

Session 6 : Bottom Profilers - Sonar - Video - Cartography - Bathymetry**LASER IMAGING TECHNOLOGY FOR SUBSEA INSPECTION : PRINCIPLES AND APPLICATIONS**

J.O. Klepsvik, H.O. Torsen and K. Thoresen

Seatex A/S
Norway

Abstract

Recent advances in solid state green laser technology offers a unique possibility for developing compact, low power instruments for high-resolution underwater 3D imaging and surveying. The paper reviews the principles and limitations of underwater imaging and describes two new instrument developments; Spotrangle and Spotscan, utilizing the new laser technology for detailed ROV based inspection and surveying. A number of actual field applications are given, including structural inspection, detailed seabed surveying, dimensional control measurements and pipeline free-span measurements.

1. Subsea robotics.

The oil price crash of 1986 caused the North Sea oil companies to abandon many of the high cost approaches to field developments and to focus on lower cost alternatives. The key issues in this process are remote control, unmanned platforms, subsea completion and multiphase pumping. Implicit in all these technical developments is an increased need for automated data collection and control systems which does not compromise the safety either for personnel or the marine environment.

The cost of subsea intervention, however, remain a major concern, be it for routine inspection, repair or maintenance. This is particular the case in deeper waters where ROVs have the greatest potential for reducing the cost of subsea operations.

As ROVs are required to perform increasingly complex tasks, a number of critical enabling technologies must be developed and in particular navigation, positioning, robot vision and control. In addition detailed improvements are required in areas such as inspection techniques, cleaning, surveying methods and construction type tasks such as welding, cutting, bolt-tensioning and remedial work.

In robotics terminology the present state of evolution of ROVs is characterized by telepresence or "man-in-the-loop" systems, and the main task of the vision sensors is to provide an appropriate representation of the ROV's environment so that the pilot/observer's intelligence, skill and dexterity can be applied most efficiently to a remote handling task. However, to advance the capability for the more complex inspection, manipulative and survey tasks, vehicle and manipulator control must be raised to the supervisory control level where the pilot/observer interact with the subsea intervention system at a task rather than the actuator level. In particular the capability to maintain a stationary position and orientation with respect to the structure of interest and to perform precise end-effector movement is mandatory for most tasks.

1.1 Basic requirement.

The most commonly used vision systems for ROVs are TV-cameras and forward-looking sonars. Despite their limited viewing capability, the TV-camera is presently unrivaled for most general inspection and close navigation tasks. The role of sonars are basically to provide long range

work-space information for navigation, relative positioning, obstacle detection and for imaging in turbid waters.

From the experience gathered in related application areas; nuclear remote handling systems, autonomous vehicles, space activities, etc., the basic requirement is for a real-time 3D-vision sensor capable of appropriate geometrical description of the working environment and accurate 3D scene characterization for manipulative tasks. For the underwater scene there is also a long-standing need to extend the viewing capability beyond the visual range of conventional TV and photography and maintain the interpretative qualities of optical imaging.

Table 1.1 give a more specific compilation of the 3D-imaging requirements for inspection, manipulator/end-effector control, metrology/surveying and search/exploration.

Table 1.1 Subsea imaging; 3D measurement systems requirements.

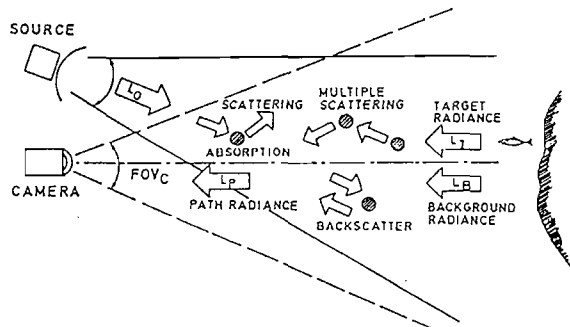
Task	Applications	Dimensional tolerance (mm)	Dimensional range (m)
Inspection	Close weld-, corrosion-, crack-inspection	0.1	0.5
	Structural repair, clearance-, free-span-, marine growth-measurements	5	5
	Debris-, pipetrench-survey	50	20
Guidance/ end-effector control	MPI, Ultrasonic, Eddy-current, ACPD	0.5	1
	Work-space geometry; cleaning cutting, welding, bolt-tensioning, mating	1	2
Metrology/ survey	ROV-positioning, navigation, docking	10	50
	Pile-, riser/flowline, subsea tie-in measurements	50	50
	Seabed mapping, pipeline profiling	10	30
Search/ exploration	Navigation, object recognition/ classification	50	50

2. Subsea imaging and metrology.

Both optical and acoustical imaging/measurement techniques have a potential for bridging the performance gap between the present, essentially 2D imaging systems and the requirements given in table 1.1. A detailed survey of the fundamentals of radiative transfer and image formation in water is given in refs. 1, and only a brief summary will be given below.

2.1 Basic limitations.

Active remote sensing in the oceanic environment is presently limited to the use of acoustical and optical radiation. A typical situation for active underwater imaging is shown in fig. 2.1. The target of interest is illuminated (insonified) by a radiative source, and the backscattered radiation is detected and spatially processed (imaged) by the receiver. In addition to the information-carrying radiation, the receiver also "sees" scattered radiation from particles and inhomogeneities in the transmission medium as well as background or ambient radiation.



The role of the transmission medium is to convey the information carried by the radiation field, and the effect is usually to degrade the information content through absorption and redistribution (scattering) of the radiation. The radiative transfer process is characterized by losses due to absorption and scattering and "gains" due to backscattering of source radiation into the receiver field-of-view.

The effect on the imaging properties of the source/receiver combination is summarized as follows:

Fig. 2.1 Schematic diagram of the imaging process.

1. Limited range capability due to attenuation of source and target radiation.
2. Loss of contrast due to backscattered radiation from particles and inhomogeneities in the water medium.
3. Loss of resolution from small angle multiple scattering of target radiation.

The attenuation properties of optical and acoustical radiation is given in fig. 2.2. Both the source radiation and the target radiation is exponentially attenuated and a characteristic parameter is the beam attenuation coefficient c (m^{-1}). The inverse quantity, c^{-1} , the attenuation length, gives the distance to which the the beam intensity has fallen to $1/e$ or approx. $1/3$ of its original value.

Both acoustic and optical attenuation shows a strong frequency dependence, however, while acoustic attenuation increases monotonically with frequency, optical attenuation is characterized by a narrow transmission window in the blue-green part of the visible region. The window characteristic is most pronounced for deep ocean water and less so for coastal and shallow water areas. Another characteristic of optical attenuation is the large variability with respect to geographic area and depth. This is illustrated in fig. 2.3 which shows the attenuation length variations for green light in the Norwegian Sea as a function of depth.

An important fact that can be observed in fig. 2.2 is that the attenuation coefficient for optical radiation in the blue-green part of the spectrum and acoustic radiation in the 1.5 mm to 0.3 mm wavelength range (1 - 5 MHz), have comparable magnitude.

2.2 Traditional methods.

The traditional methods available for subsea metrology, still widely used by divers, are taut wires in association with rulers and protractors to get distance and angle information. In addition, the use of templates and guide wires is still the preferred method for docking and positioning of tools and work modules. Other traditional tools used by subsea surveyors include inclinometers and pressure-based depth sensors. These methods are difficult, time consuming and prone to errors.

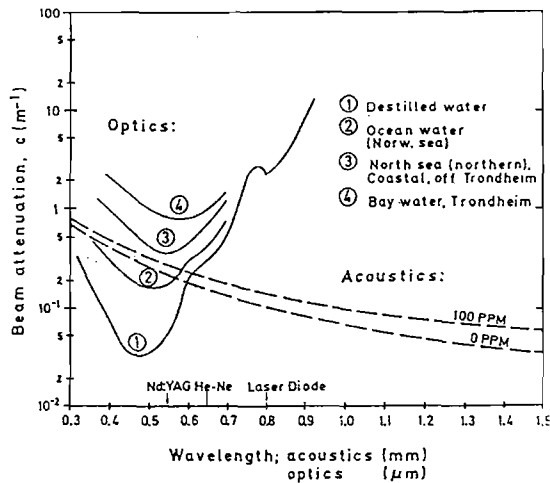


Fig. 2.2 Typical spectral attenuation coefficients for optical and acoustical radiation (refs. 1-3).

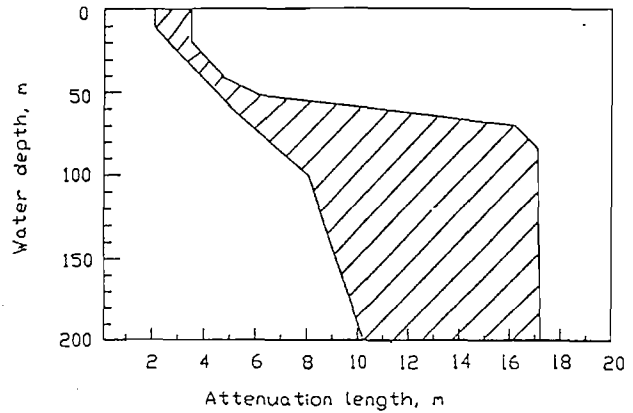


Fig. 2.3 Attenuation length variations for green light (532 nm) in the Norwegian Sea.

Acoustic positioning sensors are used for dynamic positioning of surface vessels, navigation of ROVs and positioning of towed mapping sensors for seabed surveying. In particular, the supershort baseline system (SSBL), are in extensive use for offshore operations and have been developed into versatile submersible tracking systems. The long baseline systems (LBL) have also found a number of applications for subsea operations; i.e. lowering of templates, jackets, etc.. However, acoustic positioning systems as they exist today have proved inadequate for accurate measurements close to the seafloor and within subsea structures. The main problems with acoustic systems are due to ray bending, multipath effects and shadow zones within structures.

A third group of sensors often used in combination with acoustic positioning systems are the dead-reckoning sensors; gyro-compass, doppler speed log and inertial navigation systems. These systems can provide continuous short term position information between fixes, however, since position is derived from time-integrals of velocity or accelerations, they will give unacceptable drift errors in relatively short time.

The traditional ROV imaging sensors, TV-cameras and sector scanning sonars, only have a 2D imaging capability. However, both sensors have been developed into compact, low power and versatile instruments for general inspection and navigation purposes.

3. 3D Imaging technology.

3.1 Measurement geometries.

In order to obtain (x,y,z) coordinates of an object point relative to a reference we have to measure ranges and/or angles relative to our reference. The basic geometries involved is shown in fig. 3.1. The range - angle geometry (a) has the advantage that only one observational position is needed, while for the range - range and angle - angle geometries we have to observe the object from two different positions.

The traditional distinction between imaging and surveying is related to the density and presentation of the measurements. When presented as pseudo 3D plots or contour maps we can utilize the large human capacity for shape interpretation and object recognition. However,

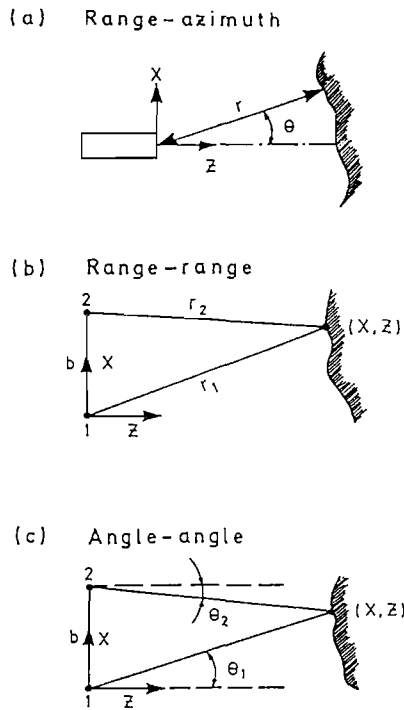


Fig. 3.1 Basic geometries for 3D imaging.
 a) Range-angle
 b) Range-range
 c) Angle-angle

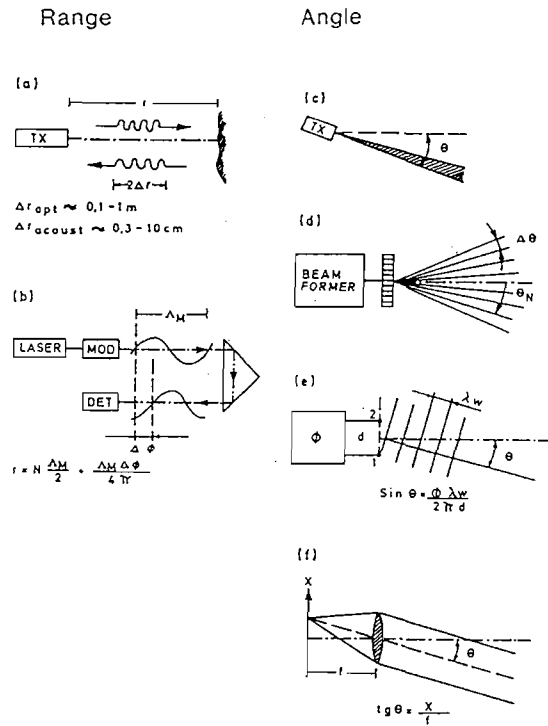


Fig. 3.2 Methods for range- and angular measurements in optics and acoustics.

the basic measurement geometries as given in fig. 3.1 are the same both for imaging and surveying system.

Fig. 3.2 shows the basic principles for obtaining range and angle information both for acoustic and optical systems. Acoustic range measurements are most easily obtained from time-of-flight measurements using short bursts of sinusoidal signals. Time-of-flight range measurements using pulsed lasers is also utilized in optical range finders for terrain profiling, shallow water bathymetry and general surveying. However, most optical rangefinders for surveying applications in air utilize light modulation and phase measurements (fig. 3.2 b) in order to obtain the required accuracy (2-5 mm).

Angular measurements can be made using simple optical, resistive or capacitive encoders for mechanically scanned sonars and optical scanners. More advanced phased-array sonars employs beamforming or phase measurements to estimate the angle-of arrival of the backscattered wavefront. Angular measurements in optical systems is most easily made using lenses as shown in fig. 3.2 f. As a matter of interest, the spatial transformation of an optical field into an angle-of-arrival spectrum which takes place in a lens, is in principle equivalent to the beam-forming algorithms used in phased-array sonars. For automated angular measurement systems, the focal-plane detector must be able to detect the position of the focused light spot, and both lateral effect position detectors and CCD-arrays have this capability.

3.2 3D Laser imaging.

Active underwater imaging is very often contrast-limited due to backscattered radiation from particles in the illuminated water volume which is superimposed on the image forming light from

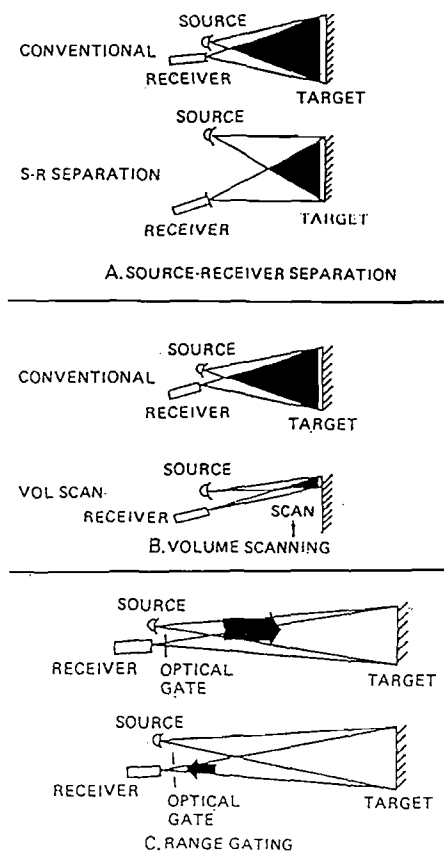


Fig. 3.3 Contrast enhancement in underwater imaging by reduction of backscatter.

reflecting objects. A typical situation is depicted in fig. 3.3. Under normal lighting condition there is a large common scattering volume within the overlapping FOVs of the camera and the light source. A simple method to reduce the common scattering volume is to increase the source-receiver separation as much as possible. Two other methods based on laser illumination techniques is shown in fig. 3.3 (b) and (c). The volume scanning technique utilizes a pencil- or fan-shaped laser-beam which is scanned synchronously with a narrow receiver FOV across the object field. The range-gating technique uses a pulsed laser and a gated receiver in order to confine the instantaneous scattering volume to a thin slice in depth. Both methods have been subject to extensive research over the last two decades.

However, the volume-scanning and range-gating techniques are only capable of relatively crude range measurements, and from the various 3D imaging techniques given in sect. 3.1, only two concepts seems capable of combining accurate 3D measurement with an effective backscatter discrimination. The first method (fig. 3.4 a), termed the triangulation technique, employs the angle-angle geometry using a lens/position detector combination for accurate angle measurement. The second method, most often referred to as a laser radar, utilizes time-of-flight range measurements and the range-angle geometry using a pulsed laser in combination with a high-speed optical detector (fig. 3.4 b).

For the triangulation method, backscatter discrimination is achieved by spatial separation of the imaged laser spot and the backscattered light, as shown in fig. 2.6. The spatial

discrimination can only be obtained using an imaging type of detector, ie. TV-tubes or CCD-arrays, and rules out the lateral effect positioning devices. Actually, the CCD-array is an almost ideal detector for this purpose providing a high spatial resolution and an inherent geometric stability for accurate position estimation of the laser spot.

The laser radar achieves backscatter discrimination through the time-separation of the backscattered light and the reflected object pulse. As shown in fig. 2.6, the detection problem is almost identical for both systems, being to isolate the reflected object signal from the backscattered light and to determine the position and amplitude of the signal pulse as accurately as possible.

3.3 Laser sources.

For a designer of imaging/measurement instruments, especially for underwater, remotely operated applications, concern about dimensions, power consumption, data transmission limitations and reliability is given a high priority. As mentioned above, the different laser imaging schemes have been subject to a number of feasibility studies and proof-of-concept laboratory work, however, reliable, working instruments has failed to reach the offshore field environment. The main reason for the slow development has been the lack of compact, efficient and robust sources of blue-green laser radiation (ref. 1). However, the recently invented diode-pumped Nd:YAG lasers should have a great potential for underwater applications, having dimensions in the 10-20 cm

range, power requirements of 20-50 W, low voltage and modest cooling requirement. At present more than 100 mW of green (frequency doubled) CW output is commercially available. Also, pulsed, Q-switched Nd:YAG lasers are now available having pulselengths of 10-15 nsec and pulse energies in the order of 10-100 uJ which can be operated to more than 10 kHz rep. rates.

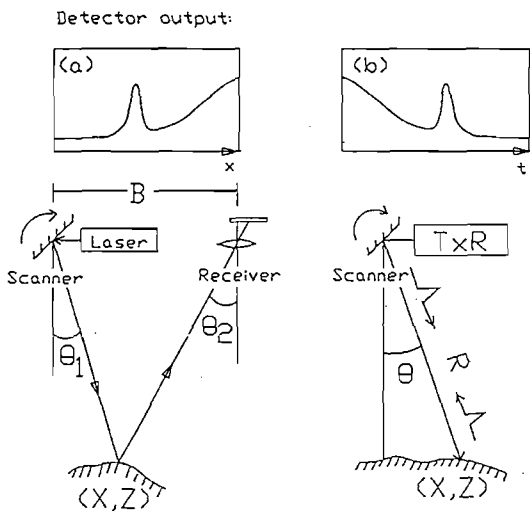


Fig. 3.4 Underwater 3D imaging techniques.
a) Triangulation
b) Laser Radar

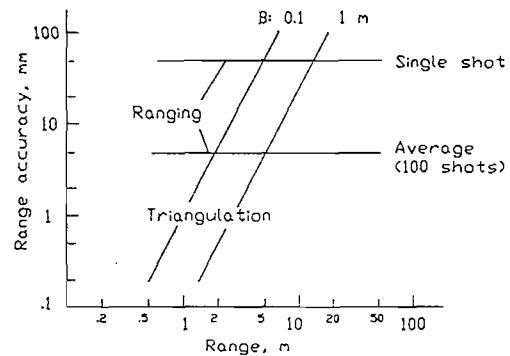


Fig. 3.5 Typical range accuracies for the triangulation sensor and the laser radar as a function of range.

3.4 Performance limitations.

The traditional criteria for evaluation of 2D imaging systems are spatial resolution and contrast which determines the smallest details that can be resolved in a picture. For active imaging systems, the range limitation is also an important parameter which is usually determined from a minimum contrast or signal-to-noise requirement. 3D imaging systems are basically evaluated from the metric accuracy of the coordinate measurements and the measurement range capability. Also, since we are considering only real-time or near real-time imaging systems, the frame-rate or measurement rate is an essential parameter.

3.4.1 Metric accuracy.

Computation of coordinates and estimation of accuracies for the triangulation sensor only involves elementary trigonometrical relations. The longitudinal resolution depends on the accuracy of the angular measurements and the base-to-range ratio. For CCD-arrays in combination with standard TV-lenses, the angular accuracy is in the order of 0.1 mrad which corresponds to a position accuracy of approx. 0.2-0.3 pixel in the estimation of the position of the laser spot on the CCD-array. Fig. 3.5 shows typical depth accuracy for triangulation sensors with baselengths from 10 cm to 1 m. At ranges less than 1 m, the depth accuracy is less than 1 mm, however, the accuracy falls off rapidly with increasing range and is typically 2-3 cm at 5 m range.

The single pulse range accuracy for a laser radar having a pulselength of approx. 10 nsec is typically 5 cm in water, which corresponds to a timing accuracy of approx. 0.5 nsec. The actual time resolution for the timing circuits is approx. 0.1 nsec, and for stationary targets, the range accuracy can be improved by statistical averaging.

However, to achieve the accuracies quoted above we have to perform a careful calibration of the systems and compensate for variations in the refractive index of water due to temperature and

salinity changes (ref. 1). We also know from experiments with laser radar for bathymetric mapping (ref. 4) that considerable bias effects are present due to multiple scattering.

3.4.2 Range and frame-rate limitations.

The dominant factor which governs the range capability of active imaging systems is the transmission losses due to attenuation and spherical propagation of the source illumination and reflected light from the target. To combat transmission losses we need high intensity illuminating sources, large aperture light collecting optics and low noise, high sensitivity detectors.

The basic system parameter which influences both the range and frame-rate capability is the measurement rate (MR), i.e. the number of range measurements per sec. Fig. 3.6 shows typical frame acquisition times vs frame resolution for different measurement rates. The present MR limitation both for triangulation sensors based standard TV CCD arrays and laser radars based on Nd:YAG lasers is approx. 1.5×10^4 , which gives frame acquisition times from 0.3 - 18 s for frame resolutions in the range of 64×64 - 512×512 .

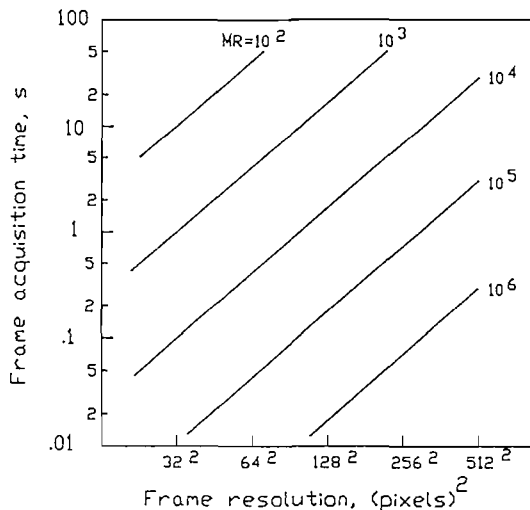


Fig. 3.6 Frame acquisition time vs frame resolution for different measurement rates (MR).

For triangulation sensors using CCD arrays, the range capability is also strongly influenced by the MR. The CCD array is an integrating detector and the integration time (exposure time), which is directly related to the MR, determines the light sensitivity of the detector. The laser radar, however, uses high speed photodetectors where the bandwidth requirement is given by the time resolution requirement and not by the MR.

Fig. 3.7 shows typical range limitations for the triangulation sensor and the laser radar. For typical North-Sea attenuation lengths of approx. 5m, scanning triangulation sensors have a practical range limitation of approx. 3-5m, and laser radar systems using commercially available laser and detector technology have a potential for ranging to more than 20 m. The main reasons for the increased range capability of laser radars are the higher peak intensity available in the short pulses (1-10 kW compared to 10-100mW for the CW lasers) and larger receiver apertures (20 cm² versus 0.5 cm²).

Fig. 3.7 also shows that for low MR (<100) we can increase the range capability considerably for triangulation sensors.

3.4.3 3D imaging systems. Typical performance characteristics

Table 3.1 summarizes the main characteristics of ROV based 3D imaging and measurement systems. The triangulation sensor is the only system capable of high resolution, near real-time 3D-imaging, while high-frequency sonars and laser radar have comparable specifications for medium range (20-30 m) mapping and search/exploration applications. 3D imaging based on stereo-TV are used to improve depth perception for manually controlled manipulators, however, automated coordinate measurements is presently limited to approx. 10 points per sec.

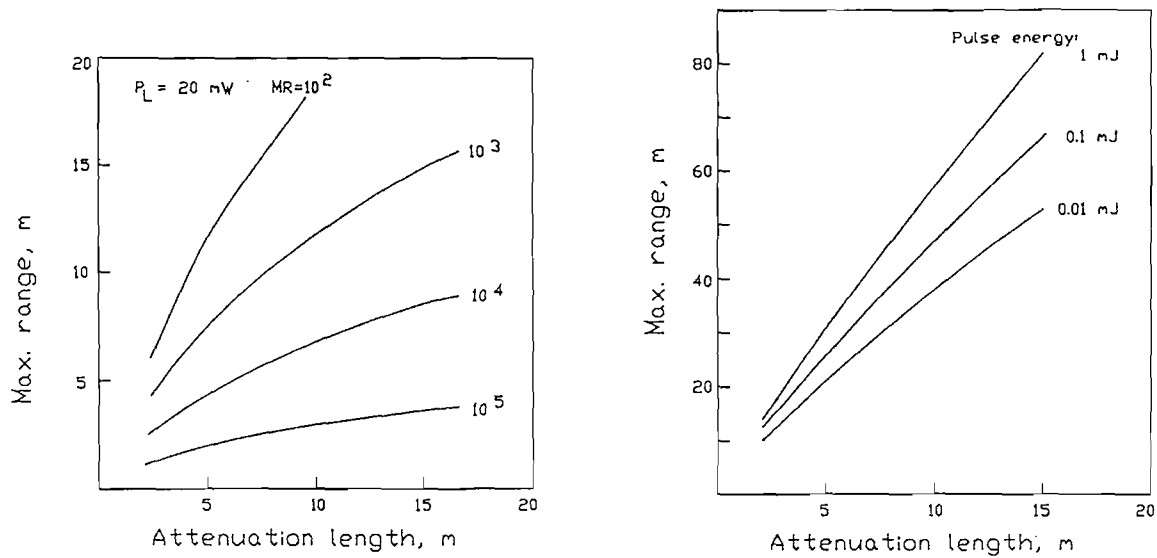


Fig. 3.7 Typical range limitations vs attenuation length.
 a) Triangulation sensor
 b) Laser radar

4. Spotrange; a simple video-enhancement technique.

The Spotrange instrument developed by Seatex was conceived in order to make possible accurate dimensional measurements within the normal viewing range of subsea TV cameras. The basic concept employs a high frequency acoustic ranger and a laser which is coaxially aligned with acoustic beam. The laser beam ensures accurate control of the range measurements in relation to the visually defined targets.

Table 3.1 3D imaging systems. Typical performance characteristics.

System	Spatial resolution		FOV (deg)	Measurem. rate (points/s)	Frame resol.	Frame acquis. (sec)	Max. Range (m)
	Lateral (deg)	Depth (mm)					
Multibeam mapping sonar	0.5	30	100x1	10^3	200x1	(0.2)	30
Stereo-TV	0.1	1 (at 1 m)	30x30	10	-	-	2
Triangul. scanner (Spotscan)	0.1	0.5 (at 1 m)	30x40	10^4	240x180	5	5
Laser Radar	0.2	50	40x40	10^4	128x128	2	20

4.1 System description.

Since the introduction in 1988, the Sporange concept has been further developed to accommodate the different requirements for accurate dimensional measurements using ROVs. The basic version of the instrument (SR01) employs a 1 MHz ranger together with a 2 mW red He-Ne laser or a 5 mW green Nd:YAG laser. The visual range of the He-Ne laser is typically 3-5 m in North Sea water depending on the amount of ambient light and the type of TV camera used, while the green laser spot can be observed to 8-12 m, exceeding normal TV ranges by a factor of two.

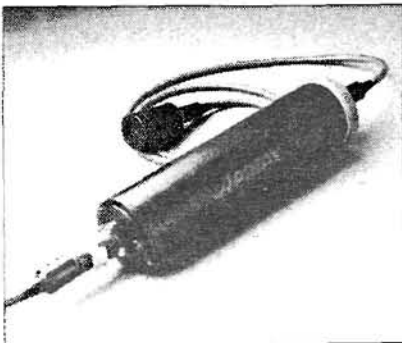
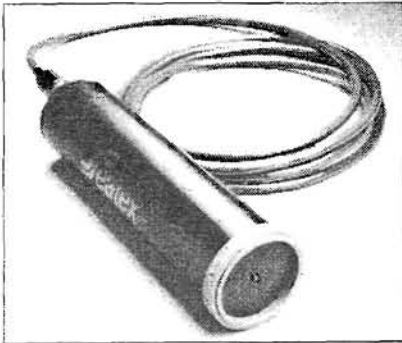


Fig. 4.1 Photograph of the Sporange subsea units, SR01 and SR02.

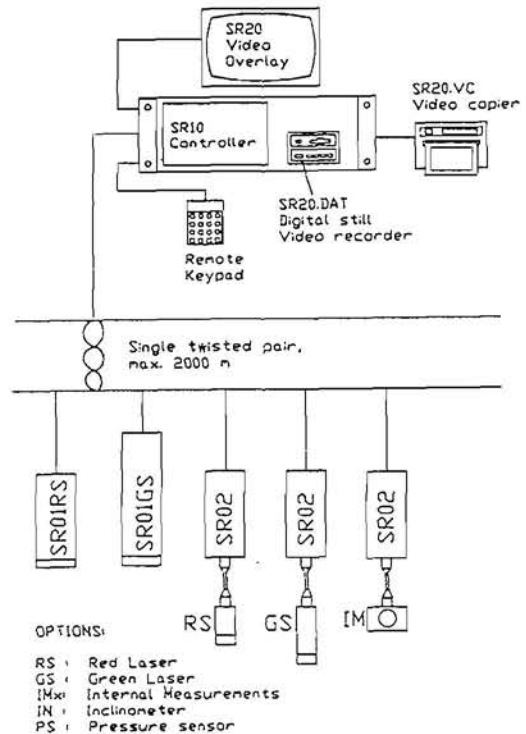


Fig. 4.2 Sporange. Schematic diagram of the system components.

In addition, three remote-head versions are available for manipulator controlled measurements. The SR02-RS version employs a 2 MHz ranger in combination with a red 5 mW solid state laser with a viewing range of approx. 2 m, while the SR02-IM unit employs 2-4 transducers for clearance measurements, internal profiling of pipes and positioning in confined areas (pipes, tanks, platform shafts).

Also, an optional inclinometer and/or a pressure sensor (digiquartz) can be fitted for accurate levelling and depth profiling.

Data transmission and communication to the surface controller occupies a single twisted pair for cable lengths up to 2000 m.

The rack mountable surface control unit is PC based with a built-in 9" monitor. The control program and application programs are menu-oriented and employs a small keypad for menu control. Optional equipment includes framegrabber (B/W or colour) for video scaling and overlay, floppy disk, hard disk, a 1 Gb DAT recorder for digital still video recording and video copier.

4.2 Video scaling.

When the focal length of the TV-camera and the distance to an object is known, then we can calculate the lateral dimensions of the object. This is illustrated in fig. 4.2. Strictly, the lateral scaling is only correct in a plane through the measured point and normal to the optical axis, however, for relatively small deviations from the measurement plane, the measurement accuracy is adequate for many applications. For a standard CCD-camera with a diagonal FOV less than approx. 60 deg, the measurement accuracy is normally within 2-3% of the object field. If the camera is corrected for distortion, the accuracy is in the order of a pixel, or approx. 0.2%. For example, if the horizontal coverage of the camera is 1 m then the accuracy is approx. 2 mm. The actual measurements are made on site using the digitized images (snapshots) and cursors identifying the measurement points, and the measurements are easily documented using a standard videocopier. Measurements can also be made from videotape and keyboard input of the overlaid range data.

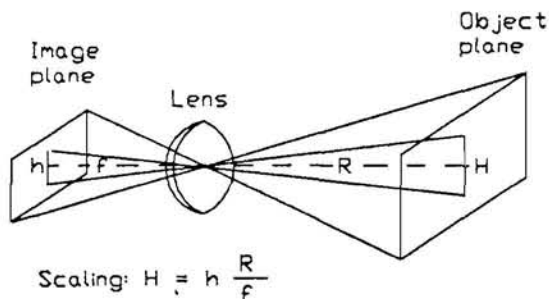


Fig. 4.2 Video scaling, measurement geometry.



Fig. 4.3 Marine growth measurement.

One particular useful application of the videoscoring technique is measurement of the thickness of marine growth, as illustrated in fig. 4.3. The diameter of tubular structures can be measured to within approx. 0.5% if the diameter of the tube covers approx. half the TV-field. Thus when the diameter of the clean tube is known, the thickness of the growth can be measured with an accuracy of approx. 3-5 mm for tube diameters of 20"-40". This has been verified both in field experiments and actual applications.

Other applications of the scaling technique includes damage inspection, weld inspection, anode inspection and sizing of biological species and debris.

4.3 Surveying/dimensional control.

In addition to the simple range measurements SPOTRANGE has two other measurement modes:

- Differential ranging
- Range-angle measurements

In the differential mode Spotrange measures the ranges to the two closest objects within the beam and calculates the range difference between them. Range-angle measurements are performed using the internal inclinometer option or an external Pan & Tilt unit with angular sensors on the pan and tilt axes.

the differential range and range-angle modes allows traditional land-surveying techniques (trilateration, triangulation) to be performed remotely using ROVs. Examples of applications using the surveying techniques given above, including pile measurements (height, inclination), relative positioning for re-entry of drill string (open hole drilling) and guide base control measurements (guidepost alignment).

The different measurement modes can also be used simultaneously, for example accurate depth profiling using the optional depth sensor and inclinometers combined with video scaling for measurement of rocks, debris, etc..

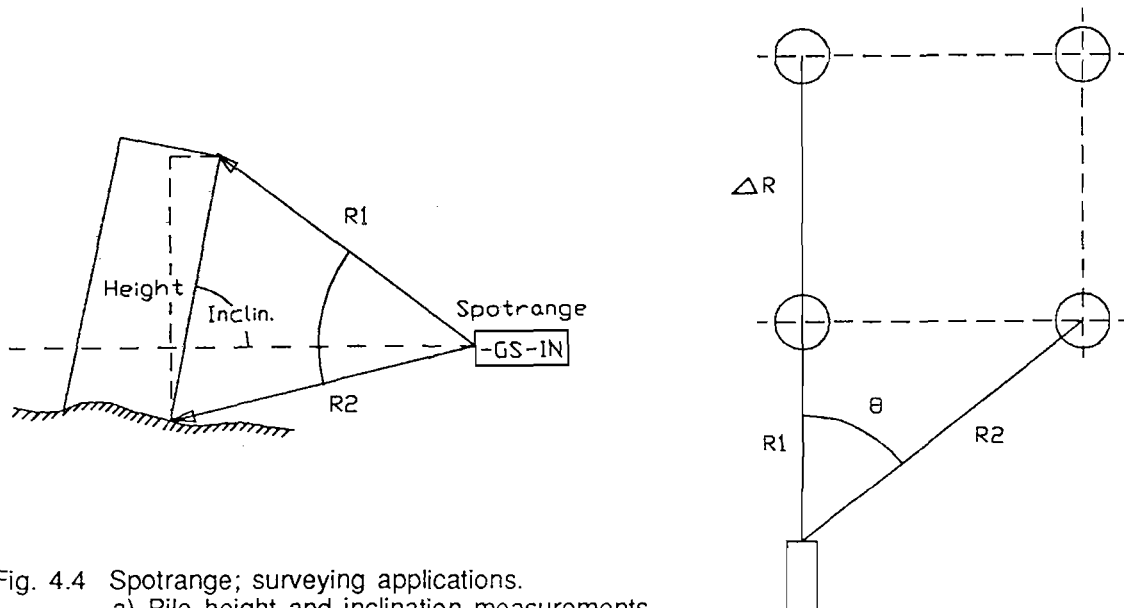


Fig. 4.4 Spotrange; surveying applications.
a) Pile height and inclination measurements.
b) Guidepost control measurements.

In many applications the different measurement modes can also be used to provide independent readings of critical distances and thereby increase the level of confidence and safety. This is illustrated in fig. 4.4, where all the different measurement techniques are employed for guide post alignment measurements.

The remote-head versions were designed for manipulator controlled measurements, and fig. 4.5 shows two particular applications; Valve stem indicator readings using SR02-RS equipped with a special adapter and riser-clearance measurements using SR02-IM fitted with two transducers.

5. Spotscan; high-resolution 3D imaging.

The Spotscan instrument utilizes the triangulation technique for high-resolution 3D imaging. Two versions of the instrument has been built ; a complete 3 D scanner for stationary object mapping (Spotscan-3D) and a linescanner (Spotscan-2D) specialized for pipeline inspection.

5.1 System description.

Figs. 5.1 and 5.2 shows photographs of the two scanner versions and the surface control unit. The -3D version uses a two-mirror scanning arrangement having a FOV of $40^\circ \times 30^\circ$ (HxV), while the -2D version employs a simple line projecting optical element to generate a single line covering 52° . Both versions uses standard two-dimensional CCD detectors for position sensing, however, the -2D version has an additional intensifier coupled to the CCD array in order to increase the range capability. The use of standard TV sensors limits the linescanning frequency

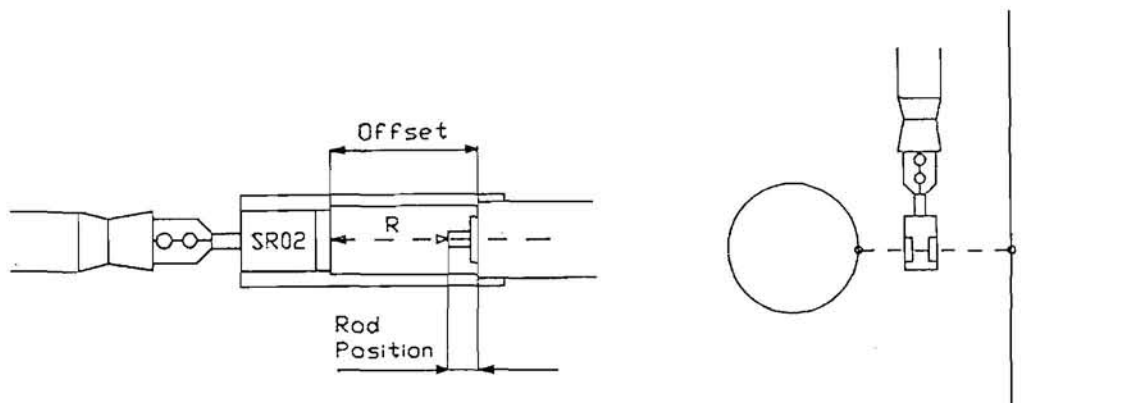


Fig. 4.5 Manipulator operated measurements.
 a) Valve stem indicator readings (SR02-RS)
 b) Riser clearance measurements (SR02-IM)

to maximum 50 lines/s for a resolution of 256 points/line (single field) or 25 lines/s with 512 points/line.



Fig. 5.1 Spotscan-3D.
 a) Subsea instrument housing.
 b) Radiometric image.
 c) Contoured plot

Fig. 5.2 shows an example of the imaging capability of the -3D scanner at approx. 1 m range, where (b) is a radiometric image in a true orthogonal projection while (c) shows a contoured map with a contour interval of 3 mm. The basic specifications for the two scanners are given in table 5.1.

The surface control unit (fig. 5.2) is PC-based with a 9" built-in monitor for system control and a VGA graphics monitor for the real time graphics display. The controller uses a Transputer based video processing and reconstruction system, a 1 Gbyte DAT recorder for digital storage of the 3D scanner data and a computer controlled video copier for real-time hardcopy documentation.

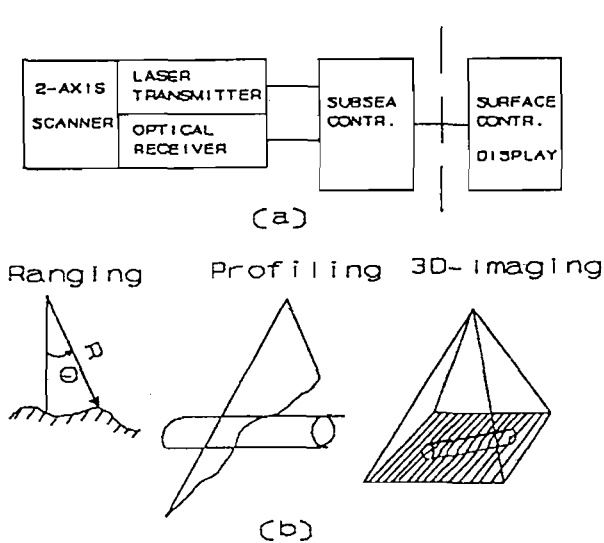


Fig. 6.1 Subsea laser radar.
 a) Schematic diagram.
 b) Operational scenarios.
 c) Design specifications

Subsea Laser Radar. Design specifications.

Ranging:

Range capability : 20-50 m (diffuse target)
 40-100 m (cooper.target)
 Range resolution : < 50 mm single shot
 < 5 mm averaging
 Measurement rate : > 10 kHz single shot
 > 10 Hz averaging
 Angular resolution : 0.1 deg
 Pointing accuracy : 0.05 deg

Line scanning:

Scanning speed : 1-64 lines/s
 Spatial resolution : 64-512 points/line
 FOV : 6-50 deg

3D mapping:

Frame resolution : 64x64 - 512x512
 Frame speed : 0.5 - 30 s
 FOV : 6x6-50x50 deg

The experience gathered from the SPOTRANGE and SPOTSCAN instrument developments at Seatex has given us confidence that subsea laser imaging systems can provide practical, reliable and, in time, inexpensive tools for subsea robotics applications.

Acknowledgement.

The Spotrange and Spotscan instrument developments are sponsored by Spisstek A/S and Amerada-Hess Norway A/S. The Subsea Laser Radar project is sponsored by Amoco Norway A/S.

References

1. Klepsvik, J.O.: "3D Underwater Inspection - Optics versus Acoustics", The 5.Th International Conference on Electronics for Ocean Technology, 24-26 March, 1987, Heriot-Watt University, Edinburgh, Scotland.
2. Jerlov, N.G.: "Marine Optics", Elsevier Oceanography Series, N.Y., 1976.
3. Clay, C.S., Medwin, H.: "Acoustical Oceanography. Principles and Applications.", J. Wiley & Sons, N.Y., 1977.
4. Billard, B., Abbot, R.H, Penny, M.F.: "Modelling depth bias in an airborne laser hydrographic system", Applied Optics, Vol. 25, No. 13, July 1986.