COASTAL BOUNDARY SURVEYS

by Captain John O. PHILLIPS, USESSA
Associate Director, Geodesy and Photogrammetry
U.S. Coast and Geodetic Survey

This paper was first presented at the Symposium on Coastal Geodesy, 20-24 July 1970, Munich, and is here reproduced by kind permission of the International Union of Geodesy and Geophysics.

INTRODUCTION

New emphasis is now being given the coastal zone as the nations enter into a new phase of world interest in the sea. Accelerated development and growth of the use of the sea are indicative of expanded exploitation for the benefit of commerce, industry, recreation, and settlement. Some day aquiculture may well rival and surpass agriculture in importance as the population growth forces increased dependence upon the marine environment for survival.

Increased international effort must be made if our technology is to be used effectively in making intelligent use of our oceanic resources. One of the basic problems now being encountered is the determination of the extent of offshore waters over which a maritime nation has sovereignty. Ownership of rights to the ocean floor, state-federal jurisdiction, the extent of fishing rights, and other factors are pressing problems.

The Geneva Conventions clarify some of the legal questions involved, but many remain unresolved. The federal-state contention in the U.S.A. over lands and minerals in the complex coastal areas is far from settled. The era of submarine law is here, and with it is a dire need for determining precise jurisdictional boundaries.

Determination of location and form of the baseline and other tidal boundaries involves two fundamental surveying procedures : (1) establishment of tidal datum planes which provides the vertical component and (2) the horizontal delineation of the shoreline at the accepted tidal datum plane elevation.

The first is performed with tide gages, and the second through aerial photomapping where the state of the art in photogrammetry provides the best alternative for the accomplishment of the boundary mapping task.

International law defines the boundaries, but they must be determined and then located and mapped for practical purposes. Furthermore, precision in offshore boundary delimitation is necessary in order to resolve legal problems of jurisdiction. This means that the boundaries must be positioned in terms of geographic coordinates.

Hydrographic offices and mapping organizations have a historic responsibility for mapping the coastal frontiers and have accumulated a vast store of pertinent data. Nautical charts and topographic and hydrographic surveys, from which the charts have been constructed, will supply a large part of the information needed in meeting modern problems in seaward boundary demarcation. These archives include a wealth of accumulated tidal information, tidal datum planes, geodetic data, and aerial photography.

The mapping becomes increasingly important as the value of onshore and offshore coastal properties increases. It is indeed a formidable task to acquire the great number of qualitative and quantitative measurements and observations necessary to produce the required coastal zone graphics. Existing charts and survey data are of inestimable value in portraying the coastal zone for boundary demarcation as well as engineering structures and alongshore economic development.

OPERATIONAL ASPECTS

Boundary "demarcation", or the laying out of a boundary on the ground and with an appropriately detailed pictorial representation, is strictly an engineering and cartographic problem. The field work involved encompasses ground control; projection of the boundary line; mapping and boundary strip; and placement of survey monuments. Problems usually encountered in demarcating a dry land boundary are considerably more complicated in the demarcation of a submerged land boundary.

In mapping the shoreline for nautical charts, the general practice of the surveyor or the field inspector of aerial photographs is to identify the mean high-water line by examining the water marks and other features of the shoreline rather than leveling from tidal bench marks.

In many of the states of the U.S.A., the riparian boundary of private property facing tidal waters is the mean high-water line; in others, it is the mean low-water line. The demarcation and mapping of those tidal boundaries are important to property owners. In a more modern context, we must deal with the delineation of the seaward extensions of national boundaries. The problem is to either physically define the boundary by bottom markers or to devise a method by which a buoy, ship, or structure can be placed on a boundary station as it is legally defined.

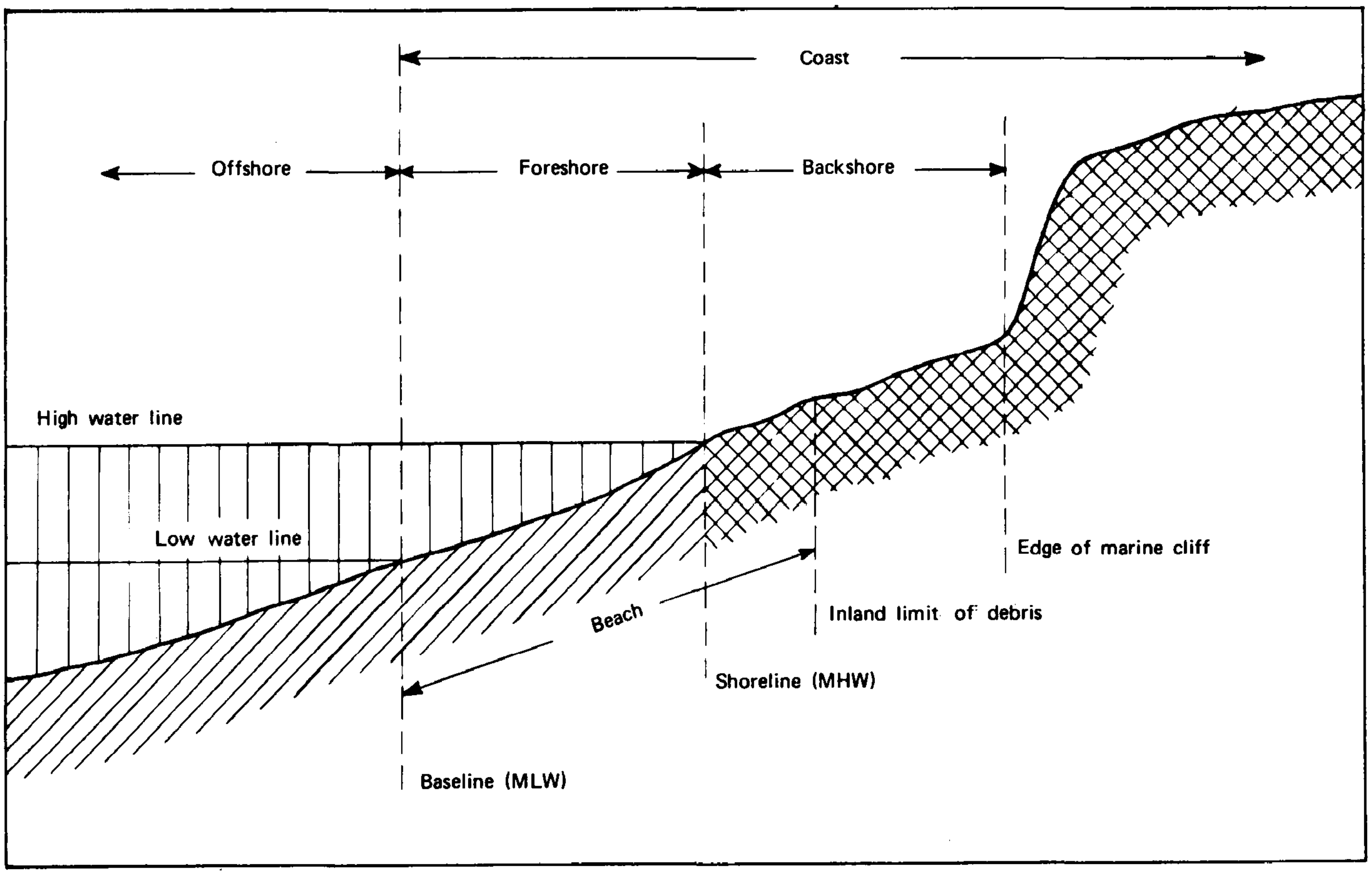

Fig. 1. — Diagram defining the limits of coastal features.

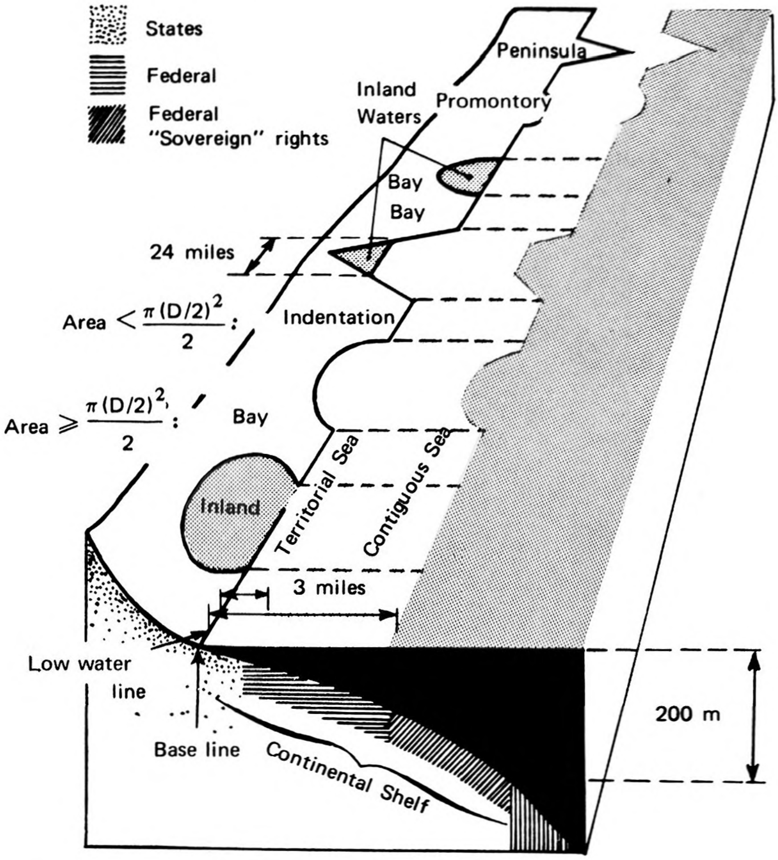

FIG. 2. — Generalized application of the principles of seaward boundaries.

Rapid developments now occurring in the coastal zone and on the Continental Shelf of the U.S.A. make it increasingly imperative that the U.S.A. accelerate its traditional shore and sea boundary program specifically for boundary purposes. Since the outer seaward boundaries for most of its coastal states extend only three nautical miles from the ordinary low-water line, accurate positioning can be obtained by onshore geodetic operations; that is, by triangulation, electronic distance measurements, or a combination of both. Accuracy obtainable should be to within less than 0.3 m which is probably far better than bottom markers can be placed or a ship can be maneuvered directly over a bottom marker or into a predefined position.

As economic factors involving the Continental Shelf require seaward extensions well beyond the 3-mile limit and the line of sight from shore, other methods for positioning must be considered. Some existing electronic positioning systems now in use provide control for distances as far out as 1 000 nautical miles. It is realized, of course, that the accuracy at these longer ranges decreases considerably.

For the recovery of a previously located offshore boundary point, there are certain applications of underwater acoustic positioning which depend on a series of arrays of active bottom markers. This method of positioning will permit high relative accuracies of a few metres in limited areas anywhere in the ocean, but the absolute positioning of this system will have to be provided by other means such as the Navigation Satellite System or some long-range electronic fixing system.

Mean sea level takes on a new significance when we deal in the offshore area. Mean sea level is defined by geodesists as the equipotential surface which the oceans would assume if the only forces acting upon them were the earth's gravitational forces and the centrifugal forces set up by the earth's rotation. There are other forces, however, with which we must deal, such as the tidal forces of the sun and the moon, and the meteorological forces such as wind, atmospheric pressure, and others which vary from time to time and place to place.

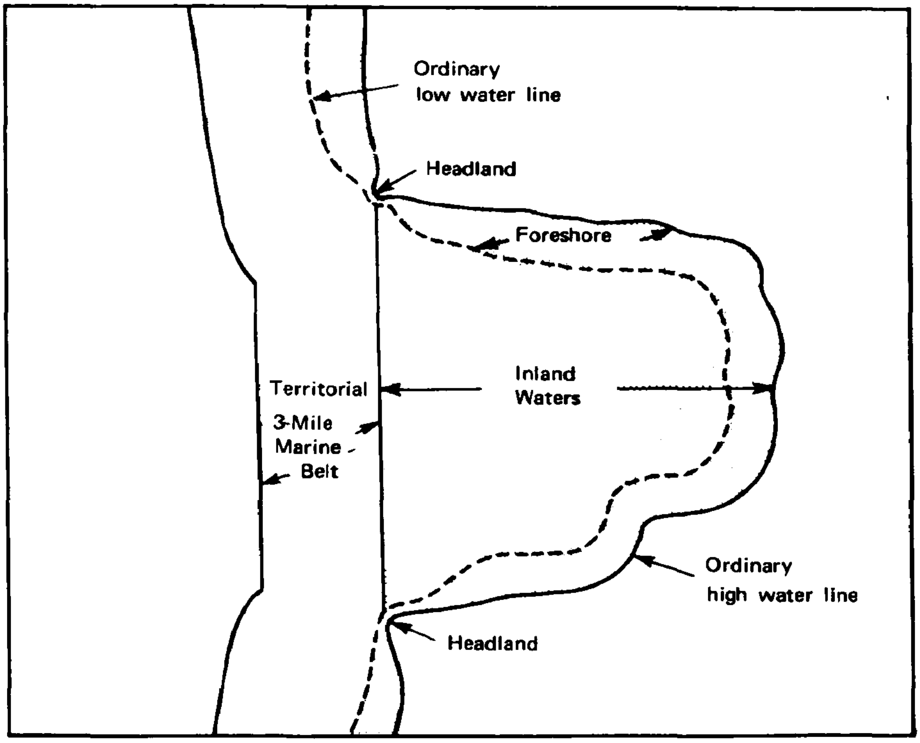

FIG. 3. — The 3-mile territorial zone and its relation to inland waters.

These forces produce an ever-changing surface of the sea which is difficult to relate to the ideal equipotential surface of the geodesists' mean sea level. It is true that the differences between the outer surface of the sea and the equipotential surface are of a rather small order; perhaps only a few metres at most. Still some oceanographers are interested in what they call the slope of the sea and its position above or below the equipotential surface at any given time at a given place.

DEFINITIONS OF DATUMS

In general, aerial photography for mapping the coastline is other than tide-controlled photography, but tide-controlled photography for the location of both the mean high-water and the low-water lines is now coming into greater use. The topographer or field inspector of aerial photographs ordinarily judges whether the elevations of the tops of detached rocks lying close to shore are between *mean low water* or *mean high water* by their appearance and with his knowledge of the stage of the tide from the predicted tide tables. The *low-water line* and the *elevation* of off-lying rocks, ledges, and shoals that are awash are of paramount importance in the establishment of sea and shore boundaries. (See pages 131 and 140).

Much of the low-water line for nautical charts is mapped by the hydrographer. Soundings are made over this line at higher stages of the tide and then reduced in accordance with the tide records. The mean low-water contour is then drawn through the zero soundings. The hydrographer also positions and determines the elevation of many of these off-lying features. He usually records the approximate elevation of rocks lying far enough offshore to be a factor in navigation.

U.S.A. practice in charting rocks awash at low tide stages along the Atlantic and Gulf coasts is to show a rock awash or by symbol on the nautical chart for land features that are bare anywhere between 0.3 m below mean low water or 0.3 m above mean high water. This practice is followed for the safety of navigation and does not bear any direct relation to boundary matters, although it becomes a factor in laying out the coastal baseline for boundary extension.

On the other hand, a low-tide elevation in terms of the Geneva Convention is a *land feature* that is bare at any stage of the tide between the low-water datum and the plane of mean high water. Occasionally, the question arises as to whether a rock awash shown on a chart may possibly be covered at low water or may be just bare at high water making it an island. Such uncertainties can usually be resolved by existing survey records. On occasion, however, it is necessary to make a more definitive field survey in an area where a significant economic factor is involved.

Although U.S.A. nautical charts, and the surveys from which those charts were made, supply some of the information for establishing sea boundaries, they do not supply all of it. It is necessary to map the normal baseline in many places specifically for boundary purposes, either because of a need for greater boundary accuracy or because the coastline has changed. Let us then consider the accuracy requirements and means for this mapping.

The survey or mapping of the "normal baseline" involves two principal components : a vertical component and a horizontal component. We must first determine the elevation to recoverable bench marks on the ground; this is the vertical component. Once the elevation of the tidal datum has been established and referred to recoverable bench marks, the local surveyor can begin to map the normal baseline. This is the horizontal component.

After the tidal bench marks are recovered, a closed line or loop of differential levels is run from the bench marks to that part of the shore where the boundary is to be located. Levels are run along the shoreline and points are selected at intervals along the shore in such a manner that the ground at each point is at the elevation of the tidal datum. Thus, the boundary is demarcated.

The surveyor then measures the horizontal distances and directions, or bearings, between each of the points and between those points and other features in the area — and/or between the points and horizontal control stations — so that the boundary may be compiled on a plat, or on a map, to an exact scale ratio and in true relation to other boundaries of the property and/or to the international geodetic datum. Tidal bench marks in the U.S.A. are set near the tide stations. It might be quite laborious for a surveyor if he had to run his levels all the way from the tidal bench marks to the place of his boundary survey where that place may be a number of miles from the tide station. Usually, this is not necessary due to the connections already made to many of the tidal bench marks to the primary level network of the nation. Thus, the surveyor usually can start his survey from the nearest bench mark of that network.

The primary level network is a U.S.A. system of bench marks established by the Coast and Geodetic Survey. These bench marks are connected by precise leveling and all are adjusted to one reference surface called the Sea Level Datum of 1929. The last continental adjustment of this network was made in 1929. At that time, the network was connected to some 28 primary tide stations distributed around the coast of the United States to determine the reference surface. Thus, *the Sea Level Datum of 1929 is not a tidal datum,* but is based on tidal datums at the 28 tide stations. The Sea Level Datum of 1929 will not always be at exactly the same elevation as mean sea level (a tidal datum) determined at any one tide station. For the purpose of boundary surveys, however, the primary level network is important only as an accurate network of bench marks when a tide station, or the tidal bench marks for that station, have been connected to the primary network. Every bench mark in the primary network then has a known elevation in relation to the tidal datums of that particular tide station.

In selecting a chart compilation scale for the mapping of the normal baseline, a scale of 1/20 000 is usually considered adequate, although some areas may require mapping at the larger scale of 1/10 000. The scale 1/20 000 is more than adequate for most practical purposes when one considers the methods that must be used in mapping anything as difficult to reach and to define exactly as the mean low-water line. These lines, marked by the intersection of the surface of the sea with the shore at a specific tide stage, are ordinarily not well defined on the ground because the water surface is seldom calm.

Because the shoreline along tidal waters changes continually in shape and horizontal position due to the rise and fall of the tide, the vertical datum has special significance. Accuracy is controlled by the number of tide observations that are made and the length of the period of the tides are observed. In this connection, the slope of the foreshore (the area between high water and low water) must be considered. The minimum degree of slope within an area to be mapped is the deciding factor. For example, in Louisiana, there are places where the foreshore is over 1 km wide with a tide range of only about 0.4 m. In this situation, the tides were observed for something over a year to establish the datum within about 0.05 m vertically. On much of the outer coasts of the U.S.A., however, the beaches are much steeper than this. If the foreshore, for example, has a slope of 5.0 degrees then an error in the tidal datum of 0.06 m will cause a horizontal displacement of the normal baseline of about 0.7 m.

PHOTOGRAMMETRIC TECHNIQUES

The Coast and Geodetic Survey has found that tide-controlled infrared aerial photography provides an excellent means of mapping the normal baseline. After the tidal datum has been established, observers at the tide stations establish radio communication with the photographic aircraft and can notify the flight crew when the water surface is at the datum elevation. Infrared photographs are then taken at the correct water level (as, for example, mean low water or mean lower low water). These show the line of intersection of the water with the land very clearly and this line is mapped by photogrammetric methods. The negative scale is 1/30 000.

Infrared photography utilizes the "near" infrared portion of the electromagnetic spectrum (wave length range of 700 to 900 millimicrons). It has a special characteristic that water areas are rendered black. This is due to an increase in absorption at 700 millimicrons. Thus, an infrared photograph shows the water as black, or very dark, in contrast to the shore and provides a sharp, well-defined line of contrast between land and water.

The techniques of obtaining good quality infrared photography are somewhat different than for panchromatic photography. Special attention must be given to the selection of the camera, the storage of unexposed film, filter, exposure, and processing, but these techniques have been quite well worked out at the Coast and Geodetic Survey and are not too difficult.

Although infrared photography is unsurpassed for mapping a shoreline contour, such as the mean low-water line or the mean high-water line, it is not very suitable for mapping very small, detached features such as small pinnacle rocks. These may be missed on infrared photography because this photography does not permit any water penetration. If the existence of such features is expected, *color* photography should be used to inventory and map them.

For example, at a mapping scale of 1/20 000, the infrared photographs might be taken at any scale between 1/20 000 and 1/40 000. The larger-scale photographs will, of course, show more detail, and this is necessary on some types of shoreline. The smaller-scale photographs will make the photogrammetric plotting easier and will require less ground control.

Normally, color photographs are taken simultaneously with a different camera in the same airplane. Also, another set of color photographs is taken at a smaller scale (for example, 1/50 000 to 1/80 000) to use for analytic aerotriangulation so as to reduce the amount of geodetic control surveys.

The first step in mapping by means of tide-controlled photography is to recover, or establish, the tide stations and to lay out, on the flight maps, the section of coastline controlled by each tide station. Along a generally straight coastline, one tide station will serve to control many miles; for example four tide stations probably will be adequate to control the photography for the entire outer coast of the State of Texas — a distance of 600 km; on the other hand, it was necessary to use eight tide stations for tide-controlled photography of the outer shoreline of the Mississippi Delta (300 km); and a few years ago, nine stations were used for tide-controlled photography of the shoreline around Nantucket Sound, Massachusetts (160 km).

Adequate tidal datums have already been established for much of the outer coast of the contiguous United States.

Many of the tide stations established in the past have been connected to tidal bench marks or to the primary level network. Speaking very generally, the datum thus established would be correct within ± 0.06 m, and in the vicinity of primary tide stations, it would be even more accurate.

Tide-controlled aerial photography must be done on days when the tide reaches the proper level during daylight hours and when the sky is cloud-free or nearly so. These are rather difficult conditions to meet, and consequently, tide-controlled photography is more time-consuming and more expensive than normal aerial photography. A special problem is encountered in areas where most of the low tides occur at night; and in some areas low water may occur in daylight hours only during the months of November to late January. In such instances, the tide-controlled photography has to be taken in the winter. Also, the cloud cover has to be considered because cloud-free photographic weather is essential. In other applications, a strong wind holding for some days could change the tides and prevent them from falling as low as mean low water.

Moreover, the period of photography is very short for any one tide (for example, 15 minutes to 1 hour). The tidal datum of mean low water is a mean of all the low waters. On any given day, the low tide will either not get as low as the datum or it will go below the datum. In other words, the low tide rarely goes exactly to the datum level and stops there for a time. As a consequence of this, mean low-water photography is taken when the falling tide crosses the datum level, or when the tide, having fallen below the datum level, crosses that level again on the rise, and these periods are very short.

It is thus very difficult to obtain photographs of all the shoreline at exactly the datum level. Usually, it is advisable to take several sets of photographs and endeavor to have these slightly above the datum level and slightly below the datum level. Then if the photography is not at exactly the datum level, an accurate interpolation can be made from the photographs taken just below and just above that level.

Some field examination of the tide-controlled photographs, or of the maps compiled from those photographs, is necessary : to ensure that no small features, such as pinnacle rocks, have failed to show on the photography and have, therefore, been missed; to check the elevations of small off-lying rocks or bars whose tops happen to be at, or very close, to the datum level; and to examine any sections of the datum line that may have been difficult to interpret from the photographs. This field inspection should be made with the tide at, or close, to the datum plane.

Questions often arise regarding the interpretation of the mean high-water line in marsh or swamp areas on our coastal topographic surveys. In marsh or swamp areas, the nautical charts show the offshore edge of vegetation (not the actual mean high-water line) as the shoreline, because this is the line that the mariner sees at high water. Consequently, the topographic surveys of the Coast and Geodetic Survey map the offshore edge of the grass in marsh and the offshore edge of brush and trees in cypress and mangrove swamps; the topographic surveys do not show the actual mean high-water line on the ground in these areas. The mean high-water line on the ground (intersection of plane of mean high water on the ground) often is not along the front or offshore edge of the marsh or at the back limits of the marsh, but meanders around between the front and back limits.

The location of a boundary as it exists sometime prior to the time of the survey is often of interest to property owners. Physical features of boundaries as they existed at some time in the past may be very difficult to determine. The shore often changes because of wave action along the open coast and because of erosion and accretion due to currents. Once a change in the shore has occurred, it is not possible to demarcate or map a tidal boundary as it existed before the change because the old boundary (for example, the mean high-water line) no longer exists and cannot be seen. This fact is readily understood if one considers that the boundary is the line of intersection of the surface of the water with the land. Obviously, if the land changes, this line will be in a different horizontal position, and if the land has changed, we have no ready means of tracing out where the line was before the change. Old maps made before the shoreline change are about the only means of finding where the boundary was in the past, that is, prior to the change. Most places have been mapped several times by C & GS and these repeat surveys serve a useful purpose in this connection.

APPLICATIONS

About ten years ago, our attention was directed to the need for more intensive surveying and charting of the coastal zone. The low-water and high-water lines on existing surveys and depicted on nautical charts, although adequate for navigational purposes, were not, in some instances, in sufficient detail for settling shore and sea boundary disputes because of the small scale of the coastal charts; they did not provide the necessary large-scale accuracy required in boundary litigation matters.

Certain coastal states and concerned agencies of the Federal Government requested assistance through the production of special purpose shore and sea maps. The request was made in recognition of the C & GS as an authority on tidal datums with long years of experience in charting these lines. Especially important was the modern use of tide-controlled infrared aerial photographic techniques.

In response to one of these requests, the low-water line mapping of most of the coast of Louisiana was accomplished through a cooperative project between C & GS, the Bureau of Land Management, and the State Mineral Board of Louisiana. Through this effort, additional basic tidal data and up-to-date planimetric maps were provided for revision of C & GS nautical charts. Also, a special set of 54 maps was produced showing the mean low-water line and the coordinates of baseline points that were especially selected by the State of Louisiana and the Bureau of Land Management for use in establishing an accurate baseline on which to base jurisdictional boundaries essential in leasing extensive offshore oil and gas fields.

Recently the State of Florida of U.S.A. requested the determination of tidal datum planes and the mapping of the mean low-water line and the mean high-water line. It is estimated that the work will be completed in five or six years — the first phase is essentially completed.

A NEW NAUTICAL CHART PRODUCT

A noteworthy by-product has evolved from recent seaward boundary surveys in the form of a nautical chart which includes aerial photographic imagery of the onshore detail. The new chart therefore can now depict the onshore information as it actually appears rather than simply with chart symbols such as swamp, trees, etc. Due to the new techniques that are applied, the details fall in their correct locations. The compilation of line drawings is greatly reduced and simplified. The new product is both more pleasing in appearance, and also more meaningful to the user — yet the cost need not be any greater.

The new product has resulted from several factors : (1) techniques had been developed for the production of accurate orthophotos; (2) several scales of excellent photographs were already available because they had been used for aerotriangulation and for shoreline compilation; and (3) a large number of accurately located points had been determined by the aerotriangulation procedure.

Perhaps I should define the term *orthophoto* map. In appearance, it resembles an aerial photograph; however, the planimetric positions of features are corrected for the tilt of the aerial camera and for the elevation of the terrain. An orthophoto may be produced photographically from an aerial photograph with a special line-scanning type of printer but, where the terrain is flat, an orthophoto may also be produced with a photogrammetric rectifying printer or by conventional controlled mosaicking. It is significant that an orthophoto map has a planimetric accuracy equal to or better than line-drawn maps.

We expect that eventually all nautical charts may include orthophoto imagery although it is now being applied only in a limited way for the seaward boundary plans. Moreover, it is also possible to use full-color orthophotos; it is my expectation that before long our charts will include this color material. The color images aid materially in their identification by the user; for example, trees and green rooftops are various colors, etc. A further improvement is also available in the form of a photographic screen that eliminates the half-tone screen in chart printing — the photo images themselves perform the printing function of the dots of a screen.

CONCLUSION

It becomes evident that as developments in the coastal zone and the Continental Shelf accelerate, an increasing demand will result for the U.S.A. to accelerate its traditional shore and sea program specifically for boundary purposes. Studies of sea and shore boundaries forcefully indicate the number of technical questions that arise and the extent of judgement required. The most that can be provided are the principles for the delimitation of sea boundaries; answers cannot be provided to every technical or interpretation problem which will arise in laying out sea boundaries in the presence of an almost infinite variety of physical features. This will require agreement and cooperation between the states and the Federal Government and probably some litigation.

TIDAL DATUMS — DEFINITIONS

Several reference planes are derived from tidal data, but only three are of interest here. *Tidal datum planes* vary somewhat with the type of tide. Along the Atlantic Coast of the U.S.A., where both semi-diurnal and diurnal types of tide occur, tidal datum planes are mean high water and mean low water. Along the Pacific Coast, including Alaska and Hawaii, where tides are chiefly of the mixed type, datum planes are mean high water and mean lower low water. A simple definition of these planes is :

1. Mean high water at any place is the average height of the high waters at that place over a given period of time.
2. Mean low water at any place is the average height of the low waters at that place over a given period of time.

3. Mean lower low water at any place is the average height of the lower low waters at that place over a given period of time.

Although tidal data observed throughout a 19-year period permits the most accurate determination of a tidal plane, determinations of acceptable accuracy for many engineering uses can be made from data observed over a much shorter period of time.

BIBLIOGRAPHY

[1] A study of the U.S. Coast and Geodetic Survey's products and services as related to economic activity in the U.S. Continental Shelf regions. Battelle Memorial Institute, January 1966.

[2] California and the use of the ocean. University of California, Institute Marine Resources, October 1965.

[3] Effective use of the Sea. Report of the panel on oceanography of the President's Science Advisory Committee, June 1966.

[4] Griffin, W.L., Jones, B.G. et McAlinden, J.M. : Establishing tidal datum lines for sea boundaries. A paper presented at the Joint American Society of Photogrammetry — American Congress on Surveying and Mapping Convention, March 1967, Washington, D.C.

[5] Man's geophysical environment — its study from space. A report to the Administrator of ESSA, March 1968.

[6] Jones, B.G. and Shofnos, W. : Mapping the low-water line of the Mississippi Delta. *International Hydrographic Review*, **XXXVIII**, No. 1, January 1961.

[7] Our nation and the sea. Report of the Commission on Marine Science, Engineering and Resources, U.S. Government Printing Office, Washington, D.C.

[8] Science and environment, industry and technology, and marine resources and legal-political arrangements for their development. In set of 3 volumes. Panel reports of the Commission on Marine Science, Engineering and Resources, U.S. Government Printing Office, Washington, D.C.

[9] Tison, J.C., Jr. : Sea boundaries and nautical charts. Paper presented at the Second Alaska Surveying and Mapping Convention, February 1967, Anchorage, Alaska.

[10] Shalowitz, A. L. : Shore and sea boundaries. Publication 10-1 in two volumes. U.S. Government Printing Office, Washington, D.C.

[11] Griffin, W.L. : The Law of the Sea and the Continental Shelf. Paper presented at the International Academy of Trial Lawyers, February 1967, Mexico City, Mexico.