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Landsat as an Aid in the Preparation of Hydrographic Charts

Costs are reduced when Landsat MSS imagery is employed in support of hydrographic surveys.

ABSTRACT: *Among the many claims made for Landsat MSS imagery is the ability to map water depths in shallow areas. A study has been conducted at the Australian National University to explore the extent to which this technique could be applied in a production mapping situation. The study, while confirming the technique in principle, demonstrated a number of implementational difficulties. The implications of these difficulties are discussed and it is shown that an integrated approach, involving satellite imagery, computer analysis, human interpretation, and ground truth collection, can overcome the major problems. Ground truth profiles at a spacing of 5 kilometres yield water penetrations to about 20 metres at an effective depth accuracy of 10 percent of measured value. The extent of supporting data determines reliability of the final product and can be varied to provide an appropriate balance between cost and reliability for a particular project.*

INTRODUCTION

MAPPING FROM satellite imagery offers three main advantages over conventional hydrographic survey techniques (Turner and Mitchell, 1977):

(1) Broad coverage is available at comparatively low cost;
(2) Those operations to which the imagery is suited—delineation of reefs and islands and mapping shallow water—are the most difficult and frequently dangerous operations for shipborne surveys; and
(3) A single image can bridge expanses of featureless ocean.

Turner and Mitchell (1977) and Lyons (1977) discuss the problem of updating charts of reefs and islands while Fleming (1977) describes the application of Landsat imagery to geometric control across large stretches of water. Here consideration is given to the depth measurement aspect of hydrographic mapping.

Other studies (Byrne and Honey, 1977; Polcyn, 1976) have demonstrated that, under favorable conditions, Landsat is able to measure water depths up to approximately 20 metres within 10 percent (RMS) of the measured value. Penetration is reduced as water clarity falls.

The principle of bathymetric mapping with Landsat is straightforward. Neglecting multiple reflections within the body of the sea, the optical model is of the form:

$$R = a + b \cdot \exp(-c \cdot z) \qquad (1)$$

where R is the radiance measured at the detector; z is the water depth; and a, b, and c depend on the prevailing optical characteristics of the sea and overlying atmosphere.

a represents the signal that would be returned from "infinitely" deep water and is the sum of the atmospheric path radiance and the radiance reflected from the sea surface and within the sea water itself. *b* gives the effects of attenuation of the light at the sea surface. Both *a* and *b* include an atmospheric attenuation term. *c* is the effective attenuation coefficient for light passing to and from the sea bed with appropriate allowance being made for the non-vertical, and possibly indirect, light path.

All coefficients are dependent on the wavelength of the light. Unfortunately, no Landsat detector is optimally placed spectrally, but the best response is obtained from the visible green sensor (band 4) while the red (band 5) may be useful in waters of up to a few metres in depth and for detecting near-surface anomalies.

In 1975, the Australian National University's Department of Engineering Physics, in liaison with the Division of National Mapping, set out to explore the extent to which the principle could be applied in a production mapping situation. The Torres Strait was selected because of the large expanses of shallow water and the number of other features of interest in the scene.

Discussions with officers of the Division of National Mapping have indicated that existing mapping standards need not be considered absolute. They argued that these had largely been determined by the capabilities of conventional survey techniques, not necessarily by what users required. In the bathymetric mapping case, where changes tend to be slow, precision was not as critical as the standards might indicate. In the light of the costs in time and money of conventional surveys, it was, in some cases, a matter of anything being better than nothing. These arguments apply to both geometric and depth accuracy.

Soundings currently used in the preparation of hydrographic charts in Australia are measured in fathoms for depths greater than 11 fathoms, and fathoms and feet for depths less than 11 fathoms; or metres for depths greater than 31 metres, and metres and decimetres for depths less than 31 metres; depending on whether the survey was carried out before or after metrication. It was realized that Landsat could not match this accuracy, and it was agreed that a depth resolution of 10 percent of nominal depth or 1 metre, whichever was the greater, would serve as a guideline.

The Torres Strait Scene

Scene 1026-00035, scanned at 10:03 am on 18th August 1972, was used for the study. Sun elevation was 46 degrees while azimuth was 58 degrees. All detectors were set at low gain. The scene stretches from Cape York in the south to Papua-New Guinea in the north, but all test areas were drawn from the south-west corner of the image (Figure 1) as this contained the most significant features.

FIG. 1. Torres Strait test areas.

Tidal height was approximately 1.4 m with a variation of less than 0.3 m across a test area (*Admiralty Tide Tables*, Vol 3, 1972). The tidal stream, including prevailing current, measured at Hammond Rock in Prince of Wales Channel was approximately 1.5 knots in a westward direction. At the entrances of the channel this rate would have been reduced to approximately 0.5 knots. Streams in Endeavour Strait lag those at Hammond Rock by about 40 minutes and, except in the more restricted sections of the strait, would not have exceeded 0.5 knots.

Ground truth soundings used in the study were generally over 30 years out of date and so it was frequently impossible, within project constraints, to determine with certainty whether some discrepancies reflected a change in water depth over time or were anomalous. In most cases the physical characteristics of the locality provided good reason to believe that the latter was true.

Experimental Method

Intensity and depth values were collected along profiles specified by reference to suitable land features. This method of data collection was selected on the grounds that it was easiest to implement and simulated the likely situation in a real survey. The geographical arrangement of the ground truth data long a profile, in itself, proved an aid to interpreting anomalies as is described below. A numerical fitting technique was used to calculate the coefficients in Equation 1. The study centered on a group of islands and reefs under the influence of a moderate tidal stream rather than on a more open section of sea so that it could reasonably be expected to uncover complications which affect the practical implementation of the technique.

Results were evaluated in four ways:

(1) Degree of fit that could be obtained along the ground truth profiles;
(2) Qualitative assessment over a broad area using a pseudo-color display of calculated depths;
(3) Location of depth contours; and
(4) Degree of fit that results along test profiles.

Effect of Tides

Tides will affect the analysis in two main ways. Firstly, tidal streams may pick up sediments and mix waters of different types. There will be consequent changes in optical parameters which must be allowed for. In addition, tides result in actual depth changes which can vary considerably over a Landsat scene.

Let D be the depth referred to the datum and y the difference between the depth at the time of the satellite overpass, z, and D. That is:

$$z = D + y \tag{2}$$

Substituting Equation 2 into Equation 1 gives

$$\begin{aligned} R &= a + b \cdot \exp\left[-c \cdot (D + y)\right] \\ &= a + \left[b \cdot \exp(-c \cdot y)\right] \cdot \exp(-c \cdot D) \end{aligned} \tag{3}$$

Equation 3 still has the same form as Equation 1 and, since the numerical fit approach is used to calculate optical model coefficients, all depths will be measured relative to the same datum used for ground truth soundings. This can result in a negative depth which is not detected as land by MSS band 7. Such a situation signifies that the sea bed is above the zero depth datum but below the surface at the time of the satellite overpass. This generally implies that under some conditions it will be exposed.

While tidal heights are compensated at any one location, tidal height differences cause the coefficient b in Equation 1 to vary from one place to another. Consequently, a new numerical fit must be calculated wherever there is a signficant variation in tidal height. Test areas in the current study are small enough for this effect to be insignificant, but it must be considered under operational conditions.

Results

Attempts to fit Equation 1 to raw Landsat data yielded maximum penetrations of approximately 15 m with an RMS error of 25 percent and with considerably higher maximum errors. There is a clear need for radiometric correction and enhancement before bathymetric mapping can be carried out. The limited useful range of signal available for oceanographic studies and the sophistication of the necessary correction procedures makes it mandatory that digital rather than photographic data be used. Data preprocessing was applied such that there was a three-times contrast stretch with an effective reduction of noise, including striping, so that it did not rise above 0.5 grey levels during the stretching process. The correction is more complex than this description might indicate and a more detailed account of the correction process is in preparation (Warne, 1977). Both penetration and accuracy were improved by the enhancement process.

Even with radiometric correction it was not always possible to get a good numerical fit in relating radiance to depth profiles. Discrepancies appeared to arise for two reasons. The first is the geometric* limitations of the data, especially after a loss of resolution resulting from the data correction process. Relatively large errors occurred in the vicinity of steep gradients or small features. Anomalous data points of this type were edited out of the profiles so as not to disturb the numerical fitting process. Secondly, the optical characteristics of the ocean and atmosphere may vary along the profile. Figure 2 shows a profile where there is a clearly defined anomaly at one end and a change in model coefficients towards the middle. In such cases it is necessary to segment the profile into lengths corresponding to homogeneous areas of ocean. Accuracy of numerical fit depends on the extent to which

* "Geometric" features denote those related to the spatial characteristics of the two-dimensional image as distinct from depth or radiometric features.

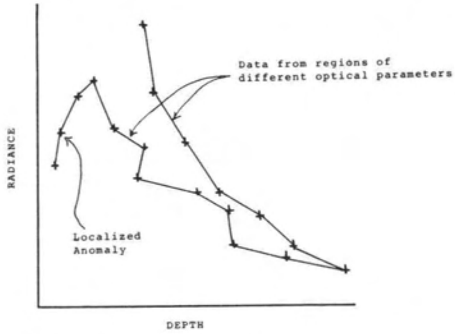

FIG. 2. Radiance versus depth diagram.

profile segmentation is carried. For reasonably macroscopic segmentation, RMS errors of about 5 to 8 percent were typical, with maximum errors a few percent higher. Figure 2 illustrates the desirability of maintaining information on the geographical relationship of the soundings. The same trends are not nearly as clear in Figure 3 where there is no clue to the order of the soundings.

All result evaluation methods confirmed the existence of broad scale and localized disturbances of the relationship between depth and radiance. In general, the very localized anomalies can be clearly seen in or inferred from the image by an interpreter with the help of ancillary data such as tidal and meteorological reports. Some broad scale trends are also detectable in this way, but others can be located only with the help of ground truth depth measurement.

Because of the variability in optical parameters, model coefficients were calculated for each test area separately. Penetration was calculated by determining the depth, z, such that the radiance, R, exceeded the deep water signal, a, by one grey level. That is

$$z = \ln (b)/c \tag{4}$$

In some areas the calculated penetrations fell below 10 metres; however, this was limited to situations where all available ground truth depths were significantly shallower than the penetration limit. Consequently, little confidence can be placed in the numerical prediction. The only confirmed penetrations less than 20 metres were in areas with the greatest tidal stream activity. This indicates that under more favorable tidal conditions the penetration would be improved. In the more favorable areas of the image, penetration was confirmed to be in excess of 20 metres. Calculated penetrations were as high as 40 metres but, once again, it was not possible to verify this figure.

The exponential form of the relationship causes resolution to fall off rapidly as depth approaches the penetration limit. Overall resolution cannot be better than that found for the control profile, which is largely determined by the level of noise. The degree to which it falls short of this figure will depend on the variation of optical characteristics that is permitted before new ground truth data are taken and new parameters calculated. Analysis of the results shows that lines of soundings 5 kilometres apart could detect the broad scale variations in Endeavour Strait sufficiently to keep the RMS errors to about 10 percent. In some instances water separated by many times this distance had the same characteristics while in others the 5 kilometre sounding pattern, while it detected the variations, was too coarse to give a good indication of where to define the boundary between the two sets of parameters. The slight tidal stream through the strait at the time of the overpass would not provide the most favorable conditions and so under some circumstances a coarser sounding pattern may be feasible. This is supported by the fact that variation was greatest where the strait was narrowest and the stream consequently at its fastest.

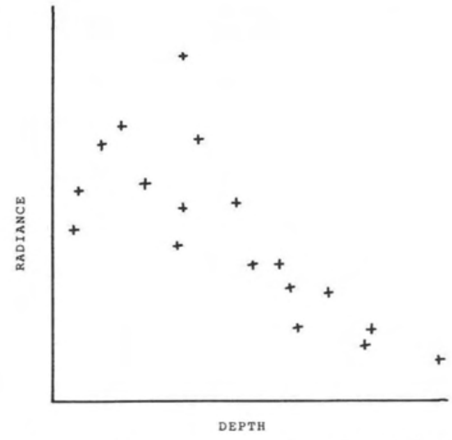

FIG. 3. Radiance versus depth with no indication of geographical relationship.

More thorough ground truth collection is required to clarify localized anomalies or alternatively the area must be left for another overpass of the satellite. These anomalies are of two types:

(1) localized disturbances in optical characteristics of the water or atmosphere; and

(2) small features and steep gradients beyond the resolving power of the MSS system and subsequent data correction process.

Likely disturbances in optical characteristics, as mentioned above, can generally be detected by an interpreter through direct observation or inference.

Discussion

The lack of homogeneity in optical characteristics seriously complicates the implementation of Landsat as an aid in the preparation of hydrographic charts. The relationship between parameter variation and tidal streams indicates that many fluctuations are temporary. Consequently, any approach based on shipborne measurement of optical parameters and subsequent calculation of coefficients for Equation 1 (Polcyn, 1976) will involve considerable difficulties in survey management. Coefficient calculation based on depth measures is more viable, but once again the coefficients cannot unreservedly be applied to a broad scale mapping.

Ground truth data will generally be in the form of depth profiles. It can be seen from Figure 2 that profiles which cross a significant ridge or trough are more helpful in detecting parameter variations than are monotonic profiles. In addition, ground truth data may be required to resolve localized anomalies. Accordingly, the Landsat image(s) should be used in determining the pattern of sounding collection. It may be that analysis based on ground truth reveals further anomalies which must be resolved by further data collection. Consequently, some degree of coordination between image interpretation and ground truth survey is required. This is far less restrictive than coordination between survey and satellite overpass.

Precise geographic positioning of ground truth data is difficult at sea due to the absence of defined landmarks. Fortunately, positioning becomes critical only in areas of significant spatial detail. Ground truth profiles may first be located approximately using standard geographic control procedures and then, if there is significant detail, the interpreter can use this detail to do the final positioning interactively. Any residual imprecision will give rise to errors in relating depth to radiance. Such errors may also occur due to a lack of sufficient spatial resolution. A slight blurring of a steep gradient may be acceptable in the final product, but the same errors in the ground truth data can seriously affect the numerical fitting of Equation 1. The interpreter must be able to edit the ground truth data to eliminate such doubtful areas.

In the above discussion there are several references to the use of an interpreter to resolve various difficulties. There is also a demonstrated need to use the imagery in its digital form. An interactive approach is, therefore, indicated. The interpreter has a number of functions, but the main one is to use his perception of the image, knowledge of marine characteristics, and ground truth data in order to segment the image into regions of sufficiently constant optical characteristics and to identify areas where such constant characteristics cannot be assumed. Once this is done the production of the depth data is straightforward. Mixing of two water bodies may complicate the procedure and such areas may need to be omitted in the particular satellite overpass under consideration or, alternatively, an interpolation approach may be used. Current interactive image analysis systems are slanted towards land cover classification applications and are unsuitable in the present context. An appropriate system is approaching completion at the Australian National University and will be described in a later paper.

Changeability in the pattern of optical parameter values allows the use of imagery from multiple overflights as a check that no parameter variation has gone undetected. Use of multiple images also permits the penetration and resolution for each area of the image to be optimized and allows the interpreter to discard doubtful results from a particular overpass.

Small features that constitute a navigational hazard but are beyond the resolution capabilities of Landsat remain a problem. Supporting aerial photography could resolve this and, at the same time, provide the interpreter with a valuable aid to his analysis. If ground truth collection is done using an airborne profiler, profiling and photography could be combined to maximize cost savings. Aerial photography with its extra resolution also gives better land shape determination. Byrne and Honey (1977) and Fleming (1977) discuss a number of advantages in combining Landsat and aerial photography.

The ANU study has confirmed that depth penetration to 20 metres at an accuracy of 10 percent RMS is feasible with Landsat, but it has also indicated problem areas that must be overcome before production run mapping is a reality. Reliability of the results will depend on the optical parameters, the number of satellite overpasses used to check the analysis, the density of ground truth soundings, and the amount of supporting information such as aerial photography. Consequently, it is closely related to the cost expended on the survey and so the authority responsible can achieve a proper balance between cost and reliability in any given project. For medium quality products meeting the standards set out in the introduction, the number of soundings is reduced by a factor of between ten and 50 which will result in considerable savings of both time and money, especially when compared to a completely shipborne survey.

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2. Ordinarily *two* copies of the manuscript and two sets of illustrations should be submitted where the second set of illustrations need not be prime quality; EXCEPT that *five* copies of papers on Remote Sensing and Photointerpretation are needed, all with prime quality illustrations to facilitate the review process.
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