Sophisticated Sonar Scene Simulation for Acoustical Imaging Applications

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Abstract

The validation of high sophisticated signal processing techniques for minehunting application requires the availability of data covering all kinds of scenarios. For this reason a sonar simulation program has been developed, which generates realistic sonar data for a wide range of sonar scenes. Acoustical data are determined by the motion of the sensor carrier, the antenna system, backscattering, and environmental parameters. Backscattering from the sediment surface, the sediment volume and the target is implemented by applying facet models, which yield realistic data. Targets can be positioned on the sea floor or in the sediment volume. Basic signal processing tools like conventional beamforming and synthetic aperture sonar (SAS) beamforming are implemented.

1 Introduction

The simulation model for minehunting sonar systems is presented below. The intention of the modelling is to simulate a typical minehunting scenario as close to reality as possible. Modelling a minehunting mission means to consider in detail mission planning, sound transmission, backscattering and sound reception, signal and display processing. A detailed characterisation of the received signal is particularly challenging, because it consists of a multitude of echoes arising from the water volume, from boundary layers and from the sediment volume as well as from objects in the water column, on the bottom and in the sediment. Therefore in addition to modelling the physical properties of sediment volume, targets and the water-/sediment boundary layer, the generation of appropriate transmitter and receiver signals is required. Special emphasis has been laid on both, lifelike modelling the motion of the sensor carrier and the receiver signals as well as on the design of signal processing procedures, these representing the main requirement for further investigations regarding motion compensation in SAS applications. In minehunting scenarios the impact of sea bottom surface and sediment volume is significant and, for this reason is modelled in particular detail. The simulation program has a modular design. It consists of the segments pre-processing, net generator, signal generator, signal fusion, signal processing and display. Each of the program segments is organised modularly, so that it can be upgraded and adapted according to a proceeding level of awareness. The concepts, the different model parts are based upon, the structure of the program and simulation results are presented below.

2 Simulation Concepts

Modelling a mine hunting scenario requires in addition to modelling sound propagation and backscattering properties, models for sensor carrier motion and motion measurement systems. To simulate the backscattered signal from extended water/sediment boundary layers, inhomogeneous sediment volumina and complex shaped targets four independent modules are required. *Transmitter/Receiver:* Positions and velocities of the hydrophones, their beam patterns and the parameters of the transmitted pulse. *Geometry:* Regarding the sediment surface a two dimensional grid model with sufficiently fine resolution is adequate. To model sediment volume and targets a three dimensional representation is necessary, assigning, where appropriate, different acoustical properties to each spatial grid point. *Interaction:* The transmitted sound wave interacts with the scattering medium and targets. The complexity of the applied interaction model has to be adapted to both, the desired preciseness of the results and to the available computational performance. *Signal generator:* At each given time and each position the resulting sound pressure is obtained according to the applied interaction model by superimposing the signals from all scatterers, taking into account Doppler shift and delay due to the sound travel time.

2.1 Sensor Carrier

The sensor carrier model simulates the motion of the carrier in 6 degrees of freedom. Each motion component is generated from a low pass filtered normal distributed random signal. By repeatedly generating a random signal different realisations of a typical motion can be modelled. By varying the cutoff frequency of the low pass filter and the parameters of the random process the program provides the capacity to model typical motion of different types of sensor carriers. The input parameters define the current sensor carrier motion. These motion data are required as input to the signal generation. Simultaneously an inertial system is simulated, providing the measured data of the sensor carrier motion. It consists of an accelerometer to measure the translational and of a gyro to measure the rotational motion components. The translational data (velocity and position) are obtained by integrating the acceleration of the sensor carrier including the typical noise of the accelerometer. By integrating the angular rate, embedded in typical gyro noise the measured angular data are calculated. The performance characteristics of the inertial system have to be defined. The correct motion data are required for assembling the receiver signal while the measured data are provided as input data for the beamformer. The motion data of the transmitter antenna and the receiver sensors are obtained by transforming the transmitter and receiver antenna system into the current sensor carrier’s co-ordinate system.

2.2 Signal

Various shapes of signals with different parameters can be simulated. At the time complex CW signals with rectangular or a cos^2 envelope are available. The signal parameters (pulse duration, pulse repetition rate, centre frequency etc.) required for the simulation have to be defined in the input dataset.

2.3 Transmitter/Receiver Antenna

Transmitter antenna and receiver elements are modelled as an arrangement of transducers, the 2-dimensional beam patterns of which are calculated in utilities outside the simulation program and are stored in data files. The currently selected antenna configuration and the names of the data files containing the beam patterns have to be defined in the input dataset. The beam pattern of the total receiver antenna, which consists of an arrangement of receiver staves, is obtained by superimposing all stave signals during beamforming in the subsequent signal processing step.

2.4 Sound Propagation and Reverberation

The sound propagation model describes the acoustical properties of boundary layers, water and sea bottom. It includes an ambient noise model, a volume reverberation model of the water, a sea surface reverberation model, a target model and, a surface and volume reverberation model of the sediment. *Ambient Noise:*The ambient noise level in the water is composed of thermal noise, sea state noise, ship noise and turbulent noise. The time signal of the ambient noise is described by a normal random process with a variance according to the ambient noise level. The environmental parameters have to be defined in the input dataset. *Sound Attenuation in Water:* Attenuation of the signal in water consists of absorption and geometrical (divergence) losses. Absorption in the water volume is calculated according to Francois-Garrison. Losses due to divergence are determined from the sound ray path. *Target Objects:* A target object is modelled as a facet model [1]. It is defined by target type (sphere, cylinder, etc.), dimension, position, and orientation. Different objects are modelled by arranging facets with aspect depending backscattering properties on the surface of the object. The backscattering of each facet is modelled as that of a plane circular element. Orientation and accordingly backscattering strength is defined by the 3-dimensional vector normal to the object surface at the facet’s grid position. The total backscattered signal of the object is obtained by coherently superimposing the reflections from all facets taking into account the Doppler shift. By scaling the target signal amplitude the result can be adapted to measurements and object material properties. The target parameters are defined in the input dataset. *Water-/Sediment Boundary:* Layer backscattering from the bottom surface is modelled by arranging scatterers on the plane sediment surface [1]. The bottom surface structure is described by an equidistant bottom grid with spacing smaller than the signal wavelength. Bottom roughness properties are reproduced by low pass filtering a 2-dimensional random process [1] and [4]. Adjusting the filter's cutoff frequency and the variance of the random process yields different bottom types. At each bottom surface grid point a scatterer (facet) with angle dependent backscattering characteristic is located. The facet orientation is given by the orientation of the surface element at this position. The facets are modelled as plane circular disks. Their backscattering strength is defined by the angles between the vector normal to the facets surface and the vectors pointing to the transmitter and receivers respectively. Thus each grid point is defined by the 3-dimensional vector normal to its surface. The backscattered signal of the total bottom area is finally obtained by coherently summing the reflections of all facets taking into account the Doppler effect. By scaling its amplitude the simulated bottom surface signal can be adjusted to other bottom models or to experimental data. *Transmission at the Boundary Layer:* Transmission at the boundary layer is determined by the transmission coefficients from water into sediment and inversely from sediment back into water. Both angular dependent transmission coefficients are calculated for a plane surface according to the type of sediment. *Sediment Volume:* Backscattering from the sediment volume contributes significantly to the total backscattering. The volume backscattering is caused by inhomogeneities like shells, inclusions of mud and variations of sediment specific density. These effects are described by the 3-dimensional density spectrum of the sediment volume [2], [3]. By Monte-Carlo realisations different realisations of the sediment density distribution can be obtained [2]. Different density spectra define different bottom types. For modelling the sediment volume an equidistant, 3-dimensional sediment grid of scatterers is spanned down to a defined depth by extending the 2-dimensional bottom grid into depth. Each grid point is characterised by its position as well as the local density gradient and reflection coefficient. By superimposing the signals reflected from all scatterers in the sediment volume the total sediment volume scattering signal is determined. Scaling can be performed in order to adjust the amplitude of the simulated volume scattering signal to the results from different reverberation models or experimental data. *Absorption:* Absorption in the sediment is calculated according to the type of sediment. Independent from the actual density within the modelled sediment volume a constant attenuation coefficient represents the absorption.

2.5 Signal Generation

The problem of signal generation is to calculate the sound pressure amplitude at each receiver and given sampling times t'. This signal is composed from contributions of all scatterers (mine, bottom surface, sediment volume). In doing so, for all scatterer-receiver combinations the Doppler shift of the scattered signal has to be determined. *Doppler Effect:* For a given receiving time t' the time t, at which the signal fraction received at t' has been transmitted, is to be determined taking into account the movement of transmitter and receiver. This has to be carried out for each t' and for all contributing transmitter-target-receiver constellations. *Signal Fusion:* To calculate the time series of the signal for all receiver elements, the following procedure has to be applied: Find the transmitting time t for all facets and for all receiving times t'. Calculate the corresponding distances from the transmitter to a particular receiver. Weight the distance with absorption, geometrical spreading loss and transmission coefficients. Determine the angle of elevation and azimuth between transmitter-facet and facet-receiver, each with regard to the orientation of both. Weight the reflectivity of the facet by transmitter, receiver, and facet pattern. Evaluate the transmitting signal at time t. Finally sum up all facet signals. This sequence has to be performed for all receiver elements. The procedure is performed for each target, bottom and sediment scatterer separately, so the bottom surface signal, the target signal and the bottom volume signal are available individually. The individual components of the simulated signal are fused with ambient noise, water volume and sea surface reverberation to create the total receiver signal. The simulated total signal is finally bandpass filtered to eliminate potentially arising bias components which cannot propagate in water.

2.6 Signal Processing

The signal processing model has the following main components beamforming (focussing near field 1D & 2D beamformer) SAS signal processing and autofocussing. The sampled receiver signals serve as input data for the conventional beamforming capacities. *SAS Processing:* SAS signal processing is performed following the standard SAS method taking into account near field conditions. The principle of the synthetic aperture is based on a physical aperture with the length of d in along track direction. While the sensor system is moving along its track, a sequence of pulses transmitted at positions spaced at intervals $d/2$ is received by the physical array. The velocity of the platform is presumed to be straight and uniform. Regarding a single scatterer, the received echoes plotted against along track distance and range form a hyperbola. Location and shape of the hyperbola depend on the distance from transmitter to the scatterer (solid arrow) and the distance from scatterer to receiver (dashed arrow). Scatterers at different ranges result in different hyperbolas. By coherently summing the echoes received by the synthetic aperture length L along the hyperbola (azimuth compression) the point of the SAS image, which corresponds to the selected range, is obtained. By SAS processing the azimuthal resolution of the sonar system is increased according to the length of the synthetic aperture (optimum $d/2$). The SAS image (azimuth compressed 2-dimensional data field) shows the echo of the scatterer at the CPA position. In order to eliminate phase errors due to not completely compensated sensor carrier motion an autofocus procedure is applied.

3 Summary

The physical and mathematical background for the concept of a simulation model for realistic modelling of a minehunting sonar scenario including the generation of sonar signals and adequate signal processing has been presented. Upon these results a simulation program has been implemented in Matlab. This new simulation tool provides the following features: to move the sensor carrier on a track in a realistic sonar scenario, to transmit sound pulses according to previously defined sonar properties, to simulate sound scattering at the bottom surface, in the bottom volume and on the target objects, to fuse scattered sound with ambient noise, water volume and sea surface reverberation and to feed these signals into the elements of a specified receiver antenna as well as to apply conventional and SAS beamforming algorithms to the received signals and to display the results as sonar images. Thereby particularly the facet sound ray model provides a simple (and in case of appropriately chosen parameters not to expensive) opportunity to simulate realistic sonar scenarios. Because the signal generation in the model considers completely the Doppler effect, any desired track can be realised. Upgrades and adjustments of the existing program is easy to accomplish due to the modular structure of the model. It has been shown, that with this new simulation utility realistic sonar images can be generated, so that it can serve as a tool for investigating and optimising advanced signal processing techniques.

4 Literature

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