February 1996

A DESKTOP EVALUATION OF THE APPLICATION OF TOWED-BODY LIDAR TO BIOMASS ASSESSMENT OF DEMERSAL FISH STOCKS

FINAL REPORT

FRRF PROJECT T93/ 240

CSIRO
AUSTRALIA

DIVISION OF **FISHERIES**

CONTENTS

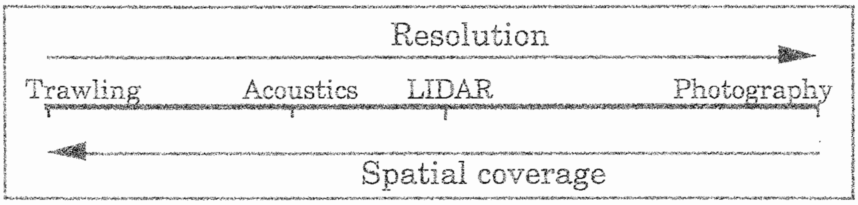
1. NON-TECHNICAL SUMMARY

Biomass assessments based on trawl surveys are fraught with difficulties. Trawl surveys are logistically difficult, often statistically weak, effort and cost intensive and frequently difficult to interpret, because of differences among vessels, and crews, fishing power and, particularly, differences among and within species in catchability. For all these reasons, individual biomass estimates based on swept area methods and the like are usually taken 'with a grain of salt' and, in Australia at least, rarely form the basis for TACs and management plans for finfishes.

Finding an alternative technique that would allow accurate and precise biomass estimates for dispersed fish species is a consistent objective of fisheries science. Towed-body LIDAR appeared to offer such an alternative. Towed-body LIDAR is a light-based system similar in concept and operation to acoustic fish biomass techniques, in which laser light rather than sound waves reflect back from the fish and is measured. First reports suggested a technological break-through, whereby large areas could be surveyed at relatively small expense (particularly as man-power and vessel requirements are slight relative to trawl surveys) while producing high quality data that just might resolve fish to the species level. Unfortunately, scrutiny of the performance characteristics of existing systems does not support first reports. Although towed-body LIDAR is a substantial improvement on photography as a means of surveying benthos, the areal coverage using existing technology is about the same as that which can be achieved with standard towed nets. Similarly, suggestions of high quality, species level identification from LIDAR images appear premature, though improvements in technology might change this in the near future. It is recommended that the fishing industry and fisheries research agencies maintain a watching brief on the technology, to see if improvements in the near future increase its usefulness for fisheries applications.

2. BACKGROUND

Inherent in management needs for virtually all stocks is an estimate of current biomass. For demersal fish stocks, fisheries-independent, direct biomass assessments currently involve one of three techniques: trawl surveys, acoustics and, occasionally, underwater photography. However, all three methods are critically limited regarding the information that can be gained from them, principally because they provide data at either end of a spatial coverage/resolution continuum. Trawl surveys, for example, can cover relatively large areas, but because of sampling problems and biases provide poor resolution of fish density and composition, whereas at the other end of the spectrum, underwater photographs can provide very high resolution, very accurate data, but only for small areas due to limits on water visibility, speed of tows, lighting, etc.



Similarly, acoustic techniques are of very limited use for species on the bottom and often have difficulty distinguishing among species.

Recently there have been reports of a new technology emerging that could provide both high resolution and wide spatial coverage. LIDAR (**Li**ght **D**etection **A**nd **R**anging) is an active sensing system, based on the analysis of the spectral characteristics of a reflected laser beam. The technology is widely used in an air-borne configuration for terrain mapping and the like, and, as an air-borne system, has been trialed for detecting surface schools of fish (with mixed results). We proposed to investigate a complementary application of LIDAR, which is also just reaching the field trial stage of development. Several overseas (mainly USA) groups are in the process of developing and trialing LIDAR in a towed-body configuration, in which the LIDAR is 'flown' above the ocean bottom and records reflectance patterns of substrata, invertebrates and fish. The principal application to date is surveying, for example, oil pipelines for evidence of leakage, in which cases the LIDAR serves primarily as a very high resolution photographic system, one that is much less affected by poor water clarity than passive photographic systems (e.g., those that depend on reflectance of natural light). During such trials and applications, it has been widely noted that fish and macro-invertebrates are often very conspicuous on the processed LIDAR images, which has lead to the suggestion that it could be useful in fish stock assessments.

Three points make this observation particularly interesting from the perspective of measuring biomass of demersal fish stocks. First, because of the speed at which the instrument records data, it can potentially be towed at 5-8 knots, while still providing high resolution spatial information regarding the substrata. Second, because the system is relatively unaffected by water clarity, it can potentially be towed at heights of up to several hundred meters off the bottom and, at that height, can scan a path several hundred meters across. The combination of this tow speed and swath width implies the potential for very cost effective, broad areal coverage of areas surveyed. And third, unpublished data suggests that the reflectance patterns of various organisms may be species specific (which is intuitively reasonable, as differently coloured fishes can be expected to reflect different spectra back to the analyser). The potential is that this system, when properly configured, is capable of high speed, very accurate counting of all fish in a sample area, identified to the species level. If so, such a system could fundamentally alter the way in which demersal fish stock assessments are carried out.

Because the cost of trialing such a system is substantial and the potential of the technology difficult for the non-specialist to evaluate, we proposed a desk study to obntain an up-dated avaluation of the system. Information on deployments and trials of the towed-body LIDAR (also referred to as a 'laser line scan system') are sketchy, in part because of potential commercial value of the information, in part because deployments for geological and engineering purposes are often not well reported in the fisheries literature, and in part because of the rapidly developing nature of the field and the long lag time before such developments are widely reported in the scientific literature. Nonetheless, at least two groups have carried out developmental trials. At the time of the proposal, field work was also planned at the University of Hawaii and an ecologically oriented trial had apparently been carried out in the Gulf of Mexico. The nature and sophistication of these trials has still to be determined. Informal discussions with the group at the Univ. of Hawaii, for example, suggested the Gulf of Mexico trials were done using relatively unsophisticated equipment and a low level of data analysis (basically black-and-white images, rather than full spectral analysis). A variety of analytical procedures have also been suggested, e.g., Raman spectroscopy, but the extent to which they were applicable to LIDAR spectra, the degree of sophistication of spectrum stripping paradigms required, and data handling capabilities used (which would be comparable to those required for acoustic data) had also not been determined.

We proposed to visit laboratories overseas where this developmental work is underway, assess the current state-of-the-art and the likely time until real-world applications are possible, and discuss data processing requirements both with the current developers and with Australian scientists familiar with the technology. On the basis of our own experience and input from Australian experts in allied fields, we would then produce an evaluation of the apparent potential of the technique and recommend the extent to which and the ways in which Australian fisheries science could benefit by involvement in the field.

3. PROJECT DETAILS

OBJECTIVE

To undertake a desk-top study to assess the potential of towed-body LIDAR for biomass determination of demersal fish stocks.

PERSONNEL

Ronald Thresher	CSIRO	Project Supervisor
Rudi Kloser	CSIRO	Electronics engineer

4. TECHNICAL RESULTS

The documents supplied by the two companies leasing towed-body LIDARs -- Science Applications International Corp. and Applied Remote Technology -- contain detailed technical specifications and descriptions of the system. These documents are attached as appendices 4 and 5. Rather than repeat this detail in the body of the final report, this section (Technical Results) will outline the basic operating characteristics of a towed-body LIDAR as it relates to fisheries applications, and then Section 5 (General Discussion) will address specifically these characteristics as they relate to requirements for biomass estimation of demersal fish stocks.

SOURCES OF INFORMATION

The following is based on information gleaned from a computer search of the recent scientific and engineering literature, a traditional literature search for relevant information in the CSIRO Marine Library, and direct contacts (including personal discussions) with a number of firms and individuals involved in development and application of LIDAR for marine systems. The latter include

The Hawaiian Institute of Geophysics (University of Hawaii)

The National Marine Fisheries Service (USA)

Applied Remote Technology (Massachusetts, USA)

Science Applications International Corporation (San Diego, USA)

Deepsea Developments International (Massachusetts, USA)

and SETS Technology (Hawaii, USA).

Primary literature sources are Caimi (1993), Fournier, et al. (1994), Adams & Koerber (1995), Sharma, et al., (1995), Gauldie, et al. (in press), and system manuals provided for their respective instruments by Science Applications International Corp. and Applied Remote Technology.

LIDAR: BASIC OPERATING PRINCIPLES

There are two sources of light available for optical analysis: natural and artificial lighting. In the parlance of optical instruments, these are referred to as passive and active systems, respectively. In the ocean, natural lighting as a source of information is severely limited by penetration depth, which in turn is a function of wavelength, water clarity and quality, etc. The problem is well exemplified by natural light photographs taken in even very clear water situations, e.g., coral reefs, where images usually have a severe blue cast (due to wavelength effects), are fuzzy and of low contrast (due to low ambient light levels and reflection). Natural light photographs of targets more than 5-10 meters from the camera, even under good conditions, usually consist of little better than pale blue blurs. Fisheries applications of optical sensors in the ocean rarely involve ideal water conditions, and hence natural light is typically of limited value in this context.

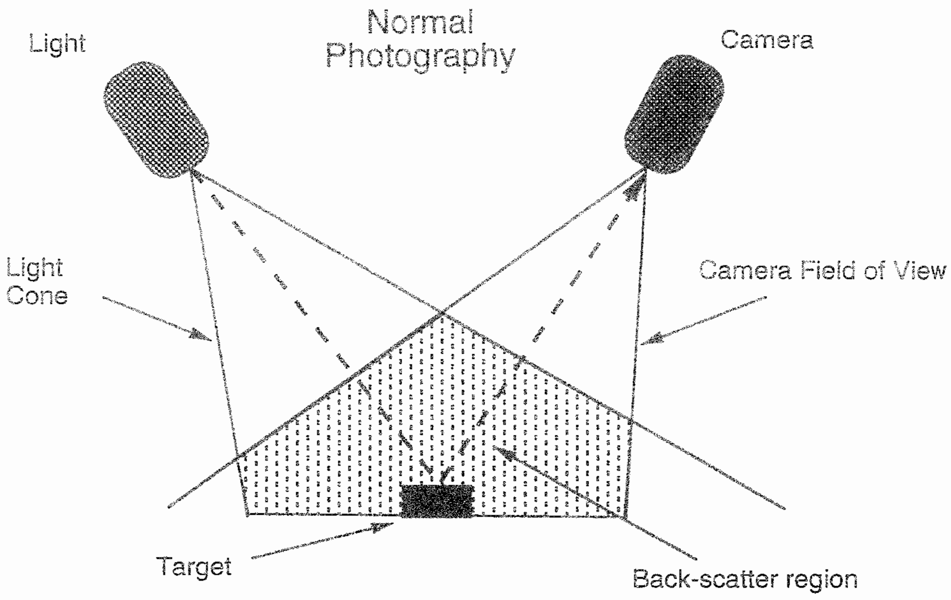
The obvious solution is to use an active light source - a flash. Flash photography provides a brief, but high intensity light source close to the target, which results in greatly enhanced colour saturation in the image, greater depth of field, etc., and overall greatly improved images. Most (if not all) 'pretty' underwater pictures are made using a flash or otherwise intense artificial light source to flood the target.

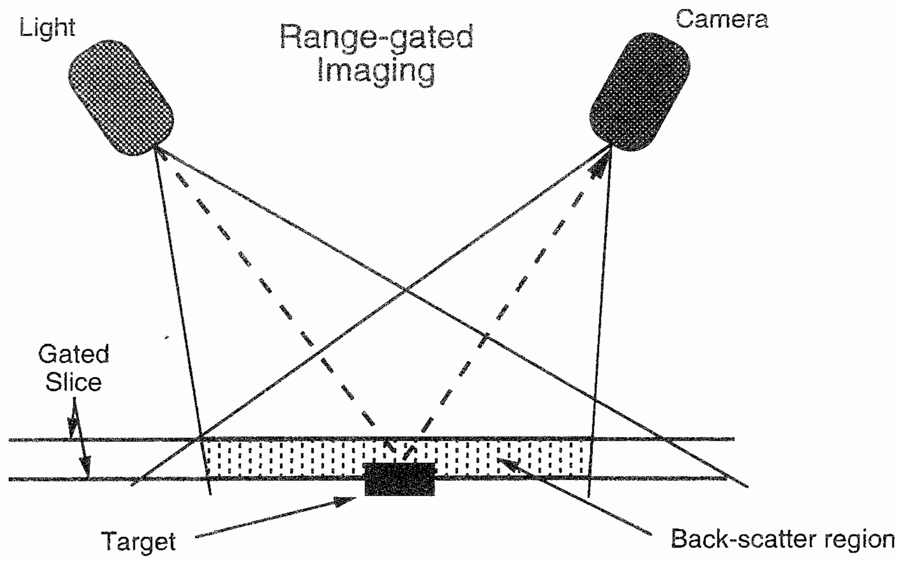
However, artificial lighting suffers a significant problem in its own right, due to back-scattering by particles in the light path. The light emitted by a flash unit reflects not only from the intended target (and thence to the camera), but also from all other targets within the light cone. The problem is well illustrated by attempts to use flash photography in silty conditions, where even with the artificial light the images are grainy and low contrast, as the film records not only the reflectance from the target, but also the reflectance of all of the particles between the target and the camera. A similar problem occurs in natural light photography, but the diffuse source of natural light reduces the magnitude of this problem relative to the others referred to above.

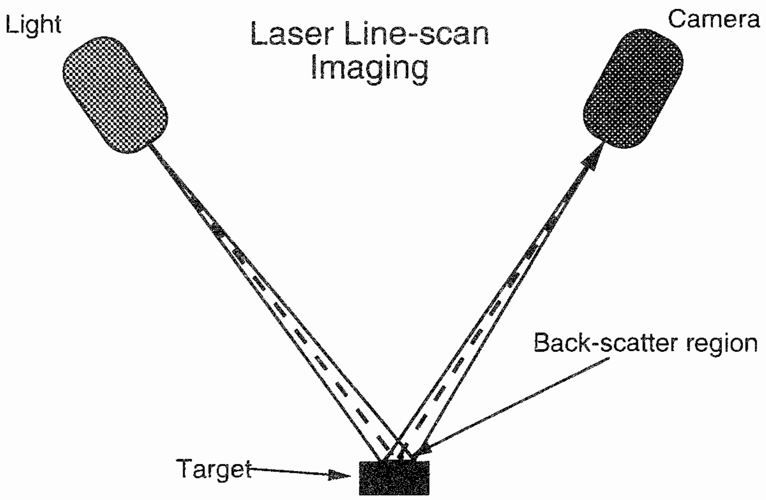
To minimise the back-scatter problem, a photographer needs to reduce the number of back-scattering particles in the joint volume defined by the intersection of the cone of light produced by the flash and the field of view of the camera. Photographers do this in two ways. First, they attempt to get as close to the target as possible (by use of wide angle, close focus lenses), which reduces the length of the light path and therefore the number of particles that will interfere with the image. Second, they separate the light source and camera as widely as possible, so that the main reflectance off back-scattering particles is in a direction other than that of the camera. Neither approach is of great value in terms of optical imaging of the sea bottom (e.g., demersal fish).

Optical engineers have devised two additional ways to reduce the back-scatter problem. The principles for both have been well known for many years, but both are critically dependent on high performance light sources and electronics that have only become available recently for deployment in a towed body or ROV. Both techniques are referred to in the literature as LIDAR, as both routinely use lasers as light sources. The two forms of LIDAR are 'range-gated imaging' and 'line scan imaging'. The principles involved in the two approaches are illustrated in Figure 1.

Range-gated imaging reduces the back-scatter problem by, in effect, opening the camera shutter only for the fraction of a second that corresponds to the return time of light from the flash to the target to the camera. By not including in the image light returning early to the camera (reflected off objects in front of


Normal
Photography
Light
Camera
Light
Cone
Camera Field of View
Target
Back-scatter region


Light
Range-gated
Imaging
Camera
Gated
Slice
Target
Back-scatter region


Light
Laser Line-scan
Imaging
Camera
Back-scatter region
Target

the target) or later (reflected off objects behind the target), the back-scatter problem is reduced to only the particles in the slice of the water column that corresponds to the gated shutter time. By varying the time the shutter is open, one can increase or decrease the width of the slice or move it towards or away from the camera. Electronically, the main challenge in range-gated systems is synchronisation of the pulsed light source (in the range of 1-5 nanoseconds) and precise gating of the electronic imaging system (usually a gated photo-multiplier tube).

Line scan systems reduce the back-scatter by narrowing both the volume of the light cone and the field of view of the camera. The process has been likened to looking at a spot from a laser beam with a telescope. The smaller the light cone and narrower the field of view, the smaller the region of overlap and the less the volume producing back-scatter. A consequence, however, is that the area imaged is also small, so that in practice a series of images are collected sequentially, to produce a composite image of the target. Hence, the light source (a laser) and imaging system (a narrowly focused electronic camera) are scanned synchronously across the target region. Image size depends on the scan rate, the focal characteristics of the imaging system and the distance between the LIDAR and the target. Geometry of the system is critical, both in maintaining the alignment of the laser and imaging system and in holding the LIDAR a fixed distance above the target (determined by the intersection distance set by the relative angles of the laser and camera and the camera's depth of field).

Both range-gated and line scan LIDARs have been built and are in routine commercial use. In order to maximise imaging, both use frequency-doubled neodymium-yagg lasers whose green light (532 nm) approximates the frequency of maximum light penetration (minimum attenuation) in the ocean (480 nm). Use of a monochromatic light source in the first instance produces black-and-white (grey scale) images. Development of multi-frequency LIDARs is apparently in progress. Additional optical information can also be potentially extracted from the monochromatic image by use of secondary spectra (see below).

The operating distance of a LIDAR in water depends on both the laser frequency and power and water clarity, quality, etc. In practice, it is usually about 5-6 attenuation depths (1 attenuation depth = distance in water irradiance is reduced to 1/e, or approximately 37%, of initial level), at lasers of about 1 watt power. This compares with 2-3 attenuation depths for normal flash photography. The maximum attenuation depth of clear water at 480-500 nm is about 20 m; hence, the maximum theoretical distance between a LIDAR and a target for which an image can be obtained is about 120 m. In practice, water is rarely optically clear, and the maximum imaging distance, although still 5-6 attenuation depths, is often much less than 100 m. In typical coastal water, maximum attenuation distance is about 5 m, and maximum imaging distance for a LIDAR about 25-30 m. CSIRO's experience with underwater demersal video on the Southeast Trawl shelf indicates maximum distance for normal artificial light video imaging is 8-10 m (at times, much less); correspondingly, a LIDAR could be expected to produce useful images at distances up to 16-20 m in this environment.

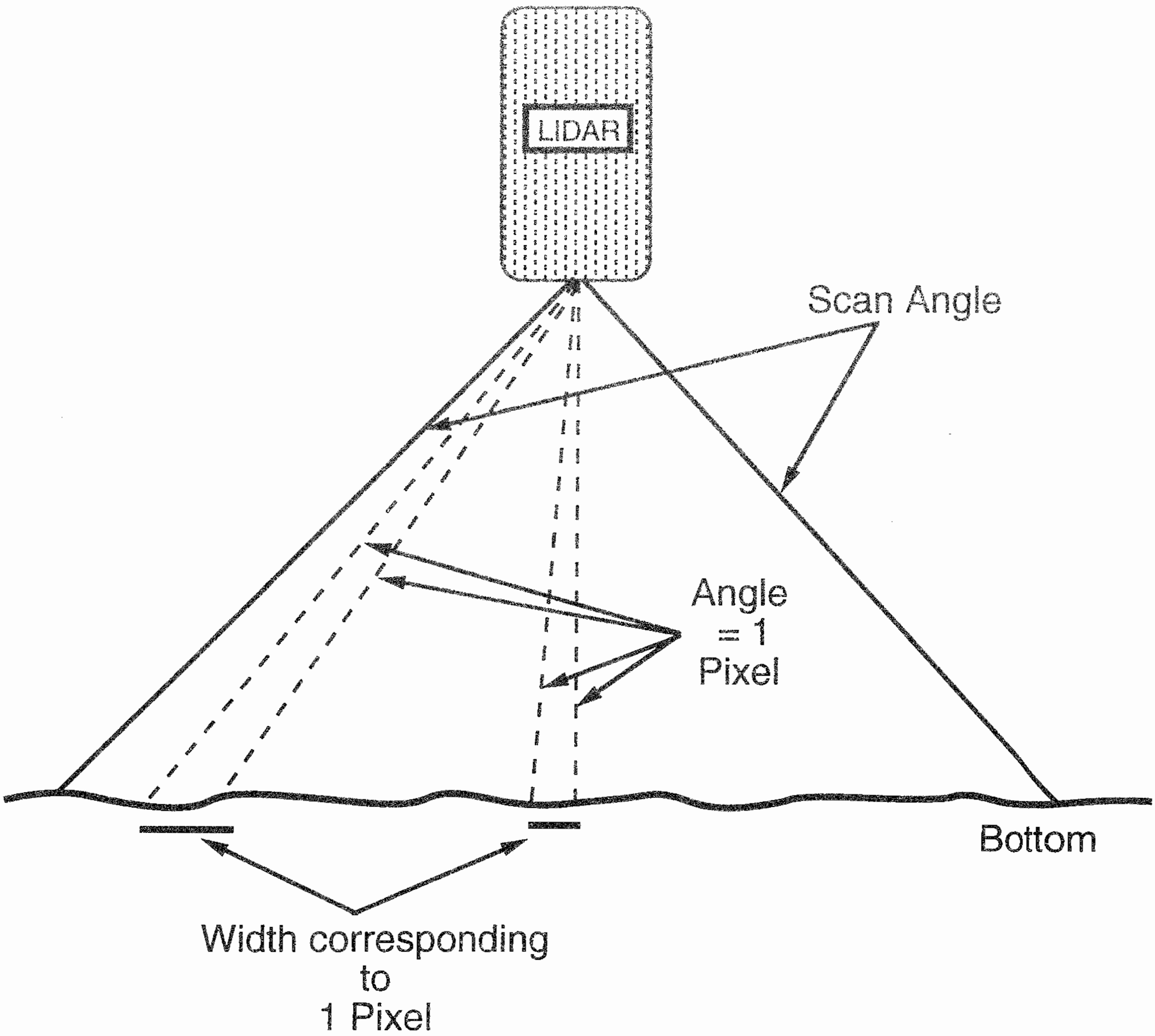
LINE SCAN LIDAR: PHYSICAL CHARACTERISTICS

The LIDAR that has been touted for its potential for biomass surveys is the line scan system. Two commercially available towed body line scan LIDARs have been produced. They have similar physical characteristics, and are described in detail, with associated technical specifications, in the system manuals, appended (appendices 4 and 5).

Physically the system consists of the laser and camera unit, which can be installed in a suitably modified (with windows) towed body, ROV, etc., a computer-based and video control console and a communications unit, that digitally ties the two together. The concept is identical to that of an acoustic towed body system, and to an extent the data handling, equipment and deployment problems and procedures are comparable. Like the acoustic system, the LIDAR equipment is inherently transportable (i.e., can be moved between vessels, as required), though it requires the usual electronic cable and stabilised winch system needed for towed body operations.

The scanning unit itself is a cylinder less than a meter long and about 10 cm in diameter. Internally it consists of a laser assembly, a digital camera and associated electronic communication equipment, and a rotating set of mirrors, which are used to scan the beam. The pulsed laser reflects off of one set of mirrors, is focussed and illuminates the target through a window in the towed body, whereas returning light enters through a second window, is focussed and reflects off a synchronised set of mirrors into the photo-electric sensor. Each laser pulse-image pair constitutes one pixel in a composite electronic image. The area corresponding to each pixel is a function of tow speed, mirror rotation speed, distance above the substratum and the angle between the LIDAR and the target (targets directly under the LIDAR are recorded at higher resolution than those at the edge of the scan path, due to the geometry of the system, fig. 2). The LIDARs currently available scan a swath 70° wide (35 ° on either side of the vertical line between the LIDAR and the substratum). This corresponds to a swath width approximately 1.4 times the distance between the LIDAR and the substratum. This swath is sampled at a resolution that is user selectable at 512, 1024, 2048 or 4096 pixels per line, corresponding to a fixed angle per pixel of 0.136°, 0.068°, 0.034° and 0.017°, respectively.

Because of the geometry of the system, based on shining a laser onto the bottom and then analysing the reflected image, it is critical that the LIDAR be



Geometry of path scanning by towed body LIDAR, comparing a fixed (= 1 pixel) angle immediately below the tow path with the same 1-pixel angle to one side of the tow path, showing effect on area of the bottom integrated into the single pixel datum.

towed a near-constant distance above the substratum. Essentially the system has a focal distance, where the angle set by the laser and the imaging equipment are optimal. This distance is user determined, based on water clarity, resolution desired, etc. Objects above and below this focal distance will reflect the laser into the camera too sharply or too widely, respectively, for optimal resolution. Presumably objects too far above or below the specified altitude will reflect light that miss the camera window altogether, and hence are not recorded. The sensitivity of the system to variations in height off the bottom (altitude, to use the jargon) is nowhere clearly specified, but is alluded to by a number of correspondents. From discussion, it appears that minor variations in altitude (due to a slowly undulating bottom, for example) are not critical, and that in normal operation, "flying" the towed body above the bottom, as is done with an acoustic towed body, suffices. Nonetheless, the implication was that a towed LIDAR system is more sensitive to effects of altitude change on data quality than is an equivalent acoustic system.

IMAGE QUALITY AND TARGET IDENTIFICATION

In normal use, LIDAR produces a monochromatic (black-and-white) video or photographic image. As noted above, resolution is to an extent chosen by the user, but is typically 1024 or 2048 pixels per width of the composite image. It is difficult to compare this directly with more commonly used indices of image quality (e.g., lines resolved per inch), as no such data are provided in the relevant publications. However, inspection of, presumably, best quality images provided in the sales brochures suggest maximum resolution comparable to a very high resolution television image.

In current applications (pipeline surveys, surveys for marine debris), target identification is based on analysis of this image, that is, by looking at the picture and assessing the targets size, shape and black-and-white patterning. Image quality can be very good in optimal viewing conditions, and can be improved further by digital image processing, which the system is designed to incorporate. Images produced by existing LIDARs, provided in the system 'sales brochures' (appended), indicate marine life can at least on occasion be visualised with sufficient clarity to 'guess-imate' species identity of the larger and more common species by means of the black-and-white images alone. The process is entirely comparable to species identification using conventional black-and-white underwater video, if perhaps with better technology, and has similar constraints. The issue of species recognition based on black-and-white video is discussed further below.

A second method that has recently been suggested to provide species level identification from LIDAR involves analysis of secondary spectra, in particular Raman spectra. The principle behind this is similar to that involved in X-ray spectroscopy. In the latter, bombardment with high energy particles and light 'pumps' electrons to higher than normal energy states. These high energy electrons decay rapidly back to their base state, emitting the 'excess' energy as radiation. The energy differences between electron states differs among elements, and hence analysis of the characteristic x-rays emitted by decaying electrons constitutes an elementally diagnostic signature. This is the basis of electron probe microanalysis, for example.

Raman spectroscopy works on a similar principle. The energy in the laser stimulates, by absorption, molecules in the target, which is subsequently re-emitted at different wavelengths. The re-emitted wavelengths depend in part on the temperature of the targeted molecule, and in part on its molecular and atomic structure. Atomic bonds among different element pairs, for example, re-emit at characteristic wavelengths, which can then be analysed and measured to help identify the emitting molecule.

The basis for using this technique to identify fish species relies on the different pigments present in the dermis. Under LIDAR stimulation these pigments (each of which has a different molecular structure) re-emit Raman spectra, which in theory can then be used to identify the target (once a library of such emission spectra has been built up experimentally). Evidence to support the applicability of this approach is scant, and based entirely on laboratory studies. Sharma, et al. (1995) exposed sections of the dorsal integument of three different pelagic fishes (black marlin, dolphin and skipjack tuna) to a LIDAR (wavelength unspecified) in the laboratory, and found significant differences in the re-emitted Raman spectra (Fig. 3). The extent to which these differences would be discernible in the field, or are relevant to whole fish signatures was not addressed in the pilot study.

5. GENERAL DISCUSSION: APPLICABILITY OF TOWED BODY LIDAR TO BENTHIC FISH BIOMASS SURVEYS

There are two essential criteria for fish biomass assessment in the context of evaluating LIDARs potential: areal coverage and fish identification. The lure of a LIDAR based system was relatively rapid coverage of a large area, combined with species level identification. The technical details available regarding current systems raises doubts about satisfaction of either criterion.

AREAL COVERAGE:

Current demersal trawl technology samples an area of about 10-20 m width, at speeds of up to about 2-4 knots (3.7 - 7.4 km/hour). The potential coverage of towed-body LIDAR is considerably greater: swath widths of 1.4 X altitude, where the latter is about 6 X absorption distances, could easily generate sampling paths greater than 100m in clear conditions, sampled at tow speeds of

4-7 knots. A swath width of 100 m at 4 knots constitutes a 500 - 2000% increase in sampling efficiency over trawl sampling.

However, there are two constraints on sampling using LIDAR. First, maximum altitude is determined by water clarity. As noted above, water clarity on the SE shelf is typically such that maximum altitude of the LIDAR would be 20 m or less, producing a corresponding swath width of less than 30 m under best conditions. Conditions in other environments, such as the NW shelf, would permit operations at higher altitudes, but at a cost in resolution.

This is due to a second constraint on areal coverage, which derives from the relationship between speed of the towed-body, altitude and resolution. In general, the greater the tow speed and altitude, the lower the resolution. Tow speed and altitude are both critical because they jointly determine the number of photons per pixel, where the latter is set by a minimum signal-to-noise ratio required by the photodetectors in use (40,000 photons/pixel): the greater the altitude (i.e., wider the swath), the slower the towed body has to be flown in order to achieve this minimum for a given target. The relationship between tow speed and altitude is non-linear (see Figures A1 and A2, Appendix 4). Even under ideal conditions, it appears that maximum working altitude rarely exceeds 15 m, at speeds generally less than 3 knots (5.5 km/hour), in order to achieve even a relatively low image resolution of 1024 pixels/line.

Areal coverage at an altitude of 15 m and 5.5 km/hour tow speed can still be about 3 times higher than achieved using conventional trawling (assuming a conservative estimate of the latter of a 10 m swath towed at 2 knots). It should be noted, however, that this coverage will vary with water clarity and could often be considerably less.

Further, coverage is also constrained by the size and reflectivity of the target, as these inherently affect the number of photons returning to the detector. Consider a redfish. A good sized redfish is about 30 cm long, and 4-5 cm across, when viewed from the top (as it would be by the LIDAR). At an altitude of 15 m and resolution of 1024 pixels/line, each pixel integrates a width of about 2.0 cm. (wider farther from the vertical line directly under the LIDAR). Hence, a LIDAR sweep horizontally across a large redfish would constitute about 2 adjacent pixels. Given that fish are not perfectly flat dorsally, it is realistic to expect signal loss due to scattering off the fish's surface, etc., such that the information content of the two pixels would be relatively low. In order to achieve a reasonable likelihood of detection during that sweep, a resolution of perhaps 4 pixels/fish would appear to be desirable, i.e., 2048 pixels/line. Figure A2 in Appendix 4 indicates that at 2048 pixels/line, maximum tow speed at an altitude of 15 m is about 0.4 knots (0.75 m/hour). <u>Hence, at a resolution apparently useful for redfish detection, areal coverage by the towed-body LIDAR is less than (about 40%) that achieved during a normal trawling operation</u>. Some of this reduced effectiveness is recovered by use of the LIDAR in continuous operation (as opposed to trawls which need to be set, recovered, etc.). However, even factoring this in suggests an areal coverage by towed-body LIDAR roughly equivalent to or less than that of conventional trawls.

SPECIES IDENTIFICATION

Despite its other short-comings, one major advantage of conventional trawling is that it produces specimens in hand, which can then be subjected to any desirable level of taxonomic or ecological analysis. LIDAR, in contrast, produces only images. As noted above, the quality (resolution) of the image depends on operating conditions.

Information as to how useful images produced would be for fish identification is not readily available. Like any other monochromatic video system, LIDAR will be incapable to discriminating among very similar species, unless these species can be delineated on the basis of other information (e.g., habitat or depth distributions). Some indication of the usefulness of the system can be gleaned from images produced in the 'sales brochures", several of which contain fishes.

Figures 3 and 4 in Appendix 4 are taken at an altitude of 8 m (swath width 11.2 m), tow speed of 1.8 m/hr (and hence areal coverage about 50% of a conventional tow), and resolution of 2048 pixels/line. Three fish are evident in the large image; a magnified image of one (a flatfish, apparently) is shown in figure 4. Comparison with the stated size of the overall image (35 feet wide by 17.5 feet long) suggests that all three fish are around 45-50 cm SL. In the magnified sub-section, a smaller (about 25 cm) individual is also visible.

Identification of the species in the image is, in my opinion, problematical (unless there are extenuating circumstances, such as only one species of flatfish is found in the area). Although gross details of the individual are clearly visible, even magnified there seems to be little basis, at this resolution, for optimism about species identification from the monochromatic images alone.

Figure 7 of Appendix 4 was also taken at an altitude of 8 m, but at a higher tow speed (7.2 m/hour) and lower resolution (1024 pixels/line). The fish in the image is approximately 81 cm SL, by comparison with the pipeline at the centre of the image, which is described as 40 inches in diameter. On the basis of the image I suspect that an experienced fish taxonomist could make a reasonable guess at the identity of the fish, based on its shape and general coloration.

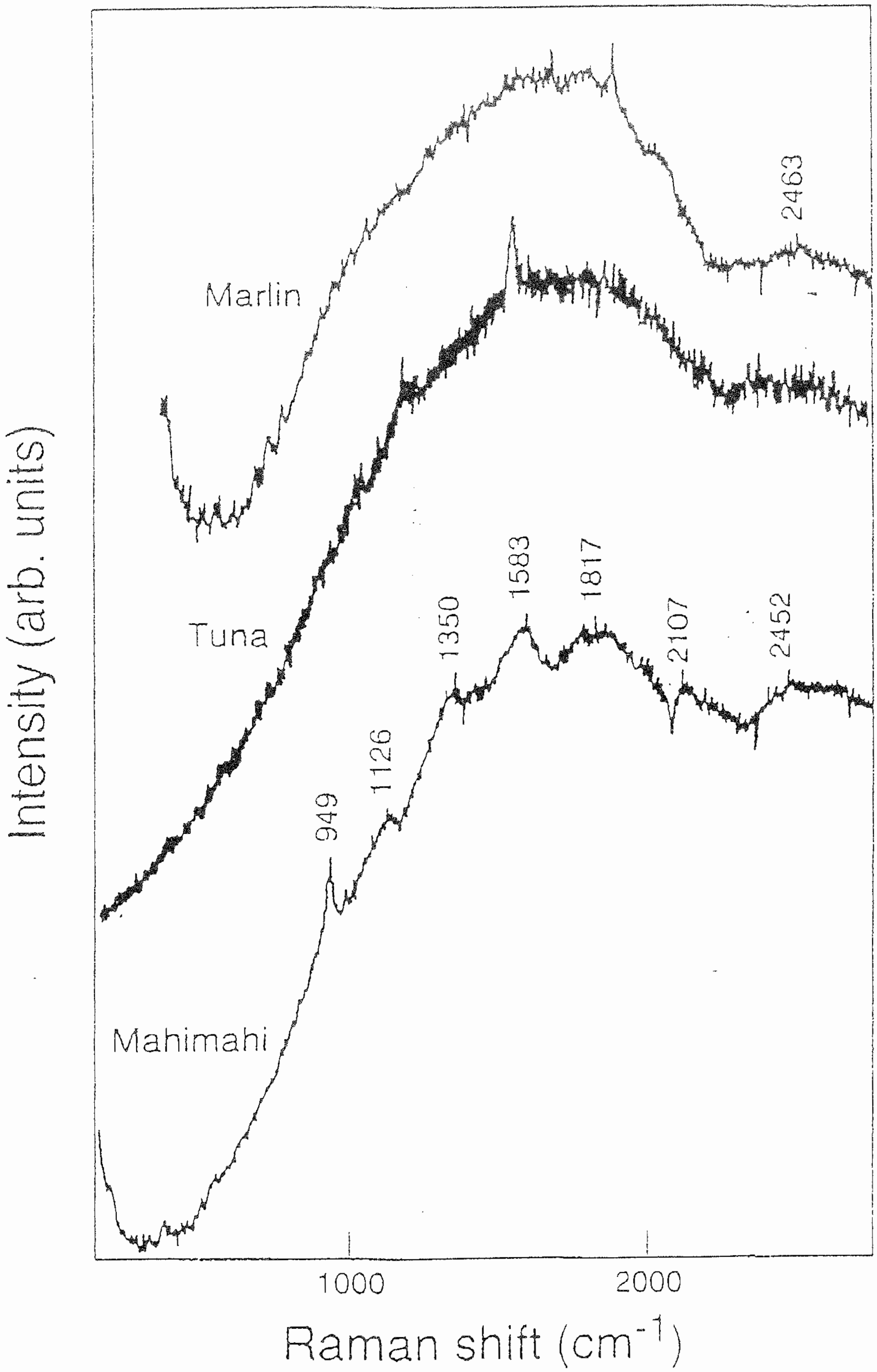
I conclude from this that at typical resolutions and low altitudes, fish identification from the monochromatic images produced by towed-body LIDAR are probably just adequate to species identification or, more likely, identification to groups of similar appearing species. The effectiveness of the system would be critically dependent on image analysis by qualified taxonomists, and would be enhanced by information on habitat requirements of similar appearing species that might facilitate species identification. I also conclude, however, that even in the presumably high quality images chosen for the sales brochure individuals much less than 50 cm SL would be difficult to identify, without ancillary information.

Two such sources of information have been tested thus far. One, noted above, is the Raman spectra. The concept of examining Raman spectra, and more broadly fluorescence signatures, re-emitted from laser illuminated objects, including fishes, is intriguing. However, there are at least three practical considerations that need to be investigated before the technique can be endorsed.

First, experimental data supporting differences among species in the Raman spectra emitted is extremely sparse, consisting virtually of a laboratory test on small sections of dorsal integument. While these test results look promising, they hardly suffice to answer questions about how a large area integrated signal from a fish with a potentially complex colour pattern would be characterised. It is also not clear that fishes with similar colour patterns might not also exhibit similar Raman spectra. Hence, while the existing data, as noted, look promising, effort should be expended in both realistic laboratory trials and, perhaps, controlled field studies, before the technique is developed for field application.

Second, it is not evident in the available literature how strong the Raman spectra are, relative to ambient light. Nor is it clear how much it would be attenuated in water of various degrees of clarity. As noted above, the LIDAR has to be slowed already and moved closer to the target in order to achieve an adequate signal-to-noise ratio even for monochromatic images (the 40,000 photons/pixel required by the detector). A similar, if probably considerably greater problem would occur in acquiring an adequate signal-to-noise ratio to pick out and measure quantitatively peaks in the Raman spectrum, implying overall light input higher than even the 40,000 photons required. If so, then this reduces even further the practical utility of the towed system for large area underwater surveys.

Third, capturing and analysing the Raman spectrum for each pixel is a hugely complex job of data management. As opposed to the monochromatic system (or acoustics), where a single datum is recorded per pixel (or its equivalent in an acoustic system), a very complex and high resolution set of data capturing intensities across a wide spectrum would have to be captured and stored for each pixel if the Raman spectrum was to be used for species identification. Current LIDAR configurations are not equipped to handle this volume of data, and developing a system that would do so automatically and efficiently is not trivial. It would also have to be matched to an equally complex system that would examine each pixel-based data set automatically, characterise the Raman



Marlin
Tuna
Mahimahi
2463
949
1126
1350
1583
1817
2107
2452
1000
2000
Intensity (arb. units)
Raman shift (cm^{-1})

spectrum at each, and plot each into a mapped image before decisions could be made about the significance of each observation.

The second approach is suggested by Churnside & McGillivary (1991), who examined the level and patterns of polarization of the light reflected off fish from a LIDAR. Basically they suspended dead pelagic fish species in an aquarium (dorsal side towards the LIDAR), illuminated a spot immediately ahead of the dorsal fin, and then measured gross reflectance, plane polarization and rotational polarization for 5 finfish species and a squid. All specimens were collected in the eastern Pacific Ocean. The results are generally promising. As expected a dark colored specimen (the squid) reflected much less light than the finfish, and among the finfishes there were strong indications of different levels of plane and rotaional polarization of the reflected light. How these would translate into a field situation with moving targets is not yet clear. As well, some of the concerns relevant to capture, analysis and interpretation of the Raman spectra apply to analysis of the polarization patterns as well.

In summary, I conclude that the existing monochromatic system is probably adequate for species level identification of large, morphologically distinct individuals, when the system is run slowly enough and at a low enough altitude to produce high resolution data. It does not appear to suffice to identify smaller fishes, unless run at extremely high resolutions (which are impractical for field surveys), and even for larger ones, ancillary information about depth and habitat preferences is likely to be crucial to narrow down the species identity from a range of possibilities. Further, I conclude that use of other spectral signatures, such as the Raman spectrum and polarization, while full of potential, is at far too preliminary a stage to justify major involvement with the approach at this stage.

6. IMPLICATIONS AND RECOMMENDATIONS

Biomass assessment based on trawl surveys are fraught with difficulties. Trawl surveys are logistically difficult, often statistically weak, effort and cost intensive and frequently difficult to interpret, because of differences among vessels (and crews,) in fishing power and, particularly differences among and within species in catchability. For all these reasons, biomass estimates based on swept area methods and the like are usually taken 'with a grain of salt' and, in Australia at least, rarely form the basis for TACs and management plans for finfishes.

Finding an alternative technique that would allow accurate and precise biomass estimates for dispersed fish species is a consistent, if perhaps low key objective of fisheries science. Towed-body LIDAR appeared to offer such an alternative. First reports suggested a technological break-through, whereby large areas could be surveyed at relatively small expense (particularly as man-power and vessel requirements are slight relative to trawl surveys) while producing high quality data that just might resolve fish to the species level. Unfortunately, scrutiny of the performance characteristics of existing systems does not support first reports. Although towed-body LIDAR is a substantial improvement on photography as a means of surveying benthos, the areal coverage is constrained by a need for high resolution at swath widths and tow speeds that are similar to that which can be achieved with standard towed nets. Similarly, suggestions of high quality. species level identification from LIDAR images appear premature, though improvements in technology might change this in the near future.

The central problem with the towed-body LIDAR at this point is lack of laser power. As currently configured, the laser in towed-body LIDARs run at a maximum of 2 watts. Though not stated explicitly anywhere, the fact that they usually run a less than half this power suggest technological difficulties of running high power operations At beam intensities ≤ 1 watt, the LIDAR is limited in its ability to produce high rates of returning photons, which might increase operational altitude (and hence swath width) and system resolution (and hence facilitate species identification). Literature reports suggest lasers of up to 20 kilowatts have been employed in the field for bathometric mapping, although not from a towed body.

There are also recent developments towards a deployable multi-frequency LIDAR, though these systems appear as yet to be mainly experimental. Multi-frequency LIDARs potentially offer the same advantage for species identification that the use of multiple frequencies does in acoustic approaches. Reflectance patterns of dermal pigments are likely to differ among species differently for each laser frequency, so that composite monochromatic images for each laser could generate useful pseudo-colour images that would improve prospects for species identification. Again, this technology is only just coming on line, and would still suffer the problems discussed above regarding areal coverage and the like.

Hence, the implications for research and management at this stage are:

1. Towed-body LIDAR is not a panacea for benthic fish surveys. It complements existing trawl-based techniques, but cannot replace them.
2. Towed-body LIDAR is a more powerful field tool that standard video systems for purposes of, for example, mapping benthos. As such, properly developed, it might provide a useful tool for sampling fish in areas too rough for conventional trawl surveys.

Therefore, we recommend

1. That a watching brief be maintained on towed-body LIDAR technology, to assess the impacts of more powerful and multi-spectral laser systems. There appears to be considerable potential for rapid technological development in these areas, which could substantially improve the performance of these systems in fisheries applications.

2. That if any research is supported, it should be in the area of species recognition. Two approaches seem worth pursuing: testing further the usefulness of Raman spectroscopy in realistic laboratory and field settings, and automated image analysis of video images for fish enumeration and identification.
3. As the data handling problems of acoustic and laser-based systems are virtually identical, continued efforts should be made to improve this capability in towed-body systems in general. Any new technology that comes on line is likely to increase, rather than reduce, the amounts and speed with which data will need to be handled and analysed.
4. Given that the interactions between fishing, fish and benthic communities is a priority issue, and likely to become more important in the future, towed-body LIDAR should be investigated as a more efficient alternative to current acoustic and video-based approaches to benthic surveys. Short duration field trials to assess the usefulness of this technology for benthic mapping appear warranted.

7. ACKNOWLEDGMENTS

We particularly thank Dr. R. Gauldie (Hawaiian Institute of Geophysics) for his advice and assistance in this study. We also thank S. Sharma, I. West, B. Cole, E. Saade and Applied Remote Technology, Inc., Science Applications International Corp., and Deepsea Systems International, for their assistance in providing information. We also thank the organisers of the First Thematic Conference on Remote Sensing for Marine and Coastal Environments and Dr. Nic Bax and the staff at the CSIRO Marine Laboratory Library for their assistance in finding relevant grey literature.

8. REFERENCES

Adams, T. & B. Koerber. 1995. Investigation of an underwater range-gated imaging system. Pp. 23-33. In: Bellwood, D. C. Choat & N. Saxena (eds.). Recent Advances in Marine Science and Technology '94. James Cook Univ. Townsville.

Caimi, F.M. 1993. Laser/light imaging for underwater use. Sea Technology (December): 22- 27.

Churnside, J.H. and P.A. McGillivary. 1991. Optical properties of several Pacific fishes. Applied Optics 30:2925-2927.

Fournier, G.R., D. Bonnier, J.L. Forand & P.W. Pace. 1994. LUCIE - laser enhanced underwater camera. Sea Technology (December):55- 59.

Gauldie, R.W., C.E. Helsley, C. Schoen, S.K. Sharma & I. West. In Press. Casting new light of fisheries monitoring problems: The LIDAR. Can. J. Fish. Aquat. Sci.

Sharma, S. R. Gauldie, C. Helsley & C. Schoen. 1995. Laser-induced Raman scattering and florescence in fish eggs. Pp. 323-331 In: Bellwood, D. C. Choat & N. Saxena (eds.). Recent Advances in Marine Science and Technology '94. James Cook Univ. Townsville.

APPENDIX 1: ORIGINAL APPLICATION

PART A - ADMINISTRATIVE SUMMARY

A1 FRDC PROJECT NUMBER

A2 PROJECT TITLE

A desktop evaluation of the application of towed-body LIDAR to biomass assessment of demersal fish stocks

A3 ORGANISATION

Name	Dr. P.C. Young, Chief		
Department	CSIRO Division of Fisheries		
Postal Address	GPO Box 1538 Hobart, Tas. 7001	Location	Castray Esplanade Hobart, Tas.
Phone	(002) 325 222	Facsimile	(002) 325 000

A4 ADMINISTRATIVE CONTACT

Name	Mr. Peter Green		
Position	Finance Manager		
Postal Address	GPO Box 1538 Hobart, Tas. 7001	Location	Castray Esplanade Hobart, Tas.
Phone	(002) 325 222	Facsimile	(002) 325 000

A5 PRINCIPAL INVESTIGATORS

1.			
Name	Dr. Ronald Thresher		
Position	Program Leader, Temperate and Deepwater Resources Program		
2.			
Name	Mr. Richard McLoughlin		
Position	Project Leader, Temperate and Deepwater Resources Program		
Postal Address	GPO Box 1538 Hobart, Tas. 7001	Location	Castray Esplanade Hobart, Tas.
Phone	(002) 325 222	Facsimile	(002) 325 000

A6 PREDICTED COMMENCEMENT AND COMPLETION DATE

Commencement date	1 April 1994
Completion date	30 December 1994

A7 PROJECT BUDGET SUMMARY

Summarise the detailed budget provided at Part C.

	1993-94	1994-95	1995-96	TOTAL
FRRF Contribution				
Salaries and On-costs	$	$	$	$
Travel	$7,000	$	$	$
Operating	$4,000	$	$	$
Capital	$	$	$	$
Total FRDC	**$11,000**	**$**	**$**	**$**

Research Organisation Contribution				
Salaries and On-costs	$33,409	$	$	$
Travel	$	$	$	$
Operating	$5,000	$	$	$
Capital	$12,000	$	$	$
Total Research Organisation	**$50,409**	**$**	**$**	**$**

Contribution by other sources				
Cash	$	$	$	$
Other (include 'in-kind')	$	$	$	$
Total Contribution by other sources	**$**	**$**	**$**	**$**

TOTAL BUDGET	**$61,409**	**$**	**$**	**$**

CERTIFICATION

The Principal Investigator and the person acting for and on behalf of the Research Organisation certify that all information contained in and forming part of this application to the Fisheries Research and Development Corporation is complete, accurate and provided in good faith at the date given to the Corporation and that any changes to the information will be notified to the Corporation as soon as possible.

Signed by the Principal Investigators)
)
)
....) ....

........./...../......
Date

SIGNED for and on behalf of the
Research Organisation)
)
)
....) ....

........./...../......
Date

PART B - PROJECT DESCRIPTION

B1 FRDC PROGRAM

Program 1 Natural Fish Resources

Sub program: Knowledge of Fisheries Resources

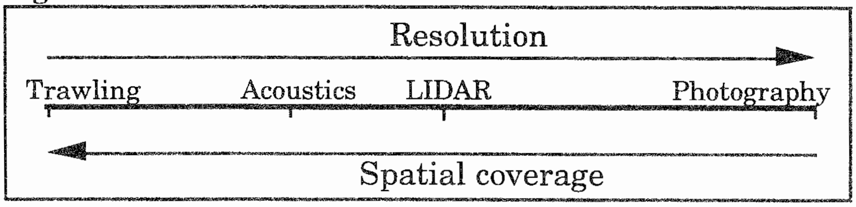
Key Issues:

Resource assessment techniques
Resource assessment
stock delineation/definition

B2 NEED

Inherent in management needs for virtually all stocks is an estimate of current biomass. For demersal fish stocks, biomass assessments currently involve one of three techniques: trawl surveys, acoustics and, occasionally, underwater photography. However, all three methods critically limited regarding the information can be gained from them, principally because they provide data at either end of a spatial coverage/resolution continuum (Figure 1) . Trawl surveys, for example, can cover relatively large areas, but because of sampling problems and biasses provide poor resolution of fish density and composition, whereas at the other end of the spectrum, underwater photographs can provide very high resolution, very accurate data, but only for small areas due to limits on water visibility, speed of tows, lighting, etc.

Figure 1



Similarly, acoustic techniques are of very limited use for widely dispersed species close to the bottom and often have difficulty distinguishing among species.

Recently a new technology is beginning to emerge that could provide both high resolution and wide spatial coverage. LIDAR (**L**ight **D**etection **A**nd **R**anging) is an active sensing system, based on the analysis of the spectral characteristics of a reflected laser beam. The technology is widely used in an air-borne configuration for terrain mapping and the like, and, as an air-borne system, has been trialled for detecting surface schools of fish (with mixed results). We propose to investigate a complementary application of LIDAR, which is also just reaching the field trial stage of development. Several overseas (mainly US) groups are in the process of developing and trialling LIDAR in a towed-body configuration, in which the LIDAR is 'flown' above the ocean bottom and records reflectance patterns of substrata, invertebrates and fish. The principal application to date is surveying, for example, oil pipelines for evidence of leakage, in which cases the LIDAR serves primarily as a very high resolution photographic system, one that is much less affected by poor water clarity than passive photographic systems (e.g., those that depend on reflectance of natural light). During such trials and applications, it has been widely noted that fish and macro-invertebrates are often very conspicuous on the processed LIDAR images, which has lead to the suggestion that it could be useful in fish stock assessments.

Three points make this observation particulalr;y interesting from the perspective of measuring biomass of demersal fish stocks. First, because of the speed at which the instrument records data, it can potentially be towed at 5-8 knots, while still providing high resolution spatial information regarding the substrata. Second, because the system is relatively unaffected by water clarity, it can potentially be towed at heights of up to several hundred meters off the bottom and, at that height, can scan a path several hundred meters across. The combination of this tow speed and swath width implies the potential for very cost effective, broad areal coverage of areas surveyed. And third, unpublished data suggests that the reflectance patterns of various organisms may be species specific (which is intuitively reasonable, as differently colored fishes can be expected to reflect different spectra back to the analyzer). The potential being hyped overseas is that this system, when properly configured, is capable of high speed, very accurate counting of all fish in a sample area, identified to the species level. If so, such a system could fundamentally alter the way in which demersal fish stock assessments are carried out.

We propose a desk study to sort out the hype from reality. Information on deployments and trials of the towed-body LIDAR (also referred to as a 'laser line scan system') are sketchy, in part because of potential commercial value of the information, in part because deployments for geological and engineering purposes are often not well reported in the fisheries literature, and in part becasue of the rapidly developing nature of the field and the long lag time before such developments are widely reported in the scientific literature. Nonetheless, at least two groups (RICHARD, NEED NAME OF THE BOSTON FIRM DOING THIS, ON THE ARTICLE IN THE FILE AND MIT, WHATEVER, FROM GAULDIE'S INFO) have carried out developmental trials. Field work is also currently underway at the University of Hawaii and a eologically oriented trial was recently carried out in the Gulf of Mexico. The nature and sophistication of these trials has still to be determined. Informal discussions with the group at the Univ. of Hawaii, for example, suggests the Gulf of Mexico trials were done using relatively unsophisticated equipment and a low level of data analysis (basically black-and-white images, rather than full spectral analysis). A variety of analytical procedures have been suggested, e.g., Raman spectroscopy, but the extent to which they are applicable to LIDAR spectra, the degree of sophistication of spectrum stripping paradigms required, and data handling capabilities used (which would be comparable to those required for acoustic data) have also not been determined.

We propose to visit laboratories overseas where this developmental work is underway, assess the current state-of-the-art and the likely time until real-world applications are possible, and discuss data processing requirements both with the current developers and with Australian scientists familiar with the technology. We bring to this assessment four critical capabilities. First, we are very familiar with the requirements for and problems associated with biomass assessment of demersal fish and shellfish stocks. Second, the spectral analysis problem is similar to those we routinely deal with in interpreting X-ray spectra for probe microanalysis. Third, data processing on the scale required is routine for the CSIRO acoustics group and, indeed, some of the software we are currently developing has been designed with portability to LIDAR data, as an example, in mind (i.e., the software is modular in form, and a designed LIDAR-oriented up-front module can be readily grafted on to the existing GIS-based processing system). And fourth, we have some (albeit not expert) background in optical sciences.

On the basis of our own experience and input from Australian experts in allied fields, with whom we will discuss the hype and available data, we will produce an evaluation of the apparent potential of the technique. We will also make recommendations regarding the extent to which and the ways in which Australian fisheries science could benefit by involvement in the developing field.

B3 OBJECTIVES

Undertake a desk-top study to assess the potential of towed-body LIDAR for biomass determination of demersal fish stocks

B4 INDUSTRY & MANAGEMENT CONSULTATION

The need for fisheries-independent biomass information has been identified by the Demersal and Pelagic Fisheries research Group has the highest priority for SET fish stocks. The priority of this work, albeit not ranked against other SET projects, was endorsed by SETMAC and by GITLC and SILC at a joint sitting to discuss research priorities in 1992. It was not specified, however, how these assessments would be carried out, for species other than those suited for acoustic biomass estimation. The current proposal will investigate a means by which this information need can be met.

B5 DIRECT BENEFITS & BENEFICIARIES

The beneficiaries of this project will be the fishing industry and fishery managers, who will benefit from substantially enhanced knowledge of the state of fish stocks. The Australian community will benefit from the enhanced capability for maintaining trawl fish stocks at sustainable levels.

B6 FLOW OF BENEFITS

Fishing Industry	30%
Fishery Managers	40%
Australian Community	30%

B7 FORM OF RESULTS

Report to FR&DC

B8 ADOPTION OF RESULTS

This project will provide a formal assessment of the efficacy of towed-body LIDAR to problems in fish stock asessment. It will thus provide the information required to objectively assess a LIDAR system by industry or government groups who might be interested in pursuing this technology for the benefit of the Australian fishing industry. No threats are seen to the adoption or use of this report.

B9 FEASIBILITY ANALYSIS

The principal threats to this project will be moves towards commercial secrecy by those individuals and institutions who are currently in the process of developing LIDAR techniques and technologies. The commercialisation potential of this technology is immense, with many offshore survey applications. It is believed that moves towards patenting and/or commercialisation by the mainly US based companies such as Raytheon and MIT will quickly erode scope for parallel development in Australia unless moves are soon made to become involved in technology development in Australia.

The main means of overcoming these problems lies in the existing skills base with regard to laser technology that resides within CSIRO, Australian universities and the DSTO. In this respect, results from the study should be easily usable within an Ausralian context.

In terms of expertise in the field of stock assessment, CSIRO has the bulk of Australian expertise in quantifying and modelling fish stocks and associated technical skills. LIDAR based information will enhance this capability for providing high quality advice regarding status of fish stocks.

B10 METHODS

This desktop study will include formal discussions and visits to those researchers currently undertaking LIDAR development and applying it to assessment of fish stock and other marine survey problems. Identification of Australian expertise in the relevant technology will be made, and an assessment made of the real costs, benefits and expectations associated with towed-body LIDAR.

Likely benefits of an enhanced stock assessment capability for various fisheries will be identified with BRS, AFMA and state agencies.

B11 PERFORMANCE INDICATORS

Production of final report, by 31 December 1994.

B12 MILESTONES

1. Contact and visit with overseas researchers working in the field of LIDAR technology and fisheries assessment, by March 1994.
2. Identification and contact with relevant Australian based laser engineering expertise, by June 1994
3. Identification and contact with relevant Australian based spectroscopic analysis expertise, by July 1994
4. Production of final report, by December 1994.

B13 OTHER RELATED PROJECTS

Acoustic stock assessment research (Dr. Tony Koslow, CSIRO)

B14 FACILITIES

All relevant facilities at the CSIRO Marine Laboratories, Hobart.

B15 STAFF

Dr. Ronald Thresher M.Sc, PhD
Program Leader, Temperate and Deepwater Fisheries Resources Program. CSIRO Division of Fisheries

Mr. Richard McLoughlin B.Sc(Hons), M.Sc.
Project Leader, Temperate and Deepwater Fisheries Resources Program. CSIRO Division of Fisheries

Mr. Rudi Kloser,
Hydro-acoustic scientist and data analyst, Temperate and Deepwater Fisheries Resources Program. CSIRO Division of Fisheries

APPENDIX 2: LETTER REQUESTING PROJECT DELAY

25 November 1994

Mr. Peter Dundas-Smith
Executive Director
FR&DC
PO Box 9025
Deakin, ACT 2600

Dear Peter

I refer to FR&DC grant DF24/CN (A desktop evaluation of towed-body LIDAR for biomass assessment of demersal fish stocks).

This project, which was funded from the FR&DC/Commonwealth Trust Fund, was scheduled for completion at the end of this fiscal year. This timetable is no longer practical, however, due to the resignation of the Project Officer involved in the study, Mr. Richard McLoughlin. Although only one of the three CSIRO staff involved in the project (the other two are R. Thresher and R. Kloser), it was expected that Mr. McLoughlin would undertake the principal tasks of assembling the necessary information from the literature and personal contacts, synthesising this information for discussion and evaluation with other project staff, and drafting the final report. Because of fiscal constraints, we have been unable to replace Mr. McLoughlin in the short term and the other staff on the project have been unable to fill completely the gap left by his departure.

All salary costs associated with the project are CSIRO contributions. No FR&DC funds have yet been expended, although work on the project has progressed.

Due to the unforeseen staffing problems and because we still feel that an evaluation of the technology has considerable value, I request that the project deadline be extended for one year (to 31 December 1995), to allow the two remaining staff time to complete the evaluation. This extension will require no additional FR&DC funds.

Sincerely

Dr. Peter C. Young
Chief
Division of Fisheries

APPENDIX 3: MILESTONE REPORT

MILESTONE REPORT — DF24/CN (A DESKTOP EVALUATION OF TOWED-BODY LIDAR FOR BIOMASS ASSESSMENT OF DEMERSAL FISH STOCKS).

As specified in the project proposal, the key milestone to be completed at this stage is contact with and communication with relevant Australian and, particularly, international experts in towed-body LIDAR technology, with specific regard to inquiries about applicability of this technology to large scale fish surveys.

A preliminary assessment of the available expertise indicated relatively little Australian-based experts in the field. Several expressed interest in the project and might be able to comment on the outcomes, but were unable to contribute substantially to the evaluation. Experts at DSTO, in particular, who are working with range-gated underwater imaging systems (similar to LIDAR) will be contacted as the final report is being drafted.

Internationally, contacts have been made and followed up with

Hawaiian Institute of Geophysics (University of Hawaii)

Applied Remote Technology (Massachusetts, USA)

Science Applications International Corporation (san Diego, USA)

Deepsea Developments International (Massachusetts, USA)

SETS Technology (Hawaii, USA), and, for background information,

the organisers of the 2nd and 3rd Thematic Conferences on Remote Sensing for Marine and Coastal Environments.

Of these, ART (developer and commercial manager of the LS-4096) towed-body LIDAR and SAIC (developer and commercial manager of thew ULISYS system) are the most important. Contacts with ART and the University of Hawaii were done in person as an adjunct to overseas trips otherwise supported by funds other than those provided by FRDC.

The results of these contacts generally support the conclusion that initial reports of the usefulness of LIDAR for demersal fish assessment were exaggerated. Final analysis of the results of the discussions and literature review is in progress, but the main conclusion is likely to be that the scan coverage possible by towed body LIDAR is likely to be too small and/or too slow to be practically feasible as a means of broad area biomass assessment.

APPENDIX 4

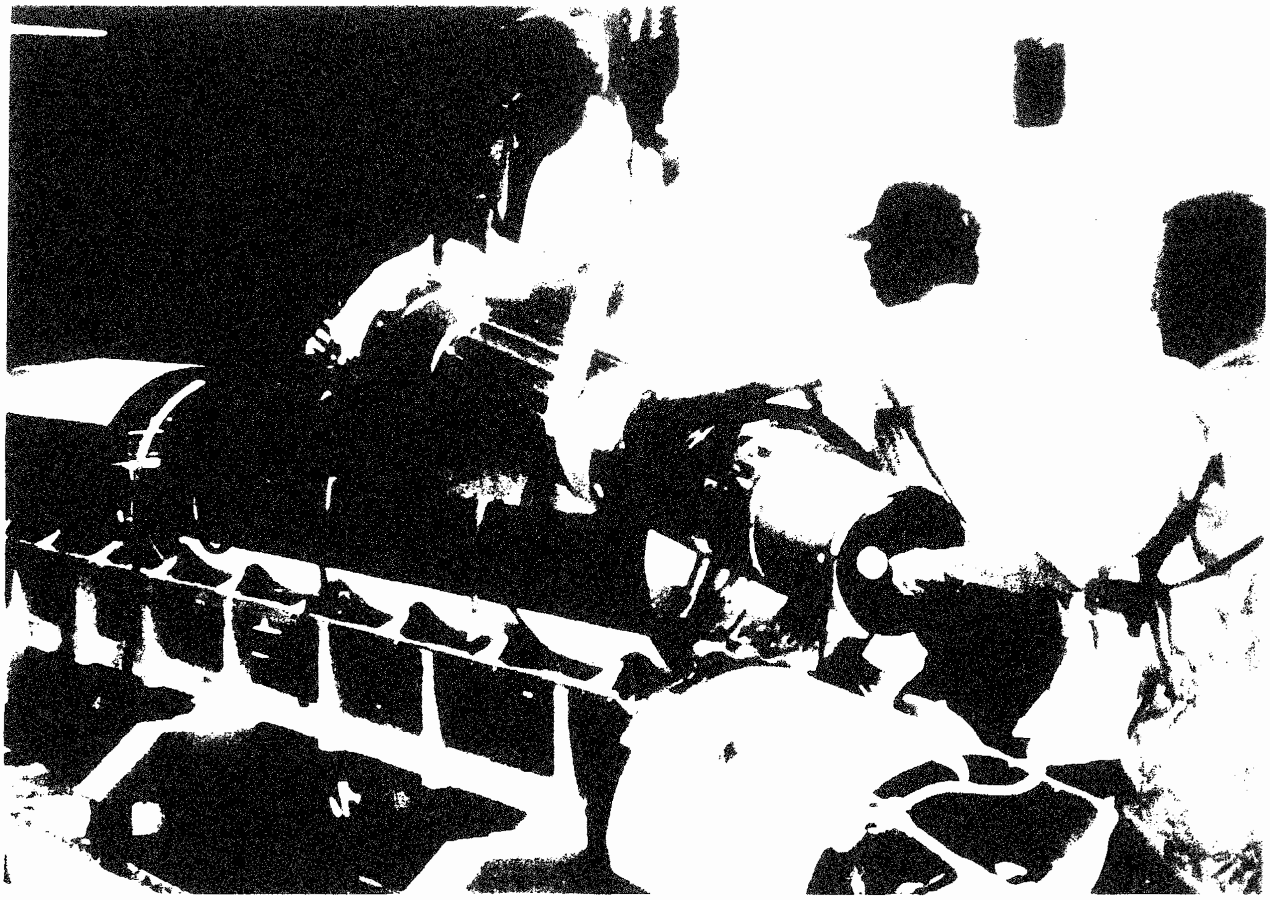
SYSTEM MANUAL

APPLIED REMOTE TECHNOLOGY

Applied Remote Technology

A Raytheon Company

LS-4096



Laser Line Scan
Underwater Imaging System

August 1994

THE LS-4096 LASER ILLUMINATED UNDERWATER IMAGING SYSTEM

Bryan W. Coles

Applied Remote Technology, Inc
9950 Scripps Lake Drive, Suite 106
San Diego, California 92131
(619) 695-9411

Revision A
30 August 1994

ABSTRACT

A new, commercially available, field-deployable laser line scan underwater imaging system, the LS-4096, has recently been developed and demonstrated under a variety of rigorous operating conditions. The purpose of this report is to provide the reader with a full appreciation for the current state of these developments. The report begins with a brief discussion of operational results obtained with the system during recent field trials in San Diego and the North Sea. Following this overview the motivated reader is provided with a brief description of the LS-4096. And finally, appendices are included that provide a quantitative review of the operating envelope that can be provided by the LS-4096 and a summary of key system specifications.

INTRODUCTION

The idea of using laser illuminated sensors in the underwater environment has been an intriguing possibility ever since the first lasers were demonstrated over 30 years ago. Possible architectures for laser illuminated underwater imaging systems were discussed publicly for the first time at the initial Ocean Optics Conference sponsored by the SPIE in 1966[1] and several programs to develop underwater laser systems were initiated and actively funded during the late 1960's and early 1970's. These initial programs, unfortunately, failed to meet their technical objectives or the expectations of their sponsors and were subsequently discontinued. Supporting technologies such as commercial lasers and digital electronics continued to mature, however, and by the mid-1980's it became appropriate to reevaluate the practical realizability and operational potential of underwater laser systems. Several underwater laser system development programs were initiated between 1986 and 1990 and have been continuously supported with the result that reliable operational systems are now becoming commercially available.

The purpose of this paper is to discuss one such system, designated the LS-4096, that is the result of the development efforts of Applied Remote Technology, Inc. (ART). This system utilizes state-of-the-art technology to provide a very user-friendly operator interface, user-selectable image resolution of 512, 1024, 2048, or 4096 pixels across the fixed 70° field-of-view, a video signal dynamic range of 84dB (14-bit), and a demonstrated useful operating range of up to six optical beam attenuation lengths (equivalent to a maximum operating platform altitude of 5 attenuation lengths). The underwater portion of the system, which is built around an efficient solid-state laser, has proven itself to be rugged, reliable, and capable of providing dependable performance in the most demanding commercial offshore environments.

SYSTEM DESCRIPTION

In its most basic form, the LS-4096 consists of the underwater Optical Sensor, the topside Control Console, and the Communication Link that ties them together. A useful operational system can be assembled by mounting the optical sensor on a deployment platform, such as an AUV or ROTV, and adding several supporting components, such as an umbilical cable and power supplies.

Two typical operational systems are shown in Figure 1. In the top photograph the LS-4096 sensor is being installed in the cargo bay of ART's XP-21 Autonomous Underwater Vehicle (AUV) and in the bottom photograph the same sensor is installed in the SubSea FOCUS Remotely Operated Towed Vehicle (ROTV). The LS-4096 was installed in the XP-21 vehicle and tested in the ocean off the coast of San Diego during April and May, 1994. During the following month, the LS-4096 was installed on the SubSea FOCUS in Aberdeen, Scotland, and tested under actual operating conditions in the North Sea.

The topside Control Console for the LS-4096 is shown pictorially in Figure 2. The console equipment is organized into two separate units to make shipping and handling easier. Each unit consists of a rugged high-density polyethylene (HDPE) shipping case that is fitted with a shock mounted EIA standard 19-inch equipment rack. The electronic equipment is bolted into these racks and the two units are interconnected via cables that plug into their back panels. Unless brackets need to be welded to the ship's bulkhead or some other indirect tasks must be completed the entire LS-4096 system can be installed, interconnected, and certified for operational deployment in two hours or less.

The LS-4096 produces images that have high resolution, wide field-of-view, and high dynamic range. This combination of high performance characteristics, which is unique in the world of underwater optical sensors, results in images of unsurpassed information content. Large amounts

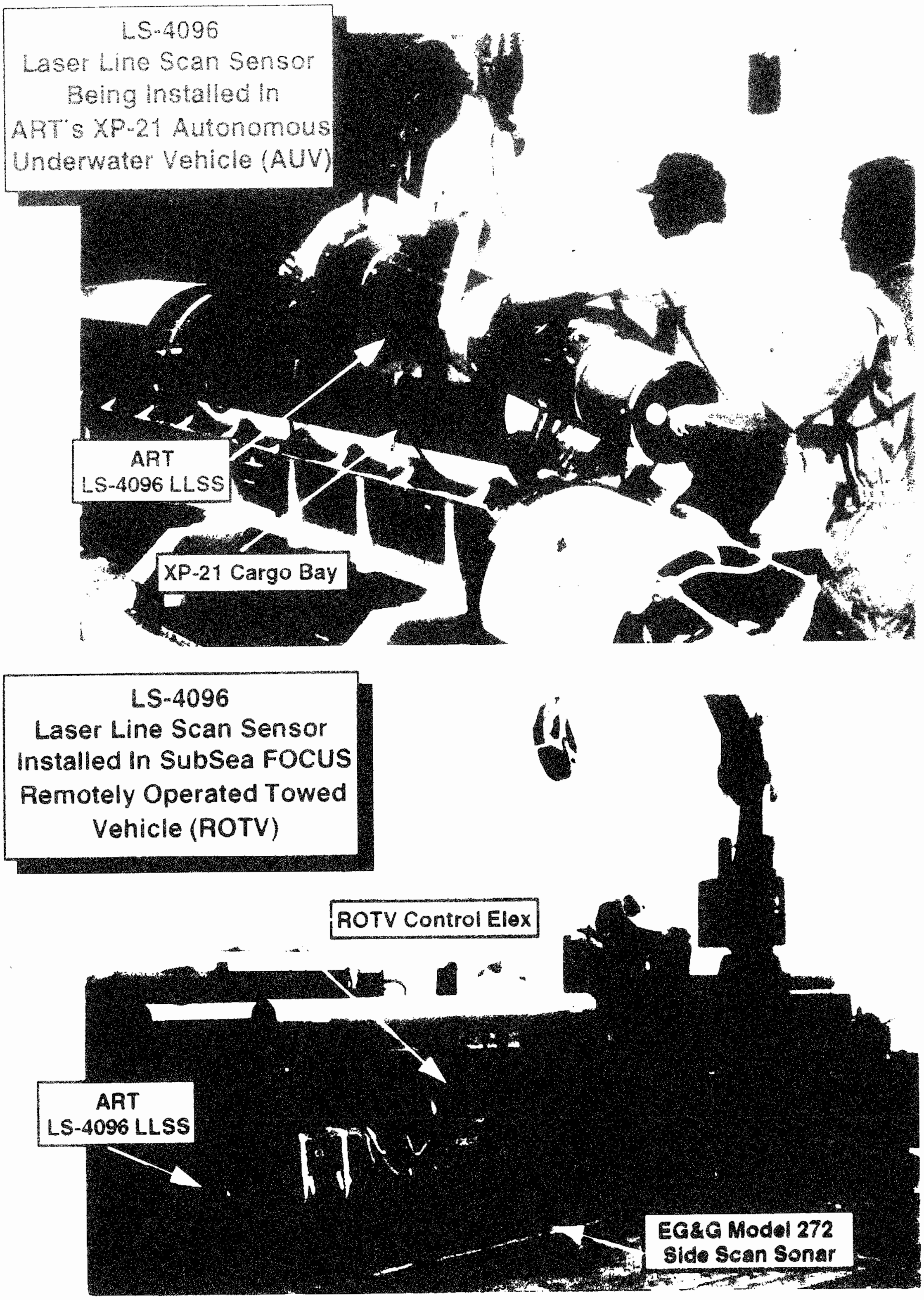


Figure 1
Typical operational implementations of the LS-4096 Laser Line Scan System

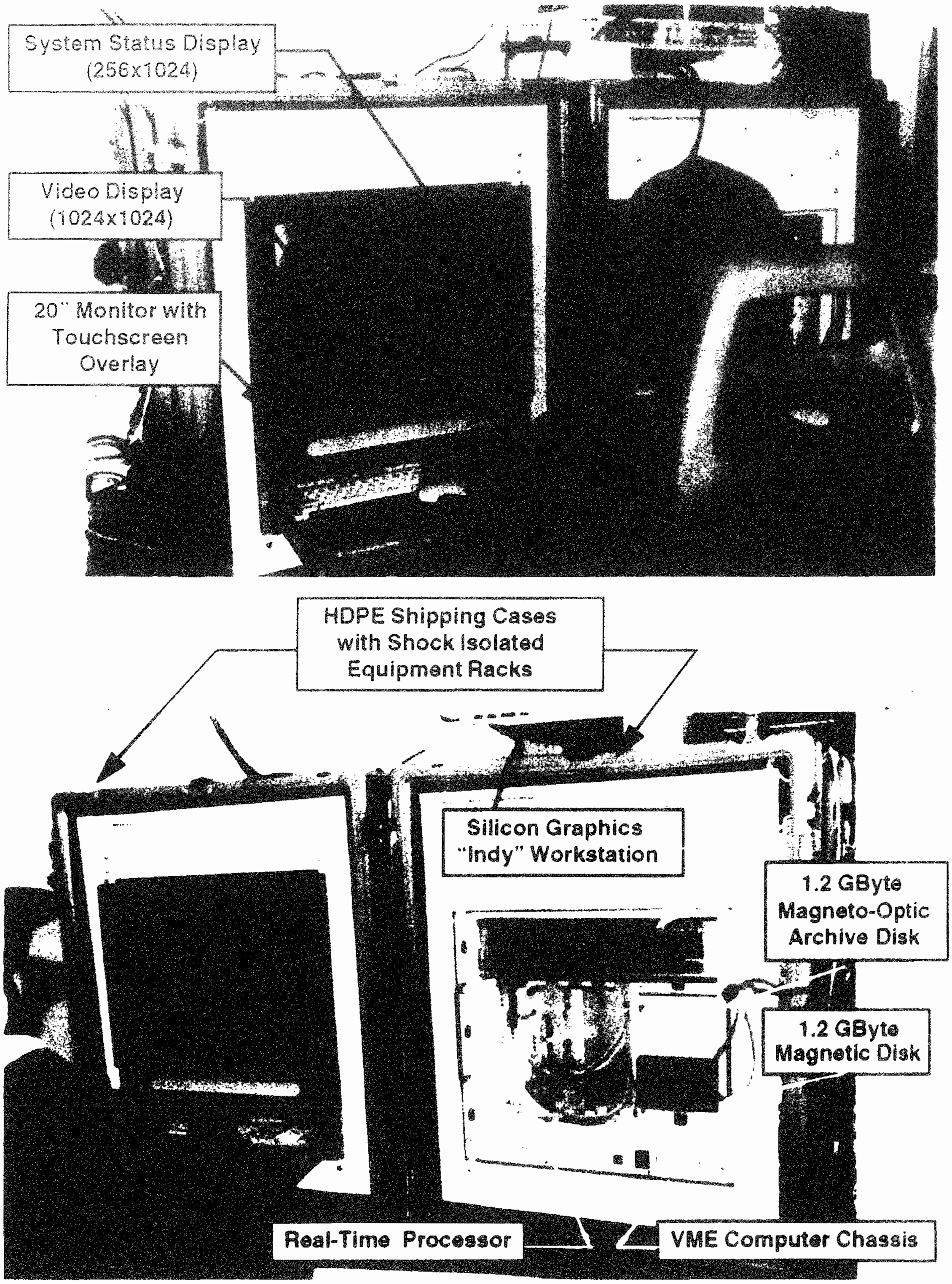


Figure 2
Typical shipboard installation of the LS-4096 Control Console equipment. Installation, integration, and system check-out generally requires two hours or less.

of data can, of course, present the operator with significant problems as well as substantial benefits. The system Control Console has been designed with this in mind.

As mentioned above, the topside Control Console equipment is packaged into two separate units. One unit, designated the Real-Time Processor, contains a single-board computer, an array processor, the surface telemetry electronics, digital data recording equipment, and additional support electronics. All this equipment is installed in a ruggedized 6U VME electronic chassis. The second unit, designated the Display Controller, is a ruggedized Silicon Graphics workstation that is built around a MIPS R-4400 RISC processor running at 150MHz.

The data processing capability of this equipment represents a quantum leap beyond the capability of the PC-based equipment that has been used in the past. This higher class of equipment was selected for use in the LS-4096 for two reasons. First, the higher processing throughput that this equipment provides is required by the adaptive digital signal processing algorithms that are used to give the operator an optimized video display in real time. And second, the processing throughput of the system and the extensive library of sophisticated image processing software that is available for the Silicon Graphics workstation provide the software and hardware resources that are required for efficient and effective post processing of the recorded data.

Our operational experience with the LS-4096 has definitively demonstrated that our choice of console hardware is correct. The console provides the operator with a nearly optimum video image in real time by implementing adaptive data processing algorithms that continuously adjust themselves automatically to accommodate changes and variations in the acquired data. These adaptive algorithms cannot be run in real time on less capable hardware. The key element of this entire process is the word "automatic" since all data acquisition, processing, and display functions are performed automatically by the console without any required input or action on the part of the operator.

An additional benefit of using a Silicon Graphics workstation as the Display Controller is the ability to provide the operator with an efficient, interactive graphical user interface that is combined with the video display on the system monitor. This interface provides different users to access to different levels of system control depending on their experience and training. And also, since the interface is software based, it can be easily modified and improved in response to the suggestions or requirements of individual operators.

The true power of this system is realized during the "post acquisition processing" phase of a mission. The raw image data is acquired with a higher dynamic range, 84dB, and higher resolution, up to 4096 pixels/line, than can be displayed on any monitor or printed on any hard copy output device. Even though this image information cannot be displayed or printed in its raw form it can be accessed through direct post processing techniques. Individual features and details can be extracted and enhanced for review and analysis using any of the image processing and image analysis tools that already exist in the Silicon Graphics library or new special purpose tools can be written to perform a specific task. Other practical post processing tasks include geometric correction of distorted images, generation of digital visual mosaics of large areas, and quantitative measurement of target details. A very important characteristic of the LS-4096 system is that the video data is digitized **in the sensor** and then transmitted to the Control Console via the digital telemetry link. The digital video data is then recorded, in digital form, **before** any processing whatsoever is applied. This procedure ensures that the data is always recorded with maximum fidelity and in a form that is most desirable for post processing.

FIELD TRIAL RESULTS

San Diego

One of the images that was generated by the LS-4096, while it was installed on the XP-21, is presented in Figure 3. Several details of this image are expanded and presented in Figure 4. These images were taken in approximately 300-350 feet of water about four miles west of Point Loma off the coast of Southern California. These images were collected in an area where the water close to the bottom exhibited a characteristic beam attenuation length of 3.5-4.0 meters. This is typical for this specific operating area and is also typical of most coastal areas at this depth.

The seabed in this area is a fine, reddish-brown mud that is very smooth and offers very little contrast. For this reason it is considered to be a very difficult area in which to collect good optical images of the bottom. In fact, as can be seen in Figure 3 and Figure 4, virtually all of the contrast in the image is provided by the biology that happened to be present.

This image is very interesting from a biological point of view because it demonstrates that it is now possible to determine the spatial distribution, average biomass, species diversity, and other important biological parameters regarding benthic flora and fauna. The wide swath width of the LS-4096 provides the panoramic view and large area coverage required for good statistical sampling and the high resolution and high signal-to-noise ratio of the images allows individual species to be identified. This combination of capabilities cannot be matched by any other known sensor.

Data can now be collected rapidly and economically on a large enough spatial scale to provide reliable statistics without interfering with the existing biological communities in any way. Conventional grab sampling techniques, on the other hand, do not provide reliable statistics when the biomass concentration is very spotty or patchy, as is so often the case, and they can be unacceptably destructive.

Conventional imaging techniques can provide very useful detail regarding individuals and biomass concentrations over very limited scales but the limited operational range of conventional imaging techniques makes it difficult and expensive to collect data over a statistically large sample area. The short operating range of conventional sensors also requires them to be placed very close to the target of interest which often causes the behavior of the target bic'ogy to change. This invasive nature of conventional techniques is especially serious when the sensors are mounted on ROV's which are, by their nature, relatively noisy and intrusive. We have consistently found that the LS-4096 sensor mounted on the XP-21 or a towed vehicle, provides a data collection technique that is essentially benign. The extended operating range, relatively low level of emitted light, and low acoustic signature of the platforms all combine to provide a package that has a very limited, if any, effect on the behavior of the biology being studied.

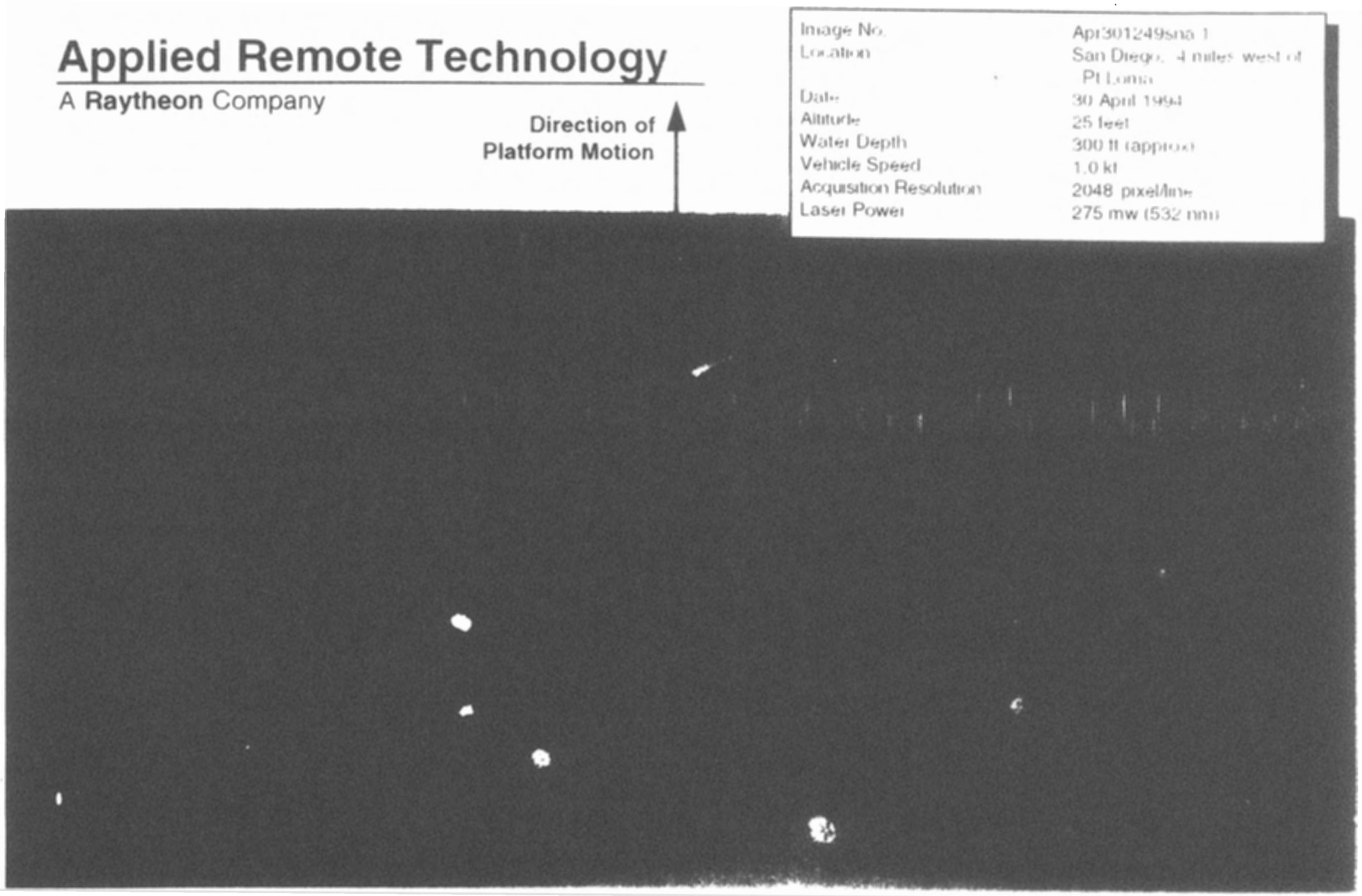


Figure 3

This image shows a section of the seabed that is 35 feet wide and 17 5 feet long. The edges are somewhat darker than the center of the image because no correction or post processing of any king has been applied. Notice that the very fine contour structure of the bottom is highlighted and very visible, especially on the right side of the image

Applied Remote Technology
A **Raytheon** Company

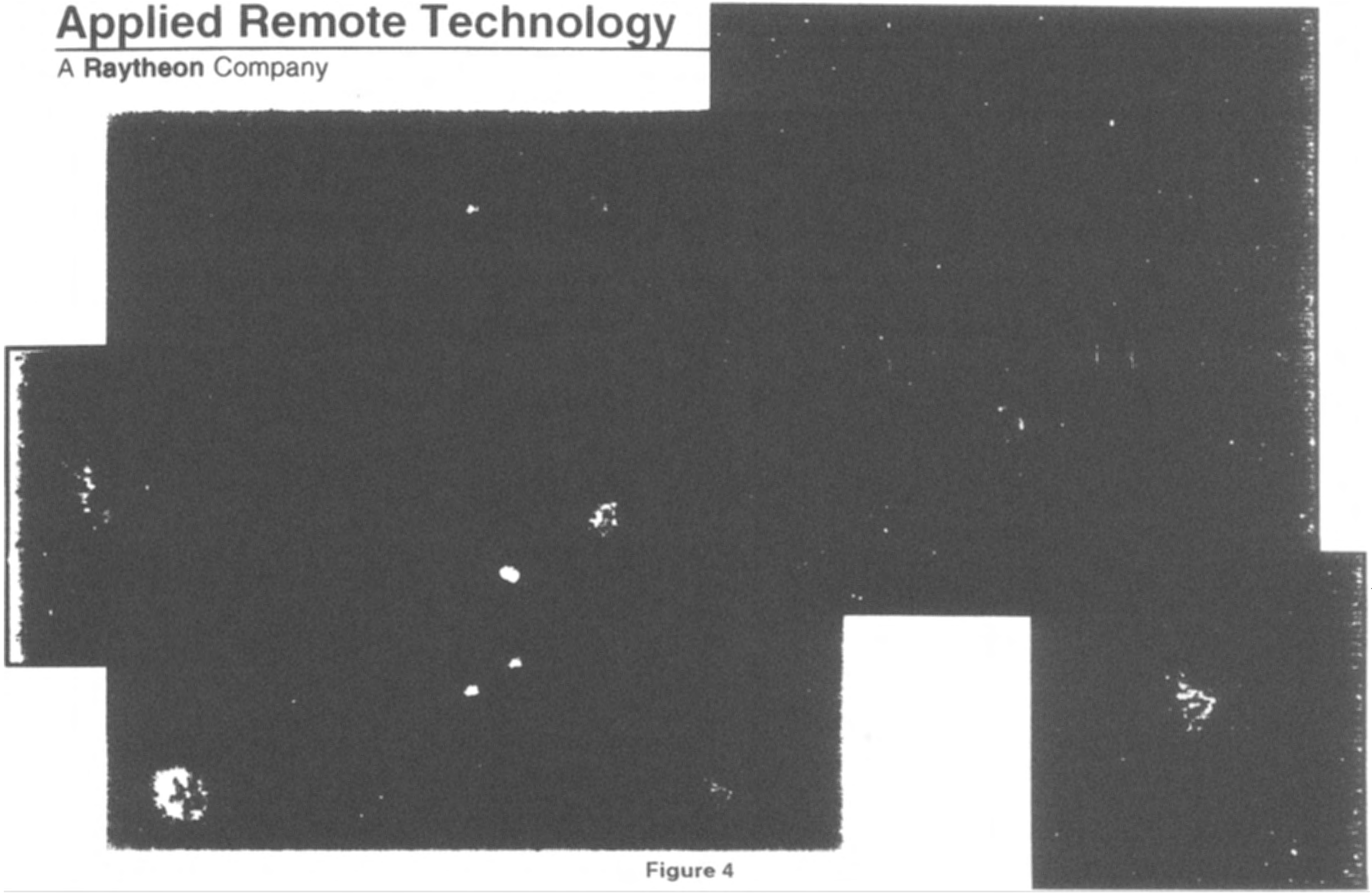


Figure 4

This figure shows several details of the image in Figure 3. The combination of Figure 3 and Figure 4 demonstrate that the LS-4096 is capable of providing imagery that at once has a wide enough swath width (broad area coverage) to allow spatial density and average biomass statistics to be calculated and also evaluate details such as species diversity

North Sea

> These North Sea trials were conducted as a cooperative program between Applied Remote Technology, Inc. (A Raytheon Company) and SubSea Survey (a division of SubSea Offshore, Ltd).

In June, 1994 a joint program was initiated by Applied Remote Technology (ART) and SubSea Survey (SSS) of Aberdeen, Scotland to test the effectiveness of the LS-4096 Laser Line Scan System when integrated with the SubSea FOCUS ROTV and operated under realistic operational conditions. The LS-4096 was shipped to Aberdeen and installed on the FOCUS at SSS's Greenwell Base facility. The LS-4096/SubSea FOCUS system was then installed on the M/V BRITISH VIKING, a 75 meter work boat, and deployed to the test site in the Norwegian sector of the northern North Sea. Installation of the system onboard the ship required approximately 8 hours to complete. The bulk of this time was required to weld the winch and deployment crane to the deck and to certify the structural integrity of the crane. After the handling equipment was installed, the FOCUS vehicle with all the operator consoles and electronic surface equipment was installed, inter-connected, and certified to be ready for deployment in less than 2 hours.

The specific location for the trials was the point at which the new ZeePipe was being laid over the existing StatPipe. This location provided the unique opportunity to survey both a new and an established pipeline during one dive. The objective of the trial was to demonstrate that the LS-4096/SubSea FOCUS system could provide an economical method of surveying pipelines. The criteria for success of the trial was established by the desire to "produce useful visual images of pipelines from an altitude of at least 5 meters at a speed of at least 2 knots." Several miles of pipeline were surveyed during the 6 hour deployment, all at an altitude of 8 to 10 meters and at a speed of 3.5 to 5.5 knots. During the bulk of the trial, the platform altitude was maintained at 8 meters above the seabed and the platform velocity averaged 4 knots. The television cameras mounted on the ROV that was being used to confirm the "as laid" condition of the new ZeePipe, on the other hand, had a maximum useful visual range of approximately 2 meters and that conventional system was capable of inspecting the pipeline at a rate of 0.5 to 0.75 knots. The LS-4096/SubSea FOCUS was therefore demonstrated to be capable of inspecting more than 100 miles of pipeline per day compared to the 12 to 18 miles per day that were possible with the Television/ROV system.

The trial was considered to be thoroughly successful. The criteria for success that were established prior to deployment were not only satisfied, they were surpassed by a wide margin. The only desired demonstration that was not performed was span detection. One of the objectives of the trial was to rotate the sensor in the vehicle to provide a "side looking" view of the pipeline and demonstrate the capability of the system to detect and measure areas of pipeline spanning. Rotating the sensor in the vehicle required recovery and re-deployment of the system and the work schedule of the vessel unfortunately precluded the possibility of performing this procedure. A second trial is therefore being planned to demonstrate span detection and measurement.

Figures 5 through 9 present a sample of the images that were recorded during the trial. These images demonstrate the ability of the LS-4096 to provide the operator with a view of the pipeline in the context of its surroundings. The images also demonstrate the ability of the LS-4096 to provide adequate detail, even at a resolution of 1024 pixels/line which is well below the maximum available resolution of 4096 pixels/line, to evaluate the physical condition of the pipeline and to identify objects in the immediate vicinity of the pipe.

In addition to producing useful visual images the LS-4096 is capable of measuring the physical dimensions of items in its field-of-view in real time. At any time during the survey, the operator is able to "freeze" the image displayed on the Control Console's monitor and with a few simple "point and click" operations the size of the desired object is displayed on the screen along with a visual confirmation of the exact measurement that is being made. This capability was, for example, used to confirm the diameters of the two pipelines and to measure more intricate details such as the mesh size of the entangled net shown in Figure 7.

The LS-4096 is designed to be operable in a fully automatic mode with a minimal amount of operator intervention. This capability was demonstrated by putting an ROV operator in charge of the system for a short period of time. Even though this was the operator's first experience with a laser line scan system, he was able to operate it, at a minimal level, with less then 10 minutes of informal instruction.

No equipment malfunctions or failures of any kind were observed in either the LS-4096 or the SubSea FOCUS systems during the entire deployment. Previous sea trials with laser line scan systems have demonstrated that it is difficult, if not impossible, to follow a pipeline for more than 200 meters when a passive or uncontrolled tow body is used. With the SubSea FOCUS we followed the pipeline for 6.5 miles and were able to keep the pipeline in the desired portion of the LS-4096 field-of-view the entire time.

The stability and controllability of the SubSea FOCUS vehicle were shown to be exceptional. The vehicle flew with a consistent nose down pitch of approximately 3.5° and the vehicle exhibited stable roll angles of up to 3° when the lateral excursion of the vehicle exceeded approximately 20 meters. These attitude variations were stable and had no noticeable effect on the quality of the images produced by the LS-4096. They are most probably due to a shift in the center of drag caused by the presence of the LS-4096 sensor and can be corrected by adjusting the location of the tow point.

Applied Remote Technology

A **Raytheon** Company

Image No.	Jul01071212.dat StatPipe/ZeePipe Crossing
Location	North Sea, Norwegian Sector
Date	01 July 1994
Altitude	8 meters
Water Depth	120 meters (approx)
Vehicle Speed	4.0 kt
Acquisition Resolution	1024 pixel/line
Laser Power	275 mw (532 nm)
Notes	The new pipe on the right is 44 inches OD, the old pipe that is buried under the gravel on the left is 40 Inches OD

Direction of Platform Motion

11 meters

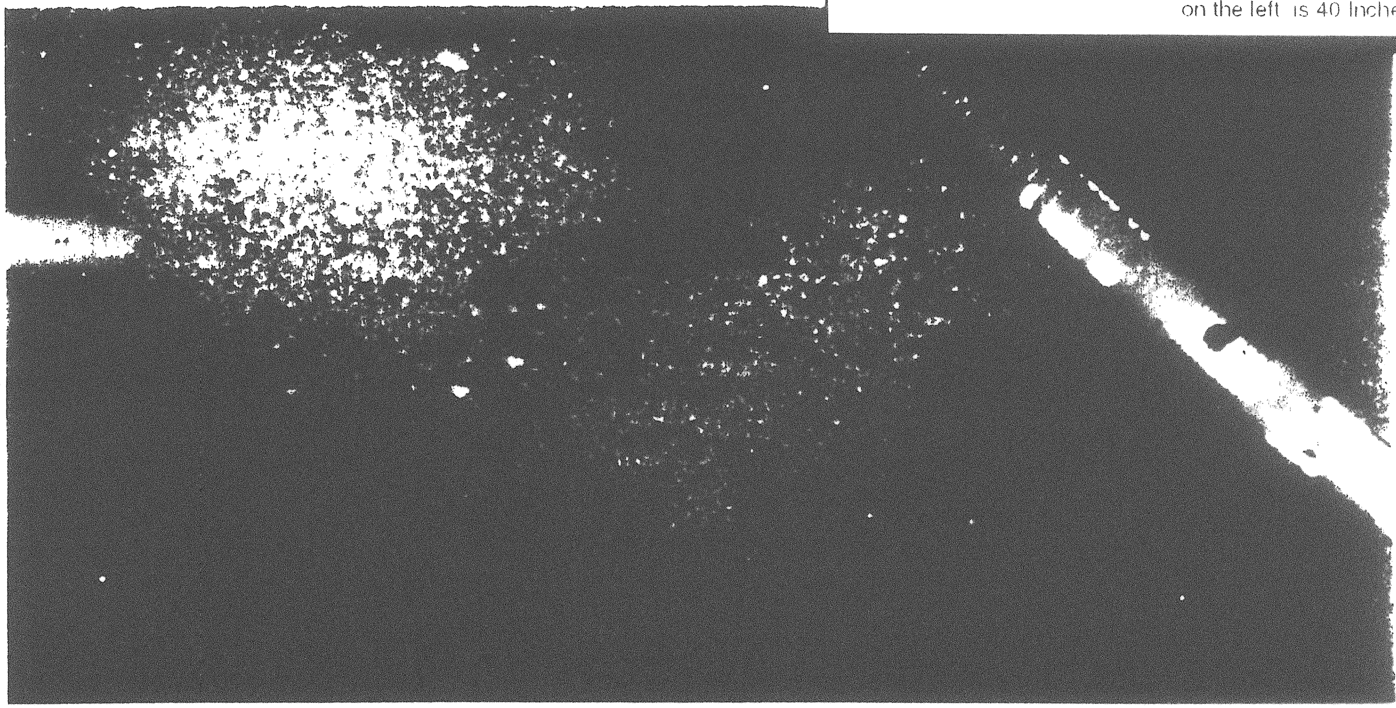


Figure 5

This is an image of a pipe crossing. The old existing pipeline, a short section of which is shown on the left side of the frame, was covered with gravel and the new pipeline was then laid on top of the gravel mattress. This image was taken less than one day after the new pipeline was put in place. The boundary between the gravel dump and the natural seabed can be seen in the lower left quadrant of the image. The entire length of the gravel dump was inspected in approximately 12 seconds.

Applied Remote Technology

A **Raytheon** Company

Image No.	Jul01061209.dat
Location	North Sea, Norwegian Sector
Date	01 July 1994
Altitude	8 meters
Water Depth	120 meters (approx)
Vehicle Speed	4.0 kt
Acquisition Resolution	1024 pixel/line
Laser Power	275 mw (532 nm)
Notes:	This pipeline is 40 inches OD and has been in place for approximately 12 years.

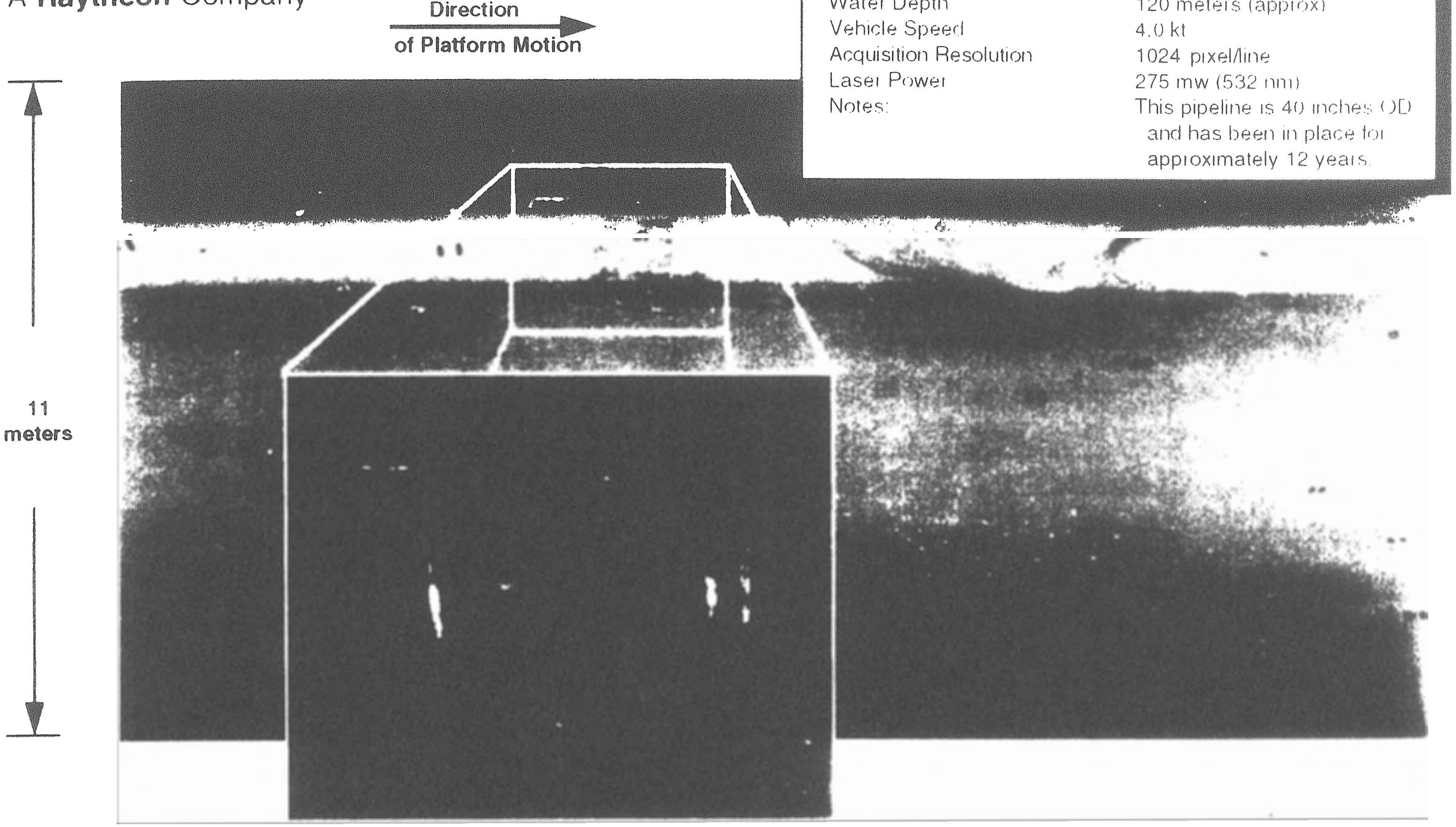


Figure 6

This is an image of a 12 year old , 40 inch diameter pipeline showing a detail of a field joint. Notice that three of the joint bands are still in good mechanical conditionbut one band has broken. This is a typical example of how the LS-4096 can provide a wide, panoramic view of an object in its surroundings and at the same time provide high resolution imagery of detailed aspects of the object.

Applied Remote Technology

A **Raytheon** Company

Image No	Jul01061209.dat
Location	North Sea, Norwegian Sector
Date	01 July 1994
Altitude	8 meters
Water Depth	120 meters (approx)
Vehicle Speed	4.0 kt
Acquisition Resolution	1024 pixel/line
Laser Power	275 mw (532 nm)
Notes	The pipeline in this image is 40 inches OD and approximately 12 years old

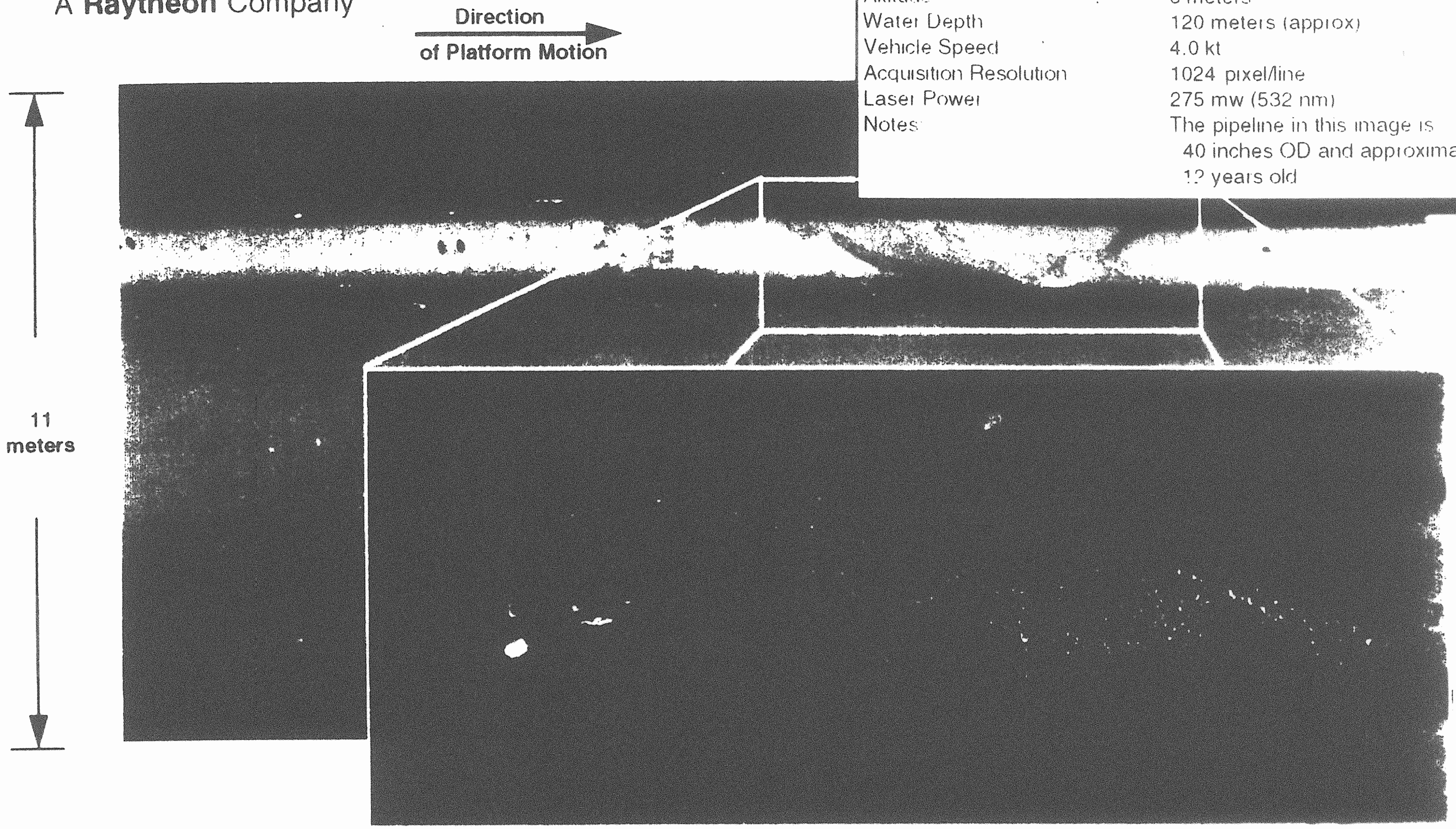


Figure 7

This is an image of a 12 year old, 40 inch diameter pipeline showing a detail of an entangled fishing net. Notice that the individual threads in the net can be seen. The mesh size of the net was measured to be approximately 1.5 inches. This is a typical example of how the LS-4096 can provide a wide, panoramic view of an object in its surroundings and at the same time provide high resolution imagery of detailed aspects of the object.

Applied Remote Technology
A **Raytheon** Company

Image No.	Jul01061752.dat
Location	North Sea, Norwegian Sector
Date	01 July 1994
Altitude	8 meters
Water Depth	120 meters (approx)
Vehicle Speed	4.0 kt
Acquisition Resolution	1024 pixel/line
Laser Power	275 mw (532 nm)
Notes.	This is an image of a 12 year old, 40 inch OD pipeline

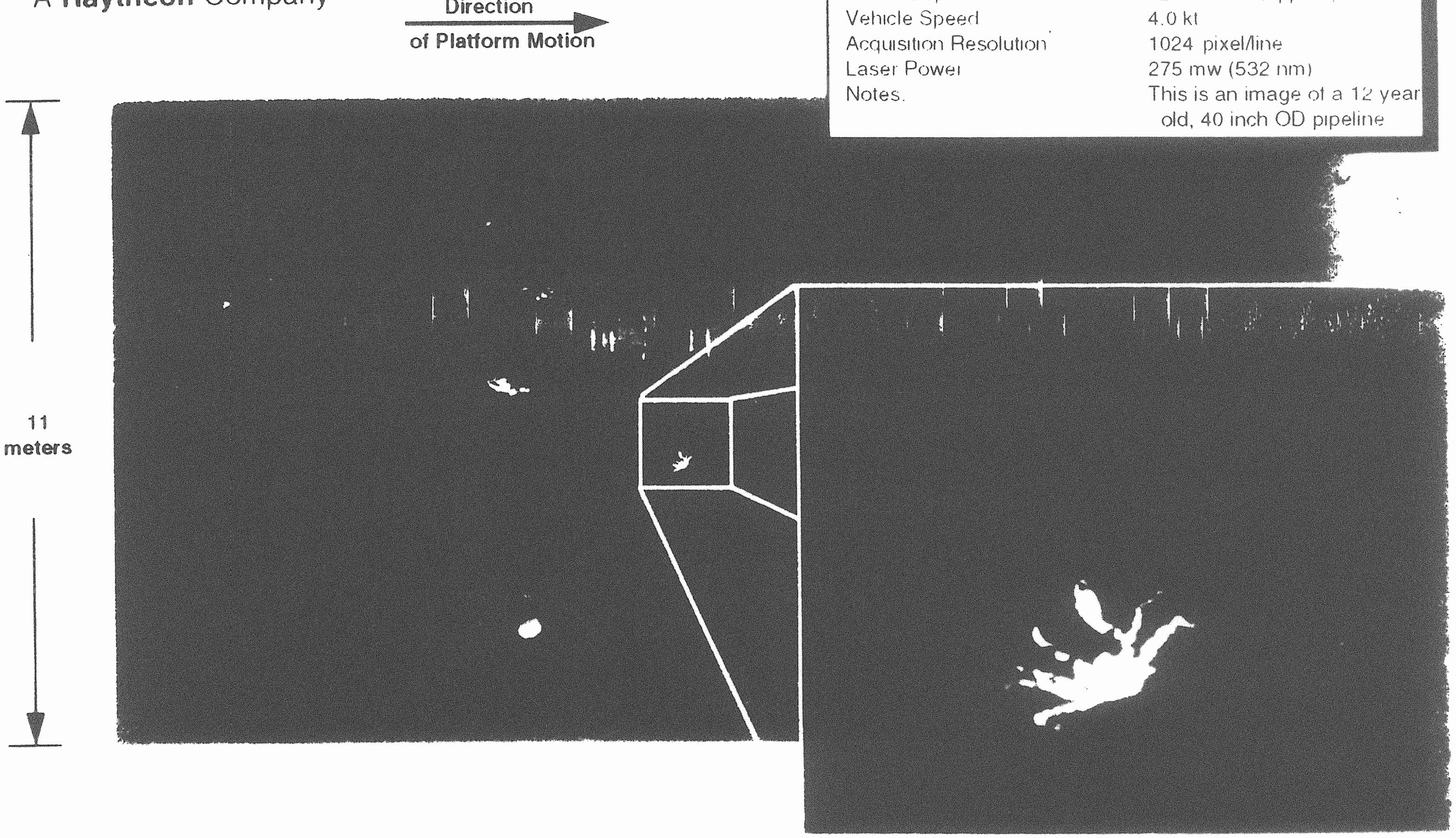


Figure 8

This is an image of a 12 year old, 40 inch diameter pipeline. The detail of the crab is expanded to show the level of detail that can be extracted from the wide-field panoramic images provided by the LS-4096 Laser Line Scan System. Notice also that a fish is visible in the full size image immediately above the upper left corner of the detail.

Applied Remote Technology

A **Raytheon** Company

Image No.	Jul01045508.dat Sand Bag on ZeePipe
Location	North Sea, Norwegian Sector
Date	01 July 1994
Altitude	8 meters
Water Depth	120 meters (approx)
Vehicle Speed	4.0 kt
Acquisition Resolution	1024 pixel/line
Laser Power	275 mw (532 nm)
Notes:	This is an image of a newly laid 44 inch OD pipeline

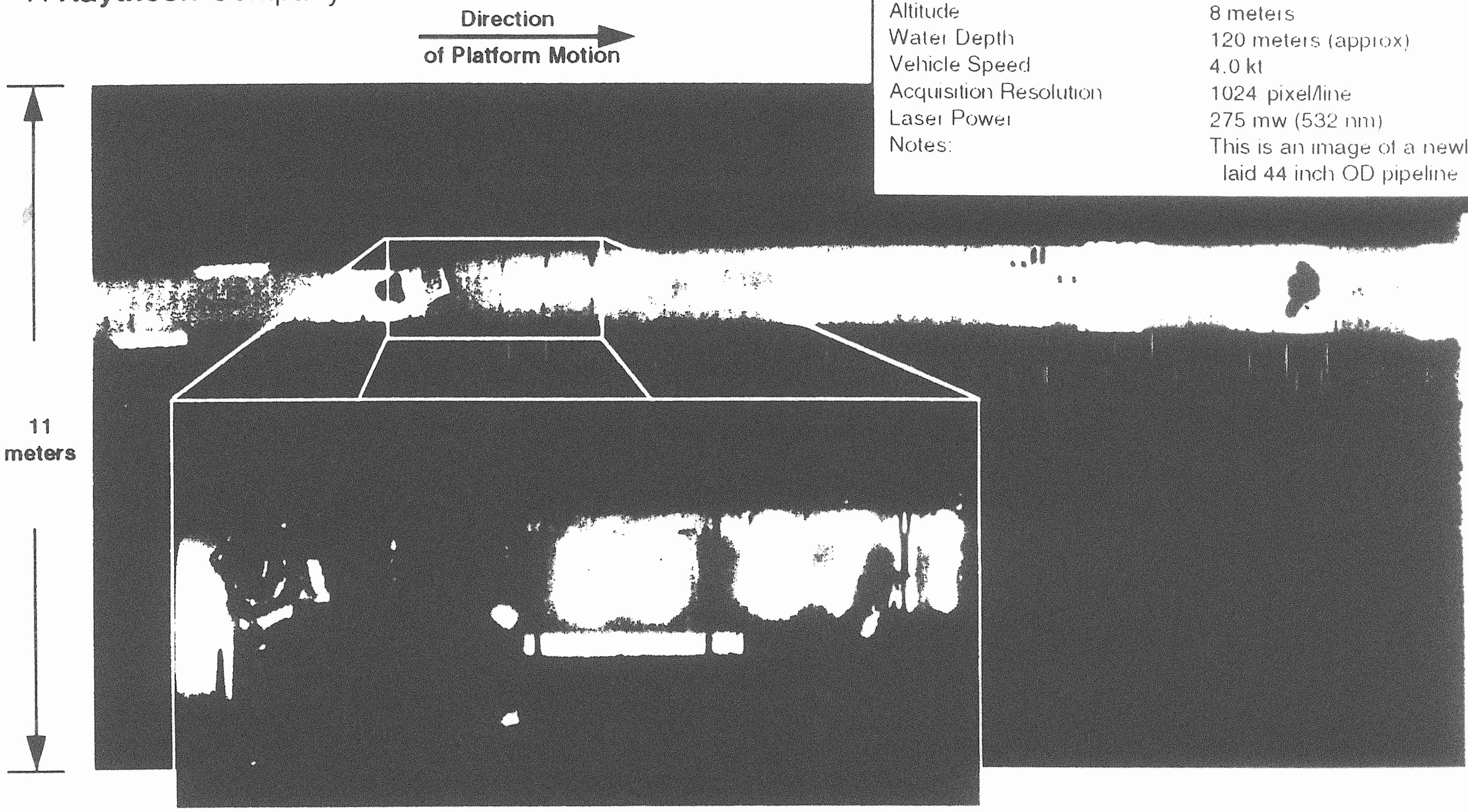


Figure 9

This image of a 44 inch OD pipeline was taken approximately 1 day after it was laid. The square package shown in the detail is a sandbag that had been tied to the pipe as an anchor for an acoustic transponder. The transponder's acoustic release had been activated and the transponder had been recovered shortly before this picture was taken. Notice that in the detail even the grappling hook that was used to attach the line to the pipe is clearly visible.

THEORY OF OPERATION

The suspended particulate matter that is present in most ocean water makes it very difficult to obtain acceptable performance with conventional underwater imaging systems such as television cameras or photographic film cameras. The suspended particles scatter light and this scattered light, which can be thought of as optical noise, seriously degrades the quality of the image produced in the focal plane of the camera. The laser line scan system has been designed specifically to address this problem and provide an imaging sensor that is significantly less sensitive to the deleterious effects of these light scattering particles than its conventional predecessors. The key aspect of the sensor design that results in this reduced sensitivity to the environmentally generated optical noise is the use of a laser to provide a very narrow instantaneous field-of-illumination and a specially designed receiver that provides a very narrow instantaneous field-of-view. The laser illuminates a minimum volume of water and therefore allows only a minimum number of scattering particles to interact with the light. Minimizing the volume of illuminated water thereby minimizes the amount of scattered light that is generated. The second part of the design, the use of a receiver with a narrow instantaneous field-of-view, minimizes the amount of scattered light that is allowed to reach the optical detector. The undesired electrical signal that is generated by scattered light is therefore kept to a minimum by the two-pronged approach of minimizing the amount of scattered light that is created and minimizing the amount of this scattered light that is allowed to reach the detector.

The downside to this design, quite obviously, is the fact that the system has an instantaneous field-of-view of less than 1°. This problem is solved by the scanning process. Scanning the target expands the limited instantaneous field-of-view into a very acceptable 70° field-of-regard. The difficulty here is that the narrow field-of-illumination and the receiver's narrow-of-view have to be scanned over the target in a coordinated, synchronous manner. Synchronization of the scanning process is much more easily done in one dimension than in two and that is why the first fully operational synchronous scanning system to be realized in practice, the LS-4096, is a line scan system rather than a two-dimensional system.

A conceptual sketch of the LS-4096 Optical Sensor is presented in Figure 10. Two rotating mirrors are rigidly attached to a common rotating shaft and a laser is oriented such that its output beam is incident on one of the mirrors. .This mirror causes the laser beam to be reflected toward, and illuminate, the target. As the laser beam travels toward the target, it is scattered and absorbed by the intervening seawater and any suspended particulate matter that may be present in the water column. As mentioned in the preceding introductory paragraphs, absorption and scattering are the processes that have historically made it very difficult to generate high quality images of submerged objects at acceptable operating ranges.

The unscattered, unabsorbed laser light that manages to reach the target illuminates a relatively small, localized area that is called the primary scan spot. This is the area of greatest interest because it is from this confined area that the primary optical signal is generated.

As the mirrors rotate, the scan spot traces a continuous curve, or scan line, across the target instantaneously illuminating a very small localized area of the target. When there is relative motion between the scanner and the target perpendicular to the scan direction then sequential scan lines will be traced, each successive line being displaced slightly from the previous line, and the target will be effectively scanned in two dimensions. By coordinating the scan rate with the relative velocity that exists between the sensor and the target, it is possible to control the spacing between sequential scan lines and thereby ensure that the desired rectangular sample pattern is achieved.

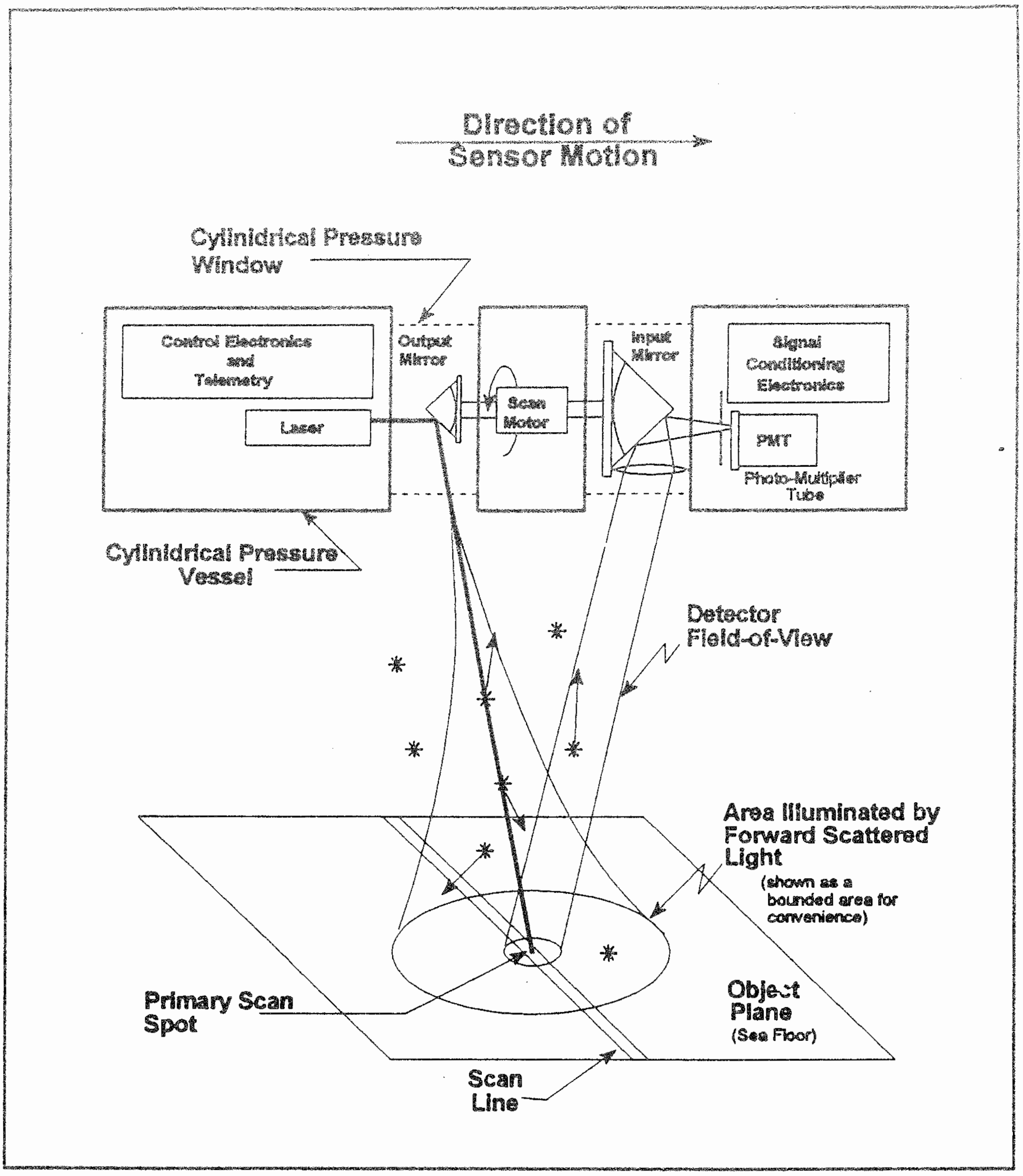


Figure 10
Conceptual Sketch of LS-4096 Optical Sensor Operation.

The narrow field-of-illumination provided by the laser, and the narrow instantaneous field-of-view provided by the receiver, combine to effectively reduce the sensitivity of the sensor to the deleterious effects of light scattered by the water and suspended particulate matter. An operationally effective, 70° field-of-regard is achieved by synchronously scanning the target. By scanning the target in one dimension and moving the entire sensor in a perpendicular direction, a two-dimensional reflectance map of the target can be created.

The target reflects a portion of the incident energy back toward the sensor. If the scan spot is incident on a bright, reflective portion of the target then a relatively large fraction of the incident energy is reflected and conversely, if the scan spot is incident on a dark, nonreflective portion of the target then a relatively small fraction of the incident energy is reflected. The reflected energy is scattered and absorbed as it travels back toward the sensor and a small amount of the remaining energy will enter the sensor's receiver aperture through the cylindrical input window. If the power in the laser beam is held constant and if certain geometric factors are ignored, then it can be assumed that the amount of energy reflected by the target, and therefore the amount of energy received by the sensor, is proportional to the local reflectance of the target (by local reflectance we mean the reflectance of the target averaged over the area illuminated by the scan spot).

By sampling the output of the photo-multiplier tube (PMT) at times that are synchronized with the mirror rotation, it is possible to build up a two-dimensional reflectance map of the target. This is accomplished by digitizing the sampled PMT signal and storing the resulting digital data in a video random access memory (VRAM) module. This stored data can then be read and displayed by a CRT controller. If the whole process of data sampling, storage, and display is properly integrated and synchronized then there will be a direct relationship between each physical location on the screen of the CRT and a specific location on the target. And, if the assumption that the amount of light sensed by the PMT is proportional to the local reflectance of the target, the brightness of the display at each point will be proportional to the reflectance of the target at the corresponding point.

The data displayed on the CRT therefore represents a two-dimensional "reflectance map" of the target rather than a conventional image. But even though the display differs from a classical image in theoretically significant ways the differences are, in general, moot to the operator because the display appears to be a very realistic visual representation of the target and that, in the final analysis, is all that usually matters. As the sensor passes over a stationary target, for example, the display can be controlled in such a way that the data from each new scan line is always displayed at the top of the screen. As each new line of data is added to the screen all previous lines are sequentially moved down the screen to make room for it and the result is a "waterfall" display that gives the operator a very realistic view of the passing target.

PHYSICAL DESCRIPTION OF THE LS-4096 SYSTEM

Optical Sensor

The underwater Optical Sensor consists of four individual subassemblies; the sensor control electronics subassembly, the laser subassembly, the scanner subassembly, and the detector subassembly. These four subassemblies are integrated into a single physical assembly and installed inside a watertight cylindrical pressure vessel.

The laser subassembly consists of the solid-state, diode pumped, frequency doubled Nd:YAG laser and assorted beamforming and beam steering optics. The Nd is shorthand for neodymium and YAG is an acronym for yttrium-aluminum-garnet. In this particular laser, a YAG crystal is doped with a few neodymium atoms and this doped crystal is the part of the laser that actually produces the output light. The Nd:YAG crystal is optically pumped with diode lasers and the result is a laser that produces infrared light at a wavelength of 1064 nanometers. This infrared light is put through another special crystal that doubles its frequency thereby producing light that has a wavelength of 532 nanometers. This green light is close enough to the optimal wavelength to be very useable by underwater optical systems.

The green output of the laser is directed to the scanner subassembly. The scanner subassembly consists of the output mirror, the input mirror, the scan motor that spins these two mirrors, and the scan motor control electronics that keep the scan motor spinning at the desired speed. As discussed above, the scanner subassembly causes the target to be optically scanned by the laser beam and the detector in a controlled and synchronized manner.

The detector assembly consists of the optical detector, miscellaneous optical components, and electronics that amplify and condition the electrical output of the detector. The detector, which in the LS-4096 is a photo-multiplier tube, is the device that converts the received photons into an electrical signal. The electrical output of the detector is passed directly to specially designed electronics that amplify and filter this signal preparing it for digitization.

The control electronics subassembly consists of a computer and the analog-to-digital converter (ADC) that converts the analog electrical output from the detector subassembly into a digital signal that can be transmitted to the control console. The computer consists of a single board computer (SBC), an analog output board, and an analog input board. These three boards are contained in a 3U VME card cage along with the telemetry unit and the ADC.

Communication Link

The telemetry system performs the following three primary functions

1- Transmit functional commands from the Control Console to the submerged sensor

2- Transmit digitized video data from the sensor to the Control Console

3- Transmit status data from the sensor to the Control Console

In addition to these primary functions, the telemetry system performs the secondary function of providing a transparent bi-directional digital data link for external equipment that is configured with a standard RS-232C or RS-422 interface.

All data is transmitted in digital form and, depending on the length of the communication path, can be passed over coaxial cable, twisted/shielded wires, or optical fibers. Optical fiber options include dual multi-mode fibers, dual single-mode fibers, or a single single-mode fiber with wavelength division multiplexing (WDM). In its standard configuration, the system provides an optical signal, generated by low-cost light emitting diodes (LED), that are designed to be interfaced to multi-mode optical fibers. In this configuration, the telemetry link supports data transmission between the sensor and the console at the rate of 60 megabits/second over two separate optical fibers. The performance of this link has been successfully tested over 4,000 feet of multi-mode optical fiber. Higher data rates and longer cable lengths are possible by implementing an optional solid-state laser as the light source and using a single-mode optical fiber as the transmission medium. The digital transmission format was selected to provide the 84dB dynamic range required to support full fidelity of the video signal and the fiber-optic transmission medium was selected to provide the 20 Mega-bit/sec bandwidth that is required to support full video dynamic range and resolution at high search rates.

In the baseline two fiber configuration, one fiber is dedicated to downlink transmission and the second fiber is dedicated to uplink transmission. The downlink transmission is primarily command data sent from the console to the sensor. The uplink transmission consists of sensor status data and digital video data. As mentioned above, a transparent serial data port is provided to support, for example, the interchange of command and status information between a vehicle control console on the surface and the sub-surface vehicle controller. This data port is transparent in the

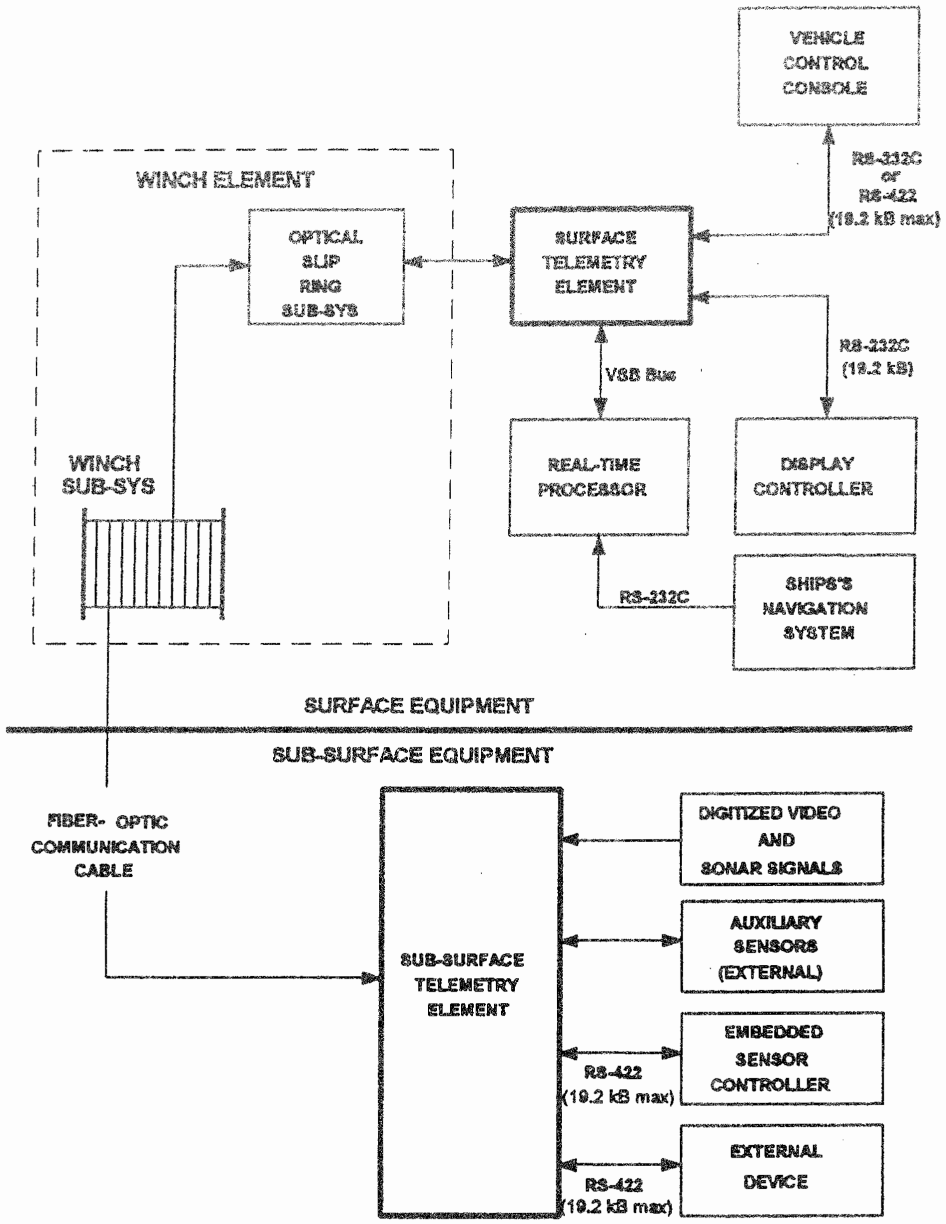


Figure 11
Top level Functional Block Diagram for the LS-4096 Communication Link

sense that the communication link does not need to be specially configured to match the data rate or format of the vehicle control link. This allows any RS-232C device to be connected to this port on the surface with matching equipment connected at the sub-surface end.

A typical configuration for the LS-4096 Communication Link is shown in Figure 11. In this figure the Surface Telemetry Element and the Sub-Surface Telemetry Element are highlighted for clarity. The Surface Telemetry Element is a single circuit board that physically resides in the 6U VME card cage along with the Real-Time Processor. The Sub-Surface Telemetry Element is also a single circuit board and it resides in the 3U VME card cage with the Embedded Sensor Controller.

The detailed configuration and operation of the Surface Telemetry Element and the Sub-Surface Telemetry Element are described in the following two sections. These elements are described in more detail than other elements of the LS-4096 system because their configuration and function are exceptionally important when the LS-4096 is being integrated into a complete operational system.

The Surface and Sub-Surface Telemetry Elements both utilize Transparent Asynchronous Transmitter/Receiver Interface (TAXI) integrated circuits, manufactured by Advanced Micro Devices, and Programmable Gate Arrays (PGA), manufactured by Xilinx. The TAXI chips perform the serial-to-parallel and the parallel-to-serial data conversions, data synchronization, Manchester encoding/decoding, and data packing/unpacking. The PGA's function as custom multiplexers/demultiplexers, timing generators, and test pattern generators.

Surface Telemetry Element (STE)

A Functional Block Diagram of the Surface Telemetry Element (STE) is shown in Figure 12. This element is packaged on a single 6U-VME circuit board that occupies one slot in the Real-Time Processor (RTP) chassis. The inputs to the Surface Telemetry Element are shown on the left side of the diagram and the outputs produced by the element are shown on the right side.

Inputs to the Surface Telemetry Element

The high-speed digital communication input from the Sub-Surface Telemetry Element can be received as either an electrical signal on a coaxial cable or as an optical signal on a fiber-optic cable. The baseline configuration is an optical signal on a multi-mode optical fiber. The digital/optical configuration comfortably supports the signal bandwidth, signal dynamic range, and cable lengths associated with the LS-4096.

A serial input data port is provided to receive digital data from the Display Console. This port is configured as a standard RS-422 serial port with a data rate of 19.2 kiloBaud. If desired, this port can be optionally configured to meet the specifications of RS-232C. This dedicated port provides the requisite command and control communication path between the laser line scan sensor and the operator console. In the system's standard configuration, a command string is sent to the Sub-Surface Telemetry Element every 100 milliseconds at the rate of 19.2 kiloBaud.

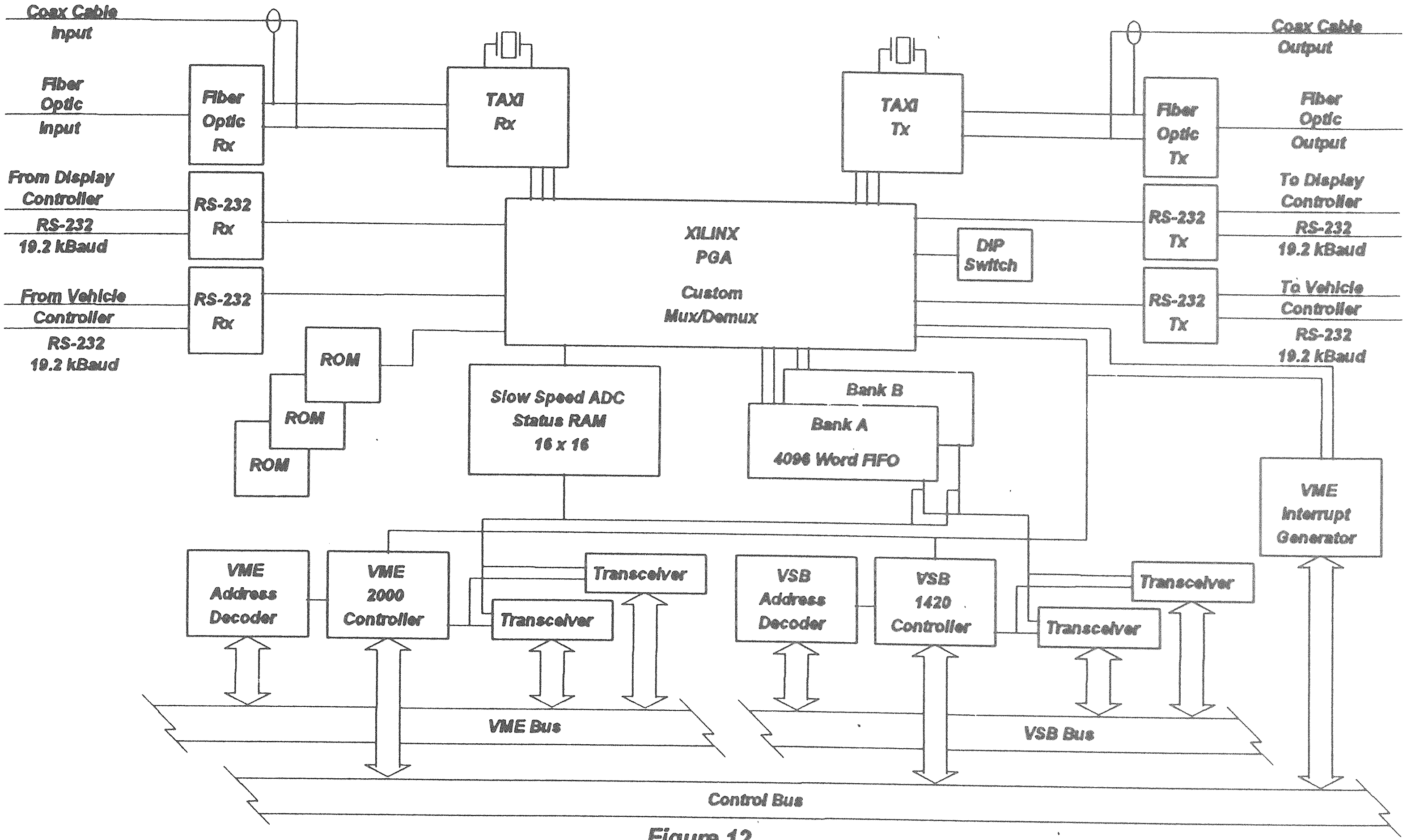


Figure 12

Functional Block Diagram of the Surface Telemetry Element

A second serial input data port is provided to receive digital data from the support vehicle's console or some other source that is external to the laser line scan console. This port is configured as a standard RS-422 serial port with a data rate of 19.2 kiloBaud or less. The Surface Telemetry Element electronics sample the signal on this port and transmit the data to the Sub-Surface Telemetry Element. The Sub-Surface Telemetry Element reconstitutes the signal and places it on an output data port. The telemetry system does not need to know the data rate or format used by this data link, it simply places any signal it senses at the input on the output. This entire process happens in a transparent manner such that any equipment attached to the output port of the sub-surface unit behaves as though it were connected directly to the surface data port. This allows any equipment that uses standard serial data communication to be connected easily and directly without any reprogramming or reconfiguration of existing equipment.

Outputs From the Surface Telemetry Element

The digital output from the STE is the command string from the Control Console to the Optical Sensor that allows the operator to control the operation of the sensor. As stated previously, this output can be provided as either an electrical signal on a coaxial cable or as an optical signal on a fiber-optic cable. In its standard configuration, the system provides an optical signal, generated by a low-cost light emitting diode (LED), that is designed to be interfaced to a multi-mode optical fiber.

A serial data output port is provided to transmit sensor status data to the Display Console. This port is configured as a standard RS-422 serial port with a data rate of 19.2 kiloBaud. If desired, this port can be optionally configured to meet the specifications of RS-323C. This dedicated port provides the requisite communication path between the laser line scan sensor and the operator console.

A second serial output port provides support for the support vehicle's console or some other destination that is external to the Operator Console. This is the output half of the "Vehicle Controller" input port.

Sub-Surface Telemetry Element (SSTE)

A Functional Block Diagram of the Sub-Surface Telemetry Element (SSTE) is shown in Figure 13. This element is packaged on a single 3U-VME circuit board and the analog-to-digital converter (ADC) is mounted as a "daughter" board. The entire assembly occupies two slots in the 3U-VME card cage that also houses the sensor's embedded controller. The inputs to the Sub-Surface Telemetry Element are shown on the left side of the diagram and the outputs produced by the element are shown on the right side.

Inputs to the Sub-Surface Telemetry Element

The digital communication input from the Surface Telemetry Element can be received as either an electrical signal on a coaxial cable or as an optical signal on a fiber-optic cable. The baseline configuration is an optical signal on a multi-mode optical fiber. The digital/optical configuration comfortably supports the signal bandwidth, signal dynamic range, and cable lengths associated with the LS-4096.

A serial input data port is provided to receive digital data from the support vehicle's controller or some other source that is external to the sensor. This port is configured as a standard RS-422 serial port with a data rate of 19.2 kiloBaud or less. The Sub-Surface Telemetry Element electronics sample the signal on this port and transmit the data to the Surface Telemetry Element.

The Surface Telemetry Element reconstitutes the signal and places it on an output data port. The telemetry system does not need to know the data rate or format used by this data link, it simply places any signal it senses at the input on the output. This entire process happens in a transparent manner such that any equipment attached to the output port on the surface behaves as though it were connected directly to the sub-surface data port. This allows any equipment that uses standard serial data communication to be connected easily and directly without any reprogramming or reconfiguration of existing equipment.

A second serial input data port is provided to receive digital data from the sensor's embedded controller. This port is configured as a standard RS-422 serial port with a data rate of 19.2 kiloBaud. If desired, this port can be optionally configured to meet the specifications of RS-232C. This dedicated port provides the requisite command and control communication path between the laser line scan sensor and the operator console.

Five digital timing signals are provided to the Sub-Surface Telemetry Element. These signals, which are all generated by electronics in the laser line scan sensor, include the Optical Trigger, Index, EC-Data, EC-Gate, and EC-Clock signals. These signals are combined with other inputs and used by the Sub-Surface Telemetry Element's programmable logic array (PGA) to generate the Integrator Control signal and the timing signals that control the video ADC.

The analog video signal is connected directly to the input of a high-speed 14-bit analog-to-digital converter. In response to commands from the PGA, this ADC produces a 14-bit parallel digital output which becomes a data input to the PGA.

In addition to the video input, up to 16 analog signals can be connected to the Sub-Surface Telemetry Element. These input signals are single-ended and bi-polar with a voltage range of -10 volts to +10 volts. One signal can be sampled at a rate of up to 300 kHz with a dynamic range of 12-bits or multiple signals can be sampled at lower rates. The rate at which each input is sampled can be programmed by replacing the PGA ROM's.

Outputs From the Sub-Surface Telemetry Element

The digital communication output from the Sub-Surface Telemetry Element can be provided as either an electrical signal on a coaxial cable or as an optical signal on a fiber-optic cable. In its standard configuration, the system provides an optical signal, generated by a low-cost light emitting diode (LED), that is designed to be interfaced to a multi-mode optical fiber.

A serial data port is provided to transmit digital data to the sensor's embedded controller. This port is configured as a standard RS-422 serial port with a data rate of 19.2 kiloBaud. If desired, this port can be optionally configured to meet the specifications of RS-232C. This dedicated port provides the requisite command and control communication path between the laser line scan sensor and the operator console.

A second serial output port provides support for the vehicle's controller or some other destination that is external to the sensor. This port is configured as a standard RS-422 serial port with a data rate of 19.2 kiloBaud or less. The Surface Telemetry Element electronics sample the signal on an input port in the surface console and transmits the data to the Sub-Surface Telemetry Element. The Sub-Surface Telemetry Element reconstitutes the signal and places it on the output data port.

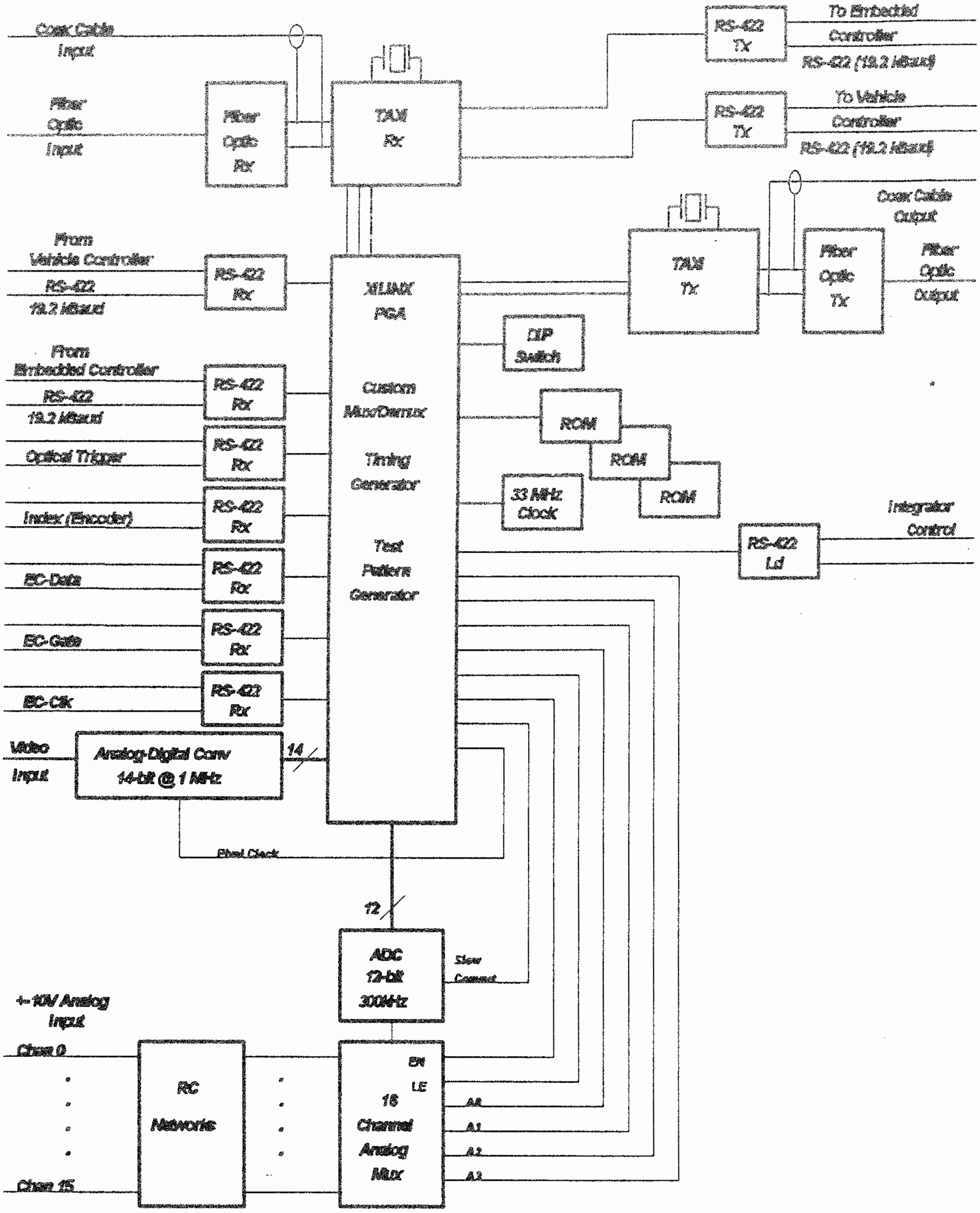


Figure 13

Functional Block Diagram of the Sub-Surface Telemetry Element

The telemetry system does not need to know the data rate or format used by this data link, it simply places any signal it senses at the input on the output. This entire process happens in a transparent manner such that any equipment attached to the output port behaves as though it were connected directly to the input port on the surface. This allows any equipment that uses standard serial data communication to be connected easily and directly without any reprogramming or reconfiguration of existing equipment. This output port combined with the input port described in the previous section provide a complete, transparent, full duplex, serial digital data link.

The remaining output produced by the Sub-Surface Telemetry Element is the Integrator Control. The PGA accepts the five digital inputs discussed in the previous section, combines these signals with commands received from the Embedded Controller, and produces the Integrator Control signal. This signal controls the operation of the video integrator, synchronizing its operation with the analog-to-digital conversion process.

CONTROL CONSOLE

The Control Console provides the operator with control over all system functions including electrical power control, data management, data acquisition, data display, data processing, data recording, aperture and beamformer control, PMT gain, laser operation, and sensor altitude and speed inputs. Most of these functions are normally controlled automatically but the operator is given the ability to override these automatic features and control any desired function manually. The Control Console also provides the operator with continuously updated displays of sensor status data and video data.

The Control Console consists of a VME computer chassis, a high-resolution video monitor, and a keyboard. These major components can be installed in an EIA standard 19 inch electronics rack or in specially designed ruggedized containers as shown in Figure 2. Standard rack mounting is generally preferred if the installation is intended to be permanent and container mounting is preferred for mobile systems whose installation on the surface support vessel is intended to be temporary or short term. A top level Functional Block Diagram of the Control Console is shown in Figure 14.

The VME chassis contains the Surface Telemetry Element (STE), the Real-Time CPU (RTP), the Digital Signal Processor (DSP), the low resolution CRT Controller, the bus interface between the real-time system and the Display Controller (DC), the magnetic hard disk, and the magneto-optical disk drive.

Digital video and status data are received by the STE from the Optical Sensor via the umbilical cable. Status data are passed through the STE to the DC over a bi-directional RS-232C serial communication link. The raw digital video data are passed over the VSB bus to the DSP where it is processed prior to display. At the operator's option, and on his command, raw, unprocessed digital video data can be passed over the VME bus and through the RTP to the magnetic hard disk where it is recorded. Processed video data is passed through the VME/GIO Bus Interface to the DC where it is displayed on the high resolution monitor.

Raw digital video data received by the STE is passed to the Digital Signal Processor (DSP) over the VSB bus, processed for display, and subsequently passed through the VME/GIO Bus Interface to the Display Controller. The DSP is a SuperCard 3 array processor manufactured by CSPI. The DSP evaluates the digital video data on a line-by-line basis, calculates the appropriate correction factors, applies this correction to each pixel of data, and converts the result to the 8-bit format required for display. During early phases of laser line scan system development the signal processing that was applied to the video signal was done with dedicated analog circuitry. This

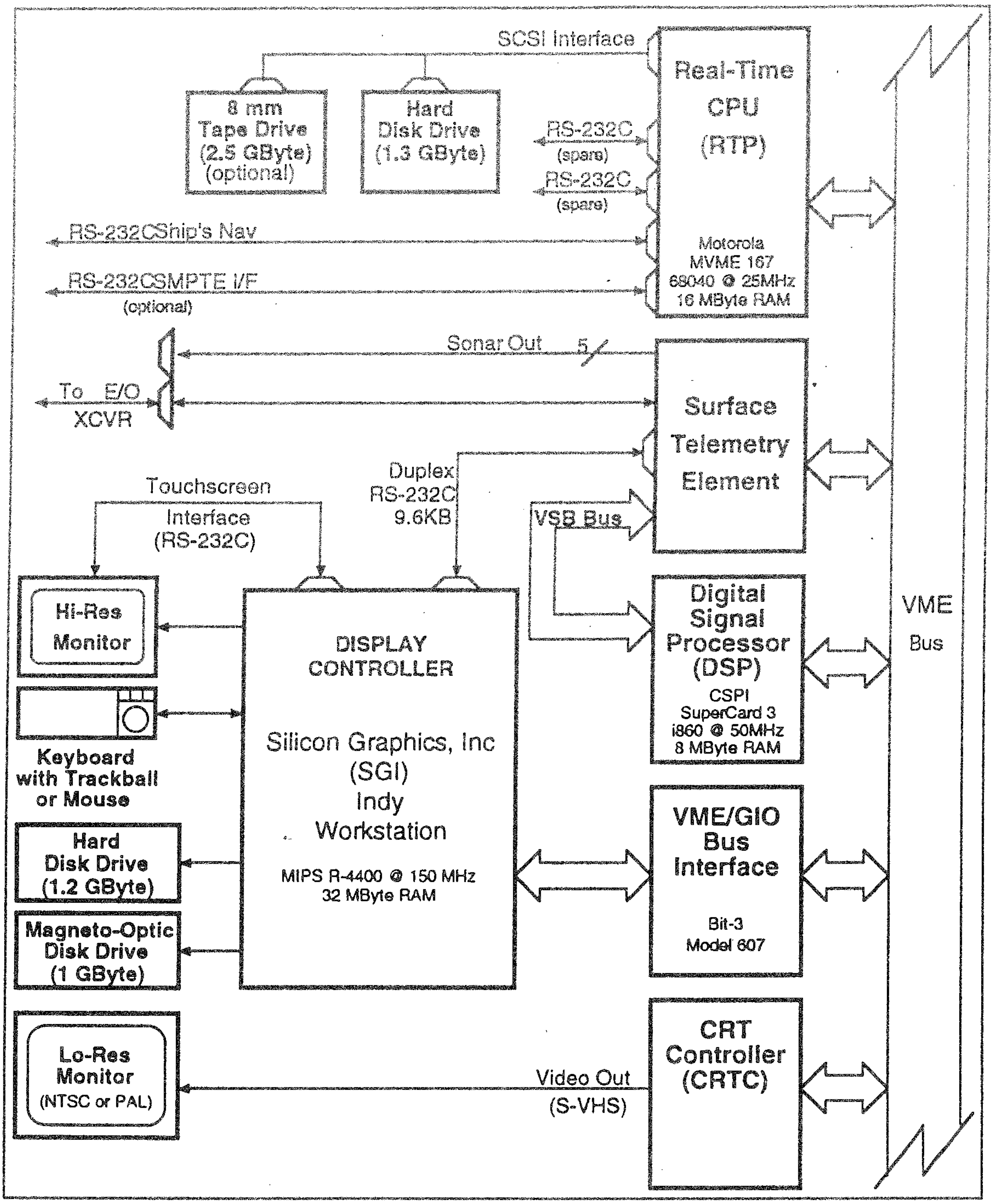


Figure 14
Top level Functional Block Diagram of the LS-4096 Control Console

processing was limited by the electronic options that were available and consisted of applying individual gain factors to the signal from each of the four optical channels (channel equalization), and applying a second-order spatial gain correction to the resulting equalized data (shading correction). These techniques provided reasonable results but were never optimum. By replacing the analog circuitry with high speed digital signal processing hardware it has become possible to develop data processing techniques that provide vastly improved results.

The early channel equalization/shading correction techniques were based on two assumptions. First, it was assumed that the difference in the signal level that was produced could be removed by applying a simple scale factor, or gain, change. And second, it was assumed that the same second order shading correction was appropriate for all four optical channels.

Analysis of unprocessed digital data recorded by the LS-4096 has shown both of these assumptions to be gross oversimplifications. Channel-to-channel variations in average signal level are not constant across the scan line and therefore cannot be corrected with a simple constant multiplier. Also, the spatial variations in signal level across individual scan lines, i.e., shading, have proven to be quite complex and differ widely between channels. It is therefore impossible to properly compensate for these variations with a second order correction and unique spatial corrections must be developed for, and applied to, each individual channel. To add to the complexity of this problem it has been demonstrated that the characteristics of the optimum correction algorithms are significantly dependent on operational variables such as the water clarity, the range to the target, and the reflective characteristics of the target. These factors can vary dramatically over short periods of time which places an unacceptable load on the operator of any manual system.

For these reasons the LS-4096 uses adaptive digital signal processing techniques to correct the raw video data. The operator has the ability to inhibit this processing or to control key parameters that effect the operation of the processing algorithms. But for the most part, the video data processing is automatic and requires minimal involvement of the operator. The raw video from each channel is constantly evaluated, the proper corrections are determined for each optical channel, and the corrections are applied. All this processing is accomplished in real-time and the characteristics of the corrections are continuously evaluated and automatically adjusted when necessary to maintain a continuously optimized image on the video monitor.

The processed video data from the DSP is received by the Display Controller where it is combined with the Graphic User Interface and then displayed on the high resolution system monitor. A picture of the resulting display is presented in Figure 15. This picture shows how the 1280x1024 pixel display area on the monitor is divided into the 1024x1024 pixel Video Display on the left side of the screen and the 256x1024 pixel Primary Status Display on the right side of the screen. The image in the Video Display "window" is presented in a waterfall format and can be panned and zoomed in real-time. The display can also be "frozen", i.e., the waterfall update can be halted, and the image can then be scrolled vertically as well as panned and zoomed. The Primary Status Display contains information and controls to which the operator must have constant and immediate access. This includes operational data such as the location and altitude of the vehicle as well as sensor status data and alarms.

Navigation data that specifies the position of the ship, and optionally the position of the underwater platform on which the Optical Sensor is mounted, are received by the DC via a dedicated RS-232 serial data link. These data are reformatted as necessary by the DC and displayed at the top of the Primary Status Display window.

The operator controls various aspects of system operation by activating two types of controls, push-buttons and slide pots. The controls can be activated, at the operator's option, with a track-ball, a mouse, or the touchscreen monitor. Our experience has demonstrated that the touchscreen option

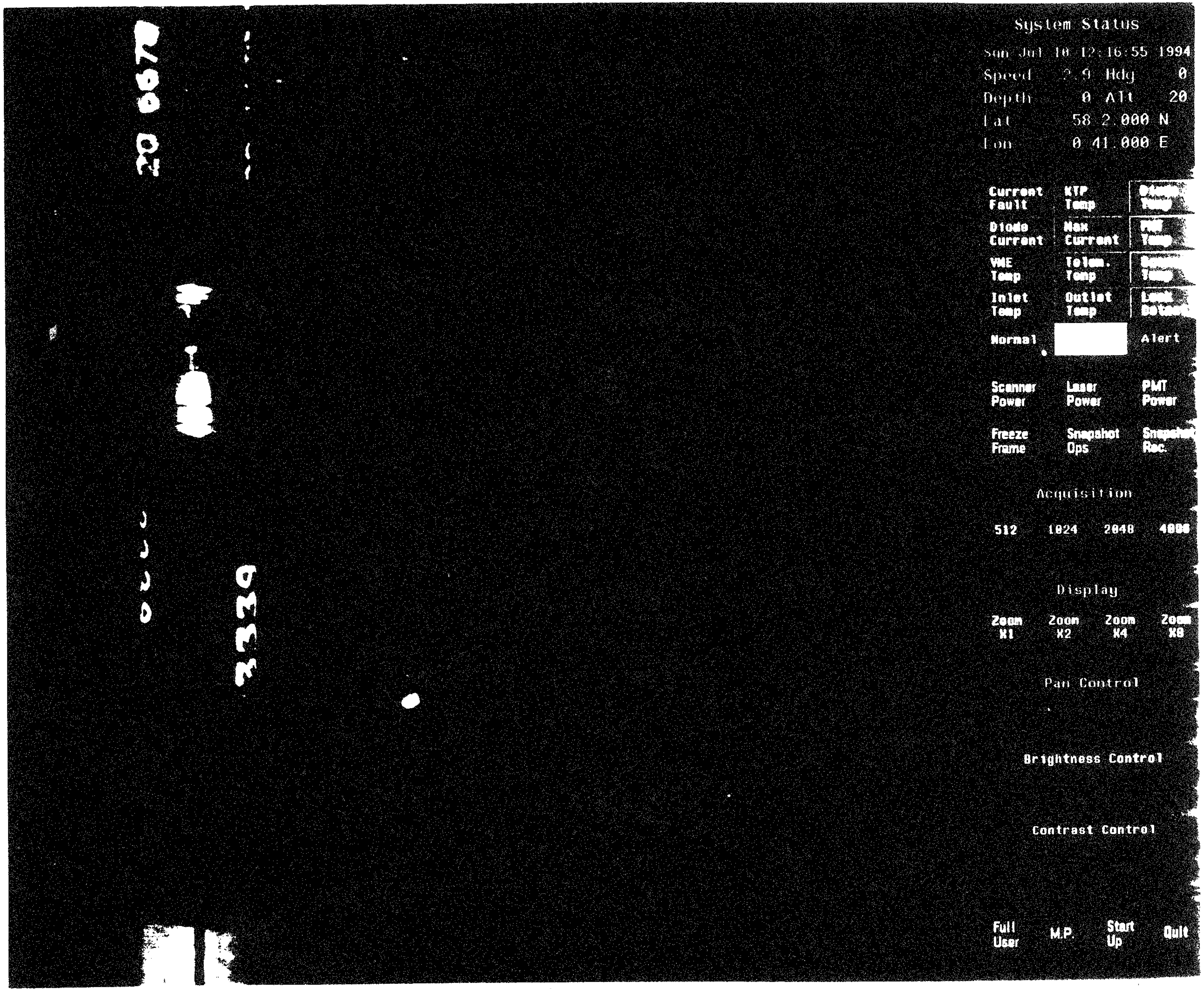


Figure 15

LS-4096 Control Console. Full Video Display.

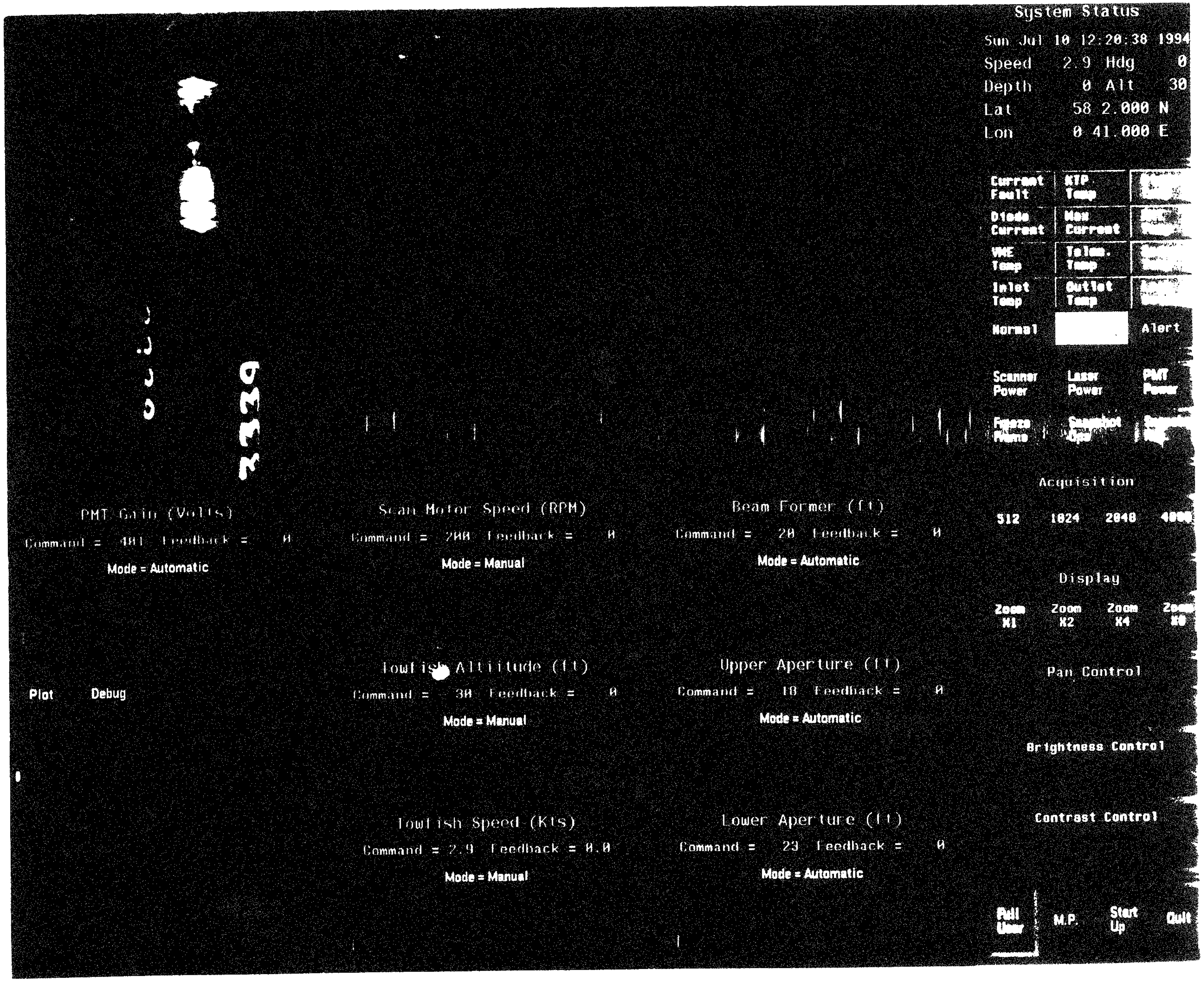


Figure 16

LS-4096 Control Console. Full User Display.

is the most comfortable at sea and the following discussion therefore assumes the use of this option.

The pushbuttons are activated by simply touching the monitor within the labeled box. When this is done, the activated button changes color as a feedback to the operator that the command has been registered by the computer. The digital status display is also updated which provides the operator with a second, quantitative feedback signal that the proper command has been registered.

The slide pots are activated in one of two ways. For coarse adjustment the operator touches the slide pot bar and drags his finger to the left or right. The slide pot bar will follow the motion of the operator's finger and the status display will change to show the new value of the input parameter as it is changed. For fine or incremental adjustment the operator touches the arrow at either end of the slide pot. The desired parameter is incremented or decremented each time the arrow is touched and the status display is updated with the new value.

Due to the limited space available in the Primary Status Display window only a minimal number of controls are included. As stated above, only those controls to which the operator needs continuous and immediate access are included. All other controls are accessed by activating secondary windows. Figure 16 is a picture of the computer generated display with one such secondary window, the Full User window, activated. Notice that the "Full User" button at the bottom of the Primary Status Display is green, indicating that it has been activated. The operator caused the Full User window to be displayed in the video window by "pressing" this button.

The Full User window contains several examples of the slide-pots that were discussed above. These slide-pots allow the operator to select manual or automatic operating mode, change the command value for the parameter when manual mode is active, and displays the feedback value for the parameter in addition to the command value. These kinds of controls provide the operator with all the data and power that he needs to keep the LS-4096 functioning properly.

One of the most powerful aspects of this graphical user interface is the ease with which it can be modified. The display configuration that is represented by the examples in Figure 15 and Figure 16 is the result of almost two years of field trials and operational experience. Many other features are available that are unfortunately beyond the scope of this discussion. It should be sufficient to state here that the configuration, options, and capabilities of the LS-4096 operator interface will continue to evolve and develop. And as this evolution occurs, all improvements will be made immediately available to existing systems via updated software. This planned methodology for system improvement has been instituted to ensure a maximum useful lifetime for every LS-4096 system.

CONCLUSIONS

Laser illuminated underwater imaging systems are becoming an operational reality and the LS-4096 laser line scan imaging system is one of the first such systems to become commercially available. By integrating the LS-4096 with appropriate acoustic sensors and the necessary support sensors it is possible to realize a well balanced, fully integrated system for underwater search and survey applications. As our understanding of the underwater imaging process continues to improve and the capabilities of available supporting technologies increase we are sure to experience continued evolutionary improvement in our ability to generate high quality images of submerged objects at extended ranges.

Appendix A

LS-4096 System Capabilities

The following paragraphs develop the equations that are important in the specification of the operating characteristics of the LS-4096 Laser Line Scan System. It should be noted that the optical power equations estimate the magnitude of the optical signal received by the detector in the LS-4096 sensor and ignore the concurrent optical noise. Since system performance should really be specified by the signal-to-noise ratio we have obviously only dealt with half the problem. Unfortunately, optical noise is a very difficult parameter to calculate reliably for underwater systems. On the positive side, our operational experience has demonstrated that the signal-to-noise ratio produced by the LS-4096 system is adequately high to produce acceptable quality images whenever the predicted signal level is kept above a specified minimum level. The validity of the operating envelopes specified in the figures of this section have been consistently verified by every operational trial and deployment that has been undertaken during the past two years.

The optical signal power incident on the receiver of a synchronous scanning system, P_r, can be shown to be, to a first order, proportional to the output power of the laser, the reflectance of the target, the optical speed of the receiver optics, the range to the target, and the clarity of the water in accordance with the following proportionality.

$$P_r = P_o \cdot \rho \cdot (A_r / R^2)\, e^{-2cR} \qquad (1a)$$

where

P_o = the optical power output of the laser

P_r = the optical power of the signal incident on the receiver (this does not include optical noise or light scattered by the water)

ρ = the local reflectivity of the target

(A_r / R^2) = the solid angle subtended by receiver aperture at the (the target is assumed to be a distance R from the receiver)

e^{-2cR} = the bi-directional attenuation suffered by the light as it propagates from the source to the target and back to the receiver

Laboratory experiments have shown that this proportionality is not strictly correct. Using the beam attenuation coefficient, c, to estimate the optical losses that occur as the light propagates from the target back to the receiver underestimates the magnitude of the received flux because forward scattered light that originated at the object point is not included. In order to correct this deficiency it is reasonable to replace the beam attenuation coefficient, c, with the diffuse attenuation coefficient, k. This replacement results in the following proportionality:

$$P_r = P_o \cdot \rho \cdot (A_r / R^2)\, e^{-(c+k)R} \qquad (1b)$$

Experiments have shown that this equation overestimates the received flux but provides a more consistent proportionality.

In order to begin the discussion it is helpful and appropriate to assign values to the key variables. The initial values we have chosen are as follows.

P_c = 1 watt = 2.5 10^{18} photons/sec @ 500 nm (approximately)

ρ = (0.05/π) = 0.016 (this is the reflectance, in terms of watts per steradian, of a 5% Lambertian reflector)

A_r = 0.022 ft^2 (this is the area of a 2 inch diameter receiver aperture)

To estimate the total number of photons available to constitute the signal for an individual pixel, Equation (1b) can be modified by multiplying the received signal level, P_r, by the signal integration time for a single pixel. The pixel integration time is the inverse of the sample rate.

The sample rate, the maximum number of pixels sampled per second, can be calculated from various operational parameters as follows.

$$R_{sample} = (S_{motor}(\text{rev/sec}))((360\ /\text{rev})/(70\ /\text{line}))(N\ \text{pixels/line}) \qquad (2)$$

R_{sample} = the pixel sample rate (pixels/second)

S_{motor} = the scan motor speed (revolutions/second)

N = the image resolution (pixels/line)

The scan motor speed, S_{motor}, is dependent on the platform altitude, the platform speed, the required image resolution, and the desire to keep the aspect ratio of the pixels in the center of the image equal to 1.

The transverse size of the pixels in the center of the field-of-view is equal to

$$T_{pixel} = ((70^\circ\ /\text{line}) / (N\ \text{pixels/line})) \cdot (0.01745\ \text{radians/degree}) \cdot (R\ \text{feet})$$

Where R, the range to the center of the target, is also the altitude of the platform.

In order to maintain square pixels, the line to line spacing must be equal to the transverse size of the pixels, T_{pixel}. Once this dimension is established, the required time interval between lines can be easily calculated as follows when the platform velocity is known.

$$t_{line} = (T_{pixel}\ (\text{feet/pixel})) / (V_{platform}\ (\text{feet/second}))$$

then

$$S_{motor} = 1 / ((\text{tline}\ (\text{seconds/line})) \cdot (4\ (\text{lines/revolution})))$$

Combining these relations results in the following equation that relates the pixel sample rate to the required image resolution, the platform velocity, and the range to the center of the target.

$$R_{sample} = (1.05 \ N^2 \ V_{platform}) / R \qquad (3)$$

Since the signal integration time for each pixel is the inverse of the sample rate and since it is desirable to maximize the integration time, it is obviously desirable to minimize the pixel sample rate. Equation (3) shows that the sample rate is proportional to the square of the number of pixels per line (the image resolution) and linearly proportional to the platform velocity. These conclusions are not surprising. The fact that the pixel sample rate is inversely proportional to the platform altitude is, however, somewhat unexpected. The reason for this inverse proportionality is the fact that the pixels are spaced at constant angular intervals, not constant spatial intervals. Therefore, as the platform altitude increases, the transverse pixel spacing increases proportionately. Since it is desirable to maintain square pixels, at least in the center of the field-of-view, this increase in transverse spacing results in an equal increase in the line-to-line spacing. Increasing the line-to-line spacing results in a reduction in motor speed and a proportional reduction in sample rate.

Using the typical values for P_o, r, and A_r that are listed above Equation (1b) can be rewritten as

$$P_r = (8.8 \cdot 10^{14}) \cdot ((e^{-(c+k)R}) / R^2) \text{ photons/second}$$

where

$$k = 0.2 \cdot c + 0.04 \qquad \text{(Shannon equation)}$$

This equation can be used to estimate the signal photon flux incident on the photomultiplier tube. The estimates provided by this equation are higher than those that have been experimentally measured for a variety of reasons. There are several minor factors such as the fact that this equation does not take Fresnel losses at the optical surfaces into account but the primary problem is the fact that the factor (c + k) underestimates the attenuation losses. The equation is useful, however, to evaluate trends and the relative effect that individual system and operating parameters have on the received signal level.

Laboratory experiments, confirmed by in-situ field trials, have demonstrated that the LS-4096 produces good quality images of realistic, low contrast targets whenever the above equations estimate a received signal of $4.0 \cdot 10^4$ photons/pixel or more. This value can therefore be justifiably used to estimate the operational limits of the LS-4096 under any desired set of environmental conditions.

Equation (1b), Equation (3), and a threshold value of $4 \cdot 10^4$ photons/pixel were used to generate a family of curves that prescribe the limits of the operating envelope for the LS-4096 System. These curves are presented below in Figures A1 through A2. The following assumptions were used to generate these graphs.

1. A single-mode solid-state Nd:YAG laser is used as the light source. This laser is capable of producing a useable output of slightly more than 250 milliwatts which results in approximately 200 milliwatts of optical energy entering the water.

2. The scanner design uses four-faceted mirrors and the receiver optics have a clear circular aperture that is 2 inches in diameter.

3. The maximum allowable scan motor speed is 4000 rpm.

4. The maximum possible platform speed is 6 knots (9.6 feet/sec).

5. The target behaves like a Lambertian reflector with a mean reflectance of 5%.

Operation of the system may be limited by the scan motor speed, which cannot exceed 4000 rpm, the platform speed, which cannot exceed 6 knots, or the received signal level, which must exceed the established minimum required number of photons per pixel. The specific portions of the operating envelope that are established by each of these limits are identified in Figure A1 and Figure A2. If a minimum allowable platform speed exists, which could be established by towfish hydrodynamics or support ship characteristics, a fourth line must be added that would enclose the lower portion of the operating envelope.

The maximum allowable scan motor speed and the maximum allowable platform speed are determined by practical design considerations. The minimum required optical signal strength depends on water clarity and has been established by experiment and operational experience.

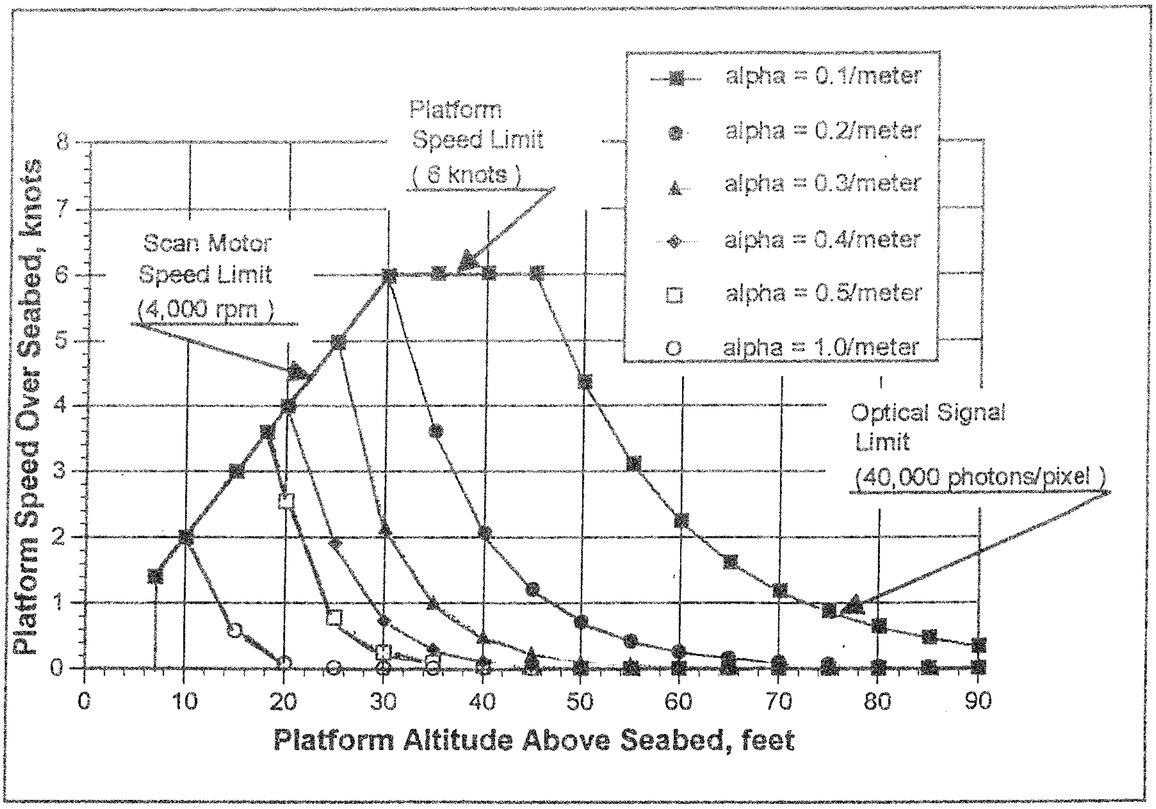


Figure A1

The curves in this figure enclose the operating envelope of the LS-4096 laser line scan system. Any platform speed/altitude combination that lies under the curve that applies to the water clarity in the operating area can be supported. For example, in 10 meter water (alpha = 0.1/m) the maximum allowable platform speed at an altitude of 70 ft is 1 knot and the maximum speed at 50 ft is 4 knots.

The curves were calculated on the basis of the following assumptions

1-	Image Resolution	=	1024 pixels/line
2-	Field-of-View	=	70 degrees
3-	Laser Output Power	=	200 milliwatts
4-	Target Reflectivity	=	5%

The vertical line on the left side of the envelope defines the minimum operating range of the sensor which is established by the optical design of the receiver. The straight, positively sloped line defines the portion of the envelope that is established by the maximum scan motor speed. The horizontal line at the top is established by the maximum platform speed, assumed to be 6 knots. And curve on the right defines the portion of the operating boundary that is defined by the minimum required optical signal level.

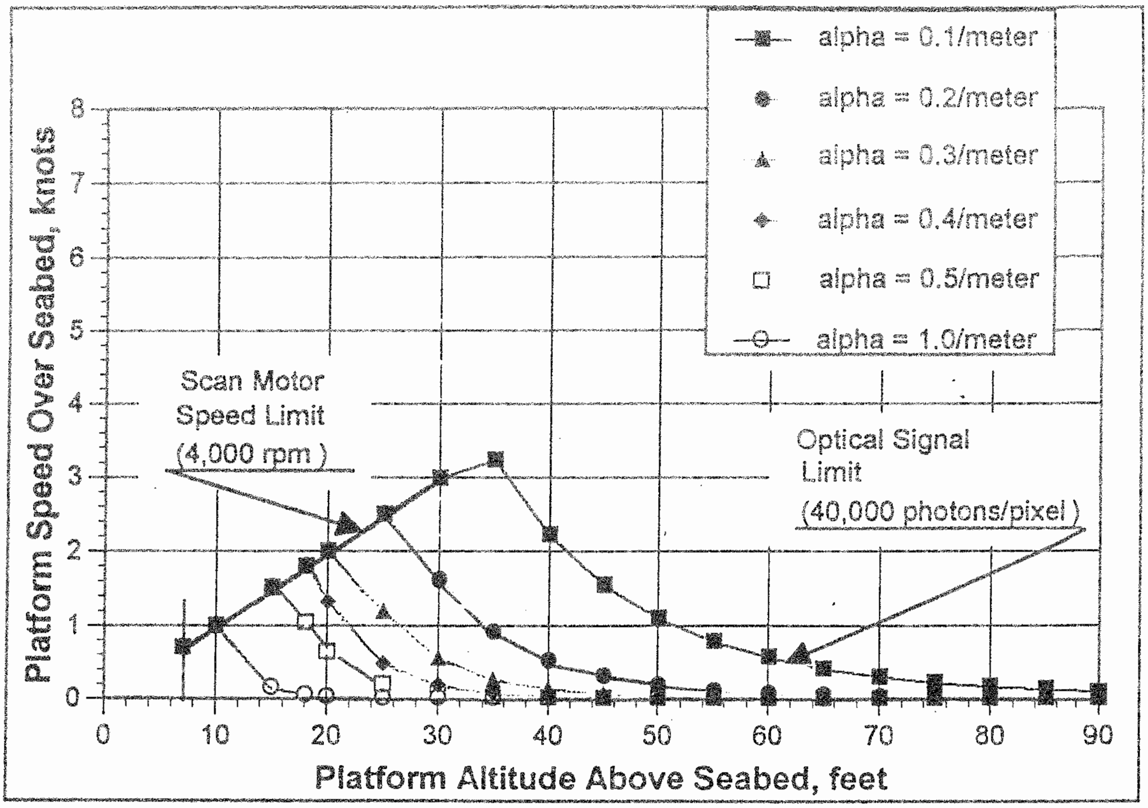


Figure A2

The curves in this figure enclose the operating envelope of the LS-4096 laser line scan system. Any platform speed/altitude combination that lies under the curve that applies to the water clarity in the operating area can be supported. For example, in 10 meter water (alpha = `.1/m) the maximum allowable platform speed at an altitude of 50 ft is 1 knot and the maximum speed at 35 ft is 3 knots.

The curves were calculated on the basis of the following assumptions

1-	Image Resolution	=	2048 pixels/line
2-	Field-of-View	=	70 degrees
3-	Laser Output Power	=	200 milliwatts
4-	Target Reflectivity	=	5%

The vertical line on the left side of the envelope defines the minimum operating range of the sensor which is established by the optical design of the receiver. The straight, positively sloped line defines the portion of the envelope that is established by the maximum scan motor speed. The horizontal line at the top is established by the maximum platform speed, assumed to be 6 knots. And curve on the right defines the portion of the operating boundary that is defined by the minimum required optical signal level.

Appendix B

Summary Specifications

LS-4096 Laser Line Scan System
Adapted for FOCUS 1500

LS-4096 Laser Line Scan Sensor

Physical Dimensions	82.75 in. long x 10.9 in. diam. (See ART Drawing No 140K0081 for details)
Electrical Connectors	See ART Drawing No 140K0081
Weight and Balance	375 pounds in air 170 pounds in sea water (See ART Drawing No 140K0081 for details)
Depth Rating	
Operating	5000 fsw
Crush	6500 fsw
Input Electrical Power	
Peak	
110 VAC 1ϕ	1.5 amps
29 VDC	9.5 amps
Steady State (nominal)	
110 VAC 1ϕ	1.0 amps
29 VDC	4.5 amps
Optical Output Power	200 milliwatts @ 532 nanometers
Operating Envelope (Optical)	See Figure 1 (attached)
Image Resolution, Acquisition (operator selectable)	512 pixels/line 1024 pixels/line 2048 pixels/line 4096 pixels/line
Image Resolution, Display	1024 pixels x 1024 lines
Dynamic Range, Acquisition	84dB (14-bit)
Optical Field-of-View	70° (fixed)

LS-4096 Processor Console

Physical Dimensions	See ART Drawing No 140K1007
Electrical Connectors	See ART Drawing No 140K0064 (sheet 1)
Weight	See ART Drawing No 140K0064 (sheet 1)
Input Electrical Power	
110/220 VAC 1ϕ **47-63 Hertz**	900 watts (maximum)

LS-4096 Display Console

Physical Dimensions	See ART Drawing No 140K0064 (sheet 2,3)
Electrical Connectors	See ART Drawing No 140K0064 (sheet 2,3)
Weight	See ART Drawing No 140K0064 (sheet 2,3)
Input Electrical Power **110/220 VAC 1ϕ** **47-63 Hertz**	400 watts (maximum)
Display Resolution	1024 pixels x 1024 lines
Display Functions (Operator Accessible)	Pan (Horizontal) Scroll (Vertical) Zoom (X1, X2, X4, X8)
Image Recording Formats	Snapshot (digital frame) Video Tape (optional) Continuous Digital (optional)

LS-4096 Communication Link

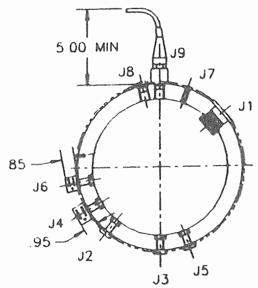
Format	Digital
Bandwidth	40 Mbits/sec to 100 Mbits/sec (application dependent)
Configuration	Optical (standard) Electrical (optional) Full Duplex 19.2kB RS-232C for commands and status High speed digital serial for digitized video signal
Umbilical Cable Requirements	2 multi-mode optical fibers (standard) 1 single-mode optical fiber (optional)

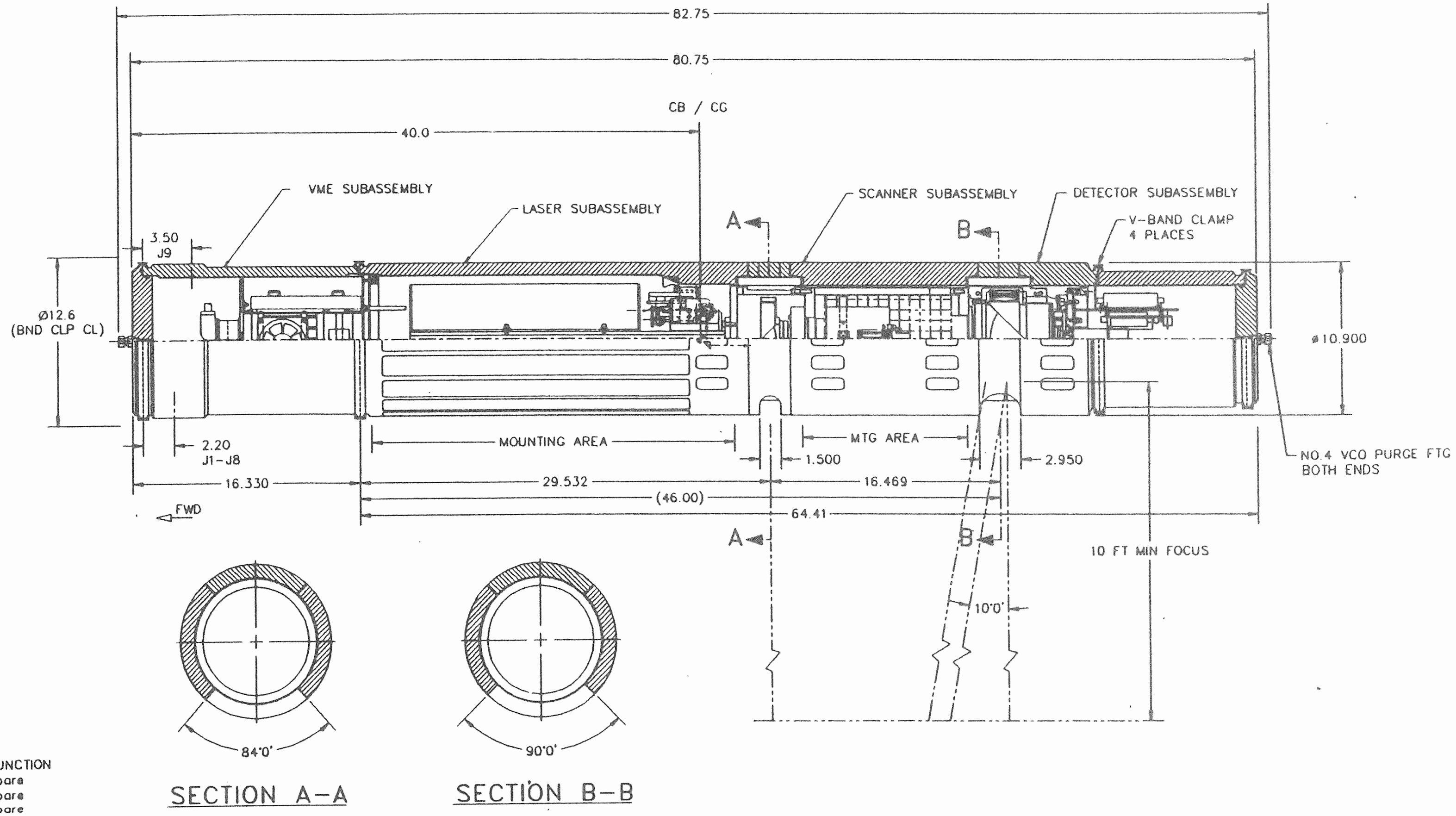
Appendix C

Technical Drawings

LS-4096 Laser Line Scan System

ZONE	REV	DESCRIPTION	DATE	APPROVED
	–	INITIAL RELEASE		
	A	UPDATED	940329	



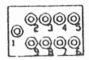


J1 PLUG, 140D0076-1
J2 spare
J3 spare
J4 'IMPULSE' LPBH-9-MP
(MATE: LPIL-9-FS)
J5 spare
J6 'IMPULSE' LPBH-7-FS (DIGN)
(MATE: LPIL-7-MP)
J7 spare
J8 spare
J9 FIBER OPTIC FEEDTHRU

SEE DWG 110D0262-2 FOR
CONN HOLE DETAILS

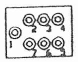
J4

PIN	FUNCTION
1	+29V A
2	RTN A
3	+29V B
4	RTN B
5	115 VAC HI
6	115 VAC LO
7	spare
8	spare
9	CHASSIS



J6

PIN	FUNCTION
1	spare
2	spare
3	spare
4	spare
5	spare
6	spare
7	spare



WEIGHT IN AIR:	375 POUNDS
WEIGHT IN SEA WATER:	170 POUNDS

		\	A	REV STATUS OF SHEETS
4	3	2	1	

QUANTITY PER ASSEMBLY		CAGE CODE	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ZONE	ITEM NO

PARTS LIST

INTERPRET DRAWING IAW DOD-STD-100

NEXT ASSEMBLY	USED ON
–	L

APPLICATION

DO NOT SCALE DRAWING

DRAWN	G.ADAMSON	930238
CHECK	–	–
RESP ENGR	O.KIRSTEN	–
	–	–
	–	–
	–	–
	–	–
	–	–
	–	–

APPLIED REMOTE TECHNOLOGY, INC.

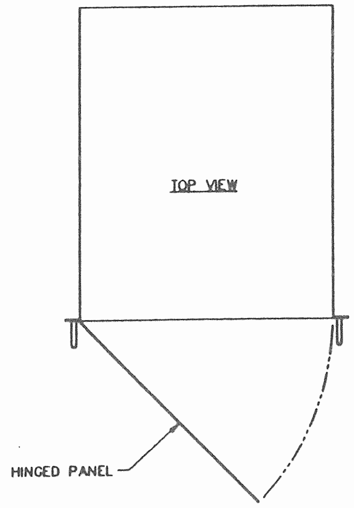
GENERAL ARRANGEMENT
SENSOR – LS-4096

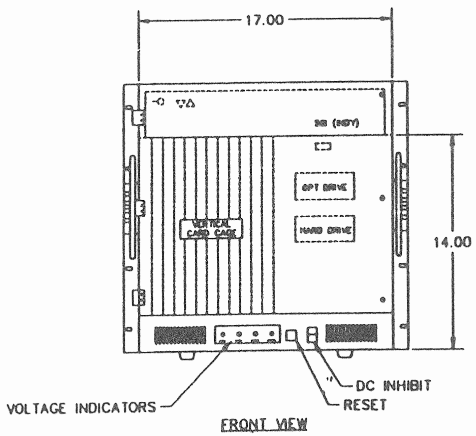
SIZE		DWG NO.	REV
D	8X890	140K0036	A

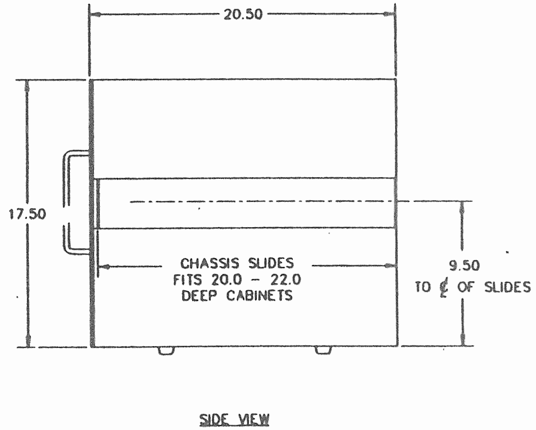
SCALE 1/4 SHEET 1 OF 1

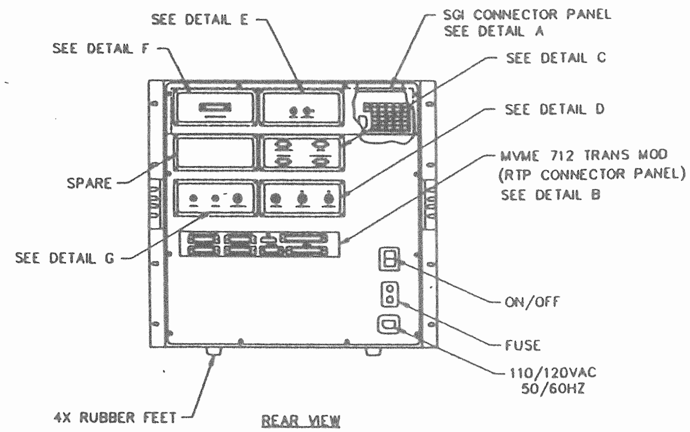
140K0066 A

	REV	DESCRIPTION	DATE	APPROVED
	–	INITIAL RELEASE		
	A	UPDATED FOR WEIGHT INFO; DELETE SH 3	940401	
	B	CHANGE DWG NO FROM 140K0064; DELETE SH 2	940412	
	C	ADD NEW SHEET 2, ADD DETAILS A,B,C,D UPDATE REAR PANEL ADD CONNS TO COVERS	940517	









CONSOLE SPECIFICATIONS:
- FRONT ACCESS CARD CAGE WITH 12 VERTICAL SLOTS
- BACKPLANE: 12 SLOT VME
- 19" RACK MOUNT WITH CHASSIS SLIDES
- LIFT-OFF HINGED FRONT PANEL WITH HINGES ON LEFT
- 3 EA 70cfm COOLING FANS
- INPUT POWER REQUIREMENTS: 500 WATT POWER SUPPLY 110-120VAC, 50-60Hz 4.3 AMPS

SGI (INDY) SPECIFICATIONS:
- INPUT POWER REQUIREMENTS: 540 WATT POWER SUPPLY 120VAC, 60Hz 4.5 AMPS

ESTIMATED WEIGHT: 87 LBS

		\	C	REV STATUS OF SHEETS
4	3	2	1	

QUANTITY FOR ASSEMBLY	CAGE CODE	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ZONE	ITEM NO

PARTS LIST

INTERPRET DRAWING IAW DOD-STD-100

NEXT ASSEMBLY	USED ON
140A1000	LS-4096

APPLICATION

DO NOT SCALE DRAWING

G.ADAMSON 940223
T.WILKINSON

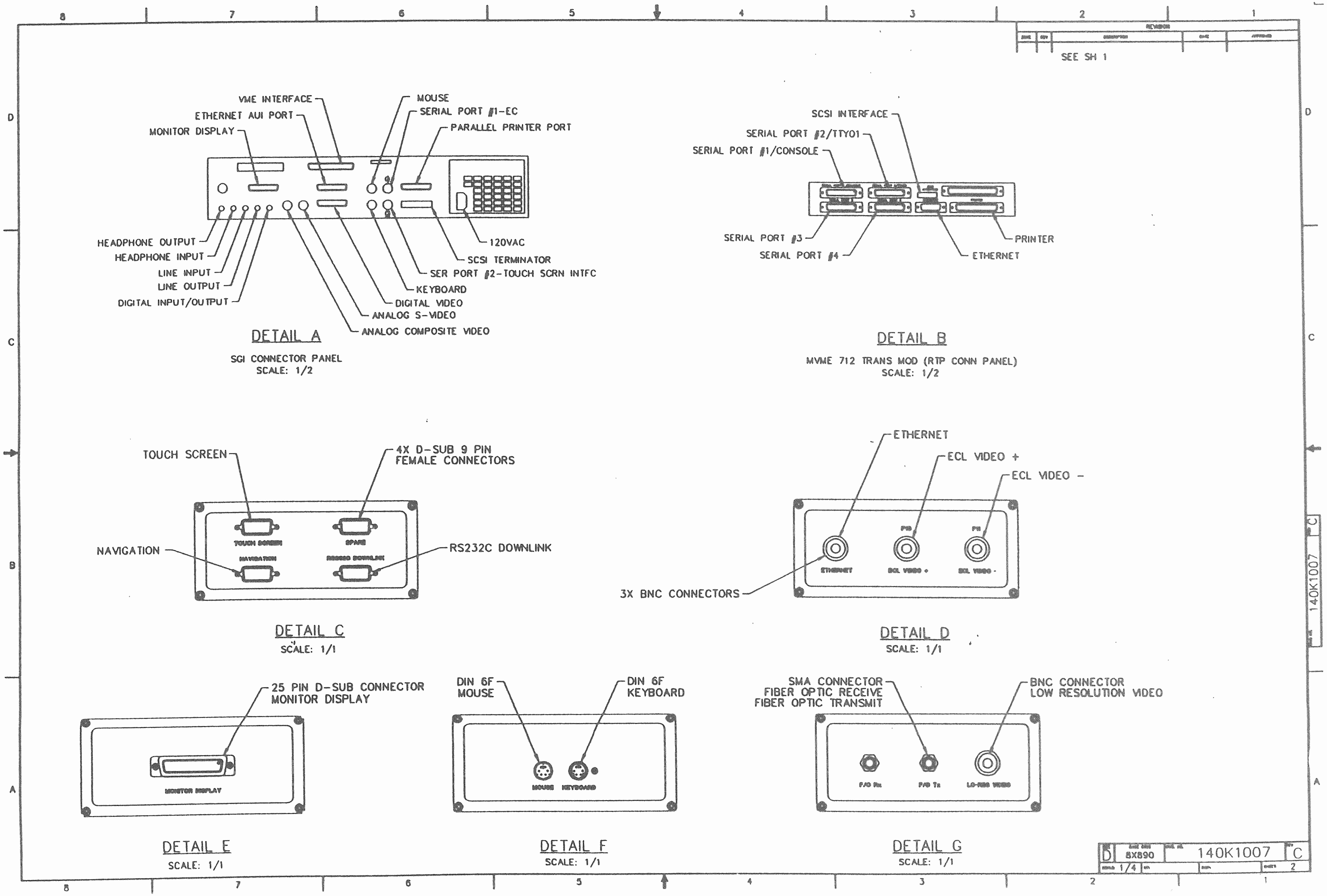
APPLIED REMOTE TECHNOLOGY, INC.

INTFC CONTROL DWG., CONTROL CONSOLE #1 - LS-4096

D 8X890 140K1007 C

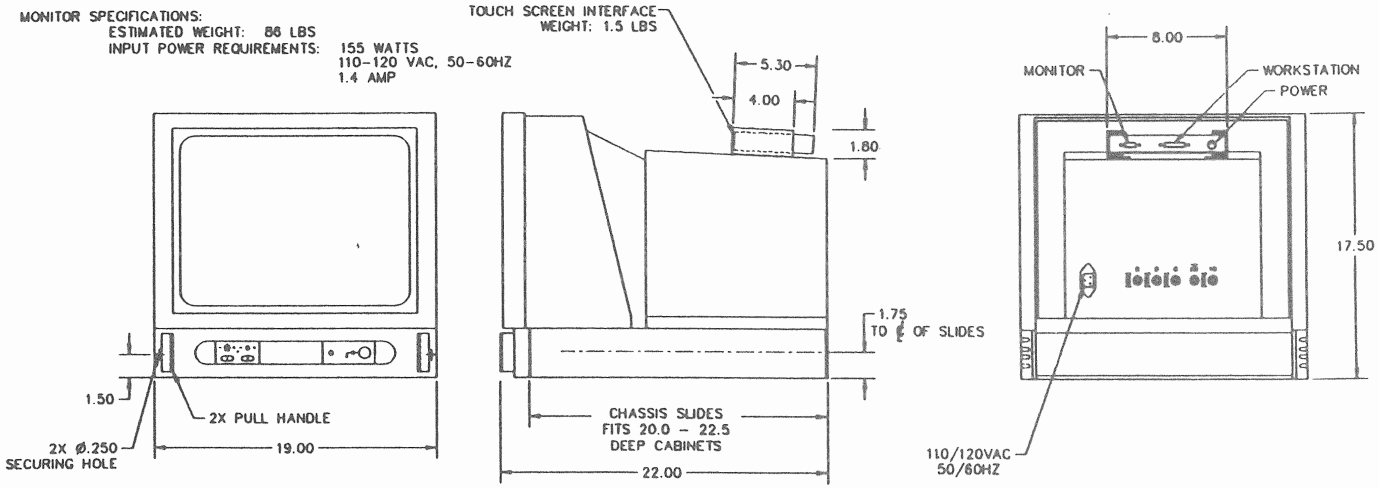
SCALE 1/4 SHEET 1 OF 2

140K1007 C


SEE SH 1
VME INTERFACE
ETHERNET AUI PORT
MONITOR DISPLAY
MOUSE
SERIAL PORT #1-EC
PARALLEL PRINTER PORT
HEADPHONE OUTPUT
HEADPHONE INPUT
LINE INPUT
LINE OUTPUT
DIGITAL INPUT/OUTPUT
120VAC
SCSI TERMINATOR
SER PORT #2-TOUCH SCRN INTFC
KEYBOARD
DIGITAL VIDEO
ANALOG S-VIDEO
ANALOG COMPOSITE VIDEO
DETAIL A
SGI CONNECTOR PANEL
SCALE: 1/2
SCSI INTERFACE
SERIAL PORT #2/TTY01
SERIAL PORT #1/CONSOLE
SERIAL PORT #3
SERIAL PORT #4
PRINTER
ETHERNET
DETAIL B
MVME 712 TRANS MOD (RTP CONN PANEL)
SCALE: 1/2
TOUCH SCREEN
4X D-SUB 9 PIN
FEMALE CONNECTORS
NAVIGATION
RS232C DOWNLINK
DETAIL C
SCALE: 1/1
ETHERNET
ECL VIDEO +
ECL VIDEO –
3X BNC CONNECTORS
DETAIL D
SCALE: 1/1
25 PIN D-SUB CONNECTOR
MONITOR DISPLAY
DETAIL E
SCALE: 1/1
DIN 6F
MOUSE
DIN 6F
KEYBOARD
MOUSE
KEYBOARD
DETAIL F
SCALE: 1/1
SMA CONNECTOR
FIBER OPTIC RECEIVE
FIBER OPTIC TRANSMIT
BNC CONNECTOR
LOW RESOLUTION VIDEO
DETAIL G
SCALE: 1/1
D
8X890
140K1007
C
1/4
2

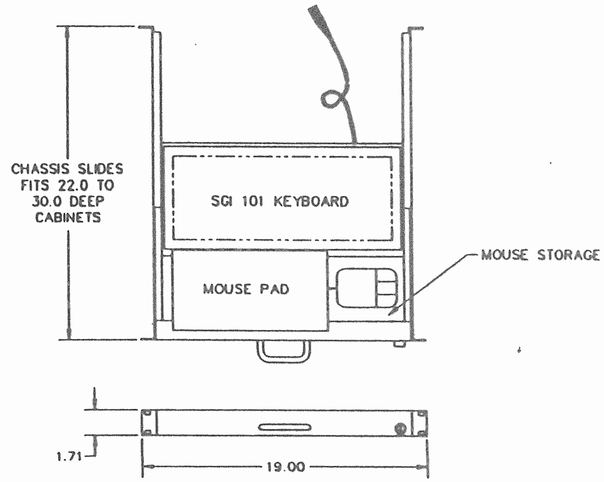
REVISION				
ZONE	REV	DESCRIPTION	DATE	APPROVED
	–	INITIAL RELEASE		

MONITOR SPECIFICATIONS:
ESTIMATED WEIGHT: 86 LBS
INPUT POWER REQUIREMENTS: 155 WATTS
110–120 VAC, 50–60HZ
1.4 AMP



ASSEMBLY WEIGHT (IN LBS)

HARDIGG SHIPPING CASE/RACK (NOT SHOWN):	73
MONITOR:	86
KEYBOARD/MOUSE DRAWER:	18
MISC (POWER STRIP, PANELS, ETC.):	10
TOTAL ESTIMATED WEIGHT:	187 LBS



KEYBOARD/MOUSE DRAWER SPECIFICATIONS:
RACK MOUNTED 101-KEY AT KEYBOARD
3 BUTTON SGI MOUSE
DRAWER WITH CHASSIS SLIDES AND LOCK
ESTIMATED WEIGHT: 18 LBS

QUANTITY PER ASSEMBLY		CAGE CODE	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ZONE	ITEM NO
				PARTS LIST			

INTERPRET DRAWING IAW DOD-STD-100

NEXT ASSEMBLY	USED ON
140A1006	LS-4096

APPLICATION

DO NOT SCALE DRAWING

G.ADAMSON 940223
T.WILKINSON

REV STATUS OF SHEETS				
			\	–
	4	3	2	1

APPLIED REMOTE TECHNOLOGY, INC.

INTFC CONTROL DWG., CONTROL CONSOLE #2 – LS-4096

SIZE D | 8X890 | 140K1008 | REV –

SCALE 1/4 | SHEET 1 OF 1

Appendix D

Side Looking Geometry

LS-4096 Laser Line Scan System Installed in SubSea FOCUS

Figure D-1 and Figure D-2 describe the geometry associated with two installations of the LS-4096 in the SubSea FOCUS. These sketches have been specifically developed to evaluate geometries that are possibly appropriate for pipeline inspection and span detection. Figure D-1 shows the geometry of the current installation with the lower edge of the LS-4096 pressure vessel 200 mm above the lower surface of the FOCUS's lower tubes. This is the standard installation geometry which was chosen to provide a high degree of protection for the LS-4096.

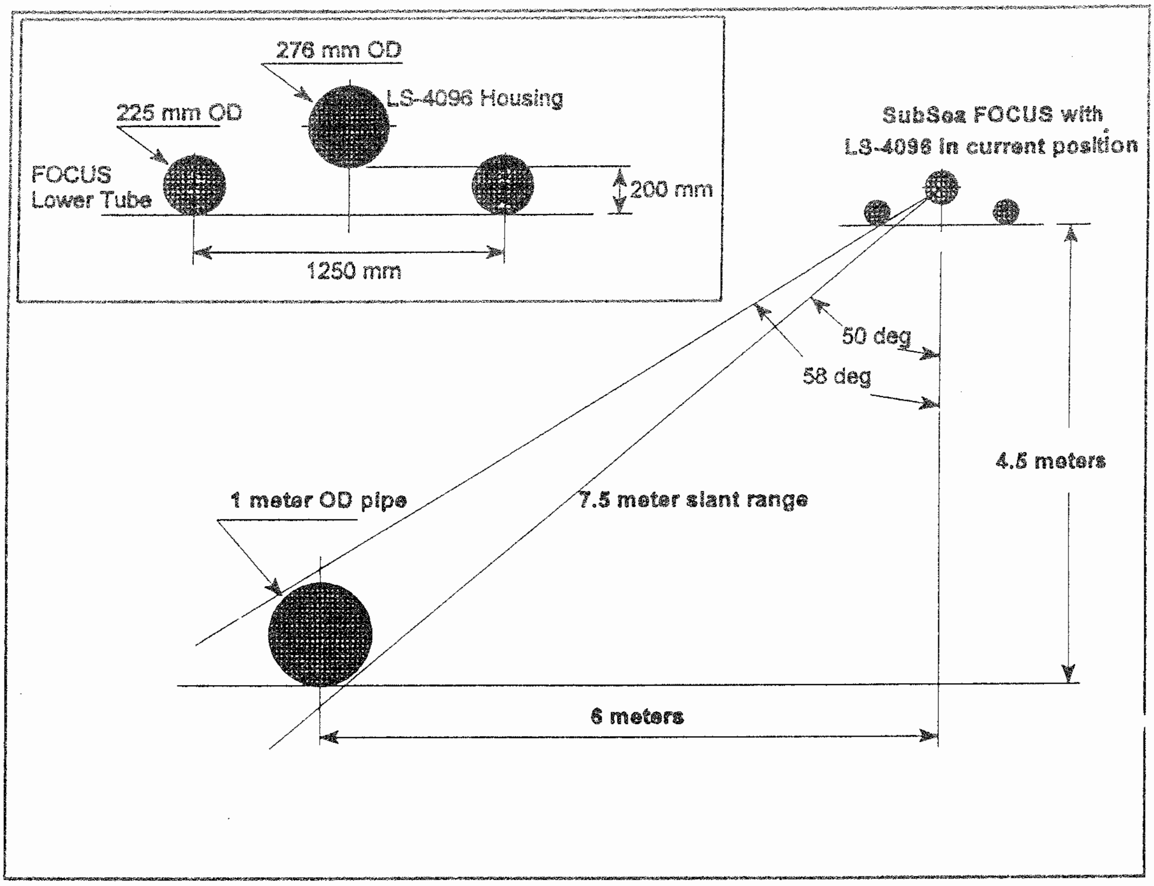


Figure D-1

This figure shows the inspection geometry for the LS-4096 mounted in the SubSea FOCUS at the existing location. The lower edge of the LS-4096 pressure vessel is 200mm above the lower edge of the FOCUS's lower tube.

Figure D-2 shows the improved inspection geometry that can be achieved by dropping the position of the LS-4096 100 mm. Positioning the sensor lower in the vehicle allows it to be rotated through a larger angle and increases the marginal viewing angle by approximately 10°. This improved viewing angle provides a broader view of the side of the pipe, a better view of the point at which the pipe contacts the bottom, and a higher probability of detecting locations where the pipe is inadequately supported.

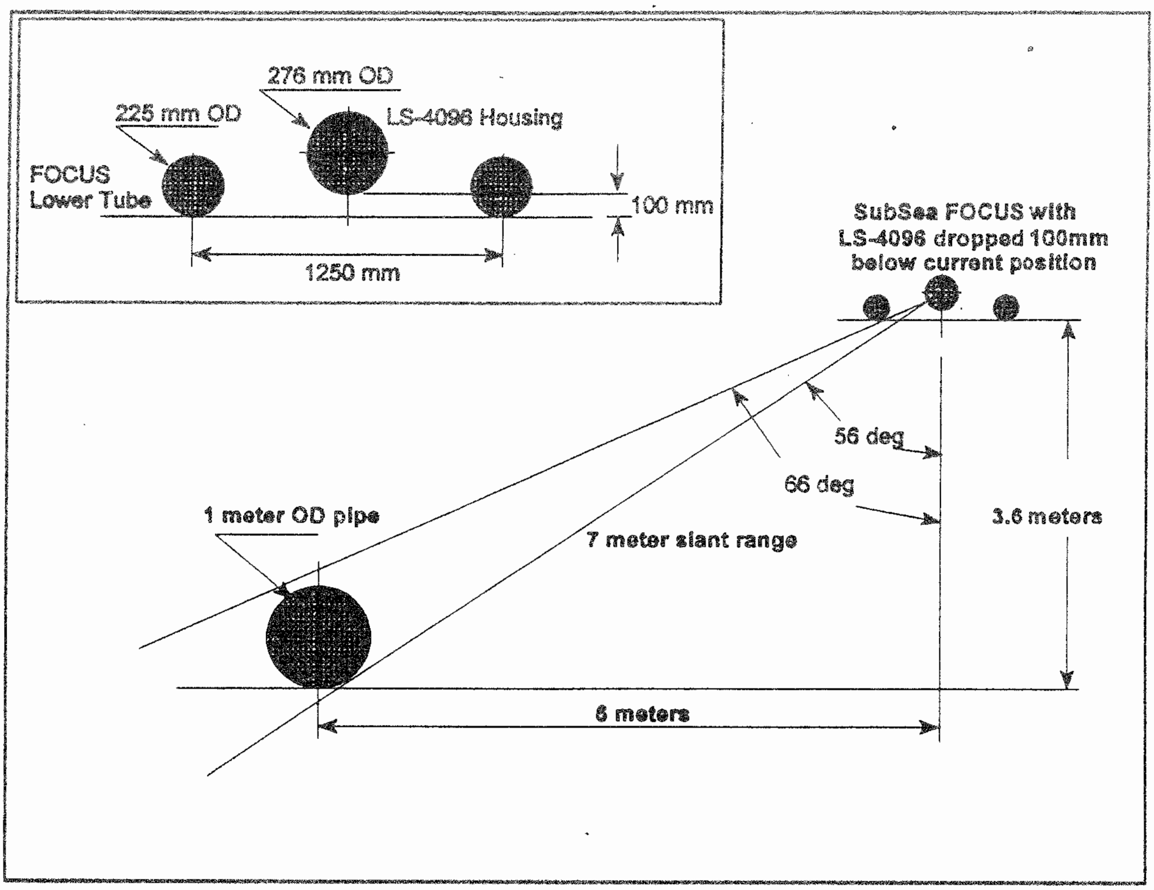


Figure D-2

This figure shows the inspection geometry for the LS-4096 mounted in the SubSea FOCUS at a location that is 100mm lower than its initial position

APPENDIX 5

SYSTEM MANUAL

SCIENCE APPLICATIONS INTERNATIONAL COORPORATION

UNDERWATER OPTICAL SEARCH AND SURVEY TECHNOLOGY LASER LINE SCAN SYSTEM

DEEPSEA DEVELOPMENT SERVICES
a Division of

For More Information Contact:

Mr. Ed Saade
DEEPSEA Development Services
a Division of
SAIC
3330 Industrial Court
San Diego, CA 92121-1003
(619) 792-2159 Telephone
(619) 792-2116 Facsimile

DEEPSEA DEVELOPMENT SERVICES

A Division of SAIC

UNDERWATER OPTICAL SEARCH AND SURVEY TECHNOLOGY

LASER LINE SCAN SYSTEM

APRIL 1995

DEEPSEA DEVELOPMENT SERVICES
A Division of
SAIC.

SCIENCE APPLICATION INTERNATIONAL CORPORATION

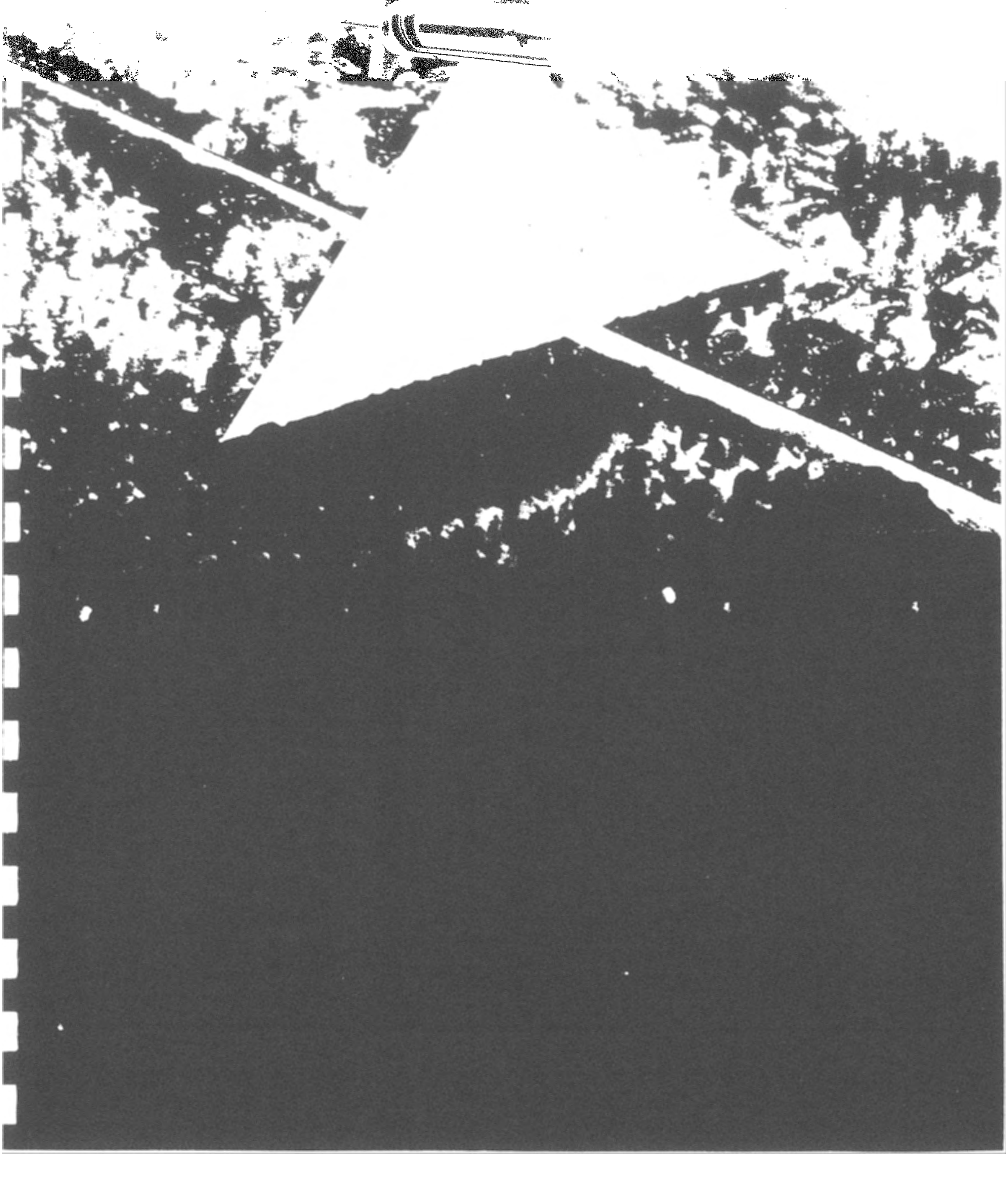
- Founded in 1969
- 1994 Revenues of 1.7 Billion
- 17,000 Employees
- 300 Locations Worldwide
- Science & Technology Orientated Company
- 90% Business from Services

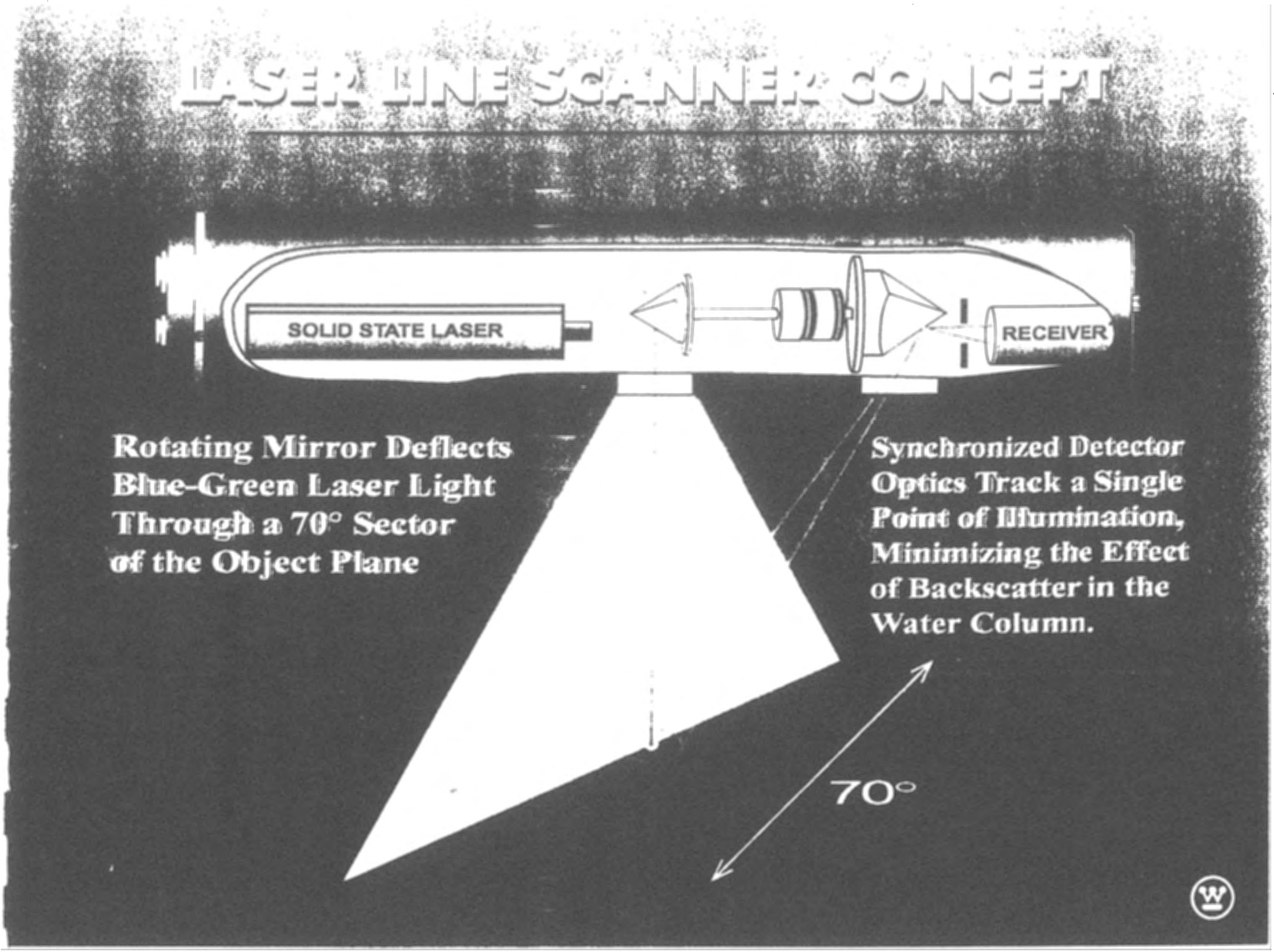
SAIC LASER LINE SCAN SYSTEM DESCRIPTION

- Towed, High Resolution Panoramic Underwater Optical Imaging System
- A Synchronous Scanning Laser
- Effective Viewing Ranges of Roughly 5 Attenuation Lengths or 2-4 Times that of Conventional Video Systems
- High Area Coverage Rates are Accomplished with Millimeter to Centimeter Resolution
- Survey Depth of 3.0m - 800m at Speeds of 1-6 Knots

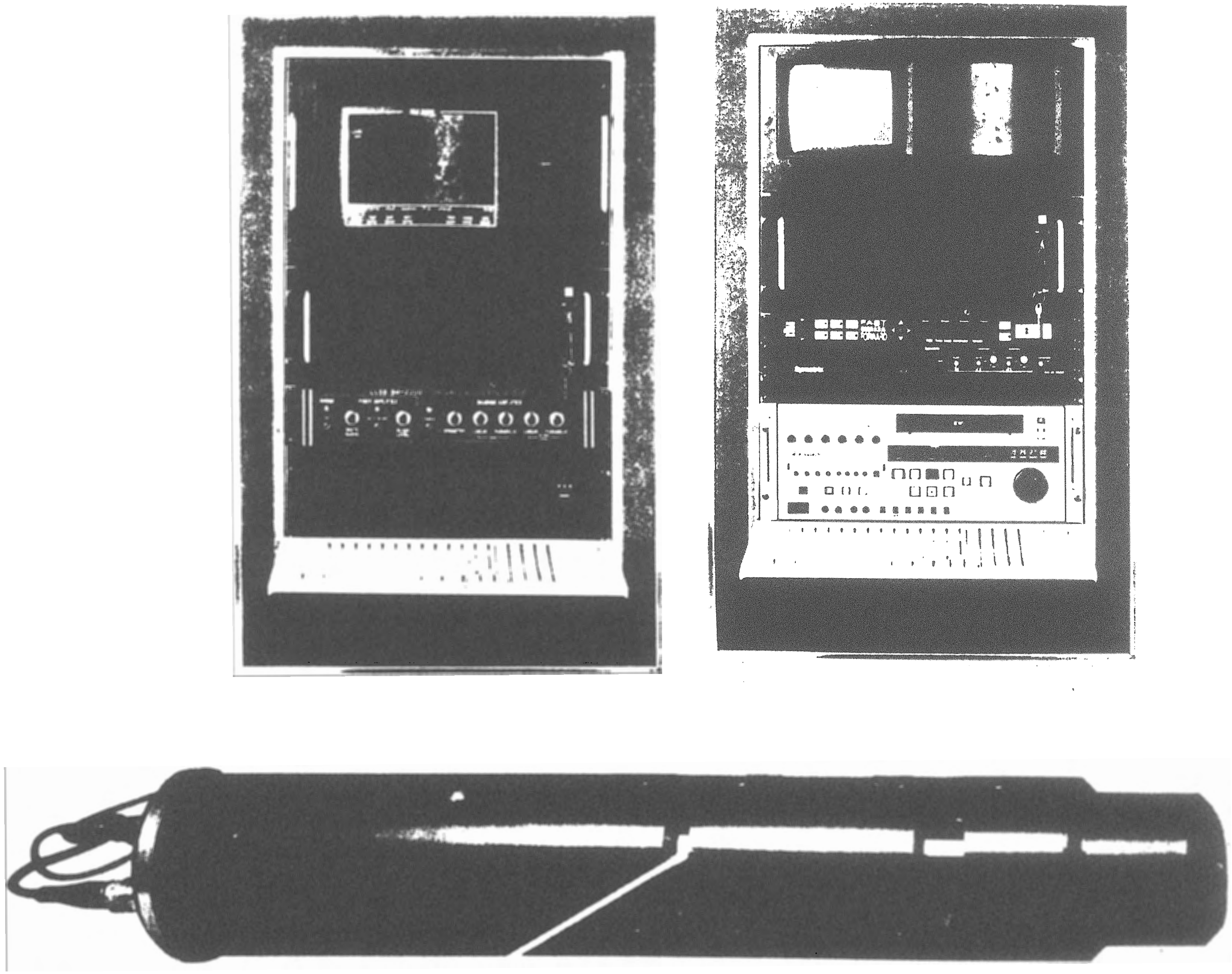
The Systems are available for Field Operations
Around the World through DEEPSEA Development Services

DEEPSEA DEVELOPMENT SERVICES
A Division of



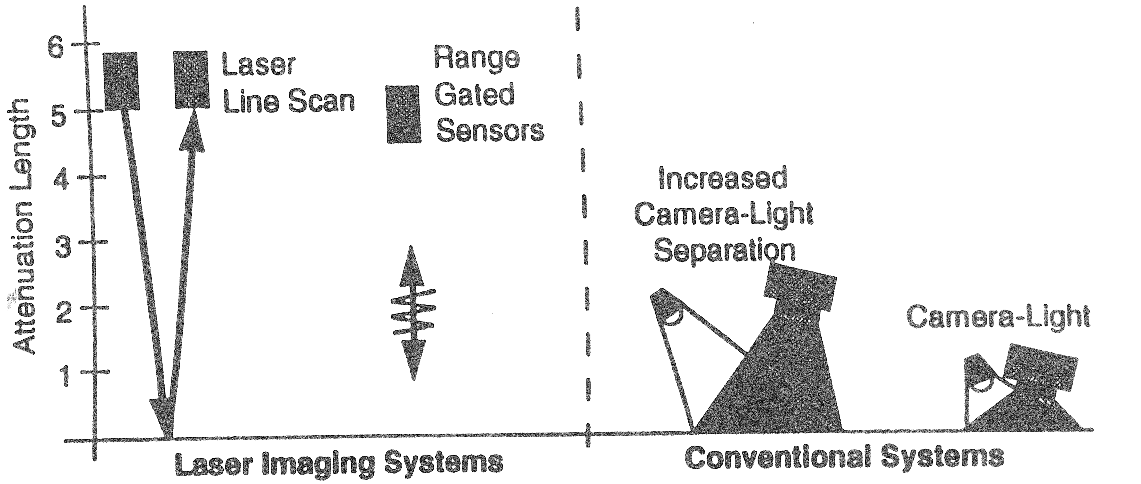


The SM2000 is a synchronous scanning system. A solid state blue-green laser continuously scans a narrow beam across a selected area with a 70° field of view, illuminating only a small spot at a time. A highly sensitive receiver tracks the beam with a narrow view angle, counteracting the effect of backscatter in the water column. The receiver's output is digitized in real-time and stored in a digital image buffer. As the sensor moves forward, new lines of data are stored and the resulting imagery is displayed and recorded as conventional RS-170 video. Digital data is stored as digital still images.



The SM2000 underwater sensor shown with the surface control unit and digital data recording system.

UNDERWATER IMAGING APPROACH



	LLS	RGI	Increased Separation Conventional Imaging	Conventional Imaging
Range	~5R	4-5R	2R	R
Resolution	G	G	E	E
Search Rate	E	M	P	P

E: Excellent
G: Good
M: Moderate
P: Poor

SAIC

DEEPSEA DEVELOPMENT SERVICES
A Division of

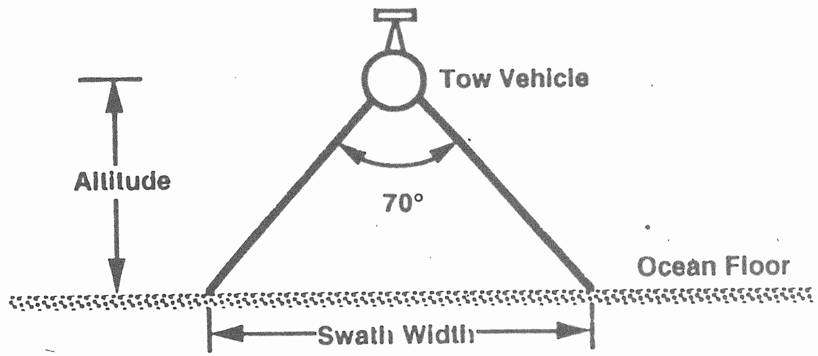
UNDERWATER IMAGING TECHNIQUE COMPARISON

	Laser Line Scan	Side Scan	ROV
RESOLUTION	High	Very Low	High
GEOGRAPHIC ACCURACY	<5m	<5m	<5m
RATE OF COVERAGE	High	Very High	Low
SEA BOTTOM IMPACT	None	None	Medium

DEEPSEA DEVELOPMENT SERVICES
A Division of SAIC.

REPRESENTATIVE LASER LINE SCAN SYSTEM PERFORMANCE

Water Clarity	Typical Imaging Range	Swath Width	Area Coverage Rate (3 Knots)	Sampling Resolution (At 2048 Samples)
Very Clear (Hawaii, GOM - Deepwater)	45m	65m	346,000 m2/hr	3 CM
Clear (San Diego, Eolian Islands)	22m	30m	161,000 m2/hr	1.5 CM
Moderate (Washington State, Massachusetts Bay, GOM)	9m	13m	69,000 m2/hr	0.6 CM
Poor Boston Harbor, Baia, Western GOM)	3m	4m	23,000 m2/hr	0.2 CM



DEEPSEA DEVELOPMENT SERVICES
A Division of

SAIC.

UNDERWATER IMAGING APPLICATIONS

ENVIRONMENTAL SURVEYS

Hazardous Waste Container Surveys
Dredge Material Monitoring
Habitat Assessment
Geologic Mapping
Fish Stock Assessment
Benthic Resource Assessment

ENGINEERING APPLICATIONS

Cable/Pipeline Route Surveys
Cable/Pipeline Inspections
Structure Inspections
Oil & Gas Exploration
Template/Site Assessment

UNDERWATER SEARCH OPERATIONS

Accident Investigations
Archaeological Surveys
Intelligence Gathering
Underwater Weapon Location

LASER LINE SCAN SYSTEM ELEMENTS

- **Ship of Opportunity**
- **Tow Body**
  - Laser Line Scan Images
  - Altitude Sensor
  - Acoustic Transponder
- **Winch**
- **Tow Cable (up to 1500m)**
- **Deck Cables**
- **Processing, Display and Recording Equipment**
- **Flexibility in Topside Console Design allows for Numerous Laser Line Scan Video Data Recording**
- **Options Including:**
  - VHS and SVHS Tape of RS170 Video
  - 12-bit Digital "Snapshot" High Resolution Image Captured on Hard Disk
  - Digital Recording of 8-bit Processed Image Data

ADDITIONAL SURVEY SYSTEM CAPABILITIES

▸Survey System Capable of Accommodating Additional Sensors such as:

Dual Frequency Side Scan Sonar
Sub-bottom Profiler
CTD Instrumentation
Optical Beam Attenuation Meter (Transmissometer)
Motion Sensors
Heading Sensors
Magnetometer

▸Integrated Navigation System

Geodetic Location
Differential GPS
Acoustic Positioning of the Towfish

▸Vessel Control

Survey Setup
Video Display
Autopilot Interface

▸Track Reconstruction

Navigation Data Archive
Towfish Track Plot
Target Plot

LASER SURVEY

- Rapid, High-Resolution Panoramic Survey
- Real-Time Monitoring & Data Recording
- Accurate Survey Area Reconstruction

**COST EFFECTIVE SOLUTION
OF
WIDE AREA UNDERWATER SURVEY JOBS**

DEEPSEA DEVELOPMENT SERVICES
A Division of

SAIC.

HIGH RESOLUTION, HIGH SEARCH-RATE UNDERWATER IMAGING USING LASER LINE SCANNING

NOVEMBER 2, 1993

GREG MOORADIAN, JAY EGGERT, ED SAADE, DREW CAREY
Science Applications International Corporation
11803 Sorrento Valley Road
San Diego, California 92121-1006

ABSTRACT

SAIC has recently completed a series of experimental tests and shipboard operational deployments of a new sensor system for underwater optical imaging. The Laser Line Scan (LLS) system produces high resolution, "high quality" panoramic surveys at rapid area coverage rates, real time data monitoring and storage of digital images for post processing, analysis, and accurate survey area reconstruction. The system has produced high resolution images with 70° swath widths at altitudes from 8 ft. to 130 ft. above the seafloor at speeds up to 6 kts. in water depths up to 2300 ft. Applications to mine detection and special purpose surveillance is possible in both towed systems as well as UUV's.

1.0 INTRODUCTION

The requirement to project power in the near land/over land environment places surface ships at risk from a wide variety of submerged sea mines. Damage to US surface forces in Desert Storm were largely due to unsophisticated sea mines. The traditional approach to this problem has been to employ acoustic and magnetic sensor technology. In addition to mine countermeasure (MCM) applications, high resolution underwater visual surveillance will continue to be of critical importance to the military as well as in the environmental characterization field. Science Applications International Corporation (SAIC) has recently completed a series of experimental tests and shipborne operational deployments of a new sensor system for underwater optical imaging. The Laser Line Scan (LLS) system produces high resolution, "picture quality" panoramic surveys at rapid area coverage rates, real time data monitoring and storage of digital images for post processing, analysis, and accurate survey area reconstruction. Applications to mine detection and special purpose surveillance is possible in both towed systems as well as UUV's.

The system has produced high resolution images with 70° swath widths at altitudes from 8 ft. to 130 ft. above the sea floor at speeds up to 6 kts. in water depths up to 2300 ft. To date, operations have taken place over a wide range of coastal and open ocean environments from the Pacific Northwest to Southern California, and from New England to the Gulf of Mexico. This paper consists of a brief LLS system description and provides selected images acquired by the LLS system. This imagery demonstrates the value of this system for search and locate operations, in-situ monitoring of subsurface structures and analysis of environmental parameters.

The LLS imaging sensor is installed in a hydrodynamic tow body which is connected to the tow vehicle with 3,000 ft. of electro-optic cable. The sensor system is based on a synchronously scanned blue/green transmitter and photomultiplier tube (PMT) receiver which laterally scans as the tow body moves above the bottom. The image is formed by assembling successive laser line scans into a two-dimensional pushbroom "image". This system utilizes state-of-the-art technology to provide a user-friendly operator interface, user selectable resolution of up to 2048 pixels across a fixed 70° field-of-view, fiber optic data and telemetry, and 12-bit digital video signal dynamic range.

The LLS system has demonstrated useful operating platform altitude of up to 5 optical attenuation lengths. For example, in typical Southern California water clarity, tow body altitudes of 40 ft. with image swathes 56 ft. wide are consistently recorded at high resolution of "a few mm" scale. In very clear water, SAIC models predict sharp imaging of a few cm resolution at ranges in excess of 150 ft. and 210 ft. swathes with survey rates of 346,000 m^2/hr. This system provides a unique capability since it exceeds side scan sonar resolution by over an order of magnitude while providing search rates several orders of magnitude larger than conventional imaging systems deployed on ROV's.

2.0 LASER LINE SCAN SYSTEM, GENERAL DESCRIPTION

The towed laser line scan system is a laser illuminated optical device designed for acquiring high resolution, large area surveys of the seal floor. The LLS system is capable of detecting millimeter to centimeter size objects at ranges two to four times the range of conventional underwater camera and light systems.

Operation of the LLS system is based on the latest advances in laser scanning technology. Laser scanning, in essence, can be described as the building up of an image from a rapidly acquired series of spots on the seafloor, each sequentially illuminated by a pencil sixed diameter laser beam. This technique of underwater imaging minimizes the effects of back scattered and forward scattered light, permitting increased range and high resolution data collection.

The LLS system is compactly packaged in a rugged pressure housing integral to the towed vehicle. Data is transmitted via fiber optic cable to the monitoring and recording station on the survey vessel. From the operator station on the vessel, a single operator can adjust the parameters of the LLS system, monitor the output in real time and control the recording of the data in video or digital format on tape. Survey operations are conducted in a manner similar to side scan sonar systems.

The tow vehicle is configured to operate as a "heavy fish" to depths in excess of 2000 feet. At this point in the system development cable length limits depth, the LLS itself is designed for depths to 6000 ft. Vehicle heights above the bottom is displayed and recorded at all times with an altimeter system. The information acquired from the system permits post analysis of the survey area in a convenient SVHS video format as well as 8 bit continuous and 12 bit "snapshot" digital data. In addition, bottom features mosaics, and post plots can be generated for display and presentation purposes.

3.0 LASER LINE SCAN SYSTEMS, TECHNICAL DISCUSSION

The concept of using of laser illuminated sensors in the underwater environment has been discussed as possibility for almost 30 years. The most developed current approaches are Range Gated Imaging and Laser Line Scanning. Because of the straightforward application to search and survey operations, the Laser Line Scan approach was selected for development on IR&D. In January of 1993 SAIC began operating a complete towed Laser Line Scan System which was the product of a cooperative research and development program undertaken with Applied Remote Technology (ART) of San Diego. This system utilizes state-of-the-art technology to provide a very user-friendly operator interface, user-selectable resolution of 512, 1024, 2048 pixels across a fixed 70° field-of-view, a video signal dynamic range of 72dB (12-bit), and a demonstrated useful operating range of up to six attenuation lengths (equivalent to a maximum operating platform altitude of 5 attenuation lengths).

LLS System Description

In its most basic form, the LLS "System" consists of the underwater optical sensor, the topside control console, a hydrodynamic tow body, and a shipboard handling system with an umbilical cable and power supply.

Optical Sensor

The underwater optical sensor consists of the imbedded sensor control electronics subassembly, the laser subassembly, the scanner subassembly, and the detector subassembly. These four subassemblies are integrated into a single physical assembly and installed inside a watertight cylindrical pressure vessel. A conceptual sketch of the optical sensor is presented in Figure 1.

The scanner subassembly is composed of two rotating, four faceted mirrors which are rigidly attached to a common rotating shaft. The illumination laser is oriented such that its output beam is incident on one of the four facet mirrors. The laser beam is reflected toward (and illuminates) the target. The receiver views the larger of the four faceted mirrors and synchronously scans (i.e., views) the laser spot on the target. As the laser beam travels toward the target, it is scattered and absorbed by the intervening sea water path. Absorption and scattering not only reduce the signal available for detection but the scattering introduces noise in the image and reduces contrast. These processes have historically made it very difficult to generate high quality images of submerged objects at acceptable operating ranges.

The unscattered, unabsorbed laser light that manages to reach the target illuminates a small, localized area that is called the primary scan spot. This is the area of greatest interest because it is from this area that the optical return signal is generated. As the mirrors rotate, the scan spot traces a continuous line across the target instantaneously illuminating a very small localized area of the target. When there is relative motion between the scanner and the target perpendicular to the scan direction then sequential scan lines will be displaced slightly and the target will be effectively scanned in two dimensions. By synchronizing the scan rate with the relative velocity between the sensor and the target, it is possible to control the spacing between sequential scan lines and thereby ensure that the desire rectangular sample pattern is maintained and true image aspect ration is preserved.

The target reflects a portion of the incident energy back toward the sensor. If the scan spot is incident on a bright portion of the target then a relatively large fraction of the incident energy is reflected and conversely, if the scan spot is incident on a dark potion of the target then a small fraction of the incident energy is reflected. The reflected energy is scattered and absorbed as it travels back toward the sensor and a small amount of the remaining energy will enter the sensor's receiver aperture through the cylindrical input window. If the power in the laser beam is held constant and if certain geometric factors are ignored, then it can be assumed that the amount of energy reflected by the target, and therefore the amount of energy received by the sensor, is proportional to the "local reflectance" of the target. In this case, local reflectance represents the reflectance of the target averaged over the area illuminated by the scan spot.

By sampling the output of the photo-multiplier tube (PMT) at times that are synchronized with the mirror rotation, it is possible to build up a 2-dimensional reflectance map of the target. This is accomplished by digitizing the sampled PMT signal and storing the resulting digital data in video random access memory (VRAM) module. This stored data can then be read and displayed by a CRT controller. If the whole process of data sampling, storage, and display is properly integrated and synchronized then there will be a direct relationship between each physical location on the screen of the CRT and a specific location on the target. As the sensor passes over a stationary target the display can be controlled in such a way that the data from each new scan line is always displayed at the top of the screen. This requires that all previous lines are sequentially moved down the screen to make room for the new line and results in a "waterfall" display that gives the operator a very realistic view of the passing seafloor and target.

Communications Link

The communication interface that has been developed for use with the SAIC LLS system transmits video data and status from the optical sensor to the Control Console and transmits command data from the Control Console to the optical sensor. All data are transmitted in digital form over fiber-optic cables. The digital transmission format was selected to provide the 72dB dynamic range required to support full fidelity of the video signal. The fibre-optic transmission medium was selected to provide the 20 mega-bit/sec bandwidth that is required to support full video dynamic range and resolution at high search rates. The status and command data are transmitted using the standard RS-232 format operating at 19.2 kilo Baud.

Control Console

The control console provides the operator with control over all system functions including electrical power control, data management, data display, data recording, scan rate, sample rate, adjustable aperture positions, beam former position, PMT gain, laser output power, AGC mode, sensor altitude and speed inputs, channel equalization, and shading correction (required because the signal return form the target areas at the edge of the scan have larger attenuation and path loss). Most of these functions are normally controlled automatically but the operator is given the ability to override these automatic features and control any desired function manually. The Control Console also provides the operator with displays of sensor status data and video data. Status data is displayed on the Virtual Control Panel (VCP) and the video data is displayed on a separate high resolution video monitor. The operator can record individual images in digital form on the Console Computer's hard disk, or record live video in analog form on a standard video cassette recorder using the NTSC RS-170 video output.

4.0 LASER LINE SCAN SYSTEM PERFORMANCE.

The operating envelope for the LLS system is obviously a function of the specific system parameters. The following assumptions represent either the actual system parameters or the parameters used in modeling the results:

- A multi-mode argon ion laser is used as the light source. The beam is reduced in divergence using a x2 beam expander. This laser is capable of producing a usable output of slightly more than 2 watts which results in up to 1.75 watts of optical energy entering the water. Nominal operation in the field is approximately 1 watt.

- The scanner design uses a four-faceted mirror and the receiver optics have a 2 inch clear circular aperture operating a f/2 with a field of view that is several times the laser divergence (to collect a portion of the multiple scattered signal reflected from the target).

- The maximum allowable scan motor speed is 4,000 rpm and the maximum possible platform speed is 6 knots.

- The target is modeled with a mean reflectance of 5% that behaves like a Lambertian reflector.

- The receiver sensitivity threshold is modeled at 40,000 photons/pixel, or approximately 6,000 photoelectrons/pixel.

Operation of the system may be limited by the scan motor speed (which cannot exceed 4,000 rpm), the platform speed (which cannot exceed 6 knots), or the received signal level (which must exceed the established minimum required number of photoelectrons per pixel to achieve sufficient signal-to-noise). Specific portions of the LLS operating envelope are established by each of these limits above. In addition, LLS "system" level constraints can also define portions of the operating envelope; e.g., because of tow fish hydrodynamics, a minimum allowable platform speed exists for a stable tow; speed constraints of the support ship characteristics; tow cable speed/depth limitations.

Figure 2 represents the performance envelope for three classes of water clarity, three platform speeds, and two sampling resolutions (2048 and 1024). The imaging range performance for "dirty water" (0.5 m^{-1}) is indicated below. This water clarity (i.e., "2 meter" water) is certainly not as turbid as coastal ocean water can get, but is indicative of stressing conditions. For example, as can be seen from the table, range performance at 1.5 kts. is between 25 and 32 ft. (depending upon sampling rate) with sampling resolution of 0.21 to 0.52 in. For turbid water, the relaxation of resolution by a factor of two only has a small improvement range. Note: The system does not satisfy operation criterion in this dirty water condition with 2048 samples at 3 kts. because the motor speed is limited to 4,000 RPM. At the reduced range and platform speed, the LLS cannot maintain a contiguous scan.

For very clear water (attenuation coefficient = 0.05 m^{-1}, or "20 m water"), the range performance at 1.5 kts. increases to 123-169 ft., depending on sampling rate, with sampling resolution between 1.1 and 2.8 inches. As can be seen from the table, range is a strong function of water clarity but does not scale directly with attenuation coefficient (if speed and sampling rate is held constant). This is because the range performance is not only dependent upon the exponential attenuation of the water but also the R^2 spreading losses of the signal reflected from the target.

The value for sampling resolution is approximately the swath width (for 70° this amounts to 1.4 times the altitude off the bottom) divided by the number of samples. this results in samples of approximately 0.6 mrad/pixel (the geometric projection will make the pixels at the end of the scan somewhat larger, however). The range performance for the 1024 pixel resolution is larger than the 2048 because the LLS system operating at the lower sampling rate collects twice as many photons/pixel as the 2048 and therefore has longer range performance. This is, however, at the expense of spatial resolution. It may not be obvious, but range performance is also tow speed dependent as this is one of the factors which determines the amount of signal received (i.e., receiver integration time).

5.0 LASER LINE SCAN IMAGERY

The imagery obtained by the SAIC LLS system in real-world conditions permits the best assessment of performance. What is shown in the following figures is a series of imagery over a wide range of coastal and open ocean environments from the Pacific Northwest to Southern California, and form New England to the Gulf of Mexico. The precise quantification of the subsurface environment is generally very difficult to obtain, especially in turbid coastal areas.

Figure 3 shows a corroded waste drum sitting on the bottom. This image was collected at a depth of 240 ft. in the old industrial waste site in Massachusetts Bay. This area received a wide variety of industrial waste including barrels of hazardous waste, construction debris, and telephone poles. This corroded metal barrel is typical of the waste containers identified in this area by ROV and submersible surveys. The location of a concentration of barrels was known from previous acoustic side scan surveys. The LLS system succeeded in collecting high resolution images of seventeen barrels in less than an hour whereas an ROV survey required seven days to investigate 64 barrels.. The sediments in this area are a fine sandy silt and the image was taken at a range of 8 ft. through a layer of very turbid water 10 - 15 ft. thick. Figure 4 shows a lobster pot and man object at a tow fish altitude of 8 ft., in relatively turbid water, with the sensor field-of-view reduced to 16 ft. This wiremesh lobster trap is typical of modern fishing gear in the Northeast. The image is sharp enough to distinguish the white plastic clips that hold the wire sides together, the rope netting inside and the bright white underside of a skate used for bait. Ten to twenty-five of these traps are strung along the bottom on 1/2" line to form a "trawl". The rectangular object above and to the right of the lobster trap is thought to be a man-made object (probably a concrete block). This image was collected in a boulder field in 70 ft. of water off Cohasset, MA while earching for radioactive waste containers. The containers were believed to have been dumped in this area of rough bottom by fishermen who found the containers in their nets. It is not known whether this object is one of these containers.

Figure 5 shows a WWII diesel submarine lost in 950 ft. of water off of Cape Flattery in the Pacific Northwest. This image was obtained at an altitude of approximately 30 ft. The wooden deck of the submarine has rotted off over the years and deck structure is clearly visible. The object in the lower left of the image on the seafloor appears to be man made but is unknown.

The image in Figure 6 shoes numerous sea anemones (Metridium) attached to metal debris and a variety of fish in a location west of San Diego Bay in 650 ft. of water. The image was obtained in moderate clarity water at an altitude of 40 ft. These anemones are robust filter feeders that come in a variety colors (white, red, orange, and various shades of brown). Note that the LLS system does display different reflectivity from one anemone to the next. This is probably due to pigment differences. Within and around the anemones there are several demersal (bottom living) fish including hake, rockfish, and redfish. The inset in the lower right shows a particularly sharp image of a clump of anemones, a starfish and a fish. Note the distinct shadows in form of the fish and anemones.

Figure 7 shows a deep water spider crab and man made "bucket" from an altitude of 33 feet. Water clarity in this deep water site was good (attenuation coefficient $<.02$ m^{1}) and good imaging performance was obtained to altitudes in excess of 100 feet. This image was taken in the Green Canyon section of the Gulf of Mexico in a water depth of 1810 ft. at a speed of 2 kts. with a laser power setting of 0.6 watt. In addition to the fine detail of the crab, note the degree of bottom contour/texture imaging. The bucket is believed to be a marker object indicating a patch of chemosynthetic biology. A small portion of the patch may be seen in this image.

Figure 8 shows a transverse pass over a 12 in oil pipeline in the Gulf of Mexico at a depth of 1050 ft. This LLS image was obtained in moderate water quality from a tow fish altitude of 50 ft. at a speed of 3 kts. and a laser power setting of 1 watt. Note the readable pipe joint marking numbers and the indications of a disturbed bottom imaged as bright areas on either side of the pipe. This disturbance was observed at periodic intervals along the pipeline.

6.0 CONCLUSIONS

The SAIC Laser Line Scan (LLS) system has produced high resolution, "picture quality" panoramic surveys at rapid area coverage rates with real time data monitoring and storage of digital images for post processing (i.e., detailed analysis and accurate survey area reconstruction). The SAIC LLS system has produced high resolution images with 70° swath widths at altitudes from 8 ft. to 130 ft. above the seafloor at speeds up to 6 kts. in water depths up to 2300 ft. with water clarity varying from very turbid to clear. To date, operations have taken place over a wide range of coastal and open ocean environments form the Pacific Northwest to Southern California, and from New England to the Gulf of Mexico. The system appears to be performing as predicted by the SAIC developed underwater imaging propagation models. The imagery shown here demonstrates the value of this system for search and locate operations, in-situ monitoring of subsurface structures and analysis of environmental parameters in a wide variety of conditions. Applications to mine detection and special purpose surveillance is possible in both towed systems as well as UUV's.

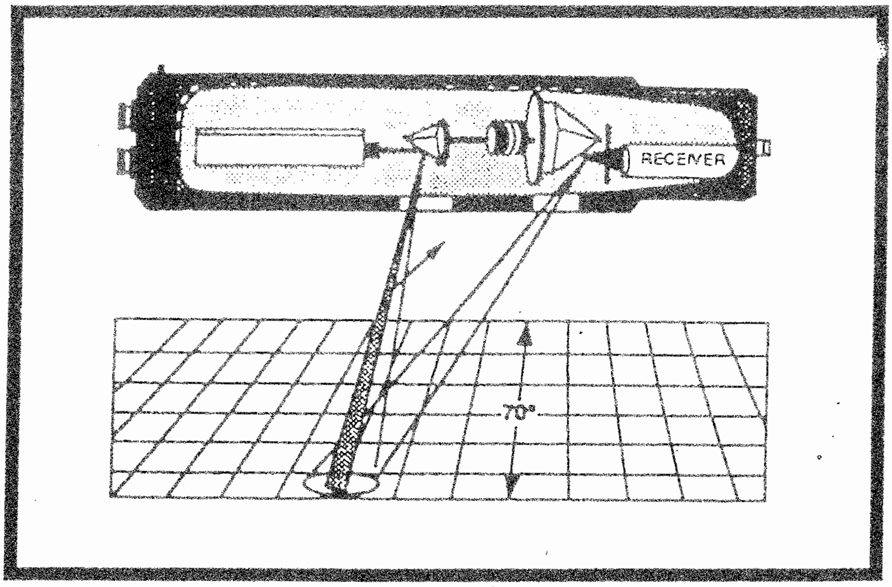
REFERENCES

P. Heckman, Jr., P. MacCardell, "A Real Time Optical Mapping System," SPIE Proceedings, Vol. 160, 1978

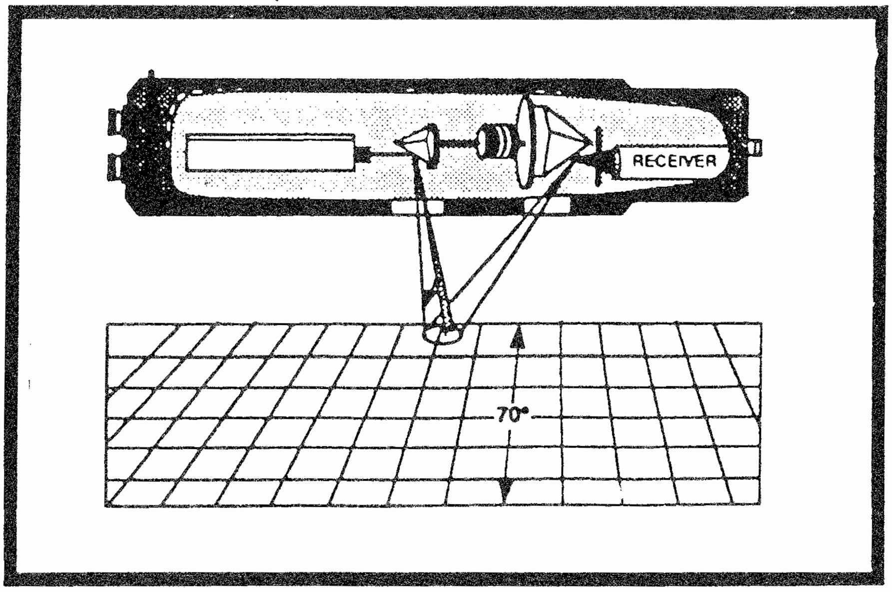
J. Leathman and B. Coles, "Use of Laser Sensor for Search and Survey," Underwater Intervention, '93, Marine Technology Society, January 1993

A. Gordon, "Underwater Laser Line Scan Technology, " Underwater Intervention '93, Marine Technology Society, January 1993

B. Schwartz, "Diver and ROV Deployable Laser Range Gate Underwater Imaging System," Underwater Intervention '93, Marine Technology Society, January 1993



Rotating Mirror Deflects Blue-Green Laser Light Through a 70°
Sector of the Object Plane.



Synchronized Detector Optics Track a Single Point of Illumination,
Minimizing the Effect of Backscatter in the Water Column

FIGURE 1 CONCEPTUAL SKETCH OF A LASER LINE SCAN SENSOR

PROJECTED PERFORMANCE IN DIRTY WATER (0.5 M^{-1})

	2048 SAMPLES		1024 SAMPLES	
V (SHIP)	ALTITUDE	SAMPLING RESOLUTION	ALTITUDE	SAMPLING RESOLUTION
3 kts.	N/A	N/A	28 ft.	0.46 in.
1.5 kts.	25 ft.	0.21 in.	32 ft.	0.53 in.
0.75 kts.	28 ft.	0.23 in.	36 ft.	0.59 in.

PROJECTED PERFORMANCE IN MODERATE CLARITY WATER (0.2 M^{-1})

	2048 SAMPLES		1024 SAMPLES	
V (SHIP)	ALTITUDE	SAMPLING RESOLUTION	ALTITUDE	SAMPLING RESOLUTION
3 kts.	50 ft.	0.41 in.	57 ft.	0.94 in.
1.5 kts.	57 ft.	0.47 in.	65 ft.	1.07 in.
0.75 kts.	62 ft.	0.50 in.	70 ft.	1.15 in.

PROJECTED PERFORMANCE IN VERY CLEAR WATER (0.5 M^{-1})

	2048 SAMPLES		1024 SAMPLES	
V (SHIP)	ALTITUDE	SAMPLING RESOLUTION	ALTITUDE	SAMPLING RESOLUTION
3 kts.	108 ft.	0.9 in.	153 ft.	2.5 in.
1.5 kts.	132 ft.	1.1 in.	169 ft.	2.8 in.
0.75 kts.	148 ft.	1.2 in.	196 ft.	32. in.

FIGURE 2 LLS SYSTEM PERFORMANCE PROJECTIONS

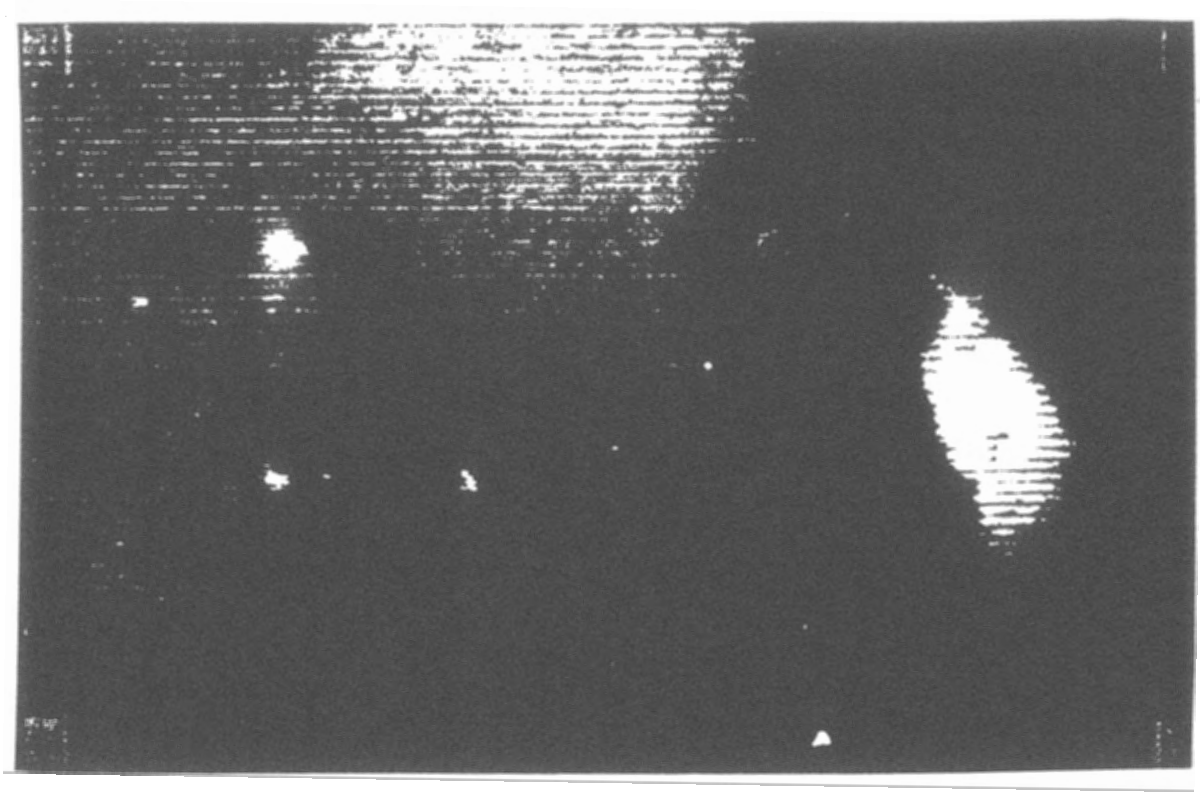


FIGURE 3 CORRODED WASTE DRUM IN MASSACHUSETTS BAY

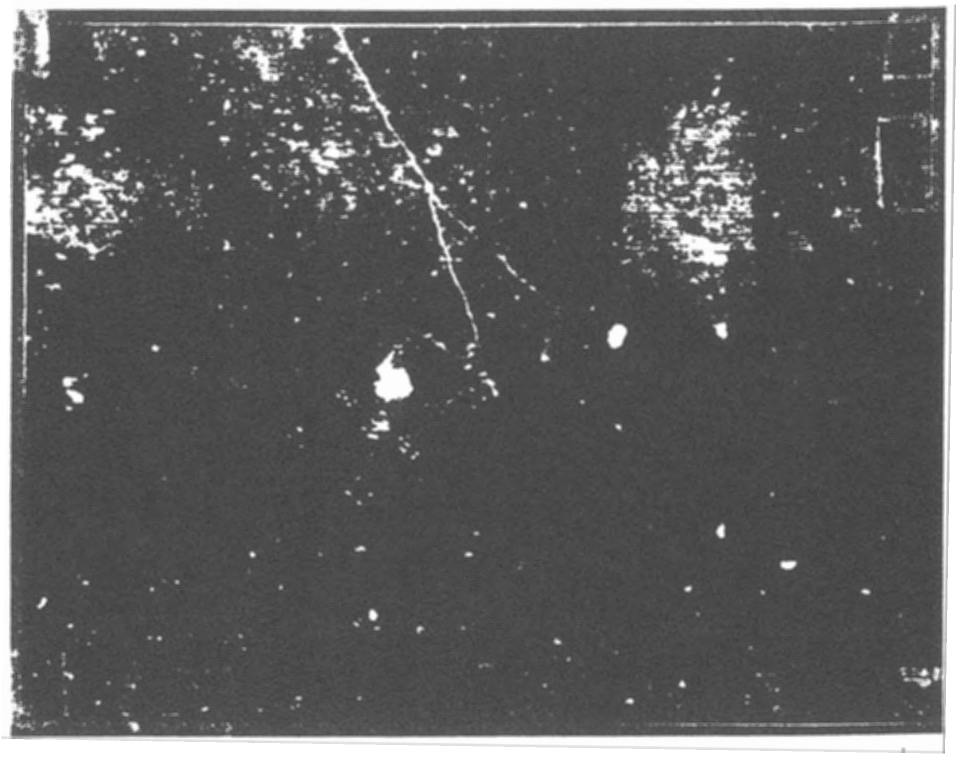


FIGURE 4 LOBSTER POT AND MAN MADE OBJECT

These images collected by LLS system incorporating Westinghouse SM2000 optical sensor. The sponsor was the U.S. Army Corps of Engineers, New England Division, DAMOS Program.

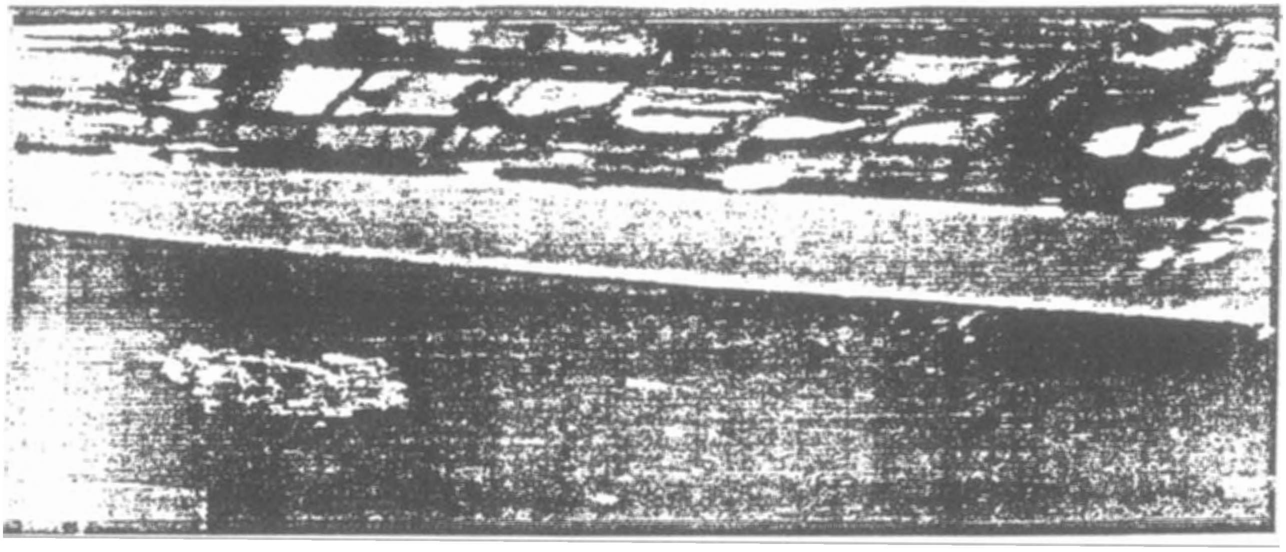


FIGURE 5 WW II DIESEL SUBMARINE AT 950 FT.

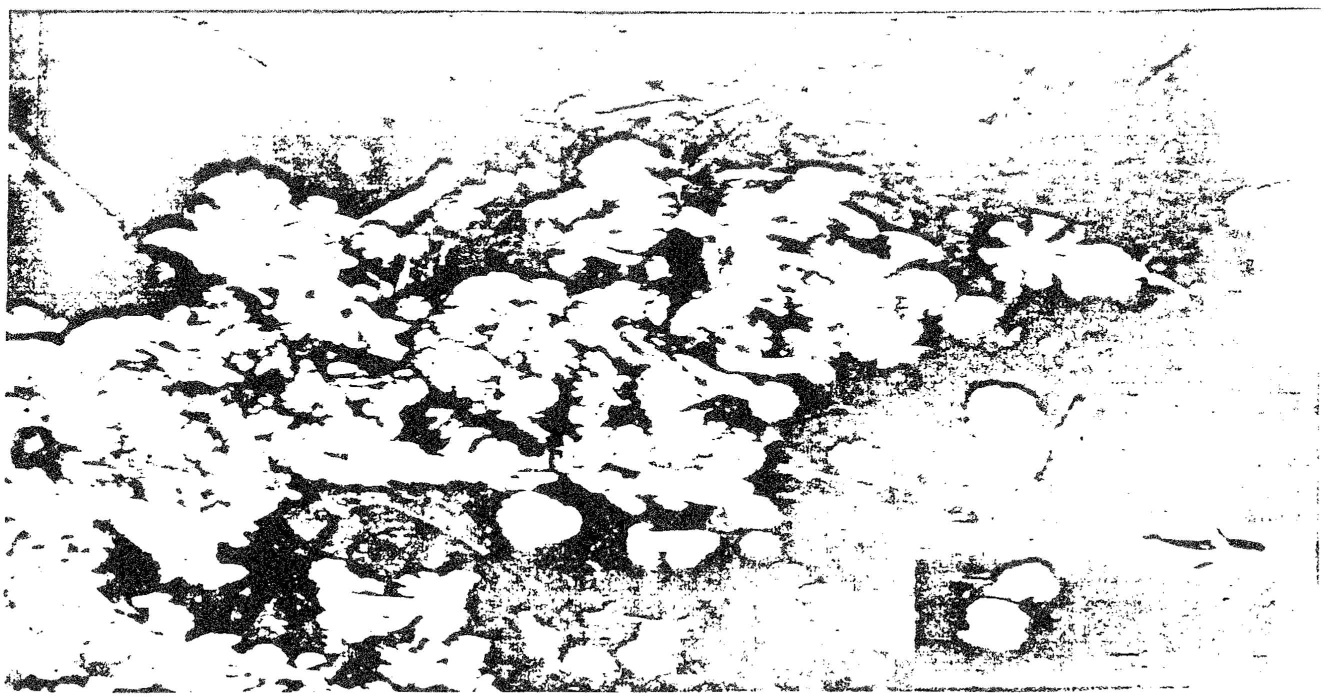


FIGURE 6 DEBRIS FIELD WITH GROWTH OFF SAN DIEGO
These images collected by LLS system jointly developed by SAIC and ART, San Diego.

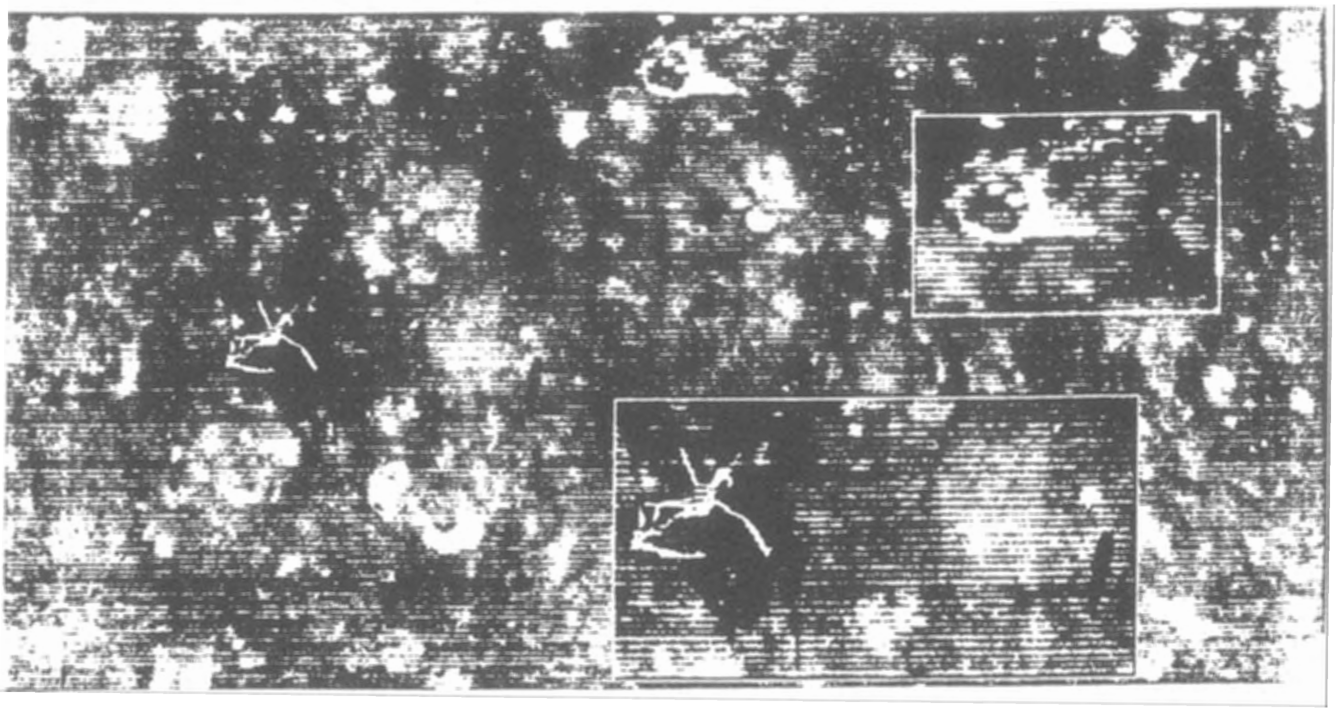


FIGURE 7 SPIDER CRAB NEAR CHEMOSYNTHETIC SITE IN GULF OF MEXICO

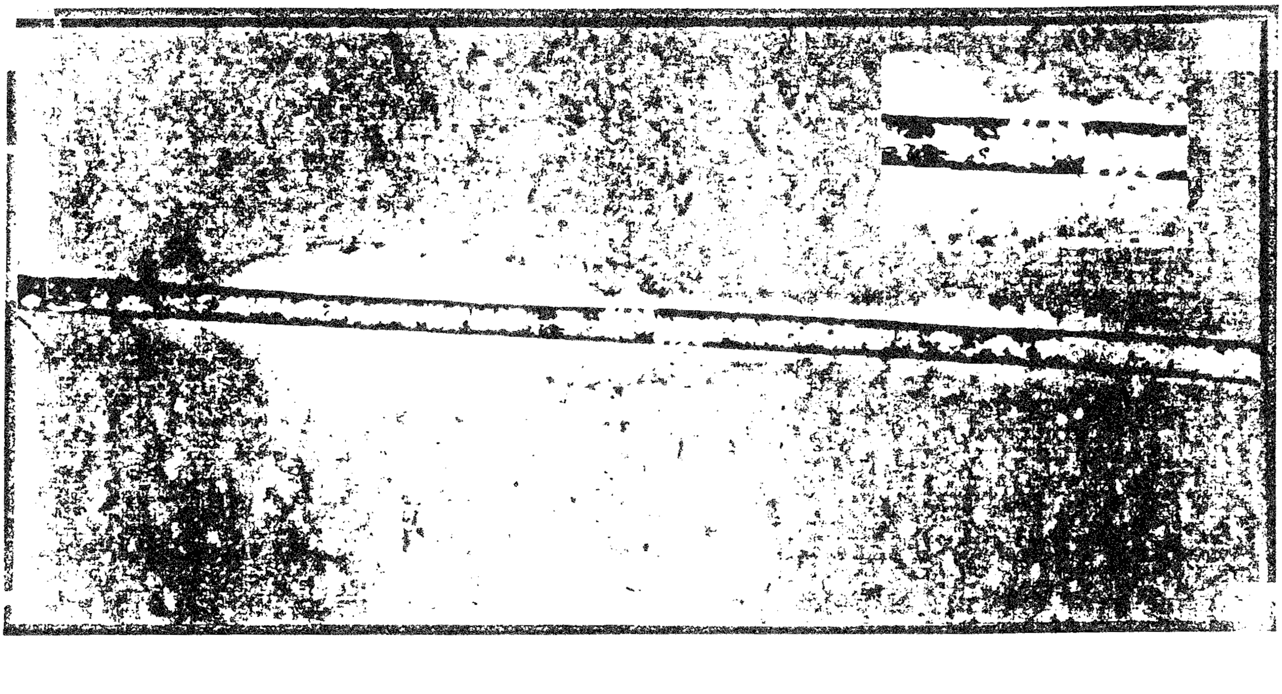
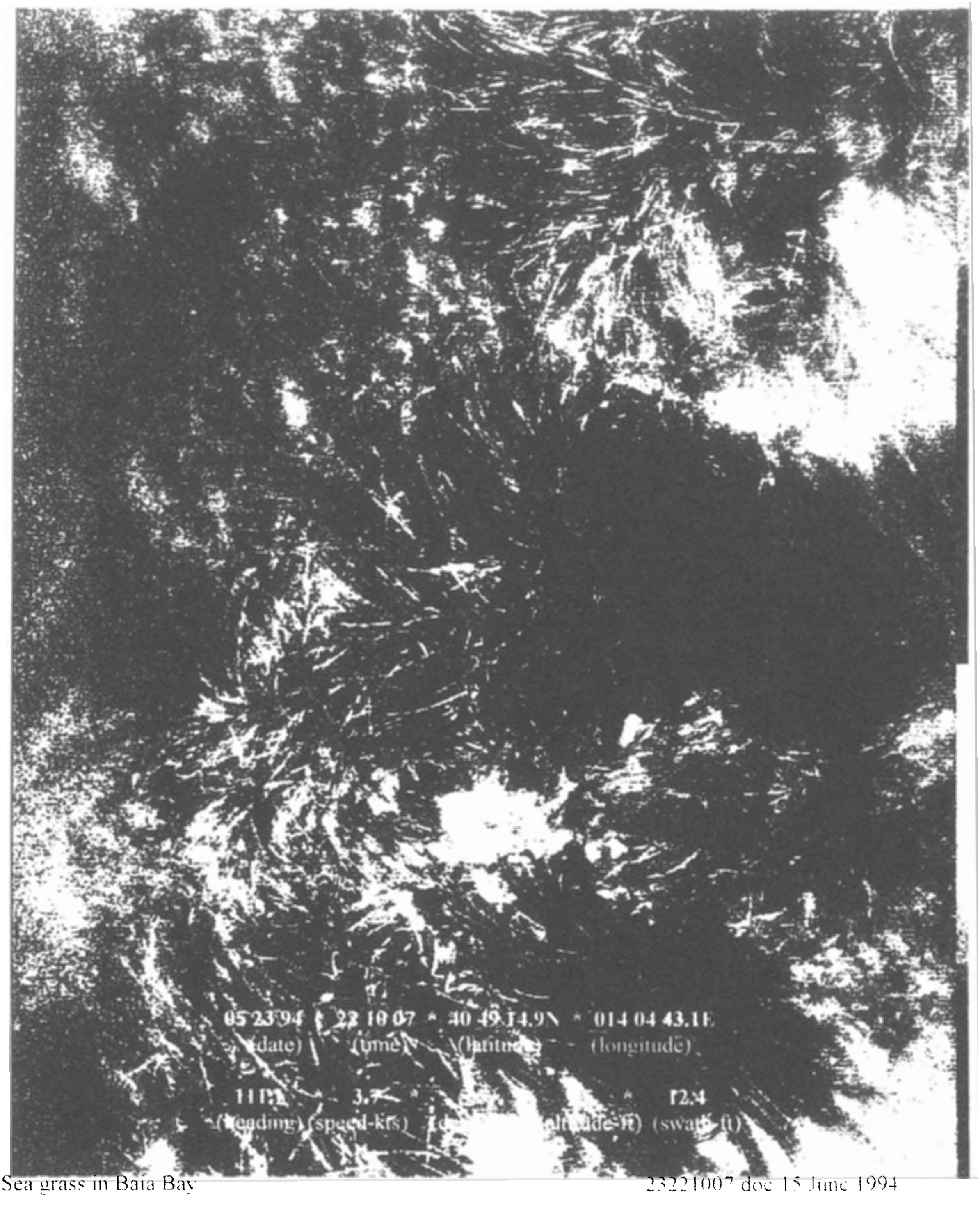


FIGURE 8 OIL PIPELINE IN GULF OF MEXICO

SOLID STATE LASER LINE SCAN IMAGE



Sea grass in Baia Bay

23221007 doc 15 June 1994

SOLID STATE LASER LINE SCAN IMAGE

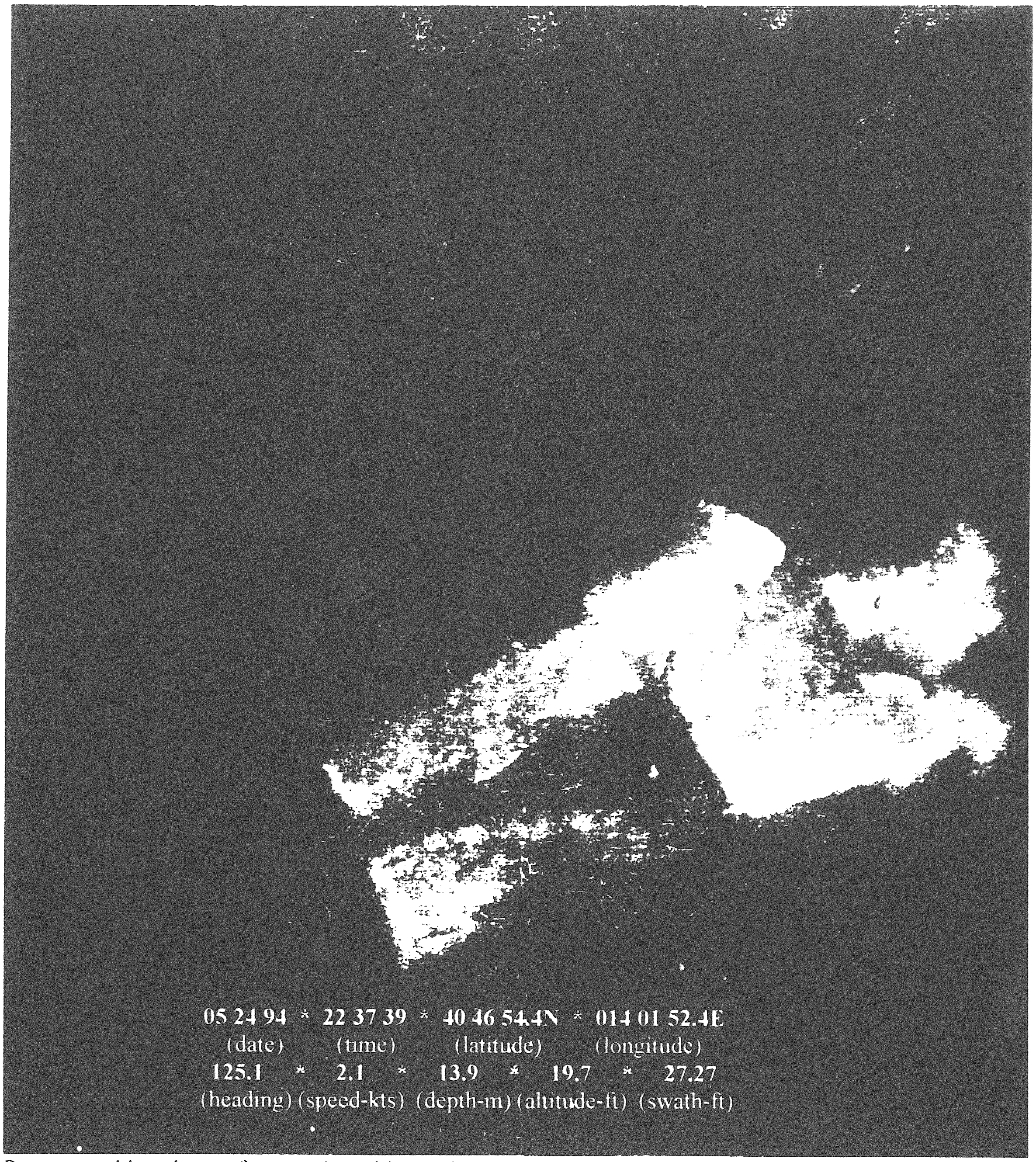
10-cm power cable, showing free-spans. Note sea grass and growth on cable. Disrupted image due to scanner timing adjustments for high-relief changes on seafloor. 24212453.doc/16 June 1994

SOLID STATE LASER LINE SCAN IMAGE

Submerged Roman Villa Baia

23222047 doc 15 June 1994

SOLID STATE LASER LINE SCAN IMAGE



Roman marble columns from ancient shipwreck 24223739 doc 15 June 1994