AN INTEGRATED COMPUTER SYSTEM FOR UNDERWATER ACOUSTIC DETECTION ANALYSIS*

Institute for Applied and Computational Mathematics, Foundation for Research and Technology Hellas, PO Box 1527, 711 10 Heraklion, Crete, Greece.

An integrated computer environment has been developed for the analysis of underwater acoustic detection systems. It can treat passive detection, broadband or LOFAR, as well as active detection, monostatic or multistatic. The system contains efficient databases for environmental (e.g. oceanographic, geological) and operational data (e.g. detection system parameters, target characteristics). Acoustic propagation calculations are performed with normal-mode, parabolic approximation and ray-theoretic codes supporting broadband calculations in range-dependent environments. The results include transmission loss, reverberation levels, detection thresholds and probabilities of detection for a number of user-defined operational scenarios.

1. INTRODUCTION

The objective of underwater acoustic detection systems is to sense the presence of acoustic signals emitted by or reflected from underwater objects. The detection performance critically relies on the propagation characteristics and, thus, propagation modelling plays a central role in the analysis of underwater acoustic detection systems, Burdic (1), Urick (11). The ocean environment is in general range dependent and may range from deep to shallow water, whereas the acoustic signals may be of low or high frequency, broadband or narrowband, depending on the type of detection. On the other hand, different acoustic propagation models have different domains of applicability concerning environmental and signal characteristics, Etter (2). To address the variety of cases encountered in acoustic detection a pool of propagation models is required, from which to select the most appropriate one in each case.

An integrated computer environment has been developed for the analysis of underwater acoustic detection systems, and it was given the name ΚΑΛΥΨΩ (CALYPSO). ΚΑΛΥΨΩ has been designed for the treatment of passive detection, broadband or LOFAR, as well as active detection, monostatic or multistatic. Acoustic propagation calculations are performed with normal-mode, parabolic-approximation and ray-theoretic codes supporting broadband calculations in range-dependent ocean environments, from low to high frequencies and from deep to shallow water. Propagation characteristics are combined with signal-processing parameters and receiver operating characteristics to obtain the probability of detection as a function of range and depth.

ΚΑΛΥΨΩ can accept user-defined or adjusted public-domain environmental databases (oceanographic, bathymetric, geological); all databases are in geospatial form (i.e. they use vector rather than gridded format), enabling the direct import and exploitation of in situ measurements of environmental data. Further, there are databases of operational characteristics (e.g. detection system parameters, target characteristics) allowing the easy setup of a variety of operational scenarios. ΚΑΛΥΨΩ has been developed for MS/Windows and requires no additional supporting software. The communication language is Greek.

* Work supported by the Greek MOD
2. SYSTEM STRUCTURE

The system is built around a small and efficient kernel module that interacts, manages and controls all other system components shown in Fig. 1. These other components include several databases, the acoustic codes and a graphical user interface. The system kernel module is augmented by a large number of additional modules containing specific functions and data infrastructure for the performance of certain tasks. There are two kinds of system modules. *Native* system modules provide all the essential system functionality required during a session with KAALYP. *External* system modules are autonomous components that utilize the kernel system infrastructure to further augment the capabilities of the system.

**Native System Modules**

The system contains over 30 native modules carrying out specialized functions. To preserve the computer resources while KAALYP is running, only a small number of essential native modules are active continuously, while all other modules are activated on demand. Some of the most important native modules are:

![System Structure Diagram](image)

*Fig. 1. Block structure of the KAALYP system*
Geographical Map Module. This module supports a fully interactive geographic map that is available at all times during system operation. Beyond the usual map functions (zoom, pan, scroll, area selecting etc.) ΚΑΛΥΨΩ map supports dynamic placing and steering of operational vessels as well as dynamic selection and steering of sections/bearings.

Problem Definition Module. This module manages all functions related to the definition of a problem. To define a ΚΑΛΥΨΩ problem the user must specify a geographic location, a valid scenario and detection type as well as several other parameters. ΚΑΛΥΨΩ supports various types of carriers (ship, submarine, etc.) that can be combined to produce different scenarios. A typical ΚΑΛΥΨΩ scenario could be: "submarine is detected from a surface ship / active detection."

Environmental Database Management Module. ΚΑΛΥΨΩ supports four kinds of environmental databases (coastline, bathymetry, oceanographic and geological data) whereas it allows for the import and direct exploitation of in situ measurements of environmental data. This module supports all actions related to the access, modification and maintenance of the above databases.

Operational Database Management Module. ΚΑΛΥΨΩ supports different databases containing the operational characteristics of Transceivers, Sources and Receiving Arrays. Elements from these databases are combined to define a specific operational database containing the operational characteristics as well as the physical properties of Carriers. This module supports all actions related to the access, modification and maintenance of the above databases.

Acoustic Code Evaluation and Selection Module. ΚΑΛΥΨΩ features three different acoustic propagation codes. The user can either select manually or let the system pick the most appropriate code automatically. The selection is based on the evaluation of the codes for each particular case. This evaluation is carried out by an expert subsystem checking a number of applicability criteria for each method/code.

Problem Solving Module. The solution of a ΚΑΛΥΨΩ problem is carried out in three distinct phases. Phase 1 involves the execution of an acoustic propagation code for several frequencies. Phases 2 and 3 use the produced acoustic results as well as the source and receiver characteristics to calculate the detection threshold and probability of detection. If the problem consists of multiple sections then the above procedure is repeated for each separate section. The problem solving module contains functions that manage and monitor the solution process. It also contains functions that provide the user with a visual progress feedback, remaining time estimation and the capability of partial or complete cancellation of the solution process.

Results Management and Displaying Module. When a ΚΑΛΥΨΩ problem is solved several kinds of results are produced. These include transmission loss, reverberation level, detection threshold and probability of detection. This module contains a number of graphical functions for displaying the results in a variety of display modes. It also associates the results produced with the problem that produced them. This way each time a problem is opened its results are also opened and displayed on screen.

Problem Management and Integrity Module. This module is used for checking all information collected during the definition phase of a problem for consistency, completeness and integrity. It also contains functions for checking the integrity of the files that are loaded/stored whenever a problem is opened/saved.

System Management and Integrity Module. This module is part of the kernel of the system. It contains functions that monitor ΚΑΛΥΨΩ during its operation ensuring its integrity at all times. It also supports the management of the system configuration parameters as well as the user preferences.

User Support and Assistance Module. The User Support and Assistance Module provide help to the user in several ways including standard context-sensitive on-line help, extensive FAQ and ‘How-To’ lists of topics and a standard ‘Tip-of-the-day’ feature on startup.

External System Modules
As stated above, the external system modules are autonomous components that utilize the kernel system infrastructure to further augment the capabilities of the system. Only one external module can be active at any given time. Currently ΚΑΛΥΨΩ contains over 10 external system modules including a Oceanographic Data Editing Module, a Geological Data Editing Module, an External Results Management Module, a Multiple Mode Results Comparison Module, a Multistatic Source Positioning Analysis Module and more.

3. SYSTEM DATABASES

During its operation ΚΑΛΥΨΩ has access to databases containing environmental, operational and local user data.

Environmental Databases
The initial environmental data used by the system during the creation of a problem are extracted from four separate databases called Master Environmental Databases. These databases contain coastline, bathymetry, oceanographic and geological data. All databases support geospatial data format (i.e. data are stored in vector rather than gridded format).

When a problem area is defined, the system extracts all coastline, bathymetry, oceanographic and geological data found in that area, into the problem database. Subsequent data manipulation such as editing or data completion with in-situ measurements is performed on the problem database.

Operational Databases
The system supports different databases for the operational characteristics of Transceivers, Sources and Receiving Arrays. Elements from the above databases are combined to define a specific operational database containing the operational characteristics as well as the physical properties of individual Carriers.

ΚΑΛΥΨΩ supports a number of different types of carriers (ship, submarine, etc.) Each carrier can be fitted with different transceivers, sources and receiving arrays, up to eight of each type. Each record in the Carriers database includes fields containing the carrier’s type ID and name, as well as the description of all devices fitted on it. It also contains information about its physical characteristics (acoustic signature and target strength). This last information is necessary in case the carrier gets the role of target in a ΚΑΛΥΨΩ scenario. When a carrier is given a certain role in a ΚΑΛΥΨΩ scenario then the user may select which of the devices fitted on it will be used.

Local User Databases
Apart from the data contained in the environmental databases the system allows the import and direct exploitation of in situ measurements of environmental data. The new data collected this way are kept in separate local databases (bathymetry, oceanographic and geological data) having similar structure to the corresponding master environmental databases.

Data Confidentiality
To ensure data confidentiality and maximize the dissemination of the software, ΚΑΛΥΨΩ is initially furnished with a set of environmental and operational databases containing figurative
(hence unclassified) data. These data have been collected from the public domain and they are accurate enough to demonstrate the capabilities of the system.

\textit{KAATYPΩ} features a switching mechanism that allows the user to switch among any number of available environmental or operational databases at any time.

During \textit{KAATYPΩ} installation the user is informed that the databases installed are for demonstration purposes only and advised to replace these figurative databases with ones containing real data. This action can be taken either during the installation procedure or at any time thereafter.

4. ACOUSTIC PROPAGATION CODES

Three different acoustic propagation codes, CRAY, CNM and CPE, are incorporated in \textit{KAATYPΩ}. These are FORTRAN codes developed for \textit{KAATYPΩ}. They all allow for broadband calculations in range-dependent ocean environments.

CRAY is a code for transmission-loss and reverberation calculations based on ray theory (high-frequency asymptotic approximation), Jensen et al. (4). The code assumes linear bathymetry and constant water/bottom stratification within each range segment, whereas it allows for refraction at the vertical interfaces between adjacent segments.

CNM is a normal-mode code for transmission-loss calculations, Jensen et al. (4). Range-dependent environments can be treated using either adiabatic or coupled modes assuming constant bathymetry and water/bottom stratification within each range segment, Evans (3). For the solution of the vertical eigenvalue problem CNM adopts the Sturm method implemented in the KRAKEN code, Porter (8), Porter and Reiss (9), and applies frequency interpolation for eigenvalues and eigenfunctions to accelerate broadband calculations.

CPE is a code for transmission-loss calculations based on the parabolic approximation, Lee and Pierce (5). CPE applies a finite-difference scheme and automatically selects the narrow-angle or wide-angle approximation, Tappert (10). The use of an impedance condition at a fixed depth below the bottom boundary, Papadakis (6), (7), minimizes the computational domain. Range dependence can be treated by assuming either constant bathymetry and water/bottom stratification within each range segment or a piecewise linear variation of the water/bottom properties in the horizontal.

Normal-mode theory and the parabolic approximation are applicable to low/intermediate frequencies and/or shallow-water environments. Prior to the integration of the acoustic propagation codes in \textit{KAATYPΩ} excessive benchmarking has been carried out in the frequency range 0.1-60 kHz (0.1-10 kHz for CNM and CPE), using a variety of characteristic environments.

In \textit{KAATYPΩ} the selection of the more appropriate code in each case is carried out either directly by the user or automatically by the system. The automatic selection is based on the evaluation of the codes for each particular case. This evaluation is carried out by an expert subsystem checking a number of applicability criteria for each method/code.

5. RECEIVER OPERATING CHARACTERISTICS

For specific target/detection characteristics and for a particular environment/geometry \textit{KAATYPΩ} provides the spatial distribution of the probability of energy detection assuming Gaussian statistics of the noise and the signal plus noise, and using the corresponding receiver operating characteristics, Burdic (1), Urick (11).
When the time-bandwidth product is large ($TB>>1$), which is usually the case in passive detection, the asymptotic form of the receiver operating characteristics is used, Urick (11), relating the probability of false alarm, the probability of detection, and the signal-to-noise ratio at the output of the integrator. In passive detection the time is the integration time and the bandwidth is the receiving bandwidth.

When the time-bandwidth product is comparable to unity ($TB\sim1$), which is usually the case in active detection, the full expressions for the receiver operating characteristics, also depending on the time-bandwidth product, Whalen (12), are used. In active detection the time equals the pulse duration and the receiving bandwidth is the reciprocal pulse duration (in case of zero Doppler) such that the time-bandwidth product equals 1. In case of relative motion the receiving bandwidth is broadened to accommodate Doppler shifts and the time-bandwidth product is larger than 1, still not large enough for the asymptotic form of the receiver operating characteristics to be valid.

6. GRAPHICAL USER INTERFACE

Special effort has been devoted to the design of a graphical interface that is friendly enough even to the unsophisticated user. Because of the large system complexity, the main screen of $KAΛΥΨΩ$ contains only the most essential features. All other (mainly advanced) system features are available on demand through separate screens. To further alleviate the system complexity, $KAΛΥΨΩ$ features three modes of operation corresponding to the natural steps taken during the definition and solution of a problem:

- **Problem Definition Mode**: The user selects a problem scenario, defines the geographical area of interest and fills in a number of other problem parameters. This action triggers the automatic generation of a local problem database containing environmental and operational data retrieved from the corresponding global databases. While in the problem definition mode the user may also edit the extracted environmental data providing external values that complement or substitute the ones extracted from the databases.

- **Problem Solution Mode**: The user selects the most appropriate code for the calculation of propagation characteristics, or instructs the system to do so, and initiates the solution process. Before solving the problem, the user has the opportunity to revise the model created for the acoustic environment, and/or fine tune the acoustic propagation codes by altering their intrinsic parameters.

- **Results Studying Mode**: The user views, combines and compares the results produced (transmission loss, reverberation level, detection threshold and probability of detection) in a number of different ways. The results produced when solving a problem are bundled with the problem itself and treated as a single entity, that can be stored on the disc for later use. This way every time the user opens a saved problem all existing problem results, as well as the background information, become available for studying.

The user can switch back and forth among these three modes of operation at any time.

$KAΛΥΨΩ$ also features a standard on-line context-sensitive help available throughout the system. It also features a Novice User Mode which -when activated- provides extra instructions and advice to the novice user during his navigation through the system. Other ways to provide help include extensive FAQ and ‘How-To’ lists of topics and a standard ‘Tip-of-the-day’ feature on startup.

The system GUI currently consists of over 30 primary and 45 auxiliary screens. The following figures display some representative screens of $KAΛΥΨΩ$. 


Fig. 2. The main screen of ΚΑΛΥΨΩ containing the geographical subsystem (definition of geographical area and geometry) and the remaining problem definition/treatment screens. Here the operational scenario definition screen (definition of detection type and involved carriers) is shown with the scenario of bistatic active detection with multiple receiver bearings selected.

Fig. 3. The acoustic environment editing module. The acoustic environment as retrieved from the environmental databases (left) is discretized into a number of range segments (right) depending on the desired resolution (middle). All parameters within a range segment are editable.
Fig. 4. The editing screen for stations of environmental data (the particular snapshot refers to the bathymetry/coastline stations). Any modifications are applied on copies of the environmental databases created for the area of interest of the particular problem. The user is allowed to deactivate stations or introduce new ones (local database).

Fig. 5. Management & editing screen for the database of operational carriers/platforms. The active/passive target/detection characteristics of available carriers are summarized at the top, and they can be edited in the bottom half of the screen.
Fig. 6. Typical results from detection analysis for a given bearing, including the probability of detection vs. range and depth (middle) as well as vs. range for a particular depth (top). Other possible types of results include the broadband transmission loss and detection threshold (shown in minimized/clickable form at the bottom) as well as reverberation levels. At the bottom right corner the three more recent probability-of-detection results are shown in minimized/clickable form, for comparison. Alternative presentation modes and actions can be selected from the toolbar at the top of the screen.

Fig. 8. Screen for comparison of results from different problems, or from the same problem for different bearings (as shown here), or different analysis selections (e.g. different acoustic propagation codes or detection parameters). Alternative comparison modes and actions can be selected from the toolbar at the top of the screen.
Fig. 8. Synthetic display of the transmission loss results for multiple bearings at a depth of 93m. The exact bearing positions can be observed in Fig 2. Similar graphs are produced for detection threshold and probability of detection results.

REFERENCES