1970-1990: Airborne Lidar Hydrography Status

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ABSTRACT

This paper gives a course-grained historical overview of activities in airborne Lidar hydrography (ALH), starting with the general operating principles of the technique, then followed by a synopsis of the principal, worldwide ALH efforts over the past two decades. The main focus, however, is given to a discussion of the performance objectivities and design trade-offs in the SHOALS system, Optech Inc's current ALH program for the US Army Corps of Engineers. Finally, a comparison is given of the current ALH operational capabilities (depth, area coverage, accuracy, reliability, cost-effectiveness) to the currently used acoustic methods.

INTRODUCTION

Airborne lidar hydrography is a relatively new technique aimed at augmenting nautical chart production and bathymetric mapping capability in shallow coastal waters. The potential of water-penetrating airborne laser radar to provide cost effective characterization of underwater topography to depths as great as 50 m (depending on water clarity) has triggered a number of R & D efforts worldwide over the past two decades. Currently ongoing, however, and aimed at providing operational ALH tools, are Optech Inc's "SHOALS" program for the US Army corps of Engineers, and Royal Australian Navy's "LADS" program.

The motivation to develop ALH technique to operational status is primarily two fold: the speeding up of the surveying tasks that exists under the current mandate of the various hydrographic agencies, and the anticipated, significant savings in the cost-per-unit-area-surveyed. Millions of Km2 of uncharted waters with depths of less than 50m, that still exist world-wide, present a blocklog of hundreds of ship-years to conventional acoustic, surveying. Additionally, much of surveyed, navigation routes have bottom types that is sufficiently dynamic, in the short term, to require frequent resurveying. The much greater speeds, than that of surface vessels, of ALH platforms have already reasonably well demonstrated, in Canada over the last five years at least, that the nedded surveys can be done faster and more economically. Furthermore, because airborne, the use of ALH to carry out whatever surveys may be suitable to its capability provides a benefit of flexible deployment in distant areas with small operational windows, or shallow areas unsafe for survey boats. And, though perhaps not yet adequately appreciated throughout all of the hydrographic community, ALH offers, as standard, the benefit of virtually uniform x-y sounding distribution.

1. PRINCIPLES OF OPERATION

Figure 1 illustrates the operating of an ALH system. Laser-generated optical pulses, of wavelength suitable for propagation through water, are transmitted from an aircraft towards the water. An optical receiver, co-located with the transmitter, detects the pulse reflections from both the water surface and the bottom. The water depth is determined from the elapsed time between these two reflection/scattering events, after accounting for the operating geometry and corrections for propagation-induced biases and waveheight and tide effects. In the operational scenario shown, the laser pulses are scanned sequentially across the water surface to produce, when combined with the aircraft's forward velocity, a swath of soundings of uniform spatial distribution. The horizontal co-ordinates of the soundings are determined from the knowledge of the aircraft position, laser-beam exit angles, the aircraft altitude and attitude, and the measured water depth.

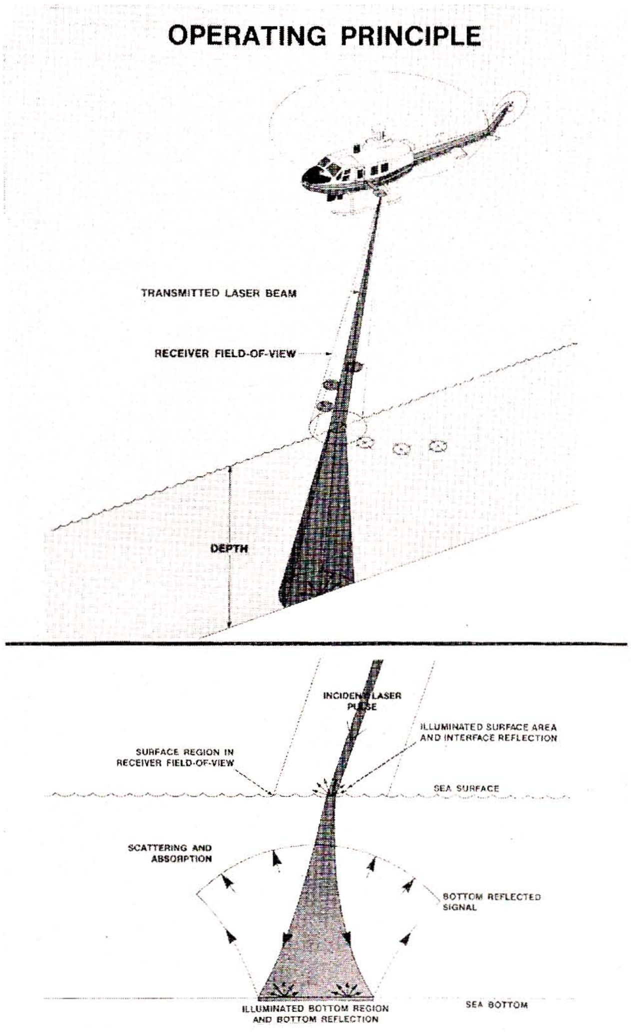

Fig. 1 - Airborne Laser Hydrography Schematic of Principle of Operation.

2. SUMMARY OF THE MAIN ALH EFFORTS

In the pre-1970 era most ALH-type work was sponsored by the US Navy, related to submarine detection (Ott., 1965 & SorensoN, 1966) and, at that time, classified. The first work, reported in the open literature came from University of Syracuse (Hickman, 1969) in 1969. During the early-to-mid 1970's experimental, profiling ALH-type systems were deployed by NASA (Kim, 1974) and US Navy (Cunningham, 1972) in the US, by Canada Centre for Remote Sensing (CCRS)/Optech in Canada (Ryan, 1980), by the Weapons Research Establishment (WRE) of The Australian Royal Navy (RAN) (Clegg, 1978), and by Defense Research Institute (FOA) in Sweden. These efforts gave rise to follow-on work in the mid-late 1970's: in the US a joint effort by NASA, NOAA and US Navy, with AVCO as the contractor, produced a scanning Airborne Oceanographic Lidar (AOL) (Avco, 1975). In Australia, WRELADS-2 followed, another scanning system, built upon the experience of WRELADS-1, the initial profiling prototype. In the early 1980's in the US, an attempt to take the AOL experience into the operational domain resulted in the HALS program (Hydrographic Airborne Laser Sounder) (Houck 1980), sponsored by DMA, NASA and the US Navy, with AVCO as contractor. In Australia, during the same period, WRELADS-2 carried on with an extensive set of field trials and data evaluation (Abbot, 1980). In Canada a similar process was taking place with the profiling Mark-2 ALH system, while in Sweden, FOA carried out again similar trials with Optech's assistance, using Canada's system augmented with a scanning capability (Steinvall, 1981).

In the mid-1980's Optech developed LARSEN-500 ALH system, an operational prototype, with support from the Canadian Hydrographic Service (CHS) and CCRS (Banic, 1986). In the latter 1980's Sweden's FOA sponsored the development of a prototype scanning ALH system, FLASH-1, with Optech Inc. as the major contractor. In the US HALS, after prolonged programmatic difficulties, was resurrected within the confines of a wider effort on the part of the US Navy, the Airborne Bathymetric System (ABS) (Harris, 1986). During this period Optech Inc. also built the ALARMS (Airborne Laser Radar Mine Sensor) scanning system for the US DARPA which, though essentially an ALH system, has as its primary objective the detection of water-column-suspended mines. During 1988/89 both SHOALS, the US Army Corps of Engineers sponsored, operational ALH system, being built by Optech Inc. (Banic, 1990) and LADS, the RAN sponsored operational ALH system, being built by BHP Industries (Compton, 1988), started the latest phase of efforts in the ALH area.

The current (autumn 1991) status of ALH is as follows:

(a) In Australia, the LADS program is near completion, with field trials taking place this fall and throughout next year.

(b) In France, Thompson-Sintra-ASM is in the process of putting together a profiling ALH system, scheduled for field trials in the Spring/Summer-1992.

(c) In Canada/US, Optech Inc. is nearing completion of its SHOALS program, with field trials scheduled during the June-December, 1992 period.

(d) In Canada/Sweden, based on the SHOALS design, Optech Inc. is under contract, via SAAB, to the

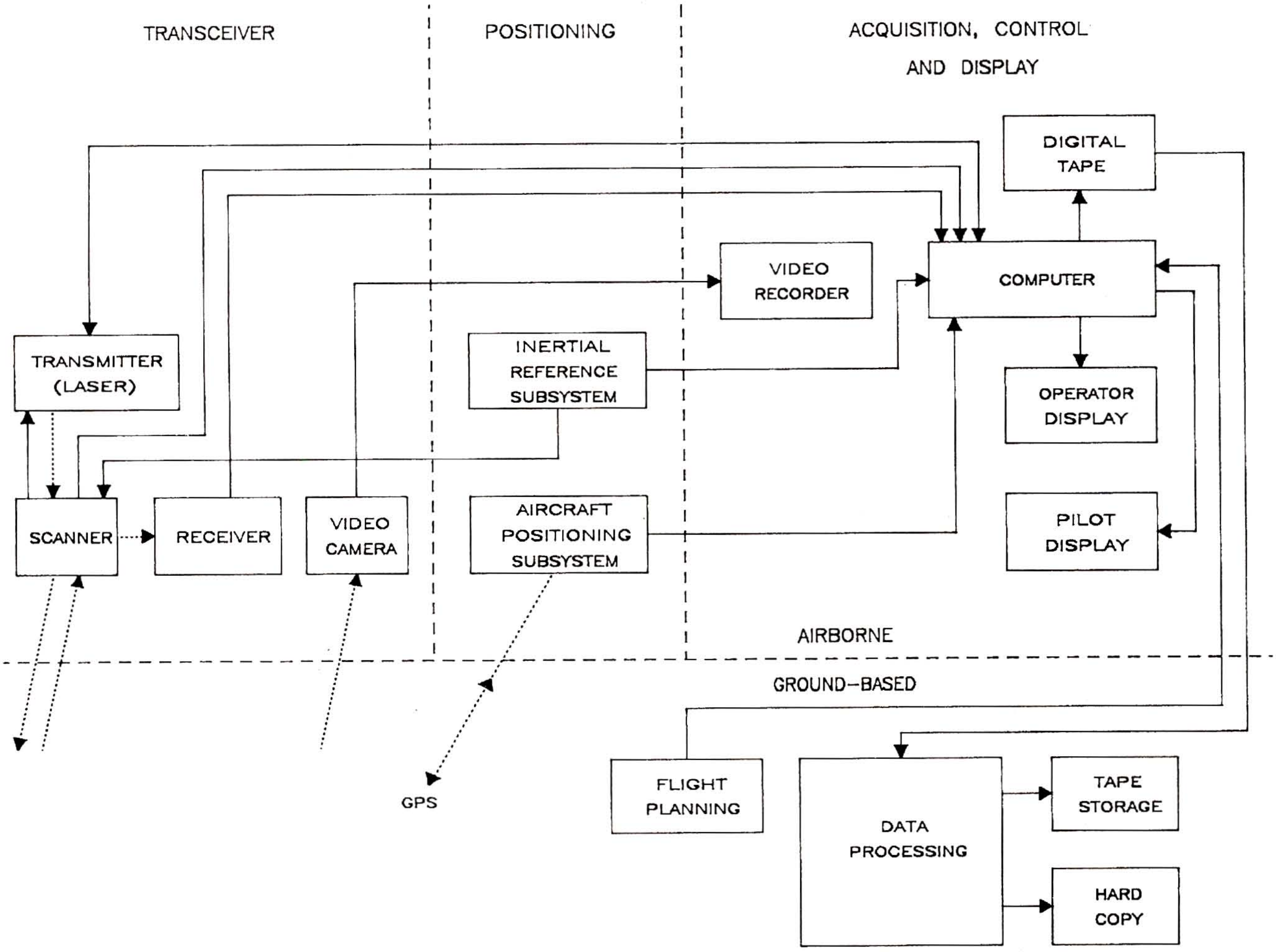

Fig. 2 - SHOALS System Block Diagram.

Swedish Royal Navy and the Swedish Hydrographic Department for the delivery of the airborne-sensor subsystem for two new FLASH-2 ALH systems.

And, currently still being used in a regular fashion to carry put hydrographic survey missions are the Swedish FLASH-1, operated by FOA/Swedish Hydrographic Department, and the canadian LARSEN-500, operated by Terra Surveys of Sidney, British Columbia.

3. SHOALS OBJECTIVES

The primary objective of the SHOALS program is to provide an airborne bathymetric survey capability concomitant with the US Army Corps of Engineers "reconnaisance" and "condition" type surveys on a variety of navigational channels throughout, and around, the United States. To this end SHOALS is to be compatible with a helicopter platform, typical of the Bell 212 (or smaller); a nominal operating altitude of 200m; a swath width variable from zero to 40 degrees; and a daytime, maximum depth penetration capability (designated by the product of the water-diffuse-attenuation-coefficient, k, and the water depth, d) of $(kd)_{max} \approx 4$.

A second objective of the SHOALS program is to make the SHOALS system simultaneously suitable to the needs of the broader and international hydrofraphic community. This will have been achieved, hopefully, by (a) ensuring that the SHOALS performance capabilities meet the International Hydrographic Organization (IHO) standards, (b) not requiring a dedicated aircraft, but making SHOALS compatible with a variety of both fixed-wing and rotary platforms, and (c) adopting design/manufacturing approaches that, for subsequent units, would make it affordable to a greater variety of users.

4. SYSTEM OVERVIEW

Figure 2 shows the SHOALS block diagram. It consist of three major airborne subsystems, and a ground-based data processing subsystem.

The transceiver subsystem generates laser pulses, scans the laser beam, performs the detection and preprocessing of the optical return signals and provides a high resolution video image of the sounded sea. The positioning subsystem receives aircraft position data from GPS or a microwave transponder system and, with an inertial refernces system provides the angular orientation of the transceiver. The above, together with the scan-angle data, are used to determine the horizontal position of the soundings. The data acquisition, control and display subsystem provides the operator interface, captures and stores all data and displays the system status and quality control parameters. Additionally, it provides information and guidance displays for flight-line management by the pilot. The ground-based data processing subsystem analyses the acquired data to produce corrected depths, corresponding horizontal positions and assigns confidence values to each sounding. It enables data examination and editing by the operator, generates the desired XYZ databases and provides hard-copy (sounding plot) data output.

5. SUMMARY OF ALH CHALLENGES

An operational ALH system needs to provide an optimized solution to a number of diverse, and difficult technical problems. Areas that have historically provided their share of "the-tough-nuts-to-crack" in most ALH design-and-build efforts have generally been among the following:

- reliable, power-efficient, high PRF laser of adequate pulse energy and suitable emission wavelength
- accurate and reliable determination of the instantaneous water-surface position at the laser-beam entry point
- compression of the large dynamic range in the received-signal intensity to a level suitable for transient recorders
- accurate algorithm for propagation-bias corrections
- reliable and accurate algorithm for instantaneous mean-water-level determination (i.e. waveheight corrections)
- efficient handling/processing of vary large data sets
- high automation level in the data processing to "validated XYZ" stage
- acceptable data-processing-time/data-acquisition-time ratio
- compatibility of processed-data format with current hydrographic usage

6. DISCUSSION OF SOME SHOALS DESIGN TRADE-OFFS

As it is not considered within the scope of this paper to provide an exhaustive trade-off analysis of an ALH system design, this section discusses only a few of the technical challenges identified in the previous section, this with a view of providing some visibility into the approach of trade-offs adopted in the design of the SHOALS system.

(a) *laser* - optimal transmission in most coastal waters dictates that the operating wavelength of an ALH system, if not tuneable, be somewhere in the 490-550 nm spectral range. Historically, the most frequently selected source has been the frequency-doubled Nd-YAG laser, operating at 532 nm. Most workers have concluded that for readily manageable receiver/scanner apertures (typically 20-30 cm diameter) a laser pulse energy of 5-10 mJ, at 532 nm, was a good trade-off with the depth penetration capability, desired sounding density and area-coverage rate (limited by the concomitant maximum laser available PRF) and the laser weight/power consumption/reliability. The SHOALS design has also settled on a choice of a Nd-YAG laser, frequency doubled, with a PRF of 200 pps and with a pulse of 5 mJ energy and 5 ns width, nominally. As there is hardly one such item available off-the-shelf from laser manufacturers, the SHOALS laser has been developed specifically to its purpose, relying heavily on previously proven subsystems, many of these from military systems. Since the newly-advancing diodepumped ND-YAG technology has not just yet progressed adequately to make a laser with SHOALS requirements easily affordable, the design approach for the SHOALS laser has, at least, put one foot forward into this new arena: it utilizes a diode-pumped oscillator and a flashlamp-pumped amplifier approach. In this manner size and power-consumption are somewhat reduced, while the overall reliability is improved. The laser's 200 Hz PRF allows uniform sounding density of 8 m nominal grid spacing, for an aircraft at an altitude of 300 m and ground speed of 100m/s (200 knots), while permitting survey-data collection at more than 50 Km^2/hr. Furthermore, SHOALS' ability to vary the scan angle under computer control allows a ready operational trade-off between the sounding grid-spacing and survey area rate, thus permitting a finer, or coarser, sounding density than the nominal, depending on the requirement of any given mission.

(b) *water-surface location* - the SHOALS system design has adopted the approach of sending a simultaneous, collinear, infra-red beam with the green one for each laser pulse transmitted. The beams are nominally transmitted at a constant angle of incidence with respect to the water surface (typically in the 15° - 20° range) for reasons of minimizing raw depth bias errors due to beam propagation in the water. Since the raw water depth is first determined relative to the instantaneous local water surface, a precise knowledge of the time - location of the air/water interface event on the backscattered intensity-vs-time signature is required. However, since the water surface is highly variable in regard to its reflective/scattering properties, driven primarily by the wind/wave conditions, the return signal intensity of the air/water interface event of both the infrared and the greenbeams can vary by many orders of magnitude over a range of environmental conditions that would be operationally acceptable.

To ensure reliable availability of an air/water interface event in the detected backscattering signature the SHOALS design utilizes three separate signal channels: the infra-red channel that yields a backscattering signature *up to* the water surface, the green channel that yields one *through, and below*, the water surface, and a red channel (Raman return stimulated by the excitation of the water molecules by the green beam) that yields the backscattering signature only from a relatively thin *surface water layer*. None of the three channels, by itself, can provide reliable, and/or accurate, air/water interface returns over the entire range of operating altitudes and environmental conditions, and, hence, a prioritized combination of all three is used.

(c) *data handling* - the SHOALS system could, during an operational day's surveying collect up to several gigabytes of airborne data. The ground-based data handling/processing system has, as a target, the objective of processing one day's acquired data overnight. It has to move the airborne data from the airborne storage medium, through processing steps, and into files available from editing. Datafile format must allow for a variety of searchers as part of the processing editing task and for the ability to provide easily new user searches at later times.

An analysis of the approaches to optimally meet the above requirements has narrowed to a relational batabase. It allows quicker access to data organized into smaller files, with search criteria as keys. It provides efficient use to disk space. It does, however, create redundant data because search fields may be repeated in multiple files, but only data that exists is stored. Although most searchers are predefined, new searches can be easily added without programming by using the end user query system. The overall effectiveness of this approach to data handling on SHOALS is still in the evaluation process.

7. LIMITATIONS

The main limitations of the system are its maximum and minimum depth capability, weather-related phenomena, and bottom structure. Water clarity will typically limit the system's maximum depth penetration capability to less than 50 meters in very clear water, and 20-30 meters in moderately clear waters. (Areas of high turbidity will significantly degrade SHOALS performance, and will need to be identified as part of the survey planning process.) The minimum depth measurement capability of the system will be approximately 1 meter, determined primarily by the system hardware. Weather-related phenomena such as high surface waves, heavy fog and precipitation, and surface sun glint, will degrade the system performance by decreasing depth penetration and/or depth measurement accuracy. Similarly, operation in areas where the bottom is heavily vegetated or covered with "fluid mud" will, as with acoustic techniques, present serious challenges to the system's ability to recognize the bottom signal.

8. COMPARISON WITH ACOUSTIC SYSTEMS

It is difficult to make a widely applicable comparison between the SHOALS system and a variety of acoustic approaches being used today, as most such comparisons are meaningful only if done for specific scenarios and, better yet, after-the-fact. However some comments of a general nature can be made:

- depths accessible to sounding by the ALH approach with a SHOALS-type system, even under the best of conditions, are at maximum 50 m, and more typically 20-30 m. It is therefore only in this depth range than any comparisons can be meaningful.
- area coverage rate will, for the most part, be greater with an ALH system by from 10 to 100 times, depending on the type of area to be surveyed, the sounding density required, the survey resources deployed, and the distance of the area to be surveyed from the base where the survey resources are normally located.
- the accuracy of the two different approaches is comparable within the 50 m depths considered here, although ambiguities exist with both techniques when soft/extended bottom-type/structure is present. The horizontal accuracy is governed by the same parameters for both approaches and is, therefore, largerly equivalent.

- operational reliability for the ALH systems has yet to be established. Early systems have been of prototype nature and, consequently, not overly reliable. However, operational systems such as SHOALS and LADS have been designed for reliable operation, which nevertheless has yet to be verified in field use.
- cost effectiveness analyses (Golaszewski, 1989 & Enabnit, 1978) have indicated and anticipated performance from 5-10 times to the advantage of a SHOALS-type system, but actual cost effectiveness will be highly dependent on the specific survey mission. Candian experience, over the range of Canadian coastal waters, with a historically relatively low-reliability, relatively-low sounding-frequency system has demonstrated cost savings in the range of 2-4 times over previously used acoustic approaches.

CONCLUSIONS

Now that ALH is coming of age there remains little doubt of its effectiveness to enhance the ability of the hydrographic agencies to carry out their mandate. Over the next couple of years systems like SHOALS and LADS will confirm, in a statistically more meaningful manner, the actual extent of the operational enhancement that ALH offers. But as a new tool in the hydrographic arena, complimentary to the acoustic one, ALH is here likely to stay.

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