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Assessment of sensor performance

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Assessment of sensor performance

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Abstract

There is an international commitment to develop a comprehensive, coordinated, and sustained ocean observation system. However, a foundation for any observing, monitoring, or research effort is effective and reliable in situ sensor technologies that accurately measure key environmental parameters. Ultimately, the data used for modeling efforts, management decisions, and rapid responses to ocean hazards are only as good as the instruments that collect them. There is also a compelling need to develop and incorporate new or novel technologies to improve all aspects of existing observing systems and meet various emerging challenges.

Assessment of Sensor Performance was a cross-cutting issues session at the international OceanSensor08 workshop in Warnemünde, Germany. The discussions were focused on how best to classify and validate the instruments required for effective and reliable ocean observations and research. The following is a summary of the discussions and conclusions drawn from this workshop, which specifically addresses the characterization of sensor systems, technology readiness levels, verification of sensor performance, and quality management of sensor systems.

1 Introduction

The progress in any branch of science is heavily dependent on the types and required accuracy of measurements that are needed to describe the status and the processes under investigation. In ocean sciences, physical and biogeochemical processes of diverse temporal and spatial scales are strongly coupled. Therefore, a huge variety of parameters is needed to uniquely characterise the status of the system and reveal the relationship between ongoing physical, chemical, and biological processes. In this context it is of utmost importance to precisely state the level of knowledge in regard to measurement uncertainties for each of the relevant parameters being defined by the measuring principle and the respective instrument in use.

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Within ocean sciences, knowledge is rapidly growing because of continuous advancements in technologies and methodologies. However, with innovation come challenges, as systematic evaluation of the different methods, and an understanding of how sensors systems should be applied properly, is often lacking. A number of researchers simply rely on the specifications of the manufacturer and the accompanying recommendations for using their instruments. A serious problem arises when manufacturers themselves do not have a clear notion of the performance of their instruments. This lack of knowledge is often caused by i) a poor understanding of definition for basic terms to describe the specifications as exemplified in a description of AMS (2008), ii) the incorrect implementation of basic calibration methods, or iii) the economic pressure resulting in some sort of optimistic assessment of the performance of their sensor product. These situations often lead to extra efforts for the user if inconsistencies during the comparison of different parameters or different measuring methods of the same parameter show up, or in other words, if questions regarding adequate data quality are raised. The common saying in ocean sciences – “never measure the same parameters with different methods” – is a consequence of the reasons stated earlier and may actually prevent necessary progress in this field. Furthermore, it can lead to serious delays in efforts such as designing a long term monitoring strategy for the ocean environment on the global scale.

In the framework of the permanent ocean observations, like the ARGO float program or the planned ocean observatories, it is essential to reach consensus of assessment of the quality of the collected data (Pouliquen et al., 2009). The rationale for this is that the measured values are no longer just processed and used by an individual scientist or used for an individual science mission, but they are made available for the entire ocean science community. Only if the end user has sufficient confidence in the quality of the collected data, the information of different sources is directly comparable, and he will be able to test models or use them for assimilation purposes.

This concept dictates that all branches of ocean sciences involved have a common vocabulary to uniquely describe the measurement process and constraints. Thus, the

necessary next steps are to leverage existing knowledge about doing measurements, which, for instance, in physics has been cultivated for centuries (Sullivan, 2001). The keepers of this knowledge are the national standard laboratories that are responsible for delivering and disseminating calibration standards and methods in accordance with the definition of terms. It is part of their mission to support any activity that leads to an objective assessment of the performance of any kind of sensor system, be it in ocean sciences or any other branch.

Although appropriate services are available, ocean sciences does not make full use of it. As a matter of fact, for certain parameters like temperature and pressure, it is already common practice, but for almost all the other parameters it is not. The reason for that lies often in

- cost considerations
- lack of knowledge
- lack of acceptance in the ocean science community
- lack of time/the need for quick results; in ocean sciences, the focus is on the interpretation of data rather than on analysis of the measuring principle
- constraints imposed by the measuring method itself, like in the case of conductivity where laboratory calibrations are very demanding (Saunders et al., 1991; Bacon et al., 2007)
- alternative strategies employing extensive and complex in situ intercomparisons of instruments employing the same measuring principle (Gouretski, 2007)
- possibility of comparison with other parameters and judging on the accuracy based on consistency of the results (Bates, 2000)

SI units are often just seen as recommendations for specifying the units of measuring results. Obviously this is insufficient as, if measuring results are specified in SI units,

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this also implies that the measurements are traceable to SI standards. In fact, salinity as it is defined in ocean sciences right now is not traceable to SI units.

These are not insurmountable obstacles. There simply has to be incentives to overcome the conventional attitude that the idea of building commonly used infrastructures might be a starting point. In the centre of the following discussion lies the description of a suggested basic vocabulary to describe the measurement process and the role and need of calibrations and testing. It is logical to make use of the competence that has been built up in national standard laboratories and independent, third-party test organizations. In order to become an integral part of the calibration chain defined by the national standard laboratories, which is also called metrological traceability, it is necessary to accept their procedures, policies, and terminology. This would be the first step to achieve a consistent, coherent approach for ocean sciences. In cases where parameters are not traceable to SI units, intermediate solutions have to be identified and established, as it is the case for salinity, which is related to the standard seawater artefact. For each parameter, it has to be made clear how the measuring scale is defined, to what standards it refers to, and how the conducted measurement can be traced back to this standard.

The users and manufacturers/developers of sensor systems are obviously two groups with distinct interests and within both groups, problems regarding the quality of data can have their origin. While the user is interested in a flawless operation without dwelling too deep on engineering issues, the manufacturer is often aware of limitations of the instrument that might result from the technical realisation of the sensor or is related to constraints based on basic physical principles. The communication process on these issues has to be improved. In this complex framework standard laboratories, and programs like the Alliance for Coastal Technologies (ACT), can play a role as a facilitator in regard to establishing a firm ground for assessing sensor performance. From their perspective, every process step as for instance in regard to calibration has to be uniquely identified and made transparent to allow for controlling. This approach is strongly related to the concept of quality management. In the case of sensors, it means

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that every process step is clearly described and documented based on an agreed upon measuring protocol or documentary standard. With the right guidelines the calibration and testing of sensors can equally be conducted by companies or research institutions. Employing an accreditation system, like ISO/IEC 17025 (2005), each manufacturer will be able to specify its products according to agreed upon standards with appropriate documentation. The feasibility of this concept is demonstrated in everyday business all over the world.

This illustration also brings up the question whether a central ocean sensor calibration laboratory, either national or international, is needed. In particular, it has to be considered in the context that, within planned ocean observatories, hundreds of sensors shall be deployed and operated concurrently. Without attempting to answer the question conclusively a distributed calibration system seems to be more viable and appropriate. To achieve comparability consensus on testing and calibration procedures has to be reached. A promising example for a successful consensus on standard calibration and measuring techniques in the field of chemical oceanography without a laboratory entity being involved is reported in Dickson et al. (2007) and within the QUASIMEME project. This standard work in the field of ocean CO₂ measurements incorporates contributions of numerous scientists and was released under the auspices of PICES and the UNESCO. A similar guide for ocean acidification research and data reporting is currently in review state (Riebesell et al., 2009).

In ocean sciences, certain parameters that are measured have no unique definition in a metrological sense (e.g., primary productivity and turbidity). Rather, certain measuring parameters are used as an indirect measure for the parameter of interest. To preserve the pragmatic approach, at least the need to uniquely define the measuring process has to be satisfied to allow for the repetition of the measurement and/or by employing parameters measured in SI units to allow for traceability.

In the case of conductivity measurements, it has been the intention to closely relate the standard to the actual measuring problem. However, this approach resulted in the definition of an artefact that is prone to change. With the present definition salinity

is not traceable to SI units and therefore has been named Practical Salinity Scale. Instead of using an artefact as a standard a measuring process should be defined that allows every standard laboratory in the world to calibrate salinometers. By that it can be guaranteed that all salinity measurements are comparable now and in the future. The problem became apparent and led to a new initiative to define salinity as an absolute quantity (Millero et al., 2008).

2 Definition of terms

As a first step towards achieving a unique assessment of sensor performance, a certain set of definitions and description of terms becomes necessary. This can be summarised in a vocabulary, which is a terminological dictionary that contains designations and definitions from one or more specific subject fields. In this vocabulary, it is taken for granted that there is no fundamental difference in the basic principles of measurement in physics, chemistry, ocean sciences, biology, or engineering. The International vocabulary of metrology – Basic and general concepts and associated terms (VIM, 2007) is the reference for all national standard laboratories and should also be used for measurements in ocean sciences. As an example, a definition of the terms “resolution” and “sensitivity” is given in Appendix A2. The definitions of these two terms show clearly how a careless use of terms can lead to confusion. In most cases people are using the terms synonymously, although they are mostly interested in the resolution of a measuring system to predict whether they could see a change in the parameter under investigation.

Another concept that comes into play and may help in the introduction of the illustrated principles is the Sensor Web Enablement (SWE/SensorML; M. Botts, University of Alabama at Huntsville) concept that, besides other issues, aims at defining a so-called “controlled vocabulary to uniquely describe sensor systems and the measuring process”. As SWE is following a process-oriented approach, which means that it only describes the process and gives references to definition of terms, VIM can be easily in-

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tegrated. The ultimate goal of SWE is that with the establishment and practical use, the scientific user does not have to consider specific details of characterising the sensor in use, but rather can rely on the established metadata information system delivered by the sensor itself through the entire processing chain. Currently there are still issues with the unique description of measurement properties with metadata. This goes back to fact that every community is defining its own vocabulary in describing the performance of their tools. The Marine Metadata Initiative (MMI project) is aiming to resolve some of the issues by, for example, offering tools to map vocabularies. In any case a harmonised vocabulary or an according ontology is a necessary step to make ocean observation systems interoperable.

In the past twenty years a paradigm change in measurement has occurred. In the classical approach (Kohlrausch, 1968), it has been assumed that the result of a measurement (the measurand) can be described by a single true value, and due to errors caused by the measuring instrument, the actual values is offset from the true value. The errors (i.e., the deviations from the true value) were typically designated as random and systematic errors. This led to the situation where no single value was attributed to a describe measurement error, in large part because it was unclear how to treat these two separate numbers in a consistent way. The Guide on Uncertainty in Measurements (GUM, 2008) is actually addressing exactly this issue. It is much more helpful to introduce a single parameter that *can* be calculated, and that parameter is the *uncertainty* – . . . a parameter, associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the measurand.

Within this new approach, the measuring process is judged as a system where the measurand, the measuring environment, and the measuring instrument interact. This actual constellation leads to an uncertainty of the measurand. It used to be common practice to talk about measurement errors, while today the introduction of GUM uncertainty is the accepted term.

GUM replaces the formalism of random and systematic errors with type A and type B uncertainties. Type A evaluations of uncertainty are based on the statistical analysis

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of a series of measurements. Type B evaluations of uncertainty are based on other sources of information such as an instrument manufacturer’s specifications, a calibration certificate, or values published in a data book. There are rules on how to combine Type A and B uncertainties into one quantity (see Fig. 1) depending on the actual measuring task. It should be noted that for subsequent use of the calculated uncertainty it has to be treated as Type B by agreement.

A measurement result is expressed as a single measured quantity value and a measurement uncertainty:

$$\text{Measured value} = \text{best estimate of value} \pm \text{uncertainty} \quad (1)$$

where the best estimate could be e.g., the mean of a series of repeated measurements.

The uncertainty is calculated employing well known statistical methods evaluating the variance and standard deviation of the measurement sample. GUM recommends using the expanded uncertainty as the final number value, where the coverage probability or level of confidence of the specified uncertainty is 95%. This is described with the coverage factor k :

$$\text{Uncertainty} = k \cdot \text{standard deviation} \quad (2)$$

If the probability should be 0.95 that all measured values are lying between $\pm \text{uncertainty}$ of the best estimate, the coverage factor, k , would be approximately equal to 2.

The advantages of using GUM are:

- Internationally credited/accepted approach to calculating and expressing uncertainties.
- Allows everyone to “speak the same language”.
- Allows the term “uncertainty” to be interpreted in a consistent manner.

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- A “must” for everyone working in standards/calibrations laboratories and growing in importance in industrial laboratories – key phrase is that it will “increase competitiveness”.
- Becoming essential knowledge in many other fields, including forensic, medical, and biomedical.
- Likely to be around for some time to come.

Until the advent of GUM, inconsistencies existed worldwide in the way uncertainties were calculated, combined, and expressed. Without international consensus on these matters, it is difficult to compare values obtained through measurement in different laboratories around the world.

In the appendix, a few definitions will be given for terms that are important to describe the performance of a sensor based on the International Vocabulary of Metrology (VIM), including notes with further descriptions.

3 Characterisation of sensor systems – generic sensor model, identification of functional blocks

Sensor, transducer, and detector – these terms are sometimes used synonymously although they have slightly different meanings. In this text, a sensor shall be part of the transducer, which is in compliance with VIM. Sensor and detector describe basically the same system and it depends on the type of measurement which term will be used. To define a sensor model that is in compliance with GUM, the basic measuring process has to be defined. A measurand or a parameter p under investigation often cannot be measured directly. Therefore, a number of input quantities have to be measured to determine the measuring value. This can be formally written as a functional relationship

$$p = f(x_1, x_2, \dots, x_n)$$

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where $x_1 \dots x_n$ describe the n input quantities and p the parameter of interest. The n input quantities can either be repeated measurements or different input parameters. The model allows for calculating the influence of the uncertainty in the individual input quantities x_j on the measurement value p . Within a more generalised model, the step response time can be included in this model as well. Within GUM, this functional relationship (called the measurand model) is essential in determining the uncertainties taking all relevant input parameters into account.

As an example, the model of a platinum resistance thermometer is described through:

$$R(t) = R_0(1 + \alpha t) \quad (3)$$

where $R(t)$ is the resistance of the platinum element at the according temperature t , R_0 is the resistance at 0°C and α is the temperature coefficient. Rearranging Eq. (3) to solve for t delivers:

$$t = \frac{R(t) - R_0}{R_0 \alpha} \quad (4)$$

From this equation the Type B uncertainty for the temperature, Δt , can be calculated from:

$$\Delta t = \frac{\Delta R}{R_0 \alpha} \quad (5)$$

where ΔR is the uncertainty in the resistance measurement. The model is, therefore, a tool to calculate the propagation of uncertainties at the input through the different elements of the transducer system.

The block diagram of Fig. 2 shows a generic model of a sensor. The model function can be associated with the extended transfer function of the sensor. This is of particular importance in calculating type B uncertainties.

This schema should be considered as a start to identify certain functional blocks of a generic sensor system, as certain aspects may still not be accounted for properly. For

instance, a clear distinction between interfering input, which addresses added noise components and modifying input, which accounts for changes of the transfer function may not be possible in all cases. In Fig. 2a feedback from the sensor output to the transfer function is inserted, accounting for possible feedback mechanisms to correct for recurring/systematic errors.

It is obvious that for every sensor system and each application (e.g., ocean observatories), the schema or measurand model has to be stated and published. It is also important to clearly identify all possible measuring errors and to allow the expert user to judge the performance of instruments. The final aim is to relieve potential users from this burden. This could be accomplished by formalising the process. Again, the introduction of SWE was intended to provide this procedure, which contains categories for relevant input requirements.

The aim of this exercise is to demonstrate that certain features are common to all sensor systems and, accordingly, that principles applying to one particular sensor, for instance a CTD sensor, may equally well be applied to other sensors (e.g., biochemical sensors). In the following paragraph this concept is extended to the assessment of the development stage of a newly introduced sensor system.

4 Assessment of development status employing the concept of Technology Readiness Level (TRL)

Sensors undergo different maturity levels during their development. From the time the method has been conceived through different realisation stages until final verification of operational status through several successful missions, it is a process that may take several years or even decades. Although it is not uncommon for the development process to be extended in an attempt to produce a perfect instrument, technical constraints are often the most challenging and time consuming. If a prototype has been produced, the next obstacle is unforeseen effects derived, for instance, from interfering parameters. In particular in ocean sciences, the requirements on in situ measure-

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ments in regard to resolution and accuracy are extremely high and often reach the limit of what can be done in the laboratory. In addition the needs on the engineering side within ocean sciences are demanding as well (e.g., low power consumption and short response time/time required for a measurement). The discrepancy between the needs/expectations and limited time available to finish product development can lead to unsatisfactory performance of new sensor systems. However, common approaches of other science and engineering disciplines can be utilized to demonstrate what development steps are necessary until the final system is truly operational.

One approach for the distinct description of the development status of a certain system is given by the Technology Readiness Level (TRL). Large government agencies (such as the US Department of Defense and National Aeronautics and Space Administration [NASA]) typically define nine levels of maturity of a particular technology, which allow for a consistent comparison between different technology types and a determination of when instruments are ready for reliable, operational use. For example, NASA uses the TRL for space technology planning (Mankins, 2005, see also appendix).

Obviously the TRL steps defined by NASA are very detailed in their description because this particular field has been using this type of scale for many years. In ocean sciences, this is certainly not the case. Therefore, it has been suggested to group individual TRL stages to consolidated, four Ocean Sciences Technology Readiness Levels (OS-TRL):

1. Proof-of-concept/development (TRL 1–3)
2. Research prototyping (TRL 4–6)
3. Commercial (TRL 7–8)
4. Mission proved (TRL 9)

The transition from stage 3 to 4 should include independent testing, validation, and verification. The individual manufacturer or developer can classify their product into an appropriate TRL stage, but proof (adequate data and documentation) must be made

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available. In contrast to the original TRLs this schema assumes that, in any case, all stages have to be passed.

5 Verification of sensor performance and the role of calibration procedures

A common problem in the development process is the verification of the performance of a newly developed sensor by conducting laboratory calibrations, beta or field performance testing, or in situ intercomparisons. It is not only necessary to demonstrate the operational status of the sensor itself, along with its manageability, but also the practicability of the relevant measurement method for a certain parameter under defined conditions. As mentioned, most parameters are connected to others by carrying implicit information about others. For example, electrical conductivity of seawater has a strong temperature dependence. Thus, conductivity values can be correlated with measured temperature profiles to identify artefacts. As a matter of fact, validation can be done in three different ways:

1. Comparison with higher accuracy standard instruments or artefacts

Measurements are conducted in a calibration laboratory with higher accuracy lab instruments or reference standards are sent around to different labs to do inter-comparisons. Both approaches have its pros and cons, in particular, if operational constraints are taken into account.

2. Comparison with other methods measuring the same parameter

This is of particular interest when doing in situ calibrations. Other methods can be based on water samples to be measured on the ship or alternative in situ sensors. As mentioned in the introduction, this also allows for verification of how precisely the measuring task or to be measured parameters have been defined in a physical sense. Vicarious calibrations also belong into that category where known events or phenomena are used to check for calibration shifts. For this to

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be successful, care has to be taken so that water with the same (or at least very similar) properties is sampled using the different methods.

3. Comparison with other method measuring a parameter that carries implicit information about the parameter under investigation

This is combined with the use of a model that assimilates different parameters and finally leads to a statement in regard to the consistency of the individual parameters measured. This method can be described as a predictive model feedback. Again it has to be ascertained that the water sampled by the different methods has the same properties.

The independence of the validation or verification of a sensor is also critical for the credibility of results. An example for an independent and transparent type of third-party testing is the Technology Evaluations conducted by the Alliance for Coastal Technologies (ACT, www.act-us.info). ACT conducts two types of sensor testing. Technology Verifications that equal TRL 7/8 or OS-TRL 3 are rigorous evaluations of commercially available instruments to verify manufacturers' performance specifications or claims, which are carried out in the laboratory and under diverse field conditions and applications. Technology Demonstrations are a less extensive exercise where the abilities and potential of a new technology is established by working closely with developers/manufacturers to field test instruments. This would correspond to TRL 6 or OS-TRL 2.

However, ACT only quantifies the performance of sensors against a community agreed standard (e.g., dissolved oxygen sensor and Winkler titration) and not against other instruments.

It should be noted that there is no exception for an individual parameter to be verified according to the above mentioned methods. This also means that people should be encouraged to use templates from other developments, for instance the well investigated CTD sensor systems. Formal certification of calibration facilities is not necessarily required for the mentioned procedures. However, guidelines for assessing the sensor

performance and the definition of standard operating procedures in testing and use of different sensor systems will be necessary in the future and should build up on existing efforts.

An often neglected fact is the dynamic behaviour of sensor systems. In most cases, the sensor is not deployed at a single location for long-term measurements but is used for taking horizontal or vertical profiles. In the latter case, a well-defined dynamic model has to be used to correct or filter the raw data. The CTD gives a good example in that context, as temperature and conductivity sensor systems show completely different temporal behaviour. Therefore, before the data are merged to derive salinity and density data a dedicated filtering process is applied that matches the temporal behaviour of these sensors together. The metric to evaluate the quality of the result is the so-called spiking of the derived parameters that shows up in strong gradients. Again, it should be kept in mind that a lot of experience with the processing already exists in the realm of CTD, where for instance it has been shown that speeding up the sensor response by enhancing the higher frequency response of the transfer function leads to extensive noise.

As most ocean measurements are done with multiple sensor systems, there are opportunities to examine the temporal performance of a newly designed sensor by comparison with other parameters to be collected. Strong gradients in temperature and salinity are often related to corresponding gradients in other parameters, which then can be used to validate the temporal performance of the sensor measuring the parameter of interest.

6 Quality management of sensor systems – service and maintenance procedures, implications for observatories

The need for instrument quality management is always essential and of particular importance when real-time data are collected and distributed. The users of these data should be able to retrieve all relevant information about sensor and resulting data qual-

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ity either from the operator or another institution that oversees the data collection process. In a qualitative sense, it means that the data are made trustworthy by setting appropriate flags and, in a quantitative sense, that the uncertainty is specified.

Typically, quality management is associated with quality control (QC), which in its simplest form means filtering out outliers. This is an unwanted but in most cases necessary step. In addition, there are also cases where this filtering process leads to significant errors, as natural variability can have an unexpected intensity. Therefore, the issue of QC is strongly interlinked between sensor performance and process evaluation. If one focuses on the sensor side quality assurance is of utmost importance.

That implies the following procedures:

- Basic check of sensor by visual inspection and basic electronic check
- Pre-deployment calibrations
- Post-deployment calibrations
- Monitoring the performance (temporal variability) at sea
- Comparing with historical and climatological data
- Taking in situ water samples to compare with the sensor

All the processing steps as listed above have to be traceable by employing a thorough documentation. There are templates available from certain laboratories in Europe (IFREMER) and North America (WHOI), and there is also a need to summarise the experience and to recommend best practices. The impetus for that might again come from the different ocean observatory initiatives as has been described above. In any case, quality management procedures are aiming to decentralise processes that lead to accurate ocean data, and therefore, they are of high importance in implementing a global data quality standard.

A number of initiatives in those directions already exist. There is the QARTOD/Q2O project funded by NOAA (see references on the QARTOD and Q2O projects) that

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is explicitly addressing these issues and the Marine Metadata Interoperability project (MMI project) coordinated by MBARI that aims at formalising the issues into interoperable metadata descriptions. These metadata will be accessible and linked to the data streams.

5 7 Template sensor system – CTD as use case

Probably the best known sensor system in ocean sciences is the CTD. Since the first laboratory tests 100 yr ago (Forchhammer, 1865) and first in situ implementation in the 1950s (Hamon, 1958), CTDs have been extensively used and validated. Probably the most critical tests have been with floats that have been in operation over several years, where the drift has been checked by employing well-known T-S relationships. With this approach, it has been demonstrated that for instance salinity drift in some CTD-system has been less than approximately 0.01 (units reported by instruments) after two years of operation (Janzen et al., 2008).

Calibration routines have been described in detail in different publications, such as the UNESCO Technical Papers (1994). In a sense these works give a template of how to deal with other sensor systems, in particular, in regard to the description given for the CTD-sensors that involve in detail:

- modelling the sensor behaviour
- definition of calibration routines, precautions in operation
- processing of data
- exchange of data

All these are necessary steps to determine the operational status of a parameter in ocean sciences and assess the performance of the involved sensor system.

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8 Conclusions

Assessing sensor performance, and proper instrument calibration and use, is critical to the success of any ocean observing initiative, research program, or management effort. Instrument verification and validation is also necessary so that effective existing technologies can be recognized and promising new technologies can be incorporated in such efforts. While the framework described above identifies the needs in this area, a formal international working group, like a SCOR working group (<http://www.scor-int.org/about.htm>) should be established to build consensus and provide guidance and guidelines, structure, and standardization. International organisations, such as International Ocean Commission (IOC), who is overseeing the Global Ocean Observing System, could support these activities. ACT can be expanded in its scope and its extent to form a nucleus for the planned working group. This newly established body can take the lead on developing standard operating procedure documents, certification/accreditation protocols for specific sensors or parameters, and other required activities.

Appendix A

A1 Technology Readiness Levels summary according to (Mankins, 2005)

A1.1 TRL 1 – basic principles observed and reported

This is the lowest “level” of technology maturation. At this level, scientific research begins to be translated into applied research and development. Examples might include studies of basic properties of materials (e.g., tensile strength as a function of temperature for a new fiber).

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A1.2 TRL 2 – technology concept and/or application formulated

Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be “invented” or identified. For example, following the observation of high critical temperature (H_{tc}) superconductivity, potential applications of the new material for thin film devices (e.g., SIS mixers) and in instrument systems (e.g., telescope sensors) can be defined. At this level, the application is still speculative; there is not experimental proof or detailed analysis to support the conjecture.

A1.3 TRL 3 – analytical and experimental critical function and/or characteristic proof-of concept

At this step in the maturation process, active research and development (R&D) is initiated.

This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute “proof-of-concept” validation of the applications/concepts formulated at TRL 2.

A1.4 TRL 4 – component and/or breadboard validation in laboratory environment

Following successful “proof-of-concept” work, basic technological elements must be integrated to establish that the “pieces” will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier and should also be consistent with the requirements of potential system applications.

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A1.5 TRL 5 – component and/or breadboard validation in relevant environment

At this level, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements, so that the total applications (component-level, sub-system level, or system-level) can be tested in a “simulated” or somewhat realistic environment.

A1.6 TRL 6 – system/subsystem model or prototype demonstration in a relevant environment (pressure chamber, test basin, ocean)

A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or systems – which would go well beyond ad hoc, “patch-cord”, or discrete component level breadboarding – would be tested in a relevant environment. At this level, if the only “relevant environment” is the ocean environment, then the model/prototype must be demonstrated in the ocean. Of course, the demonstration should be successful to represent a true TRL 6. Not all technologies will undergo a TRL 6 demonstration; at this point, the maturation step is driven more by assuring management confidence than by R&D requirements. The demonstration might represent an actual system application, or it might only be similar to the planned application, but using the same technologies.

A1.7 TRL 7 – system prototype demonstration in a space environment (in ocean sciences accordingly in an ocean environment)

TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in the ocean environment. In this case, the prototype should be near or at the scale of the planned operational system, and the demonstration must take place in the ocean. The driving purposes for achieving this level of maturity are to assure system engineering and development management confidence (more than for purposes

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of technology R&D). Therefore, the demonstration must be of a prototype of that application. Not all technologies in all systems will go to this level. TRL 7 would normally only be performed in cases where the technology and/or subsystem application is mission critical and relatively high risk. Example from space science: the Mars Pathfinder Rover is a TRL 7 technology demonstration for future Mars micro-rovers based on that system design.

A1.8 TRL 8 – actual systems completed and “ocean mission qualified” through test and demonstration

By definition, all technologies being applied in actual systems go through TRL 8. In almost all cases, this level is the end of true “system development” for most technology elements.

A1.9 TRL 9 – actual system proven through successful mission operations

By definition, all technologies being applied in actual systems go through TRL 9. In almost all cases TRL 9 marks the end of last “bug fixing” aspects of true “system development”.

A2 Definition glossary with reference to VIM (2007)

A2.1 Traceability

Traceability is the property of a result of a measurement or the value of a standard whereby it can be related to stated references through an unbroken chain of comparisons all having stated uncertainties.

Notes:

1. Traceability applies to the documentation process for all intermediate calibration steps, as well as to the check of all used intermediate calibration tools.

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2. An established calibration hierarchy has to be established.
3. For measurements with more than one input quantity to the measurement function, each of the input quantities should itself be metrologically traceable.

A2.2 Measurement accuracy, accuracy of measurement, accuracy

- 5 Accuracy describes the closeness of agreement between a measured value and the assumed true measurement result. The concept “measurement accuracy” is not associated with a numerical value. A measurement is said to be more accurate when it offers a smaller measurement error.

10 According to these definitions, traceable accuracy is not a standard term; it is not defined and therefore should be discarded. As a matter of fact, the term mixes two processes that have to be considered separately. GUM suggests specifying the uncertainty as a numerical value to describe the “trueness” of the measurement.

A2.3 Measurement precision, precision

15 Precision specifies the closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions which includes measurements taken under different conditions. This value is usually expressed numerically by terms of imprecision, such as standard deviation or variance under specified measuring conditions. It should not be mistaken for measuring accuracy.

20 A2.4 Stability of a measuring instrument, stability

Stability is the property of a measuring instrument, whereby the environmental conditions are kept constant in time. Stability may be quantified through a time interval where the measured value changed by a certain amount or through quantifying a factor describing the temporal change.

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This parameter is closely related to the conventional notion of accuracy. Although some manufacturers tend to specify the residual deviations from the calibration function as accuracy (in the conventional sense), it is obvious that the temporal stability also has to be taken into account. A numerical value for this can only be gained through repetitive calibrations.

A2.5 Resolution

Resolution describes the smallest change in a quantity being measured that causes a perceptible change in the corresponding indication. Resolution will depend on, for example, noise (internal or external).

A2.6 Sensitivity of a measuring system, sensitivity

Sensitivity is a relative measure describing the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured. Sensitivity of a measuring system can depend on the value of the quantity being measured. The change considered in a value of a quantity being measured must be large compared with the resolution.

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Table 1. Consolidation of TRL to OS-TRL.

TRL	Sensor development status	
	Short description	OS-TRL
1	Basic principles observed and reported	
2	Technology concept and/or application formulated	1
3	Analytical and experimental critical function and/or characteristic proof-of concept	
4	Component and/or breadboard validation in laboratory environment	
5	Component and/or breadboard validation in relevant environment	2
6	System/subsystem model or prototype demonstration in a relevant environment	
7	System prototype demonstration in a space/ocean environment	
8	Actual systems completed and “ocean mission qualified” through test and demonstration	3
9	Actual system proven through successful mission operations	4

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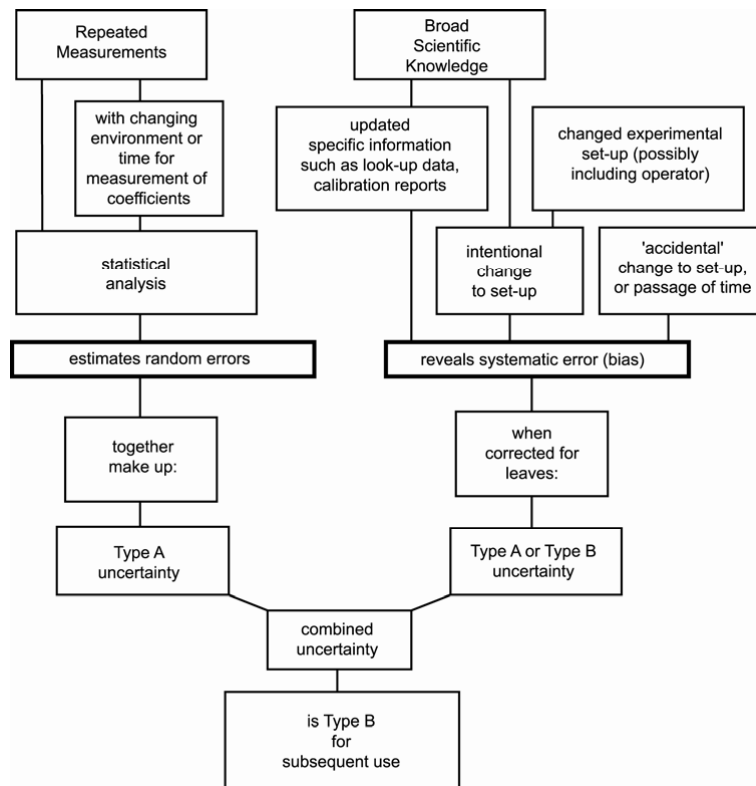


Fig. 1. The explanation and combination of Type A and Type B uncertainties (from Kirkup et al., 2006). Type A uncertainties are related to the former random errors, while Type B uncertainties have a connection to the former systematic errors.

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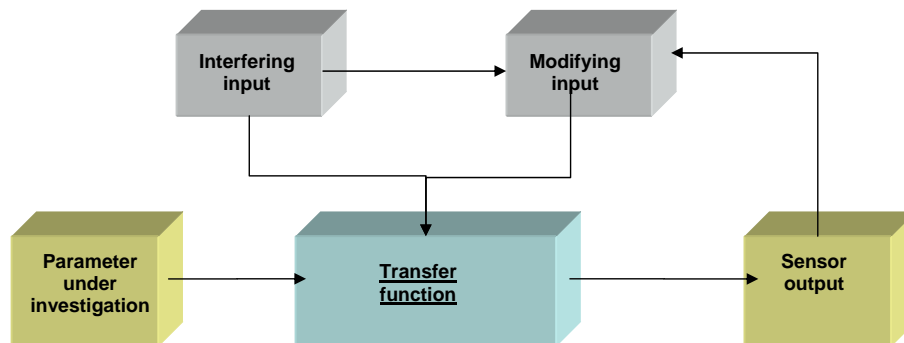


Fig. 2. Generic sensor model or input-output schema, where modifying input means influencing the transfer function and interfering input means adding to the uncertainty as noise component.

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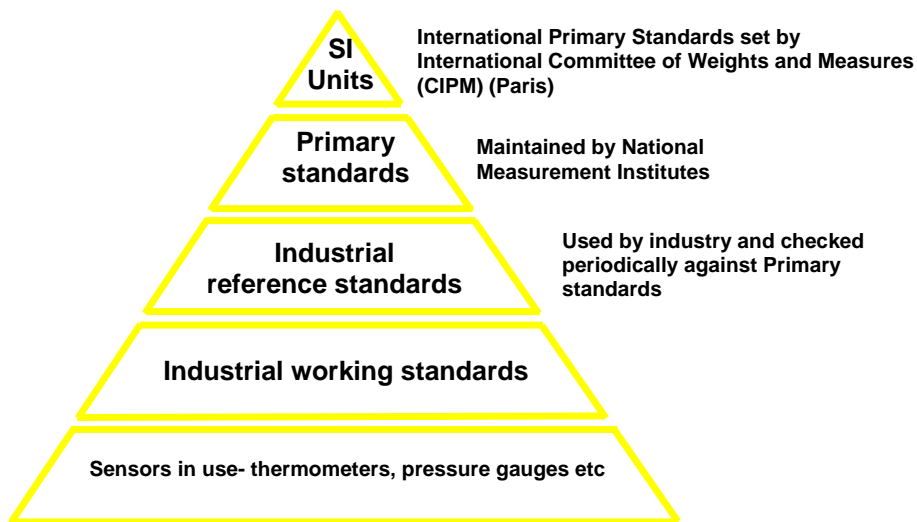


Fig. A1. Standards are traceable through a chain of comparisons.

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