RECENT ADVANCES IN ACCURATE UNDERWATER MAPPING AND INSPECTION TECHNIQUES

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ABSTRACT. The offshore oil and gas industry in the North Sea has set new standards and led to increased demands for accurate and cost effective subsea mapping and inspection techniques. The present paper reviews some of the recent advances within this field and focuses on different three dimensional (3D) mapping and imaging techniques. A new class of high resolution wide-swath bathymetric systems is described and compared. These systems requires positioning input of the highest accuracy and consistency and the role of the Global Position System (GPS) to meet these demands is discussed.

The paper puts special emphasis on the potential use of laser scanning and laser radar techniques for high resolution 3D-imaging and mapping. The basic criterias for use of optics subsea are discussed and exemplified through the description of SPOTRANGE and SPOTSCAN instruments as well as a new concept for a laser radar now being developed at Seatex.

1. INTRODUCTION

1.2 General Background

The spur to the recent advances within underwater mapping and inspection techniques in the North Sea area stems mainly from the development of offshore oil and gas resources in the North Sea. Starting back in the late sixties, there has been more than 20 years of continuous operations, oil field development, pipeline installations, introduction of subsea production units, remotely operated techniques, etc. in an area with rough environmental conditions, waterdepths ranging typically from 70-400 m and partly very rough bottom topography due to iceberg scourings and ploughmarks.

The size and importance of offshore oil and gas development is probably best illustrated by the fact that the yearly average investments (in Norway and UK) over the five last years are approximately ten billion US$. And although seafloor surveying and subsea inspection are not in the centre of the oil mans interests and priorities, they still form an important part of the total picture. So

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offshore surveying which traditionally used to be a domain for governmental agencies and research organisations has become a rapidly developing industry in the North Sea, presently representing a 2-300 million $ market. The commercial demands from this market together with direct infusion of significant R&D money from the oil companies to the instrument developers (approximately 4-6 million $ yearly in Norway) have resulted in a variety of new sensors, systems and methods which are currently in its early application phase. Today is it probably a fair judgement to say that the commercial surveying industry in the North Sea Region is quite a bit ahead of the governmental and military survey agencies both in terms of methods, equipment, technical and operational expertise.

2. SEAFLOOR MAPPING

2.1 Some Typical Survey Requirements and Specifications

The ultimate results from a seafloor survey is normally a 3-D description of the bottom, presented as a contoured map. The quality of the map is again a function of the accuracy of the depth (z) measurement (sounding) and the position (x-y) of the depth measurement. A "rule of thumb" often applied is that depth accuracy should be 1/10 of position accuracy.

In the North Sea survey industry, a typical set of requirements and specifications for a detailed pipeline survey would be:

Survey depth	: Ranging from 50-300 m
Depth resolution	: 10 cm to 50 cm
Lateral resolution (footprint)	: 1 x 1 m up to 5 x 5 m
Survey corridor	: 1 x 200 km = 200 km^2
Positional accuracy	: 2-5 m
Survey speed	: Better than 4-5 knots
Area overlap	: 50-100%
Operational sea state	: At least sea state 5

These technical and operational requirements together with the demand for improved cost-efficiency have led to the development of several new high resolution wide-swath sonar systems as well as improved surface and underwater positioning systems, digital map processing techniques, improved tidal correction models, ray tracing models, etc.

2.2 Examples of Wide-Swath Bathymetric Sonar Systems

In the following three different high resolution wide-swath systems are described; systems which all, to some extent, can fulfil the above-mentioned specifications but which technically or operationally are quite different. Main system specifications are given in Table 1.

EM100. The EM100 is a shipborne, multibeam sonar system produced by SIMRAD A/S, Norway. It has been on the market since 1985 and is today the most utilized system for accurate seafloor mapping in the North Sea.

Benigraph. The Benigraph is a prototype development made by Bentech Subsea A/S, Norway. It is a very sophisticated, towed multibeam sonar system which includes both a hydroacoustic and inertial positioning system. The prototype version is fully operational and is being used on commercial jobs with excellent results.

Bathyscan.
The Bathyscan manufactured by Bathymetrics, UK, is a so-called topographic sidescan sonar or interferometric sonar which measures range and angle (phase) to the reflecting object thereby generating topographic 2-D information as the acoustical pulse travels along the seafloor. Bathyscan is currently used for detailed seafloor mapping in the North Sea, especially in shallower water.

TABLE 1. Wide-swath bathymetric sonar system.

Manufacturer	Type	Model	Frequency (kHz)	Range (m)	Max swath (m)	Beamconf. (no/x°x y°)	Range resolution (cm)	Max Prf (Hz)
SIMRAD	Multibeam	EM100	95	650	800	32/3°x2.5°	7.5	3
BENTECH	"	Benigraph	515	60	80	200/2°x1°	3	10
	"	"	740	50	70	200/1.5°x0.75°	3	10
	"	"	1000	40	60	200/1°x0.5°	3	10
BATHYMETRICS	Interf. sonar	Bathyscan 300	300	150	200	2/1°x50°	10	5

A comparison of the different systems involves a number of parameters, however, in Seatex we have recently made a comprehensive study for a major oil company where cost-efficiency has been calculated for a large range of different mapping systems including those mentioned above. Cost-efficiency is defined as how many km² processed map you get for 1.0 million US$. This study was based on the pipeline case mentioned above. Some of the main conclusions are:

- Shipborne multibeam systems are the most cost-effective, approximately 3 times better than the singlebeam echosounder and approximately 2-3 times better than the towed topographic sonar.

- The towed topographic sonar is approximately two times more cost-effective than the towed multibeam sonar.

- The most cost-effective system can produce up to 400 km^2 of digitally processed map per million US$.

3. POSITIONING

The positioning accuracy necessary to make a digitally processed map with grid size of e.g. 5 x 5 m, must at least be better than 5 m. In order to achieve such accuracies, the oil industry operates its own surface radio navigation systems in the North Sea, typically two classes:

- 2 MHz systems (over the horizon system), with range capabilities up to 3-400 km and accuracies ranging from 6-30 m. Such systems are Hyperfix, Argo, Spot, Geoloc.

- Line of sight systems, with range capabilities up to 100 km (depending on antennae height) and accuracies 2-10 m. Such systems are Syledis, Miniranger, Microfix, etc.

The TRANSIT satellite system is only used for positioning of fixed platforms, or as one of many inputs in large integrated positioning systems.

The Global Positioning System (GPS) has been operational as a test system for 6 years, but due to a limited number of satellites it gives only approximately 2 x 3 hours of coverage per day in the North Sea area. The system which is a military system operated by the US Air Force, today gives an accuracy of approximately 30-50 m for civil users (CA-code), with approximately one fix per second while the restricted code (P-code) gives an accuracy of approximately 10 m and very high dynamics. By the end of 1991 the GPS will have worldwide, continuous 3D coverage.

In spite of poor coverage, the oil companies in the North Sea have recognised the potential of the GPS as the future positioning system, offering continuous, worldwide 3D coverage both for offshore and onshore operation. The oil industry has therefore supported various developments to improve accuracy, to adopt the system to the needs of the offshore surveyor, to test and gain operational experience during the GPS trial period. In Seatex we have been developing two techniques, Differential Positioning Techniques (SEADIFF) and Phase Measurement Techniques (SKYPHASE). The differential technique is shown in figure 1 and is based on the assumption that the position errors measured based on pseudo range on a fixed reference station, can be used to correct the position measured on the mobile unit. The corrections are then transmitted in real time to the mobile unit either by separate broadcast or coded onto another radio navigation signal (e.g. Argo, Hyperfix). The differential technique has shown that the position accuracy can be improved by almost a factor of ten, from 50 m rms to 5 m rms. The results of the differential technique is dependant on the distance between the reference station and mobile unit (baselength), however good results are achieved with baselengths up to 1000 km.

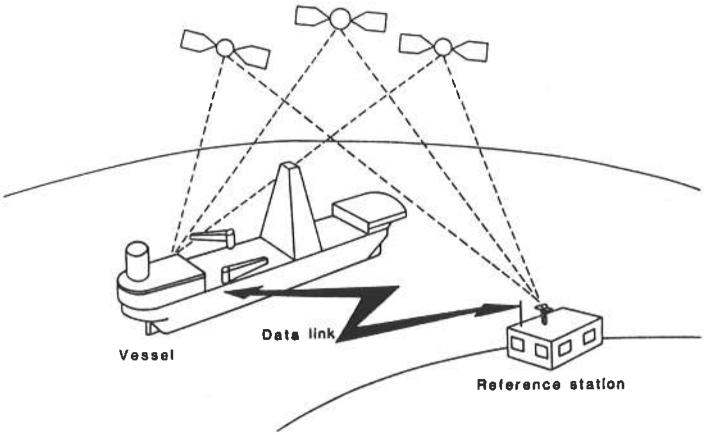


Figure 1. Differential GPS

The SkyPhase technique is currently based on the fact that mobile unit is fixed for approximately 30 minutes while it takes measurements from the same cluster of satellites as the reference. Typical achievable accuracy is 1-2 PPM (parts per million) of baselength. With a baselength of 10 km, this means 1-2 cm accuracy.

The GPS opens up a revolution in positioning and navigation both offshore and onshore. The big uncertainty just now is to what extent the CA-code will be degraded for civil users. But even with more degradation, there are ways to improve the system performance to the extent that GPS seems to be the ultimate answer to our positioning problems within EEZ.

4. DETAILED INSPECTION TECHNIQUES

4.1 General Background

The offshore industry has also a great demand for detailed underwater inspection and mapping techniques. Basically they need to visually inspect their installations in order to verify its structural and mechanical integrity, a requirement which normally has been satisfied by use of underwater photography and TV, operated either by ROV's or divers. Standard TV and photo are 2-D techniques giving little quantitative information apart from the visual interpretation.

As the offshore industry has moved into deeper water and seafloor based production systems have come to replace traditional platform solutions, there is a growing requirement for online 3-D imaging and mapping techniques both for inspection purposes but even more as an active tool during interventions, installations, docking operations, levelling of structures, alignment of components, mating operations, accurate positioning, etc.

4.2 Optical Imaging in Water

A typical situation for active underwater imaging and surveying is shown in figure 2. The target of interest is illuminated by a light source, and the reflected radiation is detected and spatially processed (imaged) by the camera. In addition to the information-carrying radiation, the receiver also "sees" scattered radiation from dissolved particles and other inhomogenities in the transmission medium. This so-called path-radiance has two significant contributions.

1. Backscattered source radiation into the receiver field-of-view (FOV).

2. Forward scattered radiation due to multiple scattering.

The first contribution tends to reduce the overall contrast of the image, while the second contribution tends to reduce the spatial resolution.

Attenuation. Both the source radiation and the reflected radiation is exponentially attenuated due to the scattering process described above and to absorption in the transmission medium. A characteristic parameter is the beam attenuation coefficient c (m^{-1}). The inverse quantity, c^{-1} (m), the attenuation length, gives the distance to which the radiation intensity has fallen to 1/e, or about 1/3, of its original value.

The attenuation coefficient varies strongly with wavelength. Figure 3 shows the spectral characteristics of the attenuation coefficients. Attenuation of optical radiation is characterized by a narrow window in the blue-green part of the visible region. The window characteristic is especially pronounced for deep-ocean water, but less so for typical coastal and shallow water areas. Also shown is the beam attenuation for acoustic radiation.

The important fact that can be observed in figure 3 is that the attenuation coefficient for optical radiation in the blue-green part of the spectrum and acoustic radiation in the 1-5 MHz range have comparable magnitudes. The attenuation length has also recently been measured in the Northern North Sea during summer conditions. Figure 4 shows measured attenuation length variations visibility as function of depth for the green part of the spectrum. Below 100 m, the attenuation length varies from 10-16 m, indicating that considerable viewing distances are possible.

Principles of 3D-Imaging and Surveying. In order to obtain the (x,y,z) coordinates of an object relative to a reference-frame given by the orientation of the imaging instrument, we have to measure ranges and/or angles relative to our reference. The basic geometries involved are shown in figures 5 and 6. The range-azimuth geometry (a) has the advantage that only one observation position is needed, while for the

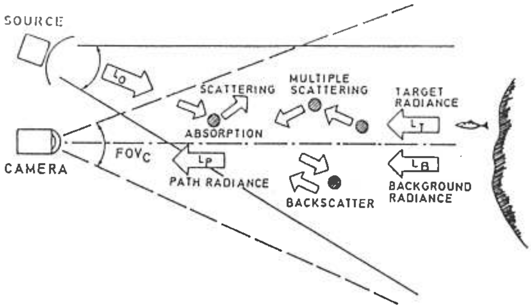


Figure 2. Block diagram of basic imaging situation.

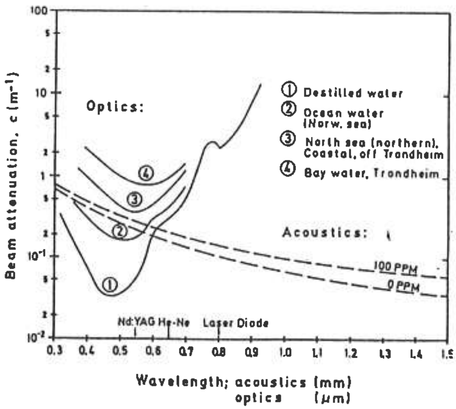


Figure 3. Typical spectral attenuation coefficients for optical and acoustical radiation.

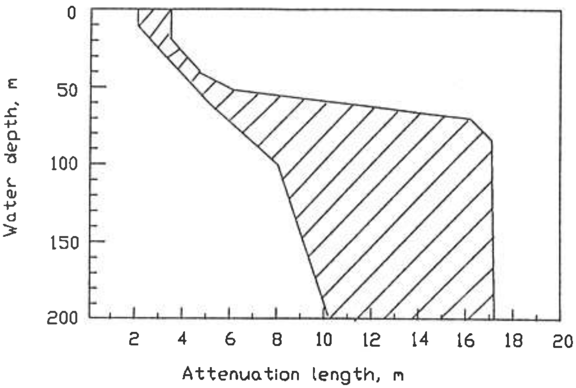


Figure 4. Attenuation length as function of depth in Norwegian Coastal Water.

range-range and angle-angle geometries we have to observe the object from two positions in space. For the last two geometries, the longitudinal resolution (Δz) strongly depends on the base-to-depth ratio (b/z), which should be larger than approximately 0.1. The computation of coordinates and estimates of accuracies only involves elementary trigonometrical relations. In optics, angular information is easily obtained using lenses. Range information can also be obtained from time-of-flight measurement using pulsed lasers.

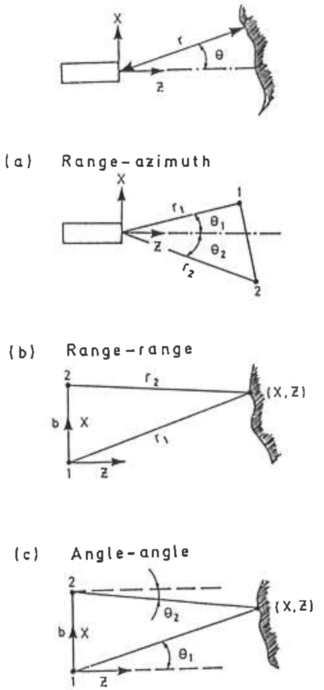


Figure 5. Basic 3D imaging/ surveying geometries.
(a) Range-azimuth
(b) Range-range
(c) Angle-angle.

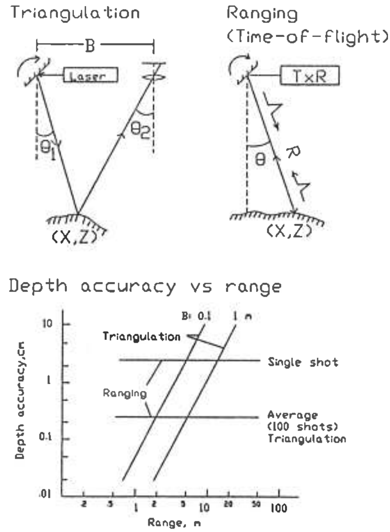


Figure 6. 3D imaging techniques. Depth accuracy vs range.

4.3 Examples of Laser Based Subsea Inspection Instrumentation

<u>SPOTRANGE</u>. The SPOTRANGE instruments developed by Seatex A/S, combines acoustics and a laser. Range measurement is done using acoustics, and the laserbeam is coaxially aligned with the narrow acoustical beam and provides an accurate visual definition of the target.

SPOTRANGE can be used in combination with most TV-cameras; colour, vidicon, CCD and SIT. The intensity of the laser beam is automatically adjusted and modulated to ensure optimum definition of measurement targets throughout the visibility range.

Two versions of the subsea unit are available; a single-unit model employing a 2 mW He-Ne laser and a close range version featuring a separate sensor-head with small dimensions for use on manipulators, etc. (Fig. 7). The latter employs a 2 mW red laser diode as a pointer. The specifications for the subsea units are given in Table 2.

Figure 7. Photograph of SPOTRANGE subsea units, SR01 and SR02.

TABLE 2. SPOTRANGE. Specifications for the subsea-units.

Depth rating: 1000 m

Ranger (acoustic)	SR01	SR02
Frequency (MHz)	1.0	2.0
Range, max/min (m)	30/0.1	10/0.1
Resolution (mm)	5	3
Beamwidth (deg)	1.5	2.0
Laser pointer		
Wavelength (nm)[1]	633 (red)	670 (red)
Visible range (m) (Vidicon, CCD)	4-8[2]	3-4
Beamwidth (deg)	0.1	0.1
Dimensions/power		
Diam. (mm)	100	50
Length (mm)	375	80
Power (VA)	24/1.5	24/1.0

[1] Green (532 nm) is also now available with considerable increase in visible range.

[2] About twice normal TV-range.

SPOTRANGE Applications. Until now SPOTRANGE has been used for accurate navigation of ROVs, metric scaling of video pictures by a grid overlay technique and accurate differential range measurements between two abigued objects.

The SPOTRANGE concept also opens up the use of triangulation and trilateration methods in subsea surveying, as depicted in figure 8. Other applications which are presently undertaken by Seatex A/S include:

- Laser guidance in docking operations: Installation of subsea modules using ROVs.

- Subsea levelling of templates and other bases for subsea construction.

- Continuous profiling of structural details for damage assessment, etc.

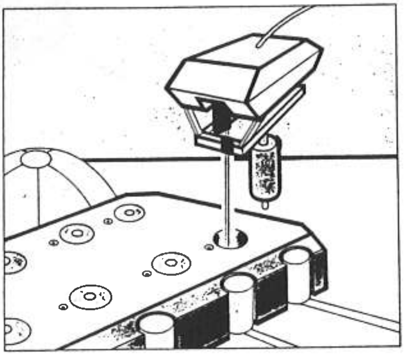
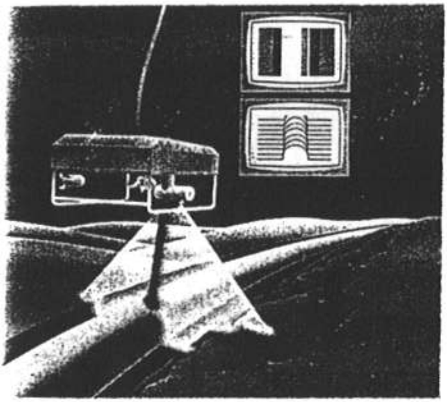


Figure 8. Application of SPOTRANGE in a docking operation.

SPOTSCAN. Automated optical 3D systems, i.e. stereo-TV and laser scanners use the angle-angle geometry, and angular measurements are obtained using image-plane position sensors. Stereo-TV (videogrammetry) is based on measurement of parallax-differences, and requires a fairly complex correlation processor as well as high contrast images in order to extract depth information.

Laser scanning techniques have been in use for several years in high-resolution printing applications. Raster scanning of the laser beam is obtained by two scanning mirrors having a high resolution angular pick-off. A more detailed description of the imaging geometry is shown in figure 9. The laser spot is continuously observed by a camera using a position sensor as detector, and this combination provides the second angle, V_2, in the triangulation geometry.

The SPOTSCAN 3D imaging system, currently undergoing seatrials and industrialization at Seatex A/S, is based on the principles outlined above. SPOTSCAN can be used both in a profiling mode and full 3D imaging mode and provides a real-time alternative to close-range photogrammetry using stereo-photography. SPOTSCAN is also an imaging instrument in the traditional sense, providing TV-pictures with a comparable resolution, but with a limited framerate capability compared to TV. However, in situations where the TV-system is backscatter limited, SPOTSCAN can provide enhanced viewing ranges and image-contrast due to the inherent backscatter discrimination properties of the scanning method.



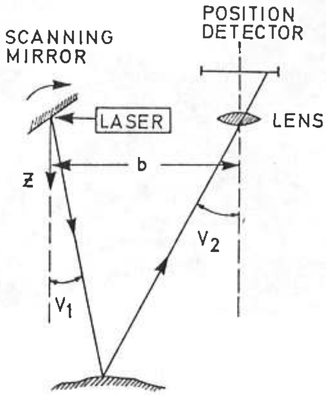


Figure 9. SPOTSCAN 3D-laser scanner.
(a) Measurement geometry. (b) Pipeline profiling.

SPOTSCAN specifications are given in Table 3 and compared to stereo TV (videogrammetry). The SPOTSCAN uses a new solid state green laser, wavelength 532 nm, and output power of 20 mW which in relatively clear seawater should give ranges of 5-8 m.

TABLE 3. 3D imaging systems. Typical performance characteristics.

System	Spatial lateral (deg)	Resolution depth (mm)	Frame resolution (typical)	3D-Frame acquisition time (s)
Stereo-TV (videogrammetry)	0.1	1-3 (at 0.5 m)	256 x 256	10 - 20
Laser-scanner (SPOTSCAN)	0.1	0.1 - 0.5 (at 1 m)	240 x 180	3
Laser radar (RANGE FINDER)	0.1	30 - 50	64 x 64	0.5 - 1

The application areas for subsea inspection includes detailed (sub-mm) corrosion-monitoring, crack-inspection, marine growth assessment, fast pipeline profiling, etc., as well as shape and dimensional control in general, as exemplified on figure 10.

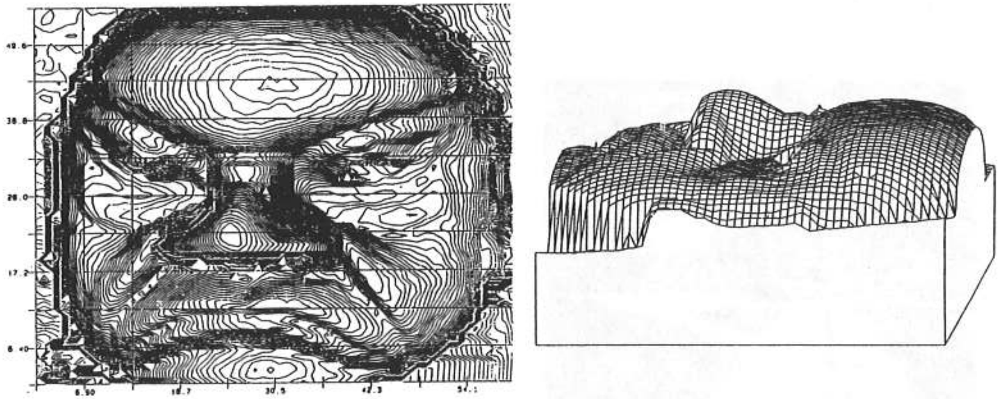


Figure 10. 3D contour map (left) and isometric projection generated by SPOTSCAN. Contour interval is 0.5 mm.

4.4 Future Developments

The SPOTSCAN continuous scanning principle is best suited for accurate 3D close up (1-3 m) inspection with submillimetric resolution, which results in a compact and rugged instrument. For longer ranges, the range-azimuth principle is favourable, using high energy, pulsed green laser where range is derived from time of flight measurements. At Seatex we have recently undertaken a comprehensive design study on a subsea laser rangefinder utilizing Q-switched solid state green lasers and fast optical detectors.

The principle is shown in figure 6 and system configuration in figure 11.

Range capabilities for the optical range finder are determined by laser pulse energy and the attenuation length in water. Based on attenuation length figures given in figure 4 (Norwegian water), we have predicted range capabilities for our new range finder and compared them to existing instrumentations as shown in figure 12. The interesting conclusion is that in relatively clear deep sea water, imaging ranges up to 50-60 m will be possible, with depth resolution in the cm-range.

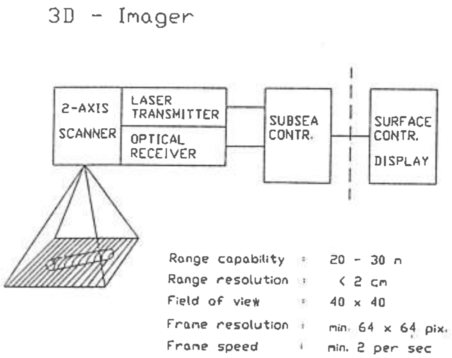


Figure 11. System configuration for laser radar (range finder).

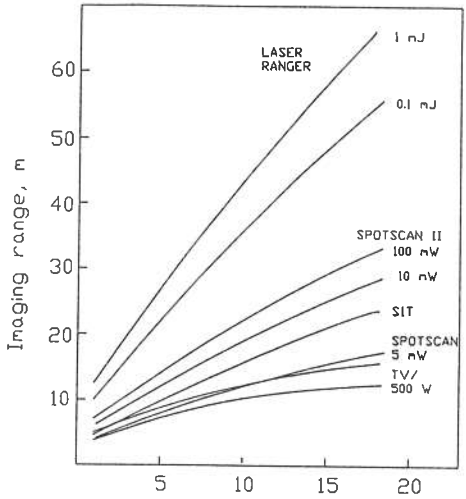


Figure 12. Range capabilities as function of attenuation length.

5. CONCLUSION

The demand and requirements set forth by the offshore oil industry operating in the North Sea, has resulted in a strong and continuous development within accurate underwater and mapping techniques.

For seafloor mapping, high resolution wide-swath, multibeam sonars have led to significant improvements both in terms of dataquality, accuracy as well as cost-efficiency.

Positioning is an equally important parameter in the seafloor mapping process as the depth measurement. The introduction of GPS as a fully operational system from 1991 opens up a range of new applications and techniques which will revolutionize marine positioning and navigation.

For detailed 3D subsea imaging, the new laser techniques open up a new dimension for accurate, real-time inspection and surveying methods that can fulfill our dreams of mastering and exploring the underwater world.