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TITLE : Characterization and observation of the sea-floor with a new multibeam front-scan sonar system (project **COSMOS**)

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CHARACTERIZATION and OBSERVATION of the SEAFLOOR with a NEW MULTIBEAM FRONT-SCAN SONAR SYSTEM

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SUMMARY

The Shared Cost Action project COSMOS, an investigation for a new surveying tool to produce bottom characterization, bathymetry and imaging, started on 1 October 1997 and runs for 36 months. The main aims of project COSMOS are described and the work plan is outlined.

1. INTRODUCTION

1.1 CONTEXT

For some years, there has been a growing interest for techniques to achieve sea-floor characterization. Studies intend to define parameters that depend on the interaction of acoustic waves with specific structures of the sea bottom. For instance, the echographic response with respect to the grazing angle is investigated as this dependence gives pertinent results (e.g. [1-3]). Hence, a systematic measurement of this dependency is essential for sea-floor characterization. A lot of work is running in order to derive sea-floor characterization from sidescan sonars and multibeam echo-sounders data [1-12]. With both systems, each ping insonifies the sea-floor in the across-track direction. A complete coverage is obtained after merging data corresponding to each scanned line into strips that are eventually mosaicked. Algorithms based on segmentation, incidence correction, spectral and texture analysis are investigated. However, because of the usual operating conditions, each individual patch of the seafloor is seen under a single incidence angle so that the systematic local angular dependency of the target strength is not available.

Sidescan sonars and multibeam echo-sounders provide images of the backscattered acoustic intensity, and enable to build maps of the relief [e.g. 13-14, also huge literature on the topic]. The strongly anisotropic way these system gather data influences the spatial distribution and the quality of the resulting information. They cannot deliver images of the nadir area. The blind sector extends roughly up to 10° on each side. In addition, only the multibeam echo-sounders deliver bathymetry samples of this area by processing specular echoes, which leads to classical artifacts [15-16]. An auto-calibration method has been also investigated for bathymetry data gathered with a multibeam echo-sounder [17], but the geometry of the setup yielded poor results (lack of redundancy, too narrow along-track angular aperture).

Recent efforts are supported in Europe and abroad for studying sonar systems based on synthetic aperture techniques (e.g. see [18]). Other systems based on improved athwartships multibeam technologies are also developed [19]. However, the data acquisition is still performed with a side-looking geometry, carrying the same drawbacks as side-scan sonar systems with respect to the relative lack of data redundancy and blindness in the nadir area.

On the other hand, several forward looking systems are proposed by different manufacturers ([20-21]). These systems are primarily devoted to object detection or obstacle avoidance. For this purpose, the transmitted beam is designed as a solid angle that is wide in the azimuth plane and narrow in site, i.e. the total aperture in the vertical plane is typically less than 15°. Images of the sea-floor are built using low grazing beam angles. Such a geometry does not provide a sampling of the seafloor over a large range of incidence angles, so that these systems are not suited for seabed characterization. They do not deliver bathymetry data of the front area either.

1.2 OBJECTIVES AND EXPECTED ACHIEVEMENTS

The general objective of project COSMOS is to make a significant progress in the acoustical methods for observing and analyzing large areas of the sea-floor by means of a solution that is meant to be complementary with the above mentioned techniques. The project is based on an original forward looking sonar that features a very large aperture in the vertical plane (see Figure) and an interferometric capability. The aim is to demonstrate - with data acquired at sea - that this geometry brings definite scientific and operational assets for the characterization of the seabed, mapping the relief and imaging the sea-floor. Such a system should fulfill the need in marine research programs for a fast, non destructive, cost effective technique to determine the nature of the sea-floor.

There is no such system available on shelf, so that the project includes the design and building of a prototype sonar whose dimensions and range capabilities are sized by the chosen frequency, i.e. approximately 100 kHz. The maximal slant range is several hundred meters, and the typical across-track width of the observed area is equal to the altitude of the antennae. Hence, this system can be used for surveying the continental shelf as well as the deep ocean floor, depending on the mounting platform, e.g. ship-hull, towed fish, Autonomous Underwater Vehicle or Remote Operated Vehicle. Within the scope of this project, experiments will be carried with a ship-hull mounted configuration.

With the proposed geometry, most parts of the sector that is scanned during each ping are repeatedly insonified (several tens times) under different incidence angles while the sonar is moving forward. This overlap provides the unique capability to measure the systematic angular dependence of the target strength over a wide domain ($\approx 75°$). Several classes of processing schemes that takes advantage of the multiplicity of data available on every elementary patch of the surveyed sea-floor will be investigated to achieve seafloor characterization.

The project addresses also new techniques that take advantage of the high data redundancy to derive an accurate bathymetry of the band centered on the survey track. Two approaches will be investigated and compared : 1) an interferometric method that features a self-calibration capability ; 2) an image based method derived from the stereo photogrammetry technique that is currently used with radar systems. Foreseen as leading to an attractive operational benefit, the feasibility to implement the in-line preview of the relief ahead of the platform will be assessed (using the interferometric scheme).

About imagery of the backscattered echoes, a non-coherent processing of data issued from successive, overlapping snapshots is expected to produce high quality mosaic images of the nadir area, where classical systems such as multi-beam echo-sounders and side-scan sonar systems are blind.

Together with these technical and scientific issues, the industrial and economic potential outcomes of this new tool will be analyzed.

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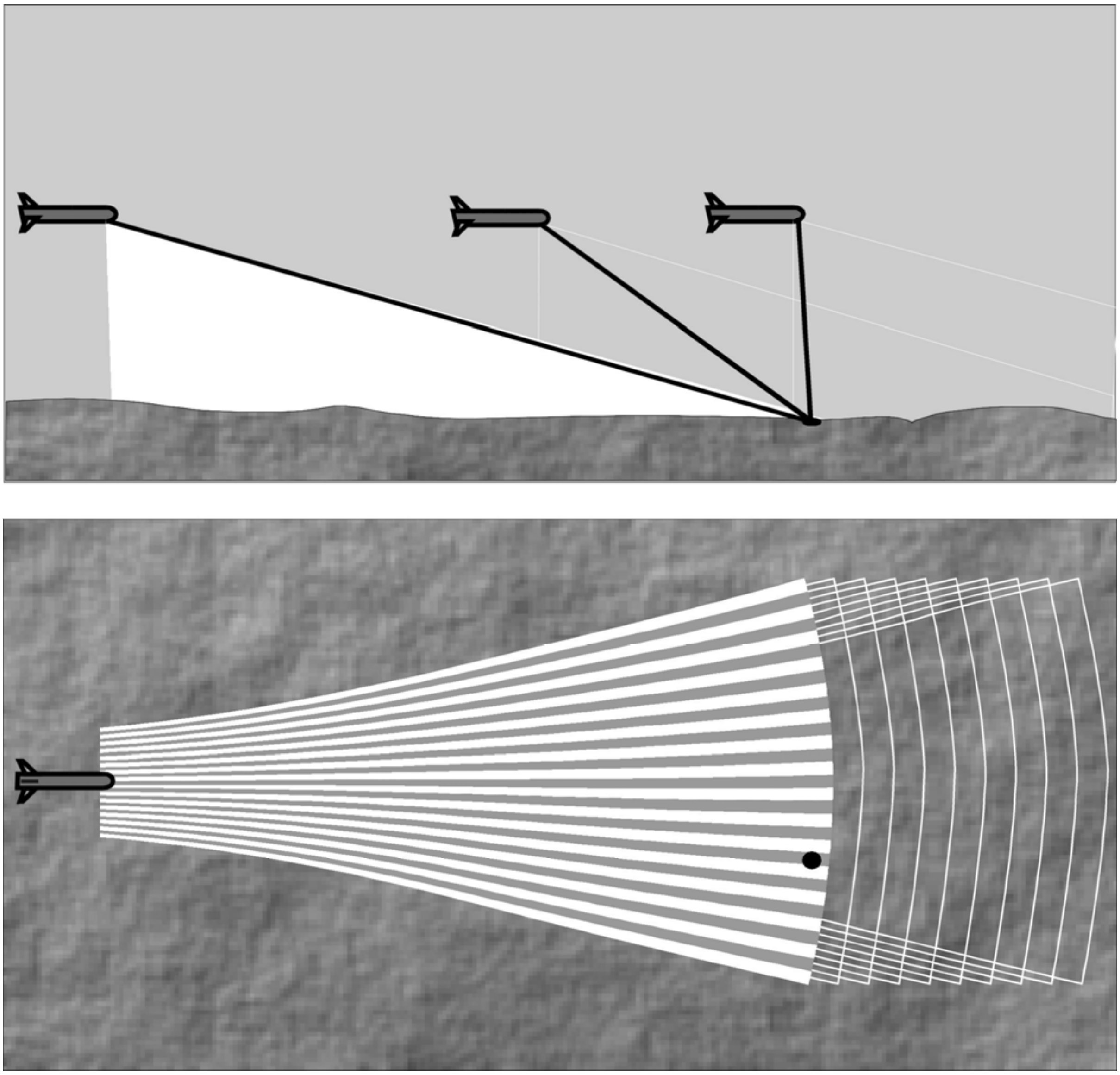

Schematic representation of the COSMOS beams pattern

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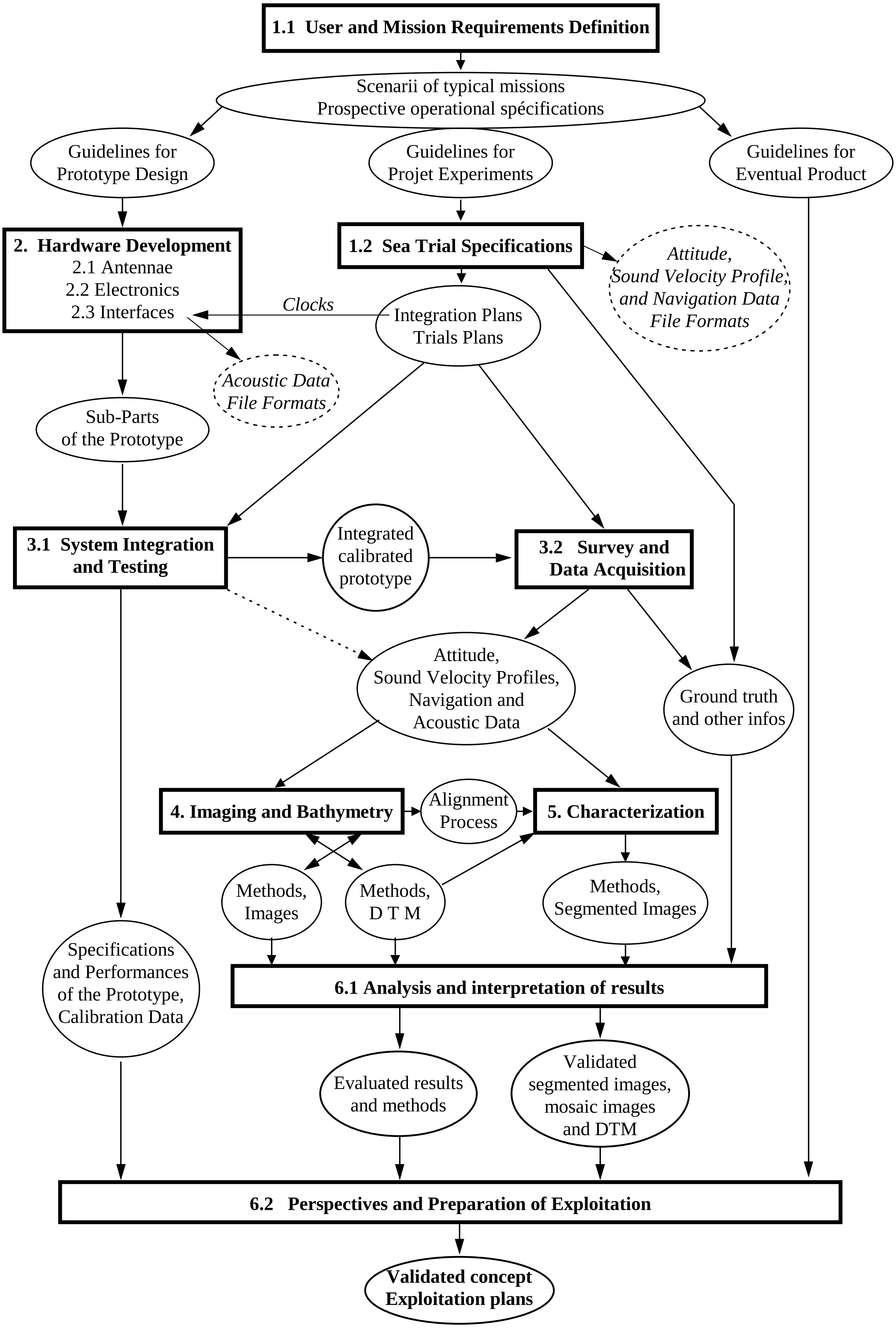
2. WORKPLAN



TASK 1 - PROJECT DEFINITIONS

The first part of this task concern the definition of user and mission requirements, including the prospective operational specifications. Several scenarii of typical missions are prepared. For example, operating simultaneously a COSMOS system and a multibeam echo-sounder will allow to deliver bathymetric data of the whole covered area, including at nadir of the platform (ROV, AUV, ...) track, with an even accuracy. Taking into account the constraints related to the navigation, scientist users give their specification to reach these goals. User requirements for accuracy of bathymetry, survey speeds, and accuracy of platform roll/pitch/yaw and heave measurements are examined. About seabed characterization, the prospective levels of classification are defined by reference to the scenarii. Specific requirements related to pipeline burial and cable laying are assessed. This task includes also the definition of the requirements for interfacing to standard sensor packages for platform motion. The requirements within the potential user community for transfer of data to standard visualization and analysis packages is also assessed.

The second issue addressed in this task is the sea trial specifications. The goal is to prepare the sea trials and data collection, to choose the locations of the field operation, and to gather available information concerning these areas. The definition of the sea trials methodology and infrastructure includes for example : the way to refer clocks, attitude sensors and antennae to each other ; the file formats concerning attitude, navigation, sound velocity profiles. Sea trial areas (for calibration, evaluation of the system and comparison processes) are selected according to data availability (seismic data, cores, images and bathymetry) by using a wide scientific data base.

TASK 2 - HARDWARE DEVELOPMENT

With a central frequency close to 100 kHz, experience showed that a technology of antennae based on composite ceramics is cost effective, provides a good efficiency, and allows versatile antenna geometries. The design aims at limiting the number of elements and the size of the antennae in order to facilitate the eventual implementation on a small platform. The total aperture encompasses a large solid angle : the center of the extreme beams formed at receive will be 25° apart in azimuth ; In the vertical plane, the coverage starts from near nadir (5° in order to avoid diaphony with backward echoes) to about 80°. Both transmitting and receiving antennae are mounted along an horizontal axis that is perpendicular to the platform track. The shape of the transmitter is part of a torus whose cross section features a non constant curvature : This geometry allows to control the transmit beam pattern (e.g. by maximizing the energy sent at the largest range), and gives an active surface that is large enough to obtain a sufficient source level. The receiving antenna consists of two parallel rows of phased arrays in order to perform beamforming (resolution better than 2° in azimuth) and interferometry (baseline ≥ 2 wavelengths).

The electronic design of both transmitter and receiver is mostly based on digital techniques, but for the front-ends. The transmitter delivers a large power (several kW). The transmitted signal is frequency modulated (3 kHz - 8 ms) in order to apply a pulse compression technique. It increases the effective transmitted power and improves the signal / noise ratio at receive. The receiving system performs first amplification with time varying gain, base-band demodulation, anti-aliasing filters and digitization. Then, beamforming is achieved in-line according to several azimuth angles, followed next by a pulse compression stage. The resulting complex acoustic data are stored in buffers.

The main output of the system consist of digital complex values. The prospective spatial sampling is about 20 cm in slant range and 1° in azimuth, i.e. about 256k complex values per second of echoes recording. The recording of this amount of data will be managed with resources that are currently available and whose complexity and cost are reasonable with respect to the size of this project (removable hard disks). File format will be chosen to be compatible with on-shelf software packages. System controls include items such as : Display of images that are refreshed after each ping ; Monitoring and recording of time varying gain ; Clock synchronization.

TASK 3 - SYSTEM TEST AND DATA COLLECTION

The first part of this task consists of : Testing in tank the different subparts of the system ; Achieving the mechanical and electronical integration of the different subsystems in the perspective of the sea trials ; Performing a first sea trial (planed schedule : March 1999) that is primarily intended for the testing of the integration of all the required hardware and software, and for assessing the functional validity of the system, including calibration. The prototype will be ship-hull mounted. Already available attitude sensors and differential GPS receivers will be used.

Then, as defined in Task 1.2, the ship-hull mounted calibrated prototype will be used to collect data for post-processing purpose and database elaboration (planed schedule : October 1999). The characterization, mapping and imaging capabilities of COSMOS will be thoroughly investigated with these sets of data. All information that is required for the proper exploitation of data acquired with the prototype system, e.g. sound velocity profiles, attitude and navigation data, raw acoustic data, will be assembled and archived on CDROM.

TASK 4 - BATHYMETRY AND IMAGING

This task deals with building mosaic images of the acoustic intensity backscattered by the seafloor, mapping the relief, and supplying pertinent inputs for the characterization of the seabed. The common issue that is addressed in this task is to find the location of the areas on the seafloor from where originated the recorded data. The space-time correspondence between data acquired during successive pings will be derived, at several levels of accuracy.

Within a first step, the radiometric transforms to map data in a common reference system will be derived from the available information on the platform cinematic, beam angles, and assumed relief. According to these relations, the primary sectorial images will be converted into ground-projected gridded images, and next, be merged in mosaics. The ratio width / length of the resolution cell decreases when comparing the first images where a given area appears far ahead of the platform, with the last images where the platform comes close to nadir of the same area. Hence, it seems reasonable to expect that mosaic images thus obtained by non coherent synthesis will be easier to interpret, because the linear resolution is more homogeneous, and because the speckle effect is drastically reduced.

Another domain of investigation concerns bathymetry obtained by means of the interferometric technique, i.e. the differential phase measurement of signals received on the pair of receiving arrays. Data are derived from the temporal evolution of the elevation angle corresponding to incoming echoes within each beamformed direction. The accuracy of the correspondence between phase and geometric angles is altered by numerous space-time varying factors, e.g. celerity profile in the water column. A common practice is to build conversion tables with a calibration process. These tables are occasionally updated using empirical methods, or corrected with deterministic models. However, bathymetry profiles exhibit often remaining biases. We propose to study a technique that takes advantage of the data redundancy to update continuously the conversion tables. The devised technique is based on the statistical analysis of the mismatches between along-track profiles yielded by successive pings. The feasibility to implement this technique in-line will be also assessed.

The geometry of COSMOS opens a promising alternative method similar to the stereo-photogrammetry technique currently applied with data acquired by satellite to provide terrain-elevation measurements at high vertical and horizontal accuracy. Each ping provides an image that is well defined in terms of slant range and azimuth direction. During the platform motion, part of the same landscape is still viewed, but with a representation that changes in this coordinate system and that depends on the relief. Hence, mismatches between the projected images obtained with the a priori mapping are likely to remain because of the discrepancy between the assumed relief and the actual relief. Correlation and triangulation techniques performed on images that are not featureless are expected to give a fairly accurate measurement of these discrepancies, hence enabling to derive the actual relief. This method presents an advantage of paramount importance : whenever features on the seafloor can be properly tracked during several pings (i.e. with an along-track baseline that is large enough), the accurate 3-D positioning should be successfully achieved without demanding requirements with respect to the accuracy of the platform location. In addition, once each individual image has undergone these fine corrections, it is expected that the fusion process will deliver high quality mosaic images. Actually, the devised method is kind of a non coherent synthetic aperture technique with a self-focusing capability.

TASK 5 - CHARACTERIZATION OF THE SEABED

The aim of an automatic seabed characterization system is to "segment" the sea bottom into smaller regions, and to assign one of several sediment types to each region, in reasonable accordance with ground truth. The objective of this task is to assess the system potentialities in this domain, by studying thoroughly a few typical cases of seabed configurations. COSMOS is particularly well suited to deliver convenient data for this investigation, since any given patch of the seabed will be successively insonified from various incidence angles. Hence, the nature of the seabed does not need to be (at least partially) homogeneous along the swath, a condition that must be fulfilled with classical systems. Several classes of processing schemes will be investigated :

The backscattering strength dependence on angle will be exploited after correction for the local slopes derived from the bathymetry processing, and compensation for the propagation losses and for the geometry of the beam footprints. The method will be applied on data obtained on various sediment configurations, in order : 1) to establish typical average relations between backscattering strength and incidence angle, 2) to study their potentialities for automated identification; and 3) to use them in sonar image correction in order to remove the average angle influence on local reflectivity.

The signal statistics from one single beam may be studied both in the time and in the spectral domain. Considering the short wavelengths used by the system, there is evidence that structural parameters of the surface affect the time evolution of the amplitude of the backscattered echoes. Several amplitude analysis techniques (e.g. fractal properties, statistical feature selection, higher order spectra, Markov random fields) will be compared. The signals will also be analyzed with classical spectral analysis approaches. The respective influences of the beam grazing angle and azimuth direction will be checked. The methodology will be the same as in the previous sub-task : processing data from well-calibrated zones, definition of typical values for classifying descriptors, and exploitation for identification. The results will be compared with studies based on side-scan sonar data.

A statistical analysis of the phase derived by the interferometric process will be performed. The dependence on the sea-floor characteristics and on the grazing angle will be investigated. The second order statistics of the phase values may be a function of the height and correlation length of the bottom roughness.

Task 6 - System Evaluation and Perspectives

At the end of the project, the collected information will be interpreted and evaluated, in order to assess the validity of the new concept COSMOS. The next steps that are likely to be the continuation of this project will be prepared.

The system will be tested over well-known areas. Hence, the quality of mosaic images, bathymetry and characterization maps will be evaluated by comparison with the available data base and ground truth information. Statistical analysis of the sedimentary properties together with their geological interpretation will be performed and correlated with acoustical data collected by the system. The degree of correlation between the fine-scale variability, or texture, of the images, and the different seafloor types, will be assessed. Digital terrain models derived from the interferometric and photogrammetry techniques will be compared. After demonstrating the progress achieved with respect to other survey systems, the most proficient, cost-effective methods to obtain seabed characterization, bathymetry and images will be selected and proposed for applications.

Using an existing database of potential users, the potential of the system will be analyzed, and the likely response of the market to the new system be assessed. The possible benefits of the system when compared to those already on the market will be studied. Factors of interest will include the coverage rates, the accuracy of bathymetric information and the degree of portability for use on vessels of opportunity. Factors to be considered in determining the future direction of the project will be the nature of the results obtained, and the reaction of the user community to these results. Of considerable importance will be the suitability of the system for production, i.e. the amount of work needed on hardware and software development before it can be deemed to be a finished product. The above factors will be analyzed in order to produce a recommendation for the continuation of the project and to prepare exploitation.

As a whole, the expected outcome of this project is a validated concept for a new surveying tool. Examples of applications that are likely to be eventually considered are : Equipment of ROVs ; Bathymetry surveys ; Optimization of pipeline burial ; Preparation of the setting of off-shore equipment ; Monitoring of sedimentary processes ; Archaeological surveys ; Detection and monitoring of environmental hazards.

Part of this project share common interests with the MAST III project ISACS (Integrated System for Analysis and Characterization of the Seafloor) under contract n° MAS3-CT95-0046. "The objective of Isacs is to prove the feasibility of the analysis and characterization of the seafloor by the exploitation and by the suitable integration of data gathered from commercially available sonar equipment." Because COSMOS may become another available tool, the potential for a future "Concerted Action" with ISACS will be considered.

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