Standards Requirements for LADARs? *

Geraldine S. Cheok[a], William C. Stone[a], and Alan Lytle[a]
cheok@nist.gov, william.stone@nist.gov, alan.lytle@nist.gov

[a]National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899-8611

ABSTRACT

This paper presents a discussion of standards requirements for LADAR. Two specific questions are addressed: (1) is there a need for such standards and (2) what types of standards are required? LADAR standards development issues and current standardization efforts are also summarized.

1. INTRODUCTION

LADAR (laser distance and ranging) technology has been available since the 1970s. Its widespread use (for examples see Fig. 1), however, was not achieved until the latter part of the 1990s because of a combination of instrument cost and limitations in data analysis software. LADAR technology advances have led to increases in speed of data acquisition, range accuracy and reliability as well as reduction in size and costs of the instruments. Corresponding improvements in computer technology have led to development of software that allows real-time processing, visualization, and manipulation of large data sets (several million data points). LADARs have been used to create 3D models of structures and scenes for quality control, surveying, mapping, reverse engineering, terrain characterization, and disaster reconnaissance. In addition, LADARs have been used for dynamic applications such as autonomous vehicle navigation and vehicle-based safety and warning systems.

Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

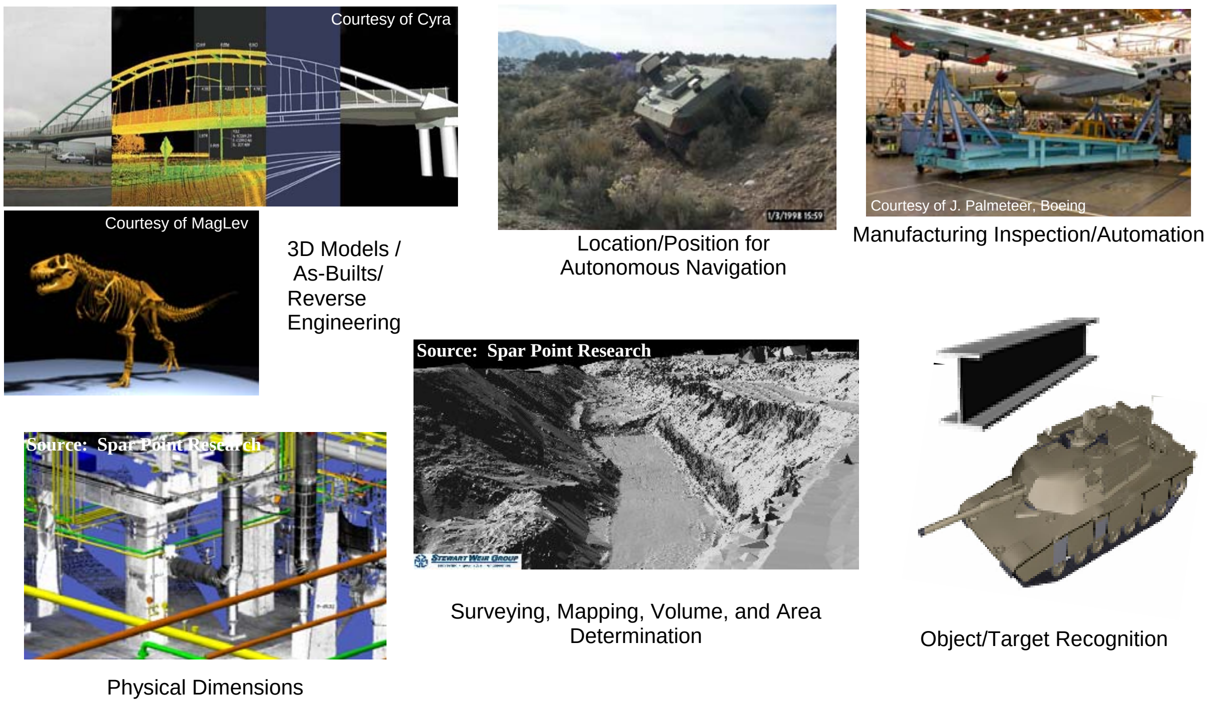

Figure 1. Some LADAR Applications.

As the use of LADARs increases, the need for the capability to characterize LADAR performance and to develop confidence limits for the LADAR data and their end products grows in tandem. Most manufacturers have developed their own test procedures and targets/artifacts to calibrate and evaluate their own products; these procedures are mostly proprietary. Some researchers have also developed methods and targets/artifacts to evaluate LADAR performance[1-13]. However, despite these efforts, there are currently no standard test protocols for the characterization and performance evaluation of LADARs or easily accessible facilities in which to conduct the evaluation.

In the past few years, there have been some nascent efforts to remedy this lack. One such effort is by the National Institute of Standards and Technology (NIST). The desired outcomes of this effort are the:

- ability to make rational comparisons between commercially available instruments through
    - clarification of commonly used terminology
    - development of standard test protocols and reporting
- facilitation of "factory floor" calibrations through the use of traceable artifacts and standard procedures
- availability to manufacturers and end users of a neutral facility for testing/calibration in environmentally controlled conditions

The other effort is by the International Society of Photogrammetry and Remote Sensing (ISPRS), Commission V, Working Group 3[†].

This paper will describe the need for LADAR standards and discuss the types of and issues related to standards needed for LADAR performance evaluation.

2. IS THERE A NEED FOR STANDARDS?

Most manufacturers and users agree on the need for some form of standardization[14] in terms of commonly used terminology, test protocols, and targets/artifacts. For a user, decisions to purchase an instrument are based, in part, on the manufacturer's specifications. Confusion as to the definitions or usage of common terms such as accuracy, resolution, and sampling speed may lead to the purchase of an instrument (a large capital expense) that may not be the best suited for the intended application. From a manufacturer's viewpoint, different definitions of the terms may lead a potential buyer to incorrectly conclude that one instrument is better than another. Additionally, availability of standards will tend to increase a user's confidence in LADAR measurements and encourage greater utilization of LADARs.

Besides standard definitions, standard test protocols and reporting of results are also required to allow for fair comparisons of instrument capability. Let's assume, for example, that the agreed upon definition for error is the difference or deviation of the measurement from the "true" or accepted reference value. The adoption of a definition alone, however, is not sufficient to give a buyer a sufficient basis for making a rational comparison. If the stated manufacturer accuracy[‡] is ± 1 m, can a buyer assume that if a target is located at 100 m, the measurements will be between 99 m and 101 m 100 % of the time? If so, how would one verify this? The obvious answer would be to conduct a performance evaluation or "calibration"[§] of the instrument which requires test protocols. In this case standard protocols are desirable because different test protocols will likely yield different results. The test protocols should detail the methodology and how the results are reported.

With regards to the method used to determine measurement uncertainty, the following issues should be considered: how many measurements are made, what are the range intervals, how many repetitions at each range interval, how long does the instrument "dwell" on a point (some instruments can take multiple measurements at a point and report the average of these measurements as a single measurement), what type of targets (reflectivity) are used, what is the test environment, how are the "true" or reference measurements obtained.

In terms of reporting results, do you report the mean of the deviations or the maximum deviation. Do you include the variability of the deviations – two instruments may have the same mean deviation but one could

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[†] Although the NIST and ISPRS efforts were initiated independently, the researchers involved in these efforts intend to keep abreast of each other's efforts and to participate in each other's efforts when possible.

[‡] Commonly, specifications for an instrument include accuracy and is specified as, for example, "Accuracy = ± 10 cm". This usage is incorrect as accuracy is a qualitative concept. It is believed that what is meant by the specification for "accuracy", in this case, is the uncertainty of the measurement. This again points to the need for clarification and proper usage of terms.

[§] As noted at the 2003 NIST LADAR workshop[14], even the term "calibration" has different meanings for different people. As defined in the VIM[15], calibration is "… a set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards." A manufacturer will typically calibrate an instrument to eliminate systematic error. An end-user will typically perform a calibration to verify an instrument is operating within stated tolerance.

have measurements with a lower uncertainty associated with them (more precise) than the other (less precise), etc. The differences in reporting uncertainty and in interpreting results are illustrated in Fig. 2.

It is commonly accepted that the true measurement is unknown; however, in Fig. 2, it is assumed that the conventional true value, obtained by calibration, is known. The difference between the conventional true value and the measurement is measurement error, E - a measure of accuracy.

In Fig. 2a, let two instruments, 1 and 2, have similar test results, but the reported error was defined as the absolute value of the mean of errors for instrument 1 and the reported error for instrument 2 was defined as the absolute value of the maximum error. A user will be misled into thinking that instrument 1 was more accurate than instrument 2.

Figures 2b and 2c show the results for 2 instruments – both instruments have the same mean error but the standard deviation of the errors for instrument 1 (σ_1) is less than that for instrument 2 (σ_2). For the situation illustrated in Fig. 2b, with all else being equal, instrument 1 would be a better choice than instrument 2. However, if the situation is as shown in Fig. 2c, 99 % of the measurements from instrument 1 would be within the bounds, $\overline{E}_1 \pm 3\sigma_1$, and would be less than the conventional true value. Instrument 2, on the other hand, may yield measurements that are equal to the truth some of the times, but these measurements have a greater uncertainty associated with them.

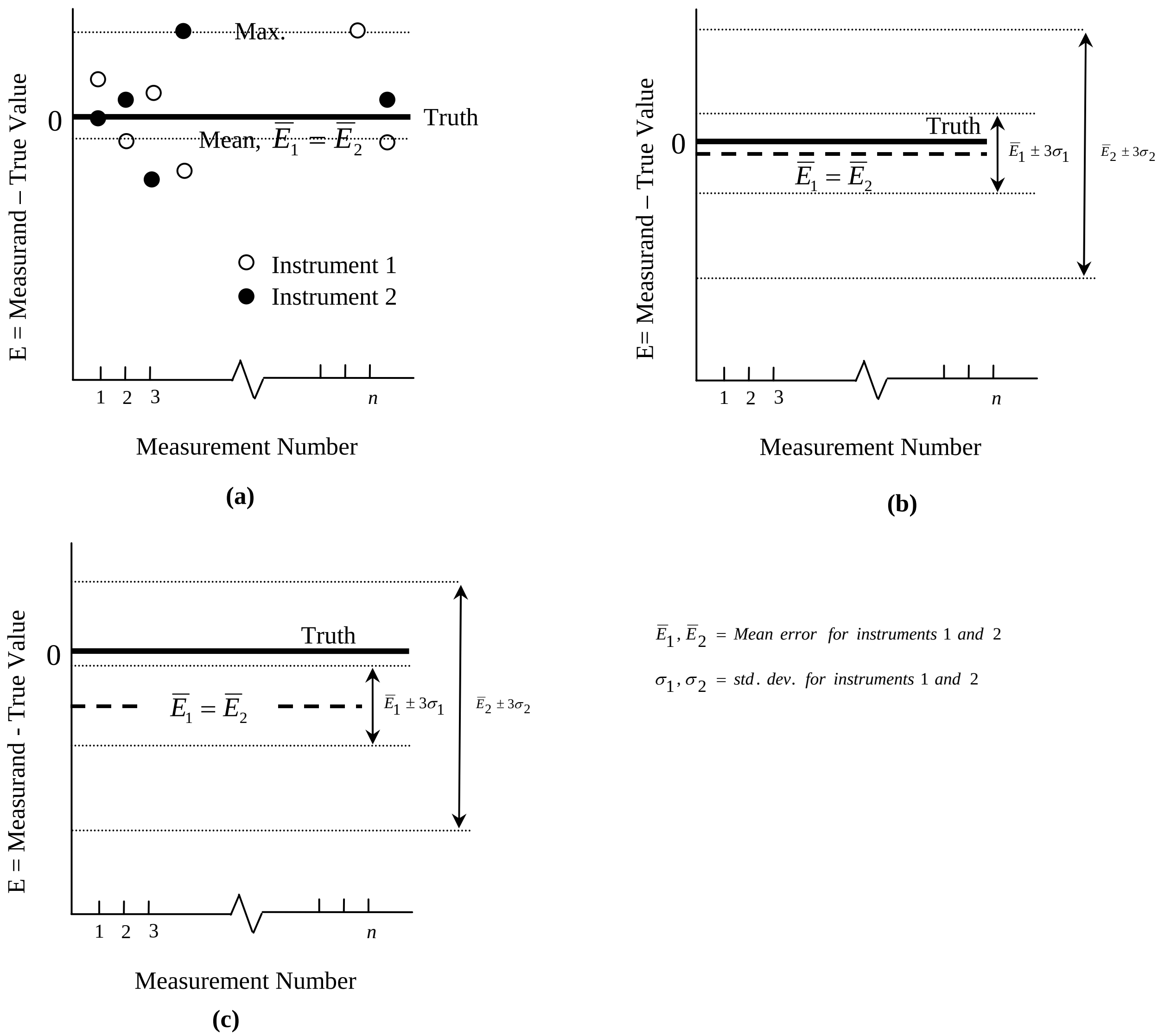

Figure 2. Reporting Test Results.

In addition to knowing the specifications of an instrument, users also need to know if an instrument is suitable for their particular application. For example, if the LADAR is going to be used for recording historic structures or works of art, the ability of the scanner to capture small features is important. If the instrument resolution were to be defined as the smallest distance – in the range (depth), horizontal, and vertical directions – between two objects that is discernible by the instrument, then standard procedures have to be developed on how one would go about determining the instrument's resolution in all 3 directions. A possible method would involve the use of artifacts; thus, standard artifacts (size, shape, material, etc.) will have to be developed as part of the methodology. Again, standardization of these procedures would allow for fair comparisons between instruments.

In situations where there is potential for litigation, the existence of standards is crucial in substantiating one's findings or results. These situations include the use of LADARs for documenting crime scenes, surveying, as-built modeling, and determining billable costs such as excavation and dredge volumes.

3. LADAR STANDARDS

3.1 TERMINOLOGY

Many of the terms such as accuracy, uncertainty, and repeatability already have universally accepted definitions that were developed by standards organization such as the International Organization for Standardization (ISO) - International Vocabulary of Basic and General Terms in Metrology (VIM), American National Standards Institute (ANSI) - U. S. Guide to the Expression of Uncertainty in Measurement[16], and ASTM (American Society of Testing and Materials) International – ASTM E456 – 02[17] Standard Terminology Relating to Quality and Statistics. In these cases, the existing definitions will be used.

It should be noted that these standard definitions have been in existence for many years, but there still exists some confusion in the marketplace as to their meaning or in their usage. The commonly used term "accuracy" is an ideal example. Accuracy is defined as the closeness of the agreement between the result of a measurement and a true value of the measurand and is a qualitative concept (VIM 3.5)[15]. However, the term "accuracy" has often been used interchangeably with precision and is assigned a value. First, the term "precision" is not defined in the VIM but in the VIM definition of accuracy, Note 2 states that "precision should not be used for accuracy." The term "precision" is defined in ASTM E456-02 as "the closeness of agreement between independent test results obtained under stipulated conditions." The notes included with the definition states that "precision depends on random errors and does not relate to the true value" and the measure of precision is "computed as a standard deviation of the test results." To lessen the confusion, Fig. 3 could be used to illustrate the difference between the concept of accuracy and precision.

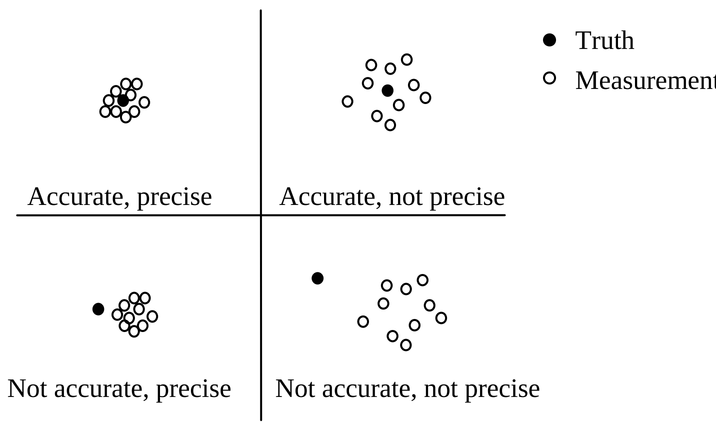

Figure 3. Accuracy vs. Precision.

Secondly, as noted earlier, rather than use the phrase "accuracy of ± *X* mm" which is incorrect usage, it is suggested that the specifications report the combined standard uncertainty, u_c, of the measurement and a level of confidence for the interval defined by u_c.

Other terms that are more specific to LADAR do not have definitions that are universally adopted. Such terms include range resolution, horizontal and vertical resolutions, and frame rate. Even the term LADAR for laser scanners is not universally used and causes some confusion in the marketplace. Often, the sample rate, points per second, is included in the instrument specifications. A more informative value may be the frame rate as a function of field-of-view and point spacing or angular increment. Consensus on the definitions of these and other terms will have to be achieved.

3.2 TEST PROTOCOLS

The assessment of LADARs is a two-part process. In the first part, certain basic characteristics of the instrument would be determined such as:

- Range uncertainty as a function of target reflectivity, range, and angle of incidence
- Pointing/angular uncertainty
- Repeatability – "Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement"[15].
- Reproducibility – "Closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurements"[15]. This is important since frequently the conditions under which the instrument is operated differ from those under which the instrument was originally evaluated or calibrated.
- Correlation
- Instrument resolution (smallest distance between objects that is discernible)
  - Range (depth)
  - Horizontal
  - Vertical

This evaluation would either be performed at an indoor facility where the environment can be controlled, or at an outdoor facility which would simulate actual operating conditions.

While the development of test protocols for some of the LADAR characteristics may seem straightforward, it is not. In the case of range uncertainty, some instruments are not designed to make single measurements as most LADARs are designed to function in a scanning mode. The laser will move from a position (point) once a measurement is taken and repeated measurements of the same point are not possible unless it is assumed that the instrument moves back to the exact same starting position. Also, centering the laser on the target is essential since any offset from center will introduce an error in the measurement. However, as many instruments employ lasers that are not visible, centering of the laser or determining perpendicularity of the target to the laser will be difficult.

The determination of the range uncertainty, a fundamental characteristic, however, is just a first step as conventional uncertainty analysis techniques are inadequate for complex 3-D shapes and surfaces. Contributions to the uncertainty budget from the instrument and environmental conditions and their propagation through computational formulas still apply. However, "simple" $(x, y, z) \pm [U(x), U(y), U(z)]$[**] representation for free-form shapes and for surfaces with complex features has to address issues such as:

- Varying data density across the scan region
- Uncertainties of the measurement device correlated with the geometry of each area being measured
- Positioning imprecision due to lack of natural coordinate origin, axis, or landmarks

Therefore, the development of a methodology to address the dimensionality and correlations of errors in measurements of three-dimensional artifacts is also essential for the first part of the assessment process.

[**] $U(x)$, $U(y)$, $U(z)$ are the uncertainties associated with the x, y, z values, respectively.

In the second part, the evaluation of the instrument will be based on answering the question – "how well would this instrument do what I need done?" As this is application specific, different evaluation procedures will have to be developed depending on the desired end product. For example, if the LADAR application is to track the amount of excavation performed at a construction site for billing purposes, the accuracy of the calculated volume is of paramount importance. Note that there are two sources of uncertainty in the calculated volume: 1) the uncertainty of the point locations as measured by the instrument and 2) the method of calculation such as meshing and its software implementation.

To illustrate the issues that are typically encountered when determining uncertainties of measurements based on LADAR data, the case of volume determination will be discussed in more detail. The uncertainty of individual LADAR measurements, in particular, the uncertainty of range measurement r_i causes uncertainty in volume measurements. One approach to assessing the latter uncertainty is to use the first order error propagation formula

$$u^2(V) \approx \sum_i^n \left(\frac{\partial V}{\partial r_i}\right)^2 u^2(r_i) + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\frac{\partial V}{\partial r_i}\frac{\partial V}{\partial r_j}u(r_i, r_j)$$

where a functional dependence of the volume $V = V(r_1, \ldots, r_n)$ on original range measurements r_i is assumed. Because of the large number of such variables, possibly in the millions, it is not practical to account for the cross-correlational terms involving the factors $u(r_i, r_j)^2$. However, consideration of these terms would be necessary, if the uncertainty specifications include systematic error sources. For this reason, the error propagation formula can only be used to gauge the effect of random instrument errors. This means that, in the above formula, the right most summation is removed and the uncertainties $u(r_i)$ are replaced by the observed standard deviations about expected values. Even then neglecting correlational effects needs to be justified. Nevertheless, assessment of the instrument noise will permit the evaluation of the volume uncertainty resulting from systematic errors.

The determination of volume uncertainty is, however, complicated by the fact that volumes are typically not expressed as an algebraic equation in terms of variables, but rather based on involved algorithms. It requires further research. The effect of systematic errors in individual instrument measurement may well be dominated by systematic errors caused by the choice of computational algorithm and scan registration.

Generally, the 3D data points defining the volume derive from separate scans and have been "registered" so as to refer to a common coordinate frame. Such registration methods tend to be involved and will constitute a major source of uncertainty by themselves. Standard data sets may be used to determine the uncertainty of the registration methods. The use of standard data sets, however, may not isolate the sources of registration error arising, for instance, from locating fiduciary target centers, placement of targets[9], and fitting algorithms for spheres – commonly used 3D reference artifacts for registration.

Direct experimentation, thus, may be the only way to quantify the uncertainties of volume calculation. Development of these experimental procedures would include addressing the following issues:

- If a test site or terrain is used,
  - How do you measure the true volume?
  - What is "typical" terrain?
  - How do you handle occlusions / how do you determine optimal locations for the instrument?
- If artifacts are used:
  - Can you extrapolate the results for well-defined, manufactured artifacts when the actual "object" is amorphous, unstructured, and of varying reflectivity?

  - What kinds of artifacts would be appropriate?
  - What is the size(s) of the artifact?
  - Since the size of a construction site is several orders of magnitude larger than any potential artifacts, is there a scale effect and if so, would the uncertainties scale linearly?
- How do you post-process/ filter/ clean data?

Although the details may differ, many of the main issues for volume determination are also relevant to other “static” applications. Other issues such as frame rate and post-processing speed need to be addressed for dynamic applications such as the use of LADARs for vehicular collision avoidance where obtaining real-time data is crucial.

Another issue that will need to be addressed is a standard LADAR data format which would enable interoperability between any instrument and any software package.

3.3 SIMILAR STANDARDS

Other instruments used to obtain 3D measurements include laser trackers and coordinate measuring machines (CMMs). Both laser trackers and CMMs are contact instruments (there are non-contact CMMs, but currently, non-contact CMMs are not as accurate as contact CMMs and are not widely used). Standards are available for evaluating and re-verification of CMMs (ASME B89.4.1 – 1997, ISO 10360-2, ISO 10360-4) and a draft standard (ASME B89.4.19) is available for laser trackers – the draft standard is expected to be adopted within a year. These standards may be helpful in the development of standards for LADARs, for instance, the tests to assess the ability to measure known lengths in B89.4.19. However, these related standards are not directly applicable to LADARs because:

- The sources of errors for LADAR measurements are very different from those for CMMs because they are fundamentally different instruments. These sources of error vary depending on the type of LADARs (e.g., time-of-flight, phase-based, triangulation) and the architecture/mechanism (e.g., rotating mirrors, stepper motors) and assembly of the instrument. Determination of these errors require intimate knowledge of the instrument, and for proprietary reasons, such knowledge is generally not available.
- LADARs have the ability to capture millions of points in a matter of minutes which is several orders of magnitude above that for CMMs and laser trackers. This being the case, the applications for LADARs are vastly different from those for CMMs and laser trackers. In general, LADAR data is not the ultimate product but rather derived quantities such as 3D models, topographical maps, and volumes which involve the use of software (e.g., registration, meshing, fitting algorithms). Therefore, knowing the uncertainty of the range measurements is just a first step towards quantifying the uncertainty of derived quantities.

4. CURRENT EFFORTS

As mentioned earlier, although there have been efforts made to evaluate LADAR performance, there is a lack of standardization of these test protocols. Since measurements and standards are at the core of NIST’s mission, NIST researchers in the Building and Fire Research Laboratory (BRFL), Manufacturing Engineering Laboratory (MEL), and the Information Technology Laboratory (ITL) are working towards developing some of these protocols.

In June 2003, NIST held a LADAR Calibration Facility Workshop. The main objectives of the workshop were to provide a forum for sharing and discussing current efforts in LADAR calibration, to explore the need for a neutral calibration facility, and to determine the types of test protocols required. The participants agreed on the need for some form of standardization and a neutral facility. However, the general consensus was that a single facility that would encompass the entire range of LADARs would be impossible. Therefore, three kinds of testing facilities were envisioned as being necessary:

- a small, highly climate controlled, indoor, artifact-based facility for highly accurate, short range instruments (< 10 m).
- a medium sized, climate controlled indoor facility for instruments with ranges up to 50 m.
- an outdoor testing area for long range instruments and for testing in a more realistic environment.

Recommendations from the workshop include developing definitions for common terminology, standard targets/artifacts/standard reflectivity, and standard procedures for performance assessment/evaluation.

Since the workshop, NIST has focused on establishing a small indoor facility given the availability of funding and lab space. A high resolution scanner with a range uncertainty of ± 100 µm (k = 2) and a maximum range of 24 m was acquired and some potential prototype artifacts have been explored (See Fig. 4). Active research is also underway at NIST regarding the establishment of an outdoor facility that will initially address performance metrics for unmanned ground vehicle LADAR imagers and obstacle avoidance algorithms. A second workshop will be held on March 15-16, 2005 at NIST to solicit input from end users, manufacturers, and researchers to develop a list of commonly used terminology for LADARs and their definitions, to determine what types of measurements are required, and what type of artifacts are required to evaluate a given measurement.

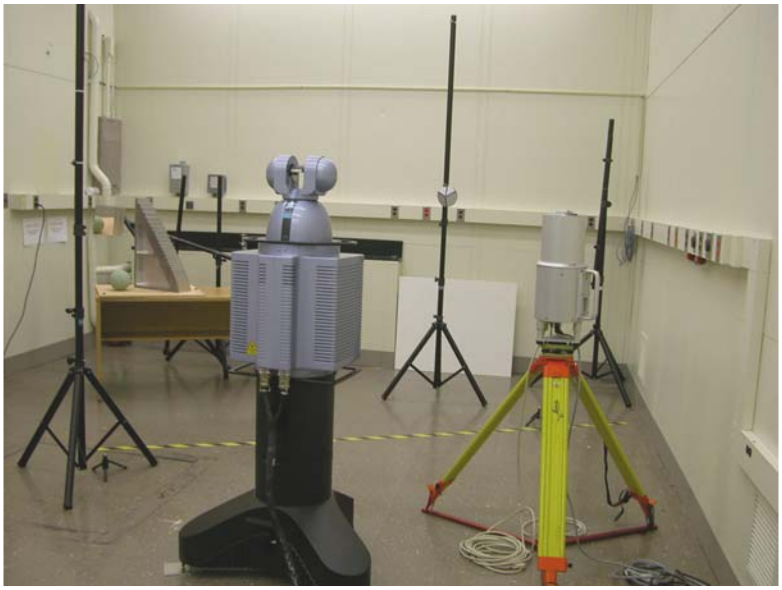

Figure 4. Small, Indoor Artifact-Based Performance Evaluation Facility.

In addition to NIST's efforts, an international effort was recently initiated by the ISPRS Working Group V/3 Terrestrial Laser Scanning to address standardization of test protocols for LADARs. The areas of interest or issues that the ISPRS working group is working on include[18]:

- Automated algorithms for sensor orientation, including practical evaluation of registration algorithms
- Scene classification and feature extraction
- Integration with other data sources, particularly imagery for texture mapping, and other sensors for observing exterior orientation elements
- Modeling of systematic error sources and development of calibration procedures
- Modeling laser scanner measurement processes internal and external to the instrument

The working group plans on having datasets, captured with different scanners, available to working group members for testing and comparing registration algorithms in the near future.

SUMMARY

"The current strategic environment in which measurements are being conducted in both the public and private sectors is characterized by rapid changes in technologies, the continued emergence of new measurement areas and nontraditional measurement needs, and increasingly blurred lines between disciplines; accompanied by increasingly blurred lines between the national and international measurement systems. … The rate of change in new technologies is in some cases outpacing the ability of national and international bodies to come to consensus on needed support (standards, mutual recognition arrangements, etc.) and put the appropriate infrastructures in place, leading to the emergence and proliferation of private groups establishing standards, measurements, certifications, with or without governmental and international buy-in."

These statements, taken from a NIST U.S. Measurement System Task Group's white paper, are applicable to all aspects of current LADAR technology. Applications for LADAR span many disciplines and the use of LADAR has increased rapidly in recent years; however, standard performance evaluation/calibration protocols have yet to be developed.

In this paper a case for standardization of terminology and test protocols for LADARs is presented. It points to a need by manufacturers with large financial stakes in producing and selling their instruments and by end users with large investments tied up in equipment and who have vested interest in LADARs to improve their productivity.

The need for standard protocols appears to be the most pressing for certain basic LADAR characteristics such as range uncertainty, pointing uncertainty, repeatability, reproducibility, and correlation. Included in this process is the development of targets with standard reflectivity. A second type of protocols involves standard procedures such as those for evaluating resolution, object segmentation/identification, volume determination, extracting dimensions, etc. These procedures may involve the use of artifacts and/or software (e.g., registration, ground truth determination, object segmentation/ feature extraction). Therefore, standard artifacts and standard data sets would have to be developed.

Anyone who has been involved in the development of standard procedures can attest to the fact that this is a very long process and involves long-term commitment. Considerable research is required to determine relevant or contributing factors. Care has to be taken to ensure procedures that are not biased towards or against any instrument and do not exclude any instrument. And finally, a consensus has to be reached. It is encouraging to note efforts underway in these areas[1-14] by researchers, manufacturers, and end users around the world. In the short term, it is also worth noting that if there is an industry need, guidance documents or best practices may be developed as part of the standards development process. Those interested in participating in this process should contact the authors directly at the email addresses listed on the first page.

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