surface to the water depth that the red channel is insensitive; Deep – from red-channel insensitivity depth to the lidar bottom-detection limit.

Land/water discrimination

The idea of using ALB as a land/water discriminator for shoreline mapping is not a new one. The most commonly used algorithm with SHOALS lidar data uses the presence of a saturated peak in the infrared-channel waveforms (Guenther et al., 1994; Guenther, 2001). The definition of a land sounding is that at least 5 time bins in the IR-channel waveform should have an extremely high value (digital number), almost at saturation levels. The difficulty with this approach is that, because the green channel return from very shallow waters is very similar to that from the land return, there is often uncertainty about the location of the land/water boundary. Because the red (Raman) channel is extremely sensitive to the presence of water, it can provide the information needed to refine the discrimination in the shallow-water zone. Based on SHOALS-400 data from Lake Tahoe and Lake Michigan, Pe'eri and Philpot (2007) modified the algorithm that uses the saturation of the infrared-channel waveforms with the peak value in the red-channel waveforms. Another published algorithm is an index algorithm that compares the ratio between the green-channel, red-channel and infrared-channel waveforms to discriminate land from water soundings (Sosebee, 2001).

The algorithms mentioned above were designed using the older SHOALS-400, and some were not directly applicable to the later SHOALS systems because of differences in dynamic range and waveform record length. The SHOALS-400 system used a 10-bit digitizer with 41-bin waveforms, whereas the SHOALS-1000/3000 systems used an 8-bit digitizer with an 80-bin waveform. In addition, the difference is affected by the SHOALS-400 waveforms being linearly logged, whereas the waveforms from the SHOALS-1000/3000 were logarithmically logged. Red-channel waveforms from land measurements show a very weak Raman peak or even no peak at all in all three systems.

Preliminary results

The new algorithm, based on the 3-level categorization (Figure 3) is conceptually different from the algorithms mentioned above and is designed to be effective with all generations of SHOALS data. Preliminary results of this land/water discriminator algorithm show good correlation to the aerial imagery mosaic. This algorithm is intended for all three lidar systems. Figure 5 presents preliminary results from Stateline Point, Lake Tahoe, CA-NV SHOALS-400 soundings classified as land or water based on the red-channel waveforms.

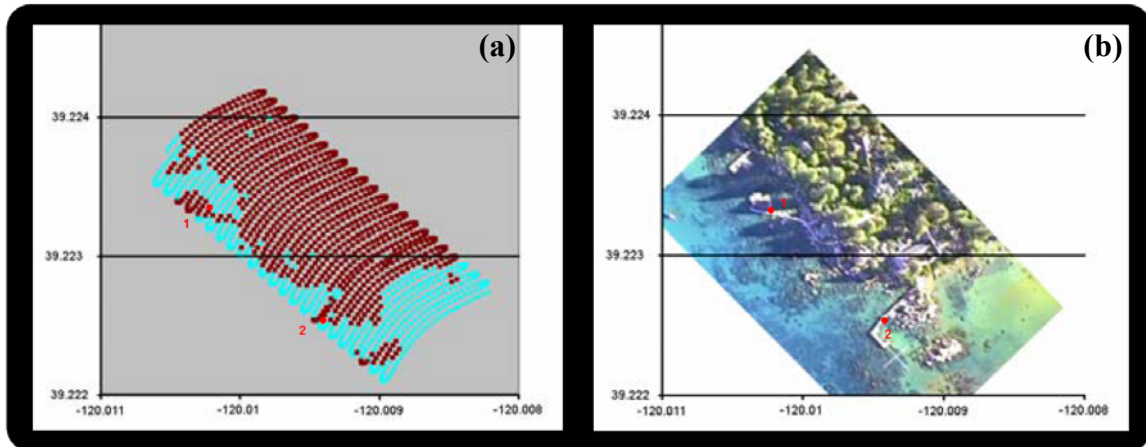


Figure 5. (a) Preliminary land/water discrimination results using the standard deviation algorithm. (b) Video mosaic of the study area. Points 1 and 2 are common control points in both images.

The red-channel shoreline algorithm presented here is only one of the steps needed for the production of shoreline vectors for charting. As mentioned in the introduction, the ALB system provides measurement of the topography and bathymetry. Using the inferred shoreline vector from the land/water discriminator and the DTM from the topography and bathymetry measurements, MHW and MLLW lines can be produced.

The authors plan future work on further understanding lidar capabilities as a tool for shoreline mapping. This work plan includes a comparison of the produced vectors from the red-channel shoreline algorithm to vectors produce from other available algorithms (Guenther, 2001; Sosebee, 2001). Also, the accuracy of the produced vector will be assessed.

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