Airborne Laser Hydrography II

(Blue Book II)

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NOAA PROFESSIONAL PAPER SERIES
National Ocean Service 1

AIRBORNE LASER HYDROGRAPHY

System Design and Performance Factors

Gary C. Guenther

Charting and Geodetic Services
National Ocean Service
Rockville, Md 20852

March 1985

U.S. DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

National Oceanic and Atmospheric Administration
Anthony J. Calio, Acting Administrator

National Ocean Service
Paul Wolff, Assistant Administrator

Charting and Geodetic Services
John D. Bossler, Director

Blue Book I

To the Pioneers
and to those
who kept the Faith

Blue Book I

Organization

- Designed to provide an “orderly, logical sequence, from the historical perspective, through the basic physics and terminology, to the detailed technical results and their ramifications. “
- “Specific areas of research and technical results may be accessed directly by referencing the appropriate section.”

Blue Book I

Blue Book II

1. Preface
2. Introduction
3. History and Reference Guide
4. Environmental Optical Properties
5. Basic Concepts and System Design (Includes radiative transfer models)
6. Basic Concepts in Data Processing
7. Depth Measurement Accuracy
8. Acceptance Field Test Objectives and Approaches
9. Applications, Ancillary Sensors and Fusion
10. Epilog (emerging and existing systems)

Blue Book II

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Blue Book II

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4. Environmental Optical Properties
5. Basic Concepts and System Design
    - Radiative transfer modeling (system, waveform, calibration, …)
    - Eye safety
    - System design, optimization, and constraints
    - Systems summary
6. Basic Concepts in Data Processing
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Blue Book II

Broad beam systems: Deep Water

		System		CZMIL	HawkEye II	Hawkeye III	LADS-MK3
		Company		Optech	AHAB	AHAB	Fugro LADS
HYDROGRAPHY	Laser	**Wavelength(s) (nm)**		532 & 1064 nm	532 & 1064 nm		532 nm
		Beam divergence (mrad)		7 mrad	11 mrad		3-8 mrad (adjustable - depends on survey height)
		Pulse duration (ns)		2 ns	5 ns		5-6 ns
		Power per pulse (mJ)		3 mJ	3 mJ		7 mJ
		Pulse rep. freq. (KHz)		10 kHz	4 kHz	10 kHz 35 kHz	1.5 kHz
		Total laser power (W=J/pulse * KHz)		30 W	12 W		10.5 W
	Scanner	**Scanner type**		Rotating Fresnel lens	2-axis servo-controlled scanner mirror		Oscillating mirror
		Scan pattern		circular	even distribution (arc shaped)	Elliptical scanning pattern	rectilinear
		Scan rate (Hz)		27 Hz	up to 13 Hz		18 Hz
		Off-nadir swath angle		20° (fixed)	±0-25°		adjustable
	Detection	**Aperture size (cm)**		20 cm	18 cm		15 cm
		detector FOV (mrad)		1.9 (shallow); 40 (deep)			
		Data sampling Rate (kHz)		10 kHz (deep); 70 kHz (shallow)	4 kHz		1.5 kHz
		Max. Secchi depth		2.5-3 x Secchi	3 x Secchi		2.5 x Secchi
		Max depth ($K_d D_{max}$)		3.75-4.0 @ ρ_{bot}>15%	3.0 @ 4 kHz; 3.5 @ 1 KHz	4 2	3.7
		Minimum depth		< 70 cm (system); <0.15 m (shallow water algorithm)	30 cm		50 cm
		Depth Accuracy	**System**	±30 cm, 2σ	±25 cm (IHO 1b)		< 50 cm (IHO 1)
			System+GPS	$[0.3^2+(0.013d)^2]^{1/2}$m, 2σ	???		???
		Horiz. Accuracy	**System**	???	±2.5 m		< 5.0 m (IHO 1)
			System+GPS	(3.5 + 0.05 depth) m, 2 σ	???		???
		Object detection		2m x 2m x 2m object	IHO 1		IHO 1a
	Position	**IMU**		Applanix POS AV AP50	Applanix 410	LCI-100-Litef IMU & SPAN	Applanix POS AV 610
		GPS		GPS/GNSS/Galileo/L-Band receiver (OmniSTAR capable)	???		Fugro OmniSTAR

Blue Book II

Narrow beam systems: Shallow Water

				Narrow beam systems (shallow water)				
		System		Aquarius	Chiroptera	EAARL-B	VQ-820-G	
		Company		Optech	AHAB	USGS	RIEGL	
HYDROGRAPHY	Laser	Wavelength(s) (nm)		532 nm	532 & 1064 nm	532 nm	532 nm	
		Beam divergence (mrad)		1 mrad	3 mrad	1.5-2 mrad	1 mrad	
		Pulse duration (ns)		7 ns	2.5 ±1 ns	1.3 ns	1.2 ns	
		Power per pulse (mJ)		0.1 mJ	0.1 mJ	0.07 mJ	0.02 mJ	(max 0.02 mJ)
		Pulse rep. freq. (KHz)		30 kHz	18 kHz	10 kHz	138 kHz	(up to 520 KHz)
		Total laser power (W=J/pulse * KHz)		3 W	1.8 W	0.7 W	2.76 W	max?
	Scanner	Scanner type		Oscillating mirror	Palmer scan mechanism	oscillating mirror	rotating 4-faceted pyramidal miror wheel	
		Scan pattern		Sawtooth	Ellipsoidal	rectilinear	Elliptical section	
		Scan rate (Hz)		0-70 Hz	up to 70 Hz	20 Hz	10-200 Hz	
		Off-nadir swath angle		±0-25°	±14-20°		±21-30°	
	Detection	Aperture size (cm)		5 cm	5 cm	15 cm	5 cm	
		detector FOV (mrad)						
		Data sampling Rate (kHz)		70 kHz	35 kHz	150 MHz	< 200 kHz	
		Max. Secchi depth		1 x Secchi	1 x Secchi	1.5 x Secchi	1 x Secchi	
		Max depth ($K_d D_{max}$)		1.5	< 1.5 @ 10% reflec	3.2	0.5	
		Minimum depth		30 cm	30 cm	30 cm	25 cm	
		Depth Accuracy	System	???	15 cm rms (seabed)	3-5 cm	± 2.5 cm	
			System+GPS	???	???	???	???	
		Horiz. Accuracy	System	???	75 cm rms	< 1 m		
			System+GPS	???	???	???	???	
		Object detection		???	???	???	???	
	Position	IMU		Appllanix POS AV 510	AEROcontrol IMU IIe	???	IGI IMU-IId	
		GPS		Appllanix POS AV 510	Dual frequency, 2 Hz	???	???	

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   - 6.1 Inverse problems of waveform processing
   - 6.2 Depth evaluation accounting for pulse shape
   - 6.3 Estimate of the diffuse attenuation coefficient
   - 6.4 Bottom reflectance estimation
   - 6.5 Effects of Forward scattering.
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5 Basic Concepts and System Design

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5.1 Basic System Design – an overview

Shachak Pe'eri

The design of all scanning lidar systems (terrestrial, atmospheric, topographic or bathymetric) is similar in general (Bunkin and Voliak 2001; Wehr 2009; Measures 1992; Renslow 2012). All require the same basic set of system components: a laser transmitter, a scanning mechanism, a receiving telescope, a narrow band filter matched to the laser wavelength, a detector – usually a photomultiplier tube (PMT) or an avalanche photodiode (APD) – and signal processing hardware to digitize, filter and store the returning backscatter. For airborne lidar bathymetry (ALB) systems it is convenient to divide the components into four main system units: a laser transmitter unit, a scanning unit (moving mirror), a detector unit (telescope, filter, detector and digitizer) and auxiliary systems (e.g., stabilization, time, attitude and position). Each of the main system units contribute to the overall uncertainty of an ALB survey and the specific characteristics of each must be considered in evaluating the overall design (White et al. 2011). In this section a general description will be provided for each of the system units. For an introduction to the more basic calculations based on the parameters of each system unit, the authors recommend Balstavias (1999) as a starting point reference. A detailed development of the design characteristics specific to ALB is presented subsequent sections of this chapter.

5.1.1 Transmitter unit

The laser transmitter unit includes the laser together with the optical elements that define the energy of the laser pulse, the pulse repetition frequency (PRF) and the beam divergence. ALB systems use a pulsed, frequency-doubled Nd:YAG (neodymium-doped yttrium aluminum garnet) laser that transmits at 532 nm, in the green part of the spectrum, near the optimal wavelength for maximum transmission in water over a wide range of conditions (Austin and Petzold 1984).

The power of the laser transmitter is a fundamental issue in lidar design. Simplistically, the greater the power, the greater the penetrations depth will be. However, power is limited by a number of considerations, probably the most significant being eye safety. The American National Standards

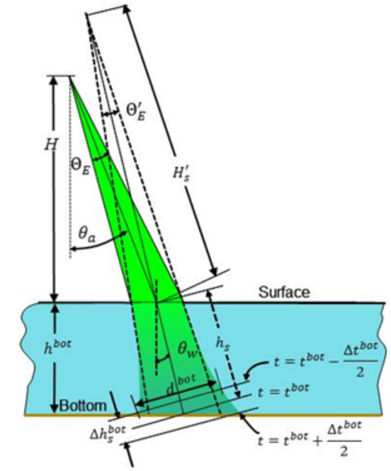


Figure 5.2.4. "Geometric stretch" of bottom-reflected lidar signal.

5.2.2 Return waveform

Guenther (1985) introduced two functions that will be useful for describing the temporal patterns in a lidar return signal resulting from a single emitted laser pulse:

- The "Impulse Response Function" (ImpRF), $S_\delta(t)$, defined as the temporal distribution of optical signal power at the lidar photo-detector for the case of infinitesimally short sounding pulse (delta-function),
- The "environmental response function" (EnvRF), $S_p(t)$, defined as the distribution of optical signal power at the photo-detector, generated by an actual (finite-duration) sounding laser pulse shape, $p(t)$, $0 \le t < \infty$.

The environmental response function, $S_p(t)$, may be represented as a convolution of the ImpRF with the sounding pulse shape,

$$S_p(t) = \int_0^\infty S_\delta(t - t') \cdot p(t')\,dt' = S_\delta(t) * p(t)\,, \qquad (5.2.6)$$

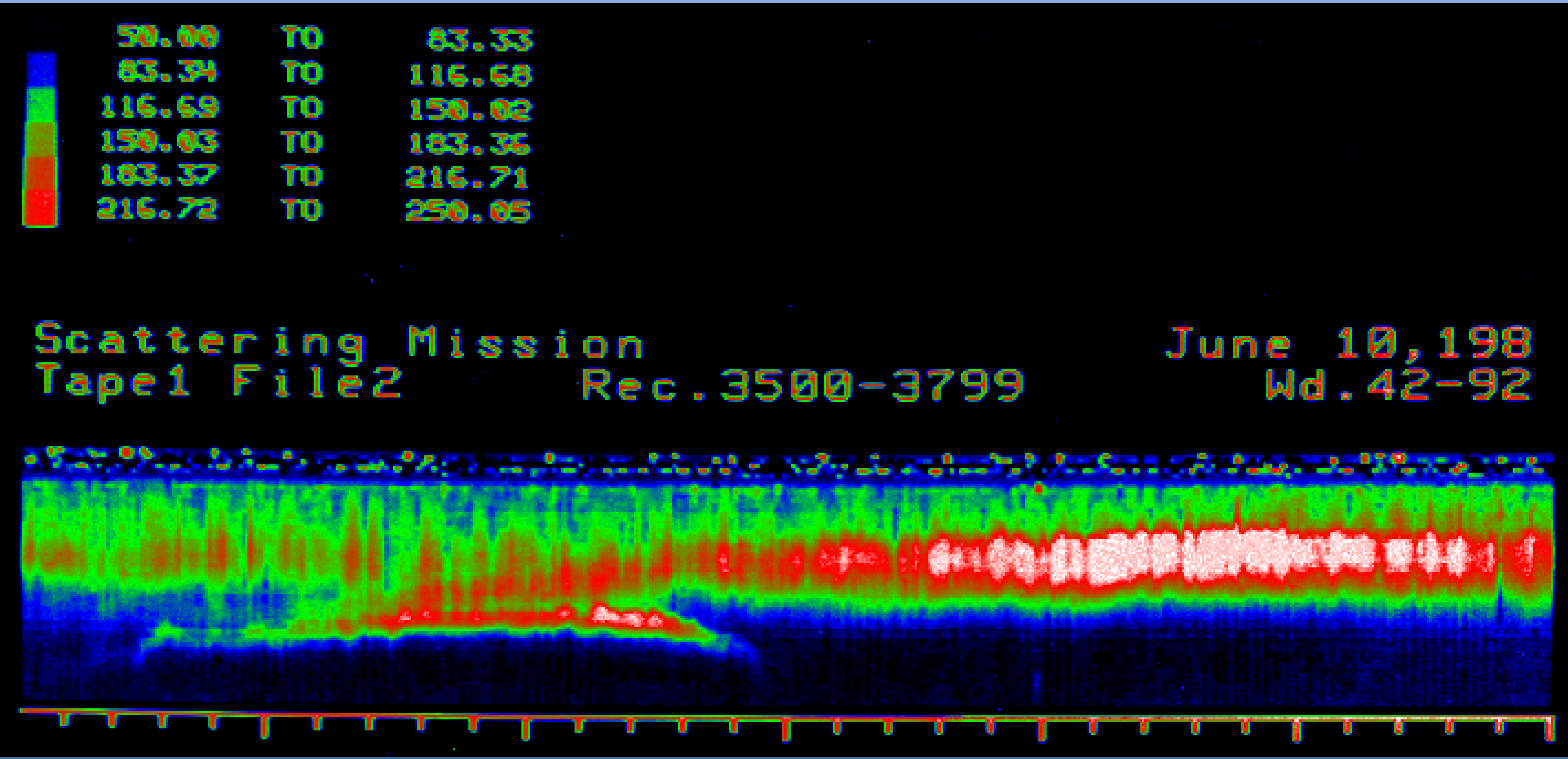
Blue Book II

- Equations:
  - Microsoft Equation editor
- References:
  - RefWorks;
  - Chicago 16th edition;
  - DOI
- Hard cover version
- On-line version:
  - video
  - interactive graphics, etc.

Blue Book II

1	Preface (2 pages)*		Gary Guenther
2	Introduction (5 pages):		Wozencraft & Lillycrop
3	History and Reference Guide (30 pages):		Wozencraft
	3.1.	Australia	Mark Sinclair
	3.2.	Canada	LaRocque
	3.3.	United States	Wozencraft
	3.4.	Sweden	Ekelund
4	Environmental Optical Properties		Pe'eri
5	Basic Concepts and System Design (pages):		Feygels & Kopilevich
6	Basic Concepts in Data Processing (pages):		Feygels & Kopelivich
7	Depth Measurement Accuracy (pages):		Philpot
8	Acceptance Field Test Objectives and Approaches (pages):		Pe'eri
9	Applications, Ancillary Sensors and Fusion (pages):		Wozencraft & Reif
10	Epilog (2 pages):		Philpot
		Emerging and existing systems, projections on direction	

AOL (Airborne Oceanographic Lidar)



Track from offshore to onshore, near Wallops Island, VA.
Note the entrainment of sediment in the current from the shoal.

Applied Optics, Vol. 27, Issue 19, pp. 3969-3977 (1988)
http://dx.doi.org/10.1364/AO.27.003969

Gonsalves, Michael Oliver. 2010. "A Comprehensive Uncertainty Analysis and Method of Geometric Calibration for a Circular Scanning Airborne Lidar." Ph.D., The University of Southern Mississippi.

Gordon, Howard R. 1982. "Interpretation of Airborne Oceanic Lidar: Effects of Multiple Scattering." *Applied Optics* 21 (16): 2996-3001. doi:10.1364/AO.21.002996.

Guenther, Gary C. 1985. *Airborne Laser Hydrography: System Design and Performance Factors*. Rockville, MD: NOAA Professional Paper Series, National Ocean Service.

Guenther, Gary C., Thomas J. Eisler, Jack L. Riley, and Steven W. Perez. 1996. "Obstruction Detection and Data Decimation for Airborne Laser Hydrography." 1996 Canadian Hydrographic Conference Halifax, Nova Scotia, Canada.

Habib, A., A. P. Kersting, Ki In Bang, and Dong-Cheon Lee. 2010. "Alternative Methodologies for the Internal Quality Control of Parallel LiDAR Strips." *IEEE Transactions on Geoscience and Remote Sensing* 48 (1): 221-236. doi:10.1109/TGRS.2009.2026424.

Hickman, G. D. and J. E. Hogg. 1969. "Application of an Airborne Pulsed Laser for Near Shore Bathymetric Measurements." *Remote Sensing of Environment* 1 (1): 47-58. doi:10.1016/S0034-4257(69)90088-1.

IEC. 2014. *American National Standard for Safe use of Lasers*. Vol. IEC 60825-1 Ed. 3.0. http://www.refworks.com/refworks2/default.aspx?r=references; MainLayout::init.