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TOPOGRAPHICAL MAPPING SYSTEM FOR RADIOLOGICAL AND HAZARDOUS ENVIRONMENTS ACCEPTANCE TESTING*

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DISCLAIMER

Topographical Mapping System for radiological and hazardous environments acceptance testing*

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ABSTRACT

During the summer of 1996, the Topographical Mapping System (TMS) for hazardous and radiological environments and its accompanying three-dimensional (3-D) visualization tool, the Interactive Computer-Enhanced Remote-Viewing System (ICERVS), were delivered to Oak Ridge National Laboratory (ORNL). ORNL and Mechanical Technology, Inc., performed final acceptance testing of the TMS during the next eight months. The TMS was calibrated and characterized during this period. This paper covers the calibration, characterization, and acceptance testing of the TMS.

Development of the TMS and the ICERVS was initiated by the U.S. Department of Energy (DOE) for the purpose of characterization and remediation of underground storage tanks (USTs) at DOE sites across the country. DOE required a 3-D, topographical mapping system suitable for use in hazardous and radiological environments. The intended application is the mapping of the interior of USTs as part of DOE's waste characterization and remediation efforts and to obtain baseline data on the content of the storage tank interiors as well as data on changes in the tank contents and levels brought about by waste remediation steps. Initially targeted for deployment at the Hanford Washington site, the TMS is designed to be a self-contained, compact, and reconfigurable system that is capable of providing rapid, variable-resolution mapping information in poorly characterized workspaces with a minimum of operator intervention.

Keywords: Topographical mapping system, structured-light, underground storage tank, radiological environment, hazardous environment

1. INTRODUCTION

This paper focuses on the acceptance test of the Topographical Mapping System (TMS). The TMS was tested for a resolution of 25.4 mm (1.0 in.) and an accuracy of +/- 6.35 mm (+/- 0.25 in.) over the specified range of 13.7 m (45 ft). The TMS was tested to ensure that the unit can be deployed through multiple risers and maintain accuracy and registration of the surface mapping data. In addition, the TMS was disassembled, reassembled, and redeployed to test field replacement of sensor head modules that are deployed in the vapor space of the underground storage tanks (USTs).

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The TMS was developed by the U.S. Department of Energy (DOE) Tanks Focus Area under the sponsorship of the Office of Science and Technology (EM-50). The Oak Ridge National Laboratory (ORNL)-developed surface mapping system (deployed in the K65 storage tanks at Fernald in 1991) and the prototype surface mapping system developed under a Cooperative Research and Development Agreement (CRADA), which was demonstrated at the Hanford site in 1993, were funded by the DOE Robotics Technology Development Program. (Additional funding was provided for the CRADA by MTI.)

1.1 ORNL USTs

The primary mission of ORNL during WWII was the processing of pure plutonium metal in support of the Manhattan Project. By-products of this process include radioactive cesium-137 and strontium-90. Between 1943 and 1951, the gunite and associated tanks at ORNL were built to collect, neutralize, and store these by-products. Currently, there are 12 gunite tanks and 4 stainless steel tanks located on the ORNL complex. These tanks hold approximately 284 kL (75,000 gal) of radioactive sludge and solids and over 1.325 ML (350,000 gal) of supernatant. Characterization studies of these tanks in 1994 indicate that the structural integrity of some of the tanks is questionable. Consequently, there is a potential threat to human health through contamination of soil and groundwater. These risks provide the motivation for remediation and relocation of waste stored in the tanks.

1.2 HANFORD USTs

USTs at DOE sites, such as the Hanford site in southeastern Washington State, contain hazardous, radioactive waste generated during defense material production during the past 50 years.[1] A number of the tanks have been used past their intended design life and are deteriorating; some have leaked contamination into the surrounding environment. Stabilization and remediation of these tanks is a high priority for the DOE Environmental Restoration Program. The TMS will gather vital data needed to respond to ongoing questions about the safe storage of waste materials and to quickly investigate tank events that raise safety concerns; e.g., leaks.

There are 149 single-shell tanks (SSTs) at the Hanford site. The SSTs range in size from 208,000 to 3,800,000-L (55,000 to 1,000,000 gal). The tanks are cylindrical, constructed with reinforced concrete, and lined with carbon steel. The 208,000-L tanks (there are 16 total) have flat tops and are 6 m (20 ft) in diameter. The larger tanks have domed tops and are 23 m (75 ft) in diameter. Tank heights vary depending on capacity. There is considerable variation in the number, location, and type of openings in the tops of the tanks, with the majority having at least one 107-cm (42 in.) diameter opening in the center and one or more 10.16-cm (4 in.) opening around the periphery. The top of a typical tank is 2.5 m (8 ft) below grade.

The original waste consisted of liquids (strong acids) from the plutonium separation process. The acids were neutralized before they were put in the tanks. The neutralization process caused a complex mixture of solids to precipitate and form a layer of sludge in the bottom of the tanks. To reduce the volume of the liquids, as well as remove radioactive isotopes of cesium and strontium, a waste reduction process was initiated in the 1960s. This program significantly reduced the amount of water (using evaporation) and the concentration of cesium and strontium. The result was a concentrated salt slurry, which was returned to the USTs. The salt slurry is now salt cake. Although not fully characterized, it is estimated that radiation levels near the surface of the salt cake in a typical tank are less than 1 Gy/h (100 R/h). The USTs at Hanford contain residual liquids and sludges from past radiochemical separation processes.

2. TOPOGRAPHICAL MAPPING SYSTEM

In 1991, ORNL developed and deployed a structured-light-based surface mapping system in the K65 tanks at the Fernald site.[2] The structured-light surface mapping system was used to determine the waste surface data and clay cap surface data. The data was used to ensure that the clay cap that was applied over the waste was a minimum of 30.48 cm (12 in.) deep at all locations, per U.S. Environmental Protection Agency requirements. In 1993, ORNL and Mechanical Technology, Inc. (MTI), initiated a CRADA for the development of a structured-light surface mapping system for deployment in the USTs at the Hanford site. The successful CRADA demonstration at Hanford in June of 1994 proved that a structured-light surface mapping system could be built to penetrate a 10.16 cm (4 in.) clear aperture and map the insides of a UST to ranges of 13.72 m (45 ft) with an accuracy of 6.35 mm (0.25 in.). Based on the results of the deployment at Fernald and the CRADA, a request for proposals was generated in February of 1994 to develop a surface mapping system that could withstand the radiological and hazardous environments at the Hanford site. The contract was placed in May of 1994 to MTI of Albany, New York. The system was delivered to ORNL in June of 1996 for acceptance testing and completed acceptance testing in February of 1997. The TMS was deployed in tanks W5 and W6 of the South Tank Farm (STF) at ORNL in February of 1997.

After deployment at ORNL, the system was delivered to the Hanford site and used to demonstrate volumetric measurement of waste in the Fuel Materials and Examination Facility cold test facility in March of 1997.[3] The development of the TMS was initiated by DOE for the purpose of characterization and remediation of USTs at DOE sites across the country. DOE required a three-dimensional (3-D), TMS suitable for use in hazardous and radiological environments. The intended application is the mapping of the interior of USTs as part of DOE's waste characterization and remediation efforts and to obtain baseline data on the content of the storage tank interiors as well as data on changes in the tank contents and levels brought about by waste remediation steps. The TMS initially targeted for deployment at the Hanford site USTs, which are defined in the Westinghouse Corporation documents WHC-EP-0352, *Single Shell Tank Waste Retrieval Study*,[4] and WHC-SD-RE-TI-053, *Riser Configuration Document for Single Shell Tanks*.[5] *The Topographical Mapping System for Radiological and Hazardous Environments Statement of Work*[6] defines the performance specifications of the TMS and the environmental conditions under which the TMS must operate. The TMS was designed to be a self-contained, compact, and reconfigurable system that is capable of providing rapid, variable-resolution mapping information in poorly characterized workspaces with a minimum of operator intervention.

2.1 SYSTEM REQUIREMENTS

The primary purpose of the TMS is to generate reliable, registered, and accurate 3-D maps of the internal surfaces of USTs. In addition to the walls, dome, and waste, these tanks also contain salt pumps, air circulator risers, thermocouple trees, and objects that have fallen into or been placed in the tanks. One use for this mapping system is in creating and maintaining a current 3-D map of the tank interior as input to a robotic "world model" that is used to test remediation strategies or plan robot trajectories. Another use is tracking the movement of the waste surface as it responds to expanding bubbles of trapped gas. A third use of the TMS is to perform a volumetric analysis of the amount of waste removed from the tanks during remediation by mapping the waste before and after remediation activities. A fourth use of the TMS is in determining how much waste is left in the tank. The fourth application requires accurate drawings of the tank or a method by which an accurate description of the tank structure can be constructed.

Performance requirements are based on the *Functions and Requirements for the Light-Duty Utility Arm Integrated System*[7] document from Westinghouse Hanford Company (WHC) and Pacific Northwest National Laboratory (PNNL) along with insights and lessons learned at ORNL through previous surface mapping projects. The primary requirements are as follows:

1. Accuracy requirements may vary considerably. For example, to track the movement of the waste surface, it may be necessary to measure changes as small as 2.54 mm (0.10 in.). For collision avoidance, measurement errors of 101.6 mm (4.0 in.) are acceptable. The TMS has been specified to provided an accuracy of +/- 6.35 mm (+/- 0.25 in.) over a range of up to 13.7 m (45 ft).
2. Mapping data densities should be at least one point per 152.4 by 152.4 mm (6 by 6 in.) region covering up to 95% of the surfaces in the tank. The time required for mapping cannot exceed 2 hours at this data density, although more time would be allowed for mapping at higher densities. The highest density that the TMS is required to provide is one point in every 25.4 by 25.4 mm (1.0 by 1.0 in.) region of surface [the present system can provide one point every 2.54 by 2.54 mm (0.10 by 0.10 in.)].
3. The TMS has been specified to operate in a continuous flux of 5 Gy/h (500 Rads/h) and an intermittent peak flux of 10 Gy/h (1000 Rads/h) up to a total absorbed dose of 1.0E+4 Gy (1.0E+6 Rads) over a six-month period without failure caused by radiation.
4. The TMS has been specified to be deployed through a 88.9-mm (3.5 in.) clear aperture to allow deployment through the 101.6-mm (4 in.) risers at the Hanford site but can also be deployed through the 304.8-mm (12 in.) or larger risers.
5. The TMS has been specified to be Class 1 Division 1 Group B hazardous environment compliant to permit the use of the TMS in tanks that contain volatile gases.
6. A temperature range of 10 to 50°C (50 to 122°F) with a noncondensing relative humidity of 100% has been specified to allow the TMS to operate in the varying environments that may be found in the tanks at the Hanford site.

2.2 SYSTEM DESCRIPTION

The TMS is a distributed architecture computer-based system that also collects temperature and radiation flux measurements and has a single point laser range finder. The topographical mapping sensor uses structured-light for surface mapping. Structured-light is a triangulation-based range measurement technique. The structured-light measurement technique projects a laser plane on to the surface to be mapped. The resulting intersection of the laser plane and the surface produces a contour line annotating the shape of the surface. A camera is used to image the resulting laser plane's contour line. Figure 1 is a time-lapsed photograph of the TMS scanning the laser over a simulated waste surface of sand and salt-cake. The charge-coupled device (CCD) camera has a vector assigned to each pixel in the CCD array. Every point that is illuminated by the laser line reflection is passed to analytical routines for processing. The analytical routines solve for the intersection of the fixed vector assigned to the pixel in the camera with the equation of the plane of the laser (each intersection of a vector and the laser plane produces an <XYZ> point in space). In summary, by combining the range measurement with the geometric relations between the camera and the laser, the TMS is able to determine the <XYZ> description of points located on the surfaces of the interior of the USTs with respect to a world coordinate frame located typically at the bottom center of the tank.

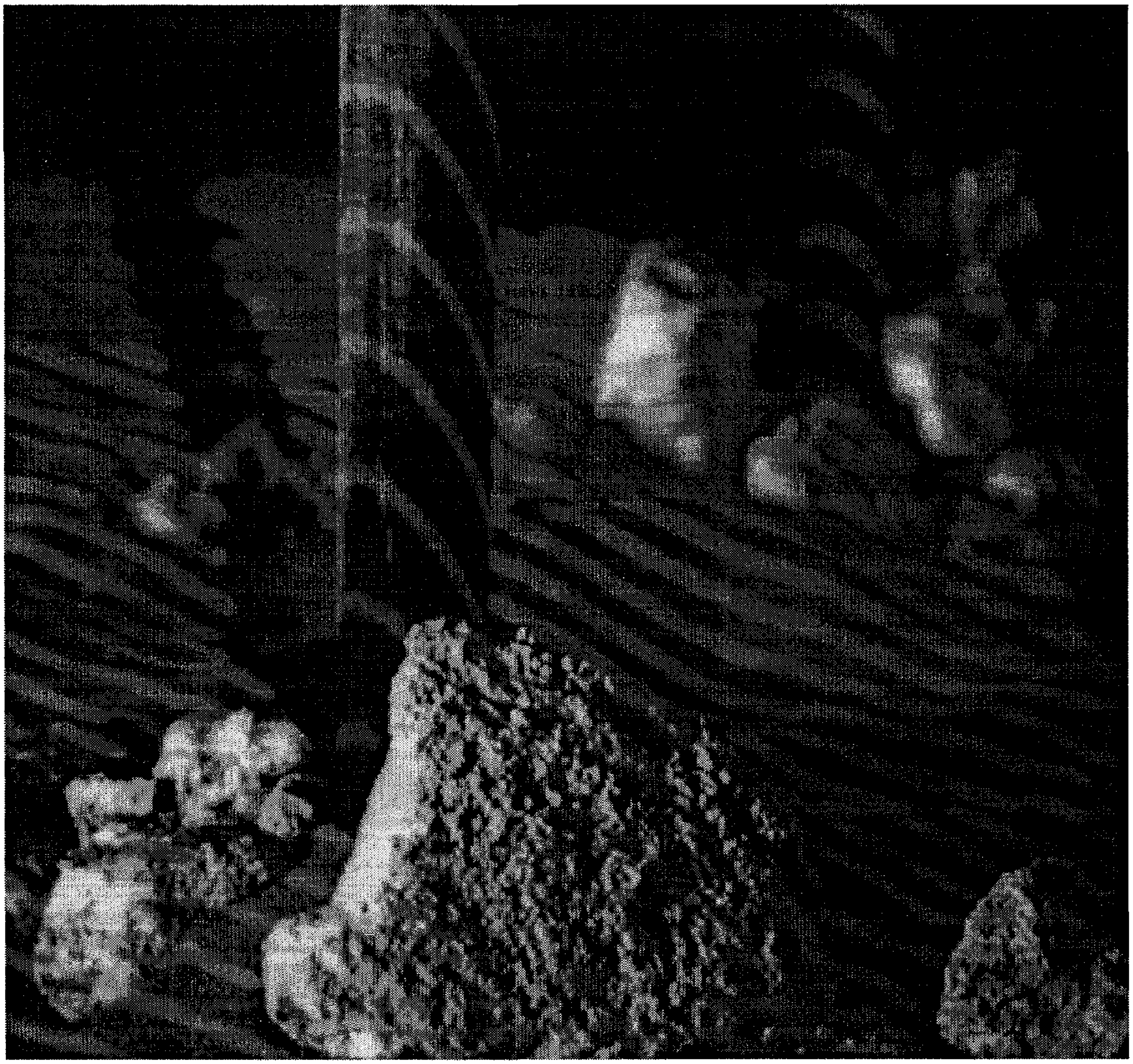

Figure 1. Time-lapsed photograph of the structured-light mapping process. The photograph illustrates the manner in which the laser plane creates a contour line where it intersects with the surface. Objects in the photograph include sand, simulated salt-cake (the white rocks) and two black vertical pipes.

The TMS has four major components:

1. The sensor head contains the optical metrology sensors that penetrate the vapor space of the tank and provide the topographi map of the interior surfaces.
2. The environmental enclosure box (EEB) contains all the support electronics that require proximity to the sensor head (e.g., fra grabber, motor controllers, and the local control computer).
3. The human machine interface (HMI) is located in a control trailer located at most 274.3 m (900 ft) away and is used supervisory control, limited data visualization, and data archiving. The HMI is a UNIX-based scientific and engineer workstation that provides the graphical operator interface and supports the various command, control, and communicat functions.
4. The plug gauge is used to test the clear aperture of the riser deployment of the sensor head. The plug gauge also contains environmental sensor section (ESS) that provides measurements of temperature, radiation, and range that are used to deploy sensor head. (The ESS can also be attached to the distal end of the sensor head, or the sensor head can be deployed with a dum ESS module.)

The 3-D visualization system used by the TMS is the Interactive Computer-Enhand Remote-Viewing System (ICERVS) softw tool.[8] ICERVS was developed by MTI for use in DOE characterization and remediation efforts under contract to the Federal Ene Technology Center. The ICERVS tool allows for display and analysis of the unusually large data sets generated by mapping US that can be as large as 22.86 m (75 ft) in diameter with 7.92 m (26 ft) walls. Mapping the walls, floor, and dome of typical 22.86 (75 ft) diameter empty tank would generate 3 million data points (or a 180-MB file).

The system block diagram is illustrated in Figure 2 and the sensor head deployed in a UST is illustrated in Figure 3.

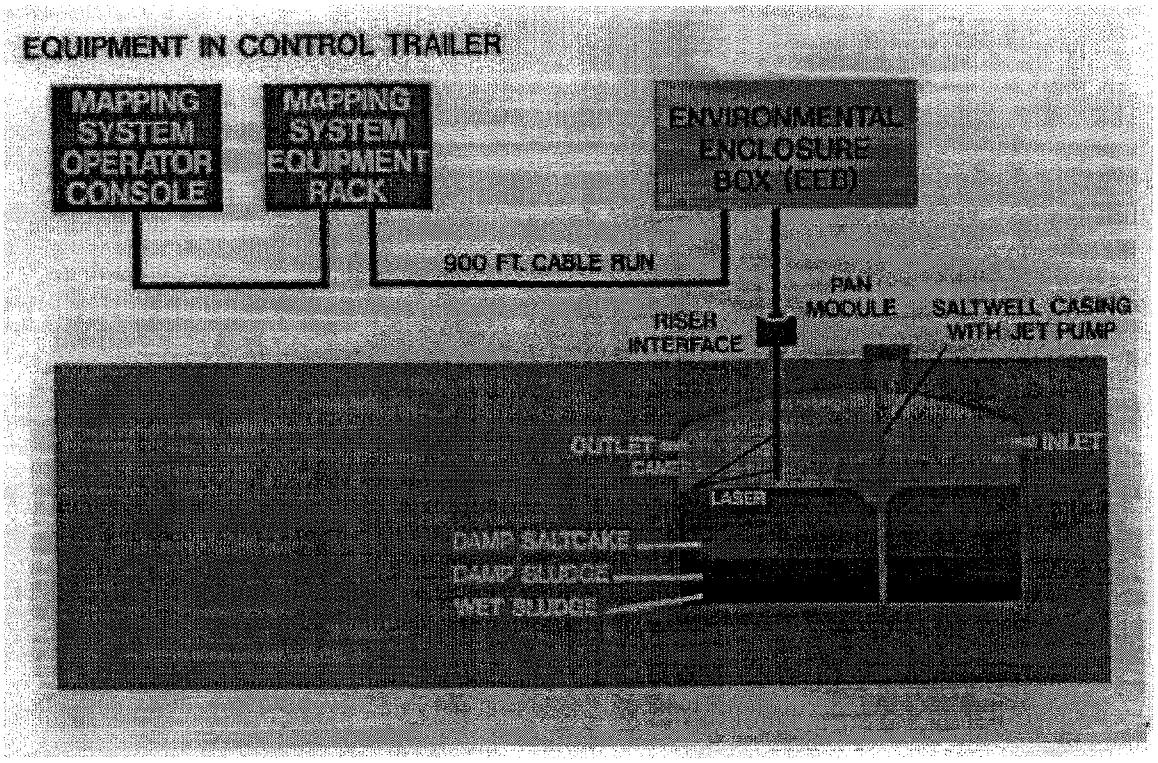

Figure 2. TMS block diagram.

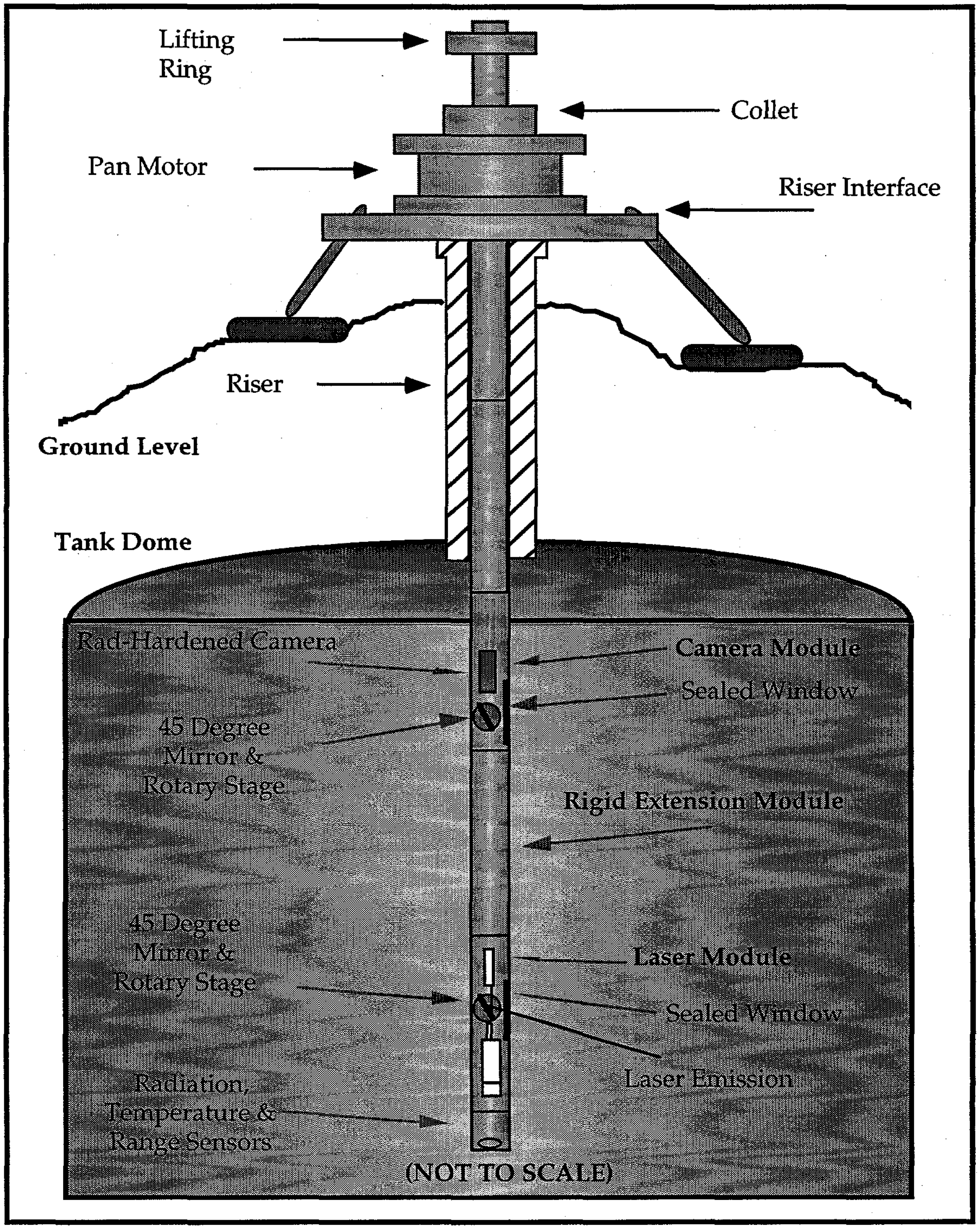

Figure 3. TMS sensor head deployed in a UST.

Other systems needed to deploy the TMS that were not included as part of the base system include a purge gas supply and withdrawal system, the structure used to position and hold the TMS sensor head over the riser (such as a trailer and strong-back), containment systems used to contain the riser openings, and containment storage structures. These systems, or suitable alternatives, have to be supplied on site as they are not currently part of the TMS deliverables. The ICERVS tool has been delivered to DOE, but third party licenses necessary to use the tool must be provided by the user.

2.3 CALIBRATION AND CHARACTERIZATION

The TMS has been calibrated and characterized through the use of the high bay and basement in the Robotics and Process Systems Division's (RPSD's) facility at ORNL. The TMS sensor head was deployed through a 10.16-cm (4 in.) hole bored in the floor between the high bay and the basement. The high bay provided access to the pan motor and the EEB and allowed for overhead crane deployment of the TMS. The testing area in the basement is approximately 18.3 m (60 ft) long and 9.14 m (30 ft) wide. The floor of the basement is 6.1 m (20 ft) below the floor of the high bay, which puts the TMS camera at 5.33 m (17 ft, 6 in.) above floor level. This provides for a maximum range of 10.6 m (34 ft, 8 in.) from a diagonal that originates at the camera at the proximal end to the bottom of the wall 9.14 m (30 ft) away at the distal end. The minimum range was 5.76 m (18 ft, 11 in.) because of the 22-degree half-angle occlusion area directly beneath the TMS sensor head. This permits angles of incidence that range from 22 to 60 degrees. A top and side view of the TMS sensor head deployed in the RPSD facility is illustrated in Figure 4.

The floor of the basement was marked off with a metal measuring tape that was positioned for alignment with the Y axis of the TMS coordinate system in its home position. The measuring tape was aligned with a theodolite that was centered on the TMS sensor head. The theodolite ensured that the measuring tape was laid out directly down the Y axis of the TMS. Measurements made in the measuring tape coordinate frame could be quickly mapped into the TMS coordinate frame for comparison purposes. To further facilitate the verification and testing of the TMS's ability to accurately measure points in the basement, a Pentax PTS-V Total Station[9] was used to accurately survey points in the basement. After registering the Total Station coordinate space and the TMS coordinate space to a known reference space, the surveyed points were then transformed to the TMS coordinate frame for direct comparison with the TMS measurements.

The first part of the calibration of the TMS involved the alignment of the laser and camera modules on their respective rotary stages. The second part of the calibration determined the fixed vectors that are assigned to each camera pixel and the kinematics of the laser and camera rotary stages. The camera vectors are determined by the two-plane camera calibration method.[10,11]

The final part of the TMS calibration was to calibrate the five coordinate frames between the three joints and the various modules used to configure the TMS sensor head. The first deployment of the TMS was scheduled for the USTs in the STF at ORNL, shown in Figure 5. As a result, the six calibration targets were placed in positions to optimize the TMS's measurement accuracy for measuring degradations in the ORNL UST walls of tanks W5 and W6 at the STF. Tanks W5 and W6 are 15.2 m (50 ft) in diameter with 3.6 m (12 ft) walls and are capped with domes that crest 1.8 m (6 ft) above the walls. The central riser extends 2.1 m (7 ft) up past the dome that is then bermed with dirt. The height from the top of the central riser to the bottom of the tank is 7.6 m (25 ft). For the ORNL deployment, only the walls of the tank were mapped. (The first deployment at ORNL was to measure cracks and spalling concrete as well as signs of structural instabilities in the UST walls, so the TMS was optimized for these measurements.) This calibration step required that six targets be position in the measurement space of the TMS in the RPSD basement. The targets consisted of 21.6 x 27.9 cm (8.5 x 11 in.) sheets with a donut shaped target. The targets were mounted on vertical bars that permitted the height of the targets to vary from 0.6 to 3.6 m (2 to 12 ft). Four targets were placed at 7.6 m (25 ft) laterally out from the TMS sensor head. One target was placed at 7.0 m (23 ft) and the remaining target was placed at 8.2 m (27 ft). The total station was used to measure the position of the targets and these positions were then transformed to the TMS coordinate space. The TMS then measured the position of the six targets and the Simplex optimization algorithm was used to minimize the error vectors while calibration coefficients in the TMS mathematical model were modified. The dimensions of an STF UST and the TMS sensor head are illustrated in Figure 5.

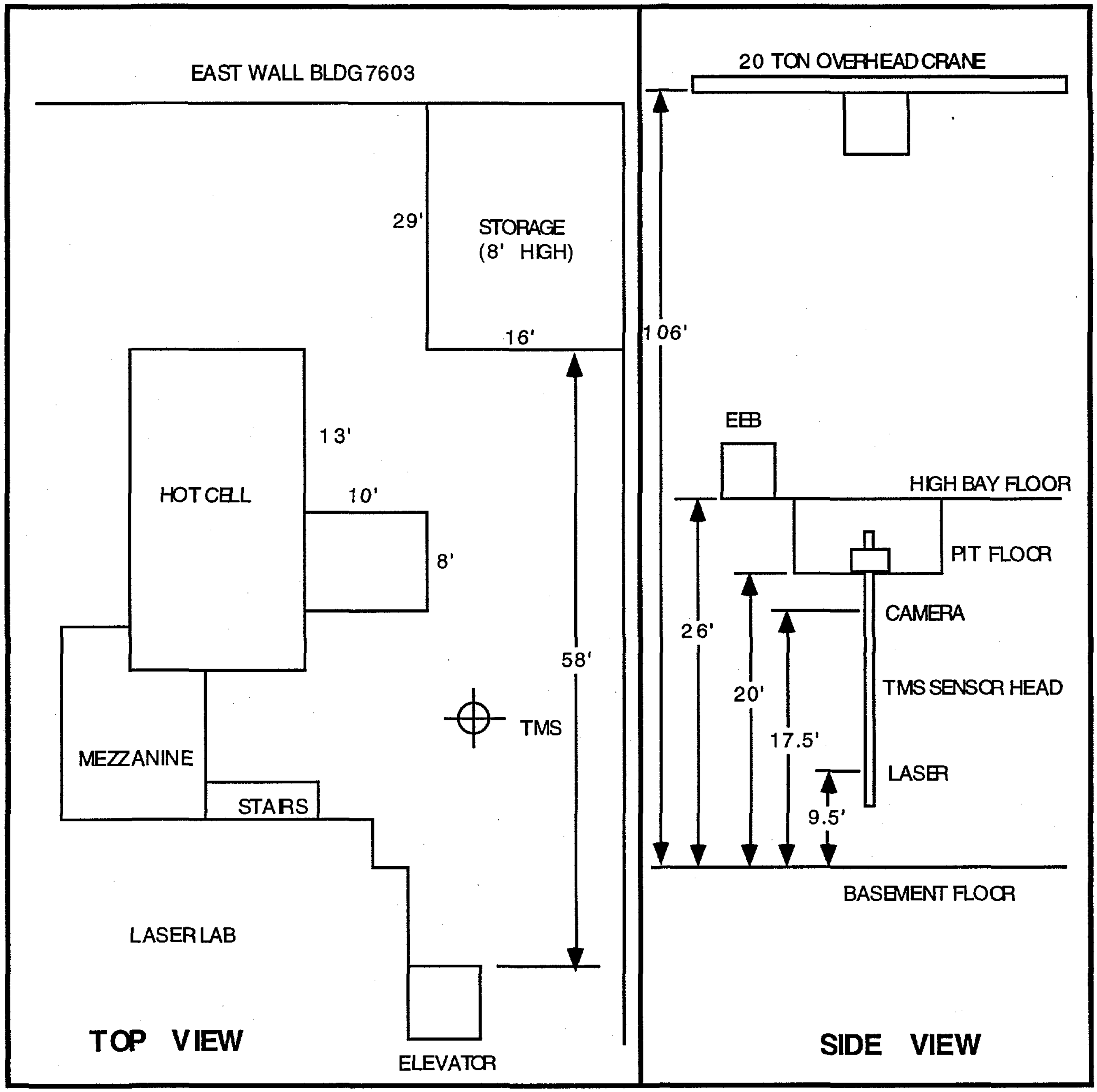

Figure 4. Deployment of the TMS sensor head in the RPSD facility at ORNL.

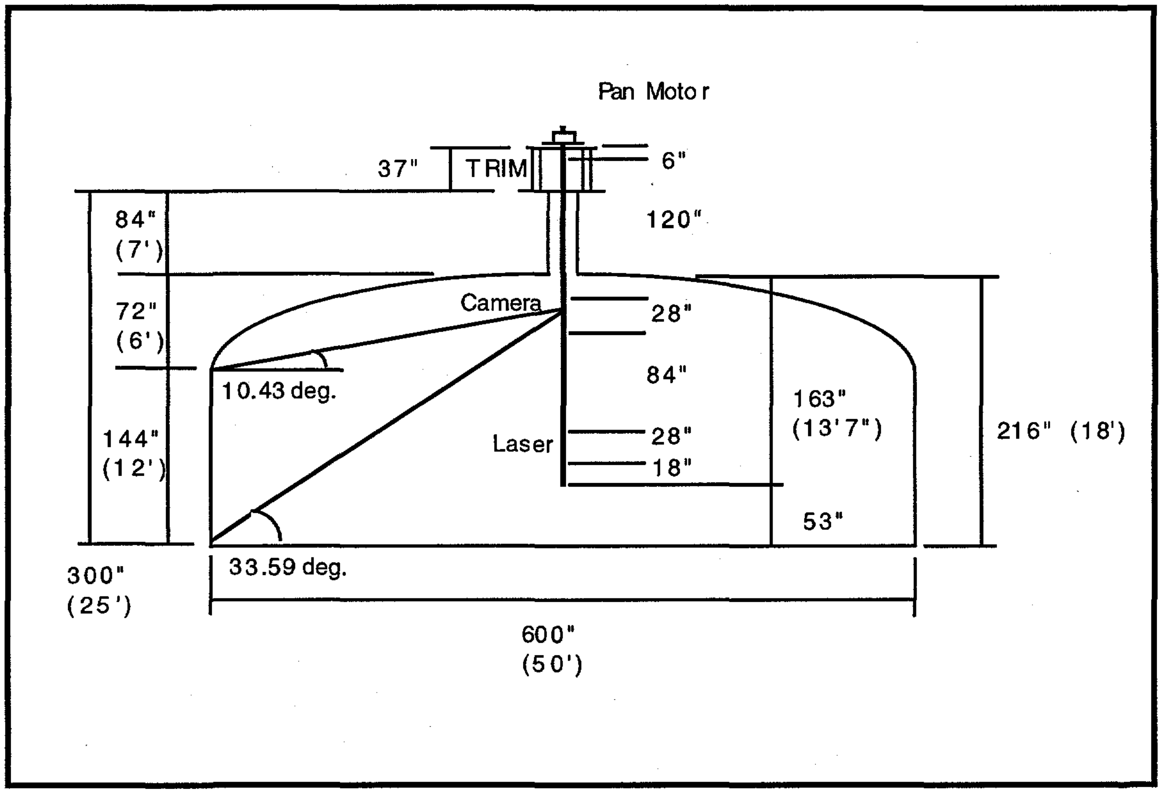

Figure 5. TMS sensor head and ORNL UST dimensions.

The characterization of the TMS was performed using a machined target box, shown in Figure 6. The box dimensions are 30.48 x 30.48 x 30.48 cm (12 x 12 x 12 in.) with 15.24 cm (6 in.) flaps. The box was designed to allow plane fitting to determine the several vertices on the box. The ICERVS tool has the capability to fit three planes to three operator-selected surfaces of the box and solves for the intersection point of the fitted planes. This is performed by placing a box over a portion of the surface for which a surface plane fit is desired. Once the ICERVS fits all three planes, it then solves for the intersection of the three planes to define the vertex point.

The results of the characterization of the TMS are presented in Figure 7 below. The relative RMS error varied from 10.16 mm (0.400 in.) at 3.66 m (12 ft) to 6.35 mm (0.250 in.) at the optimized 7.62 m (25 ft). The system error was driven primary by the lateral error. The axial or range error was very low, ranging from 0.43 mm (0.0170 in.) at 5.79 m (19 ft) to 1.8 mm (0.0709 in.) at 8.84 m (29 ft). As the cubic box that was used to make the measurement was placed on the center of the field of view of the system (which was necessary to keep the entire box within the 10-degree fan angle of the system), the range measurement was always down the center of the field of view. Because the misaligned laser had the biggest visible effect in laterally skewing the resulting surface map, the largest errors would then be driven by the lateral measurements, which is the case here.

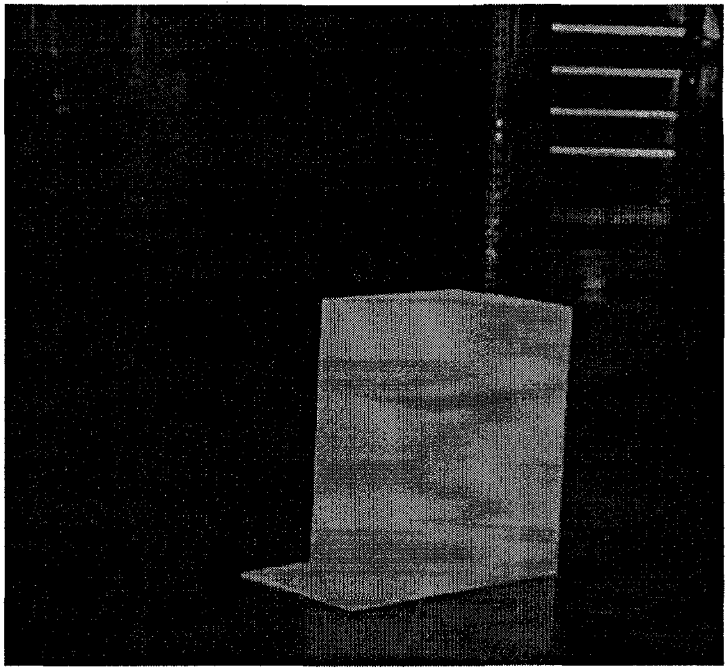

Figure 6. Calibration box used to determine the relative accuracy.

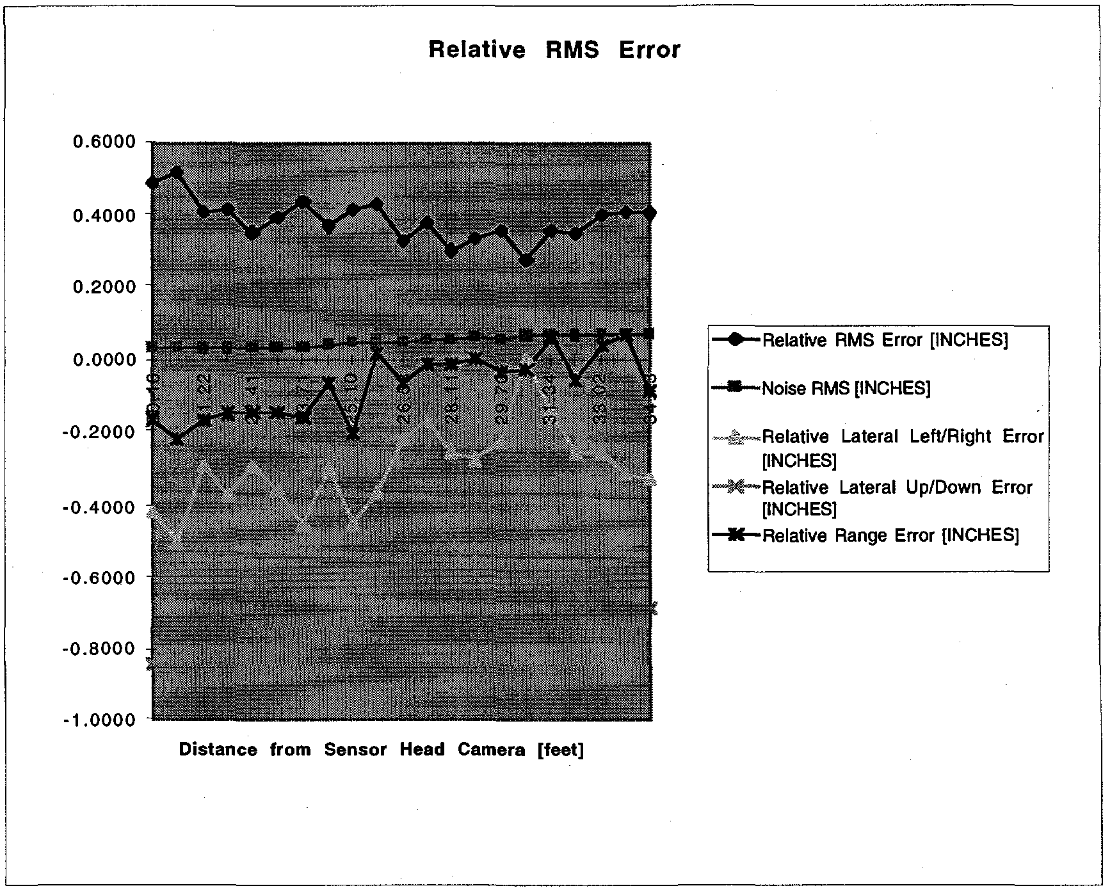

Figure 7. Relative accuracy of the TMS.

3. FUTURE WORK

More work is required on the TMS system before it can be used effectively to perform such functions as measuring the volume of the waste in a UST or building a 3-D model for robotic path planning. Three areas need work. First, the laser-pointing system needs further calibration to improve the absolute accuracy of the system. When the calibration was performed at ORNL, it was believed that if the misalignment in the laser pointing could be carefully characterized and incorporated into the kinematic model, the system should be able to operate within the required specifications of +/- 0.25 in. at 45 ft. However, this has not proven to be true. Because of the interaction among the 45-degree pointing mirror, the rotary table, and the laser, the laser must be pointing perfectly horizontal when the rotary table is at 0 degrees. After the laser is aligned and the system is calibrated, a full characterization needs to be performed to determine the system accuracy over its targeted measurement space. The delivered system was properly calibrated but due to a water ingress problem at ORNL, the laser stages rotary table had to be replaced. This necessitated recalibration at ORNL. Second, a volumetric analysis capability needs to be added to the ICERVS 3-D visualization software. The current ORNL-developed volumetric analysis tool can determine only the volumes for very structured environments with no vertical surfaces present. The ICERVS can more easily deal with the unstructured environments of the USTs because of the use of an octree database. In addition, the identification and elimination of structural elements within the UST that should not be in the waste volumetric calculation can easily be achieved by functions within the ICERVS tool. The volumetric measurement capability would enable ICERVS to quickly generate volumetric measurements of waste in the tanks, measure the amount of waste removed from a tank, or measure changes in the waste surface (due to the build-up of gases below the surfaces.) Third, the error model that indicates the confidence of the measurement based on (1) range, (2) contrast, (3) signal-to-noise ratio, (4) camera sensitivity, (5) laser power, (6) angle of incidence, (7) kinematics of the sensor head, (8) temperature, and (9) radiation needs to determined and characterized. Currently, the TMS has been characterized along one horizontal plane extending out the Y axis of the sensor in the home position. The characterization needs to be extended to include multiple such characterizations on horizontal planes every 1 m (3.28 ft) over the entire measurement space. This would allow arrays of characterization data to be formulated for axial range, lateral range, and angle of incidence over the targeted measurement space. In addition, more data needs to be gathered on the TMS's capability to surface map surfaces of varying texture and therefore reflectance and absorption properties. For the current characterization, most of the measurements were performed only one time. A subset of the data points needs to be collected multiple times in an effort to gather statistics on the system's repeatability. The error model and full system characterization will aid remediation scientist in making decisions with the data provided by the TMS and will be useful in the fusion of the TMS surface map with maps provided by other sensors.

In addition, there are a few improvements that could be made to the system that would greatly improve its versatility as well as it deployability. A set of lights distributed about the sensor head would greatly aid in tank inspection, as well as installation, and removal through the riser. Lights could also be added to the extension modules or the dummy ESS. This would allow the lights to be designed for decontamination as opposed to adding lights to the outside of the sensor which would further restrict the aperture of the penetration. In addition, a zoom camera with a dedicated pan and tilt mechanism could be added to the bottom of the ESS.

4. FUTURE PLANS

PNNL and ORNL have written a proposal for deploying the TMS in UST AX104 at Hanford during FY 1998 to measure the remaining waste left in the tank. In addition, ORNL has requested FY 1998 funds for the procurement of a second TMS system for use at ORNL.

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