DIGITAL GEOMETRIC RECTIFICATION OF SONAR IMAGES WITH INTERFEROMETRIC METHODS

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ABSTRACT

The knowledge of bottom topography of our oceans is one of the assumptions for engineering and marine geology. Especially in shallow coastal areas, however, topography is frequently changed by storms and tidal currents. Short-time surveying repetitions are necessary for up-to-date information. The employment of echo-sounders, which can take one depth-profile at time, means a great expense for this work. This paper presents a new system called Interferometric Side-Scan-Sonar (ISSS), that records images with fringe pattern, which are geometrically related to several depth profiles. The evaluation of these data is done by digital image processing methods with respect to a geometrical model for the recording situation. Necessary additional data for outer orientation as rotation and positioning of the sensor are taken into account.

1. Introduction

Side-Scan-Sonar is nowadays an operational underwater system for sea-floor mapping. The system containing transducers for sound propagation is towed by ship and transmits acoustic pulses orthogonal to the towing direction. The emitted acoustic field is vertically wide open and horizontally narrow bound, which has the effect that each single pulse only "sounds" a small sea-floor strip. The reflections from the sea-bottom (echos) are received by the same transducers and recorded in an image line, wherein the position of an image point corresponds to the target range (determined by signal running time) and the point density to the echo intensity. By towing the sensor and pulsewise repetition of transmitting and receiving sound an image is built up line by line.

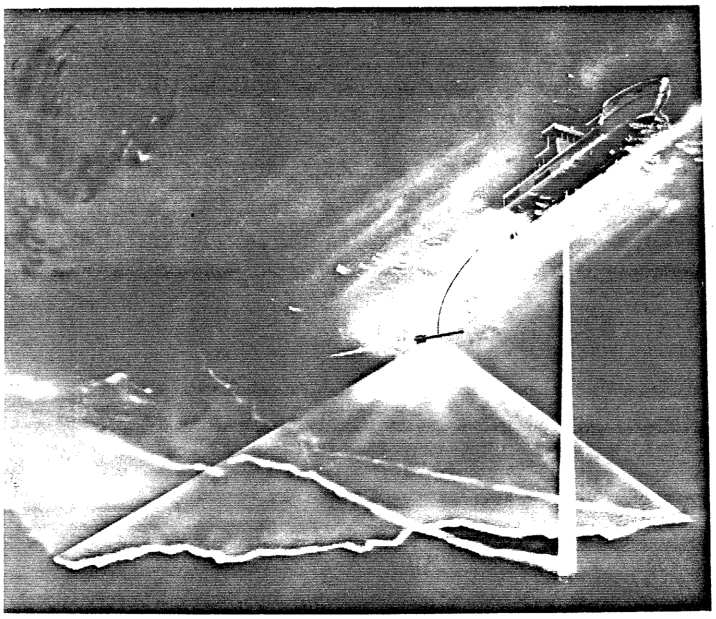

Fig.1: Side-Scan-Sonar System (EG+G)

Side-Scan-Sonar images are mainly used for the detection of natural and man made bottom features such as rocks, sandripples, boulders, shipwrecks, pipelines, drilling-activies etc. They are taken for control puposes, for change detection and for geologic interpretations. For the overview of greater areas two or more image strips can be combined to a mosaic. This requires for acceptable interpretation a rough geometric correction of the single strips before mosaic production. Standard correction procedures are the conversion from the obtained slant-range image to ground-range presentation for uniform scale in transmitting direction and the adaptation of the scale in towing direction. This can be done optically, with some difficulties. A much better way is the correction by digital methods if data are recorded on tape (Kolouch, 1983). For the application of the side-scan-sonar for geodetic survey to obtain depth information from these images only little activities are known. Tests made by Mittleman and Malloy and by Clerici (1977) dealt with photogrammetric stereoscopic methods from overlapping image strips. These tests were only partly successful. The diffilculties for stereoscopic processing mainly are based on the lack of point correlation in both images due to image quality and standard side-scan-sonar image normally contain not many sufficient "acoustically" prominent topographic details of the sea bottom. The second reason for the prevention of stereoscopic viewing is the relative geometrical distortion of each single image because of sensor movement. These two reasons restrict stereoscopic methods to point-wise techniques.

More successful for area covering depth determination from side-scan-sonar images is the application of interferometric methods. The foundation of this technique is the mixing of coherent signals travelling along different paths to a surface target, respectively back to the receiver. This effects fringe pattern in the image, which are extremely sensitive for depth changes. In this field previous studies have been done by Chesterman (Chesterman et al., 1967) and Heaton (Heaton and Haslett, 19791) with patterns caused by surface reflection (Lloyd-Mirror effect) and by Stubbs (Stubbs et al., 1974) using a pressure reflector. Newer developments have been done by Parker Verboom (1982) and Klepsvik (1983) and last not least by the author (Kolouch, 1983a). In a "Special Research Project" at Hannover University, called "Vermessungs- und Fernerkundungsverfahren an Küsten und Meeren" an interferometric hardware system was developed. The evaluation of the image data recorded by this equipment is done by digital image processing software. To get absolute three-dimensional coordinates from the image, positioning and angular movements of the platform is taken into account.

2. Fundamentals of Interferometric Fringe Pattern

2.1 Lloyd-Mirror-Effect

The natural Lloyd-Mirror effect appears in standard side-scan-sonar images only under special weather conditions. The sea surface must be considerably calm and work as a mirror. The fan-shaped sound beam then reaches the sea-bed on two paths, directly and after sea-surface reflection.

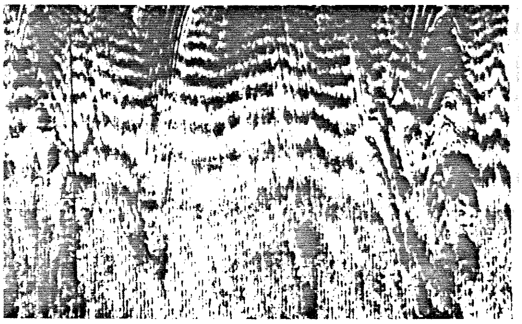

Fig.2: Lloyd-Mirror in standard sonar image (from Belderson et al., 1972)

These signals from the same transmitters are coherent and can interfere. If the path difference is an odd number of half wave-length (because of phase-change of 180° at surface reflection) the resulting signal is reinforced, otherwise at differences of even numbers it is extinguished. Due to different ranges and view-angles a lot of reinforcements and extinctions are recorded and repeated transmissions give a series of fringe patterns in the sound image (Fig.2).
The corresponding geometric situation of Lloyd-Mirror is shown in simplified manner in Fig.3. Confined to signal reinforcement - further on called interference - this geometry leads to expressions for the determination of water depth and horizontal distance for an interference point P_n. Because of the physical situation range and recording direction can be fixed.

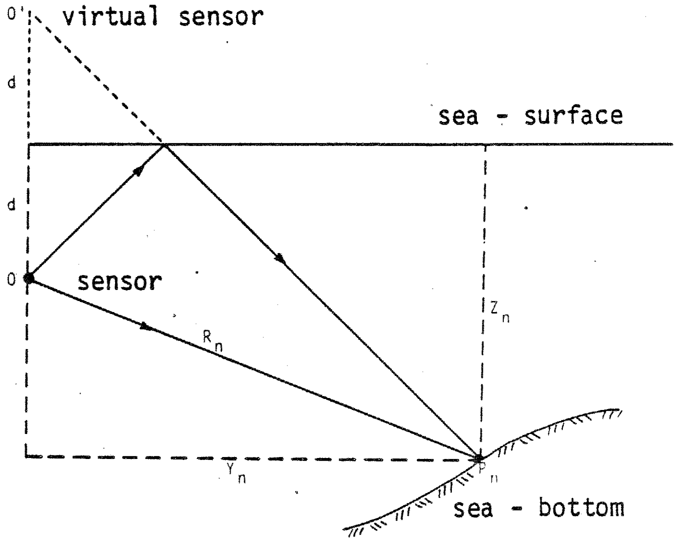

Fig.3: The geometry of Lloyd-Mirror

The path difference of the two signals can be expressed as

$$\overline{O'P} - R_n = (2n-1)\cdot\frac{\lambda}{2} = (n-\frac{1}{2})\cdot\lambda \qquad (1)$$

Refering to Figure 3 is

$$\overline{O,P} = ((Z_n + d)^2 + Y_n^2)^{1/2} \qquad (2)$$

and

$$Y_n^2 = R_n^2 - (Z_n - d)^2 \qquad (3)$$

The combination of (1), (2) and (3) leads to

$$Z_n = \frac{(2n-1)\cdot\lambda\cdot R_n}{2d} + \frac{(n-\frac{1}{2})^2\cdot\lambda^2}{4d} \qquad (4)$$

$$Y_n = (R_n^2 - (Z_n - d)^2)^{1/2} \qquad (5)$$

where n = number of fringe areas

R_n = range of P_n (can be taken from image refering to scale)

λ = used wave length

d = towing depth

Z_n = water depth of P_n

Y_n = horizontal distance of P_n

The equations [4] and 5] are the fundamental relations for the determination of discrete three-dimensional coordinates from a two-dimensional image if fringe order n and towing depth d are known.
The missing coordinate X_n is exclusively given by the sensor position due to ship speed and recording time.

2.2 Synthetic Processing of Interference Fringes

The natural appearance of Lloyd-Mirror fringes is limited because of wind and weather conditions. For a convenient use of this effect for topographic mapping it has to be processed synthetically. Preserving the hydrodynamic properties of a towing system it is necessary to use two transducers which work exactly synchroneous and are transmitting to the same side an in the same plane. The interference geometry then is simplified because of loss of surface reflection. This situation is shown in Fig.4 [Kolouch, 1980].

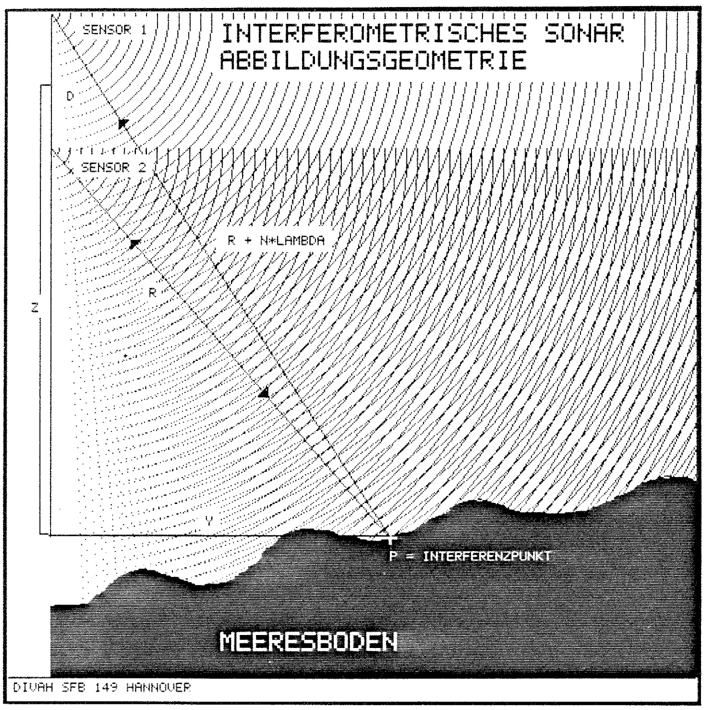

Fig.4. Interference pattern processing using two transducers

The water depth is now calculated from the sensor centre as zero point. There is no longer a phase change at reflection and therefore path difference has to be now an integer number of wave length used. The towing depth is replaced by half of sensors distance D. Regarding to this situation the equations [4] and [5] change to

$$Z_n = \frac{R_n \cdot n \cdot \lambda}{D} + \frac{n^2 \cdot \lambda^2}{2D} \qquad [6]$$

$$Y_n = [R_n^2 - [Z_n - \frac{D}{2}]^2]^{1/2} \qquad [7]$$

3. The Interferometric Side-Scan-Sonar Equipment

The equations [6] and [7] are valid only for the case of an absolute vertical baseline D between the two transducers. This is not given because of the dynamic towing situation. Mainly rolling in ω changes the effective direction of the coordinate reference plane and leads to a wrong determination of the water depth Z_n, if this parameter is not recorded and taken for correction. Pitch [ϕ] and Yaw [κ] have more influence on X_n- and Y_n-coordintes and falsify water depth only little. Nevertheless, synchronous recording of all angular parameters is necessary for further evaluations.

3.1 The Interferometric Side-Scan-Sonar Sensor [ISSS-Fish]

Realisation of the theoretical fundamentals of Interferometric Sonar was made at Hannover University [Kolouch in SFB, 1979]. Based on the electronic components and the original transducers of the system Mark1B from EG+G a new tow fish was built, which carries both transducers on one side.

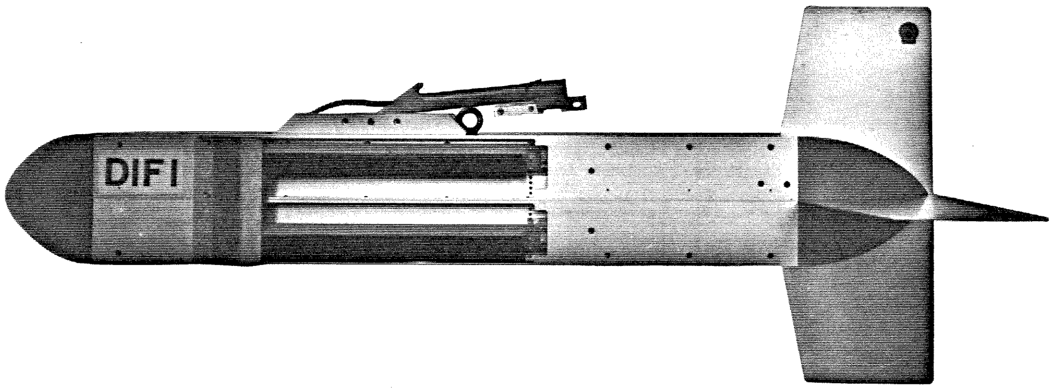

Fig.5: Interferometric Side-Scan-Sonar Fish [closed]

The depression of the transducers can be adjusted up to 35° down for different water depth. The fish-length is about 1,30 m and its weight 72 kg. The transducers baseline can be varied from 10 to 25 cm, which allows the processing of 17 interference lines at a frequency from about 105 KHz. The fish is made of aluminium hollow sections, which are flooded while surveying. Inside the fish a water-tight tube is mounted, which contains the standard electronic elements, a three-axis rate transducer and a telemetry system, that makes a transmission of the rate signals possible using a standard tow cable [Figure 7 and Figure 8].

In deviation from the concept mentioned before the interference patterns are produced indirectly. Because of loss of coherence of the two outgoing signals from the two transducers only the lower one is transmitting. The returning echos are received by both and the interference signals is processed by electronic signal mixing. In addition this procedure has the advantage of synchronous processing of standard and interferometric sonar image, which are in this system recorded on the original port and starboard channels.

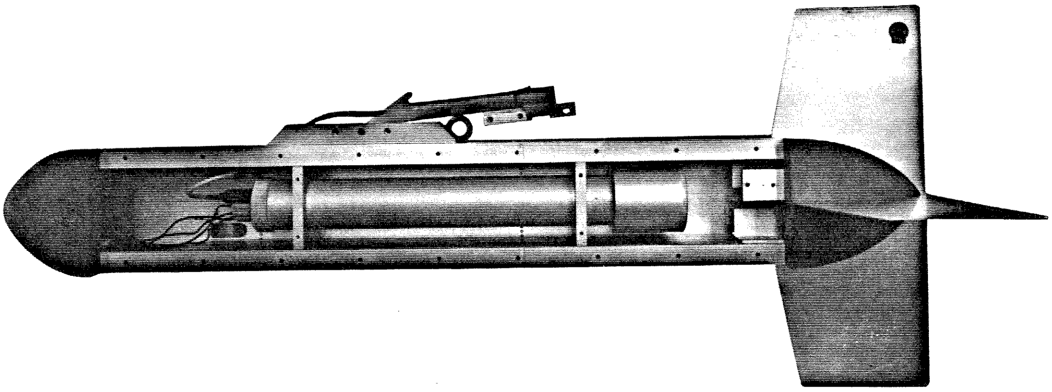

Fig.6. Interferometric Side-Scan-Sonar Fish (open)

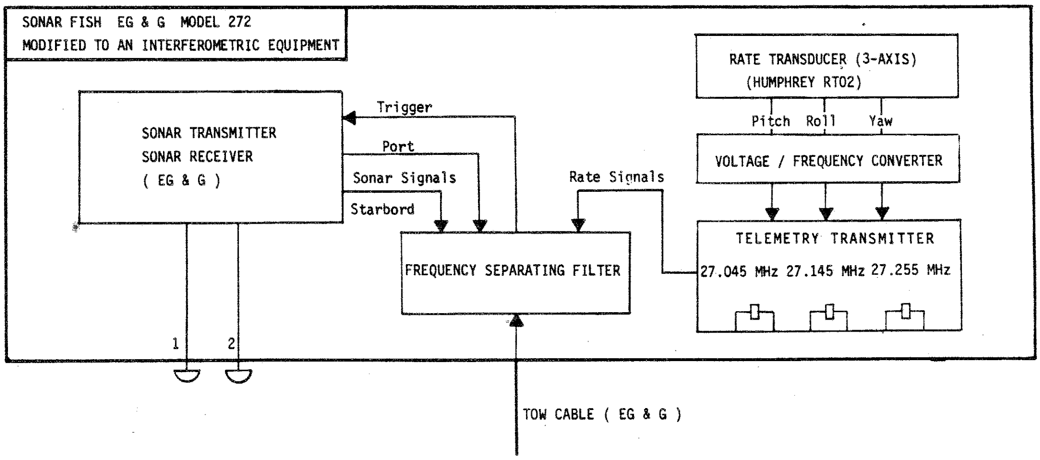

Fig.7: Electronic equipments in the ISSS-fish

3.2 A Special System for Data Preprocessing and Recording

Signal processing and recording is still controlled by a standard recorder belonging to the EG+G system. Between fish and recorder a special data processing equipment is installed. It is the housing of the explained electronic signal mixing, whjch includes a changeable low-pass filter and a frequency control unit. Furthermore this system contains the electronic parts for seperation of rate-transducers signals and the two image data strings. All information is stored on PCM-controlled videotape, organized as follows: One channel on tape starts with the rate signals followed by the image data of an interferometric image line, while the other channel gets the standard sonar signal with the trigger pulse at the beginning. Trigger and rate signals are recorded with negativ sign and are later used as indicators for line start at analog/digital conversion. The electronic parts are installed in a transportable cabinet, which enables employment on different vessels.

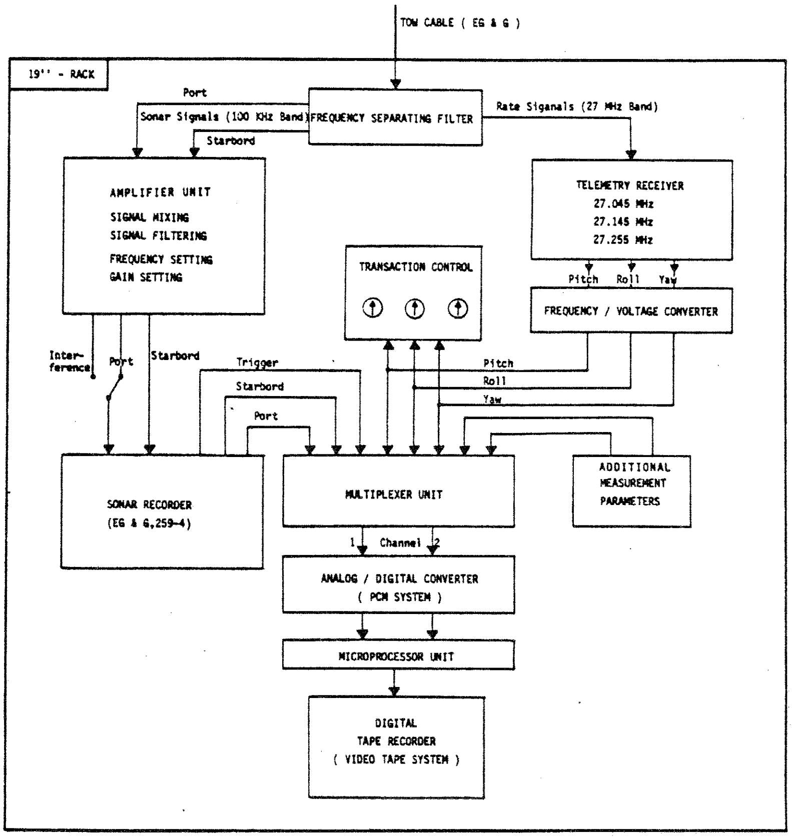

Fig.8. System for Data Preprocessing and Recording

4. The Data Processing Software System

The hardware system presented before is a prototype for interferometric sonar imaging with the aim of processing these data for the determination of three-dimensional space-coordinates from the sea-bottom. The system works up to water depths from about 60 m and ranges up to 150 m. Figure 9 shows a part of a track recorded near Hoek van Holland in cooperation with the North-Sea Directorate of Rijkswaterstaat in the Netherlands.

From the beginning it was the idea to process the obtained data off-line with digital methods. This is done by special image processing software, which is part of an extensive modular software system at Hannover University called MOBI (German: Modulares Off-line Bildverarbeitungssystem), that is made for the evaluation of remote sensing data (Kolouch et al., 1981). The videotape recorded sonar data are first of all digitized by using an A/D-converter and a double buffer interface at a DEC VAX 11/750 computer system. The images are stored on CCT (computer compatible tape) for further evaluation. Prerequisite for this is the development of a geometrical and mathematical model.

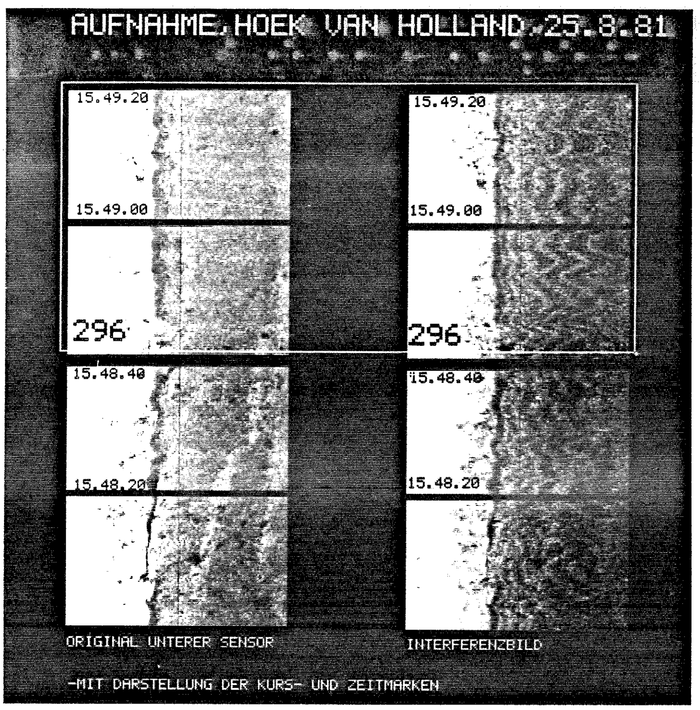

Fig.9: Synchronous recorded interferometric and standard sonar image

4.1 A geometrical-mathematical Model for Data Evaluation

Side-Scan-Sonar is a dynamic imaging system and by that the definition of mathematical connections between image coordinates and space coordintes depend on the recording time. In this case each image line is recorded with an own geometric situation. This will be marked in the following expressions by the index j.
According to Figure 10 four orthogonal coordinate systems will completely define geometry of imaging at time t_j.

$\mathbf{X}_j'$ (X_j', Y_j', Z_j')	"dynamic" sensor system, rotating around its origin due to time
$\mathbf{U}_j'$ (U_j', V_j', W_j')	"static" sensor system, defined with horizontal plane U,V in the same origin
$\mathbf{U}_j$ (U_j, V_j, W_j)	ships coordinate system, parallel to the $\underline{U}_j'$ system with the U-axis in the ships course direction, origin in ships centre
R (R, H, Z)	reference coordinate system

The connections between these systems can be found easily: $\mathbf{X}_j'$ can be transformed to $\mathbf{U}_j'$ (both have the same origin) using a rotational matrix $\mathbf{A}_j$, wich contains functions of pitch, roll and yaw. Coordinates fixed in $\mathbf{U}_j'$ are transformed to $\mathbf{U}_j$ with respect to translational parameters α_j, β_j and d, using functions of them in the matrix $\mathbf{B}_j$. At last a simple coordinate transformation from $\mathbf{U}_j$ to $\mathbf{R}$ is necessary with respect to the measured positioning data of the ship. This is done in sequences between two positioning points P_{0i} and P_{0i+1} by the valid matrix $\mathbf{D}_i$. In summary the equations for the determination of space coordinates for discrete interference points are

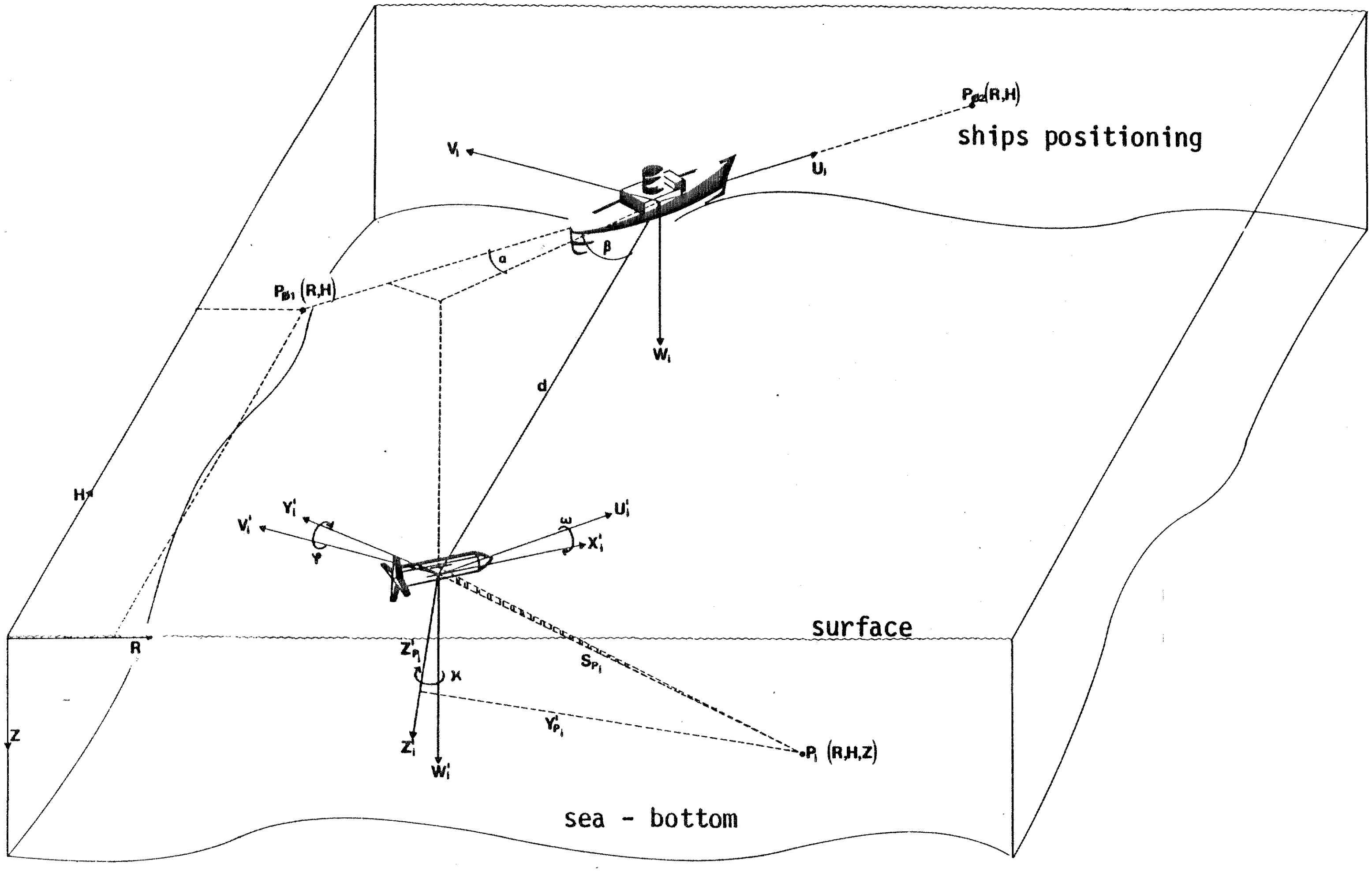

Fig.10: Geometric Model for the Situation of Imaging

$$\begin{vmatrix} R_{P_i} \\ H_{P_i} \\ Z_{P_i} \end{vmatrix} = \begin{vmatrix} R_{0_i} \\ H_{0_i} \\ 0 \end{vmatrix} + D_i \cdot \left| \begin{vmatrix} \Delta U_j \\ 0 \\ 0 \end{vmatrix} + A_j \cdot \begin{vmatrix} 0 \\ Y'_{P_{ij}} \\ Z'_{P_{ij}} \end{vmatrix} + d \cdot B_j \right| \qquad [8]$$

For these expressions two important pionts have to be mentioned: The ΔU_j coordinate depends exclusively on ship speed and is linearily determined from the recording sequence of the image line, using recording time between two positionings. The connection to the image is only given, if these positionings are marked in the image (by event mark switch). The coordinate input in the equations (8) are $Y'_{P_{ij}}$ and $Z'_{P_{ij}}$, which are determined from the image coordinates by using (6) and (7). That means, the processing of space coordinates in the coordinate system X_j' from all the imagery is done before determination of (8). Using digital image preprocessing routines, this can be done automatically and by this all the evaluation process is automized.

4.2 Determination of Interference Pattern Image Coordinates

Digitized images are organized in raster coordinates. Each image point is fixed by row and column and has an allocated density in integer values between 0 and 255 (8-bit conversion). The automatic determination of the image coordinates for the fringe pattern is in every single row, which contains the original data, really diffilcult. Figure 11 shows why.

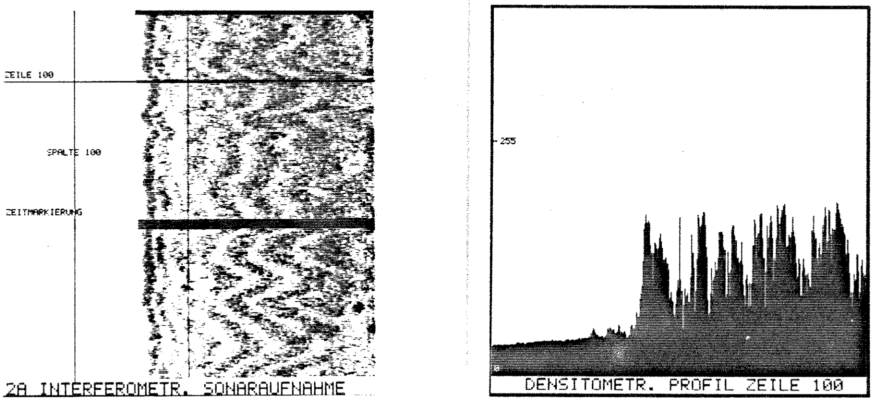

Fig.11: Interferometric sonar image with densitometric row profile

While the human eye can detect the pattern by accounting the whole image information, it is not possible for a single row, as the densitometric profile shows. Six maxima values should be found. These difficulties depend on strong image noise caused by the different electronic elements for signal processing. Noise has to be removed for further operations.

Tests with simple digital filters like moving average or median filtering gave not the desired results (Kolouch in SFB, 1982). To find a better working filter function, the image was analyzed by Fourier transformation (Castleman, 1979). This could be done one-dimensionally because the image contains parts, where no sound reflection takes place. In this area no image information is received, while the electronic elements are already working, so only noise is expected.

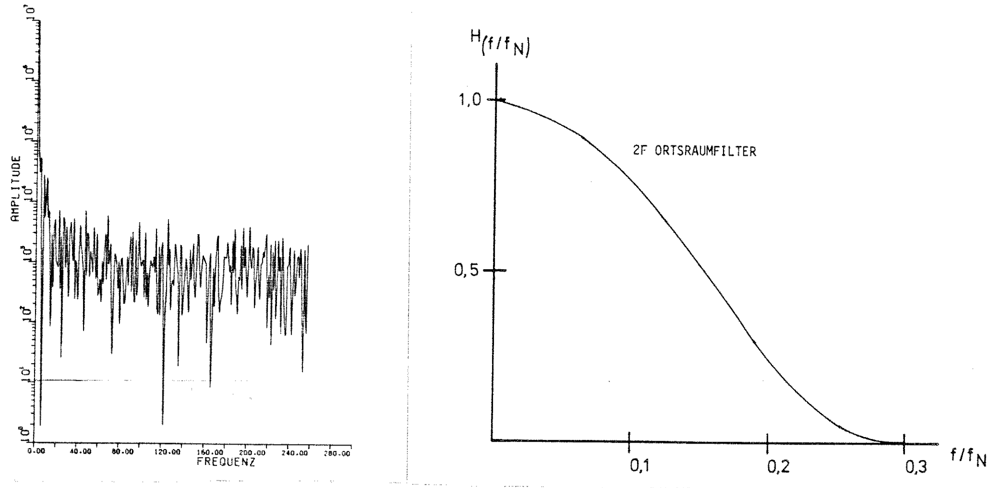

Fig.12: One-dimensional Fourier transform and designed filter function

Figure 12a) shows the power spectrum. There is no longer intensity loss at frequencies greater than 0.2 f_N (f_N = Nyquist frequency). In these frequency areas more noise than signals takes place. Outgoing from this analysis a low-pass filter function was designed (Figure 12b), which works in the space domain. Filtering in the frequency domain was tested too, but gave not essentially better results.

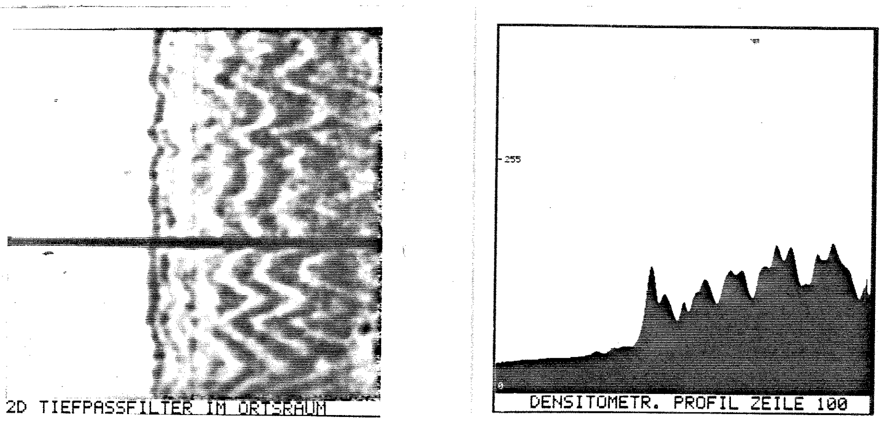

Fig.13: Filtered ISSS-image with densitometric row-profile

The filter result can be seen in Figure 13a), again shown with a densitometric profile of the same row. The image got blurred, but the profile demonstrates, that an automatic pattern detection now is possible with additional simple procedures (Ehlers and Kolouch, 1982).

5. Data Processing

The developed hardware requipment for synchronous interferometric and standard sonar imaging allows in combination with the introduced software package the determination of discrete three-dimensional coordinates from two-dimensional image coordinates. These data can be used for further processing with different aimes. This can be the interpolation of a Digital Terrain Model (DTM) with following automatical depth-line plotting. Figure 14 shows an example, which was processed from only one short interferometric side-scan-sonar record.

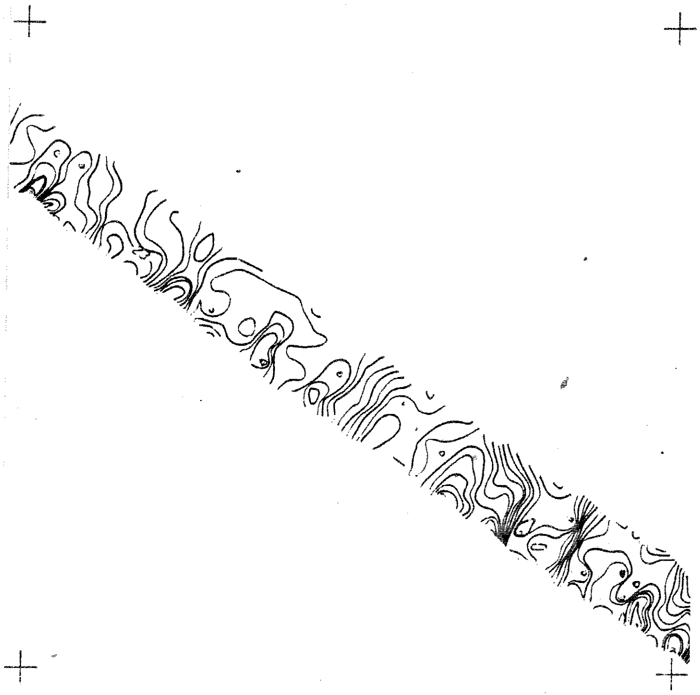

Fig.14: Automatically processed sea-map (plotting with TASH, Kruse, 1980)

On the other hand the data obtained can be used for the rectification of the standard sonar image.

As mentioned before interferometric and standard sonar images are recorded synchroneously. Therefore the image coordinates in the digital raster correspond to each other. Referring to equations (6) and (7) horizontal distances Y'_n and water depth Z'_n are determined from discrete image coordinates for the interferometric pattern in each single image line. To rectify the standard image in such a way that all image points are represented in an horizontal plane the Z'- and Y'-coordinates must be transformed from the "dynamic" sensor system to the "static" sensor system. If correction by image line by image line is intended only rolling in ω has to be taken into account. That is a simple coordinate transformation

$$W'_n = Z'_n \cos\omega - Y'_n \cdot \sin\omega \qquad (9)$$

$$V'_n = Z'_n \cdot \sin\omega + Y'_n \cdot \cos\omega \qquad (10)$$

The now horizontal distances V'_n correspond to the measured image coordinates in the standard image and an orthophoto can be processed by using these passpoints by simple linear and polynomial interpolation line by line. Figure 15 shows this processing from the original sound image using the interferometric pass point information to a ground range representation with depth lines in overlay.

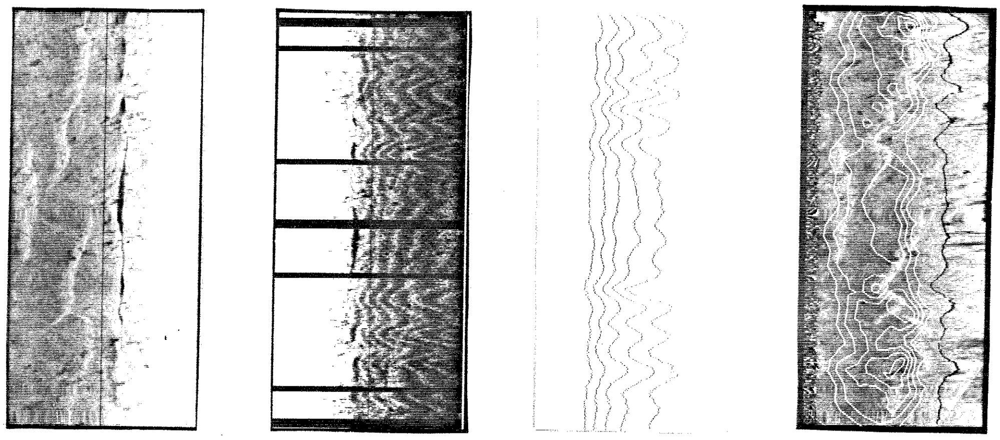

Fig.15: Orthophoto processing

It has to be mentioned, that this processing is not a strong orthophoto rectification. But as pitch has no influence on horizontal distance and yaw motion is in the order of the horizontal image point resolution this form of rectification is good enough for interpretation and planning activities. A further step is the consideration of sensor positioning for absolute rectification.

6. Conclusion

In combination with the hardware equipment an interferometric recording and processing Sonar-System has been developed, which is able to produce topographic maps from the sea-floor together with geometrical corrected images. This rises the possibilities for better interpretation of sea bottom features. Controlling activities in prospectorial areas as well as change detection in tidal areas can be done with less operational expense because of area covering data recording. The digital data evaluation gives the possibility for automatic processing. The software is part of the extensive modular system for digital geometric and densitometric image processing called MOBI, which allows special evaluations for better feature seperation. The hardware system is developed for shallow water areas, but it seems possible to use a system like this for deep sea activities.

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