Potential Applications of Digital Image Analysis Systems for Displaying Satellite Altimetry Data*

Rostam Yazdani, Nikolaos Christou, and *Eugene Derenyi*
Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B. E3B 5A3, Canada

ABSTRACT: DIPIX ARIES II and a Perceptron EASI/PACE digital image analysis systems were used for displaying geoidal and sea-surface heights. These data sets were transferred to image files for display. Black-and-white and color density slicing, and enhanced color display techniques were employed to better visualize these surfaces. An analytical relief shading program was developed to make the small local undulations in height visible. The shape and orientation of the various surfaces were compared by a differencing program specifically written for this purpose. The processing and display techniques employed offered additional capabilities in examining and interpreting the displayed surfaces. They also offered better discrimination of certain features which were not discernible from the conventional contour displays.

INTRODUCTION

DIGITAL IMAGE ANALYSIS SYSTEMS have been used for processing of non-image data such as geochemical, geophysical, medical, and topographic data. Studies conducted by Aronoff and Hawkins (1984), Aronoff and Goodfellow (1985), Haxby *et al.* (1983), and Marsh *et al.* (1986) are some of the many examples that are recorded in the literature.

In this paper we consider the application of the ARIES II system for displaying and manipulating spatial data sets of geoidal heights and altimetry derived sea-surface heights with the hope that we will be able to improve the time, effort, and visual interpretation capabilities usually required and provided by conventional displaying techniques. Almost real-time interactive file handling and data file differencing, and directional illumination of a three-dimensional object, are much more easily handled tasks using an image analysis system. Also data set overlays are more rapidly and more easily accomplished by a digital image analysis system. Thus, experience gained and software development for such analysis of spatial data sets in our own image analysis system is of great importance for future applications.

BACKGROUND

The geoid is the gravity equipotential surface of the Earth which best approximates mean sea level over the entire Earth (Vaniček and Krakiwsky, 1982). Because approximately three-quarters of the Earth's surface is covered by oceans, it may be said that the geoid is a representation of the Earth's figure. Because the geoid is a very complex surface, it is rather time consuming to express it analytically. The most common way to describe it is through the geoidal height or geoid undulation, which is the separation between the geoid and a reference ellipsoid.

Gravity anomalies are the principal source of data used for the determination of geoidal heights. While the density of gravity observations over land is reasonably adequate for this purpose, at least in North America, marine gravity coverage has many gaps. With the advent of Earth orbiting satellites, however, new techniques have become available to remedy this situation. In particular, satellite altimetry offers the best alternative for obtaining the oceanic geoid.

The satellite serves as a stable platform from which a radar altimeter can measure the distance to the instantaneous ocean surface. This distance is the average height of the spacecraft above the area covered by the surface resolution cell of the sensor. Knowing the orbital altitude of the spacecraft above the reference ellipsoid, the geoidal height can be obtained as (see Figure 1)

$$N = \zeta - \zeta_s = (h-a) - \zeta_s \tag{1}$$

or, as a close approximation,

$$N = h-a \tag{2}$$

where

N = geoidal height;
h = geodetic height of the spacecraft;
a = measured altitude of spacecraft above the ocean surface, corrected for a number of instrumental and geophysical effects;
ζ = height of sea surface above the reference ellipsoid; and
ζ_s = sea-surface topography.

Until recently, two major satellite altimetry data sets existed. One is from the GEOS-3 mission (1975 to 1978) and the other from SEASAT, which was operational for three-and-a-half months in 1978.

THE DATA

The following data sets have been used in this study:

- A regional data set of adjusted sea-surface height profiles from

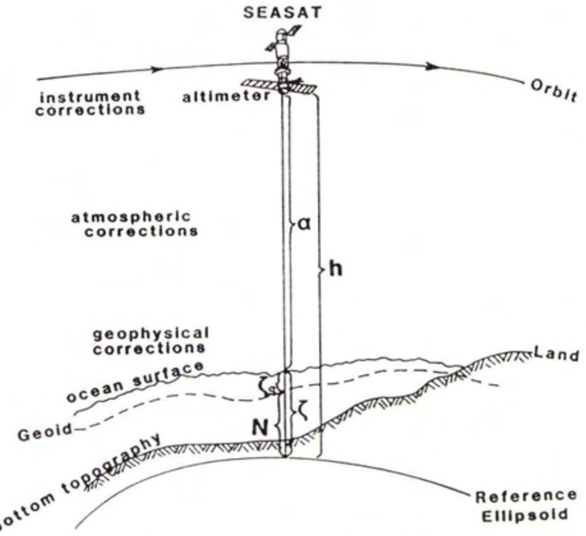

FIG. 1. Geometry of geoidal and sea-surface height determination by satellite altimetry.

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SEASAT altimetry, obtained from The Ohio State University (O.S.U.) (Rapp, personal communication, 1985) and covering the area 35°N ≤ latitude ≤ 72°N and 10°W ≤ longitude ≤ 100°W;
- a "long wavelength" pure satellite solution, namely, the GEM-9 gravity field (Lerch *et al.* 1979); and
- the World Data Bank II (WDB II) coastline (Gorny, 1977).

The O.S.U. adjusted altimetry profiles (tracks) were used to produce a detailed 10-minute by 10-minute grid of sea-surface heights over the area specified above, using a fast and very efficient interpolation procedure described in Christou and Yazdani (1986). The interpolated grid and its associated standard deviations were subsequently converted into a suitable raster format and transferred to the ARIES II system.

At the same time another file consisting of geoid undulations computed from the GEM-9 model was prepared on the same grid spacing and transferred to the ARIES II system.

The world coastline sub-file for the area of interest was resampled, using the ARIES II system, to the same pixel size as the previous two files and was used as an overlay as well as a masking file for certain over-land artifacts that the interpolation procedure had produced.

DATA PROCESSING AND DISPLAY

Contours and spot heights are generally accepted as the best means for the visual representation of elevation data sets covering large areas. Rather lengthy interpolation and plotting operations are needed to generate such displays. Figure 2 is a contour map, at 2-metre intervals, of the gridded SEASAT sea-surface heights. Although contour maps can represent three-dimensional figures with a high degree of fidelity, the surface portrayed is not easily perceivable by the viewer. Geographers have long recognized this problem and introduced color shading and hachuring to enhance the topography.

The ARIES II digital image analysis system was employed to

- expedite the visual display task,
- enhance the interpretability of the display, and
- introduce interactive processing and display techniques.

Each data set consisted of 211 lines of 542 pixels each. Geographically, it extended west from Iceland to the western shores of Hudson Bay and south from the northern shores of Hudson Bay to the middle of the Carolina coast. Each pixel represented a 10-minute grid cell in geographic coordinates.

Geoidal and adjusted sea-surface heights range from −60 metres to +70 metres in the study area and were stored in centimetre increments. A shift was applied to obtain all positive values and a scale factor was used to fit the data within the 0 to 255 operating range of the ARIES II image analysis system.

The standard gray-scale display showed only the gradual transition of the values from low (negative) at the western edge to high (positive) on the east (Plate 1). To make the local undulations visible, three types of enhancements were produced. The Look-up Table (LUT) task, which provides real time interactive manipulation of the contents of each of the three red, green, and blue image display look-up table (LUT) was used for two of the enhancements. An analytical relief shading technique was employed for the third one.

In the first LUT operation, each data set was density sliced into 32 levels whereby a contoured appearance was created. A further enhancement was achieved by color coding the slices. For easy interpretation, the color assignment followed the visible spectrum, from dark blue at the lowest points to dark red at the highest. (Plate 2).

In the second LUT operation, three bands were produced from each data set by piecewise linear contrast stretch. The three bands yielded a color composite with gradual transition from dark blue through various shades of cyan, green, and yellow to deep red.

The relief shading enhancement was achieved by a program developed at the University of New Brunswick and installed in the ARIES II. Relief shading is the gaining of a three-dimensional impression by employing variations in light and dark. It is based on the principle that the lighting of a three-dimensional object will result in varying amounts of illumination on the varying slopes. The method described by Yoeli (1965) and Woodham (1980) was used whereby the illuminance of a surface area element was taken proportional to the cosine of the angle between the light ray and the normal to the area element. In other words, the illuminance varies with the direction of the illumination and the orientation of the surface. The direction of the illumination in turn is a function of the elevation angle of the light source and its azimuth. Both variables are controlled interactively during the execution of the program. In the example shown in Plate 3 the direction of the illumination was from the northwest (top-left) at an elevation angle of 30°.

A new arithmetic operation task was written and installed in the ARIES II for obtaining the differences between non-image files. This task processed the unscaled GEM-9 and SEASAT data sets, stored as real numbers in direct access files, not the height increments used for the image data. The difference values were formed pixel by pixel then transferred into image files using the 255 grey levels. This range enabled us to display smaller height increments. For example, the vertical resolution of the differ-

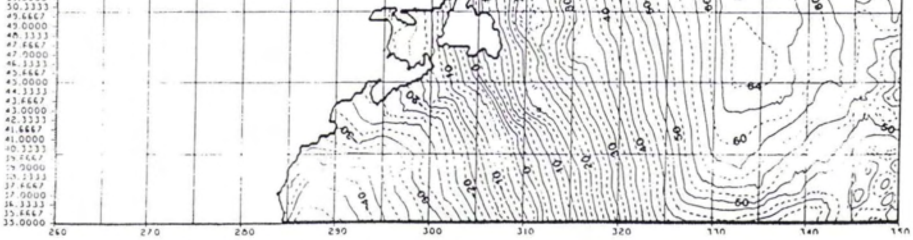

FIG. 2. Contour map of O.S.U. sea-surface heights. Contour interval: 2 m.

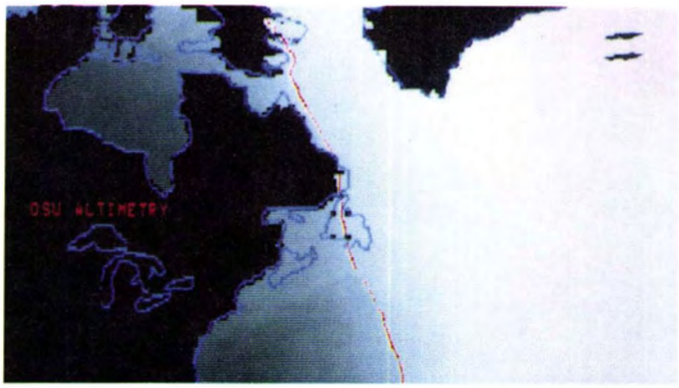

PLATE 1. Gray-scale display of O.S.U. surface heights.

PLATE 2. O.S.U. sea-surface heights density sliced into 32 levels.

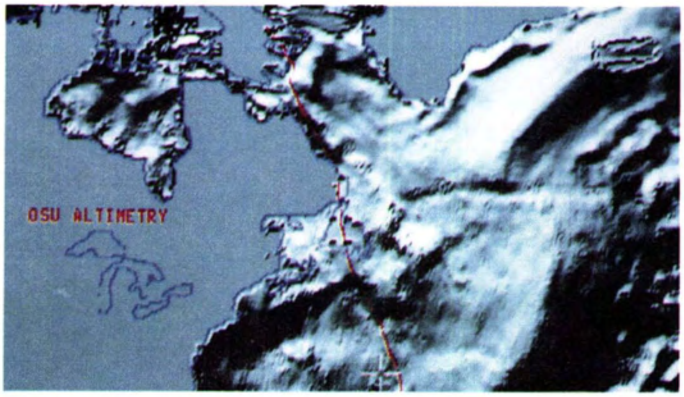

PLATE 3. O.S.U. sea-surface heights enhanced by analytical relief shading. Direction of illumination: northwest; elevation angle: 30°.

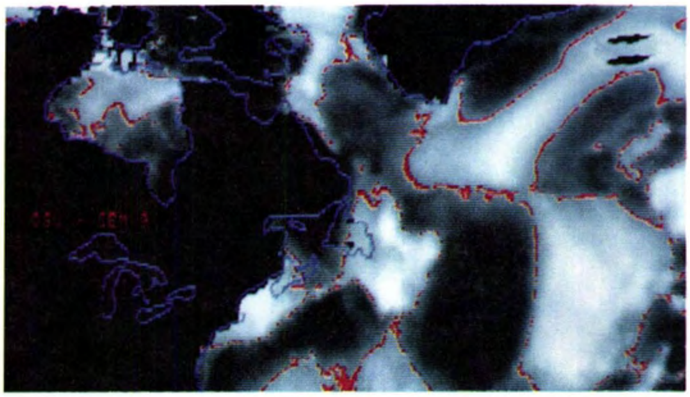
PLATE 4. Difference image of O.S.U. and GEM-9 data sets. One gray-scale increment equals 50 mm.

ence between SEASAT and GEM-9 image file data set, shown in Plate 4, is 50- millimetres.

DISCUSSION OF THE RESULTS

The gray scale display of the original data sets did not prove very useful because the general trend in the undulation of the surface from large negative values in the Hudson Bay area to large positive values in mid Atlantic was barely observable. Local undulations of several metres were not discernible by the human eye at the image gray scale increments.

Density slicing to 32 levels provided an improved impression of the general trend of the undulation, especially when color coding was introduced. Unfortunately, the contour-like slices introduced the impression of steplike changes in the surface. Color composites using piecewise linear stretch proved more useful. They preserved the impression of the general trend of the surface and, at the same time, they depicted the major local undulations.

The relief shading enhancement created the most dramatic effect. Because the slope map was computed from the original data set at one centimetre increments, local anomalies become clearly visible.

The most pronounced effect was the very clear and distinct presence of the Gibbs fracture zone, traversing and disrupting the much more easily distinguished Middle Atlantic Ridge. The conventional contour map does not help to distinguish the Gibbs fracture zone for the geophysically untrained eye. The small ripples of the contours at approximately 53°N latitude and between 310°E and 330°E longitude (see Figure 2) are not showing the same dramatic effect as it is perceived when viewing the directionally illuminated surface.

Furthermore, by changing the position of the "artificial sun" (different azimuth and elevation angle), undulations with different orientation will appear and much smaller anomalies can be shown.

Although we have formed the difference file between the altimetric heights and those implied by the GEM-9 model (Plate 4), we did not apply the directional illuminated procedure on this surface. If that were the case, then we believe that we would be able to see a lot more detail than that shown in Plate 4. Plate 4 is, essentially, the high frequency part of the northwest Atlantic oceanic geoid, because in principle it contains all those wavelengths below 1000 km (the GEM-9 geoid heights were computed from the potential coefficient expansion up to degree and order 20).

CONCLUSIONS

This experimentation with geoidal heights and satellite altimetry data has confirmed that digital image analysis systems are useful tools for manipulating and displaying spatial data. The interpretability of the displays created in this manner surpassed that of contour maps.

Unfortunately, time constraints prevented us from producing more comparisons between data sets. The loss in gray-level resolution due to data file structure was offset by the introduction of color and directional illumination. The latter enhancement method proved especially effective in depicting localized, low amplitude undulations of the surface. The illumination procedure highlighted the textural characteristics of the displayed surfaces. Major features such as the Middle Atlantic Ridge and the Gibbs fracture zone were particularly well resolved in these displays. Several other features of geophysical interest appeared with the analytical relief shading enhancement. The Flemish Cap off Newfoundland and the margins of the continental slope are much easier to distinguish than they are in the conventional contour map.

The programs and methodology developed for the DIPIX ARIES II system were transferred to the Perceptron EASI/PACE system of the Bedford Institute of Oceanography (BIO) to allow similar display and data manipulation tasks.

Finally, but most importantly, the experience gained from this study will help to further the developments in software, and the analysis of similar or other spatial data sets, in the future.

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