NPS-58AD74011A

NAVAL POSTGRADUATE SCHOOL

Monterey, California

CORRECTIONS FOR UNDERWATER GRAVIMETRY

by

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January 1974

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Monterey, California

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ABSTRACT

Because underwater gravity surveys are usually conducted in coastal waters, several unique corrections are required to reduce the observed data for calculation of free-air and Bouguer anomalies. The most logical sequence for the application of corrections would be: terrain correction (if necessary) to reduce bathymetric irreqularities to a flat, horizontal bottom; removal of the upward attraction of the water above the meter; free-air correction to bring the meter measurement to the surface of the reference spheroid; filling in the ocean below the spheroid with rock for a Bouguer anomaly calculation or with water for a free-air anomaly calculation. The terrain correction must be handled carefully as the bathymetric irregularities are immersed in water of finite density and, due to the close proximity of land, topographic irregularities immersed in air may be within the range of the correction graticule grid. Graticule compartment weighting factors for making this correction may be readily determined by breaking the bottom-land surface profile into several segments delimited by the gravimeter depth and the sea surface.

This work was supported by: Office of Naval Research through the Naval Postgraduate School Research Foundation

TABLE OF CONTENTS

CORRECTIONS FOR UNDERWATER GRAVIMETRY

INTRODUCTION

The concept that present shorelines represent generally insignificant discontinuities to the stratigraphy and structure of crustal rocks found on land and the adjacent continental terrace is basic to geology. However, the problems of safe ship navigation, sampling outcrops and crustal rocks buried by sediments, and conducting continuous geophysical surveys in the shallow coastal waters present difficulties in the testing of this continuity. For example, the correlation of land gravity measurements with sea-surface gravity surveys often requires interpolation of data across 5 to 10 km of unsurveyed terrain between the shoreline and shiptracks. One technique for filling this void is through the use of the underwater (bottom) gravimeter from a shallow-draft vessel. Although underwater gravimetry requires laborious field work, the fact that the meter is placed on the ocean bottom increases the accuracy of the observed values over those measured at the sea surface by avoiding the problems of removing the ship motion. Also, in coastal waters sea-surface gravity data may be unusable due to the degredation caused by severe ship motion and excessive course changes to avoid navigational hazards.

Although most discussions of underwater gravity surveys include some mention of data corrections, there is a general dearth of detail for a person confronted by this situation for the first time. In addition, the terrain correction for bottom gravity data can become an important factor along continental shelves cut by steep submarine canyons and valleys; the application of this correction to data collected on the ocean bottom raises some important problems to the investigator. The object of this paper is to present a simplified discussion of data reduction applicable to underwater surveys. Traditionally, gravity corrections are discussed in the following order: free-air, Bouguer, and terrain. This order is significant in terms of increasing difficulty of calculation, but it is not necessarily the most logical order for understanding the physical significance of these corrections and their proper application to a specific geologic region.

Although underwater gravity surveys have been conducted from a diving bell, lowered to the ocean bottom with a gravimeter and its operator inside (Frowe, 1947), the most practical method employs a gravimeter encased in a pressure housing and controlled remotely from the ocean surface through electrical conductors in the lowering cable. Pepper (1941) and LaCoste (1967) discussed the functioning of such gravimeters and Beyer et al. (1966) determined the feasibility and precision of measurements made with a modified LaCoste and Romberg gravimeter in water depths up to about 900 m. At the Naval Postgraduate School, the LaCoste and Romberg Model H6G Underwater Gravimeter is used for shallow-water surveys. This instrument is essentially a land meter mounted inside a shell of two thick aluminum hemispheres supported by a triangular base. Regulation of the temperature of the meter is accomplished with a thermister-transistor circuit in the meter housing within the pressure shell. Clamping and unclamping of the gravimeter beam or weight, leveling of the meter within the shell, and manipulation of the measuring screw are all remotely controlled from the sea surface. The maximum bottom slope permissible for remote leveling of the meter is 15°. From the ship, the meter is lowered and raised by a hydraulic winch containing a slip ring assembly for electrical continuity between the meter and the control box. The control box contains functions for meter temperature control, leveling, beam clamping and unclamping, and measuring screw control. Also on the control box are indicators showing possible flooding of water into the meter, unacceptable tilting of the meter due to excessive bottom slope or tipping of the meter on the bottom, and the water depth as measured by a pressure sensor on the meter, calibrated for salt water. In 50 m of water, the time required for a measurement is approximately 4 minutes. The accuracy of the meter, determined by periodic checks at a base station, is between 0.1 and 0.2 mgal (La Coste, 1967; Brooks, 1973), compared with accuracies of 1 to 2 mgal possible for sea surface gravimeters when good navigational control is available and a reasonably calm sea state prevails (Wall, Talwani, and Worzel, 1966; Beyer et al., 1966; Dehlinger and Chiburis, 1972).

CORRECTION MODELS

To demonstrate the various corrections to be applied to the observed underwater gravity values, the following models will be described: flat, horizontal bottom; smooth sloping bottom; irregular bottom. General equations for the corrections are given along with specific formulas assuming densities for sea water and crustal rocks. These formulas may be modified for particular locations using more appropriate densities.

Flat, horizontal bottom

The simplest model to begin with in discussing underwater gravity corrections is that of a flat, horizontal bottom at depth h below the sea surface and a difference between the sea surface and the reference spheroid (approximated by mean sea level) of a vertical distance (h - e) (a tidal correction) (Fig. 1). In this model no terrain correction is necessary due to the absence of bathymetric relief.

The first step in correcting the observed gravity is to remove the gravitational effect of the water above the meter. This is accomplished by calculating the effect of a 'Bouguer plate' of water of density σ_w and thickness h. The general equation for this correction (Δg_1) is:

$$\Delta g_1 = 2\pi\sigma_w G h, \qquad (1)$$

where G is the universal gravitational constant (6.670×10^{-8} cgs units).

For a water density of 1.027 g/cm^3 and h measured in meters, eq. 1 reduces to:

$$\Delta g_1 = (0.0430\ h)\ \text{mgal}. \qquad (2)$$

Since the water is attracting the gravimeter beam or weight upward, this correction is added to the observed gravity.

The second step in the correction requires, in essence, bringing the meter from the ocean bottom to the reference spheroid using the free-air correction. The general equation for this correction (Δg_2) is:

$$\Delta g_2 = 2\ GMe/R^3, \qquad (3)$$

where e is the depth of the bottom below the reference spheroid (mean sea level) (Fig. 1), M is the mass of the Earth (5.976×10^{27} g), and R is the Earth's radius (6371 km) (MacDonald, 1966), or:

$$\Delta g_2 = (0.3083\ e)\ \text{mgal}, \qquad (4)$$

where e is measured in meters. This correction is subtracted from the observed gravity as the meter is always below the reference spheroid. The value for (h - e) is numerically positive for tidal heights above mean sea level and negative for heights below this level.

The third and final step requires filling in the ocean (now air between the reference spheroid and the bottom) with rock if these gravity observations are to be correlated with land measurements. This step is numerically analogous to the 'Bouguer' correction for sea-surface gravity surveys. The equation for this correction (Δg_3) is:

$$\Delta g_3 = 2\pi\sigma_r Ge, \qquad (5)$$

where σ_r, the rock density for the Bouguer plate, is often taken to be 2.67 g/cm^3 (Dobrin, 1960). Grant and West (1965, p. 240) provide a discussion on the proper selection of the value for the Bouguer plate density as it is important to relate this value to the local geology in order to obtain a good correlation with land gravity. Using a rock density of 2.67 g/cm^3 (a value that will be used throughout this paper), eq. 5 reduces to:

$$\Delta g_3 = (0.1119\ e)\ \text{mgal}, \qquad (6)$$

where e is measured in meters. This correction is added to the observed gravity as mass is being added below the reference spheroid.

Combining all these corrections into one expression (Δg_b) gives:

$$\Delta g_b = \Delta g_1 - \Delta g_2 + \Delta g_3$$

$$= 2\pi\sigma_w Gh + 2G(\pi\sigma_r - M/R^3)e, \qquad (7)$$

or:

$$\Delta g_b = (0.0430h - 0.1964e)\ \text{mgal}. \qquad (8)$$

Since the tidal height (h - e) will be generally small relative to h, this total correction will usually be negative.

Because of the absence of bottom relief for this model, eliminating the necessity for a terrain correction, the Bouguer anomaly (BA) is defined by the relationship:

$$BA = g_o + \Delta g_b - g_t, \qquad (9)$$

where g_o is the gravity value observed by the underwater meter and corrected for earth tides, instrument drift, and earth curvature, and tied to a reference point within the international network of absolute gravity values. The term g_t, the theoretical value for gravity on the surface of the reference spheroid, is given as a function of latitude (λ) by the International Gravity Formula (Heiskanen and Vening Meinesz, 1958):

$$g_t = [978.0490\ (1 + 0.0052884\ \sin^2\lambda - 0.0000059\ \sin^2 2\lambda)]\ \text{gal}. \qquad (10)$$

Bouguer anomalies as calculated from eq. 9 for underwater gravity stations may be correlated with Bouguer anomalies for land stations.

Sea-surface gravity measurements, when corrected for horizontal and vertical ship accelerations, cross-coupling effects due to interaction between horizontal and vertical accelerations on the meter, instrument drift, earth and ocean tides, earth curvature, and the Eotvos effect, give free-air gravity anomalies when compared with g_t as formulated in eq. 10. In order to correlate these anomalies with underwater gravity measurements, a slightly different set of corrections to the observed bottom value is necessary. The first step is to remove the upward attraction of the overlying water using Δg_1 from eq. 1. Next, the meter reading is reduced from the bottom value to the value on the reference spheroid through use of Δg_2 from eq. 3. Finally, the ocean is again filled with water below the reference spheroid using the following correction (Δg_4):

$$\Delta g_4 = 2\pi\sigma_w Ge, \qquad (11)$$

or:

$$\Delta g_4 = (0.0430\ e)\ \text{mgal}, \qquad (12)$$

where e is measured in meters. This correction is positive as the mass of water added increases the downward gravitational attraction on the meter beam when located on the reference spheroid. The combination of Δg_1 and Δg_4 is called the double Bouguer correction (Sheriff, 1973, p. 61). Combining these corrections into one expression (Δg_f) gives the relationship:

$$\Delta g_f = \Delta g_1 - \Delta g_2 + \Delta g_4$$

$$= 2\pi\sigma_w Gh + 2G(\pi\sigma_w - M/R^3)e. \qquad (13)$$

Using values for σ_w, G, M, and R as defined previously and measuring h and e in meters, this equation reduces to:

$$\Delta g_f = (0.0430h - 0.2652e) \text{ mgal}. \qquad (14)$$

As with the expression for Δg_h in eq. 8, this correction will usually be negative. Thus, the free-air anomaly (FAA) for the underwater gravity measurement correlatable with sea-surface free-air anomalies is defined as:

$$FAA = g_o + \Delta g_f - g_t. \qquad (15)$$

Smooth sloping bottom

In this model (Fig. 2), the terrain correction is introduced to reduce the underwater gravity measurements. Although the bottom is sloping, there are no bathymetric or topographic irregularities in the model. The most logical approach to this problem is first to make terrain corrections that result in a model for a flat, horizontal bottom, and then to reduce the gravity data in the same manner as was discussed in the previous section. Because the bottom is immersed in water of finite density rather than in air with a negligible density and because some of the 'bottom' may be above the reference spheroid due to the close proximity of the shoreline, certain modifications of the weighting factors for the zones in the terrain correction graticule are necessary. The terrain correction chart and tables developed by Hammer (1939) may be used; these tables assume a density of 2.0 g/cm^3 for the material making up the relief. Use of digital computers in place of the charts and tables can significantly reduce the time required to make these corrections (Kane, 1962; Bott, 1959).

The first step in applying the terrain correction to the underwater station in Fig. 2 is to fill in segment A (a wedge of water between the station depth and the bottom seaward of the station) with rock of density σ_r. Since water of density σ_w already fills this wedge, the correction density of the filled wedge has the value $(\sigma_r - \sigma_w)$. Assuming densities of 1.027 g/cm^3 and 2.67 g/cm^3 for σ_w and σ_r, respectively, and using Hammer's correction tables, the total terrain correction for compartments in this segment is multiplied by a factor of 0.822 [i.e., $(\sigma_r - \sigma_w)/\sigma_t$, where σ_t is the density used to make up the selected correction table]. This correction is added to the observed gravity as it adds mass below the meter depth.

The next step requires removing the effects of the wedge of rock above the station depth (segments B and C in Fig. 2). There are two parts to this step because the material in segment B is immersed in water, while in segment C it is immersed in air. The total terrain correction for segments B and C is first calculated assuming a density of σ_r; again using Hammer's tables and assuming a value of 2.67 g/cm^3 for σ_r, this correction must be multiplied by a factor of 1.335 (i.e., σ_r/σ_t). This part of the correction is also added to the observed gravity as it represents removal of mass above the meter location. At this point it is obvious that too much mass has been removed by this correction because in segment B part of the terrain effect of the rock is balanced by water of finite density. Thus, the second part of this step of the terrain correction involves calculating the effect of filling in segment B with water. The total terrain correction for this segment must be multiplied by a factor of 0.514 (i.e., σ_w/σ_t) if using Hammer's tables. This part of the correction is subtracted from the observed gravity as it represents the addition of a slab of water of thickness h (segment B) above the meter depth.

In summary, the terrain correction involves filling in segment A with rock rather than water, filling in segment B with water rather than rock, and removing the effect of the rock above the sea surface in segment C. For the simple model demonstrated by this case, Sandberg (1958) gave tables of terrain corrections for an inclined plane with slope angles of 1° to 30° based on Hammer's graticule zones and density. If the actual bathymetry and topography of the study area can be approximated by a uniform slope, these tables may be used as outlined above for Hammer's tables.

The model for this case is now exactly the same as for the previous case, a flat, horizontal bottom, and the gravity data may be corrected to a free-air (eq. 15) or Bouguer (eq. 9) anomaly as outlined previously. Grant and West (1965, p. 240) state that "unless the heights (or depths) of the topographic features exceed one-twentieth of their distance from the reference point, they are usually omitted". This would mean for this case that the terrain correction is probably unnecessary for a bottom slope of 3° or less.

To correlate the gravity values taken over the continental shelf from the underwater meter with sea-surface gravity measurements, it is probably best to first make terrain corrections to the bottom data before calculating the free-air anomaly using eq. 15. This statement is based on the concept of downward continuation (Peters, 1949; Trejo, 1954) which shows that for a relatively horizontal bottom the terrain effect on a bottom gravimeter is greater than on a meter at the sea surface at some distance above the same station. In shallow water where the vertical angle from a given portion of bathymetric relief to the bottom station may be greater than the similar angle from the feature to the surface meter, the terrain effect may be greater for the surface meter, requiring terrain corrections to be made to the data from both meters.

Irregular bottom

Although this case illustrates the usual model found on the continental terrace, the previously discussed cases are applicable approximations in many areas. Along the central California coast in the vicinity of Monterey Bay the presence of submarine canyons which begin just seaward of the shoreline and the rugged coastal mountain range cause a rather narrow continental shelf (about 10 km wide) and a very steep continental slope (in places, bottom slopes of up to 45° have been found). Rock outcrops and fault scarps on the shelf cause many bathymetric irregularities. The model for this case may be broken into the same three segments that were discussed in the previous case, and the general method for making terrain corrections is the same, although Sandberg's correction tables for an inclined plane are probably not appropriate. Just south of Monterey Bay, Souto (1973) calculated terrain corrections of 5.5 to 5.7 mgal for stations at water depths of 60 to 75 m near the Carmel Submarine Canyon, a tributary of the Monterey Submarine Canyon. Inclinations of 28° were found on the continental slope in this area. With Bouguer anomalies ranging from +23 to +30 mgal for this area, the terrain correction is an important factor in data reduction.

CONCLUSIONS

Correcting underwater gravity data presents some unique problems to an investigator. If terrain corrections are necessary, it appears to this writer that they should be applied first to the observed gravity data to reduce the bathymetry to a model of a flat, horizontal bottom. Next the upward attraction of the water above the station should be removed and the station should be relocated on the reference spheroid with a free-air correction. Finally, water should be again added to the ocean beneath the spheroid if a free-air anomaly chart is desired for correlation with sea-surface gravity data, or rock should be added if a Bouguer anomaly chart is required for correlation with land gravity surveys. This order of application of corrections should make more apparent the physical meaning of each step and aid in determining which steps, if any, may be simplified by approximation for special bathymetric cases or eliminated.

ACKNOWLEDGEMENTS

The concepts developed in this paper were based on discussions with Joe von Schwind, Bob Brooks, Brian Cronyn, Clay Spikes, Antonio Souto, and Hap Woodson. The work was funded in part by the Office of Naval Research through the Naval Postgraduate School Research Foundation.

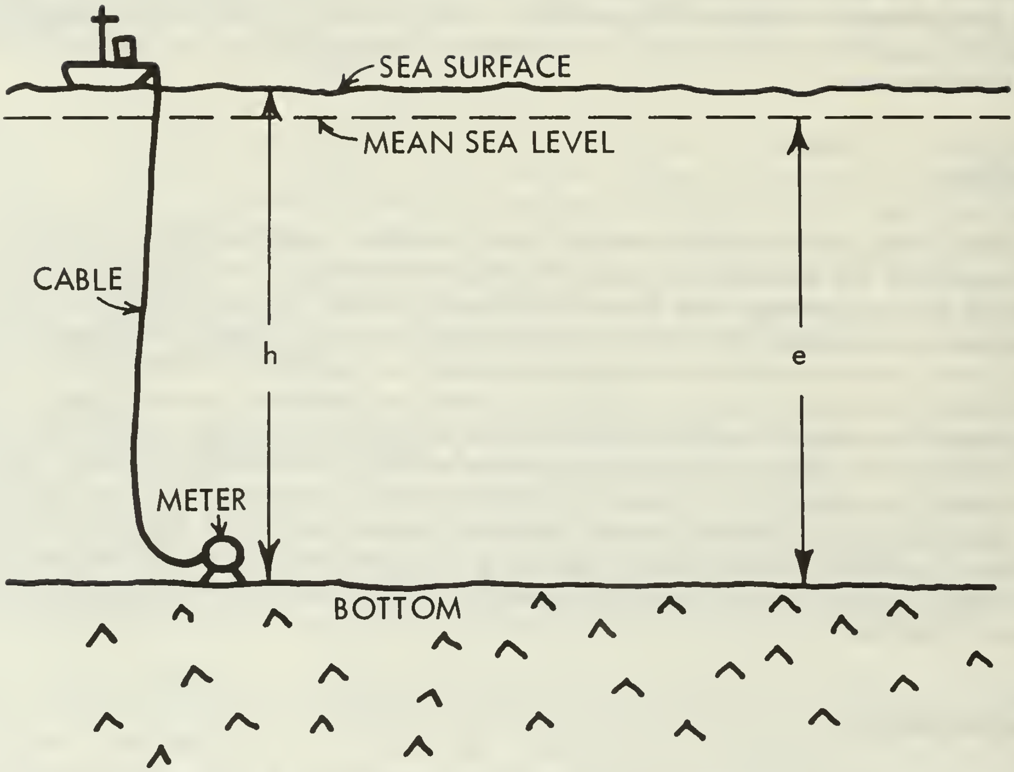

Fig. 1. Model for Flat, Horizontal Bottom.

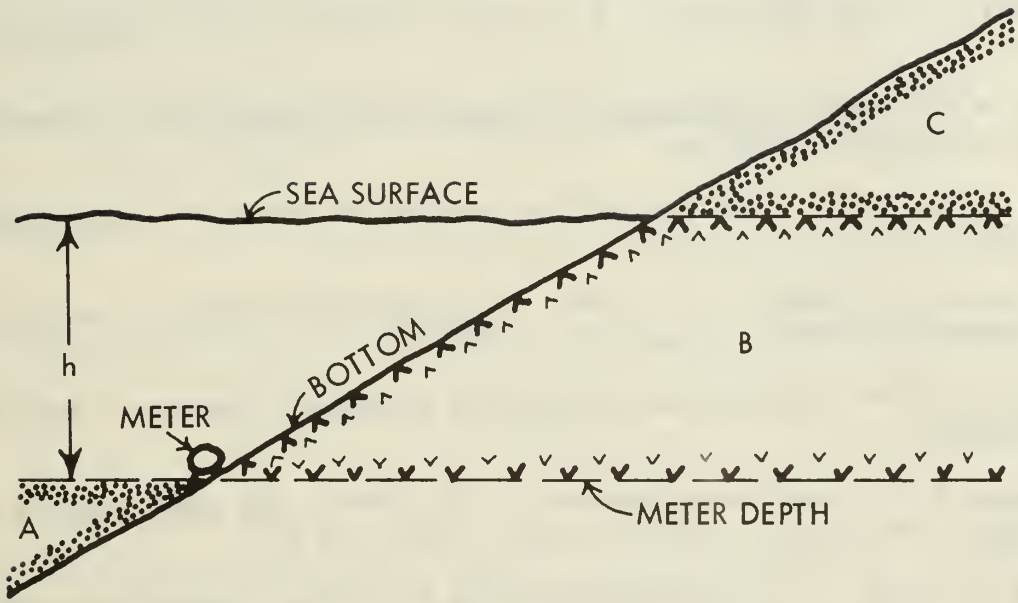

Fig. 2. Model for Smooth Sloping Bottom with Segments for Terrain Correction

REFERENCES

Beyer, L. A., von Huene, R. E., McCulloh, T. H., and Lovett, J. R., 1966. Measuring gravity on the sea floor in deep water. J. Geophys. Res., 71: 2091-2100.

Bott, M. P., 1959. The use of electronic digital computers for the evaluation of gravimetric terrain corrections. Geophys. Prosp., 7: 45-54.

Brooks, R. A., Sr., 1973. A bottom gravity survey of the shallow water regions of Southern Monterey Bay and its geological interpretation. M.S. Thesis, Naval Postgrad. School, Monterey, CA., 92 pp.

Dehlinger, P., and Chiburis, E. F., 1972. Gravity at sea. Marine Geol., 12: 1-41.

Dobrin, M.B., 1960. Introduction to geophysical prospecting. McGraw-Hill Book Co., Inc., N.Y., 446 pp.

Frowe, E. W., 1947. A diving bell for underwater operation. Geophysics, 12: 1-12.

Grant, F. S., and West, G. F., 1965. Interpretation theory in applied geophysics. McGraw-Hill Book Co., Inc., N.Y., 583 pp.

Hammer, S., 1939. Terrain corrections for gravimeter stations. Geophysics, 4: 184-194.

Heiskanen, W. A., and Vening Meinesz, F. A., 1958. The earth and its gravity field. McGraw-Hill Book Co., Inc., N.Y., 470 pp.

Kane, M. F., 1962. A comprehensive system of terrain corrections using a digital computer. Geophysics, 27:455-462.

LaCoste, L. J. B., 1967. Measurement of gravity at sea and in the air. Rev. Geophys., 5:477-526.

MacDonald, G. J. F., 1966. Geodetic data. In: S. P. Clark (Editor), Handbook of physical constants. Geol. Soc. America Mem. 97:219-221.

Pepper, T. B., 1941. The Gulf underwater gravimeter. Geophysics, 6:34-44.

Peters, L. J., 1949. The direct approach to magnetic interpretation and its practical application. Geophysics, 14:290-319.

Sandberg, C. H., 1958. Terrain corrections for an inclined plane in gravity computations. Geophysics, 23:701-711.

Sheriff, R. E., 1973. Encyclopedic dictionary of exploration geophysics. Soc. Exploration Geophysicists, Tulsa, 266 pp.

Souto, A. P. D., 1973. A bottom gravity survey of Carmel Bay, California. M. S. Thesis, Naval Postgrad. School, Monterey, CA, 71 pp.

Trejo, C. A., 1954. Note on downward continuation of gravity. Geophysics, 19: 71-75.

Wall, R. E., Talwani, M., and Worzel, J. L., 1966. Cross-coupling and off-leveling errors in gravity measurements at sea. J. Geophys. Res.,71:465-485.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NPS-58AD74011A	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CORRECTIONS FOR UNDERWATER GRAVIMETRY		5. TYPE OF REPORT & PERIOD COVERED Interim
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert S. Andrews		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School, Department of Oceanography, Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Research Foundation Monterey, California 93940		12. REPORT DATE January 1974
		13. NUMBER OF PAGES 14
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Gravimetry
Gravity Corrections
Marine Geophysics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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(Page 1) S/N 0102-014-6601 |

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