BIBLIOGRAPHY

1.0 IHO S44 Standards for Hydrographic Surveys and the Variety of Requirements for Bathymetric Data

1.1 Intended uses for bathymetric data

The traditional mandate of hydrography has been to survey, chart and supply all spatial information required to assist in safe navigation, and safety of life at sea, primarily for those commercial shipping vessels which fall under the conditions of the Safety of Life at Sea (SOLAS) convention administered by the International Maritime Organization (IMO).

However, driven by technological change, hydrographic needs and capabilities are becoming more broadly concerned with the management of spatial information concerning all marine features, processes and properties in four dimensions (space and time) including the acquisition, analysis and visualization of this spatial information (Kenny, 2000; Hecht, 2001;Monahan *et al*, 2001). Bathymetry is that aspect of hydrography that is concerned with delineating the marine floor, including features of both natural origin and those due to human activity. Bathymetric mapping has four broadly defined intended uses: to improve knowledge and understanding; to establish sovereignty and security; economic purposes (including offshore resource management and shipping) and environmental management.

Hydrographic information, in particular bathymetric information, is used to make informed decisions of several types: for example vessel navigation decisions; resource management decisions; resource development decisions; marine infrastructure decisions; marine construction decisions; coastal development decisions; tactical and strategic military decisions and environmental management decisions. The confidence with which such decisions can be made depends on the confidence that can be placed on the hydrographic (and other) information available to assist in making informed decisions. It is consequently critical that users be informed of the uncertainty associated with the data and with products constructed from it. For suppliers of bathymetry to provide information about uncertainty, they must first assess it. They are aided in this assessment by mathematical tools and an international standard, S44 of the International Hydrographic Organization (IHO, 1998).

1.2 Assessment of uncertainty in bathymetric data

The uncertainty associated with bathymetric measurements includes (a) uncertainty in the location of a measured bathymetric data point; (b) uncertainty in the depth associated with a bathymetric data point and (c) uncertainty in the backscatter strength associated with a bathymetric measurement.

Bathymetric uncertainty management involves both the design of a bathymetric system and the evaluation of results and products derived from bathymetric data. Measurements are always uncertain, to a greater or lesser degree. Uncertainties are of three fundamentally different types: *accidental*, *systematic* and *random*. Each type must be dealt with differently. A common characteristic shared by all three, however, is that the reliability with which we can determine uncertainty is completely dependant upon the degree to which the bathymetric data is redundant (repeated measurements of the same seabed feature, or even footprint, which can be directly compared to ascertain consistency).

'Data cleaning' describes methods used to deal with 'accidental' uncertainties, (also called mistakes, blunders, or outliers). Comparison of a suspected outlier with its geographical nearest neighboring data points (taking hydrographic judgment into account) is the most powerful data-cleaning tool. A rule of thumb which has emerged for cleaning high-density bathymetric data is that real features are distinguished from points created accidentally according to whether multiple consistent data points (multiple 'hits') in close proximity are observed or not.

'Artifact' describes the effect of a systematic uncertainty. 'Artifact detection' and, where possible, 'artifact removal' describe further steps in the data-cleaning process. Artifacts are most often manifested as identifiable artificial features in a data series, with a strong correlation in time or space with some other data series. Effective artifact detection requires dense data, and powerful visualization tools.

Whatever remains after (perhaps incomplete) data cleaning and artifact removal, are considered as random uncertainties, or noise, in the data. Sometimes it is appropriate and possible to reduce the noise level by use of suitable filtering and smoothing of the data, but this can be dangerous, re-introducing systematic uncertainties, due to the filtering process itself.

In any case, in the best case some remaining 'random' uncertainties will be left. Otherwise there will still be residual systematic uncertainties that cannot be removed. In extremely unfortunate cases, there may still be blunders or outliers which cannot be removed with certainty, because it is impossible to decide whether these data points represent real features, or are accidents of measurement.

To meet the requirements for informed decision-making, it must be possible to describe these remaining uncertainties in some standard way. One uncertainty descriptor is 'precision' which describes data consistency. Good precision indicates that outliers have been successfully removed, and random uncertainties are small - but large systematic effects may still exist. Another uncertainty descriptor is 'accuracy', which in a perfect world indicates the agreement of data with the 'truth' (whatever that may be). Good accuracy indicates that the systematic effects have been reduced or eliminated, although occasional outliers may still exist, and the random uncertainties may be large or small.

Both these uncertainty descriptors are based on statistical principles and standards. The 'mean' and the 'standard deviation' are the two most common statistical descriptors of measurement uncertainties. The mean describes the central tendency of a series of measurements. The standard deviation describes the dispersion of a series of measurements. If the mean value (or perhaps a 'true value' if such is known) is subtracted from every measurement, a series of 'residuals' or deviations from the mean will result. If the square root of the sum of the squares of these residuals is calculated, the standard deviation for that measurement series is obtained.

When discussing measurements that have a number of 'dimensions' or time-correlated quantities (as is most certainly the case for a modern bathymetric survey), then these concepts are extended into several dimensions by considering a 'mean vector' and a 'covariance matrix'.

Data-sets containing many measurements tend to have a special statistical character, known as a Gaussian distribution (the familiar 'bell-shaped curve'), provided all accidental and systematic uncertainties have been removed, so that the uncertainties are purely random. This Gaussian character is an approximate model of reality, and becomes a better model the larger the number of values which are being considered (something called the Central Limit Theorem), and the more rigorous or successful the data cleaning process. An important descriptor of uncertainty, when the data density permits, is the probability that the data residuals (the random component of uncertainty) obey the Gaussian distribution.

But what does all this have to do with the confidence which can be placed in the information or measurements? Another statistical principle that can be predicted, under specific statistical conditions, is how often the measurement uncertainties (or more specifically the measurement residuals) are likely to exceed a certain value. The value (or values) in question is referred to as the 'confidence region', and the likelihood that the measurements lie inside this confidence region is referred to as the 'confidence level'.

The international standard for confidence level is 95% – in other words 19 times out of 20. 95% is the confidence level associated with weather predictions. 95% is the confidence level associated with election outcome predictions or public polling results. And 95% has become the standard for expressing the confidence level for results derived from hydrographic measurements. If data has a Gaussian distribution, the 95% confidence region is related to the standard deviation (in one dimension) or the covariance matrix (in several dimensions) by a simple scale factor.

In summary, key quality factors in bathymetric survey design are 'coverage', 'resolution' and 'redundancy'. The key quality factor in bathymetric data assessment is 'uncertainty' - what are the uncertainties in the resulting bathymetric, positioning and sonar backscatter information, and how do these uncertainties compare with the informed decision-making requirements for the intended uses? Bathymetric uncertainty management requires redundancy and consists of two or three steps - data cleaning for both outliers and artifact removal, perhaps followed by a noise reduction process, and finally an assessment of the 95% confidence region associated with the remaining residual discrepancies.

Having applied the tools discussed in the previous section, it is possible to arrive at numerical values for uncertainty of the bathymetry data, either grouped by adjacent areas, or individually. One way to assess these numbers (decide if they are fit for their intended purpose) is to compare them against a standard.

A standard can be used as a planning document before data are collected and as an evaluation document after the data are in. The *a priori* approach tries to assess the uncertainty with which each piece of data could or should be collected, before a survey is conducted. This is implemented through an uncertainty prediction estimation process or model. These predicted uncertainties are compared with those required to meet the appropriate standard, and the survey redesigned if they fall short. The *a posteriori* approach attempts to determine what uncertainties actually exist in the collected data, using the data cleaning and assessment tools referred to earlier in this paper. The results of these post-survey checks are then compared with the appropriate standard, to determine whether the survey results are actually 'fit for their intended purpose'. Sometimes it is claimed that a survey 'met' the standard, but if no post survey check was carried out to verify this claim, it is not supported by evidence. Claiming that surveys were planned to meet the standard is not enough. Planning and realization are not always the same thing.

In the following sections some of the standards that are available for this assessment are considered. For simplicity, just one of the many standard parameters required for assessing hydrographic data will be addressed: the uncertainty in determination of depth.

1.3 S44 - IHO standards for hydrographic surveys

The International Hydrographic Organization (IHO) has issued standards for hydrographic surveys (S44) since 1957, and most recently in 1998 (IHO, 1998). These are the standards used by most producers of hydrographic data. Their stated purpose is:

> *To specify minimum standards for hydrographic surveys in order that hydrographic data collected according to these standards is sufficiently accurate and that the spatial uncertainty of data is adequately quantified to be safely used by mariners (commercial, military or recreational) as primary users of this information.*

S44 identifies itself as a 'performance standard' and thus contains no instructions on how to evaluate whether a survey meets the standard. Nor does it specifically require the inclusion of redundancy, the most powerful tool for evaluating the uncertainty of any set of measurements. These are left to each agency to implement:

Equipment and procedures used to achieve the standards laid down in this publication are left to the discretion of the agency responsible for the survey quality.

Producing a standard like S44 is no easy task. Usual practice is for several member states of the IHO to nominate specialists who not only have a profound knowledge of the theory underlying the subject but are also aware of upcoming improvements in the technology that may impact on the standard during its lifetime. The group must also have a strong sense of the pragmatic: there is no value in producing a standard that cannot be achieved or can only be achieved at costs not sustainable by some member states. Finally, the members must possess a thick skin, since their work can never please everyone.

The work of producing the standard is ongoing, in a periodic manner, with the published intention of issuing a new edition every five years. An examination of the changes between succeeding editions gives a strong indication the perceived progress in hydrographic technology and evolution in users' needs. For instance, the current (4th) edition:

...departs from previous editions by specifying different accuracy requirements for different areas according to their importance for the safety of navigation. The most stringent requirements entail higher accuracies than previously specified, but for areas of less critical nature for navigation the requirements have been relaxed.

Improvements in positioning technology that allow vessels to determine their locations at a level of uncertainty smaller than that required by the previous standard, together with the development of high density bathymetric mapping tools (such as multibeam sonar echo sounders and LIDAR), are reasons behind this demand for higher accuracies in certain areas. Future editions will likewise adapt the standard to evolving technology and users requirements.

S44 4th Edition classifies surveys into four different types (four 'intended uses'):

Special Order - for specific critical areas with minimum under keel clearance and where bottom characteristics are potentially hazardous to vessels (generally less than

40m), such as harbours, berthing areas, and associated critical channels with minimum under keel clearances.

Order 1 – for harbours, harbour approach channels, recommended tracks, inland navigation channels, and coastal areas of high commercial traffic density (less than 100m), such as harbours, harbour approach channels, recommended tracks and some coastal areas with depths up to 100 m.

Order 2 – for areas with depths less than 200m not covered by Special Order and Order 1.

Order 3 – for areas not covered by Special Order, and Orders 1 and 2 and in water depths in excess of 200m

For each of these it specifies Horizontal Accuracy, Depth Accuracy, 100% Bottom Search, System Detection Capability and Maximum Line Spacing.

S44 4th Edition divides depth uncertainties into two contributing types: fixed and variable. It makes no mention of the primary classification of random, systematic and accidental, within these fixed and variable types. Fixed errors dominate the uncertainty budget in shallow water. Variable (depth-dependent) errors are characterized as a fixed percentage of water depth and thus grow larger with deepening water. The two types are combined in the Root-Sum-of-Squares (RSS) sense to give the 95% uncertainty s. That

$s = [a^2+(bd)^2]^{1/2}$

Where a = sum of all depth-independent errors, b = sum of all depth-dependent errors, expressed as a fraction of water depth, and d = depth of water column in metres.

S44 4th Edition draws a distinction between the sampling of the seabed bathymetry represented by the measured depths, and the complete bathymetric model which is presented (in some form) to the end user for informed decision making. Unless the sampling density is dense enough to delineate all seabed features, this model will be based, either implicitly or explicitly, on some form of interpolation between the sampled depths. Consequently the uncertainty associated with a bathymetric model will include uncertainties introduced by the interpolation process, and will be larger than the depth measurement (sampling) uncertainty.

Order	S44 Special	S44 1	S44 2	S44 3
Depth uncertainty for reduced depths (95% Confidence Level)	a = 0.25m b = 0.75%	a = 0.5m b = 1.3%	a = 1.0m b = 2.3%	a = 1.0m b = 2.3%
Bathymetric model uncertainty (95% Confidence Level)	a = 0.25m b = 0.75%	a = 1m b = 2.6%	a = 2m b = 5%	a = 5m b = 5%

Table 1.1: *Summary of Minimum Standards for Depth Uncertainties from S44 4th Edition (IHO, 1998)*

In the case of the Special Order, this algorithm is somewhat more demanding than the single depth uncertainty specification from S44 3rd Edition (IHO, 1987), which was

30cm to the depth of 30m, and 1% of depth thereafter.

The S44 3rd Edition specification was at the 90% confidence level, and did NOT include uncertainties in water level reduction, which are included in the 4th edition specifications. For Orders 1 to 3, this algorithm results in higher permitted uncertainties than did the single 3rd Edition specification.

There are two ways in which the S44 4th Edition depth uncertainty standards can be interpreted. In the first interpretation, the word 'minimum' standards is taken as the operative word, and the unlimited extension of each of the four S44 orders to deeper depths is permitted, even though not mandatory. In the second, more limited, interpretation, each Order is assigned a maximum depth to which it should be applied (Special Order to 40m, Order 1 to 100m, Order 2 to 200m, and Order 3 in deeper water).

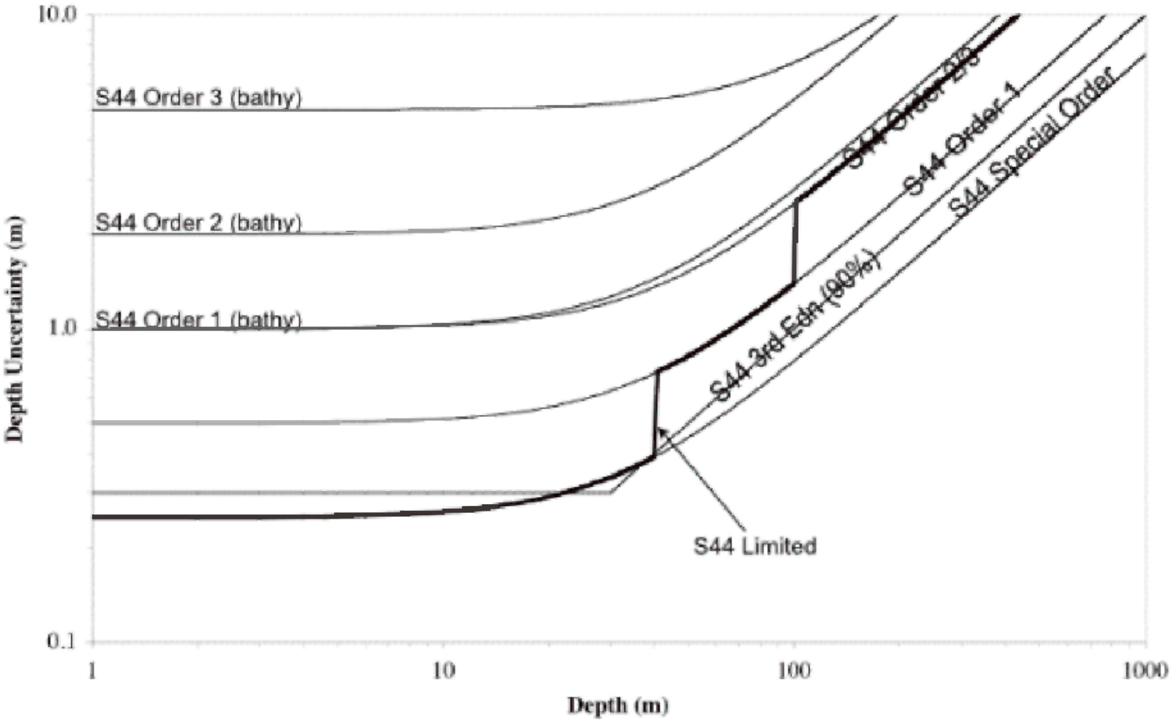

Figure 1.1: *Log-log plot of S44 3rd and 4th Editions.*

In subsequent Figures, the S44 Special Order plot is used as a reference.

1.4 Beyond S44 - other intended uses, other standards

S44 4th Edition broke a lot of new ground. It addresses the use of high density bathymetric methods, such as multibeam, sweep and LIDAR. It emphasizes the need to determine and record ('attribute') depth and position uncertainties. It distinguishes between depth measurement uncertainty and bathymetric model uncertainty.

Previous S44 editions were based on the scale of a specified chart, and the draughting skill of experienced marine cartographers. S44 4th Edition is based on uncertainty budgets and (at least nominally) on intended uses. However, despite this nominal objective, the intended use for which S44 4th Edition was created is still almost exclusively nautical charting.

Some of those seeking depth uncertainty standards for other intended uses of bathymetric information have referred to S44 4th Edition, as is (e.g. United Nations, 1999). Others have extended, modified and replaced the standards embodied in S44 4th Edition.

This paper will consider four examples of standards that go beyond S44 4th Edition:

- The Exclusive Order introduced by the Swedish Maritime Administration (SMA).
- The US Army Corps of Engineers shallow water standards.
- Standards proposed by Land Information New Zealand for deep water multibeam echosounder surveys.
- Standards proposed by the International Marine Contractors Association for offshore construction.

1.5 Swedish implementation of S44

IHO S44 are *minimum* standards. At least one hydrographic office, the Swedish Maritime Administration, has defined standards which are based on S44 4th Edition, but which are more demanding than those minimum standards (SMA, 2000).

On 1 May 2000, these new standards came into effect for Swedish surveys, and are being considered for adoption by other Baltic hydrographic offices.

- SMA extended S44 4th Edition in four ways:
- A new Exclusive Order specification was added, intended for the most demanding applications.
- 100% seafloor coverage is required in all cases by SMA, whereas for S44 4th Edition 100% coverage is specified only for Special Order and, if there is a grounding hazard, for other Orders as well.
- Depth uncertainty in the standards refer to both acoustic sounding measurements (topographical reproduction) as well as determinations of the minimum depth by means of mechanical sensors (sweeping bars).
- The SMA depth uncertainty standards include the entire error budget from the surveying uncertainties up to the final result - storage in the digital depth database. In this way, the SMA depth uncertainty standards are conceptually closer to the S44 4th Edition bathymetric model uncertainties, than to the depth measurement uncertainties. However

the SMA standards are much tighter than the S44 4th Edition standards, since the numerical values are derived from the S44 4th Edition depth measurement uncertainties.

The SMA established two 'intended uses' - 'fairway areas' and 'other'. Fairway areas are defined as:

existing, proposed or planned fairways, traffic separations, deepwater routes, ports and areas of anchorage or waiting.

Fairway area surveys require an initial acoustic sounding survey. This is followed by a mechanical bar sweep, when the acoustic soundings indicate that the fairway depths are either:

- less than 150% of the minimum existing, proposed or planned underkeel clearance safety margin, including squat, or
- the underkeel clearance safety margin is less than 1m.

Order	SMA Exclusive	SMA Special	SMA 1st	SMA 2nd	SMA 3rd
Depth uncertainty for bathymetric models (95% Confidence Level)	a = 0.15m b = 0.40%	a = 0.25m b = 0.75%	a = 0.5m b = 1.3%	a = 1.0m b = 2.3%	a = 1.0m b = 2.3%
Depth range to apply order for fairway areas		0 - 20m	20 - 50m	50 - 100m	100m +
Depth range to apply order for other areas			0 - 6m	6 - 100m	100m +
Maximum depth to apply order	50m	50m	100m	100m	unlimited

Table 1.2: *The Swedish implementation of S-44*

1.6 USACE Hydrographic Manual 2001

The United States Army Corps of Engineers has published a Hydrographic Manual, containing background information, field procedures, and survey standards for Corps hydrographic projects since 1991. This document defines two categories of hydrographic surveys (intended uses):

- Navigation and dredging support surveys, including project condition surveys of navigation channels, dredging contract plans and specifications surveys, dredging measurement, payment, clearance, and acceptance surveys, and river charting surveys.

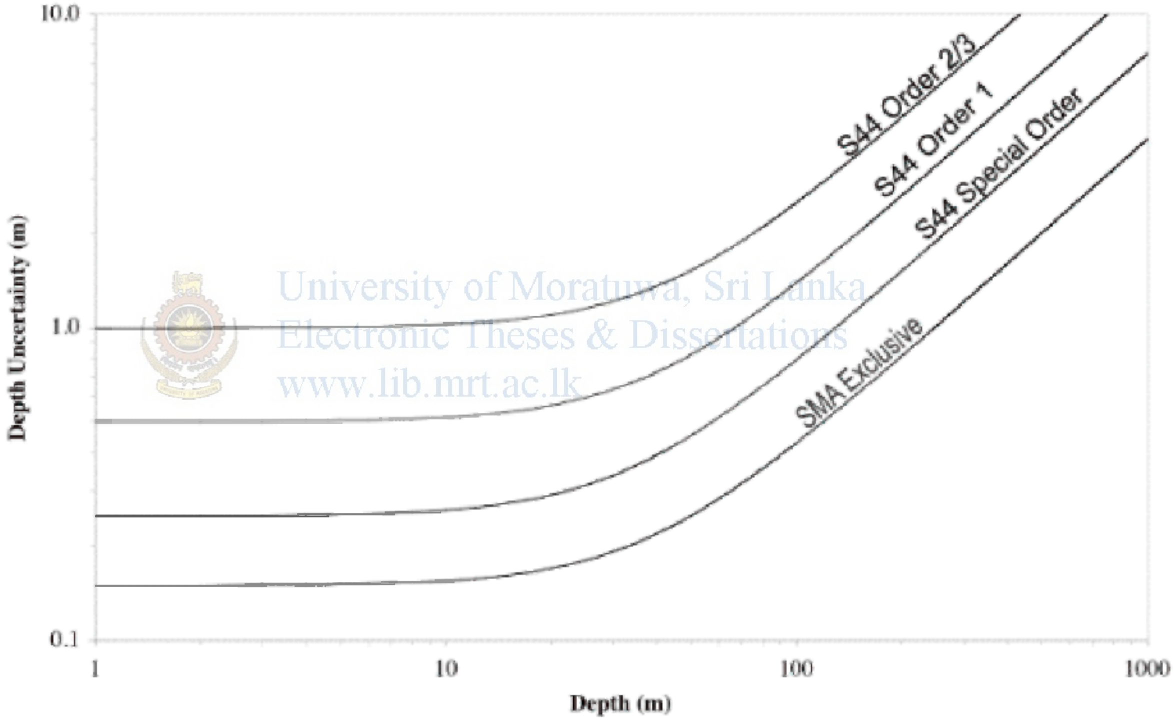

Figure 1.2: *Log-log plot of SMA implementation of S-44*

- General surveys and studies, including general reconnaissance or planning surveys/studies, flood control project surveys, reservoir sedimentation surveys, flood plain boundary surveys, hydrological and hydraulic surveys, coastal engineering surveys, beach surveys, environmental investigations, geotechnical investigations, and disposal area surveys.

Based on the following principle:

- survey instrumentation requirements, accuracy standards, and quality control procedures vary as a function of bottom type in a navigation channel; as does the required accuracy of dredge measurement and payment.

USACE navigation and dredging support surveys are further divided into three categories:

- Hard bottom material and/or new work. Navigation projects where low under-keel clearances are anticipated over potentially hazardous bottom conditions, hazardous cargo is transported, or where bottom sediment could adversely impact naval vessels transiting a project only a small number of Corps projects fall under this category.
- Soft bottom material and/or maintenance dredging. Navigation projects containing soft sand/silt bottoms not judged to be hazardous to vessel hulls; or projects with soft, featureless, and relatively continuous channel bottoms where gaps in coverage between survey lines are unlikely to yield potential hazards/strikes. The vast majority of the Corps deep- and shallow-draft navigation projects . . . fall within this category.
- Underwater investigation surveys. Precise investigation surveys of/around locks, dams, power plants, abutments, piers, jetties, bulkheads, and other structures.

The USACE depth uncertainty standards include all uncertainty components that make up a reduced elevation: uncertainties in datum, in tide/stage modelling-extrapolation-interpretation, in dynamic-latency/roll/pitch/heave, in acoustic measurement, sound speed, refraction, and beam forming, and bathymetric mis-modelling through uncertainty in horizontal positioning (depth georeferencing uncertainty). The Manual notes that mechanical and acoustic depth measurement uncertainty increases with increasing depth, that multibeam system uncertainties increase with increasing beam angle, and that tide/stage and water level surface model uncertainties will generally be smaller for shallow (<5m) projects than for deeper (>12m) projects. The USACE depth uncertainty standards are depth –dependent, but do not follow the S44 4th Edition a/b coefficient model for depth independent and depth dependent uncertainty components.

Method	**Depth**	**Nav & dredgng hard bottom**	**Nav & dredgng soft bottom**	**Other**
Mechanical	< 4.5m	a = 0.075m	a = 0.075m	a = 0.15m
Acoustic	< 4.5m	a = 0.15m	a = 0.15m	a = 0.30m
Acoustic	4.5m to 12m	a = 0.30m	a = 0.30m	a = 0.60m
Acoustic	> 12m	a = 0.30m	a = 0.60m	a = 0.60m

Table 1.3: *USACE depth uncertainty standards (2001 draft version)*

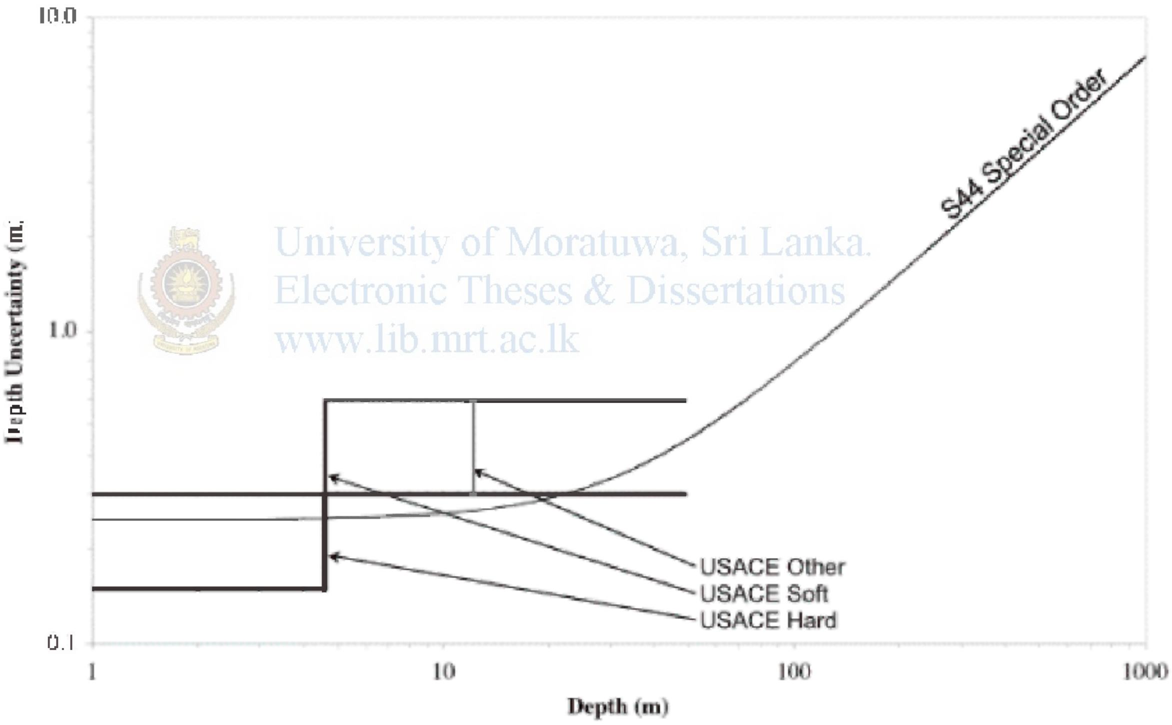

Figure 1.3: *Log-log plot of USACE standards, and S44 4th Edition Special Order*

1.6 The LINZ standard, specifically addressing MBES performance

In response to a request from Land Information New Zealand (LINZ), John Hughes Clarke, of the University of New Brunswick, prepared a set of 'Provisional Swath Sonar Survey Specifications' (Hughes Clarke, 1999) for surveys involving the use of multibeam sonar echosounders (MBES). The rationale for this project was as follows:

The [IHO S44 4th Edition] standards unfortunately contain significant ambiguity and are drafted for the sole purpose of data collection for nautical charting (a mandate much narrow than that of LINZ). One example of this broader mandate is that, as of July 1997, LINZ has taken the responsibility for New Zealand's Continental Shelf Delimitation Project. This involves the 'measurement and analysis of seabed information according to internationally agreed criteria developed by the United Nations Commission on the Law of the Sea (UNCLOS)'. Unfortunately these criteria do not include any specifications for the acquisition or delivery of data that might be acquired by MBES.

The LINZ report explains that uncertainties associated with MBES depth measurements, expressed as a percentage of water depth (coefficient 'b' in S44 4th Edition) are actually *smaller* in deep water than in shallow water. Depth-independent factors such as tide and heave, and one of the major depth-dependent factors, unstable sound velocity profiles, all have larger magnitudes in shallow (inshore) water than in deep (offshore) water. Consequently the depth uncertainties resulting from imperfect measurement/recovery of these factors, are also far more significant in shallow than in deep water. The report points out that uncertainties as small as 0.2% of water depth have been reported for deep water MBES depths. To demand only 2.3%, as specified in S44 4th Edition Order 3, ignores the capability of MBES, and is less appropriate than S44 3rd Edition, which required 1% for both shallow and deep water depth measurements.

The LINZ report also explains that MBES bottom detection, roll, and refraction uncertainties are all larger for outer beams than for inner (near nadir) beams. Bottom detection uncertainties for the inner beams of a typical MBES are in the range of 40% to 60% of the S44 4th Edition Special Order depth measurement specifications. On the other hand, bottom detection uncertainties alone will exceed the entire Special Order uncertainty limit (from all sources) for outer beams (say those with a grazing angle of less than 30°). Therefore, a MBES survey designed to meet a particular depth uncertainty standard for all beams (out to a certain outer-beam cutoff), will likely outperform that uncertainty standard significantly for the inner beam (near nadir) data.

This MBES beam-angle dependence is not addressed in S44 4th Edition. The LINZ report addresses this dependence head-on by proposing MBES depth uncertainty specifications based on the differences between inner-beam and outer-beam uncertainty performance. Rather than requiring that all depths from a MBES survey meet the same uncertainty standard, inner-beam standards are required to meet something closely related to S44 4th edition Special Order, while the outer-beam standards are more relaxed. In addition, the permitted balance between inner-beam and outer-beam coverage is allowed to relax as the survey specifications move from LINZ Special Order to LINZ Order 3.

The expected performance of a MBES is divided into several sectors, from the inner-beam sector to the outermost-beam sector. The number of sectors is allowed to increase from one to four, and the specified coverage within each sector is partitioned more generously in favour of the outer-beam sectors, as the survey order descends from Special to Order 3. Since this approach could be quite complex to design, realize and assess in practice, a simpler approach is also proposed, which is based on the performance of the worst (outer beam) sector. In each case, everything is tied to the S44 4th Edition Special Order specification, and the lower order S44 specifications are ignored. Four uncertainty levels are specified: 1.0, 1.5, 2.0 and 2.5 times the S44 4th Edition Special Order depth uncertainty specification, that is

For 1.0 x SO, a = 0.25 m, b = 0.75% of depth

For 1.5 x SO, a = 0.375 m, b = 1.125% of depth

For 2.0 x SO, a = 0.5 m, b = 1.5% of depth

For 2.5 x SO, a = 0.625 m, b = 1.875% of depth.

Order	LINZ Special	LINZ 1st	LINZ 2nd	LINZ 3rd
Depth uncertainty, by sector, for reduced depths (95% Confidence Level)	100%1.0 x SO	50%1.0 x SO 50%1.5 x SO	33%1.0 x SO 33%1.5 x SO 33%2.0 x SO	25%1.0 x SO 25%1.5 x SO 25%2.0 x SO
Depth uncertainty for worst-case sector (outer-beams) reduced depths (95% Confidence Level)	1.0 x SO	1.5 x SO	2.0 x SO	2.5 x SO

Table 1.4: *Proposed LINZ Depth uncertainty specifications*

1.7 IMCA offshore construction standards

The International Marine Contractors Association (IMCA) have adapted the S44 and LINZ standards to standards for informed decision making in offshore construction activities (IMCA, 2000). The intended uses associated with each of the four IMCA depth measurement uncertainty orders are:

- IMCA First Order - site surveys for offshore engineering, requiring high quality seafloor definition: Template or jacket installations; Detailed route engineering surveys; Route surveys in confined areas; Surveys in ports and harbours; Dredging and inshore engineering surveys
- IMCA Second Order – site surveys for offshore engineering, less stringent than First Order: Route reconnaissance surveys; Geo-Hazard and clearance surveys; Coastal engineering surveys; Deepwater geophysical and engineering surveys (conducted by remote vehicle)
- IMCA Third Order – general bathymetric surveys: Continental shelf cable route surveys; Continental shelf charting surveys; Export pipeline route surveys
- IMCA Fourth Order – Reconnaissance surveys: Deepwater cable route surveys; Deepwater charting surveys; Surveys for Exclusive Economic Zone assessments and delineation

Order	IMCA 1st	IMCA 2nd	IMCA 3rd	IMCA 4th
Depth Accuracy for Reduced Depths (95% Confidence Level)	1 x IHO SO a = 0.25 m b = 0.0075	1.5 x IHO SO a = 0.375m b = 0.01125	2 x IHO SO a = 0.5 m b = 0.015	2.5 x IHO SO a = 0.625m b = 0.01875
Maximum depth to apply order	200m	500m	750m	No maximum

Table 1.5: *Proposed IMCA Depth Measurement Uncertainty Standards*

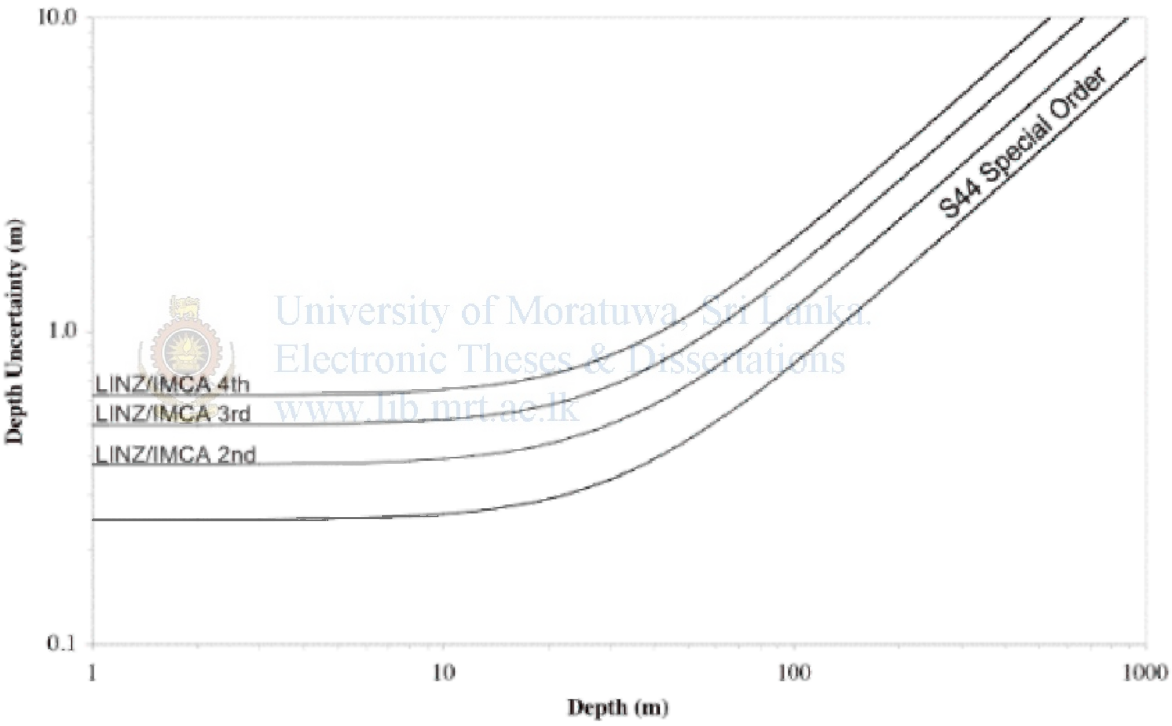

Figure 1.4: *Log-log plot of Proposed LINZ worst-case sector / IMCA depth uncertainty, and S44 4th Edition Special Order*

1.8 What's next for S44?

The IHO formally intends to reconsider S44 on a five year schedule, to account for technological and procedural improvements as they occur. Hence work on S44 5th Edition is expected to start soon. This review concludes with speculation on the issues to be dealt with by the S44 working group tasked with preparing S44 5th Edition.

Perhaps the most important issue is whether S44 5th Edition should aspire to address all intended uses for hydrographic data, as was hinted at in S44 4th Edition. As this paper has tried to demonstrate, there are many non-nautical-charting uses for hydrographic data, for which the depth uncertainty standards are quite different (often more demanding) than the standards provided by S44 4th Edition. This brief review is by no means an exhaustive survey of these other intended uses for bathymetric data.

An argument in favour of S44 5th Edition addressing all intended uses for hydrographic data, is that many Hydrographic Offices aspire to be suppliers of data/information/products to a broader clientele. It has even been argued that the survival of some HOs may depend upon cultivating a broader user base (Monahan et al, 2001). It would be appropriate for the IHO to establish data standards within S44 5th Edition which would facilitate these aspirations.

On the other hand, this approach to a new edition of S44 would require broader representation on the working group. The working group would benefit from inclusion of members involved in specifying the uncertainty requirements for several of the diverse intended uses for hydrographic data, as listed in S44 4th Edition:

Coastal zone management, environmental monitoring, resource development (hydrocarbon and mineral exploitation), legal and jurisdictional issues, ocean and meteorological modelling, engineering and construction planning.

Here are a few ideas for consideration, when work on S44 5th Edition begins:

- Consider moving S44 from a performance standard, to a document that provides guidance on how to apply the performance standard, both *a priori* for planning purposes, and *a posteriori* to determine end use (informed decision making) uncertainty.
- Recognize, as the SMA seems to have done, that the 'bathymetric model' introduced in S44 4th Edition is what both navigational and non-navigational clients want and use for

informed decision making. Place more emphasis on specifying, on methods for assessing and on methods for informing end users, of the uncertainty associated with this model, and products based upon it (in contrast to depth measurement uncertainty).

- Consider separating navigational intended uses into use for (a) certified commercial navigation, (b) uncertified commercial navigation, (c) recreational boating and (d) military operations, with uncertainty management standards specific to each category. Specify the quantity and spatial distribution of redundant measurements, as well as methods of analyzing them.
- Clarify the issue of the maximum depth to which the depth uncertainty associated with a particular order of survey should be applied. Consider removing all limits (essentially stressing that S44 represents *minimum* standards).
- Consider simplifying the relationship between the various orders of survey, by tying the depth uncertainty definitions for Orders 1, 2 and 3 to multiples of the Special Order uncertainty, as has been done in the proposed LINZ and IMCA standards.
- Reconsider depth of water column as the sole independent quality variable. For work from submerged submarines, ROVs and AUVs, depth under the sensor would be a more appropriate quality variable than depth of the water column. Accurate high resolution bathymetry is often required in deep water for marine construction surveys. Bottom slope and roughness, area ensonified and multibeam beam angle should be considered as additional quality variables.

- Consider providing guidelines for managing all three types of uncertainties (accidental, systematic and random) rather than providing a performance standard based on random uncertainties alone.

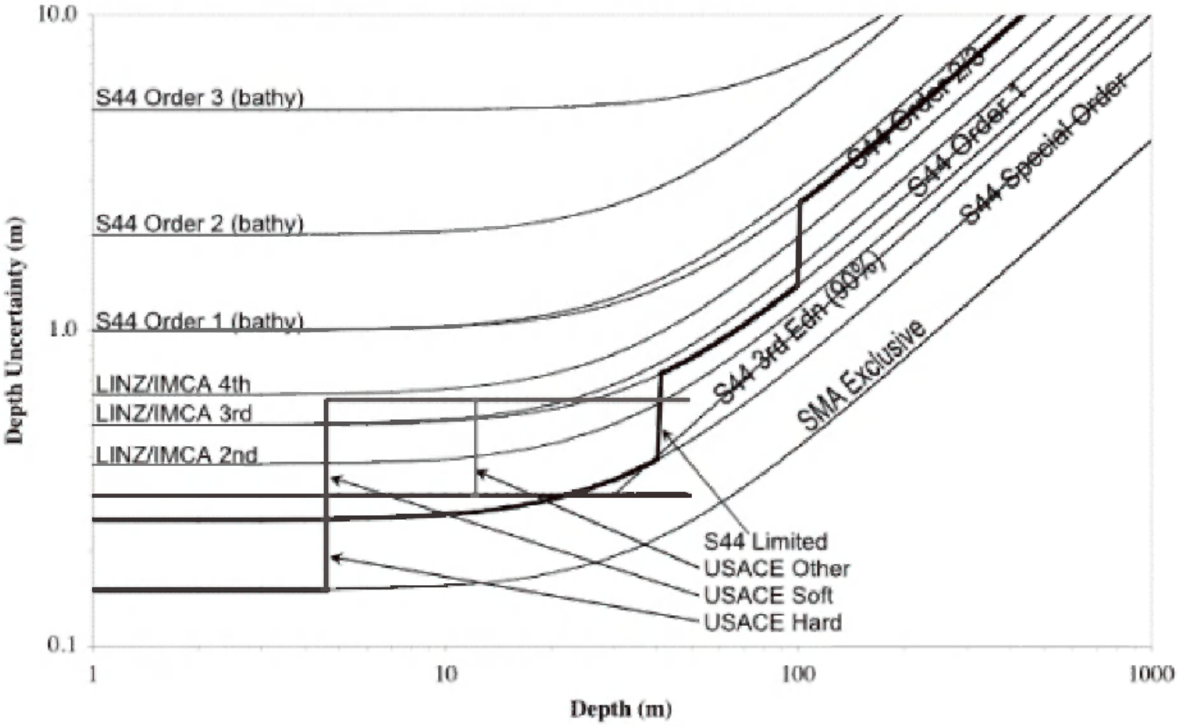

Figure 1.5: *Compilation of all depth uncertainty standards from Figures 1 to 4.*

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APPENDIX

1.0 Development Tools and Resources Required for Development

⇒ ArcView GIS Ver 3.2 with
  - Spatial Analyst Extension
  - 3D Analyst for better enhancement at User-End

⇒ Surfer Ver 7.0 or Above

⇒ Microsoft Visual Studio as Integrated Development Environment with C++ functionality with Win 32 API through Microsoft Foundation Classes

⇒ Complete Reference of (For the initial Development)
  - Visual C++ MFC Classes
  - Avenue for ArcView GIS Engine
  - Avenue for Spatial Analyst

2.0 Sample Program Listing: Using C++

Listing 2.1

```
int Celerity_Generation(int T)
{
double D,L,C,G,K,Ks;
int i,j;
char WBuff[80];
char DValue[20];

FILE *fc;
FILE *fL;
FILE *fKs;

fc = fopen("d:\\temp\\cport2.asc","w");
fL = fopen("d:\\temp\\Lport2.asc","w");
fKs = fopen("d:\\temp\\Ksport2.asc","w");

if((fc!=NULL) && (fL != NULL) && (fKs != NULL))
{
strcpy(WBuff,"ncols         500\n");
fputs(WBuff,fc);
strcpy(WBuff,"nrows         500\n");
fputs(WBuff,fc);
```

```
strcpy(WBuff,"xllcorner     0\n");
fputs(WBuff,fc);
strcpy(WBuff,"yllcorner     0\n");
fputs(WBuff,fc);
strcpy(WBuff,"cellsize      0.38\n");
fputs(WBuff,fc);
strcpy(WBuff,"NODATA_value  -9999\n");
fputs(WBuff,fc);

strcpy(WBuff,"ncols         500\n");
fputs(WBuff,fL);
strcpy(WBuff,"nrows         500\n");
fputs(WBuff,fL);
strcpy(WBuff,"xllcorner     0\n");
fputs(WBuff,fL);
strcpy(WBuff,"yllcorner     0\n");
fputs(WBuff,fL);
strcpy(WBuff,"cellsize      0.38\n");
fputs(WBuff,fL);
strcpy(WBuff,"NODATA_value  -9999\n");
fputs(WBuff,fL);
strcpy(WBuff,"ncols         500\n");
fputs(WBuff,fKs);
strcpy(WBuff,"nrows         500\n");
fputs(WBuff,fKs);
strcpy(WBuff,"xllcorner     0\n");
fputs(WBuff,fKs);
strcpy(WBuff,"yllcorner     0\n");
fputs(WBuff,fKs);
strcpy(WBuff,"cellsize      0.38\n");
fputs(WBuff,fKs);
strcpy(WBuff,"NODATA_value  -9999\n");
fputs(WBuff,fKs);

            for(i=0;i < 500;i++)
            {
                        for(j=0;j < 500;j++)
                        {
                                    D = Zzone[i][j];
                                    if(D > 0.0)
                                    {
                      if( (D/9.81/ pow(T,2) ) > 0.08)
                                                            C = (9.81 * pow(T,2) / 2 / pi)/T;
                      else if( ((D/9.81/ pow(T,2)) >   0.0025 ) && ((D/9.81/ pow(T,2)) <   0.08))
                                          {
                        //cout<<"Entered transition zone"<<endl;
                                                                                                      for(L = (9.81*pow(T,2)
/2/pi);fabs(L - (9.81 * pow(T,2) /2/pi * tanh(2 * pi * D/L))) > 0.00001;L = 9.81 * pow(T,2) /2/pi * tanh(2 * pi * D/L));
                                                            C = L / T;
                                          }
                      else if((D/9.81/ pow(T,2) ) < 0.0025)
```

```
                                        {
                          C = pow(9.81 * D,0.5);
                                        }
                                        else C = -9999;
                              }
                              else
                                        C = -9999;
                              //cout<<C<<endl;
                              strcpy(WBuff,gcvt(C,6,DValue));
                              c[i][j] = C;
                              fputs(WBuff,fc);
                              strcpy(WBuff," ");
                              fputs(WBuff,fc);
                              if(C != -9999.0)
                                        L = C * T;
                              else
                                        L = -9999;
                              strcpy(WBuff,gcvt(L,6,DValue));
                              fputs(WBuff,fL);
                              strcpy(WBuff," ");
                              fputs(WBuff,fL);
                              if(C != -9999.0)
                              {
                                        K = 2 *pi / L;
                                        G = 1 + (2 *K *D /sinh(2 *K *D));
                                        Ks = 1 / pow(tanh(K* D) * ( 1 + G),0.5) ;
                              }
                              else Ks = -9999;
                              strcpy(WBuff,gcvt(Ks,6,DValue));
                              fputs(WBuff,fKs);
                              strcpy(WBuff," ");
                              fputs(WBuff,fKs);
                    }
                    strcpy(WBuff,"\n");
                    fputs(WBuff,fc);
                    strcpy(WBuff,"\n");
                    fputs(WBuff,fL);
                    strcpy(WBuff,"\n");
                    fputs(WBuff,fKs);
                    cout<<i<<" Row completed"<<endl;
          }
                    fcloseall();
                    return 1;
}
else return 0;
}
```

Listing 2.2

```
int alpha_Generation(double AlphaInit)
{
double D,L,PrevC,PrevAlpha,alpha,G,K,Kr;
int i,j;
char WBuff[80];
char DValue[20];
FILE *falpha,*fKr;

falpha = fopen("d:\\temp\\aport2.asc","w");
fKr = fopen("d:\\temp\\krport2.asc","w");

if(falpha!=NULL)
{
strcpy(WBuff,"ncols        500\n");
fputs(WBuff,falpha);
strcpy(WBuff,"nrows        500\n");
fputs(WBuff,falpha);
strcpy(WBuff,"xllcorner    0\n");
fputs(WBuff,falpha);
strcpy(WBuff,"yllcorner    0\n");
fputs(WBuff,falpha);
strcpy(WBuff,"cellsize     0.38\n");

fputs(WBuff,falpha);
strcpy(WBuff,"NODATA_value -9999\n");
fputs(WBuff,falpha);
strcpy(WBuff,"ncols        500\n");
fputs(WBuff,fKr);
strcpy(WBuff,"nrows        500\n");
fputs(WBuff,fKr);
strcpy(WBuff,"xllcorner    0\n");
fputs(WBuff,fKr);
strcpy(WBuff,"yllcorner    0\n");
fputs(WBuff,fKr);
strcpy(WBuff,"cellsize     0.38\n");
fputs(WBuff,fKr);
strcpy(WBuff,"NODATA_value -9999\n");
fputs(WBuff,fKr);

        for(j=0;j < 500;j++)
        {
                PrevAlpha = AlphaInit;
                PrevC = c[0][j];
                for(i=0;i < 500;i++)
                {
                        D = Zzone[i][j];
                        if((D > 0.0) && (PrevC != -9999.0))
                        {
```

```
                alpha = asin(c[i][j] / PrevC * sin(PrevAlpha));
                Kr = pow(cos(PrevAlpha)/cos(alpha),0.5);
                PrevAlpha = alpha;
                PrevC = c[i][j];
                    }
            else
            {
                alpha = -9999;
                Kr = -9999;
            }
            Alpha[i][j] = alpha;
            kr[i][j] = Kr;
        }
    }
    for(i=0;i<500;i++)
    {
        for(j=0;j<500;j++)
        {
            strcpy(WBuff,gcvt(Alpha[i][j],6,DValue));
            strcpy(WBuff,gcvt(kr[i][j],6,DValue));
            fputs(WBuff,falpha);
            fputs(WBuff,fKr);
            strcpy(WBuff," ");
            fputs(WBuff,falpha);
            fputs(WBuff,fKr);
        }
        strcpy(WBuff,"\n");
        fputs(WBuff,falpha);
        fputs(WBuff,fKr);
        cout<<i<<"  column completed"<<endl;
    }
        fcloseall();
        return 1;
}
else return 0;
}
```

Listing 2.3

```
char *FgetS(char *SdeS,int No_Ch,FILE *FR)
{
char ch;
int No_Char = 0;
ch = fgetc(FR);
while((ch!=EOF)&&(ch!='\n')&&(No_Char<No_Ch))
{
*(SdeS + No_Char) = ch;
ch=fgetc(FR);
No_Char++;
}
*(SdeS + No_Char) = '\0';

if(ch==EOF)
Ret = NULL;
else if(ch == '\n')
Ret = SdeS;
return Ret;
}

char *StrChopCol(char *S)
{
static int StartPos = 0;
static int times=0;
static int i=0;
static char *Word;
        for(;*(S+StartPos)==' ';StartPos++);
        for(i=0;(*(S + StartPos + i)!=' ')&&(*(S + StartPos + i)!='\n');i++);
        times++;
        Word =(char*)malloc(i+3);
        if(Word!=NULL)
        {
        strncpy(Word,S+StartPos,i);
        StartPos = StartPos + i;
        *(Word + i) = '\0';
        }
        if (times == nCols)
        {
                StartPos=0;
                times = 0;
                i = 0;
        }
        return Word;
}
```

Listing 2.4

```
int File_Ch_Count(char *File_Name)
{
        FILE *fr;
        char ch;
        int No_Char_Line;
        int max=0;
        fr = fopen(File_Name,"r");
        if(fr == NULL)
        {
                cout<<"File Opening Error.."<<endl;
                return -1;
        }
        ch = fgetc(fr);
        while(ch!=EOF)
        {
                No_Char_Line = 0;
                while((ch!='\n') && (ch!=EOF))
                {
                        No_Char_Line ++;
                        ch = fgetc(fr);
                }
                if(ch == '\n') ch = fgetc(fr);
                if(No_Char_Line > max) max = No_Char_Line;
        }
        fcloseall();
        return max;
}
```

Listing 2.5

```
int Data_Extractor(void)
{
        int nRows,xCorner,yCorner;
        int No_Rows = 0,i;
        float CellSize;
        int No_Char_Line;
        char *Mem_Line;
        char *Ret_Fgets;
        char dest[80];
        char *ChoppedV;
        char Enter;
        FILE *fr;
```

```
No_Char_Line = File_Ch_Count("d:\\temp\\xport2.asc");
Mem_Line = (char *)malloc(No_Char_Line + 3);

            if(Mem_Line == NULL)
            return -1;
else
{
            cout<<"Memory Success"<<endl;
            fr = fopen("d:\\temp\\xport2.asc","r");
            if(fr == NULL)
            {
                        cout<<"File Opening Error.."<<endl;
                        return -1;
            }

Ret_Fgets = FgetS(Mem_Line,No_Char_Line + 2,fr);
            nCols = atoi(strcpy(dest,Mem_Line + 6));
            cout<<nCols<<endl;
Ret_Fgets = FgetS(Mem_Line,No_Char_Line + 2,fr);
            nRows = atoi(strcpy(dest,Mem_Line + 6));
            cout<<nRows<<endl;

Ret_Fgets = FgetS(Mem_Line,No_Char_Line + 2,fr);
            xCorner = atoi(strcpy(dest,Mem_Line + 10));
            cout<<xCorner<<endl;
Ret_Fgets = FgetS(Mem_Line,No_Char_Line + 2,fr);
            yCorner = atoi(strcpy(dest,Mem_Line + 10));
            cout<<yCorner<<endl;
Ret_Fgets = FgetS(Mem_Line,No_Char_Line + 2,fr);
            CellSize = atof(strcpy(dest,Mem_Line + 9));
            cout<<CellSize<<endl;
      *Mem_Line = '\0';
Ret_Fgets = FgetS(Mem_Line,No_Char_Line + 2,fr);
      *Mem_Line = '\0';

Ret_Fgets = FgetS(Mem_Line,No_Char_Line + 2,fr);
            while(Ret_Fgets != NULL)
            {
                        for(i=0;i<nCols;i++)
                        {
                        ChoppedV = StrChopCol(Mem_Line);
                        if(ChoppedV!=NULL)
                        {
                                    Zzone[No_Rows][i] = atof(ChoppedV);
                        }
                        else
                        {
                        cout<<"Memory Error.."<<endl;
                        return -1;
                        }
```

```
                        free(ChoppedV);
                        }
                        //No_Rows = 0;
                        *Mem_Line = '\0';
                        Ret_Fgets = FgetS(Mem_Line,No_Char_Line + 2,fr);
                        No_Rows += 1 ;
                        //
                        //No_Rows = No_Rows % nRows;
                }

        free(Mem_Line);
        cout<<"File Display Finished"<<endl;
        }
                Celerity_Generation(8);
                alpha_Generation(45 * pi / 180);
return 0;
}
```