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INVERSION OF MOVING-BASE GRAVITY-GRADIOMETER DATA FOR GEOPHYSICAL INFORMATION

Final Report
Contract N00014-80-C-0446

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APR 13 1983
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prepared for the
Office of Naval Research
Geology and Geophysics Group 425GG
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February 25, 1983

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BIBLIOGRAPHIC DATA SHEET

1. Report No.	2. Govt. Accession No. AD-A126725	3. Recipient's Catalog No.	
4. Title and Subtitle Inversion of Moving Base Gravity Gradiometer Data For Geophysical Information		5. Report Date February 28, 1983	6. Performing Organ. Code
7. Author(s) R. D. Brown		8. Performing Organ. Rpt. No.	
9. Performing Organization Name and Address Phoenix Corporation 1700 Old Meadow Road McLean, Virginia 22102		10. Work Unit No.	11. Contract or Grant No. N00014-80-C-0446
12. Sponsoring Agency Name and Address Office of Naval Research Geology and Geophysics Program, Code 425GG 800 N. Quincy Street Arlington, Virginia 22217		13. Type of Rpt. & Per. Cov. Final Report 5/15/80 to 12/31/82	
14. Sponsoring Agency Code			
15. Supplementary Notes			
16. Abstract <p>In the near future an exciting new type of geophysical data will become available. This data, gravity-gradiometry from a moving platform, offers an advantage over conventional gravity measurements analogous to that of a microscope over the naked eye, i.e. resolution of much finer detail at the expense of a narrowed field-of-view and decreased depth-of-field. While gravity-gradient measurements are not new, recent requirements for real-time gravity information in inertial navigation of modern weapon systems has spurred the development of very sensitive and very compact moving-base gravity gradiometers (MBGG). These instruments are relatively immune to vehicle accelerations but can measure a differential acceleration of about a trillionth of the normal value of G over a distance of 1cm. It was recognized early-on that gravity information could be obtained in this manner much faster than by conventional gravity surveys, and it could be obtained without actually setting foot on the surveyed territory. Furthermore, the spatial resolution of gravity variations sensed by MBGG is much smaller than that of gravity surveys, which permit more accurate and detailed modeling.</p> <p>→ The increased speed and resolution possible with (MBGG) comes at a price, however, i.e. the need to cope with an enormous volume of data in the 5 independent gradient tensor components and the need for non-conventional methods for extracting geophysical information from the MBCG data. To address these needs, we conducted a survey of conventional and non-conventional data processing methods which might be applied to</p>			
17. Key Words (Selected by Author(s)) Gravity Gradient Inversion Bathymetry Submarine Discrimination		18. Distribution Statement See Attached Sheet	
19. Security Claffif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

(cont)

16. Abstract (continued)

MBGG data processing. The conventional approach of simply integrating the gradient along the track of the moving platform to obtain a gravity profile ignores the information contained in the cross-track and vertical gradients. Furthermore, since the geophysicist is less interested in the gravity than in the underlying density distributions, conversion of MBGG data to gravity is a step in the wrong direction because of the inherent smoothing that integration entails. We show that the MBGG data contain much more information regarding the size, shape, and depth of buried structure than do conventional gravity data. This holds even when such structures are in isostatic equilibrium, such as a neutrally bouyant submarine, provided that the structures are not spherically symmetric. Among the non-conventional methods which showed promise were inversion techniques developed for terrain correction of gravity data. We derive and demonstrate an adaptation of these methods for direct recovery of the topographic profile which gives rise to the measured gravity gradients. One interesting application arising from the use of this technique is the rapid profiling of bathymetry via aircraft survey.

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BACKGROUND

In the near future an exciting new type of geophysical data will become available. This data, gravity-gradiometry from a moving platform, offers an advantage over conventional gravity measurements analogous to that of a microscope over the naked eye, i.e. resolution of much finer detail at the expense of a narrowed field-of-view and decreased depth-of-field. While gravity gradient measurements are not new, recent requirements for real-time gravity information in inertial navigation of modern weapon systems has spurred the development of very sensitive moving-base gravity-gradiometers (MBGG) (Heller, [1977]).

Conventional inertial navigation systems for rapidly moving vehicles such as ballistic missiles and aircraft suffer degraded accuracy due to uncertainty in the gravity accelerations which act on the vehicle. To make real-time on-board measurements of gravity is impractical because of the noisy acceleration environment of the typical maneuvering vehicle. However, a measurement of the differential acceleration between two points which sense the same vehicle acceleration would enable the separation of gravity acceleration effects from vehicle accelerations due to other sources. The required gravity information could then be derived in principle by integrating the differential accelerations (gravity gradients).

Prior to the development of modern MBGG systems, the best available device for measuring gravity gradients was a variant of the Eotvos torsion balance (Heiland, [1963]). This instrument was a cumbersome system of balance beams and proof masses hung on fine torsion wires. In use it required extreme care to isolate it from such noise sources as microseisms and wind currents, and great patience to wait for the beam oscillations to damp in each of the three azimuth measurement orientations required for solution of the gradient components. Operating such an instrument on a moving vehicle is impractical. Yet the same basic principle has been exploited in engineering the modern MBGG.

The MBGG instruments described by Forward [1965], Trageser [1970], and Metzger and Jircitano [1974] have made possible rapid airborne surveys free of the acceleration noise and altitude accuracy requirements of airborne gravimetry. These instruments are relatively immune to vehicle accelerations but can measure a differential acceleration of about a trillionth of the normal value of G over a distance of 1 cm. All of the above MBGG designs use some form of the Eotvos torsion balance on each of three non-coplanar axes. Thus, all 5 independent components of the gravity gradient tensor may be measured regardless of vehicle attitude, and the gravity along the vehicle track may be computed. It was recognized early-on that gravity information obtained in this manner could be used for geophysical applications as well as

navigation. Not only would it be faster than conventional gravity surveys, but it could be performed remotely, i.e. without actually setting foot on the surveyed territory. Furthermore, the spatial resolution of gravity variations surveyed by MBGG is much smaller than that of conventional gravity surveys, raising the possibility of more accurate and more detailed modeling and interpretation for resource exploration. Analyses of gravity gradients by Stanley and Green [1976] show that these higher derivatives of the potential are more sensitive to the shape of the underlying geological structure than are gravity data. Jordan [1978] has found that fewer and wider spaced survey tracks are needed to resolve the shape and density contrast of an isolated sphere than are required for the same inversion using gravity data.

The increased speed and resolution possible with MBGG comes at a price, however, i.e. the need to cope with an enormous volume of data in the 5 independent gradient tensor components and the need for non-conventional methods for extracting geophysical information from the MBGG data. The conventional approach of simply integrating the gradient along the track of the moving platform to obtain a gravity profile ignores the information contained in the cross-track and vertical gradients. Furthermore, since the geophysicist is less interested in the gravity than in the underlying density distributions, conversion of MBGG data to gravity is a step in the wrong direction because of the inherent smoothing that integration entails. The need for a data processing method which makes use of all the information provided by the MBGG and which can provide for interpolation of that information between survey tracks without excessive smoothing is apparent.

As a first step toward filling this need, a survey was conducted of conventional and non-conventional methods which might be applied to MBGG data processing. Among the non-conventional methods which show promise are the qualitative and semi-quantitative interpretation techniques used with torsion balance measurements a half century ago. Also, certain inversion methods used for terrain correction of gravity may be adapted for inferring density at depth from gravity-gradiometry measurements. One interesting application for MBGG arising from the use of such inversion methods is the rapid profiling of bathymetry via aircraft survey. These and other methods are described in detail in the following sections. A discussion of the activities undertaken in the past two years under this contract is presented in the next section.

SUMMARY OF ACTIVITIES

This study was a follow-on of a general review of the state-of-the-art in moving-base gravity-gradiometry (MBGG) performed under contract N00014-79-c-0409 for the geology and geophysics branch of the Office of Naval Research. That review concluded that the state-of-the-art was sufficient for useful application in mapping the marine gravity field, and recommended that a survey be conducted to establish data processing methods for the MBGG data. Thus the present study began with the goal of defining data processing methods for recovering the gravity vector from the potentially enormous quantity of MBGG data, and to do this without excessive loss of the detailed information on shape, size, and depth of the anomalous body that gravity-gradient data provide. After studying both torsion-balance techniques of the 1930's and present day gravity data processing techniques, it was recognized that integration of the MBGG data to obtain gravity information was entirely inappropriate. The needs of the geophysicist for a better marine gravity field are better served by inverting the MBGG data directly for the shape, size, and depth of the anomalous density contrast. If needed, gravity can subsequently be modeled from these quantities, but these quantities are much more pertinent to the geophysicists' need to understand the structure and tectonics of the ocean crust.

Having committed ourselves to this departure from the initial objectives, we turned to examining the parameterization of the MBGG data. It is clear from the theory and from field experience with torsion balances that the MBGG sensor responds most to the nearest and strongest density contrast. In most MBGG surveys that can be envisioned, this contrast is that of the topography. Thus the first order of business in processing MBGG data is to remove the signal due to topography. In precise gravity surveys, this is common practice requiring independent elevation information for the area local to the gravity station. Dorman and Lewis [1974], Chinnery [1961], and Hammer [1976] have developed methods for correcting airborne gravity survey data for topography. Since the topography is more dominant in the MBGG measurement than in the gravity, it occurred to us that a fruitful approach for processing MBGG data would be to invert the measurements themselves to recover the shape of the topography profile along the survey track.

Two papers (Brown, 1981a,b) developed this approach. The first, entitled "Methods of Processing Gravity Gradiometry Data-Geophysical Applications" was presented at the Second International Symposium on Inertial Technology for Surveying and Geodesy, June 1-5, in Banff, Canada. The second, entitled "Inversion of Gravity Gradients for Density Information" was presented at the 1981 International Geoscience and Remote Sensing Symposium (IGARSS '81), June 8-10, in Washington, D.C. These papers set down the theory for the data inversion, assuming no

noise, no contribution from additional density contrasts such as the air-water interface in marine surveys, and assuming that the topography profile extended to infinity in the horizontal dimensional normal to the survey track (i.e. two-dimensional topography).

Following these papers, we developed computer programs to simulate the gravity gradient of simple topographic geometries, to Fourier transform the data, convolve it with smoothing filters and windows, and finally, to invert for the topographic profile. During this period, we were privileged to attend the annual review of moving-base gravity gradiometry in March 1982 at the Air Force Academy in Colorado Springs, Colorado. At this review, we learned of the existence of actual MBGG data profiles, taken over a test range with known gravity and topography. These data are essential to the further development of our inversion technique, inasmuch as they contain the effects of uncompensated vehicle motion, gradients due to density contrasts other than that of the topography, and signals due to topography which is not two-dimensional in nature. These data have been requested from appropriate sources, and form the basis for a proposed follow-on to the present study.

PROPERTIES OF THE GRAVITY GRADIENT

Gravity gradients are simply spatial derivatives of the 3 vector components of gravity acceleration. As such, they form a covariant tensor of rank 2 written in matrix form as

$$[gg] = \begin{bmatrix} U_{xx} & U_{xy} & U_{xz} \\ U_{yx} & U_{yy} & U_{yz} \\ U_{zx} & U_{zy} & U_{zz} \end{bmatrix} \quad (1)$$

where the subscripts refer to the partial derivatives with respect to the local cartesian coordinates x, y , and z . Of these 9 components, only 5 are independent due to the commutation of derivatives of the harmonic function U , and due to Laplace's equation.

An important difference between the gravity and the gravity gradient lies in their sensitivity to the underlying density distribution. Following the development given by Sax [1966], the potential at altitude z due to lateral density variations in a buried layer bounded by surfaces $z=-L_1$, and $z=-L_2$, where $L_1 > L_2$, is given by

$$U^L(x, y, z) = - \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-L_1}^{-L_2} \rho(x', y') \ell^{-1} dx' dy' dz' \quad (2)$$

where ρ is the density in the layer L and ℓ is the distance from point (x, y, z) to (x', y', z') .

$$\ell = \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}$$

Since point (x,y,z) is outside the density distribution, U is harmonic and we may construct expressions for gravity and gravity gradients by differentiating equation (2) inside the integral, e.g.

$$U_z^L(x,y,z) = - \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-L_1}^{-L_2} \frac{\partial}{\partial z} (\ell^{-1}) \rho(x',y') dx' dy' dz' \quad (3)$$

$$U_{z\alpha}^L(x,y,z) = - \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-L_1}^{L_2} \frac{\partial^2}{\partial z \partial \alpha} (\ell^{-1}) \rho(x',y') dx' dy' dz' \quad (4)$$

where α is $x, y,$ or z . We may assume U_x and $U_y = 0$ without loss of generality, and compare the behavior of the kernel functions in equations (2-4). These functions, defined as

$$\begin{aligned} F^u(\ell) &= \ell^{-1} \\ F^g(\ell) &= \frac{\partial}{\partial z} (\ell^{-1}) = -(z-z') \ell^{-3} \\ F^{gg}(\ell) &= \frac{\partial^2}{\partial z^2} (\ell^{-1}) = 3(z-z')^2 \ell^{-5} - \ell^{-3} \end{aligned} \quad (5)$$

are plotted in Figure 1 as a function of horizontal distance from the origin $(0,0,0)$. Note the striking difference in the slope of these functions near the measurement subpoint, indicative of the relative horizontal resolving power of these measurement types. Choosing the point at which the kernel function drops to $1/e$ of its peak value as the limit of influence of the measurement, we see that a hypothetical measurement of the potential at (x,y,z) is strongly influenced by density variations up to $2.6(z-z')$ away from the measurement subpoint. In contrast, the gravity measurement is strongly influenced by density

contrasts at horizontal distances up to $0.97 (z-z')$. The vertical gravity gradient U_{zQ} is strongly influenced by density contrasts only at horizontal distance of $0.61 (z-z')$. This comparison serves to illustrate the rule-of-thumb that higher derivatives yield higher resolution. If the gravity gradient measurements are made by an MBGG on a level flying aircraft, then an essentially independent sample of the density distribution is obtained every $0.61 (z-z')$ along the track (assuming the correlation distance of density variations is smaller than this). Thus horizontal density variations with wavelength greater than $1.2 (z-z')$ can be resolved using the MBGG, compared to a minimum wavelength of about $2.0 (z-z')$ for gravity measurements.

Similar behavior obtains for kernels of the other gravity gradient components. The depth-of-field or sensitivity of the kernels to density variations with depth is also diminished for gravity gradients compared to gravity. In fact, for a measurement point outside of the attracting mass distributions of interest, i.e. for an MBGG on an aircraft or ship, the dominant density contrast represented in the measurement is that of the air-topography or water-ocean bottom. This is the reason that such great care was taken to remove topographic effects in early terrestrial gravity gradient measurements using the torsion-balance (Heiland, [1963]).

The fact that the gravity gradient attenuates with distance much faster than the gravity is a distinct advantage in deducing the shape, size, and depth of the body causing the anomaly. Also, the gradients tend to be strongest and most rapidly changing at the edges of a distributed body in contrast to the broad, smoothed out patterns of the gravity data. For example, compare the gravity and horizontal gravity gradient profiles shown in Figure 2 and 3. The gravity profiles for both the stratigraphic trap (a geophysical term for the pinch-out of one layer of geological strata by another) and the vertical fault have the same smooth shapes, despite the very different geology and shape of these structures. In fact, the depth of the vertical fault was chosen specifically so that its gravity profile would match the gravity profile of the stratigraphic trap. This demonstrates that gravity data is a relatively poor discriminant of shapes of geological structures. On the other hand, the gravity gradient profiles are distinctly different because the edges of the structures are sharply defined in the gradient. There is much less likelihood of any erroneous or ambiguous identification of structure with the gradient data than there is with the gravity data.

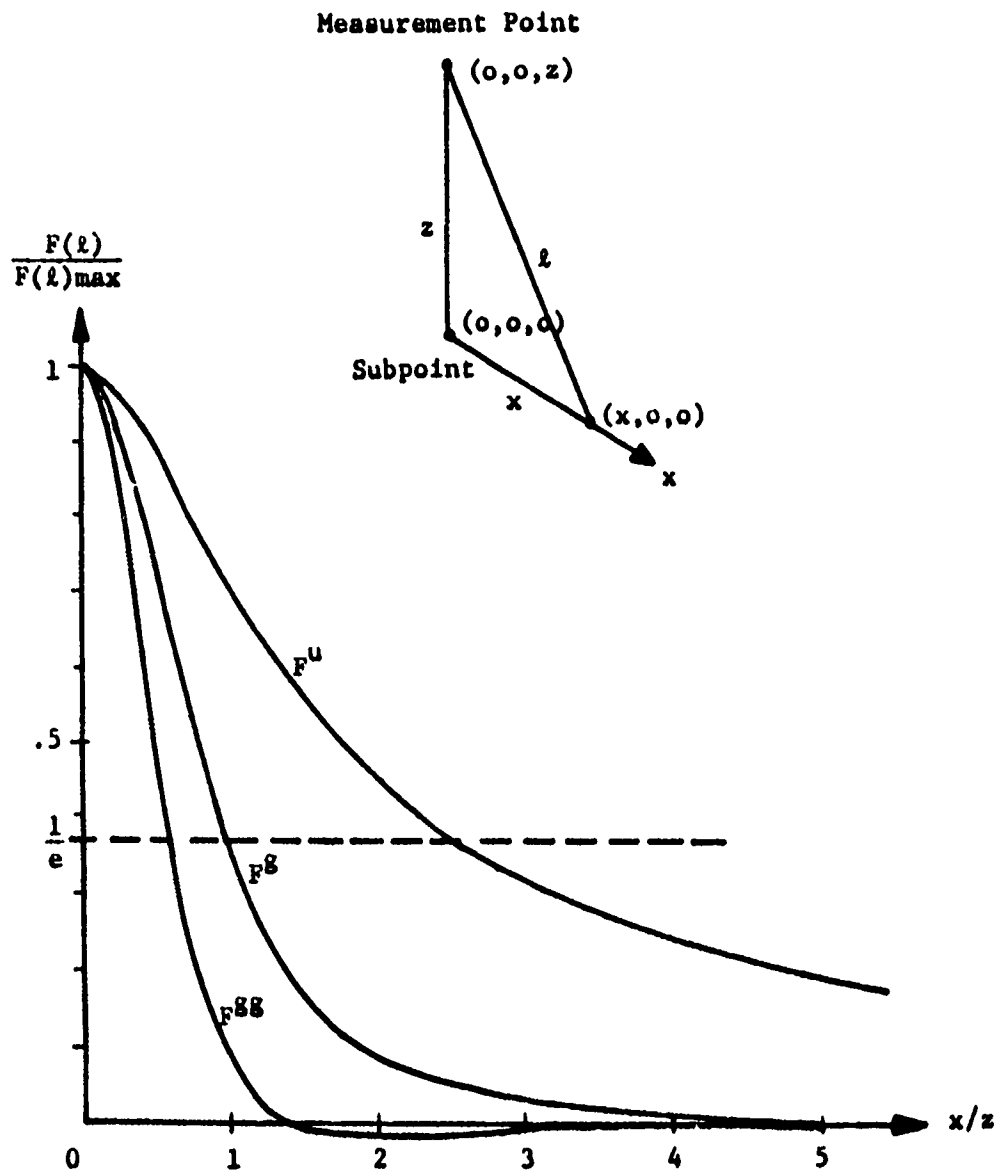


Figure 1. Kernel Functions of U , U_z , and U_{zz} .

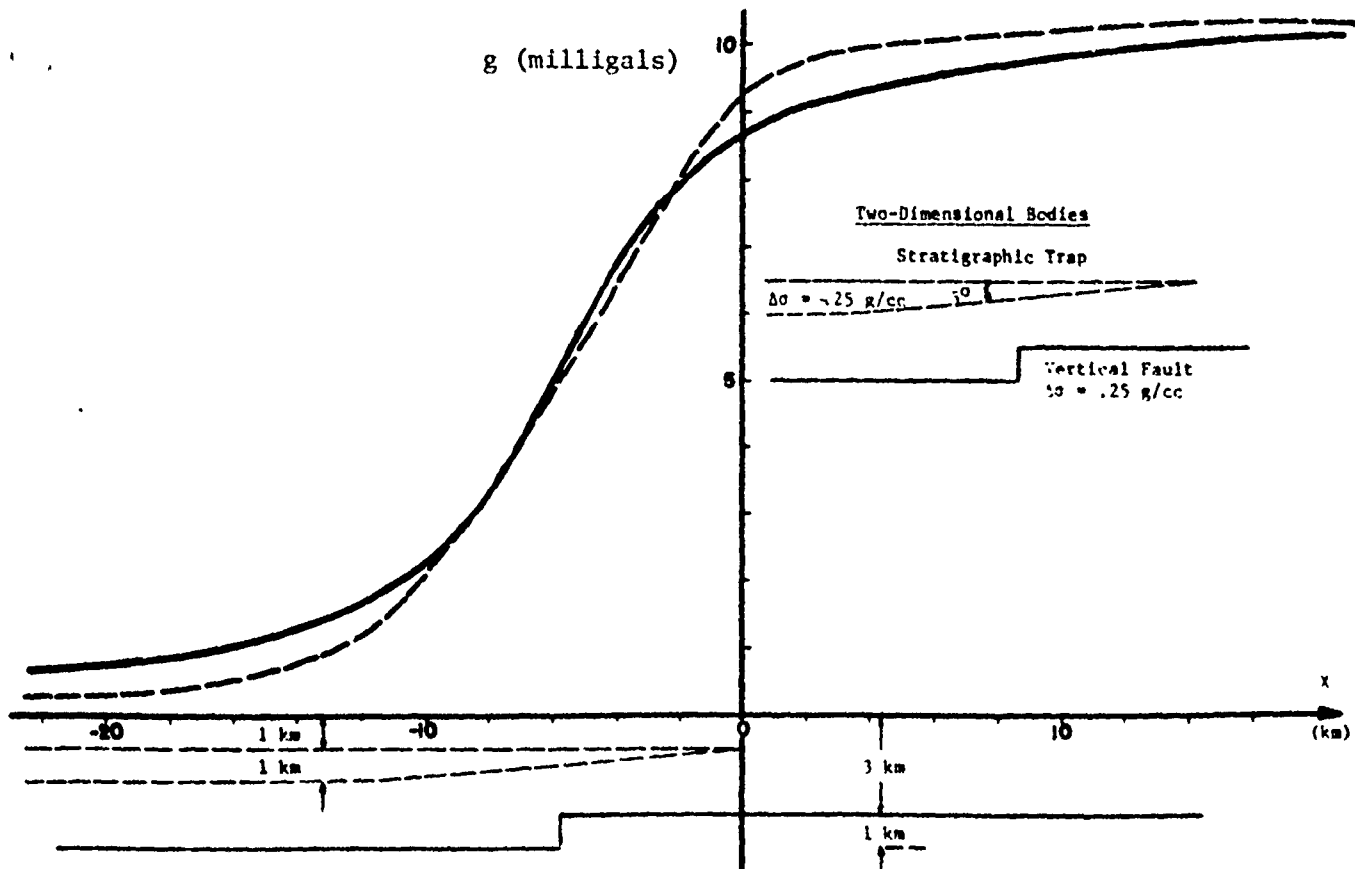


FIGURE 2 COMPARISON OF GRAVITY PROFILES FOR TWO DIFFERENT STRUCTURES: VERTICAL FAULT AT 3 KM DEPTH; AND STRATIGRAPHIC TRAP AT 1 KM DEPTH. NOTE THE SIMILARITY OF THE PROFILES

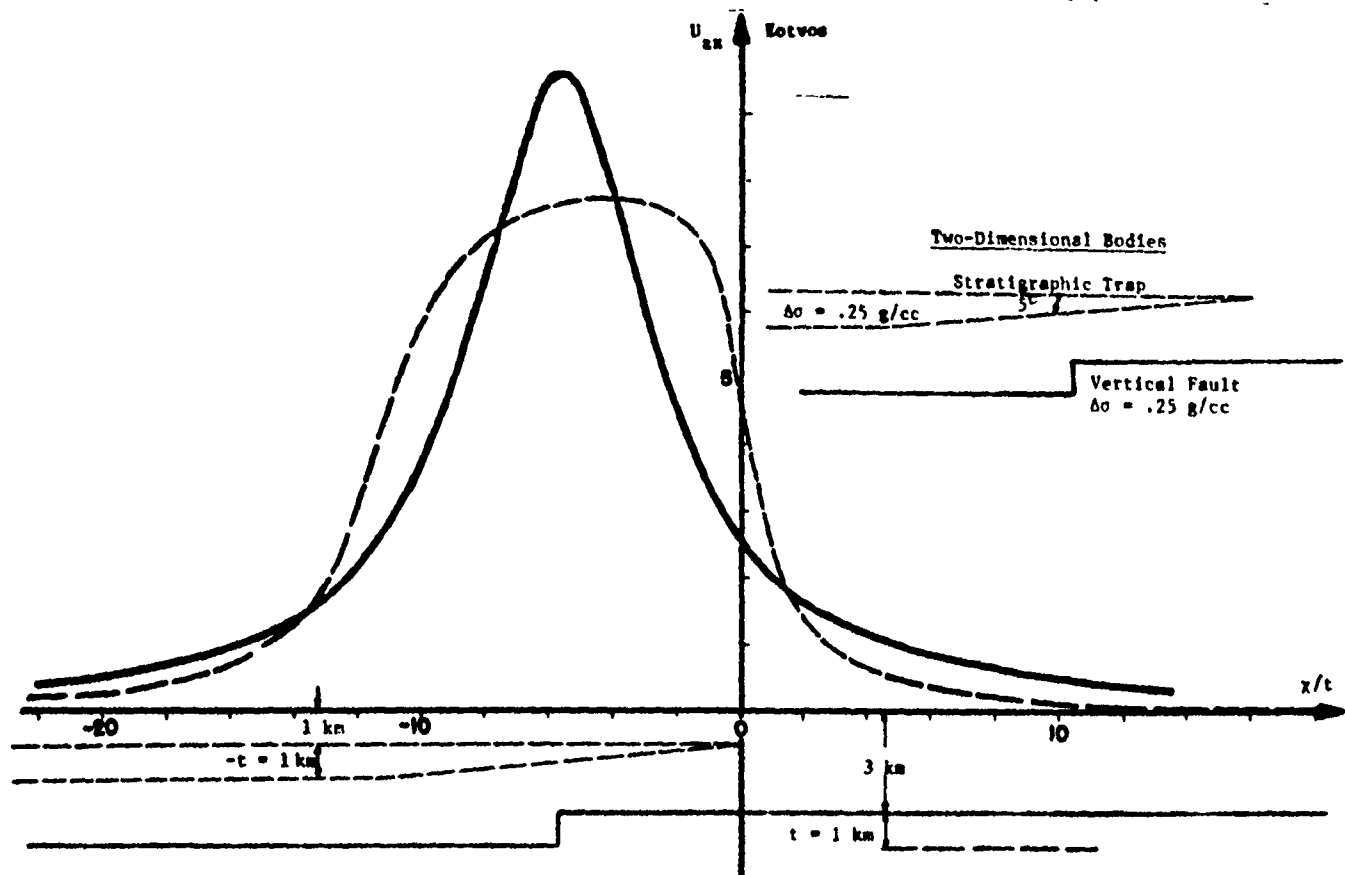


FIGURE 3 COMPARISON OF HORIZONTAL GRAVITY-GRADIENT PROFILES FOR TWO DIFFERENT STRUCTURES. NOTE THE DISSIMILARITY OF THE PROFILES AND THE DELINEATION OF THE EDGES OF THE STRUCTURES IN THE GRADIENT PROFILE.

GRAVITY-GRADIENT OF A SUBMERGED SUBMARINE

Sensing a submerged submarine by its gravity gradient may seem at first glance to be infeasible. After all, because of its near-neutral buoyancy, there is no mass excess to cause a measureable gravity anomaly. And indeed, if the submarine were constructed in a spherical shape, with uniform distribution of mass, there would be no gravity gradient. But practical submarines must of necessity depart from an ideal spherical shape. For example, one must usually attach a heavy bronze propeller at one point on the outer surface of the submarine. Then to maintain trim, a compensating mass must be attached diametrically opposite, and the buoyancy of the shell increased to maintain neutral buoyancy of the assembly. We have now a multipole distribution of mass instead of a spherically symmetric monopole, and as a result, we have created measureable gravity gradients.

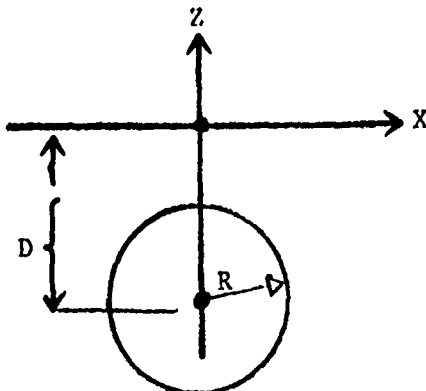
The distribution of mass in an actual submarine is exceedingly complicated, and naturally is classified information. However, one can obtain a feel for the size of a typical submarine gravity gradient from the simplistic example cited above. Assume a spherical shell submarine which must support some additional mass which is not of itself neutrally buoyant nor is it distributed uniformly. To maintain buoyancy, the submarine diameter R must be sufficient to support the spherical shell plus the added mass M . This added mass creates an effective non-zero density contrast $\Delta\sigma$ for the submarine. Considering only the gradient due to the incrementally larger spherical shell.

$$\Delta\sigma = \frac{-M}{\frac{4}{3}\pi R^3}$$

For such a geometry, we have

$$U_{zz} = \frac{G\Delta\sigma [2(Z+D)^2 - X^2]}{[X^2 + (Z+D)^2]^{5/2}}$$

where G is the gravitational constant



Normalizing by the effective volume and evaluating at $X = 0$

$$U_{zz} = \frac{8/3 \pi G \Delta \sigma}{\left(\frac{Z+D}{R}\right)^3}$$

If we have a shell of radius $R = 10\text{m}$, carrying an added mass of 100 tons, $M = 9 \times 10^7$ grams, the effective density contrast due to the slightly larger sphere is

$$\Delta \sigma = 0.02166 \text{ g/cc}$$

At the surface of the sphere, $Z = 0$, $D = R$, the measured gradient is

$$U_{zz} = 11.55 \text{ EU}$$

If the submarine is at a depth of 30m, ($Z = 0$, $D = 3R$) then the maximum gradient at the surface would be

$$U_{zz} = 0.43 \text{ EU}$$

At a depth of 100m, the gradient at $Z = 0$ would be

$$U_{zz} = 0.012 \text{ EU}$$

which is about the limiting precision of moving base gravity gradiometers now under development. This points up a fundamental limitation to the use of gravity gradiometers for submarine detection, i.e. you must be sitting practically on top of it to detect it. For this reason, the gravity gradiometer may be better suited to discrimination applications.

INVERSION FOR TOPOGRAPHY

For an MBGG survey, the strongest gradient signals are those from the nearest density contrast, i.e. the topographic relief (water/ocean bottom for marine surveys). Not only is this density contrast closer to the survey platform than any subterranean geological structures, but the magnitude of the density contrast is 2 to 4 times as great. Because of this sensitivity, the need for topographic corrections in gradiometry is much more severe than in gravity surveys. Chinnery [1961] estimates the effect due to topography on a typical aircraft survey to be on the order of 3-30 Eotvos units, or about the size of gradients of subterranean ore bodies. It is natural, therefore, to consider using an instrument so sensitive to topography as a topographic profiler. It would be an ideal passive alternative to radar altimeters or sonic sounders. As MBGG data must be corrected for topographic effects before use in geophysical exploration, it may be feasible to bootstrap the correction solely from the gradient data. To see how such an inversion of gravity gradient data for topographic elevations might be accomplished, we review the form of the gravity integral over the density contrast defined by the surface $z = h(x,y)$.

Following Dorman and Lewis [1974], we replace $\rho(x',y')$, in equation 4 by $\Delta\rho$, the assumed constant density contrast between the topography and the ambient environment, air or water. We also replace L_2 by $h(x',y')$, representing the topographic surface whose minimum elevation is $-L_1$. Then the vertical gravity gradient due to the topography is given by

$$U_{z\alpha}^T(x,y,z) = -\Delta\rho \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-L_1}^{-h(x',y')} \frac{\partial^2}{\partial z \partial \alpha} (\rho^{-1}) dx' dy' dz' \quad (6)$$

This is a non-linear integral which is not useful in its present form. Dorman and Lewis [1974], have expanded this non-linear functional in a series about the average elevation Z_{av} and perform a Fourier transform to obtain

$$\frac{\hat{U}_{z\alpha}^T(u,v)}{z\alpha} = k\Delta\rho \left\{ K_1 H_1(u,v) + K_2 H_2(u,v) + \dots \right\} \quad (7)$$

where $H_n(u,v)$ is the Fourier transform of $\left(h(x,y) - z_{av} \right)^n$
 and $K_n = \frac{-2\pi k^{n-1}}{n!} e^{-k(z - z_{av})}$

Practitioners of topographic correction for gravity gradients have found that very little error is incurred by neglecting the variation of topography in the direction normal to the survey track. Chinnery [1961] finds that terrain elements more distant than 5 times the elevation are negligible. Hammer [1976] estimates that the effect of a spherical topographic anomaly of radius R diminishes to less than 1% of its peak value within a distance of 3R. Furthermore, he finds that features which are 3 times as long as the elevation of the sensor may be considered to be infinite in extent normal to the survey track. Thus to a good approximation, we may reduce equation 7 to one dimension along the survey track. In such situations, the error incurred in neglecting the quadratic term $K_2 H_2$ in equation 7 is on the order of 3% (Dorman and Lewis, [1974]). The spectral response of gradient U_z in one dimension is thus

$$\hat{U}_{zR}^T (w) \sim k \Lambda_r \left[K_1 H_1 (w) \right] \quad (8)$$

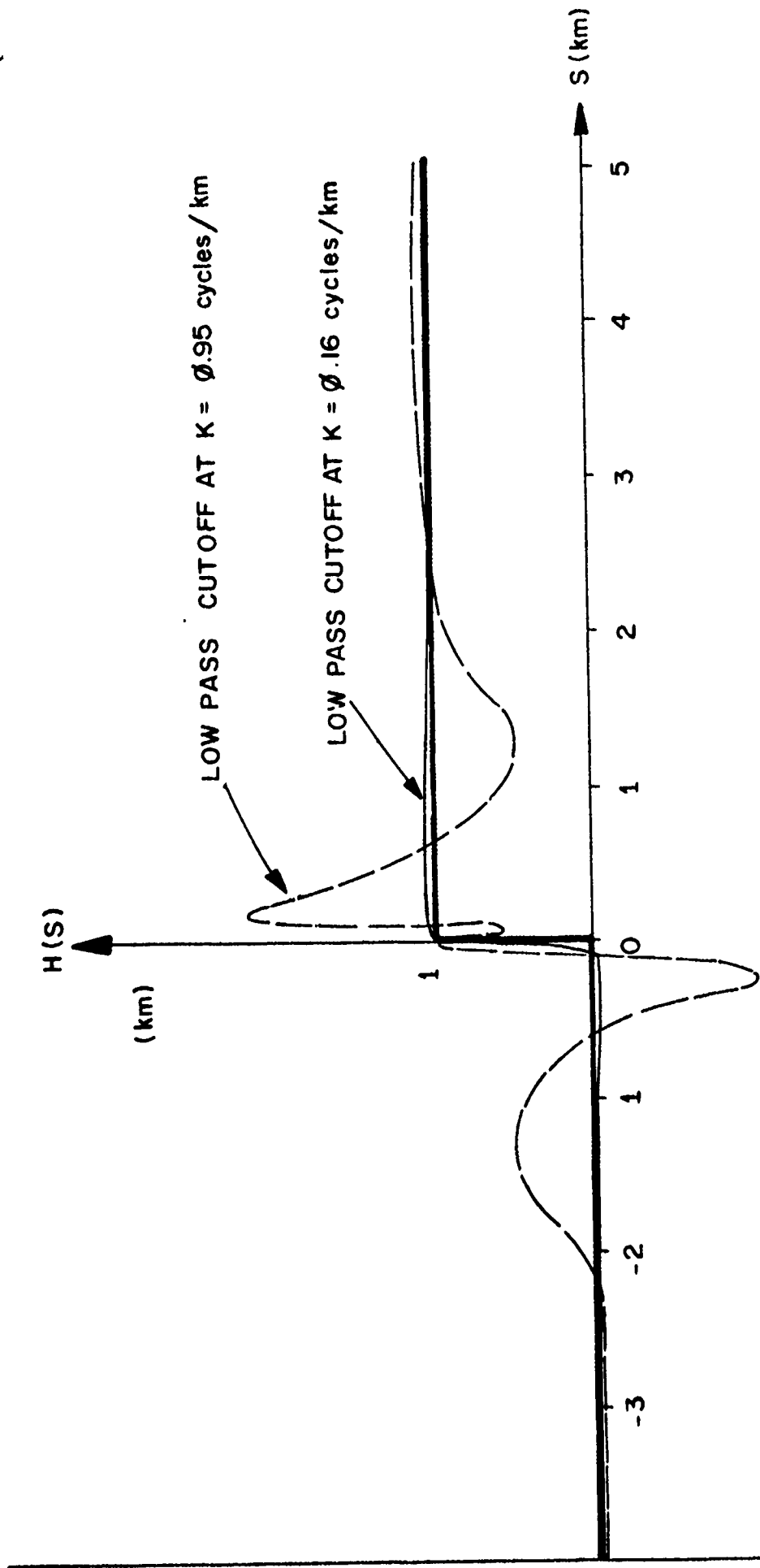
In principal, this equation may be inverted, and topography $h(s)$ along the survey track recovered by inverse Fourier transform of $H_1(w)$.

RESULTS

The inversion theory developed in the previous section has been programmed in computer simulations for recovery of the topographic profile used in simulating the gravity gradient data. The general procedure is to construct a simple geometric shape for the topography, assume a density contrast appropriate for the ocean bottom-ocean water interface, and compute the horizontal along-track gravity gradient using an adaptation of the Talwani spherical-modeling program. The measurements are assumed to have been made at the ocean surface and the geometry of the anomalous body at depth is two-dimensional. The simulated data is then processed by the Fast-Fourier Transform (FFT). The transformed data is convolved with the topography kernel (equation 7) and appropriate low-pass filters to prevent instability, then transformed to the space domain by an inverse FFT using the Bartlett window.

Examples of the results of these simulations are shown in Figures 4 and 5. Figure 4 assumes that topography is a vertical fault, infinite in extent normal to the page, of height 1 km, and at depth 1 to 2 km below the ocean surface. The density contrast is assumed to be that between water and basalt, i.e. 1.7 g/cc. The model topography is shown, together with that of two recovered profiles using different low-pass filter cutoff frequencies. For such sharp topographic gradients, better agreement is obtained for lower cutoff frequencies. Aside from the remarkable agreement obtained, this points up the instability to which this inversion is susceptible, being essentially a downward-continuation process.

Figure 5 shows the inversion results for a more realistic geometry, that of a horst structure with sides sloping at about 31 degrees to the horizontal. This was simulated as a stack of long thin layers, 100 km into and out of the page, 0.5 km thick, ranging in width from 18 km to 8 km and stacked 3 km high. The gravity profiles resulting from this body are shown at the top of the figure for water depths to the top of the horst of 1 km to 48 km. The corresponding horizontal gravity gradient is shown in the middle of the page. Note the more localized nature of the gradient signature compared to that of the gravity, and also the high gradient peaks over the slopes of the horst. It is this behavior of the gradient which makes it more suitable than gravity for recovering topography. The inversion results for various depths to the horst are shown superimposed on the horst topography. As one might expect, the most accurate results are obtained when the topography is shallow. As depth increases, the recovered topography broadens. At 24 km depth, the horst appears reduced in height to 2 km and increased in width to 80 km. This is an extreme case, however, and one which



RECOVERY OF TOPOGRAPHY OF VERTICAL FAULT
FROM SIMULATED MBGG DATA

FIGURE 4

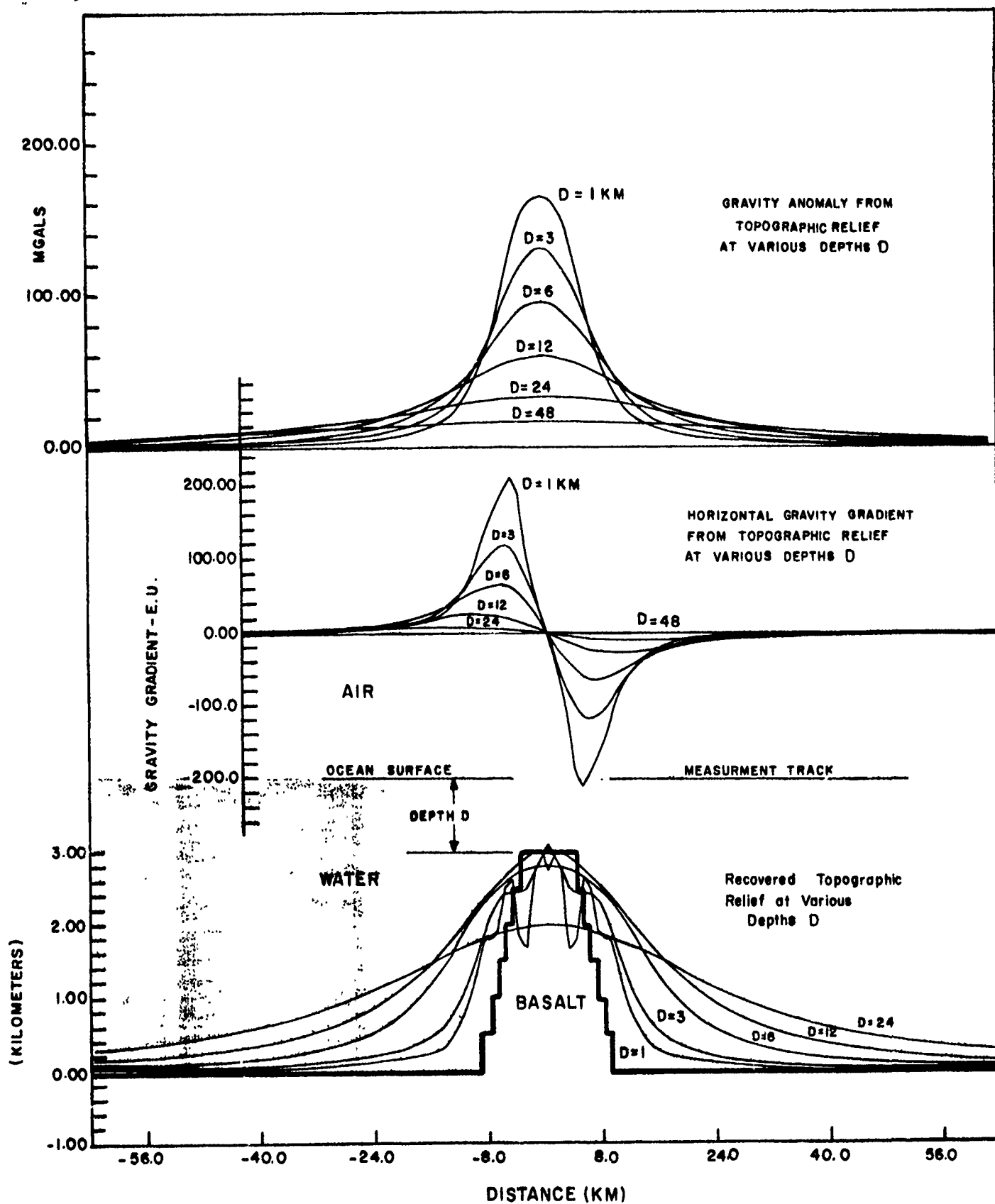


FIGURE 5: RECOVERY OF TOPOGRAPHY OF HORST

is unlikely to occur in actual marine surveys. The typical depth of the ocean is about 5 km, representative of the curves for $D=1$ and $D=3$. These two curves yield the correct height for the top of the horst, but the apparent width is overestimated by 30 to 50 percent. Also, some ringing due to Gibb's phenomena is apparent in these two profiles, indicating that our choice of filter cutoff and window parameters is still not optimum. It is possible to do some additional signal processing to these profiles to minimize such effects and narrow the apparent width, but one must be careful in the use of such techniques in the presence of broad structures with shallow slopes. Resolution of these issues will be reserved for a follow-on study.

CONCLUSIONS AND RECOMMENDATIONS

Geophysical applications of MBGG are not well-served by adapting gravity data processing methods. It is preferable to invert the gravity gradient data directly for the shape, size and depth of the causative density contrasts. This is especially true in areas where isostatic compensation occurs at short wavelengths, i.e. for areas of relatively young, thin crust. In such areas, the gravity signature of anomalous structure is highly attenuated, while the gravity gradients continue to indicate the boundaries of the structure.

As a first step in such an inversion, we have developed a method of inversion for the shape of the topography. Since topography will contribute the largest signal in most MBGG surveys and since it must be removed before one can study density contrasts at depth, correction for the topography should be the first order of business in processing MBGG data.

Simulations of inversions for topography show promising results, but also point up potential problems in the optimal selection of low-pass filter and window parameters. This parameter selection, and evaluation of the effect of measurement noise, the presence of density contrasts other than that of topography, and the effect of topography with non-two-dimensional geometry must be evaluated. The ideal way to resolve these questions involves the use of real MBGG survey data in a location where the topography and gravity are known by independent measurements.

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