Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2018, 54 (126), 84–92
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/289

Received: 07.02.2018
Accepted: 24.04.2018
Published: 15.06.2018

Reliability of navigational charts and confidence in the bathymetric data presented

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Key words: marine navigation, safety at sea, navigational charts, accuracy, reliability, zone of confidence, source diagrams, International Hydrographic Organization (IHO)

Abstract

Navigational charts are a basic source of information for seafarers. But how accurate and reliable are they? How much trust and confidence can be put in them? Unfortunately, the answer is not so simple; it is far more complicated than merely saying that one chart is accurate and reliable while another is not. However, any seafarer navigating in unfamiliar waters should have the necessary skills. It is a great challenge – some may say an impossibility – to keep the thousands of navigational charts up to date. But exactly how out of date, how inaccurate, are the chart data? Chart users will have a better idea now that the Hydrographic Office is gradually implementing a new chart feature called the Zone of Confidence (ZOC) box which replaces the Source Diagram that is currently in use on large-scale charts. Source Diagrams, and now the improved ZOCs, assist seafarers in assessing hydrographic survey data and the associated levels of risk of navigating in a particular area. According to the new edition of the International Hydrographic Organization (IHO) specifications, S-4 navigational charts will provide more information on ZOCs. The current paper discusses these new regulations.

Introduction

Most navigational charts are an amalgamation of geospatial information collected using different techniques at different times (Prince, 2017). For example, one area of a specific current-day nautical chart might be based on a lead line and sextant survey conducted in 1917, and another on the same chart might be based on a multibeam echosounder and GPS survey conducted in 2017. If we dig deep enough, we will probably even find a sounding or two from the 18th century British explorer Captain James Cook. When the International Hydrographic Organization (IHO) developed the S-4 standard, this situation was recognized and the quality of the survey data used to compile navigational charts had henceforth to be encoded within a composite data quality indicator, the 'Source Diagram'.

Source Diagrams

According to IHO S-4 (IHO S-4, 2017) consideration should be given to providing Source Diagrams on appropriate new navigational charts, and to adding them to existing charts when the opportunity arises. The Source Diagram printed in the chart title box shows when the survey was performed and the quality of the depth data. This provides an indication of the accuracy of the product. Areas surveyed in the first half of the 20th century did not receive full seafloor coverage and depth anomalies may be expected. There may be undiscovered depths in older surveyed areas. Caution must therefore be taken when sailing in these areas. It is dangerous to sail outside marked areas or the recommended route. On charts where routeing measures appear to 'direct' vessels into waters where surveys are inadequate, diagrams are particularly important to alert navigators to the

need to allow adequate under-keel clearances. The term 'Source Diagram' includes both the graphic showing the limits of the source data used, and the accompanying text. The diagram should be titled 'Sources', or its equivalent, on charts.

There are two main types of diagrams for summarising hydrographic sources:

- Conventional Source Diagrams provide information about source surveys from which the mariner can deduce the degree of confidence to place in charted depth data;
- ZOC diagrams are a type of Source Diagram providing a more qualitative assessment of the source information. They replace the former Reliability Diagrams, which are obsolescent. Dual-purpose diagrams are Source Diagrams to which other information has been added.

The Explanatory Notes under the chart title should draw attention to the presence of a diagram on a chart; for example, the origin, scale, date and limits of the hydrographic information used to compile the chart are shown in the Source Diagram. In the Source Diagram we can find the answers to the following questions (Quality Indicators): What? (soundings/hydrographic survey); Where? (area limits marked by followed letters in alphabetic order: a, b, c, etc.); When? (Survey Date); Who? (Survey Authority); and How? (Scale, and Acquisition Method). Navigation manuals should draw attention to Source Diagrams and the need to examine them when planning passages. It should be made clear that Source Diagrams cannot be expected to convey definitive information about the updating of such charted features as major navigational aids. Source Diagrams should be updated when new editions of charts are compiled. Source Diagrams may be updated by Notices to Mariners (NM), when a new survey in a navigationally significant area has been included on the chart.

Purpose of Source Diagrams

The purpose of Source Diagrams is to guide navigators, and those planning 'navigational operations' (including the planning of new routes and official routeing measures), on the degree of confidence they should have in the adequacy and accuracy of charted depths and their positions. A Source Diagram should ideally give details of the data from which each part of the chart has been compiled. As a useful by-product, Source Diagrams provide an easily accessible, but not necessarily comprehensive, record that will assist cartographers in chart revision and alert all concerned to the need for further surveys. They also alert users to the main areas updated from new sources in new editions. Some charting organizations add such details as archive numbers of documents, or the names of survey ships. It is not desirable to make such details, which are mainly of 'internal' interest, standard requirements in the IHO S-4 Specifications.

Scales of Charts Which Should Have Source Diagrams

Regional differences make it inappropriate to specify precisely which scales of charts should always have Source Diagrams. They are most useful on relatively large scales, particularly those with potentially hazardous rocky seabed areas, which have not been surveyed to modern standards, or areas of mobile seabed that have not been surveyed recently.

Charts of scale 1:500 000 and larger should be considered for Source Diagrams, special attention being paid to the largest coastal scales and those which carry routeing measures. A large-scale chart compiled from a single survey, or from routine re-surveys by a single authority, may not require a Source Diagram. In such cases the Explanatory Notes under the chart title may be adequate, for example: *Source: All the hydrography is derived from British Government surveys 1859–2000.*

Graphical Representation of Limits of Surveys

Figure 1 illustrates the conventional Source Diagram presented on a navigational chart. The linear dimensions of the graphic should be one-tenth those of the chart's neat line dimensions but may be reduced further if space is too limited for the preferred size. Continuous black lines should be used for the Source Diagram's borders, coastline and area limits. Identifying letters should be black and may be repeated as necessary. Land tint should cover land areas, and sea areas should be left white. Graduation of Source Diagrams, corresponding with the main chart, should be included for ease of use. To avoid confusion, any internal graticule should have finer lines than the area limits. Inset plans should be included in Source Diagrams, with limits being shown as bold single lines; graduation ticks and figures may be added if considered necessary. As regards larger-scale charts and plans, when there is a plan or inset within the chart boundary, the source information should be shown on the section of the diagram of the plan or inset, a note being added to

the main chart area of the diagram stating 'see Plan'. Similarly, when there is a larger-scale chart within the area, source information may be omitted and a reference to the larger-scale chart inserted instead. However, if the smaller-scale chart is the largest scale International (INT) chart, the source information should be included as 'the content of INT charts must be complete and comprehensive for use by international mariners. They should not require reference to other national charts for any information required by the international mariner' (IHO S-4, 2017).

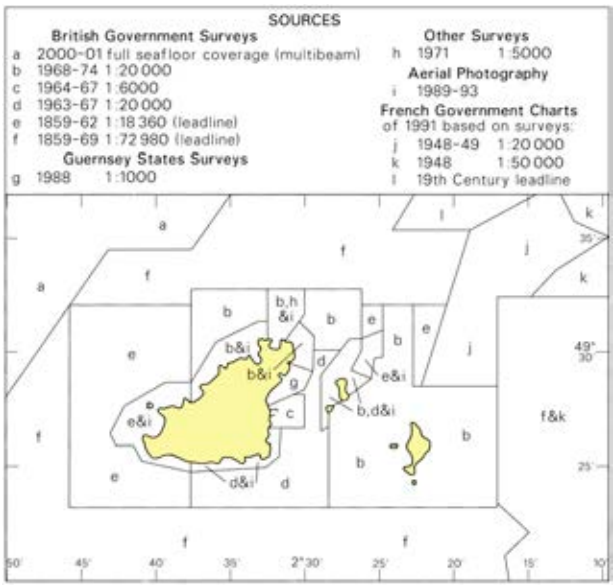

Figure 1. Conventional Source Diagram (IHO S4, 2017)

Charts may be listed as sources where details of their component hydrographic surveys are not known. In such cases the purpose of the Source Diagram, or some part of it, cannot be fully achieved because the possibility that the surveys may not fully meet modern standards may not be apparent from the dates and scales of the charts. Wherever possible, qualifying comments on likely deficiencies (for example 'from leadline surveys') should be given. Special measures may be taken in cases of particular importance to highlight more clearly where channels lie in relation to the limits of the source data, for example:

- Intertidal and shallow water tints may be inserted in the same geographical areas on the Source Diagram as they are shown on the chart;
- Magenta tint may be included to highlight the position of routeing measures, such as Traffic Separation Schemes (TST);
- Coral reef outlines or the extents of danger lines may be shown;
- Grey tint may be included to highlight areas covered by after-disaster surveys.

Details of Sources: Date and Scale

The date of a survey must be given on conventional Source Diagrams. It gives an indication of:

- The adequacy of the equipment used;
- The thoroughness of examinations of dangers at particular depths (based on the maximum draught of vessels afloat at that date);
- The likelihood of later changes in depths, particularly in areas of mobile or unstable seabed or coral growth.

The date of the edition of a published chart used can be misleading (as the source data may be much older) but may have some value. Year dates only should normally be used. Guidance on the practical significance of survey dates should be given in a national publication that advises users on the reliability of charts. The scale of a controlled survey may provide some indication of the thoroughness and the line-spacing, and should be stated in the form 1:5000, 1:15 000, etc, on conventional Source Diagrams. The scale of a chart source may have some value. If considered useful, line-spacing may be added to the details of a survey, for example '200 m', under the heading 'Line-spacing', or equivalent. For surveys gathered by systems using multibeam, interferometric, laser or Lidar technologies, scale has little relevance; a statement of whether full sea floor coverage has been achieved, or not achieved, should be given instead.

When a new survey is received and assessed by a hydrographic office, the Source Diagram would not normally be modified if it is judged that:

- changes to the charted depths are of no navigational significance so a new edition of the relevant chart is not necessary; or
- all navigationally significant depth changes can be promulgated by NM (especially on smaller scale charts).

However, if the mariner may be influenced to avoid an area because of the nature (for example, age) of the currently charted data, then a new edition must be considered to incorporate the new survey (and update the Source or ZOC diagram) even if the depths show little change. Consideration may be given to updating the Source or ZOC diagram details by NM (or NM Block). If this method is used, because the new details would not reflect the actual source used on the chart, an explanatory note should be added, for example '(most recent data used or

assessed for charting)' or equivalent, directly under the Source Diagram's title.

Details of Sources: Origin and Type

The country of origin should be given explicitly when compiling from foreign data, but may be implicit when using one's own data, for example (IHO S-4, 2017):

Foreign data	Own data
Polish surveys	HOPN (Hydrographic Office of the Polish Navy) surveys
British surveys/charts	British Admiralty (UKHO) surveys/charts
Norwegian surveys	NHS (Norwegian Hydrographic Service) surveys

The type of 'survey' should be stated on conventional Source Diagrams (the terms being translated as necessary):

- 'Survey' implies a regular, controlled or systematic hydrographic survey of any date;
- 'Sketch survey' or 'Reconnaissance survey' implies that there is a significant risk of undetected dangers, even if the 'survey' is of recent date;
- 'Passage soundings' implies soundings acquired on an uncoordinated basis over a period of years;
- Qualifying comments, for example: '(leadline)', '(no sonar)' and '(multibeam)', may be added after the type of survey where the date does not give sufficient indication of the survey methods (see Figure 1);
- Where a charted survey is supplemented by occasional soundings from older or later sources, only the main survey should normally be listed.

Guidance on the practical significance of survey types should be given in a national publication which advises users on the reliability of charts. Surveys made by non-government agencies, such as port authorities, may be identified as such. However, it is usually preferable to use the description 'Commercial Survey' or 'Other Surveys' for surveys made, for example, by gas or oil companies.

Source Lists

Sources of similar type, date and scale may have to be grouped together to avoid too long a list or too complex a diagram, for example: '*Polish surveys 1972–80 1:20000 – 1:30000*'.

Surveys of different types, for example leadline and echosounder surveys, should not be grouped together. The sources in each category of similar origin and type should be listed chronologically, preferably with the most recent first. Hydrographic surveys should normally precede references to charts, and in some cases the relative importance of a major survey may require it to be placed first.

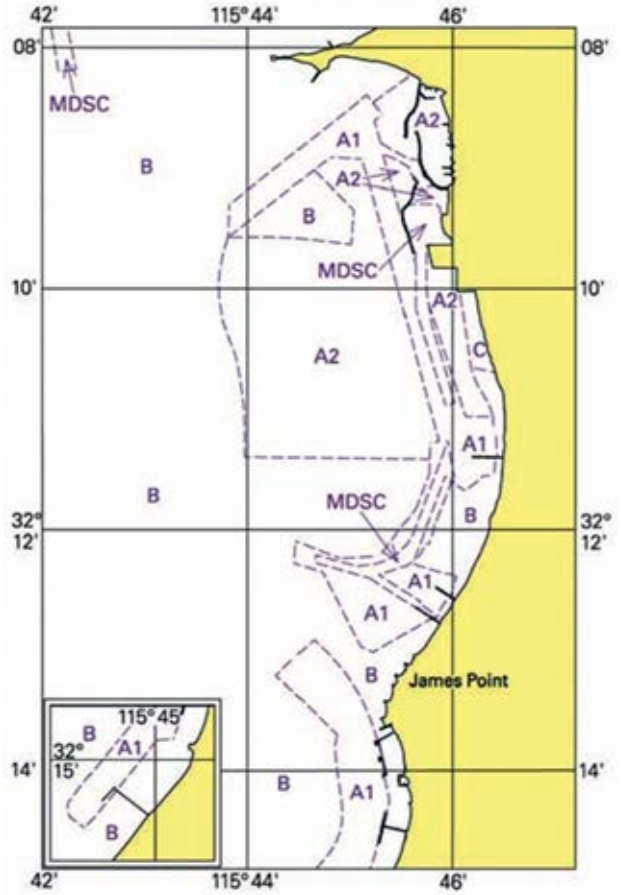

Figure 2. Zones of Confidence (ZOC) Diagram (IHO S-4, 2017)

ZOC CATEGORIES

(For details see Australian Notice to Mariners No 25)

ZOC	POSITION ACCURACY	DEPTH ACCURACY	SEAFLOOR COVERAGE
A1	±5 m	= 0.50 m + 1% d	All significant seafloor features detected.
A2	±20 m	= 1.00 m + 2% d	All significant seafloor features detected.
B	±50 m	= 1.00 m + 2% d	Uncharted features hazardous to surface navigation are not expected but may exist.
C	±500 m	= 2.00 m + 5% d	Depth anomalies may be expected.
D	Worse than ZOC C	Worse than ZOC C	Large depth anomalies may be expected.
U	Unassessed - The quality of the bathymetric data has yet to be assessed.		
MDSC	Maintained Depth See Chart		

Sources of topographic detail, if included, should appear last. Maintained, dredged and unsurveyed areas may be labelled separately, if considered useful, for example:
a) Maintained channel,
e) Unsurveyed area.

The source list, headed 'Sources' or equivalent, may be placed on any side of the graphic, but should be placed above it where available space permits. The list should be 'tied' to the graphic with an enclosing line.

Zones of Confidence Diagrams

ZOC diagrams enable mariners to assess the quality of the hydrographic data from which the chart was compiled. The use of ZOC diagrams provides consistency in the display of source data between digital and paper charts, as the Category of Zones of Confidence (CATZOC) definitions are derived directly from IHO S-57. Continuous black lines should be used for the ZOC diagram's borders and coastline. Area limits and identifying CATZOC values may be magenta and may be repeated as necessary. Grey tint (or another colour except green, blue or magenta) may be used to highlight areas covered by after-disaster surveys. The linear dimensions of the ZOC diagram shown on paper charts should be one tenth those of the chart's neat line dimensions, but may be reduced further if space is too limited for the preferred size or enlarged if the detail is complex. The quality of the hydrographic source data is assessed according to six categories: five quality categories for assessed data (A1, A2, B, C and D) and a sixth category (U) for data which have not been assessed. If none of the hydrographic sources used on a chart have been assessed, a ZOC diagram indicating only 'U' values should not be added to the chart, as it would not include any information of use to the mariner. The assessment of hydrographic data quality and classification into zones is based on a combination of: a) Position accuracy, b) Depth accuracy and c) Sea floor coverage (certainty of significant feature detection). Where a charted survey is supplemented by occasional soundings from a less accurate source, only the main survey should normally be categorised. The less accurate depths may be indicated as hairline/upright sounding figures on the chart. When a new survey of better (or possibly worse) CATZOC than that shown in the diagram is assessed between editions, consideration may be given to updating the ZOC diagram by NM (or NM Block). For a fuller explanation, a high category survey in an area of mobile seabed may need to be downgraded if a later sketch survey proves that the earlier survey is now inaccurate. Familiarisation with IHO standards for hydrographic surveys will be very helpful (IHO S-44, 2008).

Guidance on the significance of the quality categories should be given in a national publication which advises users on the reliability of charts. The higher ZOC categories, A1 and A2, demand full sea floor ensonification or sweep and require very high accuracy standards which have only been achievable with technology available since about 1980. Therefore, many sea lanes which have hitherto been regarded as adequately surveyed may carry a ZOC B classification. Modern surveys of critical areas can be expected to carry a ZOC A2 classification whilst ZOC A1 will cover only those areas surveyed under exceptionally stringent conditions for very special reasons.

Additional categories to those listed in IHO S-57 may be added to ZOC diagrams for paper charts, for example:

- Maintained Depth (MD) and Dredged Area (DA). Such areas often do not accurately indicate actual depths but do indicate minimum depths at the time of dredging.
- Unsurveyed (UNS). This should be evident from the face of the chart but may also be indicated on the ZOC diagram.

The date of a survey may be important, particularly in areas of mobile or unstable sea floor. The survey date may be inserted in parentheses against the ZOC value on the face of the diagram. To avoid too complex a diagram, dates of surveys may be grouped; a suitable note may be added to the relevant portion of the chart, rather than complicating the diagram.

Category of Zones of Confidence in Data – ZOC Table

Table 1, the so-called ZOC Table, presents categories of ZOC in data presented on navigational charts with the requirements regarding the following issues: position accuracy, depth accuracy, seafloor coverage and typical survey characteristics.

Remarks (IHO S-57, 2000):

To decide on a ZOC Category, all conditions outlined in columns 2 to 4 of the table must be met.

Explanatory notes quoted in the Table 1:

Note 1. The allocation of a ZOC indicates that particular data meet minimum criteria for position and depth accuracy and seafloor coverage defined in this Table. ZOC categories reflect a charting standard and not just a hydrographic survey standard. Depth and

Table 1. Zones of Confidence Categories (IHO S-57, 2000; IHO S-4, 2017)

ZOC Category (*Note 1*)	Position Accuracy (*Note 2*)	Depth Accuracy (*Note 3*)	Seafloor Coverage	Typical Survey Characteristics (*Note 5*)
A1	± 5 m + 5% depth	= 0.50 + 1% *d* Depth (m) / Accuracy (m) 10 / ± 0.6 30 / ± 0.8 100 / ± 1.5 1000 / ± 10.5	Full area search undertaken. Significant seafloor features detected (*Note 4*) and depths measured.	Controlled, systematic survey (*Note 6*) achieving high position and depth accuracy using DGPS and a multi-beam, channel or mechanical sweep system.
A2	± 20 m	= 1.00 + 2% *d* Depth (m) / Accuracy (m) 10 / ± 1.2 30 / ± 1.6 100 / ± 3.0 1000 / ± 21.0	Full area search undertaken. Significant seafloor features detected (*Note 4*) and depths measured.	Controlled, systematic survey (*Note 6*) achieving position and depth accuracy less than ZOC A1 and using a modern survey echo-sounder (*Note 7*) and a sonar or mechanical sweep system.
B	± 50 m	= 1.00 + 2% *d* Depth (m) / Accuracy (m) 10 / ± 1.2 30 / ± 1.6 100 / ± 3.0 1000 / ± 21.0	Full area search not achieved; uncharted features and hazardous-to-surface navigation are not expected but may exist.	Controlled, systematic survey (*Note 6*) achieving similar depth but lesser position accuracies than ZOC A2, using a modern survey echo-sounder (*Note 5*), but no sonar or mechanical sweep system.
C	± 500 m	= 2.00 + 5% *d* Depth (m) / Accuracy (m) 10 / ± 2.5 30 / ± 3.5 100 / ± 7.0 1000 / ± 52.0	Full area search not achieved; depth anomalies may be expected.	Low accuracy survey or data collected on an opportunity basis such as soundings on passage.
D	worse than ZOC C	worse than ZOC C	Full area search not achieved; large depth anomalies may be expected.	Poor quality data or data that cannot be quality assessed due to lack of information.
U	Unassessed – The quality of the bathymetric data has yet to be assessed.			

position accuracies specified for each ZOC category refer to the errors of the final depicted soundings and include not only survey errors but also other errors introduced in the chart production process. Data may be further qualified by Object Class 'Quality of Data' (M_QUAL) sub-attributes as follows:

a) Positional Accuracy (POSACC) and Sounding Accuracy (SOUACC) may be used to indicate that a higher position or depth accuracy has been achieved than defined in this Table (e.g. a survey where full seafloor coverage was not achieved could not be classified higher that ZOC B; however, if the position accuracy was, for instance, ±15 metres, the sub-attribute POSACC could be used to indicate this).
b) Swept areas where the clearance depth is accurately known but the actual seabed depth is not accurately known may be accorded a 'higher' ZOC (i.e. A1 or A2) providing positional and depth accuracies of the swept depth meet the criteria in this Table. In this instance, Depth Range Value 1 (DRVAL1) may be used to specify the swept depth. The position accuracy criteria apply to the boundaries of swept areas.
c) SURSTA, SUREND and TECSOU may be used to indicate the start and end dates of the survey and the technique of sounding measurement.

Note 2. Position accuracy of depicted soundings at 95% CI (2.45 sigma) with respect to the given datum. This is the cumulative error and includes survey, transformation and digitizing errors, etc. Position accuracy need not be rigorously computed for ZOCs B, C and D but may be estimated based on type of equipment, calibration regime, historical accuracy, etc.

Note 3. Depth accuracy of depicted soundings = $a + (b \cdot d)/100$ at 95% CI (2.00 sigma), where d=depth in metres at the critical depth. Depth accuracy need not be rigorously computed for ZOCs B, C and D but may be estimated based on type of equipment, calibration regime, historical accuracy etc.

Note 4. Significant seafloor features are defined as those rising above depicted depths by more than:

	Depth	Significant Feature
a)	< 40 m:	2 m
b)	> 40 m:	10% depth

A full seafloor search indicates that a systematic survey was conducted using detection systems,

depth measurement systems, procedures and trained personnel designed to detect and measure depths of significant seafloor features. Significant features are included on the chart as scale allows. It is impossible to guarantee that no significant feature remains undetected, and significant features may have become present in the area since the time of the survey.

Note 5. Typical Survey Characteristics – These descriptions should be seen as indicative examples only.

Note 6. Controlled, systematic surveys (ZOC A1, A2 and B) – surveys comprising planned survey lines, on a geodetic datum that can be transformed to WGS-84.

Note 7. Modern survey echosounder – high precision single beam depth measuring equipment, generally including all survey echosounders designed post-1970.

Dual-Purpose Diagrams

Dual-purpose diagrams combine diagrams for other purposes with Source Diagrams where there is insufficient space to show both separately, for

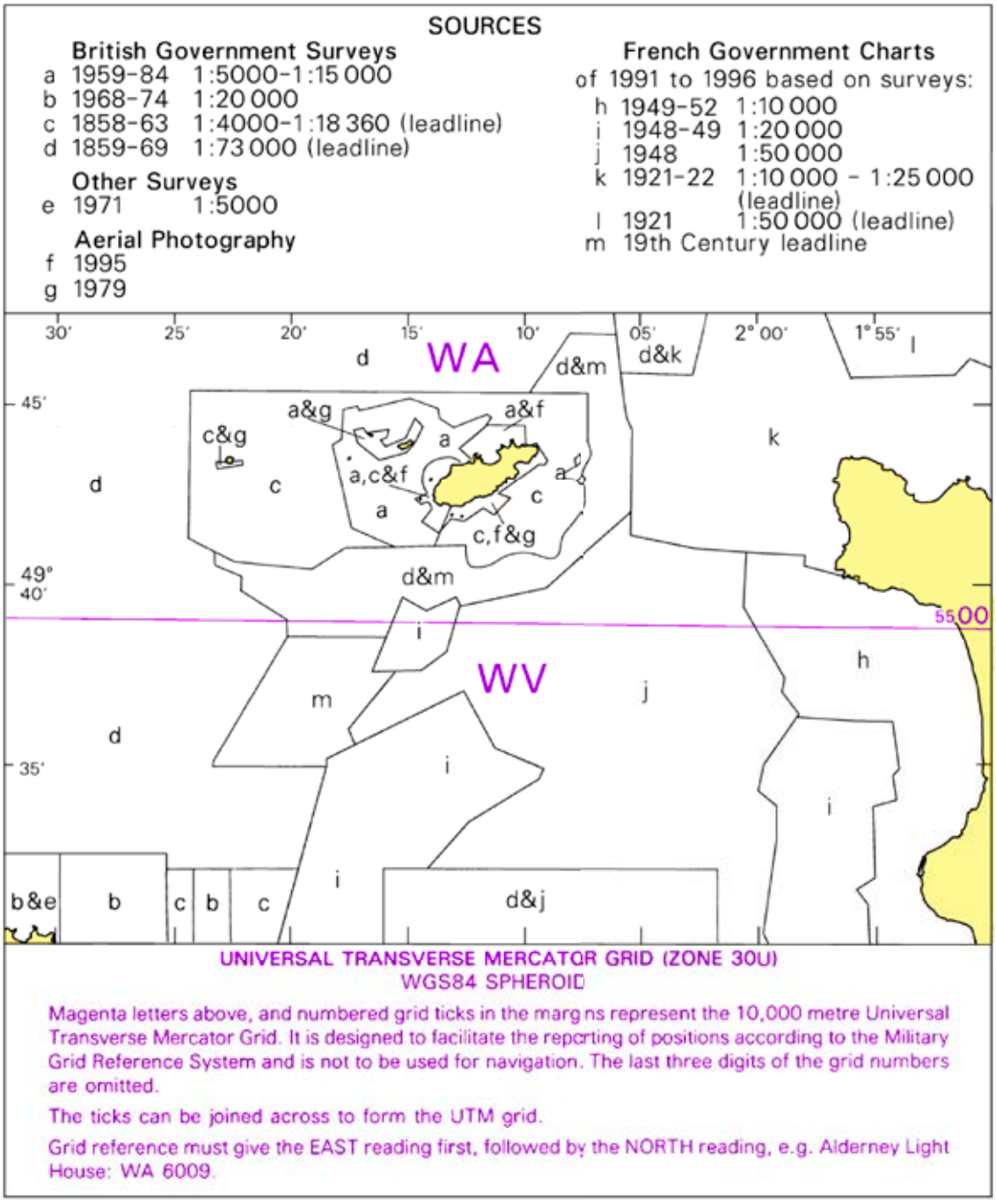

Figure 3. Dual-Purpose Diagram (IHO S-4, 2017)

example to show the limits of larger-scale charts or the incidence of grid reference letters. The Source Diagram should remain in black, with the other information overprinted in another colour, preferably magenta (Figure 3).

The linear dimensions of the dual-purpose diagram shown on paper charts should be one tenth those of the chart's neat line dimensions, but may be reduced further if space is too limited for the preferred size or enlarged if the detail is complex.

Potential Errors in Nautical Charts

The Hydrographic Offices endeavour to ensure that nautical charts and hydrographic publications are continually updated and quality assured. Despite this fact, the navigator must know that the underlying data are not always complete and up to date or positioned in accordance with modern positioning systems. The contents in the nautical chart can be erroneous for different reasons. Some of the reasons are that:

1. The depth information is incomplete due to old-fashioned survey methods having been used;
2. The depth information has changed due to bottom erosion and sand movement;
3. Floating buoys have moved out of position;
4. Building and construction close to harbours and bridges has been commenced.

When navigating in confined waters, points 1 and 2 must be taken into serious consideration. Points 3 and 4 are mentioned in NM and navigational warnings broadcast by VHF radio, NAVTEX or satellite. It is the responsibility of the navigator to update her/his navigational planning in accordance with these warnings. The navigator must at all times evaluate and decide on the reliability of the information available, at any time, to ensure a safe passage.

Why do some charts have Source Diagrams and others have CATZOC Diagrams?

The Source Diagram on a paper chart is the traditional method of indicating when and how the survey was conducted to collect the hydrographic data. From this information, the mariner must deduce the degree of confidence to place in charted data. By including CATZOC Diagrams on paper charts,

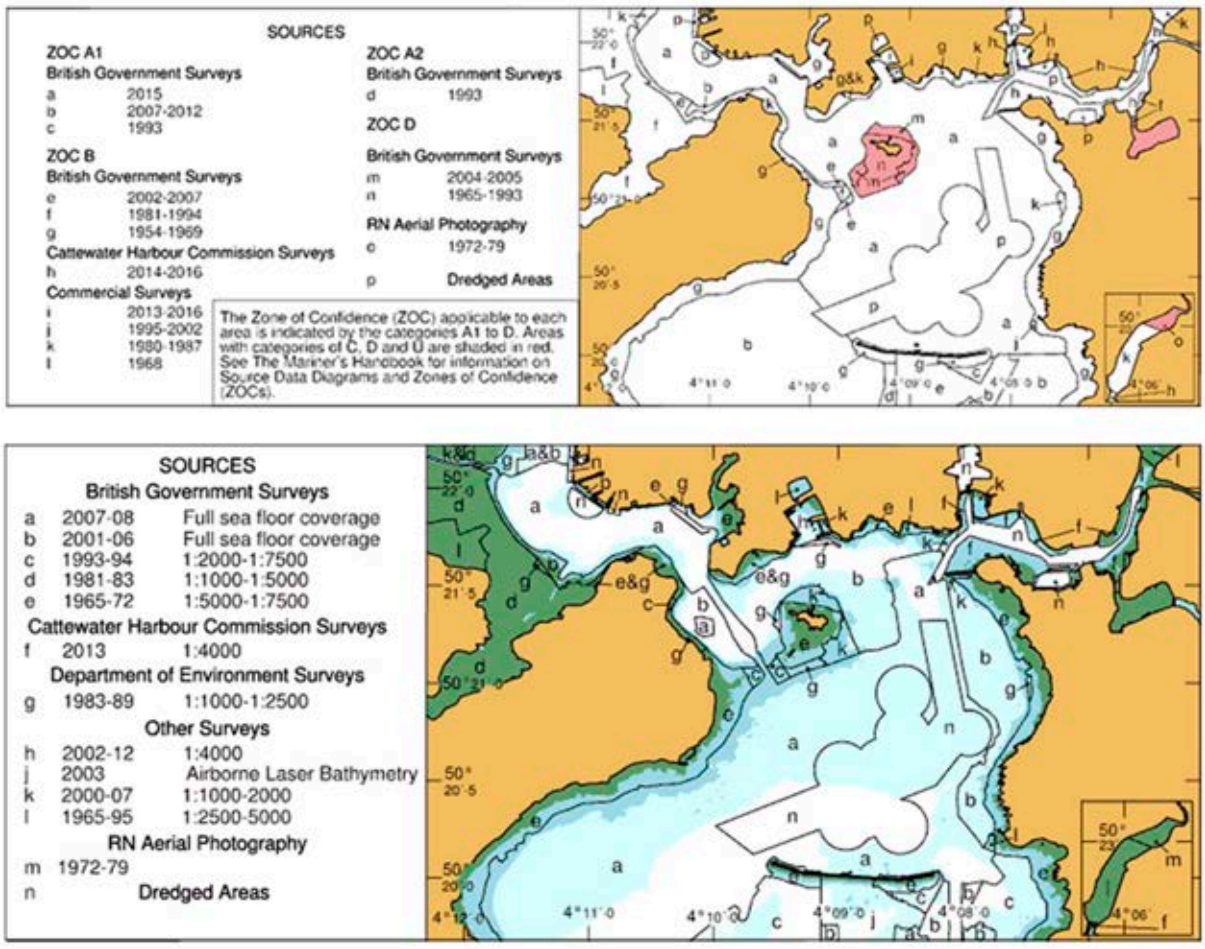

Figure 4. New CATZOC diagram (top) and traditional source diagram (bottom) (Mellor, 2017)

more detail is provided on the accuracy of the underlying hydrographic information than was previously available in the Source Diagram. Providing this additional detail means that the mariner can make more informed decisions when passage planning and calculating under keel clearances. As can be seen from the examples below (Figure 4), the UKHO is gradually moving to a new style of Source Diagrams including ZOCs.

Conclusions

All charts consist of a jigsaw of separate surveys which are combined to form the final chart. These surveys vary in age and quality, particularly due to changes in technology. However, one fundamental truth remains: a hydrographic surveyor can typically only physically see a very small percentage of their survey area – the parts which rise above the sea surface; for the remainder they must have confidence in their systems and long-standing practices to accurately and confidently chart the seabed. Because priority for surveying is given to the major shipping routes, an essential skill for mariners venturing into unfamiliar waters away from these routes is the ability to interpret the various quality indicators that are, or should be, on every chart, e.g. Source or CATZOC Diagrams. So far these are the best guides available to mariners, whether on commercial vessels or cruising yachts, to help them decide how much confidence should be had in past and current surveyors and the technology available to them when surveying the different areas of each chart. Recently the above statement has been questioned, taking into account the conclusions from the research presented, e.g. in (Harper, Wells & Gunning, 2012), or (Wyllie at al., 2017). The IHO is preparing a quite new approach to visualizing the uncertainty of bathymetric data and new proposals are presented in IHO S-101 (Gladisch & Ruth, 2016). Nonetheless, a prudent mariner should be wary of any chart that does not show these indicators, irrespective of whether it is a traditional paper chart or one of the new Electronic Navigational Charts. Finally, if in doubt, post a lookout, make your approach in daylight and good conditions or better still, go somewhere else – there is no such thing as a good vessel grounding. It will always be our fault.

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