5 Depth Sounding

Depths shall be recorded in meters, with a precision of at least centimeters. This precision shall be maintained throughout the processing pipeline and be maintained in the digital data.

Depths reported in the Descriptive Report (DR), other reports or correspondence should be rounded to the nearest centimeter and have the associated Total Propagated Uncertainty (TPU) (or Total Propagated Error (TPE) as it is often referred to) of the depth listed to the nearest centimeter.

Certain projects may require the use of single beam echosounder data. Gridding requirements for single beam data are included in section 5.1.1.3

5.1 Multibeam and Other Echosounders

Many SOWs or Hydrographic Project Instructions require the use of multibeam echosounders for NOS Hydrographic Surveys however there are occasions where there may be a requirement for single beam or in the future Phase Differencing Bathymetric Systems. Therefore, NOS Specifications, listed in section 5.1 and all its subsections, will refer to multibeam echosounders unless otherwise specified.

5.1.1 Accuracy and Resolution Standards

As mentioned in Section 1, the NOS Specifications are partly based on the IHO Standards for Hydrographic Surveys as outlined in Special Publication 44 (S-44). IHO S-44 specifications are suggested minimum standards that member states may choose to follow. The IHO minimum standards for accuracy are used in the NOS Specifications as a convenient point of reference. When the NOS Specifications refer to an IHO Order, it is usually in terms of the final accuracy of a measurement. No other claim for "meeting" an IHO Order survey is implied.

In the future, NOS Specifications will only define the requirements for grid accuracy and grid resolution, subjects not covered in the current version of S-44 (5th Edition, February 2008). As an interim step, sounding accuracy is still defined in the NOS Specifications, in addition to grid requirements.

5.1.1.1 Accuracy Standards NOS standards for the accuracy of measured depths in hydrographic surveys apply to the systematic measurement of general water depths and to the least depths determined over wrecks and obstructions. By extension, they also apply to the elevations of rocks or other features which uncover at low water and to the measurement of overhead clearances. These standards apply regardless of the method of determination; whether by single beam echosounder, multibeam echosounder, lead line or diver investigation.

The total sounding error in a measured depth at the 95 percent confidence level, after systematic and system specific errors have been removed, shall not exceed:

$$\pm\sqrt{a^2 + (b \star d)^2}$$

where in depths less than 100 meters, a = 0.5 meters and represents the sum of all constant errors, (b * d) represents the sum of all depth dependent errors, b = 0.013 and is a factor of depth dependent error, and d is depth (in meters) (IHO S-44, Order 1).

In depths greater than 100 meters, a =1.0, b=0.023, d=depth (IHO S-44, Order 2).

The maximum allowable error in measured depth includes all inaccuracies due to residual systematic and system specific instrument errors; the speed of sound in water; static vessel draft; dynamic vessel draft; heave, roll, and pitch; and any other sources of error in the actual measurement process, including the errors associated with water level (tide) variations (both tidal measurement and zoning errors).

5.1.1.2 Multibeam Resolution Standards The ability to detect objects is a function of the beam width, beam foot print on the seafloor, bottom detection algorithms, and the spacing of soundings on the seafloor, both across track and along track. The feature detection capabilities of the multibeam equipment shall be consistent with the coverage requirements in section 5.1.2. Along track coverage is also dependent on the sounding ping rate and the speed of the survey vessel. To ensure proper along track coverage, the hydrographer shall ensure that vessel speed is adjusted so that no less than 3.2 beam footprints, center-to-center, fall within 3 m, or a distance equal to 10 percent of the depth, whichever is greater, in the along track direction.

5.1.1.3 Gridded Data Specifications In the Navigation Surface approach, survey data are archived as a certified digital terrain model rather than as a set of verified soundings. While the elevation model may be archived at the highest resolution supported by the sounding data, HSD has determined that the highest resolution possible is rarely needed for navigation products. A compromise grid resolution between the highest resolution possible and a resolution required for navigation products has the advantage of preserving high-resolution data for posterity without needlessly burdening NOAA field units and contractors. The end product of creating a nautical chart is then created from scale-appropriate generalizations of the Navigation Surface elevation model.The Navigation Surface requires that each sounding have a horizontal and vertical uncertainty. To do this effectively, an error model is needed for all systems supplying measurements to compute the sounding; including not only the multibeam echosounder, but the GPS sensors, the heave, pitch, and roll sensors, the sound speed measuring devices, tide gauges, draft measurements, dynamic draft, and anything else that contributes to the calculation of a sounding. Once this comprehensive error model is assembled, then all the inherent errors in each measurement can be propagated from the measurement platform to each individual sounding. Only when each sounding has an associated Total Propagated Uncertainty (TPU), can we combine the soundings into a Navigation Surface with each node having a depth and uncertainty attribute.

Currently, the open source Bathymetric Attributed Grid (BAG) standard format does not include support for multi-resolution grids. The BAG format was developed to create an open source exchange format for gridded data. The Open Navigation Surface Working Group (ONSWG) was formed to develop the format. ONSWG is comprised of government and private sector groups. The primary goals of the ONSWG are to define an open, platform independent, grid database file format suitable for access, archival, and interchange of Navigation Surface results, and to develop an open source software access library to operate on this format. For more information see `http://www.opennavsurf.org`. The CARIS Bathymetry with Associated Statistical Error (BASE) surface has multi-resolution functionality; however, it is not presently approved for NOAA surveys. Therefore, the survey area will typically be required to be subdivided into several grids of varying resolution dependent on depth.

The hydrographer may adjust these values based on the bathymetry of the survey area, the type of multibeam sonar used and other factors. However, adjacent grids shall always overlap in depth to ensure no gaps in coverage exist at the transition from one depth grid to another.

The hydrographer shall also consider the size of objects that they are attempting to detect. Typically, a grid must have twice the resolution of the object (i.e. a 1 meter grid would be required to properly depict a 2 meter cube).

The hydrographer has the responsibility to review the surface and ensure that it truly reflects the conditions in the survey area. No algorithm will ever perfectly model the seafloor. Especially in the case of small diameter objects (pilings, small rocks, etc.), depending on the resolution of the gridded surface, it is unlikely that the surface will capture the absolute least depth on all features. An experienced hydrographer, therefore, must review the data and occasionally select "designated" soundings which override the gridded surface and force the model to recognize the shoal sounding.

Designated Soundings In depths less than 30 meters, a designated sounding should be selected when the difference between the gridded surface and reliable shoaler sounding(s) are more than one-half the allowable IHO error budget for the depth, for navigationally significant features/areas. For instance, a rock on a steep slope should not be selected if the hydrographer determines it is a navigationally significant feature based on the vessel traffic in the area.

In depths greater than 30 meters, a designated sounding should be selected when the difference between the gridded surface and reliable shoaler sounding(s) are more than the allowable IHO error budget for the depth.

Additional designated soundings may be selected by the hydrographer as deemed necessary.

Conversely, if noisy data, or 'fliers' are incorporated into the gridded solution, the surface may be shoaler than the true seafloor. In such cases the spurious soundings will need to be rejected and the surface recomputed. Therefore, if noisy data causes the surface to be shoaler than expected by an amount greater than the IHO error budget for depth, then the noisy data shall be rejected and the surface recomputed.

If an excessive number of designated soundings need to be selected, the hydrographer may need to reassess the grid resolution of the surface. If the data supports a higher resolution grid, the resultant surface may model the seafloor more accurately and result in fewer designated soundings being required. In some cases, often in rocky nearshore areas, the least depths of many features in a relatively small area may fail to be preserved, even by very high resolution BASE surfaces. In these instances the hydrographer shall designate the least depths on the shoalest features. See section 8.1.2 for guidance on delineating and characterizing this rocky seabed area.

Uncertainty By definition each node of the grid includes not only a depth value, but other attributes including "uncertainty". The uncertainty value for the grid shall be the greater of the standard deviation and the a priori uncertainty at each node. The hydrographer shall include a discussion in the DAPR on how the uncertainty was computed on each individual sounding and how the uncertainty was computed on the grid, with a justification for that methodology.

The hydrographer shall examine the finalized grids and explain in the DR any areas of unusually high uncertainty.

5.1.2 Coverage

In general, there are three classifications of multibeam coverage: Object Detection Coverage, Complete Coverage and Set Line Spacing. The survey coverage technique will be specified in the Statement of Work. Field operations shall be conducted such that the accuracy requirements in Section

5.1.1 are met for the entire multibeam coverage area and the multibeam is operated as stated in section 5.1.1.2.

In some cases a hybrid coverage technique may be used, such as, 100% side scan with Complete Multibeam Coverage. The requirements for any assigned hybrid coverage will be described in the Statement of Work or Project Instructions. If single beam and multibeam are specified in the Hydrographic Survey Project Instructions or Statement of Work and they both fall in a common area, then a separate single beam surface is required.

These requirements shall be followed by contractors unless stated otherwise in the SOW or an exemption is approved by the COTR. NOAA field units shall refer to the Project Instructions for specifics. Any deviations from the requirements shall be discussed in the Descriptive Report and NOAA field units shall notify HSD Operations.

The experienced hydrographer should use discretion when using the following gridding requirements described in sections 5.1.2.1, 5.1.2.2, and 5.1.2.3. If the required resolution of the grid for an area does not seem appropriate, the hydrographer should notify HSD or the appropriate COTR to discuss exceptions to the gridding specifications and recommend alternate gridding resolutions. The discussion should occur early in the data acquisition phase of the project, in case the exception is not agreed upon. For instance, a very narrow high resolution grid along shore in a "steep and deep" fjord serves no purpose. Also, object detection coverage gridding specifications may not be necessary areas where object detection requirements are met by side scan sonar or other technologies (and where objects found have an accurate least depth determined with an appropriate echosounder).

5.1.2.1 Object Detection Coverage

- Detect and include in the grid bathymetry all features measuring at least 1m x 1m x 1m in waters up to 20 meter deep, and a cube measuring 5% of the depth in waters 20m and deeper.
- Grid resolution shall be 0.5m in waters less than 20m deep, and approximately 5% of the water depth in waters 20m and deeper.
- The maximum propagation distance of soundings to node shall be one grid resolution or approximately 4% of depth, whichever is greater.
- At least 95% of all nodes on the surface shall be populated.
- For depths up to 30m no holiday spanning more than 3 nodes; for depths deeper than 30m,hydrographer's discretion shall be used, notwithstanding any violation of other coverage requirements.
- No holidays over tops of potentially significant features.
- An example of grid-resolution thresholds as a function of depth range:

Depth Range (m)	**Resolution (m)**
0 – 23	0.5
20-30	1
27-52	2
46-115	4
103-350	8
350+	16

5.1.2.2 Complete Multibeam Coverage

- Detect and include in the grid bathymetry from all features measuring 2m x 2m horizontally, and 2m vertically in waters less than 20m deep
- Detect features 10% of depth horizontally and approximately 5% vertically in waters above 20m.
- Grid resolution shall nominally be 1m in waters less than 20m deep, and approximately 5% of the water depth in waters 20m and deeper. Coarser resolutions may be warranted in certain areas due to bottom topography ("steep and deep"), or if side scan data is also collected, or other project specific reasons. However, there is rarely a circumstance where the depths encountered are deep enough to warrant the use of grid resolutions greater than 10m. The coarsest resolution shall be 8m for areas with depths up to 350m and a 16m resolution for areas with depths greater than 350m.
- Maximum propagation distance of soundings to node shall be one grid resolution or approximately 20% of depth, whichever is greater.
- At least 95% of all nodes on the surface shall be populated.
- No holiday spanning more than 3 nodes in waters less than 30m; for depths deeper than 30m, hydrographer's discretion shall be used, notwithstanding any violation of other coverage requirements.
- No holidays over tops of potentially significant features.
- All significant shoals or features found in waters less than 30m deep shall be developed to Object Detection standards or designate soundings from nadir beam developments.
- An example of grid-resolution thresholds as a function of depth range

Depth Range (m)	Resolution (m)
0-23	1
20-52	2
46-115	4
103-350	8
350+	16

5.1.2.3 Set Line Spacing The hydrographer shall conduct multibeam and single beam operations at the line spacing specified in the Hydrographic Survey Project Instructions or Statement of Work. For example, set line spacing may be employed in the following scenarios: (1) when acquiring multibeam data concurrently with side scan sonar operations (sometimes referred to as "skunk-stripe" coverage, where the side scan swath is wider than the multibeam swath) and 2) when acquiring single beam data in areas that are too shallow or efficient multibeam operations, or otherwise too risky of an area to use multibeam equipment.

- For multibeam operations the requirements are the same within the swath, as for Complete Coverage above. Note: that in a "skunk striping" scenario (see above) elements of object detection area also in operation, due to side scan sonar data coverage and any associated contact scanning requirments.

- For single beam operations the resolution of the single beam grid should be at least between 2m to 5m and be multiples of any overlapping multibeam grids set such that the geometry is in alignment.
- Splits between set line spacing shall be acquired for both multibeam and single beam hydrography to adequately define shoals and to verify currently-charted soundings that are shoaler than any adjacent limits of echosounder coverage.

5.1.3 Corrections to Echo Soundings

To meet the accuracy and resolution standards for measured depths specified in Section 5.1.1, and to create a BAG that includes an accurate uncertainty layer, the hydrographer should conduct an error analysis of their survey systems.

Precise measurements are fundamental to the field of hydrography. Synchronization of multiple sensors with the sonar system is essential for meaningful spatial analysis of the data. All measurements, however careful and scientific, are subject to some uncertainties. Error analysis is the study and evaluation of these uncertainties with the purpose of estimating the extent of the uncertainties and when necessary, reducing them.

Uncertainty-based processing has fundamentally altered bathymetric data processing and product creation. The validity and usefulness of the results are directly correlated to the accuracy of the individual estimates that compose the error model. The error model for CARIS contains uncertainties associated with the sensor and sonar, physical offsets, latency, draft, loading, sound speed and tide and tidal zoning (NOAA field units may refer to section 4.2.3.6 of the OCS Field Procedures Manual for more information). Non-CARIS users must build a similar model of all the correctors to the depth measurement and the associated uncertainties.

In recognition of the possibility that some discrepancies in sounding may not be detected until the final processing phase of the survey, the determination and application of corrections to echo soundings must be accomplished and documented in a systematic manner. In addition, it is preferable that all corrections be applied in such a way that the on-line values may be removed and replaced with a revised set of correctors during office processing. Corrections to echo soundings are divided into five categories, and listed below in the sequence in which they are applied:

Instrument error corrections account for sources of error related to the sounding equipment itself.

Draft corrections shall be added to the observed soundings to account for the depth of the echosounder transducer below the water surface.

Dynamic draft corrections shall be applied to soundings to correct the vertical displacement of the transducer, relative to its position at rest, when a vessel is underway.

Speed of sound corrections shall be applied to soundings to compensate for the fact that echosounders may only display depths based on an assumed sound speed profile while the true speed may vary in time and space.

Attitude corrections shall be applied to multibeam soundings to correct the effect of vessel motion caused by waves and swells (heave, roll, pitch) and the error in the vessel's heading

5.1.3.1 Instrument Error Corrections

In modern digital sounding instruments, instrument errors are generally small and of a fixed magnitude independent of the observed depth. Proper set up and adjustment of digital sounding equipment using internal checks and echo simulators will often eliminate instrument error entirely. However, to ensure the proper operation of echosounders, "confidence checks" shall be conducted periodically.

For single beam echosounders, a comparison should be made at least once per week with depths from bar checks, lead lines, or other single beam echosounders.

For multibeam echosounders, comparisons should be made at least once per week between the nadir (vertical) beam of the multibeam and a single beam system or lead line. On surveys where multiple vessels collect data that overlaps with each other to allow comparison of depths, the frequency of formal confidence checks can be reduced to once per survey. In addition, frequent checks should be made between the overlap of mainscheme and crosslines collected on different days. These comparisons should be made frequently during data collection to find errors promptly, and not saved until final data processing after the field party has left the working grounds.

Comparisons should be conducted during calm sea conditions, preferably in areas with a relatively flat sandy bottom. Any differences should be investigated, and if, after analysis, a corrector is necessary, it should be applied with an explanation of the cause of the difference explained in the Descriptive Report (DR) section B.2, Quality Control.

5.1.3.2 Draft Corrections

The corrections for draft account for the depth of the transducer reference point below the surface of the water. Draft corrections comprise a value for the draft of the vessel at rest, sometimes known as static draft, and settlement corrections which compensate for the variation in draft that occurs when the vessel is making way. The sum of the static draft and the settlement and squat correctors is known as the dynamic draft. Draft is transducer-specific. When more than one transducer is fixed to a vessel, the hydrographer must exercise care to apply the proper draft correction for each transducer. In addition to the draft values, to complete the vessels' error model, the hydrographer must determine the uncertainty associated with all draft values.

Static Draft The static draft, as an echo-sounding correction, refers to the depth of the transducer reference point below surface of the water when the vessel is not making way through the water. The required frequency of static draft measurements depends upon the range of variation in the vessel draft and the depths of water to be surveyed. For depths of 30 m or less, the static draft shall be observed and recorded to at least the nearest 0.1 m. Measurements are required with sufficient frequency to meet this criterion. When sounding in waters deeper than 30 m, the static draft shall be observed and recorded to at least the nearest 0.2 m.

Draft values for small vessels such as survey launches should be determined for the range of loading conditions anticipated during survey operations (maximum and minimum). Draft values for larger vessels must be observed and entered into the record before departing from and upon returning to port. In both cases, the draft should be determined by averaging the max/min or beginning/ending values if the differences do not exceed ±0.2 m. Otherwise, the applicable draft should be determined in at least 0.1 m increments. If significant changes to a vessel's draft (greater than ±0.1 m) occur, draft values shall be modified and applied accordingly.

Loading and static draft uncertainties typically represent a small percentage of the total error budget. However, the accuracy of the error model and the results of BAG surface processing are dependent on knowledge of all the uncertainty values that compose the model.

Dynamic Draft Transducers are generally displaced vertically, relative to their positions at rest, when a vessel is making way. Depth measurements are correspondingly affected by these vertical displacements. The displacements may be of sufficient magnitude to warrant compensation, especially when sounding at moderate to high speeds in shoal water. The factors accountable for this vertical displacement are called settlement. Major factors that influence dynamic draft are hull shape, speed, and depth of water beneath the vessel.

Settlement is the general difference between the elevations of a vessel when at rest and when making way. For lower speed, non-planing vessels, settlement is caused by a local depression of the water surface. Settlement is not an increase in the vessel displacement and, therefore, cannot be determined by reference to the water surface in the immediate vicinity. Vessels surveying at higher speeds may experience a negative settlement, or lift, when planning.

Squat refers to changes in trim of the vessel when making way and is generally manifested by a lowering of the stern and rise of the bow. Occasionally, the bow lowers on smaller vessels. Squat does not appreciably affect transducer depth on transducers mounted near amidships. Settlement, on the other hand, is almost always significant at normal sounding speeds, regardless of transducer location.

If a Heave-Roll-Pitch (HRP) sensor is used to determine changes in squat, care must be taken to ensure that squat is not corrected for twice. Conversely, if attitude corrections are not used in single beam data processing, the dynamic draft correction must include any appreciable effects due to vessel trim.

Combined effects of dynamic draft at the full range of sounding speeds must be determined to at least 0.05 meter precision, by the hydrographer at least once a year for each vessel, including launches and skiffs used for hydrographic surveying in shoal or moderate depths. Follow up measurements should be made if there are any major changes to the loading or change to the vessel power plant. When the measurements are made, each vessel should carry an average load and have an average trim. Sounding vessel speeds (or RPM) must be entered in the hydrographic records during survey operations to permit accurate corrections for dynamic draft.

The uncertainty value for Dynamic Draft will be dependent on the method that Dynamic Draft was calculated. Typically, several runs at various speeds will be used to calculate the Dynamic Draft. The uncertainty value could then be the standard deviation calculated for each speed measurement.

5.1.3.3 Speed of Sound Corrections

Special note: Sound Speed or Speed of Sound is sometimes incorrectly referred to as sound velocity in other publications and equipment literature.

General To ensure that the overall depth measurement accuracy criteria specified in Section 5.1.1 are met, speed of sound observations should be taken with sufficient frequency, density, and accuracy. The accuracy with which the speed of sound correction can be determined is a complex function of the accuracy with which salinity, temperature, and depth, or alternately, sound speed and depth, can be measured.

The speed of sound through water shall be determined using instrumentation capable of producing sound speed profiles with errors no greater than 2 meters per second. The sound speed profile must reach the deepest depths of the survey but the physical measurement of sound speed need only extend to:

- 95 percent of the anticipated water depth in 30 m or less of water. For example, if the maximum depth to be surveyed is 25 m, then the speed profile should continue to a depth of at least 23.8 m.

- 90 percent of the anticipated water depth in depths from 30 m to 100 m.
- 85 percent of the anticipated water depth in greater than 100 m of water.

Sound speed correctors must be determined accurately and often enough to ensure that the depth accuracy requirements in Section 5.1.1 are met. If changes in the temperature or salinity in the water column dictate that updated correctors are needed, additional sound speed profiles shall be acquired. Additionally, the hydrographer should establish a means of monitoring changes in the water column between subsequent speed casts.

Regardless of the sound speed determination system employed, an independent sound speed measurement system must be used to establish a confidence check. Confidence checks shall be conducted at least once per week. Include confidence check results in Separate II, Sound Speed Profile Data (see Section 8.1.3.).

A geographic distribution of profiles may be necessary to correct for spatial and diurnal variability. Speed corrections shall be based on the data obtained from the profile, and not based on an averaged sound speed reading for the water column. Survey specific sound speed information shall be included in Separate II, Sound Speed Profile Data (see Section 8.1.3 Descriptive Report Supplemental Records).

The hydrographer shall calibrate sound speed profiler(s) no earlier than six months prior to the commencement of survey operations. Calibration correctors shall be applied to all profiler data. These instrument(s) shall be re-calibrated at intervals no greater than twelve months until survey completion. In addition, the instrument(s) must be re-calibrated when the survey is complete if the completion date is later than six months from the date of last re-calibration. Copies of calibration data shall be included in Separate II, Sound Speed Profile Data (see Section 8.1.4 Descriptive Report Supplemental Records), separates to be included with the survey data.

Sound Speed Corrections for Single Beam Surveys For each individual area identified, a minimum of at least one cast each week, taken in the waters surveyed that week, is required. The variation of physical conditions throughout a survey area or any portion thereof may dictate that this minimum may not be sufficient. Where casts taken early in a project indicate that physical characteristics are extremely variable, observations of speed may be required more frequently.

Sound Speed Corrections for Multibeam Surveys The sound speed profile must be known accurately in multibeam swath sounding for two reasons. First, as in all echo-sounding, the depth is computed from the product of the speed and the elapsed time between transmission of a sound pulse and reception of its echo. Second, since sound pulses travel at oblique angles through the water column, variations in the speed profile will affect the path of sound through water. The sound path from the transducer to the bottom and back will affect not only the observed depth of water, but the apparent position of the observed sounding.

Even though sampling equipment and computer systems are capable of dividing the water column into intervals so small as to allow close approximation of the integral expression for harmonic mean speed, practical limitations may require the hydrographer to use a small number of discrete points on the speed profile for the purpose of correcting echo soundings. If the hydrographer chooses the inflection points of the smooth speed profile as the discrete points for layer boundaries, the speed curve between the points can reasonably be approximated by a straight line.

Integration of all the segments using the trapezoidal rule to approximate the area under each layer will yield very accurate results.

For multibeam operations, the following specifications apply to sound speed profile frequency and application:

- One sound speed profile shall be acquired immediately before the beginning of the data acquisition period. During the course of survey operations, changes in the water column should be monitored at a sufficient frequency such that the general requirements specified earlier in this section are met.
- Sound speed profiles shall be acquired in the immediate area where subsequent data acquisition will occur.
- When using an undulating velocimeter, the real time sound speed profiles shall extend to at least 80% of the anticipated water depth. At a minimum, one cast per 24-hour period shall extend to 95% of the anticipated water depth (30 m or less water depth).

The uncertainty value of the sound speed measurements must be part of the vessel's error model. One method used by NOAA, is to use the manufacturers uncertainty values for the measured components of conductivity, temperature and pressure. These values must then be used to compute a total uncertainty for the profile by computing how each components uncertainty is propagated through the sound speed computations.

A probe that measures speed of sound directly, could use the manufacturers advertised uncertainty value.

Ideally, sound speed uncertainty should be computed based on both the unit's accuracy and the spatial and temporal error associated with sound speed variation over the entire survey area. However, such advanced error analysis is not currently available in NOAA's processing pipeline. Therefore, NOAA field units and contractors may use the uncertainty associated with measuring the speed of sound at a specific location.

5.1.3.4 Attitude Corrections Heave, roll, pitch, heading, and navigation timing error corrections shall be recorded in the data files and applied to all multibeam soundings. Heave and heading shall be applied for all single beam data. NOAA field units should refer to section 4.2.3.6 of the OCS Field Procedures Manual for more guidance on corrections to single beam data.

Heave, roll, and pitch. Heave shall be observed in no coarser than 0.05 m increments. Roll and pitch shall be observed in no coarser than 0.1 degree increments.

Heading shall be observed in no coarser than 0.5 degree increments.

The uncertainty value for heave, roll and pitch will typically be the manufacturer's values, assuming that the equipment is properly installed and maintained. The hydrographer must explain any variance from the manufacturer's values.

Hydrographers using Kinematics shall compensate for squat if attitude is not corrected for single beam.

5.1.3.5 Error Budget Analysis for Depths The hydrographer shall discuss (in Section B.2 of the Descriptive Report) the methods used to minimize the errors associated with the determination of depth (corrections to echo soundings). Error estimate ranges for six of these errors (measurement error, transducer draft error, s dynamic draft error, sound speed error, heave error and tide/water level error) are presented below. These errors are inherent to hydrographic surveying and all have practical minimums that are usually achievable only under ideal circumstances or with highly specialized equipment. In addition, some errors may be dependent on depth (e.g. sound speed).

The error ranges provided below are first order estimates to allow hydrographers to get a basic 'feel' for the possible range in errors that may occur in practice. Hydrographers should note that the root sum square of the individual errors is used in the computation of TPU. The required depth accuracy requirements cannot be achieved if the worst error for each sensor shown below is used.

Maximum allowable errors are specified to ensure that all errors sources are properly managed. It should be noted that if the maximum value for each error source is used in an error budget (i.e. root-sum-squared), the result will exceed the prescribed accuracy standard. The minimum and maximum values discussed below are at the 95% confidence level (i.e. 2 sigma).

The hydrographer shall also discuss (in Section B.2 of the Descriptive Report) the methods used to quantify the survey systems error model. Uncertainty estimates for all components of the sounding measurement should be provided.

Measurement error: This includes the instrument error for the sounding system, the effects of imperfectly measured roll/pitch and errors in detection of the sea floor due to varying density of the bottom material. Multibeam systems are particularly susceptible to this error due to the off-nadir nature of outer beams. The minimum achievable value is expected to be 0.20 meter at 10 meters depth. The maximum allowable error is 0.30 meter plus 0.5% of the depth.

Transducer draft error: This error is controlled by variability in vessel loading, and the techniques used to measure/monitor transducer draft. This error is depth independent with an expected minimum of 0.05 meter and an allowable maximum 0.15 meter.

Dynamic Draft error: Conventional methods of determining dynamic draft are limited by sea surface roughness and proximity of a suitable location to the survey area. Careful application of modern methods (Real Time Kinematic GPS) will minimize this error. This error is also depth independent although the effect of dynamic draft is greater in shallow water. The practical expected minimum is 0.05 meter and the allowable maximum is 0.20 meter.

Sound speed error: The factors associated with this error include (1) the ability to accurately measure sound speed or calculate sound speed from temperature, conductivity and pressure, (2) the spatial and temporal changes of sound speed throughout the survey area and (3) how the sound speed profile is used to convert measured time to depth. In addition, this error encompasses depth errors associated with refraction for multibeam systems. The expected minimum is 0.20 meter and the allowable maximum is 0.30 meter plus 0.5% of the depth.

Heave error: This error is directly dependent on the sea state and the sensitivity of the heave sensor but is not dependent on depth. The expected minimum is 0.05 meter and the allowable maximum is 0.20 meter.

Tide/water level error: This error has been discussed in detail in Section 4 The practical minimum is 0.20 meter and the allowable maximum is 0.45 meter.

5.1.4 Quality Control

5.1.4.1 Multibeam Sonar Calibration Prior to commencing survey operations, the hydrographer shall conduct a system accuracy test to quantify the accuracy, precision, and alignment of the multibeam system. Testing shall include determination of residual biases in roll, pitch, heading, and navigation timing error and the uncertainty of these values. These values will be used to correct the initial alignment, calibrate the multibeam system and used in the computation of the Total Propagated Uncertainty (TPU) for each sounding. System accuracy testing should be conducted in an area similar in bottom profile and composition to the survey area, and during relatively calm seas to limit excessive motions and ensure suitable bottom detection. In addition, system accuracy tests should be conducted in depths equivalent to the deepest depths in the survey area. Static transducer draft, dynamic draft corrections, sound speed corrections, and tide corrections shall be determined and applied to the data prior to bias determination.

The order in which these biases are determined may affect the accurate calibration of the multibeam system. The hydrographer should determine the biases in the following order: navigation timing error, pitch, roll, heading. Variations from this order, simultaneous determination of all values, are other methods of determining the biases must be explained and justified.

Pitch and navigation timing error biases should be determined from two or more pairs of reciprocal lines 500–1,000 m long, over a 10–20 degree smooth slope, perpendicular to the depth curves. The lines should be run at different speeds, varied by up to 5 knots, for the purpose of delineating the along track profiles when assessing time delay. Navigation timing error bias could also be determined from running lines over a distinct feature (i.e., shoal) on the bottom, as long as the feature is pinged by the vertical (nadir) beam.

Roll bias should be determined from one or more pair of reciprocal lines 500–1000 m in length over a flat bottom. Lines should be run at a speed which will ensure significant forward overlap.

Heading bias should be determined from two or more adjacent pairs of reciprocal survey lines, made on each side of a submerged object or feature (i.e., shoal), in relatively shallow water. Features with sharp edges should be avoided. Adjacent swaths should overlap by 10–20 percent while covering the shoal. Lines should be run at a speed which will ensure significant forward overlap.

Once calibration data have been processed and final system biases determined, the new corrections shall be used in a performance check to ensure that the new system biases are adequate. The hydrographer shall discuss procedures and results in Section A. Equipment and optional Section B. Quality Control of the project Data Acquisition and Processing Report. Copies of all system alignment, accuracy, calibration reports, and performance checks shall be included in the Data Acquisition and Processing Report.

System accuracy testing shall be repeated whenever changes (e.g., sensor failure, replacement, re-installations, re-configurations, or upgrade; software changes which could potentially affect data quality) are made to the system's baseline configuration, or whenever assessment of the data indicates that system accuracies do not meet the requirements in Section 5.1.1.

5.1.4.2 Positioning System Confidence Checks Confidence checks of the primary positioning system shall be conducted and recorded in the survey records at least once every week. A successful confidence check shall compare positions from the primary system to simultaneously observed check positions from a separate, independent system with a positional accuracy better than 10 meters. The inverse distance shall not exceed 10 meters. If correctors for the primary positioning system are obtained from a non-USCG differential system, then the check system must use correctors from a reference station different from the primary systems. If correctors are obtained from a USCG differential station, the check system may use the same correctors as the primary system. The confidence checks shall be an integral part of the daily survey data record. A summary report of positioning system confidence checks shall be included in Separate I of "Separates to be Included with the Survey Data" (see 8.1.3).

5.1.4.3 Crosslines

General The regular system of sounding lines shall be supplemented by a series of crosslines for verifying and evaluating the accuracy and reliability of surveyed depths and plotted locations. Crosslines shall be run across all planned sounding lines at angles of 45 to 90 degrees. The preferred area in which to run crosslines is in an area of gently sloping bottom.

Single beam The lineal nautical miles of crosslines for single-beam surveys shall be at least 8 percent of the lineal nautical miles of all sounding lines.

The hydrographer shall make a general evaluation of the single beam crossline to mainscheme agreement, and discuss the results in Section B of the Descriptive Report. If the magnitude of the discrepancy varies widely over the survey, the hydrographer shall make a quantitative evaluation of the disagreements area by area.

Multibeam The lineal nautical miles of crosslines for multibeam surveys shall be at least 5 percent of the lineal nautical miles of all sounding lines. An independent analysis of the crossline and mainscheme data shall be conducted. An independent analysis of the crossline and mainscheme data shall be conducted. Although any crossline/mainscheme disagreements should be obvious in the attributes of the combined surface, an independent analysis is still required to ensure that the surface implementation is correct and to help find any hidden problems.

Two possible methods of conducting the independent analysis is a beam by beam statistical analysis or by a surface difference (NOAA field units should refer to section 5.1.2.2.2 of the OCS Field Procedures Manual for more information). Other methods may be used if approved in advance by the COTR or Atlantic/Pacific Hydrographic Branch.

A surface difference can be conducted by creating a surface using only mainscheme data and comparing to a surface created from only crossline data. The surfaces used to compute the difference should have at least the resolution defined in section 5.1.2.

For either method, the hydrographer shall make a general evaluation of the multibeam crossline to mainscheme agreement, and discuss the results in Section B of the Descriptive Report. If the magnitude of the discrepancy varies widely over the survey, the hydrographer shall make a quantitative evaluation of the disagreements area by area. The difference surface shall also be included in the final deliverables.

5.2 Lidar

5.2.1 Accuracy and Resolution Standards

Lidar follows the standards for multibeam see sections 5.1.1 and 5.1.1.1 for information on accuracy and resolution standards for lidar.

5.2.1.1 Lidar Resolution Standards

Spatial resolution The hydrographer shall maintain and operate the lidar system, from data acquisition to processing to detect hazardous features. As the spatial resolution (i.e., the spacing of the lidar footprint on the seafloor) is dependant on a wide range of variables: 1) propagation of light through the water 2) the received signal strength 3) the object detection algorithms used 4) changes in water depth, and 5) aircraft height above the surface the actual bottom resolution may not remain constant. The hydrographer shall make a statement in the Descriptive Report describing the areas within the survey where they are confident that the multibeam resolution standards defined in section 5.1.1.2 are met (2x2x2m cube).

Spot spacing requirement will be defined in the Statement of Work, typically 3x3 or 4x4 at 200% coverage.

5.2.1.2 Gridded Data Specifications In the Navigation Surface approach, survey data are archived as a certified digital terrain model rather than as a set of verified or certified soundings. The archived elevation model could be saved at the highest resolution supported by the sounding data. For example, if the laser spot spacing on the seafloor of a full-coverage lidar survey is 3 meters, the elevation model could be saved at a grid spacing of 3 meters. However, if environmental conditions (i.e. kelp, turbidity, or sea state) create differences in data density an alterative approach may be discussed with the COTR and clearly described in the Descriptive Report (DR). This practice has the advantage of preserving this high-resolution data for a variety of known and unknown future purposes, even if such resolution will never appear on a navigational or charting product. Charting products such as paper charts are created from scale-appropriate generalizations of the elevation model. In reality, the final resolution of the surface may be slightly coarser than "the highest resolution supported by the sounding data" due to depth ranges, bottom topography and other variables.

The data density and resulting grid resolutions created shall be discussed with the COTR during the project planning phase. Any deviations from the plan, project instructions or Specifications and Deliverables shall be discussed with the COTR and clearly described in the Descriptive Report (DR) and Data Acquisition and Processing Report (DAPR).

If in rocky nearshore areas, the least depths of many features in a relatively small area fail to be preserved, see section 5.1.1.3 for more guidance. See also section 8.1.2 for guidance on delineating and characterizing this rocky seabed area.

Uncertainty The Navigation Surface for lidar requires that each sounding have a horizontal and vertical uncertainty. The uncertainty value for the grid shall be the greater of the standard deviation and the a priori uncertainty. To do this effectively, an error model is needed for all systems supplying measurements to compute the sounding; including the GPS sensors and anything else that contributes to the calculation of a sounding. The hydrographer shall include a discussion in the

DAPR on how the uncertainty was computed on each individual sounding and how the uncertainty was computed on the grid, with a justification for that methodology.

If a complete error model is not yet available to compute the TPU for each individual sounding then the hydrographer may apply a single uncertainty value to all grid nodes that reflect the vertical error budget for a given survey. Include a discussion in the DAPR on how the uncertainty was computed with a justification for that methodology.

5.2.2 Coverage

The required spot spacing and survey coverage will be specified in the Hydrographic Survey Project Instructions or Statement of Work.

The hydrographer shall obtain 200% coverage when required to do so in the Statement of Work. In situations where poor water clarity and related environmental factors make 200% coverage impossible the COTR shall be notified. In addition the hydrographer shall identify (textually and/or graphically) those areas where full coverage was not obtained and/or further investigation using sonar may be required.

All soundings shall meet the accuracy requirements of Section 5.1.1.1. Grid resolutions shall be appropriate for the spot spacing required in the Statement of Work.

Complete lidar coverage

- Grid resolution shall nominally be 3 meters - If survey data can support higher resolutions, then use hydrographer discretion and submit a higher resolution, if appropriate.
- Maximum surface uncertainty is IHO Order 1 for depths less than 100 meters.

The hydrographer must ensure that accurate least depths are obtained on all significant features. Individual soundings that do not meet the Horizontal Position Accuracy as defined in Section 3.1 or do not meet the Vertical Accuracy as defined in Section 5.1.1., shall not be applied to the grid.

As always, the hydrographer must ensure that the data accurately reflects the condition of the seafloor at the time of the survey and adjust operations if required. Any deviations from the specifications must be clearly explained in the Descriptive Report and discussed with the COTR as they occur.

5.2.3 Corrections to Lidar Soundings

To meet the accuracy and resolution standards for measured depths specified in Section 5.1.1 and 5.1.1.1, and to create a BAG that includes an accurate uncertainty layer, the hydrographer should conduct an error analysis of their survey systems.

Precise measurements are fundamental to the field of hydrography. Synchronization of multiple sensors with the lidar system is essential for meaningful spatial analysis of the data. All measurements, however careful and scientific, are subject to some uncertainties. Error analysis is the study and evaluation of these uncertainties with the purpose of estimating the extent of the uncertainties and when necessary, reducing them.

In recognition of the possibility that some discrepancies in sounding may not be detected until the final processing phase of the survey, the determination and application of corrections to soundings must be accomplished and documented in a systematic manner. In addition, it is preferable that all corrections be applied in such a way that the on-line values may be removed and replaced with a revised set of correctors during office processing. Corrections to soundings are divided into five categories, and listed below in the sequence in which they are applied:

Instrument error corrections account for sources of error related to the sounding equipment itself.

Roll, pitch, heading, and navigation timing error (latency) corrections shall be applied to lidar soundings to correct the effect of the aircraft's motion caused by turbulence, the error in the aircraft's heading, and the time delay from the moment the position is measured until the data is received by the data collection system (navigation timing error).

The hydrographer shall also discuss (in Section B2. of the Descriptive Report) the methods used to quantify the survey systems error model. Uncertainty estimates for all components of the sounding measurement should be provided.

5.2.3.1 Instrument Error Corrections In modern digital sounding instruments, instrument errors are generally small and of a fixed magnitude independent of the observed depth. Proper set up and adjustment of Lidar equipment using internal checks will often eliminate instrument error entirely. However, to ensure the proper operation of the lidar system "confidence checks" shall be conducted periodically.

Frequent checks should be made between the overlap of mainscheme and crosslines collected on different days. These comparisons should be made frequently during data collection to find errors promptly, and not saved until final data processing after the field party has left the working grounds.

Any differences should be investigated, and if, after analysis, a corrector is necessary, it should be applied with an explanation of the cause of the difference explained in the Descriptive Report (DR) section B2., Quality Control.

5.2.4 Quality Control

5.2.4.1 Lidar Calibration Field calibration is performed by the system operator through flights over a calibration site that has been accurately surveyed using GPS or conventional survey techniques such as triangulation or spirit leveling. Typically, the calibration site may include a large, flat-roofed building whose corners have been accurately surveyed with GPS and a large, flat parking lot and runway. The calibration may include flights over the site in opposing directions, as well as cross flights. The field calibration is used to determine corrections to the roll, pitch, and scale calibration parameters. Field calibrations must be performed for each project or every month, whichever is shorter.

Prior to commencing survey operations, the hydrographer shall conduct a system accuracy test to quantify the accuracy, precision, and alignment of the lidar system. Testing shall include determination of residual biases in roll, pitch, heading, and navigation timing error and the uncertainty of these values. These values will be used to correct the initial alignment, calibrate the lidar system and used in the computation of the Total Propagated Uncertainty (TPU).

Once calibration data have been processed and final system biases determined, the new corrections shall be used in a performance check to ensure that the new system biases are adequate. The hydrographer shall discuss procedures and results in Section A. Equipment and optional Section B. Quality Control of the project Data Acquisition and Processing Report. Copies of all system alignment, accuracy, calibration reports, and performance checks shall be included in the Data Acquisition and Processing Report.

System accuracy testing shall be repeated whenever changes (e.g., sensor failure, replacement, re-installations, re-configurations, or upgrade; software changes which could potentially affect data quality) are made to the system's baseline configuration, or whenever assessment of the data indicates that system accuracies do not meet the requirements in Section 5.1.1 and 5.1.1.1.

5.2.4.2 Positioning System Confidence Checks Confidence checks of the primary positioning system shall be conducted and recorded in the survey records at least once every week. A successful confidence check shall compare positions from the primary system to simultaneously observed check positions from a separate, independent system with a positional accuracy better than 10 meters. The inverse distance shall not exceed 10 meters. If correctors for the primary positioning system are obtained from a non-USCG differential system, then the check system must use correctors from a reference station different from the primary systems. If correctors are obtained from a USCG differential station, the check system may use the same correctors as the primary system. The confidence checks shall be an integral part of the daily survey data record. A summary report of positioning system confidence checks shall be included in Separate I of "Separates to be included with the Survey Data" (see 8.1.3).

5.2.4.3 Crosslines

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The hydrographer shall make a general evaluation of the lidar crossline to mainscheme agreement, and discuss the results in Section B of the Descriptive Report. If the magnitude of the discrepancy varies widely over the survey, the hydrographer shall make a quantitative evaluation of the disagreements area by area.

The lineal nautical miles of crosslines for lidar surveys shall be discussed and agreed upon with the COTR during project planning. Under certain conditions (e.g., steep terrain, airspace restrictions, or relatively narrow band of coverage) crosslines may not be possible. In such cases, a deviation from this requirement shall be requested from the COTR and explained in the DR.

An independent analysis of the crossline and mainscheme data shall be conducted. Although any crossline/mainscheme disagreements should be obvious in the attributes of the combined surface, an independent analysis is still required to ensure that the surface implementation is correct and to help find any hidden problems. Include a statement regarding the results of the comparison in Section B of the Descriptive Report. If created, the difference surface shall also be included in the final deliverables.