



OTC 10868

A Synergistic Combination of Technologies: Multibeam Bathymetry, Acoustic Reflectivity, Gravity, and Magnetics in the Deepwater Gulf of Mexico

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This paper was prepared for presentation at the 1999 Offshore Technology Conference held in Houston, Texas, 3-6 May 1999.

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Abstract

Exploration and production in the deepwater Gulf of Mexico is hampered by an absence of existing survey data. In the late 1980s and early 1990s, NOAA ventured to map the deep Gulf of Mexico with multibeam sonar. Unfortunately, this visionary project lacked both the funding for completion and the technology to provide the survey accuracy and resolution presently desired.

An aggressive campaign has been initiated to acquire and evaluate collocated multibeam bathymetry, acoustic reflectivity, gravity, magnetic, and sub-bottom data across 17,000 square miles of the uncharted deepwater Gulf of Mexico. Evaluation of these data is being accomplished with new technology developed by the University of New Brunswick, Canada, which interactively integrates them into one common graphical environment. "Fly-throughs" of geo-referenced data provide construction planning, production analysis, and allow for the establishment of geologic correlation. Interrelationships associated with the collection, processing, and interpretation of these various data sets and the benefit of multibeam bathymetry on the 3D Bouguer correction are discussed.

NOAA Surveys

The National Oceanographic and Atmospheric Administration (NOAA) was forerunner in the application of multibeam technology in the Gulf of Mexico. From 1989 to 1992, NOAA conducted a successful campaign of mapping the Gulf beyond the continental shelf. A lack of governmental funding brought the program to a halt prior to its completion. Consequently, a large "data gap" exists in the areas of East

Breaks, Alaminos Canyon, and the western half of Garden Banks (Fig. 1).

The NOAA program involved the incorporation of two different multibeam bathymetry systems that were state-of-the-art at the time. For waters shallower than 1000 meters, the Hydrochart II was employed. This system operated at 36 kHz and provided 17 beams across a swath of 2.5 times the water depth. A 12 kHz Sea Beam system was employed for waters deeper than 1000 meters. It provided an array of 16 beams across a swath of 0.7 times the water depth.

The sounding density that resulted varies as a function of the water depth, vessel speed, and the system used, but a 250-meter bin is the most common filter applied to these data (across-track raw sounding densities range from approximately 75 meters to 130 meters). The 250-meter filter provides multiple soundings per bin, allowing statistical leverage for an accurate sounding selection.

Similar calibration methods were employed for the Hydrochart II and the 12 kHz Sea Beam systems. These comprised of iterations that included: 1) Collecting sounding data on predefined survey lines. 2) Comparing charted, overlaid contours of sounding data. 3) Scaling offsets from charts. 4) Entering offset values into LOTUS-123 spreadsheets for evaluation.^{1,2}

Considering the technical limitations of the positioning systems, motion sensors, processing systems, and multibeam systems employed at the time, this method of calibration served its purpose quite well (some organizations still employ this method in cases of shallow waters and narrow swaths).

Tolerances employed for the Hydrochart II and the 12 kHz Sea Beam during the NOAA multibeam campaign were:

	36 kHz Hydrochart II ¹	12 kHz Sea Beam ²
Positioning	±15 meters	±15 meters
Pitch	±0.50 deg.	±0.25 deg.
Roll	±0.15 deg.	±0.25 deg.
Yaw	±0.75 deg.	±0.75 deg.

Although these data were collected employing tolerances considered low by today's standards, from a regional perspective they are astounding. They comprise the foremost Gulf of Mexico bathymetric database in existence today and are utilized by the oil & gas industry throughout many stages of exploration and production. They create an extraordinary panorama of the deepwater Gulf, which aids in regional construction and development of offshore oil leases. Unfortunately, their limited accuracy reduces their effectiveness as a tool for detailed exploration and production analysis.

New-age Instrumentation

C & C Technologies, Inc. in conjunction with LCT, Inc. are "filling the gap" in the Gulf of Mexico NOAA multibeam data utilizing new-age technology that includes multibeam bathymetry, multibeam imagery (Fig. 2), gravity, magnetics, and chirp sub-bottom profiling. The survey platform being utilized is the R/V Ocean Alert, a retired 235-foot Canadian Coast Guard vessel. The Ocean Alert is fitted with the newest available scientific hardware, which includes a Simrad EM-300 multibeam system, ZLS La Coste & Romberg marine gravity meter, GEM Systems Overhauser magnetometer, Datasonics Chirp II pinger, and POS/MV GPS / Inertial navigation system.

The Simrad EM-300 furnishes collocated bathymetry and imagery at an operating frequency of 30 kHz, providing an angular coverage sector of up to 150 degrees with 135 simultaneous beams of 1 x 2 degrees. The angular coverage sector and beam pointing angles are variable in order to maximize the number of usable beams. Equidistant and equiangle modes are selectable. All beams are steered electronically for roll, pitch, and yaw. Operating depths range from 10 to 4500 meters below the transducer, accurate to the greater of 0.3 percent of water depth or 15 centimeters throughout the swath.

The ZLS La Coste & Romberg marine gravity meter is the most advanced version of the time-tested marine gravity mapping system, upgraded to sample the gravity field at 200 Hz, and average these samples into 1 Hz digital recordings. This corresponds to a digital sample being recorded approximately every 3 to 6 meters along each ship track. With advances in DGPS positioning and gravity data processing technology, we can now map the earth's gravity field on marine surveys better than ever before. Extensive areas of the deep water Gulf of Mexico have now been resurveyed with this new technology within the past 3 years.

The GEM Systems Overhauser Magnetometer (SEASPY) is a vast improvement over the proton procession models. The system produces digital RS-232 data directly from the towfish and the instrument employs a smaller diameter tow cable, much easier for shipping and handling. Data comparisons from this system show an improvement of an order of magnitude over marine proton magnetometer technology, and

compares favorably with the quality of aeromagnetic survey magnetometer data.

The Datasonics Chirp II, operating at a frequency of 2 to 7 kHz, is integrated with a hull-mounted 4 x 4 (16-transducer) array. Sub-bottom data are recorded in both digital and analog form, yielding seismic layer resolution of approximately 1 to 2 meters in 1000 meters of water. Typical penetration is on the order of 50 to 70 meters.

In addition to heave, pitch, roll, and yaw information, the POS / MV provides precise GPS navigation solutions (1 - 2 meter accuracy, in this case) for all onboard sensors. The precision of the POS / MV motion sensor allows for high calibration accuracy of the multibeam system and provides a freedom from acceleration errors induced when cornering.³

By integrating two imbedded NovAtel GPS cards with a strap-down gyro system, the POS / MV also furnishes inertial navigation solutions during GPS outages. Navigation "spikes", common in the marine environment, are eliminated. Differential corrections are supplied to the POS / MV by Satloc, a satellite-based provider.

Tolerances employed for the 30 kHz Simrad EM-300 during the C & C / LCT multibeam campaign are:

	30 kHz Simrad EM-300
Positioning	± 2 meters
Pitch	±0.05 deg.
Roll	±0.05 deg.
Yaw	±0.05 deg.

Preliminary Sea Trials

Sea trials of the EM-300 were conducted in a variety of stages. The first deployment involved a shallow-water survey at both the East and West Flower Gardens and Stetson Bank in the Gulf of Mexico for the U.S. Geological Survey. Depths in this study area ranged from 20 to 150 meters. Vessel speeds ranged from 9 to 14 knots. Results of the multibeam investigation substantiated existing information about the sites and illuminated unknown features.⁴

The East Flower Garden rises to a summit of 19 meters. The major feature of scientific interest is a brine pool with three small depression around its southeastern edge (Fig. 3a). In addition, an outflow canyon is clearly visible at the brine pool's southeastern corner. These features were mapped to a level of detail that has never before been achieved prior to the integration of this new-age technology. Additional images of these data can be viewed at the following USGS website at: <http://walrus.wr.usgs.gov/pacmaps/>.

While preparing for the Gulf of Mexico program, the R/V Ocean Alert was dispatched to a variety of projects facilitated by the Monterey Bay Aquarium Research Institute (MBARI).

MBARI was not only interested in the bathymetric component of the EM-300 data, but also its imaging potential because the reflected amplitude values surrounding each sounding are recorded in addition to water depth. These amplitude values are sampled at 4.5 kHz at selectable pulse lengths of 0.7, 2.0 and 5ms, allowing for the production of geo-referenced backscatter mosaics, vital for geologic interpretation.

Although the backscatter images produced by the EM-300 resemble towed side scan sonar records, vital differences exist between the two. Standard side scan sonars assume a flat bottom and project each amplitude response outward to a theoretically appropriate position using nadir as a time-based zero reference. The hull-mounted EM-300 knows exactly where each sounding is located in x, y, and z, therefore each corresponding amplitude value is placed in its correctly referenced position. This allows for the creation of imagery mosaics that are geometrically correct, providing true scaleable base maps for construction, design, and investigative purposes.

In the spring of 1998, a ground-truthing of EM-300 backscatter data was performed in Monterey Canyon by the MBARI deep-diving Remotely Operated Vehicle (ROV). The results concluded that "Five-meter resolution backscatter images resolve long, narrow patches of authigenic carbonate associated with areas of known cold seeps created by the outgassing of methane in underlying sediments."⁵ Further images and details of the MBARI multibeam program can be accessed at: <http://www.mbari.org/rd/Hawaii/hawaii.html>.

A deepwater Gulf of Mexico test was also performed that encompassed a 15-mile by 75-mile area in southern Alaminos Canyon with depths ranging from 1500 to 3000 meters. Discussions with geoscientists within the oil & gas industry, relating to deepwater needs, revealed that a data density of 3 to 5 soundings per each 50-meter bin was generally desired. To achieve this goal, this survey was structured such that main scheme lines were oriented east to west at 2,000-meter line spacing. The swath width was fixed at 2,100 meters to provide sufficient overlap and maintain the prescribed sounding density (the EM-300 is capable of adjusting its angular sector to maintain a fixed swath width as the depth varies). Tie lines were spaced at 11,000-meter intervals; oriented north to south, tie lines provide as a check for multibeam data quality, aid in the processing of gravity information, and tie in chirp sub-bottom horizons.

An early EM-300 software version that was in effect at the time of Alaminos Canyon data survey limited the minimum achievable swath width. This produced a large amount of overlap across adjacent swaths, resulting in a higher data density than originally planned. Consequently, this data set provides an average of more than 13 soundings per 50-meter bin as opposed to the 3 to 5 soundings earlier specified. The benefit of this "limitation" is that it provides a bathymetric

data set capable of rendering detail never before achieved over such a large section of the deep-water Gulf of Mexico.

Data Integration

In addition to multibeam bathymetry and imagery, gravity data are concurrently being sampled at a rate of 100 Hz. These data are filtered and subsequently recorded at one-second intervals throughout the project area. In units of miligals, the gravity meter measures changes in gravitational strength that are likely caused by variances in the mass of the underlying sediment and structure.

Multibeam bathymetry and gravity are complimentary for a variety of reasons. Most importantly, the gravity corrections applied in processing depend heavily upon bathymetric data. It has been demonstrated that errors in bathymetry can be a major source of error in vintage gravity measurements.⁶ The marriage of high-resolution gravity with multibeam bathymetry provides the most accurate method available today for precision gravity processing. In addition, the gravity / magnetic survey is complimentary to the multibeam program, as both types of data acquisition require only minimal adjustments in program planning and execution.

Fundamentally, a gravity meter is a spring with a weight dangling from it. The stronger the tension on the spring, the higher the gravitational pull and the more dense the associated geological mass. But unfortunately, these changes in gravitational amplitude cannot exclusively be ascribed to the underlying structure; they are more likely attributed to the local geomorphology itself. Consequently, uncharted surface expressions may have greater impact upon the resulting gravity measurement than the actual formations being studied. The integration of multibeam bathymetry during gravity processing provides a high degree of confidence in the Bouguer correction, which accommodates for the effect of geomorphic variations in the gravity solution.

Another important aspect of the data integration is the requirement to have a suitable method for the analysis of the large volumes of disparate geo-spatial data. Interactive 3D visualization provides the mechanism for not only the integration of the data, but also the disciplines that are involved in the analysis. It provides an effective and efficient means for communicating complex information. All disciplines use two and three-dimensional graphics as 'presentation graphics', primarily using them to present finished results. The volume and range of data from this type of survey requires the visualization to be used for the exploration and analysis of the data, and also to present the results.

The surfaces in Fig. 3a and 3b are both of bathymetry near the Alaminos Canyon with depths ranging from approximately 1,800 to 3,000 meters. Fig. 3a is colored by depth. Fig. 3b is colored by gravity data that are 3D Bouguer anomaly filtered

with a 20-kilometer highpass filter. The large purple gravity anomaly in the center of the image denotes an apparent salt body where the anomalous low value is located, perhaps indicating the thickest of the salt zone in the area. This is clearly correlated in the bathymetry with a relatively smooth depression to the north of the escarpment.

Interactive 3D Visualization

High-resolution data sets, which result from huge volumes of data (surveys often run into hundreds of megabytes), render traditional evaluation methods obsolete. The traditional approach to presentation of geographic data has been the 2D plot, either on a computer screen or a hard copy. This type of plot has some major disadvantages. It is not possible to show both regional coverage and detailed information in the single presentation. Also, the underlying data are normally heavily reduced and cartographic techniques, such as colors and contours are used to graphically enhance the derived information. The scale dependence of this approach also limits the variety of information that can be shown and the analysis that can be undertaken

The human visual system has an enormous capacity for receiving and interpreting data quickly and efficiently and therefore should be an integral part of any effort to understand complex data. It has been estimated that well over half of the brain is absolutely dedicated to things we see and there is the enormous capability of the human brain to detect patterns in data.⁷ 3D visualization seeks to present data graphically in an intuitive fashion to expose information hidden in data and provide new insight.

The often used quotation that “the purpose of computing is insight, not numbers” neatly encapsulates the purpose of the discipline of scientific visualization.⁸ The key is to be able to present the data in as intuitive a fashion as possible with the purpose to gain new insight. It has been found that the more intuitive way that the data can be presented, in the way that we perceive the real world everyday, the more rapidly new insight can be gained and the more new information you can extract from that data.⁷

3D visualization is in use in various areas of the offshore industry such as exploration, reservoir development, production and management, and facilities design and management. It has been shown that it can, or has in some cases, produce value in areas such as efficiency, accuracy, completeness, integration, and communication.⁷ The surveyor has no choice but to become absolutely more efficient because the number and size of surveys and the types of data that has to be processed and interpreted are increasing rapidly. Compare the progression in recent years from the profiles of single beam echosounder surveys, to the small number of beams in early multibeam systems, to the current technology where some systems now have thousands of beams per swath. In addition, the current systems provide sonar imagery across the full swath, which requires processing and interpretation to

gain maximum value from the acquired data. It is a certainty that the number of people available to process the data will not increase, but that pressure will remain to process the data in the same amount of time. 3D data visualization is part of the solution to meet this challenging processing and analysis problem. It is inevitable that without the complete picture, maximum value will not be obtained and information will be missed.

A significant area for visualization is the preview of data. Currently, it is common to use 3D data visualization only in the latter stages of processing once it is believed that the data are clean and ready for final analysis. This is under-utilizing the power of 3D data visualization and not improving the efficiency of the processing pipeline. In fact, this approach can have the opposite effect, where 3D visualization is seen as a tool that actually slows the processing because some of the new insights will inevitably be problems that cannot be located with a traditional 2D approach. The use of visualization in data preview provides the general character and structure of the sea floor that has been mapped from the bathymetry and reflectivity. It also intuitively shows the areas that will be more difficult to process and any areas of importance. In this fashion, preview assists in the planning of data processing and analysis.

3D visualization also improves the accuracy of data processing and analysis. Variations in the accuracy of a survey, from either systematic or random errors, are clearly defined. This provides an assessment of whether the survey meets requirements. Early detection of any out-of-limits condition will not only improve the accuracy of the survey, but will provide greater efficiency by limiting the requirement for re-surveying. Visualization provides the complete picture of all the available data gathered during the survey or available from other sources.

When making judgements about the relationships between objects in a 3D scene, it is important to provide as many 3D spatial cues as possible. These cues help make surface features of digital terrain and other objects clear. Thus, the spatial relationships in the visualized data are easily perceived. Interactivity provides a dual benefit. Being able to move around the 3D scene and view it from any position or orientation, further aids in the interpretation of the scene. Motion also assists in extracting information from the data. If the objects can be analyzed while they are in motion, the observer will see more information than if the image is static.⁹

If we consider surface data, there are several techniques that are commonly used to visualize data. These include pseudo-coloring, illumination and shading.

Pseudo-coloring is the process of assigning a sequence of colors to a sequence of data values. For example, each color in the sequence might represent depth changes of 100 meters. When the colors are mapped onto the depth data, the result is a

color contour map of the sea floor. By selecting different color maps, appropriate features of the surface can easily be highlighted. While the color sequences are often mapped to depths, any other variable, such as multibeam backscatter, gravity and magnetic intensity can also be mapped.

Another visualization technique commonly used is illumination and shading. Here a light source is added to the scene and the surface is shaded accordingly. Applying a lighting model to a surface greatly enhances the features of the visualized data, which makes for more effective analysis.

These aspects of visualization are implemented in a software system known as Fledermaus for the interactive visualization and analysis of data in 3D. Fledermaus incorporates a number of sophisticated rendering, viewing and data manipulation tools. What is perhaps most important is the fact that these tools are combined in a highly interactive integrated package.¹⁰

Before data can be explored in a 3D environment it is prepared in an associated application that supports the importation and preparation of data for visualization. This application also provides a number of interactive 2D tools to explore and analyze surface information. These include the ability to continuously pan and zoom around the data, make measurements on the surface, generate profiles along the surface and plan cable or pipeline routes on a given surface (Fig. 4). All data imported into the system are fully geo-referenced in that one can always query the scene to obtain coordinates and related attributes.

The first step is to create an appropriate color map through which the data can be pseudo-colored. Fledermaus provides the capability to interactively 'draw' a color sequence using the hue, saturation, and value color space, and instantly see how the resulting color sequence enhances the data that is being viewed.¹¹ It is possible to pseudo-color a particular data set, and then drape this on a fully rendered terrain model. The next stage is shading the surface by applying a lighting model. The shading program provides interactive control over various lighting parameters such as the light direction, apparent glossiness of the surface and the amount of ambient (background) illumination. A particular feature of the system is the ability to define soft cast shadows. This dramatically increases the ability to perceive certain types of terrain features such as narrow pinnacles and sand waves. The surface data can be shaded directly or a different data set can be used to map the color onto the surface. In this manner, variables such as multibeam backscatter, gravity or magnetic intensity can be draped onto the visualized surface (Fig. 5a and 5b).

Fledermaus has three distinct methods for exploring 3D data spaces. The most innovative of these uses a special six degree-of-freedom mouse (the "bat") that allows the user to

rapidly "fly" through the data by using simple hand motions.¹² You can explore your data by simply moving your hand in the direction you want to move. To move forward you just move your hand forward; to turn right you turn your hand to the right. Thus natural gestures allow you to quickly view large data volumes in a natural fashion that greatly facilitates the interpretation of the visualized data. This flying interface provides visual feedback about velocity and rate of turn in the form of a predictor (Fig. 6).

In addition to the exploration of the data contained in the computer's virtual 3D environment, Fledermaus also provides a true 3D stereoscopic display. Normal human stereoscopic vision only works over a limited range and optimal stereoscopic viewing is between 0.5 and 2 meters. Fledermaus incorporates a stereo viewing algorithm that automatically adjusts the stereo viewing parameters so that stereoscopic depth is obtained even for scenes that are at large (virtual) distances. Fledermaus is unique in that, these parameters are constantly adjusted so that even while 'flying' through a virtual data environment, stereo depth cues are always available.¹³

Conclusion

As oil & gas exploration and production continue to migrate beyond the continental shelf, a synthesis of new-age data with the tools to evaluate them become increasingly more vital. A combination of collocated multibeam bathymetry, acoustic reflectivity, gravity, magnetic, and sub-bottom data is currently being collected across the uncharted deepwater Gulf of Mexico. The integration of these new-age data with 3D interpretive visualization tools provide geoscientists and engineers with a vital resource that can be utilized well into the next century.

Acknowledgments

We wish to thank Captain Andrew Armstrong and Commander Gerald Mills (ret.), NOAA Hydrographic Surveys Division for their assistance in the retrieval of historical information.

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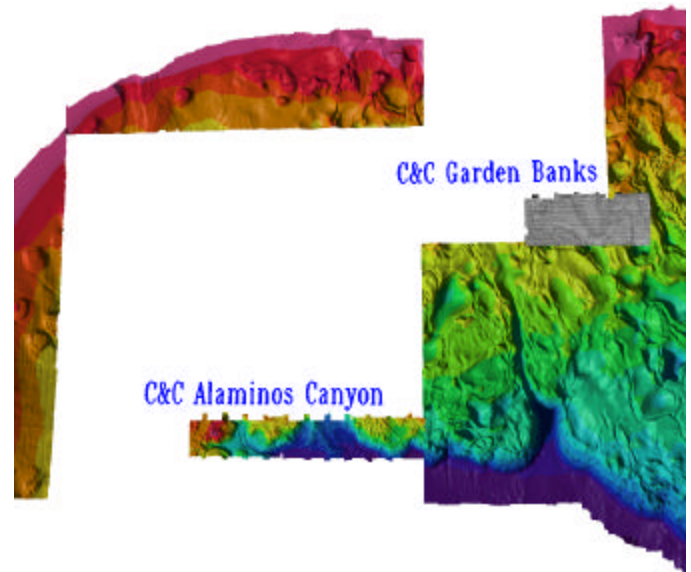


Fig. 1 - Screen capture showing the gap in the NOAA multibeam survey data and the areas surveyed by C&C Technologies by the end of 1998.

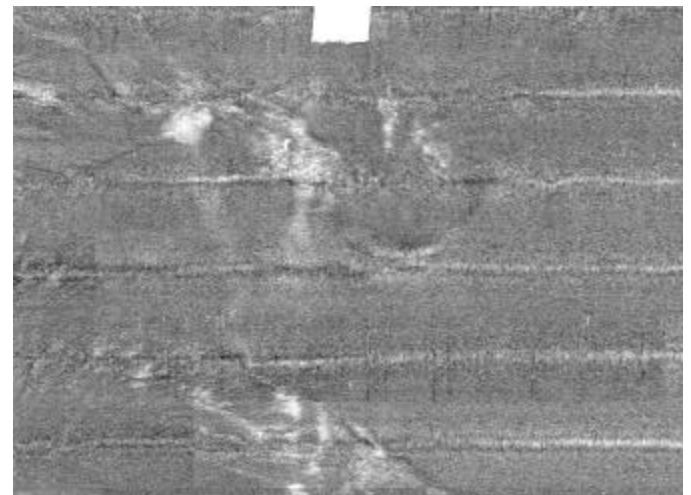


Fig. 2 – Two-dimensional plot of the multibeam backscatter from the survey in the Garden Banks area. Lighter shades indicate higher seabed backscatter.

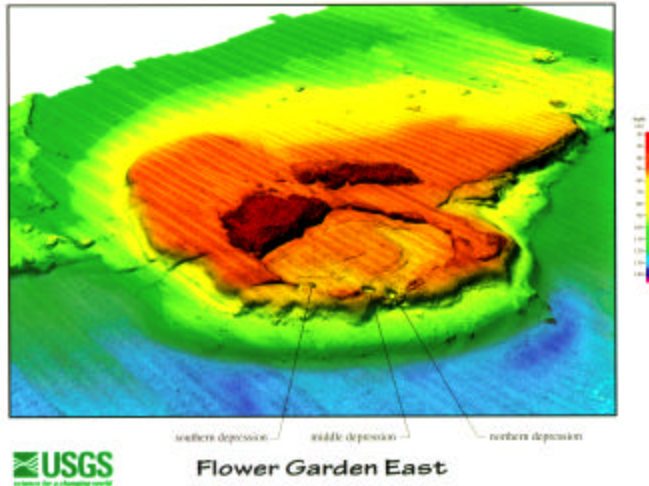


Fig. 3a – Color-coded multibeam bathymetry of the East Flower Garden revealing brine-pool and accompanying outflow canyon.

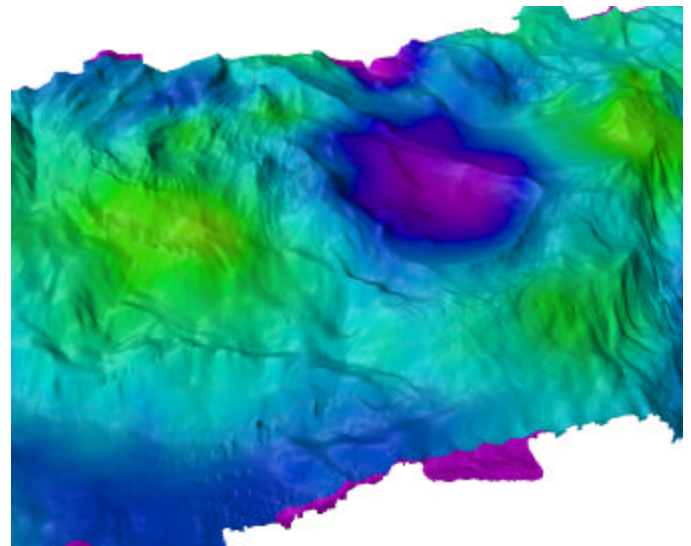


Fig. 3c - Same DTM as Fig.3b with colored gravity data that are 3D Bouguer anomaly filtered with a 20 km highpass filter. The purple indicates a relative low gravity value, red a relative high gravity value.

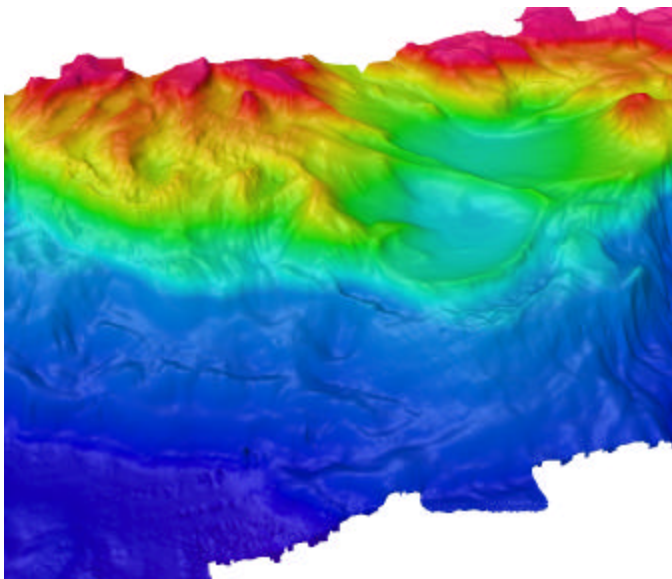


Fig. 3b - DTM of bathymetry near the Alaminos Canyon, deep water Gulf of Mexico, at the Sigsbee Escarpment, viewed from south. The surface is colored by depth ranging from approximately 1,800 to 3,000m.

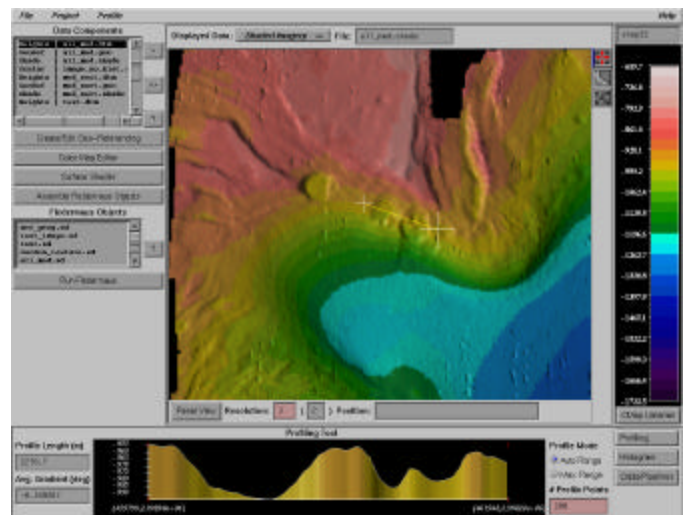


Fig. 4 - A screen image of the data preparation application with a shaded surface of the Garden Banks bathymetry. The cross section in the image is shown as a profile in the lower window. The colors in the profile correspond to the colors of the surface.

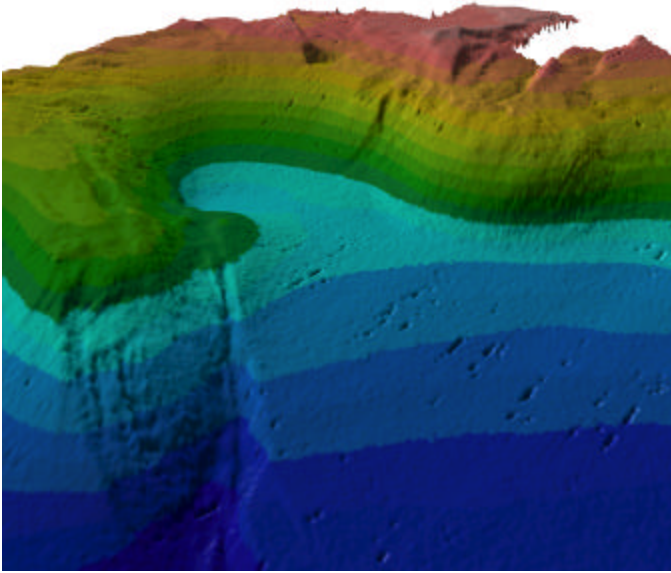


Fig. 5a - DTM of bathymetry from Garden Banks area viewed from the east, with the surface colored by depth.

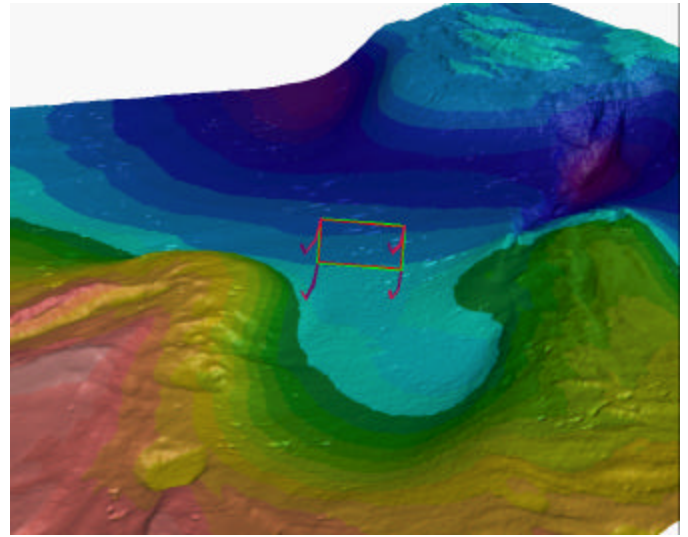


Fig. 6 – Flying over a digital terrain of the Garden Banks area. The box with the tails is the predictor from 3D flight mode. The tails indicate that the user is currently moving forward.

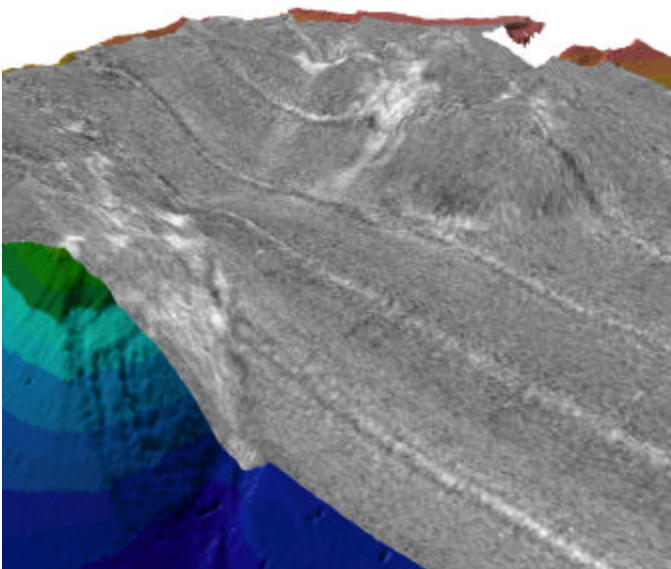


Fig. 5b - Same DTM as Fig. 6a with the multibeam backscatter signal response from Fig. 2 draped onto the surface.