

## Uncertainty Management in Hydrographic Surveys

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### Abstract

With the introduction of the 4<sup>th</sup> Edition of IHO Standards for Hydrographic Surveys (S-44) in 1998, the concept of accuracy attribution for soundings started to become entrenched in the hydrographic consciousness. Total propagated error (TPE) subsequently has become part of the hydrographic lexicon.

The estimation of random error contributions to position and depth errors in soundings for both single-beam and multibeam echosounders is reasonably well understood.

Much work has been done and numerous papers have presented ways to use depth and position accuracy attributes as an aid in automated outlier detection in dense data sets.

Methods of calibrating echosounders for systematic offsets have existed for decades. More recently, methods of detecting and correcting small residual systematic effects in multibeam echosounders have been presented.

These efforts have largely been done in isolation from the other uncertainty management elements – a three-pronged approach that looks at random, systematic and accidental errors separately.

With the 5<sup>th</sup> Edition of S-44 now in circulation to IHO member states for approval, it's an appropriate time to look holistically at the management of uncertainty from survey design through to its representation to end-users. This paper examines Uncertainty Management (of random, accidental and systematic errors) in hydrographic surveys. In addition, how Uncertainty Management fits within a quality management system will be presented.

### Introduction

A number of factors have motivated the author to write this paper. For over 5 years the CHS has been certified under a recognized quality management system (QMS): ISO 9001:2000 [Palmer et al., 2007]. Part of the planning process under this QMS utilizes project management approaches. Management of quality or its converse, uncertainty is a natural fit with either of these models as will be shown. Yet, the author is often surprised by the confusion of staff when it comes to the control of error sources and the overall quality management of projects. Perhaps because the author has been researching uncertainty for almost 15 years, it was easy to assume that everyone understands the fundamental principles of uncertainty management.

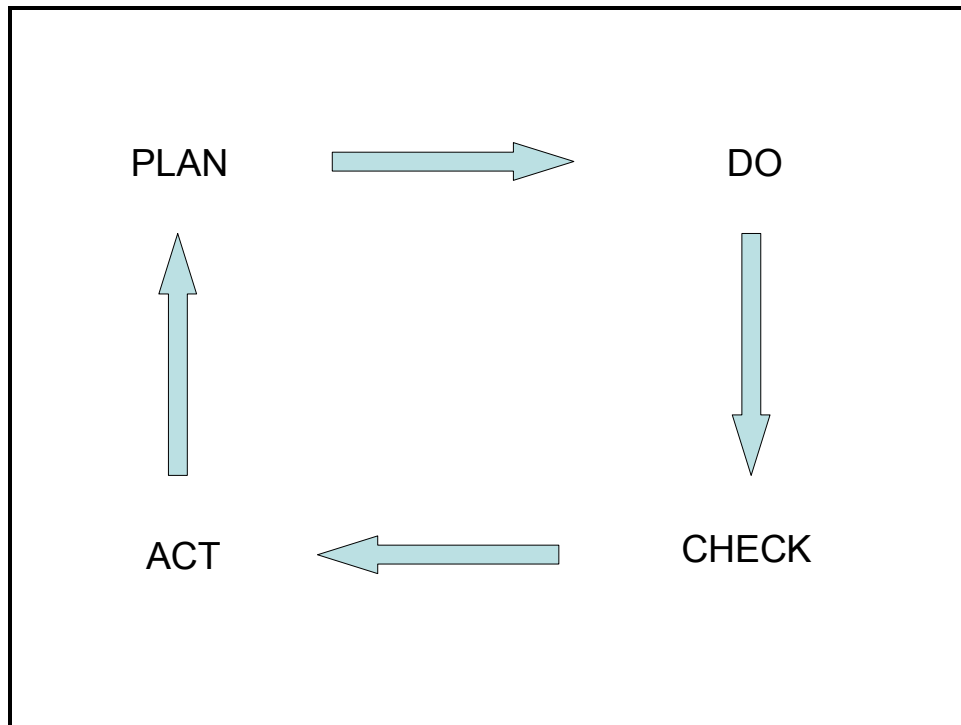
Recently, the author was asked to prepare and deliver lectures on uncertainty management to junior hydrographers and cartographers at a national course. This opportunity forced a certain amount of reflection on past years papers and presentations, researching the works of others and collecting the author's own thoughts on the subject. One of the closing statements in a "Soapbox" column from the June 2004 issue of *Sea Technology* [Wells, 2004] hit quite close to home for the author: "It is clear that communicating chart uncertainty to users is a critical issue." A first step towards this eventual outcome is the management of uncertainty in hydrographic surveys.

## Background

A number of management tools are used in the planning of operations and projects undertaken by a hydrographic office (HO). These include having a strategic business plan tightly coupled with a human resources plan and a financial plan – a budget. For larger projects, normally some form of project management approach is used in order to keep costs under control, assign resources to tasks and make sure that the project will be completed on time and budget with the deliverables demanded by the client. For an HO certified under the ISO 9001:2000 standard, it also requires adherence to quality principles and the use of a structured QMS.

## Quality Management

Quality management is sometimes defined by: the Plan-Do-Check-Act model, or "Say what you do"; "Do what you say"; and "Prove it." But a recognized QMS is much more than this. It forces an organization to know what its clients want, to measure performance against predefined targets (baselines) and to demonstrate continual improvement. It requires a structured approach to management of all facets of the organization. It requires that all processes follow the 'plan-do-check-act' model.

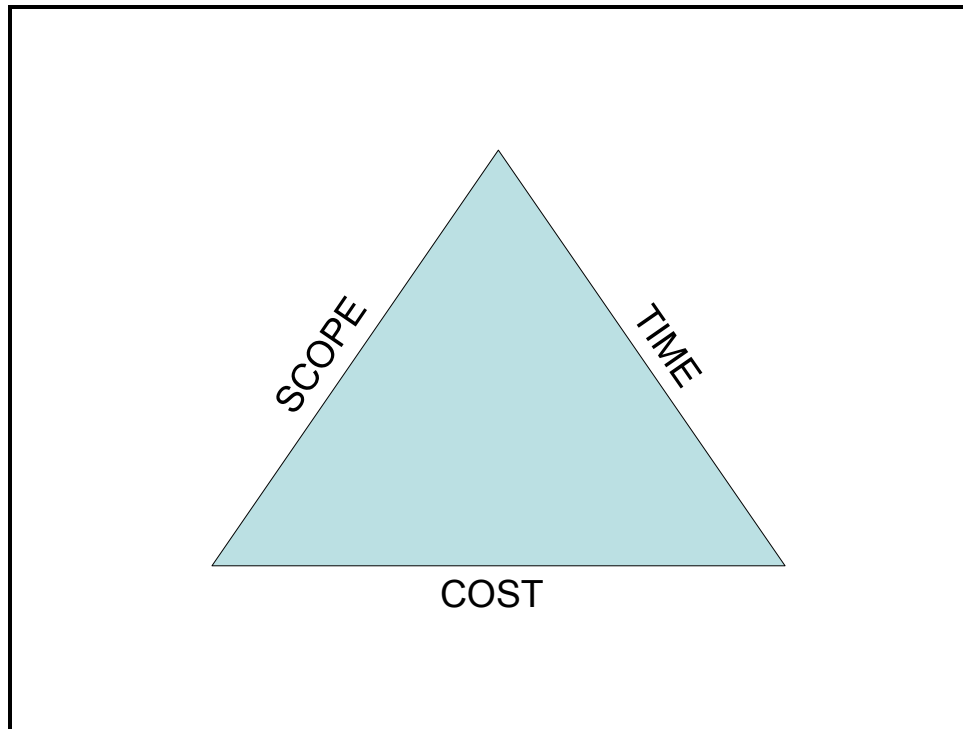


Fundamental QMS elements include:

- Customer Focus
- Strategic Planning and Leadership
- Continuous Improvement and Learning
- Empowerment and Teamwork
- Performance Measurement

### ***Project Management***

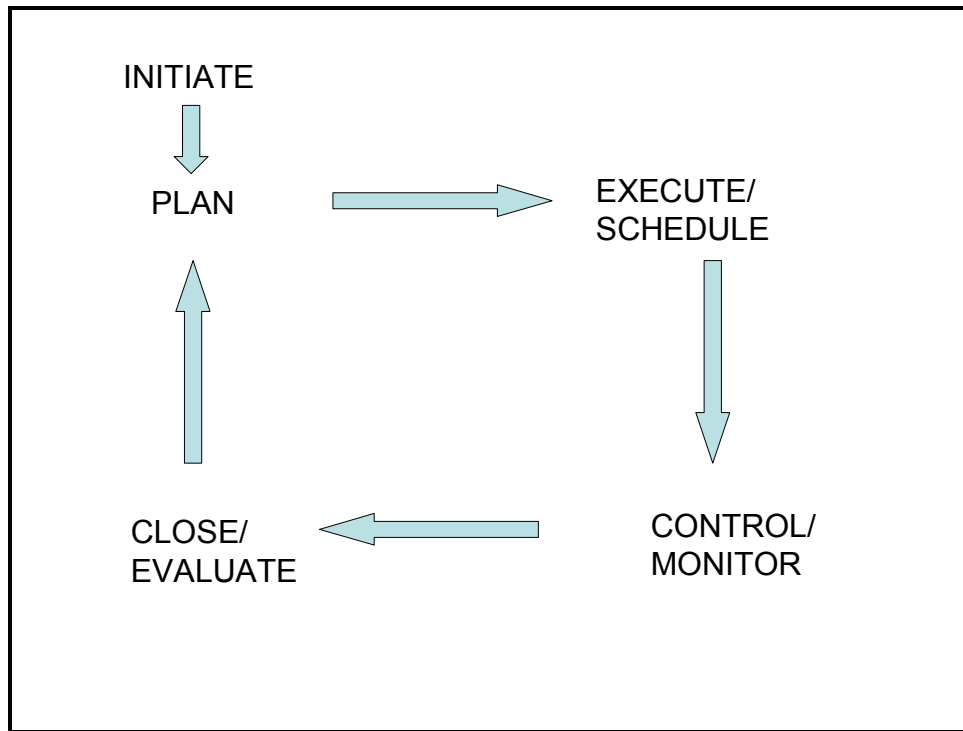
Project Management is often summarized by a triangle composed of Time, Scope and Costs (or resources). A change to any one side of the triangle will affect the other two sides. Similar to quality management, the steps involved in project management include Plan-Execute (schedule)-Control (monitor)-Close (evaluate). Monitoring is done against predefined performance targets to ensure the project is on time and on budget, among other project goals defined collectively between the client and the supplier.



Project Management is sometimes seen as the integration of the following elements:

- Scope definition
- Time (milestones, target dates, deadlines)
- Cost
- Quality
- Human Resources
- Communications
- Risk management
- Procurement

Since projects have a defined start and end, Project Management differs from Quality Management in the initiation step. Quality Management is continuous; Projects must come to a close. That should never stop us from learning from each project (evaluate) such that we improve on the next one.



One can examine the synergy between Quality and Project management by looking at the following grid.

INITIATE	PLAN	EXECUTE	CONTROL	CLOSE
		Schedule	Monitor	Evaluate
Scope	Client needs, Specifications			
Time				
Cost				
Quality		Q.A.	Q.C.	Continuous improvement
Human Resources		Teamwork		
Communications			Performance targets	Deliverables
Risk management	Levels of service			
Procurement				
	PLAN	DO	CHECK	ACT

## **Uncertainty Management**

Uncertainty Management (UM) plays by similar rules, or at least it should. Any project that proceeds without a UM plan is doomed to failure. The management of uncertainty consists of several steps and elements. The main UM steps are:

- Define performance targets, e.g. through survey specifications;
- Pre-analysis (survey design), where an estimate of the error contributions from random error sources is made in order to determine whether the equipment proposed for the survey will allow the resultant survey to meet or exceed specifications;
- Control of errors through equipment calibration and good survey practices, including monitoring system performance while data collection is underway (sometimes called real-time quality assurance (QA)<sup>1</sup>);
- Evaluation (sometimes called post-mission quality control (QC)<sup>2</sup>), where the survey results are analysed to determine whether surveys specifications have been met; and
- Documentation, where individual objects, such as soundings, navigational aids, etc., are given uncertainty attributes, and/or the metadata elements of uncertainty for the whole survey project are documented so that potential users may determine if the data set is fit for their particular purpose.

The main uncertainty elements are:

- Systematic errors or biases, which are due to system offsets or environmental effects that have not been properly accounted for by proper survey procedure such as system calibration, regular sound speed casts, good tidal models, etc.;
- Random errors, which are due to noise in the measurement process used and sometimes due to small unmodeled residual systematic biases; and
- Outliers or accidental errors, which might be due to system failures or environmental conditions that are beyond our ability to control.

### **Survey specifications (set performance targets)**

For most surveys, the survey specifications are either provided by the client, or determined from, e.g. International Standards for Hydrographic Surveys – S-44 [IHO, 1998]: the Order of survey being determined largely from the depth of water or the navigational context of the area to be surveyed – e.g. draft and volume of vessel traffic, types of cargo, risk of grounding, etc. Oftentimes, and fortunately for many HO, the client is more than satisfied with the results produced by adhering to S-44 or similar derivative national standards [e.g. CHS, 2005].

Some HOs have taken this determination one step further, by using risk classifications to prioritize a national survey and/or charting program, which may also take into consideration the dynamic conditions of the seafloor, especially in areas of mobile bedforms, rapid siltation, dredging and dumping, extreme weather events, etc., the length of time since the last surveys of the area and quality of the survey data on which the charts are based [e.g. OCS, 2006; Simões de Oliveira et al., 2007; CHS, 2007]

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<sup>1</sup> There is an accepted definition for QA that is somewhat at odds with its use in this paper - See Annex A

<sup>2</sup> There is an accepted definition for QC that is somewhat at odds with its use in this paper - See Annex A

From this it can be seen that UM can be tied directly to national business planning, service standards and the clients' needs to manage risk by understanding the quality of the information upon which they must base their navigation decisions. Think of it as establishing an uncertainty budget from which to conduct all survey operations. In many ways it will help define the scope, time and costs of a project.

### **Pre-analysis (plan)**

Pre-analysis is an oft-used tool by the surveying profession [e.g. Mackenzie, 1985; Myres, 1990; Hare, 1995]. Knowing ahead of time what instruments to use, the observational methods, the number of measurements and the geometric strength needed to meet desired specifications can save the costs of reobservation. After an assessment of "can we meet the specification?" it is not too late to change any of the elements in order to come in under budget. Most commonly, though, observational methods and number of measurements are what gets modified to meet specifications, since the cost of purchasing new equipment is often not possible, although as shown above, procurement is a planned step in the project management process.

It should be noted here that there are other elements of pre-analysis beyond meeting accuracy specifications. S-44 Orders also have requirements for seafloor coverage and target detection that must be evaluated to determine if the equipment and methods are suited to the task. These elements can be assessed before the mission, but also need to be monitored during data collection and again in post-mission to ensure specifications are met.

### **Control of errors (do, check)**

As mentioned above, there are three types of uncertainty that must be controlled. Hopefully, with the pre-analysis step we have adopted survey procedures and chosen equipment that will control the random errors as best as we are able. Systematic errors need to be controlled by careful calibration of sensors on board e.g. standard patch test [Herlihy et al., 1989] or other method [e.g. Godin, 1997; Riley, 2000; Wang et al., 2004; Bjørke, 2005], good survey practice e.g. regular sound speed casts, good tidal control through deployment of gauges, use of RTK GPS, precisely measured sensor coordinates and orientation, precisely measured latencies between sensors, well-calibrated sound speed sensors, etc. Control of outliers is not something that can be planned, but through the steps below outliers large enough to cause a problem can generally be isolated and removed.

### **Real-time quality assurance (check/monitor)**

The next step is to conduct the survey, using the calibrated equipment and methodology defined in the previous steps. Wells [2003] outlines a number of essential (E) and useful (U) steps that can be performed during data collection that will help to identify outliers and systematic artefacts so that corrective action can be taken before too much bad data is collected and while the survey is still underway:

- Track control (E)
- Coverage display (E)
- Cross-track profile (E)
- Along-track (beam-by-beam) profile (U)
- Backscatter mosaic (U)
- Sun-illuminated seafloor topography (U)

Reed et al. [1999] shows how random error estimation in real-time can be used to monitor collected data against specifications and notify the operator through alarms when preset tolerances are exceeded. Near real-time gridding of collected data, with all corrections applied, can be compared to independent (e.g. historical, other vessel, different day) bathymetry as a way of isolating systematic biases (e.g. incorrect draft, bad sound speed profile).

It is important to ensure both internal (within system) and external consistency (independent system cross check) of the data. Swath to swath checks can identify problems with patch test values, incorrect sound speed profiles, incorrect tide files or failure to apply tides, bad time stamps, etc. But independent checks can catch incorrect draft setting or failure to apply a draft correction – or worse, applying it backwards. Don't laugh – this happens all too frequently.

Corrective action might include some adaptation of the planned survey procedure proposed under the pre-analysis step, e.g. more overlap, reduced vessel speed, narrower swath width, more frequent sound speed casts, etc. Oftentimes, observations of a different type are needed to resolve what one system cannot. Field validation eliminates the need for costly rework [Varma et al., 2002].

### **Post-mission quality control (check/evaluate)**

It is important to note that in many cases, the prevalence of inexpensive processing power means that much of what was once conducted “back at the office” can now be done aboard ship within hours or even minutes of the data collection. This is a good thing. Visualization of multiple days, platforms and lines simultaneously can help to identify small residual systematic errors (e.g. [Hughes Clarke, 2003]) that can be corrected for the most part through the application of small sensor time offsets or sensor scale factors.

Field Quality Control consists of examining on-line and near-real-time processed data to assess the fidelity of the results:

- ship track parallel: imperfect water column, patch test, tides;
- ship-track orthogonal: dynamic error sources – the wobbles (dynamic error residuals)

Time delay, pitch, heading, roll and sound speed (static) error residuals can be resolved through a standard patch test [ibid., 2003]. There are also approaches to correct for small dynamic offset and ripple errors through time referencing [Jalving et al., 2005]. This should be conducted at the Control of Errors step.

Numerous methods exist for almost fully-automated detection of outliers while still in the field [e.g. Hare et al., 2004; Calder, 2003; Debes, 2001]. Assessment of the contribution of all measurements, with their associated uncertainty, to the uncertainty in the bathymetric model of the seafloor can be estimated. That is, we have at least a preliminary idea, while still in the field, whether our survey has indeed met specifications or whether we must collect additional data before pulling the plug. In some cases, the use of additional sensors may be required to resolve queries where insufficient information is available for reliable decision making. As an example, the multibeam sonar information is inadequate to detect reliably the mast head of a wreck and a diver examination or drop camera may be needed to confirm least depth and position.

Other methods exist for proving (or conversely disproving) whether specifications have been met. A tiling approach to statistical estimation of depth uncertainty (i.e. the standard deviation of measured depths within a tile or grid cell) is an empirical method that can be used to validate the theoretical (forward error propagation) approach. When used together with forward error

propagation, tile statistics can be used to confirm that correct weights have been used in the estimation of position and depth uncertainty and that a tile size appropriate to the seafloor rugosity has been chosen. One would expect to see good agreement between empirical and theoretical approaches over a flat seafloor, but to see some error growth over steep slopes or where the seafloor rugosity causes fluctuations in depth measurement not accounted for through measurement error models. One thing most tiling approaches do not consider is the depth and position error in each sounding within the tile and how that needs to be weighted within the calculation of the mean (or median) and standard deviation of the tile. Tiling/gridding algorithms have a heavy dependence on removal of systematic biases and outliers or the tile statistics will be skewed.

### **Performance measurement (check, act)**

Under an ISO QMS, continuous improvement is facilitated through ongoing performance measurement. Once a post-mission quality evaluation has been completed, the results can be compared directly with our pre-mission design specifications. If we have stuck with our UM plan one would expect all performance targets to be met. But we all know that even the best laid plans can go awry. Careful evaluation of the reasons for missed performance targets (examination of root causes) is the Check and Act part of the ISO QMS continuous improvement feedback loop.

### **Documentation - Quality assessment and disclosure (act, prove it)**

To the client or the world - the potential users of the data - arguably the most important aspect of any data set is establishing its fitness-for-purpose [e.g. Monahan et al., 2002; Wells and Monahan, 2002]. Mariners may wish to know the vertical uncertainty of the depths upon which a chart is based and over which they must navigate. On the other hand, mariners may assume that if the depths are on an official chart they must be right. If that is the case, the HO is obliged to inform the mariner in an intuitive way about the quality of the charted information.

Any claim that a data set met the standard and is fit for the intended purpose needs to be backed up with objective evidence [Wells and Monahan, 2002]. Proof that a UM plan was developed and followed throughout calibration, acquisition, real-time QA and post-mission QC steps; that an appropriate treatment was given to random, systematic and accidental errors; and that appropriate and recognized standards [e.g. NIST, 2000] were applied to the estimation of combined uncertainty in the data set are minimum requirements for this proof.

Metadata (data about data) in a standard and recognizable form, that is easily web-searchable by user-specified criteria, such as positional or depth uncertainty, needs to accompany each data set. This requirement is built into ISO metadata standards, which are linked with several product standards in development, e.g. S-100 [Alexander et al., 2007; Sebastian, 2003], BAG [Calder, 2005]. Metadata is becoming almost as important as the data itself as more users see myriad applications for spatial analysis and information generation through GIS and web-map servers (WMS).

## Discussion

New CHS hydrographic Survey standards have been recently released publicly [CHS, 2005]. The accompanying CHS Survey Management Guidelines are nearly complete. In the latter, there is a focus on most of the UM elements discussed in this paper. That is fortunate since to date, there has been little focus on UM in the draft 5<sup>th</sup> Edition of S-44. Nor is there much help provided in the 1<sup>st</sup> Edition of M-13, the Manual on Hydrography [IHB, 2005].

There are guidelines for quality control and data processing being developed as annexes to the 5<sup>th</sup> Edition of S-44. In the author's opinion, the time is right to include with this a recommendation that all HO undertake UM planning as part of any survey program. This guidance could then be incorporated into the next edition of M-13.

Hopefully by having some guidance in place, less time will be spent subjectively clipping the fuzz off multibeam data sets that is merely measurement noise. More time will be spent focusing on identification, verification and removal of outliers. Time won't be wasted discarding data in swath overlap areas where there are mismatches, where it would be better spent diagnosing the systematic errors that caused the problem (root cause analysis) and taking steps (corrective action) to address them.

Monahan and Monahan [2001] propose a retroactive quality evaluation (RQE) step as part of the quality control cycle. Calder [2006] shows how such RQE might be carried out for historic data sets and some of the problems one might expect to encounter. This seems a necessary step in addition to UM of all new survey data, since we can not expect to replace all legacy hydrographic data sets in our lifetime. If you don't estimate uncertainty, how can you integrate and validate new and old data sets where they overlap? Having an uncertainty estimate for each overlapping data set makes it possible to make informed decisions about which to keep or supersede, or whether to use some integration of both. Overlapping data sets provide the added redundancy for objectively proving the combined data set is fit for purpose. Redundancy in data provides added quality assurance, the ability of the data to self-check. Not taking advantage of that is folly.

S-44 defines a minimum performance standard to which new survey data shall be collected. Many have argued for an agreement of this standard for hydrographic surveys with S-57 and Zones of Confidence. However, with knowledge of the evaluated uncertainty of collected data sets old and new, the integrated product data set may in fact meet no particular S-44 standard old or new. This makes it impractical to classify an integrated data set to a survey standard. However, the data set quality can still be categorized into one of the ZOC categories if that is what is desired.

Monahan et al. [2002] propose a number of methods in which uncertainty information might be communicated to the mariner or other end users better than the attempts the hydrographic community has made to date. All of these proposals rely heavily on having uncertainty estimates for all our data sets and data types. Ship's bridge and risk management is performed better with uncertainty for informed decision making. Undoubtedly, other GIS or spatial analysis provides better results with uncertainty information captured as part of each data set.

As mentioned earlier in this paper, the CHS has developed a risk-based approach to chart maintenance [CHS, 2007]. While this approach was originally based on a chart-by-chart assessment, it has since been modified to look at risk by geographic area units. This seems

logical, but perhaps it could be taken one step further. Several HO have used a risk assessment of their source data as the driver for developing a national survey plan. The risk assessment can be based on age of data as a surrogate for poorer quality positioning, depth measuring technology limitations and temporal change. If a retroactive quality evaluation of the source data sets was performed, admittedly no small task for many countries, the classification of risk could be more objectively assessed. The approach of Velberg [1993] could be used to add an additional uncertainty due to seafloor change, e.g. in areas of siltation. An estimation of seafloor dynamics can be made using deformation analysis on a series of archive surveys [Dorst et al., 2006]. The process requires aligned gridded data sets with the uncertainty at each grid node. If the rate of change of the seafloor in an area was known, resurvey frequency could also be built in to the national survey plan based on clients' requirements or survey specifications. The availability of new survey data could then be used as the driver for the national charting plan.

## Summary

Uncertainty Management should be viewed as one of the most important tools in the management toolbox of any HO, or for that matter, any organization that collects spatial information through a measurement process. After all, all measurements contain uncertainty. With an Uncertainty Management Plan we can truly say what we will do, do what we have said we will do and ultimately prove it (statistically), providing documented evidence to the end user – our clients and stakeholders, mariners and everyone else – that our data is indeed fit for their purpose.

Extending our use of uncertainty to product creation and long-range planning has added benefits. Granted the focus of this paper has been on bathymetric uncertainty estimation (to which much of the literature is devoted and standards developed), but there is no reason why this could not be extended to all chart data types. Our QMS demands that we do no less.

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## **Annex A**

ISO 9000:2000 defines Quality Assurance as 'providing confidence that requirements will be met'.

Quality assurance (QA) is defined as a set of activities whose purpose is to demonstrate that an entity meets all quality requirements. QA activities are carried out in order to inspire the confidence of both customers and managers, confidence that all quality requirements are being met. [PRGL, 2006]

Quality control (QC) defined as a set of activities or techniques whose purpose is to ensure that all quality requirements are being met. In order to achieve this purpose, processes are monitored and performance problems are solved. [PRGL, 2006]

From these, QC can be seen to be monitoring and corrective action. The entire UM process can be considered QA and QC is merely a component of this.

The author has worked with both CHS (QC has been an end-of-line process) and NAVOCEANO (RTQA is quality monitoring of data acquisition sensors) – this has resulted in a bias for the particular terminology that appears in this paper.

## **Biography**

Rob Hare is Canada's member on the S-44 (IHO Standards for Hydrographic Surveys) working group. He is manager of hydrographic surveys for the west coast of Canada and is primary ISO internal auditor. He is a registered professional engineer in British Columbia and a Canada Lands Surveyor. He has worked for the Canadian Hydrographic Service since 1982 and has authored numerous papers and reports on uncertainty estimation in hydrographic systems.