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ASSESSMENT OF VARIOUS CONFIGURATIONS FOR LOCATING THE MEAN SEA SURFACE REFERENCE IN LASER HYDROGRAPHY

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Abstract

Various scanning configurations for laser-based airborne hydrography are examined to assess the implications of each in establishing an accurate reference against which sea depths may be measured. A configuration in which an infrared laser beam is scanned and co-directional with a green laser beam is found to give a significantly poorer estimation of mean sea surface location than configurations incorporating a fixed vertical wide divergence infrared beam. Furthermore, configurations that use the leading edge of sea subsurface backscatter to give estimates of local sea surface location are shown to be seriously susceptible to variations in the magnitude of that backscatter.

Introduction

Australia has a substantial vested interest in the deployment of high efficiency hydrographic tools. With a population of 17 million, which is quite small relative to the size of the Australian continent or to its 2.3 million km² continental shelf, this is not perhaps so surprising. Moreover, its economic dependence on trading, together with significant natural undersea features such as the 3000-km Great Barrier Reef stretching along most of the Queensland coast, add considerable force to the demand for hydrographic tools that are faster and more efficient in terms of their use of human and capital resources.

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Although the improvements in hydrographic technology from the old lead-line techniques have been significant, the sonar techniques commonly used today still suffer from the same fundamental limitation of being ship-bound. The operational rate of coverage is limited to the number of sonar platforms, the rate at which they can move through the sea, and all the manpower, high capital, and recurrent cost implications of that scenario.

It is against this background that Australia, through the Defence Science and Technology Organisation, has moved to take a leading role in the development of new airborne laser-based techniques for the mapping of the sea bottom. The Australian work commenced at the Electronics Research Laboratory, Salisbury, in 1972, following a request from the Royal Australian Navy (CALDER, 1980). An experimental non-scanning WRELADS I system was built and tested in 1976-77 (CLEGG and PENNY, 1978). This was followed by the successful prototype scanning system, WRELADS II (PENNY *et al.*, 1986). This latter system was the subject of very extensive testing, involving over 550 hours of test flying in seas off South Australia, West Australia and Queensland over a number of years. Of the order of five gigabytes of data representing over 15 million individual waveforms have been processed from those flights, with the results being analyzed to ensure that the system represented a precision hydrographic instrument capable of wide operational use by the Royal Australian Navy Hydrographic Service. Much of those results have already been published (PENNY *et al.*, 1986; BILLARD, 1986a; BILLARD and WILSEN, 1986; BILLARD, 1986b; BILLARD *et al* 1986a; BILLARD *et al* 1986b; BILLARD, 1986c). Design work has been completed for an operational system known as LADS (Laser Airborne Depth Sounder), which will be constructed for the Royal Australian Navy.

Australia has not been alone in its pursuit of this technology. Both Canada (CASEY and VOSBURGH, 1986) and the U.S. (GUENTHER, 1985) have pursued separate developments of laser bathymetry, with differences in design and operational scenario. Underpinning all of these developments has been the proof-of-concept work performed in the late 1960s at the Syracuse University Research Corporation (HICKMAN and HOGG, 1969).

Previous papers on the WRELADS system have concentrated on the specific WRELADS configuration, with development of algorithms and general data processing techniques appropriate to that system. While in some instances that work can be easily generalized to other configurations, such as those appropriate to the American and Canadian designs, in other cases the differences in design preclude the immediate cross-application of results. In other words, statements that are valid for one design may not necessarily be true for another.

It is the purpose of this article to withdraw one step from the examination of the immediate WRELADS design and ask instead the question (in hindsight) 'What are the essential principles for design of a laser-based airborne hydrographic system? Are there other ways of achieving the same result?' In order to restrict the range of this discussion, the focus will be limited to just the two areas that incorporate the significant differences between configurations, namely (1) the manner in which infrared (IR) laser pulses, a byproduct of the frequency doubling operation in the Nd:YAG laser, are used to provide a convenient sea surface reference and (2) the relative merits of conical and rectangular scan patterns in determining a mean sea surface reference with sufficient precision for hydrographic applications.

The general scenario for WRELADS has been described previously (PENNY *et al.*, 1986) and is illustrated briefly in Figure 1. The WRELADS laser operated at 84 pulses per second. For LADS the laser will operate at 168 pulses per second.

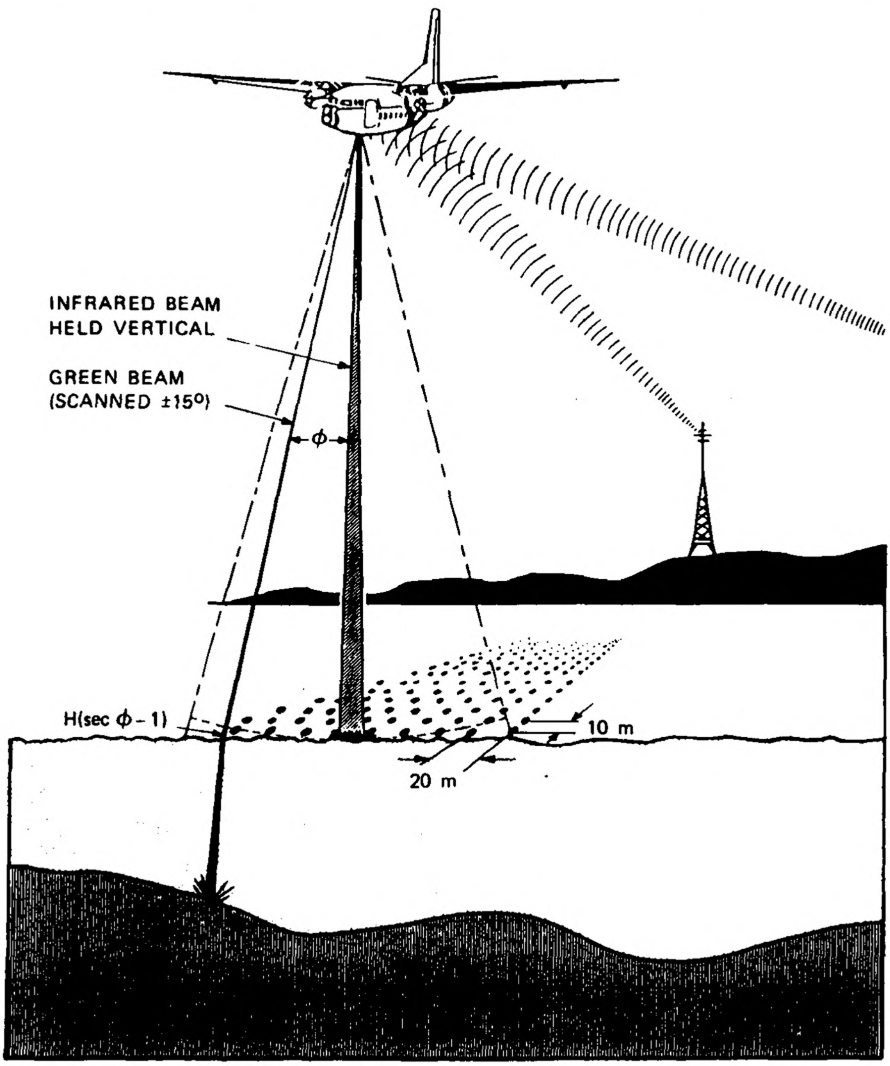

FIG. 1. — Operating scenario for WRELADS laser airborne depth sounder.

The scanning mirror system was rotated about two axes (one to compensate for the forward motion of the aircraft) to produce a rectangular array of laser spots on the surface of the ocean. With the aircraft's forward motion of 70 m/s and a sideways scan up to approximately 15° from nadir, a single cycle of pulses forms a pattern on the sea surface, as illustrated in Figure 2. For convenience, the laser pulses are often referred to by their number in the cycle. Thus, spots 1 and 13

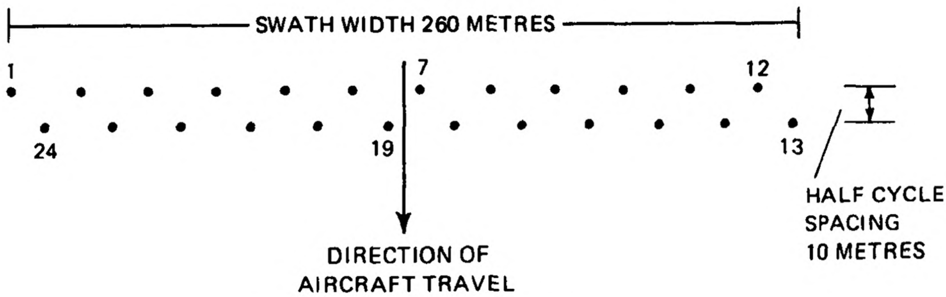

FIG. 2. — Rectangular pattern of green laser spots on the surface of the sea from a single cycle of the WRELADS scanning system.

are at the starboard and port extrema, respectively. Examples of received WRELADS waveforms across a single scan are shown in Figure 3. The method by which WRELADS uses the combination of IR and green laser pulses to accurately determine the mean sea surface position has been described in detail elsewhere (BILLARD, 1986a).

Criteria for Determining Sea Surface Location

Hydrographic sea depths are referenced to Lowest Astronomical Tide at that geographic location. With a knowledge of tide at that location at that time, this reference can be related to mean sea surface level at that time. Hence an airborne laser hydrographic system must be able to reference any detections of reflections of green laser energy from sea bottoms to a point corresponding to mean sea surface level. Failure to make this estimation renders the task of sea depth determination impossible, since there is then no practical alternative reference against which depth may be determined.

Figure 4 illustrates the time line situation for an individual green laser pulse that is transmitted from the airborne platform, with backscattered laser energy being received some microseconds later. The aim of any sea surface determination methodology must be to locate accurately (say, to within 0.15 m) the location on this time line of S, the position appropriate to the mean sea surface level.

A first approximation is obviously to take the sea surface location from any detection of reflected laser light from the sea surface. However, when the laser beam is inclined to the local vertical, these reflections are often not detected, and those that are will rise and fall with swell by much more than can be tolerated in any hydrographic system.

The discussion that follows will be broken into two separate considerations. The first concerns the need to separate out and estimate (or otherwise eliminate) any time-varying component in the positioning (in time) of the received waveform. This consideration incorporates a number of alternative configurations in which the options relate to (1) the selection of a primary reference point for each green laser pulse, (2) the possible deployment of an IR laser beam in a scanning or non-scanning mode, and (3) the selection of an appropriate divergence for the IR beam. The second consideration concerns the nature and accuracy of local sea

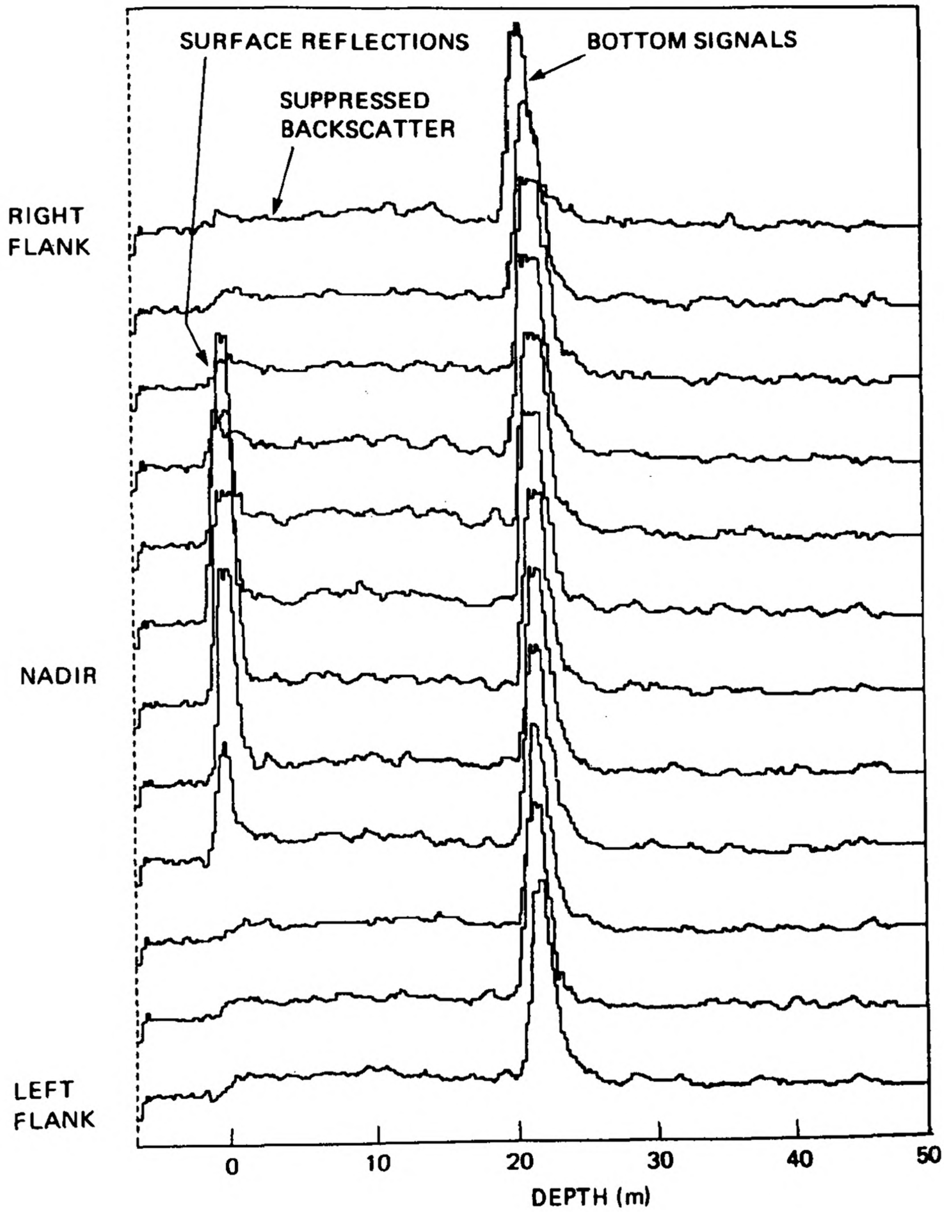

FIG. 3. — Twelve successive waveforms from green laser pulses across a single sweep of WRELADS, with photomultiplier gain control in operation.

surface determination from an individual waveform. This is relevant for those configurations that seek to accumulate data over a number of successive pulses so as to improve the estimate of a primary reference point and hence the mean sea surface location, S.

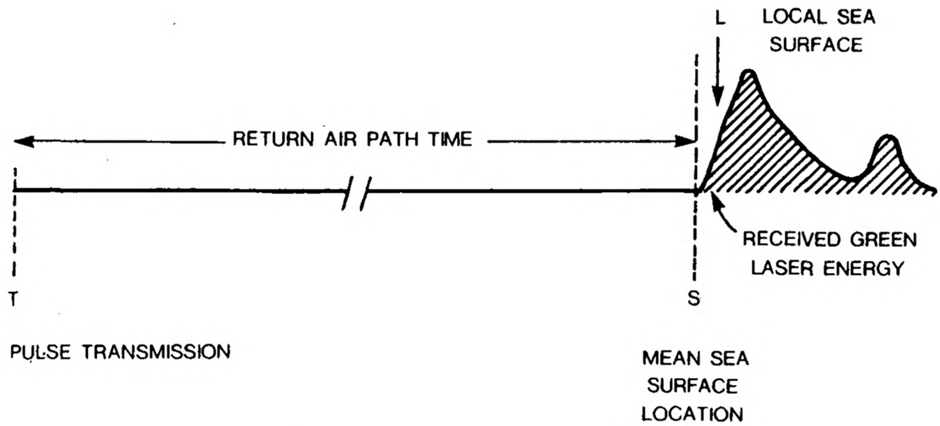

FIG. 4. — Components of received energy offset in time from laser pulse transmission.

ELIMINATION OF TIME-VARYING COMPONENTS

Selection of Primary Reference

From Figure 4 it might appear that the first and most obvious option is to accurately estimate TS, the offset in time of S from T, the pulse transmission time. The contributions to this time are: (1) the aircraft height above the local mean sea level at that time, (2) the slant angle of the transmitted beam to the instantaneous local vertical, and (3) a system offset associated with the time taken by the receiver system to record pulse transmission. It should be noted that the primary concern is with offsets that vary over a period of time for whatever reason. Offsets that are constant are removed relatively easily by calibration. The remaining discussion will assume that such constant offsets *may* exist, though they may not be directly referenced.

The dominant contributor is obviously the aircraft height, which must represent the distance to mean sea level as an *absolute* measurement. However, it is impossible to measure height with sufficient accuracy using modern position fixing equipment. Hence other techniques (using the available green and IR laser beams) must be employed to measure height to the required accuracy.

In practice the problem of accurate determination of aircraft height has been recognized, and for this reason IR pulses have been commonly employed as a means of changing the point of reference from the point T of pulse transmission to a point I of IR energy (see Fig. 5). The IR pulse is available from the frequency doubling operation of the Nd:YAG laser. Its emission is simultaneous with the green pulse, and its receiver system usually comprises a high-gain photodiode with low-threshold leading edge detection (PENNY *et al.*, 1986). However, the direction and divergence of the IR beam is not necessarily the same as for the green pulse. In WRELADS, the IR beam is held vertical and has a much larger divergence than the green beam. The Canadian LARSEN 500 system scans the IR

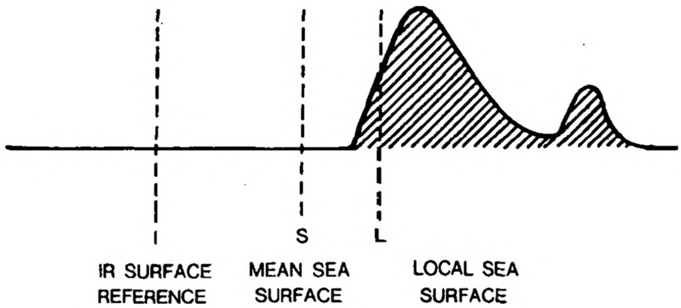

FIG. 5. — Components of received energy offset in time from the new reference point I, which locates the point of IR beam detection of the sea surface (within a constant offset).

with the green in a conical scan around the aircraft, with an IR divergence not necessarily the same as that for the green beam. (It should be noted that the way in which the IR event I is recorded on the waveform is not important. The WRELADS system lifts the whole waveform onto a pedestal whose edge starts at I. The LADS system and the Canadian system insert a marker pulse onto the waveform at the location of I.)

In addition, there are a set of options that retain the reference point T of Figure 4 and that use any local sea surface detection from the green beam (L in Fig. 4) or else IR beam detections of sea surface (I in Fig. 5) to increase the accuracy with which the aircraft height is known. These options rely on an assumption that the aircraft height will vary only very slowly relative to the laser pulse rate. Specifically, they assume that the aircraft height, and hence TS in Figure 4, will remain relatively constant during a period in which there are a sufficiently large number of individual green (or IR) pulses giving a measure of local sea surface location, L (or I) in Figure 5, such that the averaged L (or I) give an accurate estimate of S. These options will be examined again later, along with another option that also employs the local sea surface location, L.

Since there is a divergence in design options at this point, each option and its consequences must be considered separately. However, they may all be understood as possible simple variations of the WRELADS scanning beam geometry depicted in Figure 6.

Scanned IR

If the IR is scanned with the green beam (whether a conical or a rectangular pattern is used), then all influence of aircraft height is immediately removed for all those laser firings from which an IR surface reflection has been received. Furthermore, if the IR beam divergence is the same as that for the green beam, then all influence of slant (scan) angle is also removed. The resulting offset of I from S (Fig. 5) can therefore be assured of independence from aircraft height and scan angle for either conical or rectangular scan patterns.

However, if the IR beam has the same divergence as the green, as well as being codirected with the green, it becomes in many respects no better a mean

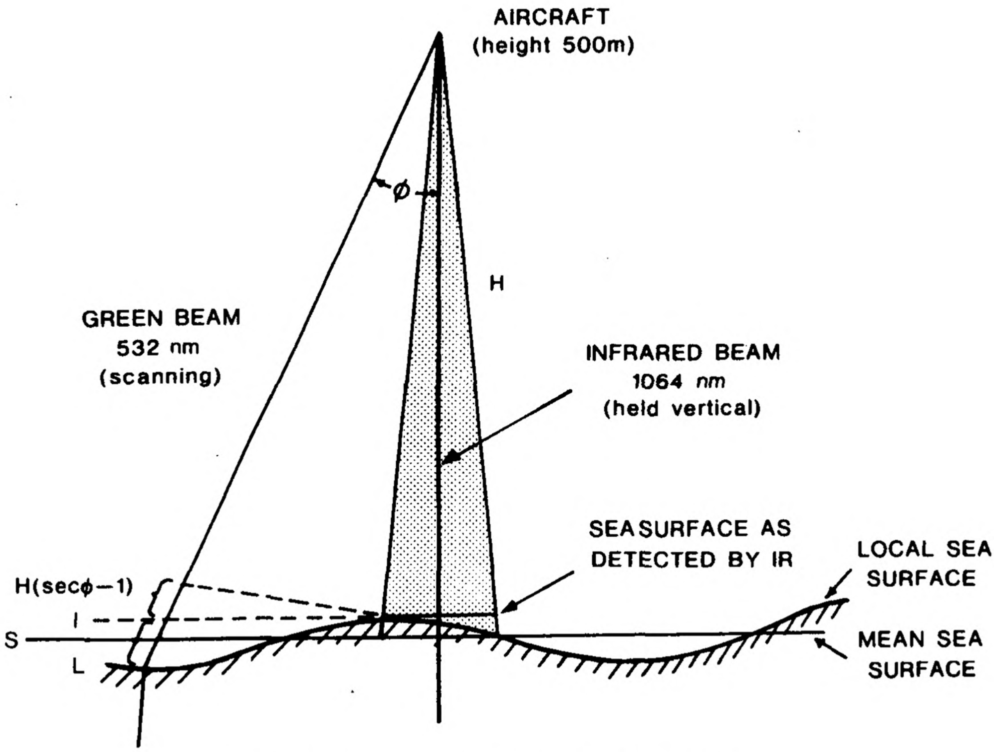

FIG. 6. — Scanning geometry for WRELADS and LADS.

sea surface reference than the point L, which is a local sea surface reference as detected by the backscattered green beam. In fact, I will be a 'cleaner' indication of the local sea surface position, since IR light is rapidly attenuated within the sea. However, it is still just a measure of local sea surface location within the narrow (say, 2 m diameter) width of the beam.

Since the point I will in this case ride up and down relative to S along with the local sea state and swell movements, it is clearly inadequate to be used on its own as a reference point for determining S.

For configurations employing a conical scan pattern, there are additional reasons why the use of a scanned IR beam with the same divergence as the green beam is not effective. Experience with WRELADS has shown that surface-reflected laser energy is mostly directed away from the aircraft at scan angles significantly greater than 10° to the local vertical (BILLARD, 1986a). It is stressed that this would be equally true for both IR and green light. This characteristic arises as a consequence of the limited range of micro-sea-surface slopes found in natural conditions. A system that relied on consistently receiving surface reflections of laser energy from a scan angle of 15° would therefore have a severely restricted operational envelope.

The only alternative to the above is to give the IR beam a much larger divergence than that of the green. In fact, the larger the divergence of the IR beam, the larger will be its footprint on the surface of the ocean, and the greater will be the likelihood of consistent surface detections. In addition, it might be expected that the larger footprint will help to average wave heights over a larger area of sea, leading to a reference point I that more closely approximates the mean sea surface S (after allowance for offsets).

The magnitude of the IR beam divergence that is required to bring about the necessary improvement in the reliability of surface detection will be a function of sea state. For example, if a statistical model of micro-sea-surface slopes is appropriate, then the probability of there being a section of sea surface oriented to reflect IR energy to the aircraft from within the IR beam footprint is a function of the area of the footprint, which in turn will increase with the square of the IR beam divergence.

Hence, increasing the IR beam divergence must be seen as a measure that *improves* the reliability of sea surface detection over a variety of sea states, but that still leaves a range of other sea states for which no sea surface detections can be made at scan angles away from nadir.

This configuration has further subtleties leading to some additional sources of error that need to be borne in mind when assessing its performance.

An IR beam that is emitted with wide divergence at an angle to the local vertical will intersect the sea surface at the same angle. For example, if the beam footprint on the sea surface has a 25 m diameter, then for a beam directed at 15° to the local vertical, the side of the beam furthest from nadir will still be over 6 m above the sea when the side nearest nadir meets the sea. Thus, for any high-gain photodiode IR detection system (which is required for high reliability) the receiver will be reacting preferentially to the near-nadir side of the IR beam footprint. This would also imply an offset of over 3 m relative to the aircraft-to-sea-surface air path in the center of the IR beam, where the green beam is located.

Consider further a situation in which the response time of the IR receiver is such that an aircraft-to-sea-surface path length variation of 1 m is the most that can be tolerated and still leaves opportunity for all IR reflected energy within that path length band to contribute to the triggering of threshold detection. In other words, at the point of threshold breaking, only IR energy received then and over the previous 6.7 ns (corresponding to aircraft-sea surface path lengths up to 1 m shorter) will be contributing to the received signal. Then the effective footprint for a beam at an angle of 15° to nadir will be a strip nearly 4 m wide, contained within the total IR beam footprint. (The actual variation that can be tolerated will be a characteristic of the IR receiver system and will in fact be one limitation on the accuracy with which the IR reference point I can be determined.)

In sea conditions having no swell, but nevertheless with sufficient wind ripples to reflect IR energy back to the aircraft from most points within the total IR beam footprint, the effective footprint will start from the near-nadir extremity (see Fig. 7). The length of that effective footprint would be of the order of 18 m.

This might seem to be a good measure, since the 18 m length of the effective footprint will help to average out components of swell with wavelengths less than 18 m in that direction. However, it is also clear from Figure 7 that the limitation of the IR receiver response in this way to an effective footprint also introduces an offset bias. (In the example considered here, with a IR beam dia-

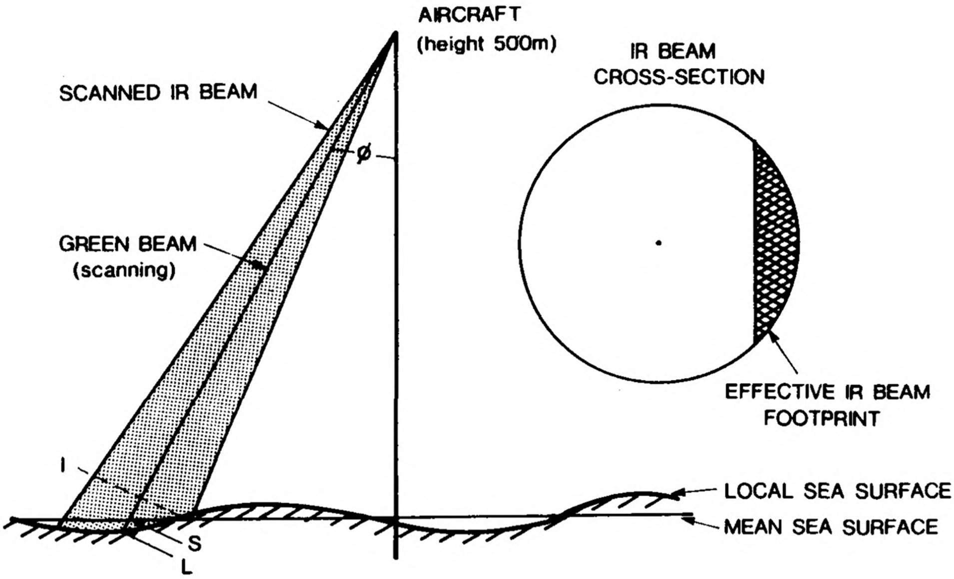

FIG. 7. — Geometry for scanned IR beam with wide divergence.

meter of 25 m, that bias will be of the order of 3 m.) Moreover, that bias will vary, depending on just where the effective footprint 'strip' is located within the total IR beam footprint. Although that location will tend, more often than not, to be nearest to the location shown in Figure 7, it will vary significantly if there is swell with crests parallel to the long axis of the effective footprint. (This corresponds to a situation in which the sea surface in the hatched area of Figure 7 is located on an away-facing side of a swell crest.)

The magnitude of any bias introduced in this way can always be limited by restricting the IR beam width, but it is clear from the foregoing that the restriction should be only in the plane of the IR beam and the local vertical. In other words, it is suggested that the IR beam would need to be codirectional with the green beam, with the same divergence as the green beam in the plane of the beam and the local vertical, but with larger divergence in the plane perpendicular to that.

This configuration will give an IR pulse detection reference point I that is an approximation to the mean sea surface reference point S (Fig. 5). Its accuracy will be a function of the size of the effective IR beam footprint *relative to* the sea state wavelength components and their orientation.

Sea state with wavelength less than the diameter of the effective footprint will be automatically 'averaged' by the receiver system, although there may still be some bias left, depending on the gain of the receiver. (For example, a high-gain threshold detector will be biased toward the wave peaks.) This bias would be a function of sea state.

Sea state and swell with wavelength greater than the diameter of the effective footprint can never be removed with this configuration. Although it might appear valid to accumulate data on local sea surface location L from a number of waveforms, the segment of the sea surface intersected by each IR pulse is different each time, and hence the bias of I from S due to 'long' wavelength swell will also be quite different. Any pulse-to-pulse accumulation of data regarding the offset of L from I would therefore be meaningless.

A derivative of the above configuration accepts the inherent inaccuracy in using I to approximate S, but seeks to accumulate the individual measurements of I relative to the pulse transmission time T from successive pulses, averaging them over a time scale during which aircraft height might be considered to be constant. In this case the laser pulse rate must be sufficient to average out not only variations due to the variable mean sea height of the effective footprint, but also variations due to the variation in location of that effective footprint within the overall IR beam footprint. The limitations of this configuration associated with aircraft height movement are addressed in a later section.

Non-scanned IR

The option of a fixed vertically directed IR beam with narrow divergence will yield a greater proportion of local sea surface detections that the comparable scanned configuration. However, its positioning of I still suffers from accuracy limitations similar to those of the scanned narrow divergence IR beam. Moreover, the smallness of the beam footprint relative to the pulse-pulse forward motion of the aircraft restricts any moves to accumulate data from successive pulses. Hence, this option has limited value and will not be considered further.

The use of a vertically propagated *wide* divergence IR beam is the option that has been chosen for use with WRELADS and LADS (see Fig. 6). Its features may be most readily appreciated by comparison with the scanned, wide divergence IR beam configuration discussed above.

Unlike the scanned IR beam cases, this approach requires an accurate estimation of scan angle (within 0.1° for a 0.1 m accuracy in path length), together with an estimation of aircraft height (within 2.8 m for an accuracy of 0.1 m in path length adjustment due to scan angle). These adjustments are made automatically in WRELADS, so that the IR reference point I in Figure 5 can be considered to have eliminated all influence of aircraft height and scan angle (within required bounds of accuracy). In this respect, it is therefore similar to the configuration discussed in the previous section.

However, because the IR beam is always directed vertically, the effective footprint as depicted in Figure 7 is always equal to the entire footprint. In fact, the aircraft-to-sea-surface path length variation from beam center to beam fringe is only 0.31 m — considerably less than the 1 m variation that must be allowed in the earlier case to ensure an effective footprint of any appreciable size.

Moreover, the vertically directed beam is alway much more likely to have IR energy reflected back to the IR receiver, rather than away from the aircraft. (Detections of IR reflected energy from the sea surface were never missed during the extensive trials of the WRELADS system.)

Finally, there is the most important difference: that is, for successive pulses, the IR beam views almost the same portion of sea at 84 pps for WRELADS and 168 pps for LADS. (For WRELADS the 25-m diameter IR beam footprint advanced by approximately 0.8 m with each pulse.) This therefore gives the opportunity of accumulating data from successive waveforms regarding the local sea surface position L, relative to I, thus giving substantial improvements in the estimation of S, the mean sea surface position (BILLARD, 1986a). This latter improvement is not possible with any of the other configurations. It allows for accurate estimation to be made of mean sea surface level even in the presence of substantial swells.

The degree of improvement is limited only by the full scan width (260 m for WRELADS and LADS) and the pulse rate necessary to gather sufficient data over that scan width to allow estimation of the IR reference bias (of I from S in Fig. 5), while that bias can be considered to have remained relatively constant. For WRELADS, that time constant was of the order of one-third of a second. (This represents approximately the time taken for the IR beam footprint to move forward by its own diameter.) For other laser pulse rates, that constant would need to be scaled appropriately.

Subject to the issues raised later regarding the accuracy and frequency with which the local sea surface L can be located, the arguments put forward here will hold whether the green laser pulses are scanned in a conical pattern (constant slant [scan] angle to the local vertical) or in a rectangular pattern as with WRELADS. Thus, as long as the IR beam is held vertical and with wide divergence and as long as the laser pulse rate is sufficiently high, then there is the *opportunity of using individual waveforms of received green light to estimate* a local sea surface position (L in Fig. 5), which may then be accumulated to give a greatly improved estimate of mean sea surface position (S in Fig. 5).

Systems Using Local Detections of Sea Surface

There now remain two general approaches for which the detection of a local sea surface (from L or I) may be used, both to remove remaining fluctuations in the estimate of mean sea surface S and to 'average over' individual failures to detect a local sea surface.

The first approach (Fig. 4) involves the accumulation of data on the local sea surface from successive pulses over a time scale during which T might be considered to have remained constant. (The principal variant is aircraft height.)

The second approach (Fig. 5) applies to the wide divergence non-scanned IR beam configuration only and accumulates data on L over a time scale during which I might be considered to have remained constant. (The principal variant is those components of swell with wavelength greater than the width of the IR beam footprint).

Both of these approaches imply use of a high pulse rate laser. In the first case, aircraft height might be expected to vary significantly over periods of 0.1 s (0.1 m for vertical movements of 1 m/s). With WRELADS, movements greater than this were frequently encountered in response to wind gusts. The WRELADS system measured vertical accelerations of 0.3 g or 3 m/s/s during trials. The nature of such movements is that they would frequently lead to vertical velocities greater than 1 m/s. The implication of this for an operational system is that the operating envelope would need to be constrained to eliminate or otherwise compensate for vertical aircraft movements sharper than 1 m/s. (The figures used here are by way of example. The precise figures will depend on the laser pulse rate, as well as the reliability and the accuracy of the local sea surface data that are averaged.)

The compensation referred to here might take the form of an accelerometer mounted on a horizontal mounting, with data from this being incorporated into a maximum likelihood (Kalman) filter that modeled and tracked aircraft vertical position, velocity, and acceleration over a time scale during which the local sea surface data (either green or IR) was accumulated.

In the second case, the limitation is the rate of movement of the IR beam footprint. (The surface of the sea will not move greatly during the times considered here.) For an aircraft ground speed of 70 m/s and an IR beam footprint diameter of 25 m, the section of sea surface viewed by the IR beam will change every 0.35 s, although, as neighboring segments of sea, the reference bias of I from S might still be expected to be related over that time. In this case the parameters of the time scale are also parameters of the system design, and hence are not susceptible to limiting assumptions about wind conditions, aircraft height movements, etc.

For either of these two approaches (whether T is the reference or I), the scanning pattern of the green beam might be conical or rectangular. The selection of the appropriate scanning pattern has consequences for both the reliability and the accuracy of local sea surface detections. For those configurations seeking to use the local sea surface as detected by the green laser beam (L), the accuracy implications will be explored in greater detail in the following sections.

ACCURACY OF LOCAL SEA SURFACE DETERMINATION

The most obvious difference between the conical and rectangular scan patterns in estimating a local sea surface position L is the frequency with which reflections of green laser energy from the surface of the sea fail to be detected at scan angles significantly greater than 10° from the local vertical. This feature has been presented and discussed elsewhere (see Fig. 8, BILLARD, 1986a, for example). That work also highlighted the consequences of any failure to discriminate between a genuine sea surface reflection and the leading edge of an envelope of subsurface volume backscatter (Fig. 9 of BILLARD, 1986a). For scan angles greater than 10° (5° in glassy seas) the need therefore arises to: (1) discriminate accurately between genuine sea surface reflections and the leading edge of an envelope of subsurface backscatter of laser light within the ocean bulk, and (2) assess whether recognized backscatter envelopes can be used (with appropriate offset) to give an estimate of local sea surface position.

Discrimination Between Surface Reflections and Backscatter Envelopes

Previous work (BILLARD and WILSEN, 1986) discussed the nature of waveforms of received green laser energy for WRELADS and the use of dynamic gain

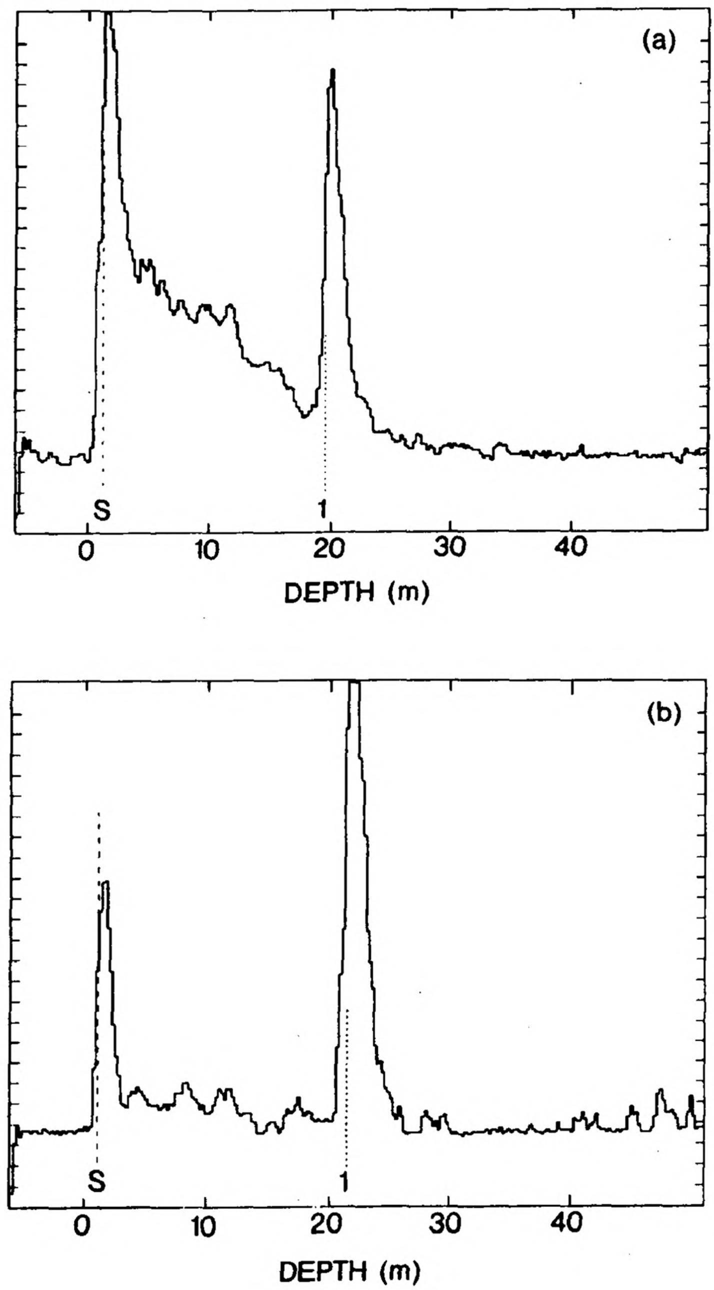

FIG. 8. — Typical WRELADS waveforms, (a) with constant gain across the waveform, and (b) with dynamic photomultiplier gain control in use.

control on the receiver photomultiplier to effectively suppress the backscatter envelope.

Figure 8a shows a typical waveform in which there is constant gain across the waveform, while Figure 8b shows a waveform in which dynamic gain control

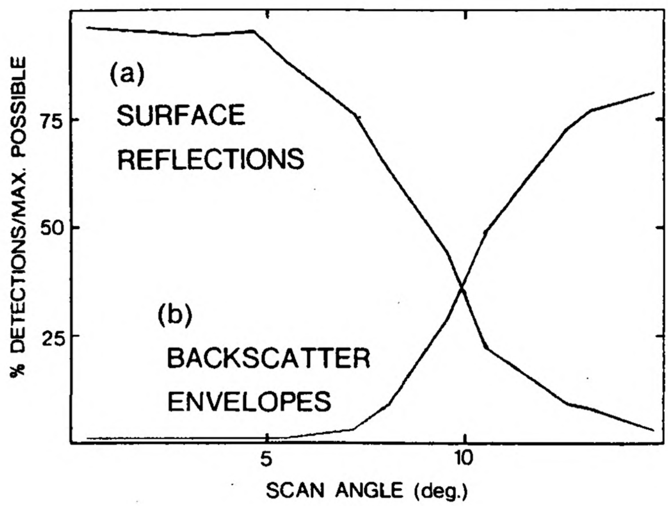

FIG. 9. — Frequency of detection of (a) sea surface reflections, and (b) backscatter envelopes, expressed as a percentage of possible detections, and as a function of scan angle. Each plot represents accumulation of data over 60 sec from the same geographic location, with overflights 40 min apart.

on the photomultiplier has been employed. Figure 8a shows a clear and sharp reflection from the sea surface, followed immediately by a backscatter envelope whose decay rate is a measure of attenuation coefficient, k, within the sea bulk. The amplitude of the envelope is characteristic of the backscatter coefficient within the sea (BILLARD *et al.*, 1986a).

Some immediate observations regarding response times may be made that will allow at least some discrimination between genuine sea surface reflections and backscatter envelopes that do not have a leading edge set by a sea surface reflection.

Rise Time Discrimination

Consider a laser pulse with rise time tp (threshold to peak) that is directed vertically at a flat homogeneous sea, such that the decay time for the transmitted beam within the sea is significantly greater than tp. Then for the rise time for the backscatter envelope, tb will be of the order of tb = 2 tp. In fact, the backscatter will be increasing most just when the peak of the laser pulse enters the sea. Consideration of leading edge rise times would therefore seem to be an attractive means for discriminating between surface reflections and backscatter envelopes. This consideration must nevertheless be qualified by inclusion of any effects of the overall response time of the receiver system.

In the case of WRELADS, the laser pulses have a half-maximum width of 5 ns. A series of calibration tests showed that such pulses, when returned through the receiver system, would show threshold-to-peak rise times of 7.5-9 ns and half-maximum widths of 9-11 ns. This suggests a system response time of 8.7 ns for WRELADS. Once allowance is made for convolving the laser beam with the effects of a disturbed sea surface within the 2-m laser beam width, the effective pulse width is, say, 6 ns rather than 5 ns, and the rise time of the backscatter envelope will be of the order of 12 ns (2 tp). Finally, after allowance for the response time of the system, it can be shown that surface reflection rise times (on the received waveform) would be around 10-11 ns, while those for backscatter envelopes should be around 15 ns.

Because of the dominating effect of system rise time, this degree of discrimination might be considered useful, but barely adequate on its own for general operational purposes.

Drop Time Discrimination

The decay time for a backscatter envelope is characterized by the attenuation coefficient, k. Experience with WRELADS suggests that interest in the output of a laser bathymeter drops rapidly when the attenuation coefficient moves significantly above 0.3 m^{-1}. (See BILLARD, 1986c, Fig. 12, for example. This would be associated with a total attenuation coefficient well in excess of 1 m^{-1}. Hence, the system would not be able to detect the sea bottom except at the shallowest depths.) Since each waveform sample of 2-ns duration is equivalent to a sea depth of 0.22 m, then an attenuation coefficient of 0.3 m^{-1} is equivalent to a decay time of 30 ns, which is well in excess of any conceivable decay time for a detected sea surface reflection. The WRELADS calibration tests referred to above showed pulse drop times around 11 ns.

However, discrimination between sea surface reflections and backscatter envelopes is not quite as simple as suggested by the big difference in decay times, since the decaying edge of a surface reflection will invariably be coincident with the rising leading edge of a backscatter envelope (Fig. 8a). Nevertheless, other measures such as 50% or 80% maximum pulse width can be easily devised to incorporate the necessary discrimination.

Thus, it is concluded that effective discrimination between sea surface reflections and subsurface volume backscatter *is* possible, as long as the green receiver system has adequate bandwidth.

Additionally, in the case of WRELADS, the use of the photomultiplier gain control, in combination with a threshold limitation on surface reflections used in the algorithm to locate the mean sea surface (S), excludes those 'in between' instances where a small amount of reflection from the sea surface is present, but where it is just comparable in magnitude with the subsurface backscatter. In those instances, the positioning of the surface reflection is biased by the superimposed leading edge of the subsurface backscatter. The inclusion of such cases would introduce a number of difficult sources of error that do not need to be pursued here.

Using Backscatter Envelopes to Determine Mean Sea Surface

Having now established a means of discriminating between sea surface reflections and backscatter envelopes, it remains to be seen whether the offset between these features can be characterized in a way that will allow their use in improving the estimate of mean sea surface location (S in Fig. 5). This step is vital if a conical scan configuration is to be employed. (The use of surface reflections only has been demonstrated already for the WRELADS case of a rectangular scan pattern; see BILLARD, 1986a).

In order to investigate these possibilities further, data from a number of WRELADS flights have been reprocessed with a new sea surface detection algorithm. The new algorithm selects out backscatter envelopes instead of genuine surface reflections as previously was the case (BILLARD and WILSEN, 1986). The local sea surface location is taken from the point where the rising edge of the backscatter envelope reaches half the maximum amplitude.

The aim of this exercise is to establish the nature of any offset between the sea surface as located by sea surface reflections, and the sea surface as located by the leading edge of backscatter envelopes. Previous work has already established that it is not feasible to mix such detections without taking account of their source (BILLARD, 1986a). The new algorithm also tends to find pure backscatter envelopes at the extrema of the WRELADS rectangular scan (Fig. 2), which will more closely reflect the situation pertaining when there is a conical scan. (In other words, there will be no nadir or near-nadir pulses contributing to the algorithm modeling the surface of the sea.)

Figure 9b shows the frequency of detection of backscatter envelopes (no surface reflections) as a function of scan angle for 60 sec of data from one flight. Figure 9a shows the comparable frequency of detection of surface reflections for 60 sec of data from the same flight and the same area of sea, but during an overflight 40 min later, when the usual photomultiplier gain controller (which suppresses backscatter envelopes) was in operation.

Figure 10 shows a comparison of the estimate of IR reference bias (a measure of IS in Fig. 5) after processing with the usual WRELADS algorithm for determination of mean sea surface position. (See BILLARD, 1986a, for definition of this algorithm.) This section of data was chosen because of the presence of a segment of higher backscatter (Fig. 10b) that would test the sensitivity of the leading edge of backscatter envelopes to fluctuations in backscatter coefficient.

Points to note from Figure 10 are as follows:

1. There is a significant offset of the IR reference bias as determined from backscatter envelopes when compared with the IR reference bias as determined from sea surface reflections. Both the presence and the direction of the offset are as might be expected.
2. Order-of-magnitude estimates of the offset are also in accord with simplistic considerations. A 5-ns laser pulse has effective width of 6 ns, say, after interaction with a non-flat sea surface. Hence, an offset corresponding to roughly half that — 0.3 m, say, might be expected if the 50% mark of the backscatter envelope was colocated with the peak of the reflecting laser pulse (if it were to be present).
3. Changes in backscatter can have an effect on the IR reference bias as measured from backscatter envelopes. This effect is up to 0.3 m, and hence beyond that which can be tolerated without correction in operational laser bathymetry.
4. Beyond the sensitivity to backscatter mentioned above, there is a signi-

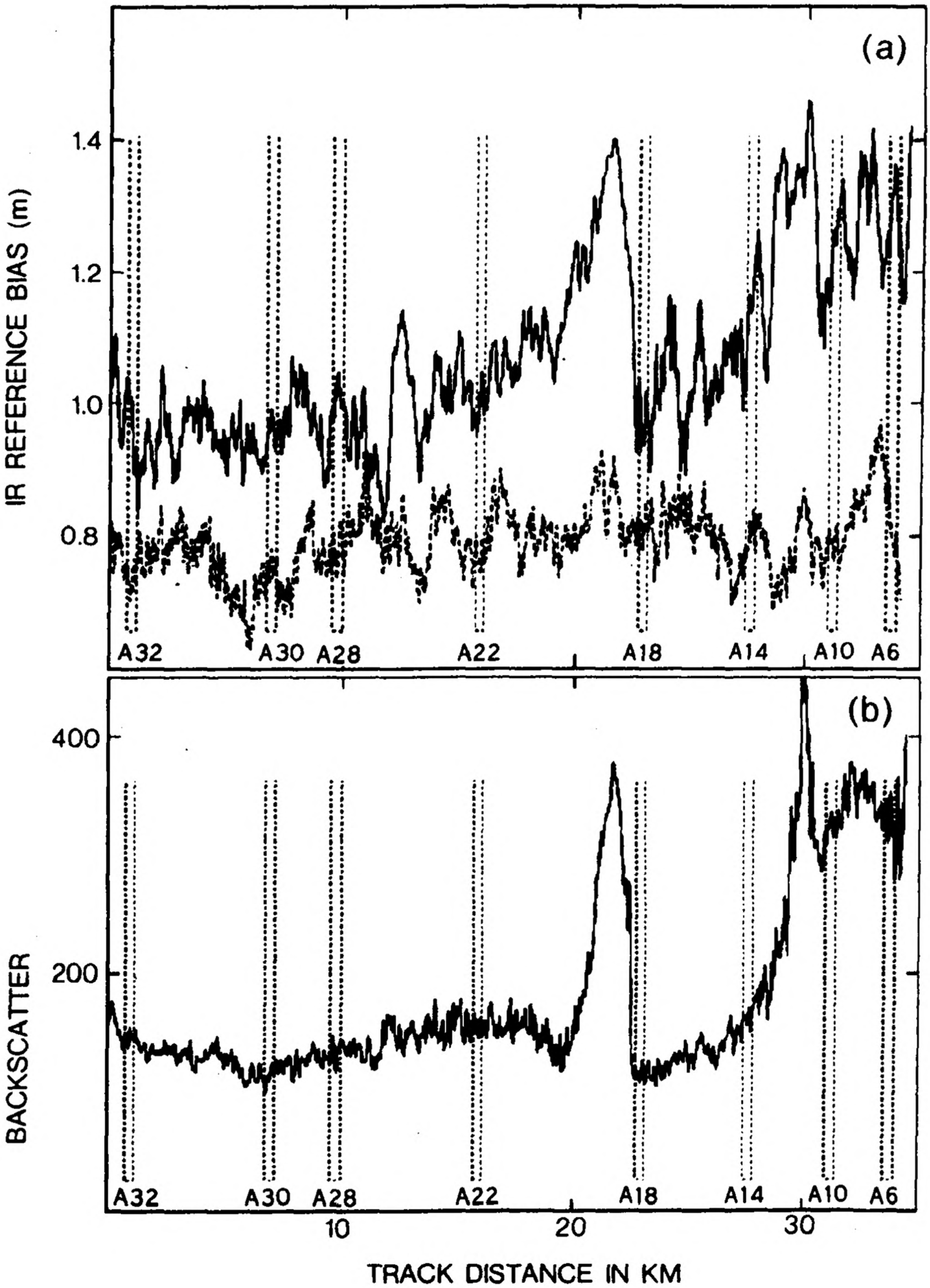

FIG. 10. — Comparison of IR reference bias (IS in Fig. 5) over the same section of sea using first backscatter envelopes only (solid line), and second, surface reflections only (broken line). (b) shows the variation in backscatter amplitude over the same section of sea. The vertical markers show the location of benchmark survey sites.

ficantly increased noise level in the estimate of the IR reference bias from the processing of backscatter envelopes.

The features noted here were repeated in data from other flights when reprocessed and analyzed in the manner described above. The conclusion that must therefore be reached is that the use of backscatter envelopes rather than sea surface reflections to estimate local sea surface location is not tenable, principally because of the variation in the consequent estimate of mean sea surface position due to variations in volume backscatter. Additionally, there are levels of noise remaining in the estimate of the IR reference bias, well beyond those arising from the use of genuine surface reflections, that are attributable to swell and general sea state. This is suggestive of significant fluctuations in the backscatter in the first meter or two below the sea surface.

CONCLUSION

A number of possible laser bathymetry hardware configurations have been considered in order to derive appropriate design criteria for a system of laser bathymetry that can provide adequately for the accurate determination of mean sea surface location. Such an accurate determination is essential as a reference against which sea depths may be measured.

The main results are as follows:

1. The scanning of an IR laser beam in the same direction and with the same (relatively narrow) divergence as the green leads to a system in which the mean sea surface location cannot be determined with acceptable reliability or accuracy. In this case, the only estimate of mean sea surface location is that given by any locally detected sea surface reflection, which will have an accuracy limited to the magnitude of the total sea state including swell. In all other respects, this configuration hence becomes equivalent to one in which pulse transmission time is relied on as the primary reference.
2. The scanning of IR pulses in the same direction as the green, but with a much larger divergence, allows for an estimate of sea surface location that is limited by the size of an effective footprint of the IR beam and the extent to which it is able to 'average' wave heights within that effective footprint. The size of the effective footprint will be a function of sea state, being larger for higher seas. The advantage of this configuration over (1) is the improved *reliability* of sea surface detections. However, serious new sources of error arise due to the variable offset of the effective IR beam footprint. This configuration is therefore not tenable unless it is incorporated within a mechanism for pulse to pulse data accumulation (see (4) below).
3. A non-scanned vertical IR beam with wider divergence is the most effective of the configurations considered here. The effective footprint of the beam on the sea surface is optimized by holding the beam vertical. Indeed, for a beam width of 25 m on the surface of the sea, the

maximum variation in path length from an aircraft at 500-m altitude is only 0.31 m. More important than the increased size of the effective footprint of the IR beam, however, is the reliability of this configuration, which permits integration of successive waveforms. This allows an estimate of mean sea surface location across a baseline equal to the dimensions of the scanning pattern, rather than just the dimensions of the IR beam footprint.

4. For a system in which no IR beam is used, the aircraft height may be refined using the green beam detections of local sea surface. Alternatively, a wide divergence scanned IR beam may be used, giving more reliable detections, at the cost of 'local' sea surface positioning accuracy. Either system is subject to the constraints outlined in (5) below, arising from the selection of conical or rectangular scanning pattern, but the major constraint is the assumption that must be made about vertical aircraft movement. For such a system to determine mean sea surface location with accuracy comparable with that obtainable from the configuration described in (3) above (and assuming a similar laser pulse rate), then additional mechanisms would be needed to monitor and compensate for vertical aircraft motion.

5. For either of the configurations (3) or (4) referenced above, assessment has been made of the potential for using backscatter envelopes rather than sea surface reflections in algorithms used to estimate mean sea surface location. Configurations utilizing a conical scan rather than a rectangular scan pattern of green laser pulses will be limited to using backscatter envelopes for this purpose if the scan angle is greater than some angle set by the prevailing wind and sea conditions. This angle can be less than 5° for glassy seas. Studies performed on WRELADS flight data using backscatter envelopes have demonstrated that they provide a poorer reference to local sea surface location than genuine surface reflections, and that they are susceptible to influence by the magnitude of subsurface backscatter, to the extent that resulting errors would be beyond that tolerable for hydrographic purposes. As a consequence, any system using a conical scan would be restricted in its operating envelope to sea conditions in which (a) sea surface reflections were consistently detected at the scan angles used, or (b) sea conditions were sufficiently slight for the reference point given by the IR beam to be an accurate measure (within a constant offset) of mean sea surface location.

In reaching the above conclusions, it should be noted that only the problem of determining the mean sea surface location has been considered. There are other issues that arise from the various biases in the measurement of sea depth that relate back to the scanning configuration employed. Some of those issues have already been referenced in previous work (BILLARD *et al.*, 1986b).

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References

BILLARD, B. (1986a): Estimation of mean sea surface reference in the WRELADS airborne depth sounder. *Applied Optics* 25:2067-2073.

BILLARD, B. (1986b): Rogue point elimination in airborne laser hydrography. *Applied Optics* 25:2074-2079.

BILLARD, B. (1986c): Remote sensing of scattering coefficient for airborne laser hydrography. *Applied Optics* 25:2099-2108.

BILLARD, B. R.H. ABBOT, and M.F. PENNY (1986a): Airborne estimation of sea turbidity parameters from the WRELADS laser airborne depth sounder. *Applied Optics* 25:2080-2088.

BILLARD, B., R.H. ABBOT, and M. F. PENNY (1986b): Modeling depth bias in an airborne laser hydrographic system. *Applied Optics* 25:2089-2098.

BILLARD, B., and P.J. WILSEN (1986): Sea surface and depth detection in the WRELADS airborne depth sounder. *Applied Optics* 25:2059-2066.

CALDER, M. (1980): WRELADS — the Australian laser depth sounding system. *International Hydrographic Review* (Monaco), LVII(1):31-54.

CASEY, M.J., and J. VOSBURGH (1986): Chartmaking with Larsen. *The Canadian Surveyor* 40:251-260.

CLEGG, J.E., and M.F. PENNY (1978): Depth sounding from the air by laser beam. *J. Navigation* 31:52-61.

GUENTHER, G.C. (1985): Airborne laser hydrography — system design and performance factors. *NOAA Professional Paper Series*, National Ocean Service 1.

HICKMAN, G.D. and J.E. HOGG (1969): Application of an airborne pulsed laser for near shore bathymetric measurements. *Remote Sensing of the Environment* 1:47-58.

PENNY, M.F., *et al.* (1986): Airborne laser hydrography in Australia. *Applied Optics* 25:2046-2058.