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DIGITAL TIDE TABLES
A NECESSITY FOR NAVIGATION IN THE ELECTRONIC AGE

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Abstract

Tide Tables, produced by the relevant Hydrographic Offices, are a mandatory complement to navigational charts for any vessel sailing in tidal waters, i.e. in all the world's oceans and almost all of its seas. Until recently, they were almost exclusively in a printed form. However, the arrival and widespread use of personal computers is changing the status quo. Several digital tidal prediction programs of varying accuracy have appeared on the market, and Hydrographic Offices are being pressured to move into the electronic world as well. To date, only a few countries produce digital versions of authorized Tide Tables, with various levels of sophistication. The introduction of the Electronic Chart Display and Information System (ECDIS) is now emphasizing the need for digital tidal data, with more Hydrographic Offices expected to comply. Those mariners using electronic navigational charts now require digital tidal predictions as a companion to the digital ECDIS.

Graphical representation of traditionally numeric tidal data is now practically "de rigueur" for Digital Tide Tables. With predictions for many secondary ports available with accuracy comparable to standard ports, the whole concept of "secondary" ports is challenged. Early versions of Digital Tide Tables had, at best, a relatively simple user menu with a listing of ports for which predictions were available. This is also changing, as Australia has already introduced a master geographical interface, showing the locations of available ports via several larger scale index charts.

The second generation of Digital Tide Tables will include a "seamless" incorporation in the ECDIS to provide authorized (i.e. legal) tidal predictions on

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demand for real-time navigation. It is anticipated that the ECDIS community will enhance this further with spatial overlays and access to shore-based modelling of tidal heights and streams, as well as real-time water level measurements, where available.

1. INTRODUCTION

It has been said that one cannot make a nautical chart without tidal information. Tides have always been important to the mariner; the very word "tide" emphasizes its importance from very early times - it is derived from the old Saxon "tid" meaning time. The modern German maintains this connection between time and tides as well, with "Zeit" and "Gezeiten" respectively. But the ancient Greeks and Romans were not particularly concerned with the tides since in the eastern Mediterranean they are almost inconsequential. This ignorance of tides led to a loss of CAESAR's war galleys on the English shore, as the commanders of the invasion failed to pull them up high enough to avoid the returning tide. Other maritime nations were always at the mercy of tides and developed an empirical knowledge of this phenomenon. At first, tides were explained by all sorts of legends, but already by the late 10th century, the Arabs knew that the timing of tides was related to the cycles of moon. In 1213, the Abbot of St. Alban's published a table from which the time of high water at London Bridge could be predicted from the number of days elapsed since new moon.

Today, the mariner determines the amount of water under a vessel's keel by adding the height of predicted tide to the depths shown on the chart, then subtracting the draft of the vessel. These predictions are based on the universal theory of gravitation developed by Sir Isaac NEWTON. The details of the tides at any given location are governed by the responses of the ocean to the gravitational forces, as modified by local coastal and bottom topography.

Nowadays, all SOLAS class vessels are required to carry the relevant official Tide Tables, which are usually published by the local Hydrographic Office or by the British Admiralty. Using the printed Tide Tables is not without problems. Predictions are usually published only for the standard ports, with mean time and height differences supplied for the secondary ports. It is practically impossible for this oversimplified method of spatial and temporal interpolation to provide accurate values of tidal heights for secondary ports or intermediate locations. Frequently, the only tidal heights published for a port are those for high and low waters. This leaves interpolation between the extrema to the mariner, who can easily lead to considerable errors where the tidal curve is highly asymmetrical, or the tidal range is large.

2. THE FIRST GENERATION OF DIGITAL TIDE TABLES

Until recently, Tide Tables were almost exclusively in paper form, but the arrival and widespread use of personal computers changed that. Commercial tidal prediction programs of varying levels of accuracy and sophistication began to appear on the market, and Hydrographic Offices had to move into the electronic world as well. Some Hydrographic Offices introduced the official Digital or Electronic Tide Tables very quickly, with France stopping altogether the production of the printed version in its area of responsibility.

These computer programs provide predictions not only for the high and low waters, but also at equi-spaced intervals, thus negating the need for temporal interpolation. In addition to the traditional alphanumeric display of times and heights of high and low waters, data is almost always represented in a graphical format. The level of sophistication of graphical display varies considerably, but the underlying authorized tidal data is usually easy to read and comprehend. The addition of capabilities such as options to enter vessel draft, datums levels, phases of the moon, dawn and dusk data, daylight savings time, etc., makes these products more useful and attractive to the mariner.

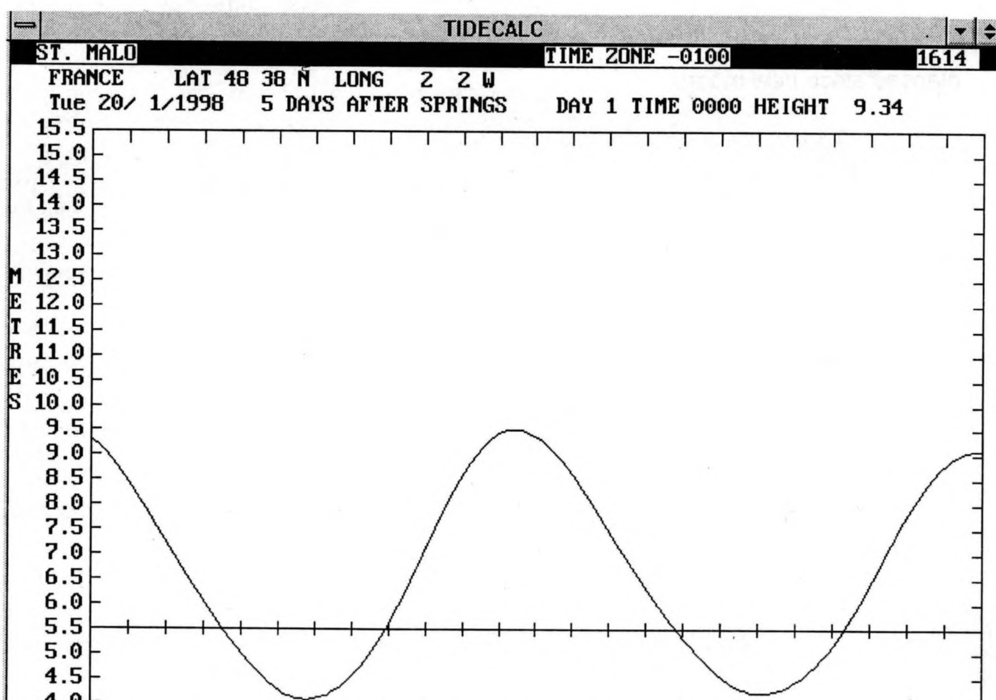

FIG. 1.- Sample screen display of the British Admiralty Digital Tide Tables.
(Tidal information reproduced by permission of the UK Hydrographic Office)

It should be mentioned here that the development of an "official" Digital Tide Table could be an undertaking of any government independently or in partnership with private interests. In many cases, governments may restrict themselves to the role of information providers. This paper does not espouse a position one way or the other but considers that, regardless of business arrangements, the final product must represent validated, official information which can eventually be used for legal navigation.

Most of these programs also provide predictions for the secondary ports. The observational data for many secondary ports is sometimes as long or longer than for some standard ports, and thus the predictions for these secondary ports are available with accuracy comparable to standard ports. In view of this, the concept of "secondary" ports needs to be reviewed. This, however, is outside the scope of this paper, and a responsibility of the relevant Hydrographic Offices.

3. PRESENT LEVEL OF DEVELOPMENT

Early versions of Digital Tide Tables had a relatively simple user menu with a listing of ports for which predictions were available. Some sort of a search facility by port name or number was provided as a rule. When dealing with the well-known standard ports, or when all the ports along a regular route are known, this approach may be considered adequate. This situation is changing, as the Australian Hydrographic Office has already introduced a master geographical interface, showing the locations of standard ports on a small scale electronic index chart, and of all available ports via several larger scale charts. A pointer is used to indicate the port for which the predictions are required. Standard ports have the official predictions encoded as look-up tables, and the predictions for the secondary ports are produced on-the-fly by a prediction subroutine using the encoded listings of constituents.

Japan and Singapore are about to introduce their own official Digital Tide Tables using the same principle of spatial referencing as the Australian version, with the Canadian Hydrographic Service and other countries considering similar initiatives in the near future.

While this is a definite improvement over the printed Tide Tables and first generation Digital Tide Tables, it still leaves a couple of problems unsolved. The first is the difficulty of obtaining tidal heights between the ports. In some cases, it is reasonably safe to interpolate between predictions for two ports, in others it would be downright dangerous. Another problem is a lack of inputs to allow for corrections due to non-gravitational effects. These effects, mostly of meteorological or oceanographic origin, can cause the sea level to vary considerably from the predicted values, with 0.3-meter discrepancies between predictions and observations being quite common. An experienced mariner is aware of these problems and, in the areas where he has local knowledge, can apply suitable corrections. But he cannot be expected to have sufficient knowledge to cover every location and every contingency. Also, with the present generation of Digital Tide Tables, the mariner has no way of knowing whether the predictions for a given port are based on a long or short period of observations.

The first problem can be alleviated, to a certain extent, by the relevant Hydrographic Office providing the spatial limits for the application of their official predictions. This is an approach proposed by Singapore for their version of the Digital Tide Tables. Singapore, however, is an exception as it has high quality tidal information for their limited area of waterways.

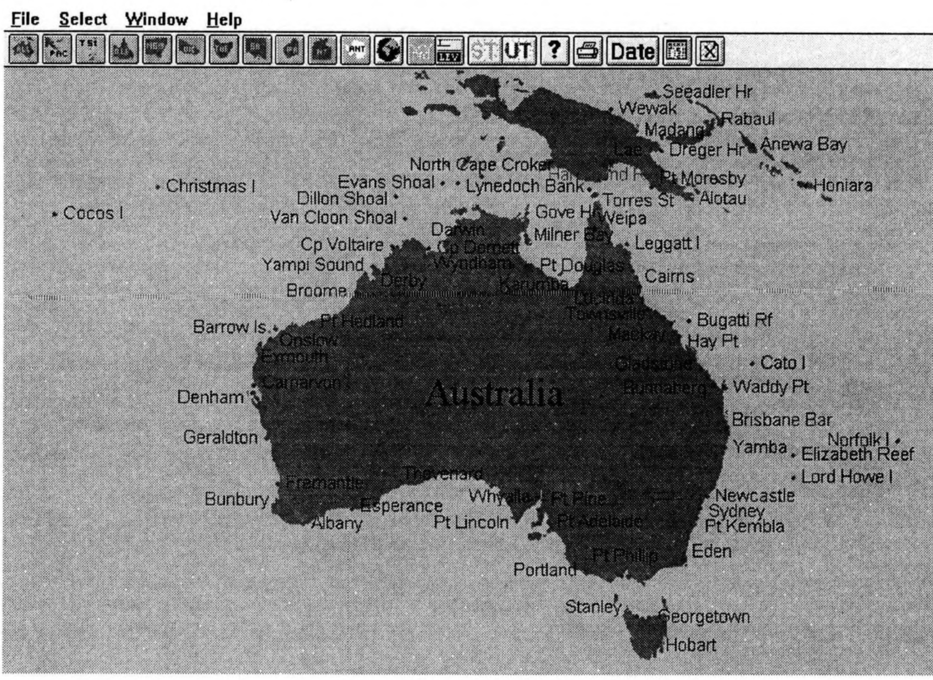

FIG. 2.- The opening index chart from the Australian Digital Tide Tables (reproduced with permission).

A slightly different approach is under consideration by the Canadian Hydrographic Service, where sufficient number of tidal stations along many parts of the Canadian coast may allow safe linear interpolation between them. Interpolated values may even be applicable to some offshore areas as well. Although this solution is one of several approaches under review, the only viable (and preferred) solution for this problem and the problem of how to correct for non-gravitational effects, is adequate tidal modelling. This will be discussed in a later part of this paper.

In addition, to address the problem of data quality (i.e. how good are these predictions?), the Canadian Hydrographic Service is presently reviewing their national set of harmonic constants to remove any unsuitable or questionable data. This will provide a means of estimating the accuracy of predictions produced for any port.

4. TIDAL STREAMS AND CURRENTS

The rise and fall of the tide also causes a horizontal movement - the tidal stream (or tidal current). These two vertical and horizontal movements are two expressions of the same phenomenon caused by the gravitational forces. They are intimately related, but this relationship is not simple, nor is it everywhere the same. Tide Tables, both printed and electronic, usually provide only the following information for specific sites - times of slack water, and times and rates of the maximum flows during each day. Equi-spaced predictions are rarely available. The Australian Hydrographic Office provides them in their Digital Tide Tables for Torres Strait and Japan intends to do the same for several sites in their waters. This permits a graphical presentation of tidal streams.

Since the predictions for tidal streams are considerably scarcer that those for tidal heights, and as tidal streams are more spatially complex than tides and can change radically in very short distances, it is practically impossible to extrapolate from the prediction site with any sort of accuracy. In addition, the predictions are based almost entirely on the gravitational forcings. Ocean currents, river runoff, wind and other oceanographic flows can modify the predicted values to a considerable degree - although some countries occasionally adjust Z0 values to account for freshwater outflow on certain rivers.

Some of the few exceptions to this unfavourable picture include the Current Atlas for the St. Lawrence River, recently developed by the Canadian Hydrographic Service (CHS). In this atlas, high-density total flow information is shown for every 20 minutes of a tidal cycle as a result of sophisticated modelling, rather than of pure tidal predictions based only on observations. In addition, CHS Pacific Region has produced a Current Atlas for Juan de Fuca Strait to the Strait of Georgia. Modelling of total flow is considered the best way of providing the flow data to the mariner. On the Pacific Coast of Canada, a commercial product produced by Channel Consulting Ltd. (TideView), using a finite element model, provides excellent spatial coverage for predicted total flow by combining the predicted tidal currents with estimated background currents and wind effects.

5. FUTURE - ELECTRONIC TIDE TABLES AND ECDIS: REAL TIME DATA AND SHORE-BASED MODELS

In the epoch of print media, tides and other time variables had to be presented in a static form. Recently however, the Electronic Chart Display and Information System (ECDIS) has been readily accepted by the world's shipping community not only for its purely navigational merits, but also as a ship management tool. We are entering the era of the electronic chart, and have a chance of moving to a dynamic presentation of tides. The principle of spatial referencing of tidal data in the Digital Tide Tables mentioned above is a perfect way of interfacing tides with ECDIS.

ECDIS provides a constant update of the vessel's position on the chart, using the GPS information. This positional reference can then be seamlessly connected to the water level and flow information program to provide on-demand water level variations (tidal or not), as well as tidal streams and currents. In addition, voyage planning can take tidal variables into account. Please note that we have to move from tide and tidal current predictions to water level and flow information, as these are the real world quantities. The mariner wants reliable, trustworthy information and is not very interested in the sources of data and in details of prediction methodologies and modelling. (Should this information be required, it will be available on request at a lower level of inquiry, as for any other data encoded in accordance with the S-57 standard [International Hydrographic Organisation, 1996a]). Mariners would also benefit from having some knowledge of the accuracy of displayed data, especially in cases where accuracy has considerable variation (e.g. areas of large tides and/or inadequate measurements). Data accuracy can be encoded under the S-57 standard and made available in text or graphical options. The IHO Tidal Committee has recommended that an accuracy threshold of 95 percent be available as a display option.

Tides and charts have to be considered as two sides of the same dynamic entity, and not as separate issues. At present the IMO/IHO requirements [International Maritime Organisation 1994, International Hydrographic Organisation 1996b] specifically forbid dynamic representation of tidal heights. This is due to insufficient density of digital bathymetric data being presently available. However, the first step towards improving this situation has been already made - tidal overlays for ECDIS are starting to appear.

A tidal overlay in ECDIS can be considered the next step after the Digital Tide Tables. It is an integrated digital layer of water level and flow data that can be displayed on the ECDIS screen if needed, overlaying the required information on the electronic chart. This ability of ECDIS to display the data on demand reduces the chart clutter and makes for a clearer, easier to use chart. The level of tidal details to be displayed, and even the method of display (e.g. alphanumeric or graphical) can be controlled by the mariner. A tidal overlay can provide seamlessly the water level information derived from any of several sources: open ocean models producing tidal predictions, official high quality predictions for most ports, various models to cover port approaches, channels, straits and continental shelves, and built-in prediction subroutines, all as required. It can also be interfaced to real-time data, where available. Current flow data, both predicted and modelled, can also be made available, as applicable.

ECDIS is more than an electronic equivalent of the paper chart; it is also a tool that can be used in two distinct modes: route planning and ship conning. During the route planning, tidal predictions will be used to determine the safety windows for difficult passages, minimum under-keel and overhead clearances to be expected, maxima of tidal streams and times of slack water. As route planning usually takes place some time before the voyage is undertaken, tidal height and stream predictions are sufficient for this purpose. The models are, in general, on a much shorter time scale (from hours to a few days) and usually require meteorological inputs that cannot be predicted too far ahead.

Under way, ECDIS is used in the conning mode. Different levels of tidal information are required in different circumstances. While traversing the open ocean, tidal overlays can be turned off and brought up occasionally to check the information. Alternatively, the mariner may decide to keep a permanent display of tides reduced to a minimum - e.g. times and heights of the high and low water for the area being traversed at the time. Since ECDIS is interfaced to the vessels' positioning system (usually GPS), tidal overlays will automatically update tidal displays with the vessels' movements. As the vessel approaches the land, the mariner may want to increase the size of the window showing tidal data. The display can be changed to the tidal curve for the day with a pointer indicating the present time on the curve. Other graphical displays will be also available. This can be supplemented by an alphanumeric display of high and low waters, and of tidal height at any time selected by the navigator. Water level and flow information can come from predictions provided by the Hydrographic Offices, or from forecasts supplied by numerical models within ECDIS or transmitted from shore based locations, as applicable. In critical areas, these predictions and/or forecasts can be supplemented by real-time data from tide gauge stations. In such situations, the real-time tidal data will be clearly flagged and will override the predicted information. The same options apply to tidal streams. In each case, the mariner will determine what information is to be displayed and in what form.

Interfaces with real-time or near real-time information sources, short term forecast models and other data providers have to be developed. A new shore-based infrastructure may be required. The Port of Singapore is actively preparing for this step. Canada also has an existing shore-based infrastructure along the St. Lawrence River; however it needs to be updated for seamless interfacing with ECDIS.

Tidal overlays that are being developed for ECDIS at present are only the first step towards very sophisticated methodologies that can be expected in the near future. Dynamic representation of tides will be demanded by the users, and the present restrictions will have to be lifted. This will not need to be a global application as tides are not an issue in deep oceanic waters, but will be of great assistance when traversing shallow straits or channels, or entering shallow ports. To achieve this aim however, the Hydrographic Offices will have to start producing high-density bathymetric data in the S-57 format for the relevant areas. Digitizing the paper charts does not produce sufficient density of data to permit dynamic changes to bathymetry; this is especially true for the presentation of contours.

Another development expected to be very useful to the development of tidal services for ECDIS is the great improvement in the vertical accuracy of the GPS. This accuracy has now reached the order of centimetres and the results are useable for tidal analyses, especially in deeper waters. In addition to providing tidal constituents for the open waters, the high accuracy of the GPS leads to a very practical application. The ship will be its own tide gauge, providing real-time data for any location, and also supplying the same information to the shore based numerical models which will be able to update their forecasts from this information. Using differential GPS, hydrographic survey vessels can also have real-time tidal data for sounding reduction, and this will lead to more accurate charts. The introduction of this application to the shipping and hydrographic communities is close at hand; indeed there is already a GPS buoy/tide gauge deployed in the Gulf of Mexico

[MITCHELL 1997]. To make this method a practical worldwide application, three dimensional separation models between the various hydrographic datums, the geoid (approx. MSL) and the ellipsoid (which is the reference level for the satellites) must be accurately determined on a global scale.

Along with the advance of GPS technology, similar strides have been made in measuring sea levels using satellite radar altimetry. Satellite missions such as TOPEX-POSEIDON, GEOSAT and ERS1 have been able to successfully determine MSL to within centimetres for the past several years. While they are very compute intensive and should not be considered real-time systems, they promise tremendous potential in defining not only MSL, but (combined with numeric ocean models) appear capable of establishing spatial tidal datum surfaces in offshore areas. Canada is actively pursuing an approach of synergizing historic tide gauge data, onshore GPS vertical control and satellite altimetry to construct unified datum separation models throughout all its coastal and offshore waters.

Once the two aims - high density bathymetric data and the development of methodologies for tidal applications of high accuracy vertical GPS positioning - are achieved, ECDIS will be able to display real-time depths for the vessel's position and the immediate area. Tidal models and predictions will also be improved as a result of the automatic data transmission of tidal data from the ship(s) computer to the shore computers. The mariner will be presented with seamlessly changing depth information of high accuracy. The shoreline will be adjusted for the changing level of the water, wherever possible and applicable. If a three-dimensional display is used, the mariner may be able to readily see the variation of the sea level.

Tidal streams and currents information will also be comprehensively displayed. Dynamic display and display of multilevel data are both possible and the symbology will have to be developed for these techniques. This information can also be shown very effectively through the water column on a 3-D display.

Lastly, as a measure to harmonize the hydrographic datums of all member states, the IHO has recently passed a resolution to adopt Lowest Astronomic Tide (LAT) and Highest Astronomic Tide (HAT), for low and high water datums respectively. As this requires the eventual migration of all IHO compliant charts to occur over the next several years, the evolution of a Digital Tide Table working in concert with digital ENCs and ECDIS will greatly expedite this process. During the several years of transition, it is anticipated that existing datums and LAT/HAT datums will have to co-exist. Digital Tide Tables should be easily capable of expressing information using multiple datums in a transparent manner. In short, the Digital Tide Tables of today are only a starting point for developing a fully dynamic, four-dimensional system, embodying several new services to the mariners. With the recent tremendous technical advances in nautical information systems, satellite positioning and vertical measurements, the navigation community requires more than ever, the capability to function in a rapidly advancing digital world.

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