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Technical Report ARWSE-TR-09007

BORE ELEVATION AND AZIMUTH MEASUREMENT SYSTEM (BEAMS)

Robert P. Pinto

October 2018

U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Weapons and Software Engineering Center

Picatinny Arsenal, New Jersey

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-01-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (*From - To*)
October 2018		

4. TITLE AND SUBTITLE

BORE ELEVATION AND AZIMUTH MEASUREMENT SYSTEM

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHORS

Robert P. Pinto

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC, WSEC
Fire Control Systems & Technology Directorate (RDAR-WSF-I)
Picatinny Arsenal, NJ 07806-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC, ESIC
Knowledge Management Office (RDAR-EIK)
Picatinny Arsenal, NJ 07806-5000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Technical Report ARWSE-TR-09007

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A compact Bore Elevation and Azimuth Measurement System (BEAMS) apparatus and method was developed,tested, and placed into practical application by the U.S. Army Armament Research, Development and Engineering Center (ARDEC). The BEAMS offers a simple approach to verify that weapon fire control pointing accuracy requirements are met. The BEAMS was demonstrated with 60, 81, and 120-mm mortar and 105-mm artillery weapon platforms and is adaptable to other weapon calibers. The BEAMS incorporates a laser apparatus designed to self-center on the weapon bore axis. An eye-safe laser is mechanically adjusted to position the laser aperture on-axis with the weapon bore. Optical adjustments within the laser housing permit the laser beam to be aligned coaxial with the true bore axis thus providing a projection of the bore axis. These features facilitate removal and/or measurement of bias from the apparatus. The BEAMS uses dual theodolites and conventional geodetic survey procedures to make three-dimensional measurements of the laser's position at two points along its path. From these measurements, the elevation and azimuth of the laser line and therefore the weapon tube axis may be computed. Accuracies on the order of 0.05 mils in elevation and azimuth are achievable in a field-test environment. The BEAMS is patent pending to the U.S. Army ARDEC.

15. SUBJECT TERMS
Evaluation azimuth measurement fire control system (BEAMS); 60, 81, and 120-mm mortar; 105-mm artillery; Eye-safe laser; Dual-theodolites; Three dimensional measurements; Field test environment; Pointing accuracy; Verify; Verification testing

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a.REPORT	b. ABSTRACT	c. THIS PAGE			Robert P. Pinto
U	U	U	SAR	51	19b. TELEPHONE NUMBER (Include area code) (973) 724-6867

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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PREFACE

The problem of verifying the fire control pointing accuracy of a mortar tube, artillery cannon, or other weapon platform at a Government or contractor test facility has been a point of contention for years. The advent of modern digital fire control systems with claims of sub-mil pointing accuracy have only served to exacerbate the issue. This report describes the design and operation of the Bore Elevation and Azimuth Measurement System (BEAMS). The purpose of BEAMS is to provide a means to make reliable, repeatable, accurate weapon pointing measurements in a field test environment. This report describes a BEAMS measurement system wherein the laser apparatus is able to self-center when placed in the weapon tube, to operate with virtually any caliber weapon tube, to calibrate and verify that the laser projection of the tube axis is coaxial with the actual weapon tube axis, to measure and/or remove bias from the fixture and laser, to include the required measurement techniques and set of equations to perform the necessary computations, and to make simultaneous elevation and azimuth measurements of the weapon tube with an accuracy and precision such that the performance of modern digital weapon fire control systems can be fully evaluated. All of which may be accomplished in a field test environment.

In striving to meet the goals cited, I greatly appreciate the insight and contributions made by John F. Casper, former Competency Manager, Artillery Fire Control Systems Division of the Fire Control Systems and Technology Directorate at the U.S. Army Armament Research, Development and Engineering Center (ARDEC), Picatinny Arsenal, New Jersey. His fire control expertise spans over four decades with its origin at Frankford Arsenal, Philadelphia, Pennsylvania. It was John who recommended adapting the dual theodolite measurement technique long used in the aerospace and shipbuilding industries for this application.

I would also like to acknowledge the efforts of Jeffery Gregor, Mechanical Engineering Technician at ARDEC's Benét Weapon Systems Laboratory, Watervliet Arsenal, New York. Jeff generated the computer aided design solid model of the laser apparatus, worked out its dimensioning and tolerancing, and generated the drawings needed for its production. I also gratefully thank the Foreman of the Benét Manufacturing Prototype Center, Leonard Darcy and his toolmakers Jack Reckner, Stanley Rysio, Howard Steller, David Hale, and David Boudreau through whose experience and skill turned the laser apparatus from our concept on paper to concept demonstrators in metal.

Comments and questions about this report are appreciated and may be sent to the author at robert.p.pinto.civ@mail.mil.

Robert P. Pinto

SUMMARY

This report describes the Bore Elevation and Azimuth Measurement System (BEAMS) developed by the Fire Control Systems and Technology Directorate at the U.S. Army Armament Research, Development and Engineering Center (ARDEC), Picatinny Arsenal, New Jersey. The BEAMS comprises both a hardware means and method to verify that the elevation and azimuth pointing accuracy requirement of a weapon's fire control system is met. Beams may be employed in either a laboratory or field test environment.

The BEAMS overcomes many of the shortcomings associated with weapon pointing measurement techniques currently in use. The BEAMS laser apparatus is designed to mechanically self-center on the weapon tube axis. An eye-safe laser is mechanically adjusted to position the laser aperture on axis with the weapon bore. Optical adjustments within the laser housing permit the laser beam to be aligned coaxial with the true tube axis; thus, the laser provides a projection of the tube axis. These features facilitate removal and/or measurement of bias from the fixture. The BEAMS uses dual theodolites and conventional geodetic survey procedures to make three-dimensional measurements of the laser beam's position at two points along its path. From these measurements, the elevation and azimuth of the laser line and therefore the weapon tube axis may be computed. The BEAMS was demonstrated with 60 81, and 120-mm mortar and 105-mm artillery weapon platforms. Accuracies on the order of 0.05 mils in elevation and azimuth were achieved. The BEAMS was granted Patent 7856729 by the U.S. Patent and Trademark Office, on 28 December 2010.

This report provides a description of the hardware components, their theory of operation, calibration, measurement procedures, and the computations required to determine the elevation and azimuth of a weapon bore.

INTRODUCTION

The U.S. Army Armament Research, Development and Engineering Center (ARDEC) engineers from the Fire Control Systems and Technology Directorate at Picatinny Arsenal, New Jersey developed, tested, and placed into practical application the BEAMS. The BEAMS provides a means to accurately measure the pointing ability of fire control for mortars, artillery, and other weapon platforms.

Heretofore, verifying weapon pointing accuracy in an engineering environment has been and continues to be a problem at many Government test facilities. Prior attempts involved the use of a single optical instrument, such as a theodolite, to align to a mechanical projection of a gun tube bore axis. This is a subjective process and highly dependent upon the skill of the theodolite operator. Shortcomings of such approaches are the inability to quantify or calibrate the mechanical apparatus and to establish or remove bias from the measurement. Additionally, these approaches may measure azimuth, but not the elevation angle.

The BEAMS offers a low cost technique to verify in a field test environment that the elevation and azimuth pointing accuracy requirement of a weapon's fire control system is met. The BEAMS laser apparatus (fig. 1) incorporates interchangeable lobes that allow for use with any weapon tube caliber. The lobes support two non-marring brass pads and a spring loaded plunger, which allows the apparatus to self-center on the weapon tube axis. The apparatus incorporates an eye-safe laser that provides a projection of the tube axis. Mechanical adjustments allow the laser aperture to be positioned on-axis with the weapon bore, and optical adjustments within the laser housing permit the beam to be made concentric with the actual tube axis. These features facilitate measurement and/or removal of bias from the fixture. The

BEAMS uses a dual theodolite approach employing conventional geodetic survey procedures to make three-dimensional measurements of the laser's position. From these measurements, the elevation and azimuth of the laser line and subsequently the weapon tube can be computed with exceptional accuracy. The computations may be performed in a spreadsheet or the use of dedicated computer software. A fully automated system may be implemented through the use of digital theodolites operating under computer control.

Figure 1
BEAMS laser apparatus for use with the 120-mm mortar

BACKGROUND

Description and Deficiencies of Alternate Measurement Techniques

Current methods employed at Government Proving Grounds for artillery and mortar weapon azimuth pointing measurements generally make use of a fixture inserted in the weapon tube. The fixture is composed of two disks, which engage the diameter of the weapon bore. The disks support a mechanical rod structure that extends the tube axis beyond the end of the tube where it may be observed. One such apparatus is shown in figure 2. As the figure highlights, the long-rod incorporates two conical alignment points, the tips of which are machined to be on axis with the long-rod. The long-rod, in turn is machined to be coaxial with the two disks. In operation, the weapon tube is positioned on the azimuth of interest and the apparatus inserted in the bore. A theodolite is then positioned at a location such that the vertical hairline of the theodolite intersects the tips of both conical alignment points. At that time, the theodolite would be positioned in exactly the same vertical plane as both conical points and therefore along horizontal projection of the azimuth of the weapon tube. Figure 3 shows a typical test setup with the theodolite positioned rearward of the mortar tube.

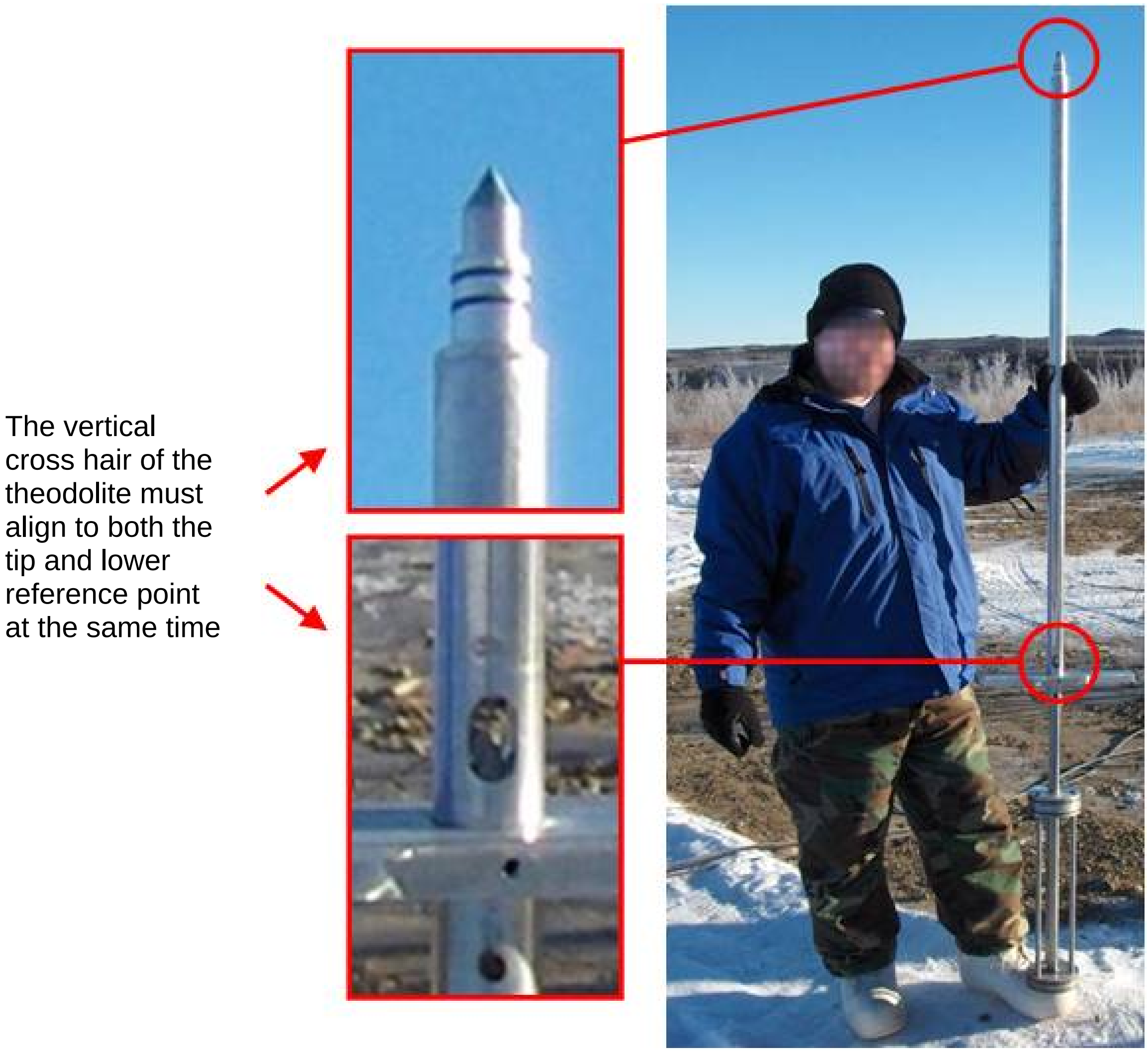

Figure 2
Long-rod fixture for use with the 120-mm mortar

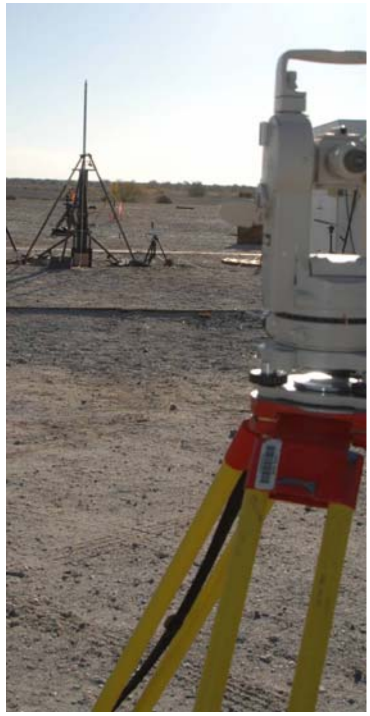

Figure 3
Theodolite positioned to the rear of a mortar tube with the long-rod fixture installed

It should be apparent that this approach is fraught with numerous obvious and some not so obvious faults, which impact accurate azimuth measurements. Clearly, the apparatus is very long and may be easily subject to damage from bending both during operation and in transportation to and from the test location. Because of its mass and large bending moment, it is cumbersome to insert and remove from the weapon bore. Although some of the mechanical deficiencies can be reduced or eliminated through careful redesign of the hardware, the underlying problems associated with the measurement technique itself cannot. The most significant of which is the process of aligning the vertical hairline of the theodolite with both points of the long-rod. This can be an extremely tedious and time consuming process and can still result in error. In practice, the theodolite must be positioned at roughly the proper position to observe the two points with one above the other. Then the instrument must be fine leveled. This alters its position in azimuth, thus the two points will no longer appear in the same vertical plane. The theodolite must then be repositioned, re-leveled, and the process repeated until the proper sight picture is obtained. This “wiggle-in” operation is entirely dependent upon the skill of the theodolite operator to accomplish the tasks in an accurate and timely manner. Additionally, when the weapon tube is placed at a high quadrant elevation (fig. 2), alignment of the two points with the vertical hairline is extremely difficult. Even a slight misalignment of the two can result in extremely large azimuth errors. At high quadrant elevations, measured azimuth errors of 10 to 15 mils or more are common.

Since bending of the long-rod under its own weight appears in the same vertical plane as the theodolite, the measurement is relatively insensitive to it. However, any bending of the rod to the left or right of the vertical plane results in an azimuth measurement error or bias error. Bias can be averaged out by rotating the apparatus about its axis 180 deg in the tube, making a second measurement and averaging the two azimuth values. However, the rotation results in the need to reposition the theodolite and repeat the leveling and repositioning cycle. In some instances the “close enough” approach is used as a time saving measure, which can make the measurement questionable at best.

An alternative method of azimuth measurement commonly employed at Government Proving Grounds is to scribe a line on the outside of the weapon tube parallel to the tube axis. Another is to use the edge of the tube itself to define a line. Both of these approaches necessitate sighting along the line or edge with a single theodolite, which must be properly positioned and leveled as previously described. In addition to the issues described previously, these methods incur their own set of issues. Typically scribe lines on the outside of the tube parallel to the tube axis are difficult to establish. Additionally, for either of these methods, if the outer tube wall is tapered it is not parallel to the bore axis. In that event, a set of azimuth correction equations need to be applied to account for the non-parallelism of the observed line to the weapon axis (ref. 1). These equations require accurate measurements of the tube diameter at the two points along the tube where the observations are made, the length along the tube between the points, the weapon elevation, and the weapon cant. Although all of these parameters can be measured, the process is time consuming and tedious.

In summary, all of these practiced azimuth measurement techniques described require:

- Procedures not typical in geodetic surveying for operation of a theodolite
- Heavy reliance upon the skill of the theodolite operator to make tedious adjustments to align the theodolite with both aim points at the same time
- Repeated relocating and leveling of the theodolite to “wiggle-in” on the single proper azimuth line
- Making measurements where identifying and sighting to the measurement points themselves is highly subject to error
- Extreme care when making measurements at high quadrant elevations

OVERVIEW

Digital fire control systems for all caliber mortar and artillery platforms are becoming more the norm than the exception. As such, there is and will always be a need to verify the pointing accuracy of these modern sub-mil capable systems. This is true for engineering development as well as system acceptance testing. The issue of making accurate elevation and azimuth measurements exist at every Government or contractor test facility where such measurements need to be made. In meeting this need, BEAMS provides:

- An extremely compact laser apparatus providing:
    - A means for the apparatus to accurately self-center in the weapon tube
    - A means to work with any caliber weapon system
    - A means to calibrate and verify that the projection of the tube axis is coaxial with the actual tube axis
    - A means to measure and/or remove bias from the apparatus
    - A means to position the theodolites at virtually any arbitrary position
- A clearly defined theodolite aim point providing a means to:
    - Use conventional geodetic surveying practices
    - Make measurements with extreme precision
    - Levels of accuracy far greater than any other current methods
    - The ability to measure elevation and azimuth at the same time

The core principle of BEAMS is that a laser may be calibrated to provide a projection of the axis of the mortar, artillery cannon, or other bore of interest beyond the end of the tube. By making horizontal and vertical theodolite observations of the laser spot at two positions along the path of the beam, the three-dimensional coordinates of the points can be computed. Further, the elevation and azimuth of the line between those points may be computed, which is identical to the elevation and azimuth of the tube. The use of two or more theodolites to establish the three-dimensional coordinates of a point has been used successfully for decades. For example, in the aerospace or shipbuilding industries multi-theodolite instrumentation was used to validate the proper curvature of an aircraft wing or ship profile. One of the first systems to incorporate this approach was the Keuffel and Esser Analytical Industrial Measuring System [AIMS (ref. 2)], which had a significant impact on the aerospace industry. More sophisticated measurement systems followed, but unfortunately none were applied to the task of weapon pointing measurements. Because BEAMS makes two measurements of the laser's position, all the measurements are effectively scaled to the same coordinate system. Therefore, the use of a calibrated scale bar or other length standard to establish accurate lengths is not necessary. However, if a length standard is used, the subsequent XYZ coordinates may be scaled into real world distance measurements.

BEAMS COMPONENTS

The BEAMS consists of three major components: two hardware components and a software component. The laser apparatus itself, which is inserted into the weapon system bore, is the principal component. A pair of conventional theodolites that measure horizontal and vertical angles comprise the second component. The software component consists of the computations that are used to convert the theodolite data into the elevation and azimuth of the weapon system. Although the computations may be performed by hand, it is far less error prone to have the computations automated in a spreadsheet or dedicated software program. These automated computations can be used in the field running on a portable computer to reduce data in real time as measurements are made. Each of these three components will be discussed in detail in the following sections.

Laser Apparatus

The BEAMS laser apparatus is shown schematically as item 10 of figure 4. A provisional patent for the design was filed with the U.S. Patent and Trademark Office in August 2007 (ref. 3) and a full application was filed in August 2008 (ref. 4). The device consists of centering the mandrel (18) that supports two lobe assemblies (22), laser assembly (42), and handle (68). The mandrel is inserted in the tube (12) and uses the handle as a convenient depth stop. When inside the tube, the lobes contact the inner tube wall (14) and the mandrel's longitudinal axis B aligns with bore axis C.

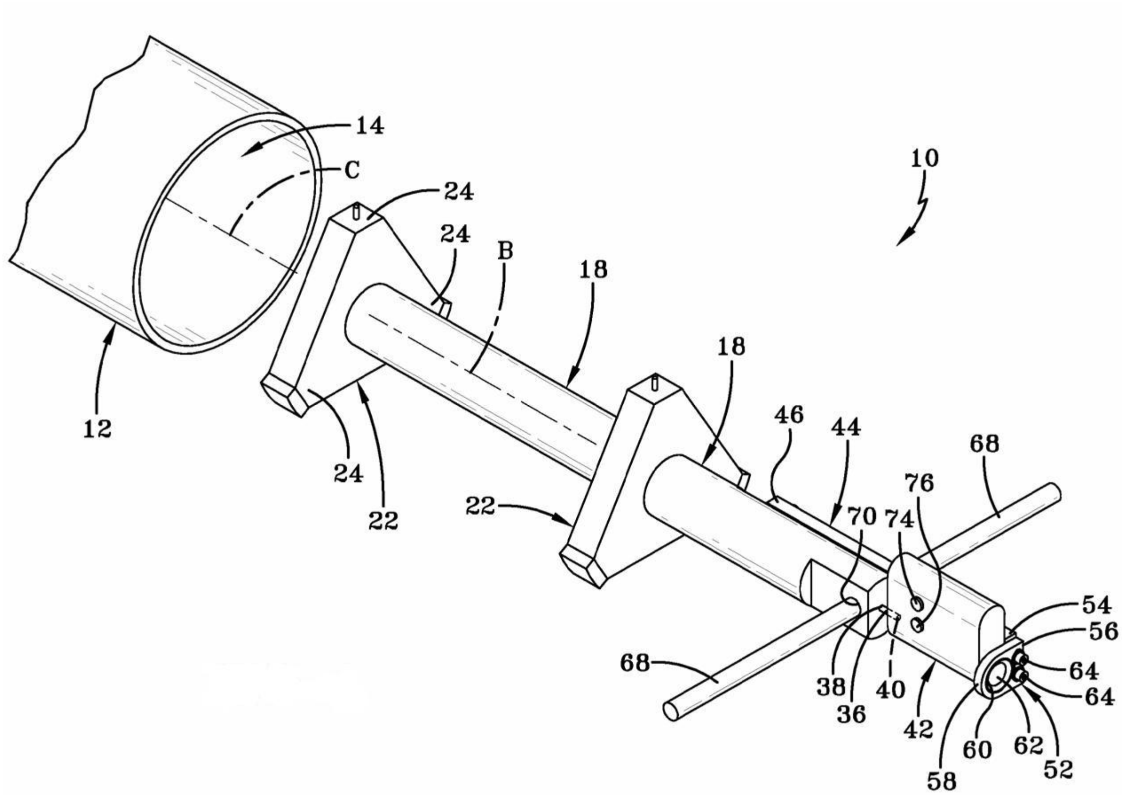

Figure 4
Perspective view of BEAMS laser apparatus

The lobe assemblies (fig. 5) are triangular in shape. The lobe assemblies were also part of a predecisor apparatus to BEAMS, the Azimuth Measuring Apparatus and Method, for which a provisional patent was filed in May 2007 (ref. 5) and a full patent application in March 2008 (ref. 6). Two of the corners of the lobe assemblies are fitted with non-marring brass pads (26), whose outer surface is machined to match the radius of the inside of the tube. These pads are dimensioned such that when they contact the interior bore wall they center the mandrel as previously mentioned. The third corner of each lobe assembly is fitted with a resilient spring loaded plunger (28), which also contacts the interior wall of the bore. The spring force maintains contact of the pads with the bore wall and therefore maintains the self-centering feature of the apparatus. Tubes with different inside diameters require different size lobe assemblies. The lobe assemblies are affixed to the mandrel by means of a single cap screw (34) and an associated flat and lock washer (not pictured). Lobe assemblies for the U.S. Army's 60, 81, and 120-mm mortar platforms were built and successfully demonstrated as part of BEAMS.

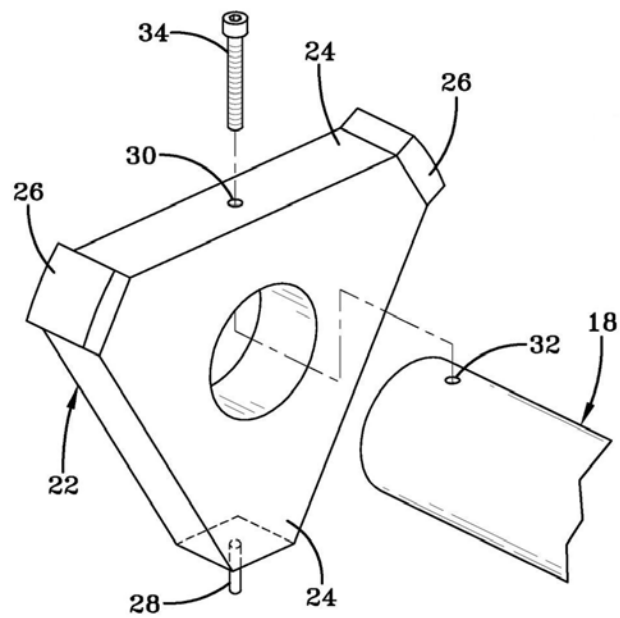

Figure 5
Exploded perspective view of one BEAMS lobe assembly (shown inverted)

The laser assembly is mounted at the end on the mandrel by three support members, shown as items 36, 44, and 52 in figure 4. The support member (36) is fixed at one end (38) to the centering mandrel and to the laser (42) at the other end (40). The support member consists of a threaded rod, which mates the rear of the laser housing to the mandrel. Once threaded into position, a flat and lock washer (not pictured) secure the support in place. The longitudinal axis of the support member is positioned such that it is coaxial with the longitudinal axis B of the centering mandrel and the axis of the laser (not shown).

The laser selected for BEAMS is shown in figure 6. It is the AN/PEM1 Laser Borelight System (LBS), also known as model LBS0300, manufactured by Insight Technology Incorporated, Londonderry, New Hampshire. The AN/PEM1 is currently in use by the U.S. Army and provides a precise method for zeroing any day optic, iron sight, or thermal weapon sight to the host weapon without the need to expend ammunition. The AN/PEM1 is normally equipped with mandrels that are fitted to 5.56 mm, 7.62 mm, and 0.50 caliber weapons and the MK-19 grenade machine gun. The unit operates from a single 1.5-V AA battery. The AN/PEM1's visible red laser is a type class IIIa having a wavelength between 620 and 680 nm and a peek power output of 0.9 mW. The class IIIa laser is rated for viewing by naked eyes or magnifying optics as long as there is no direct or intra-beam viewing. Another feature of the AN/PEM1, which makes it well suited to the BEAMS application, is its integral vertical and horizontal beam adjusters (74 and 76) shown in figure 4.

Figure 6
AN/PEM1 laser shown as part of the BEAMS laser apparatus

Figure 7 shows an expanded view of the upper portion of the laser apparatus that has been rotated 180 deg about axis B from its position in figure 4. The second support member (44) is shown affixed at one end (46) to the mandrel (18). The support member (44) is adjustable with respect to the centering mandrel in two orthogonal axes. This is facilitated by slotted openings (50) in the support member (44) though which fasteners (48) thread into openings (not shown) in the mandrel (18). The slotted openings allow movement of the support member (44) along the axis B of the mandrel (18) and more limited movement along axis D, which is perpendicular to axis B (fig. 8). Fasteners (48) include flat washers and lock washers (not shown). The flat washer allows the fastener head to bridge the slot (50) and the lock washer helps hold the fastener (48) in place during the adjustment process.

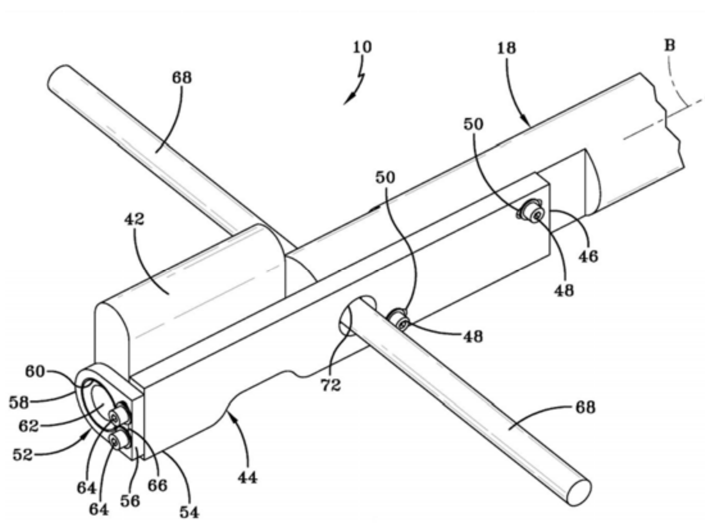

Figure 7
Upper portion of laser apparatus rotated 180 deg

Also shown in Figure 7 is the third support member (52). It is fixed at one end (56) to an end (54) of the second support member (44). The third support member (52) includes an opening (60) that captures the protrusion of the aperture (62) of the laser (42). The third support member (52) is adjustable with respect to the second support member (44) in two orthogonal axes. Figure 9 shows an end view of the third support member (52) and slot (66). The slot (66) allows movement of the third support member (52) relative to the second support member (44) along the axis R, and allows more limited movement along the axis G. Axes R and G are perpendicular to each other and to the bore axis C. Referring back to figure 7, the third support member (52) is fixed to the second support member (44) using threaded fasteners (64), in the end (54) of the second support member (44). The third support member (52) is retained to the second support member (44) by cap screws, which include flat washers and lock washers (not shown). The flat washer allows the fastener head to bridge the slot (66) and the lock washer helps hold the fastener (64) in place during the adjustment process.

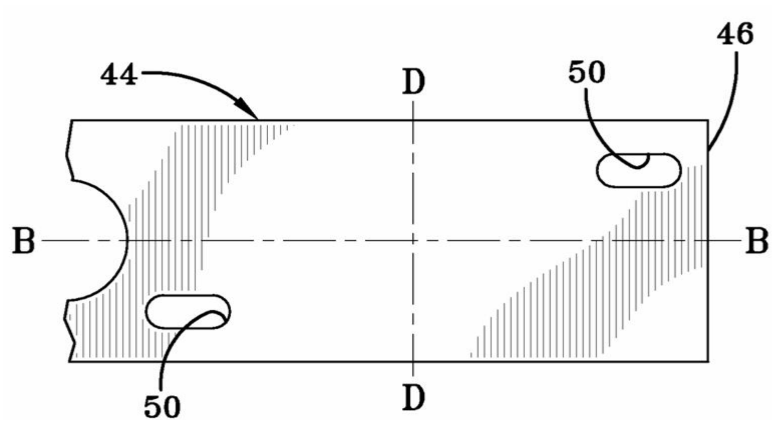

Figure 8
Side view of the second support member (44) showing axis of motion

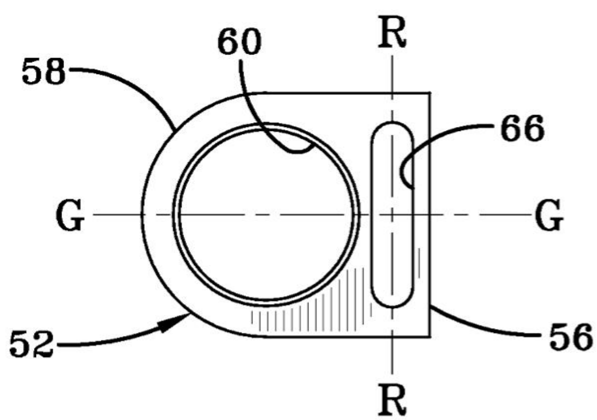

Figure 9
End view of the third support member (52) showing axis of motion

Finally, as shown in figures 4 and 7, the centering mandrel (18) includes the handle (68). The handle is used for rotating the apparatus while in the weapon bore, and also serves as a depth stop for proper positioning. The handle is a rod that extends through the opening (70) in the mandrel [18 (fig. 4)] and through the opening (72) in the second support member [44 (fig. 7)]. For convenience in storage, the handle is removable. It is held in place by a spring loaded plunger (not shown) in the body of the mandrel (18).

Theodolite Apparatus

It is not the intent of this document to describe the in-depth construction or operation of the theodolite. There are many excellent texts available that can be consulted, such as Surveying Principles and Applications (ref. 7). However, a general overview of the theodolite will be presented so the reader can better appreciate the significance of the measurement techniques related to BEAMS.

The theodolite is an instrument optimized for the measurement of angles in the horizontal and vertical planes. Theodolites have existed in some form for centuries, from elegantly crafted brass and glass to computer-controlled remotely-operated units. Regardless of the technology, their construction and functionality have remained basically the same. Essentially, a theodolite consists of an optical telescope that can move in two mutually perpendicular planes, namely the horizontal and the vertical (fig. 10). The vertical axis of the instrument is typically oriented over a specific point on the earth's surface, such as a survey control point. The alidade, or upper portions of the instrument, revolves about this axis. The horizontal or tilting axis of the telescope is perpendicular to the vertical axis, and the telescope and vertical circle revolve about it. The line-of-sight, also known as the line of collimation, is a line connecting the intersection of the reticle cross hairs (not shown) and the center of the objective lens. The line of sight is perpendicular to the horizontal axis.

Angular measurements of the telescope’s line-of-sight are made via horizontal and vertical circles. The horizontal circle measures the horizontal angular position of the line-of-sight relative to a zero-reference such as north. The horizontal angle increases relative to the zero-reference as the instrument is turned clockwise. The vertical circle measures the vertical angular position relative to one of several reference systems. A common reference system for most theodolites and the one which is used in the BEAMS computations is known as zenith angle. In this reference system, 0 deg is directly above the instrument, such that when the line-of-sight is in the horizontal plane, the vertical circle indicates 90 or 270 deg.

A Wild T2 theodolite is shown in figure 11. The T2 is genuinely a classic among theodolites, designed and built by craftsmen. The instrument has a rated accuracy of one arc-second and delivers that solely by means of precision mechanics and optics – no electronics, batteries, or software required! Albeit a vintage instrument, it still shares much of its controls and operation with modern theodolites. For example, the vertical and horizontal clamping screws are used to lock the telescope and alidade in fixed position. When unlocked, the telescope may be positioned by hand in the desired vertical and horizontal directions. When locked, the vertical and horizontal tangent screws are used to make fine adjustments to the telescope’s position in elevation and azimuth.

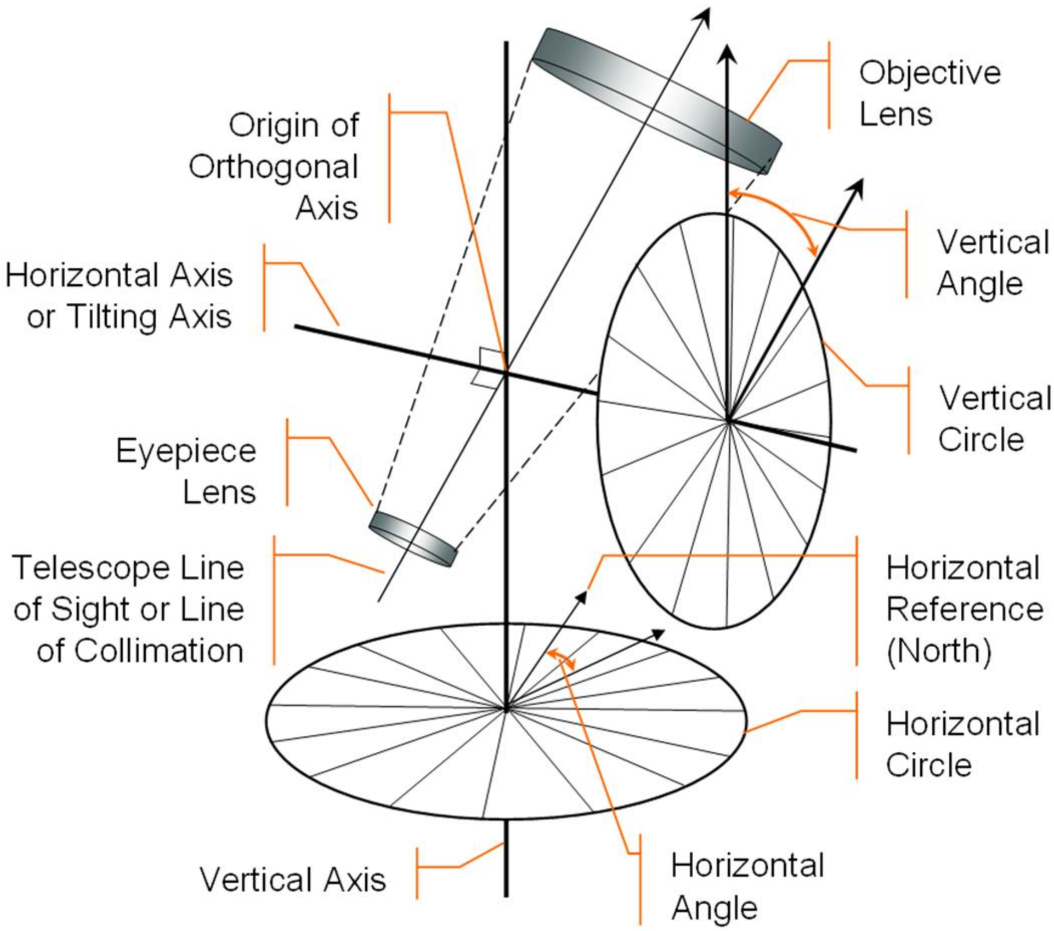

Figure 10
Theodolite

When setting up a theodolite, it must be leveled for accurate measurements. To facilitate this (fig. 11) the instrument incorporates a plate level vial, or bubble, as part of the alidade that is used to detect the tilt of the instrument. Leveling screws at the base of the unit are used to make the adjustments, which set the instrument to the vertical. Typically, three leveling foot-screws are arranged in a triangular pattern known as a tribrach. To level the theodolite, the alidade is turned so that the plate bubble tube is parallel to two foot-screws of the tribrach. The bubble is centered by adjusting the two foot-screws in equal and opposite directions. The alidade is turned 90 deg and the bubble is centered by adjusting the third foot-screw. The process of rotating the alidade through 90 deg is repeated, moving the bubble half the distance to the center during each iteration. The alidade is then rotated through 180-deg increments with the goal of either centering the bubble or having it equally un-centered on each side after the 180-deg rotations.

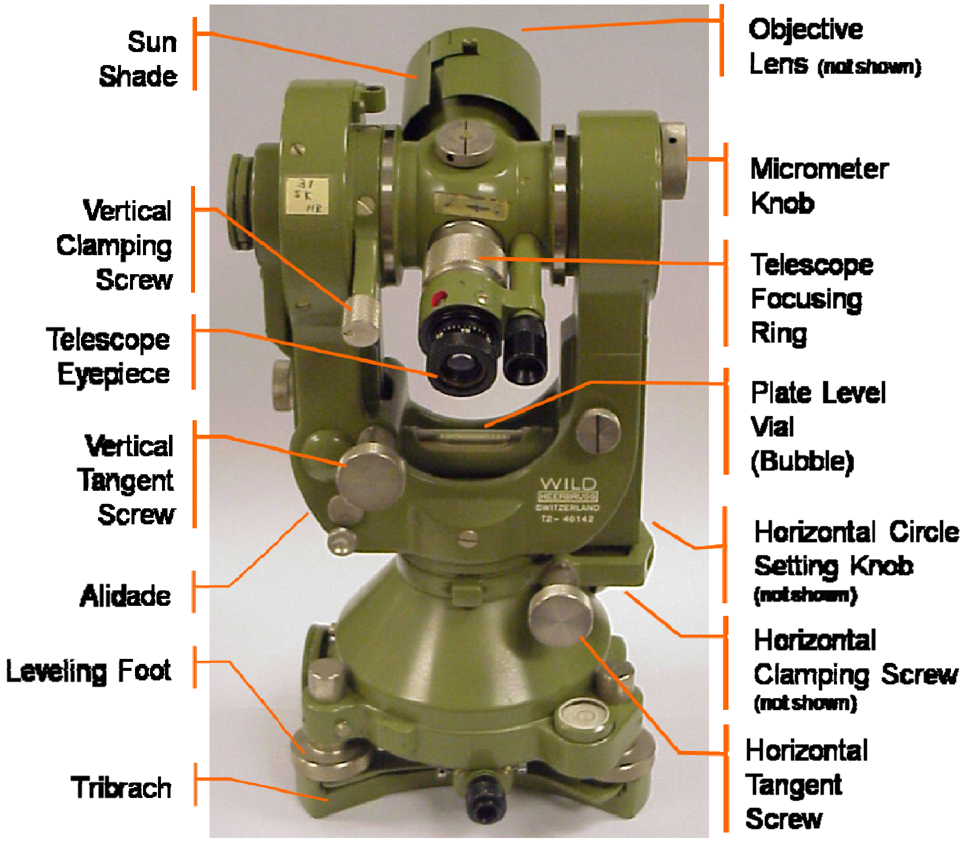

Figure 11
Classic Wild T2 theodolite showing common nomenclature

Among other things, theodolites can be classified by the precision of their angle reading system. The theodolites used for BEAMS measurements thus far have rated accuracies of one arc-second. Theodolites of lesser accuracy may be used although the distances over which the measurements are made should be kept shorter. This will be further discussed in the Operational section of this document.

Computation Component

A single theodolite can measure the horizontal angle and vertical angle to a specific laser point falling on a screen. The additional quantity needed to define the vector from the theodolite to that point is the magnitude or distance. By use of a second theodolite, the magnitude of the distance from the first theodolite to the laser point may be determined in terms of an angle. By using the opposing theodolite to establish the magnitude, a vector from each theodolite to any point may be established. Once this vector is established, as for any vector, it may be resolved into x, y, and z components in a three-dimensional coordinate system. By making the same type of theodolite measurements to another point falling on a screen at another location along the laser beam, another set of x, y, and z points may be established. These two sets of three-dimensional coordinates establish a vector in itself along the laser beam from one point to the other. From the two sets of three-dimensional coordinates, the azimuth and elevation of that vector and therefore the azimuth and elevation of the bore may be determined.

Many mathematical methods may be used to determine the vector to each laser point and the vector between the points. A straightforward approach will be presented herein. As a labeling convention:

- All horizontal angles will be designated by H
- All vertical angles will be designated by V
- All distances will be designated by D
- The two laser points closest and furthest from the laser are referenced as P1 and P2, respectively
- The two theodolites shall be referenced as T1 and T2, respectively

Figure 12 shows a top view of two theodolites, T1 and T2, each oriented to a north reference and measuring horizontal angles to a single point, Pn. As best seen in figure 13, theodolites T1 and T2 are at different heights and therefore in different horizontal planes. Theodolites T1, T2 and point Pn form triangle AEF with sides a, e, and f. Sides e and f are in the horizontal plane of T1 and side a is in the horizontal plane of T2. When viewed from above (fig. 12), the three sides a, e, and f form a triangle. That is, a triangle may be projected into a single horizontal plane. By sighting each theodolite to the other, each theodolite can measure the horizontal angle to the other theodolite. Thus, two of the interior angles of triangle AEF can be established. As shown in figure 12, angle A is equal to HT1Pn minus HT1T2 and angle E is equal to HT2T1 minus HT2Pn. Angle F is therefore equal to 180 deg minus angle A minus angle E. Since the three interior angles are now established, the Law of Sine's may be used to ascertain the relative magnitude of each of the sides of the triangle. Since the distance between the theodolites (DT1T2) is a constant, it is assigned the value of unity and all subsequent distances that are derived are scaled to DT1T2.

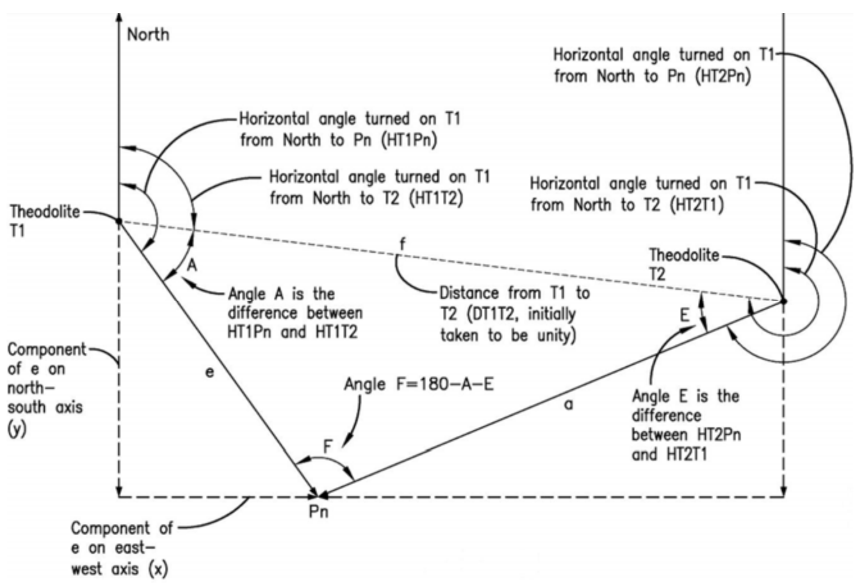

Figure 12
Top view of the theodolites and horizontal triangle AEF

From the Law of Sine's, *a*/sin(A) = *e*/sin(E) = *f*/sin(F). Therefore, *e* = [1/sin(F)] * sin(E) and *a* = [1/sin(F)] * sin(A). Thus, the relative magnitudes of all sides of the triangle are known. Because the angles are measured from a north reference, the vector *e* from theodolite T1 to point Pn can be resolved into components along the north-south and east-west axes, namely, *e* cos(HT1Pn) and *e* sin(HT1Pn), respectively. Additionally, by a similar process not shown in figure 12, the y and x (or north-south and east-west components) of the vectors between T1 and T2 and T2 to Pn may be established and those vector components may also be computed. When those two sets of components are combined, they result in the same x-y position for point Pn as computed from vector *e*, thus providing an indication of the accuracy of the angular measurements.

To establish the three-dimensional position of point Pn, the vertical angles measured by the theodolites T1 and T2 need to be evaluated. Figure 13 is a perspective schematic view of theodolites T1 and T2 and point Pn from figure 12. In figure 13, T2 is at a higher altitude than T1. From figure 13, the vertical position of Pn on the z-axis is computed as the magnitude of vector *e* multiplied by the tangent of the vertical angle from T1 to Pn, or z = *e* tan(VT1Pn). Keep in mind that when looking in a horizontal plane, the theodolite will indicate 90 or 270 deg and the appropriate value must be subtracted from the measurement to get the true angle above or below the horizontal plane. Figure 13 also shows how the same vertical measurement may be made from theodolite T2. When measuring from T2, the vertical position of Pn will be relative to the horizontal plane of T2. Therefore, the vertical position of point Pn, which is in the plane of T2, must be included. The z-axis position of Pn above pn is equal to the magnitude of side *a* multiplied by tan(VT2Pn). The additional vertical distance is the distance between the two horizontal planes of the theodolites T1 and T2. This additional vertical distance is computed from the vertical angles between T1 and T2 and the horizontal distance between them, which is DT1T2. As previously stated, DT1T2 is equal to *f*, which is given the value of unity. Therefore, the height of T2 is 1 * tan(VT1T2) and the z-axis value of Pn is tan(VT2Pn) + tan(VT1T2).

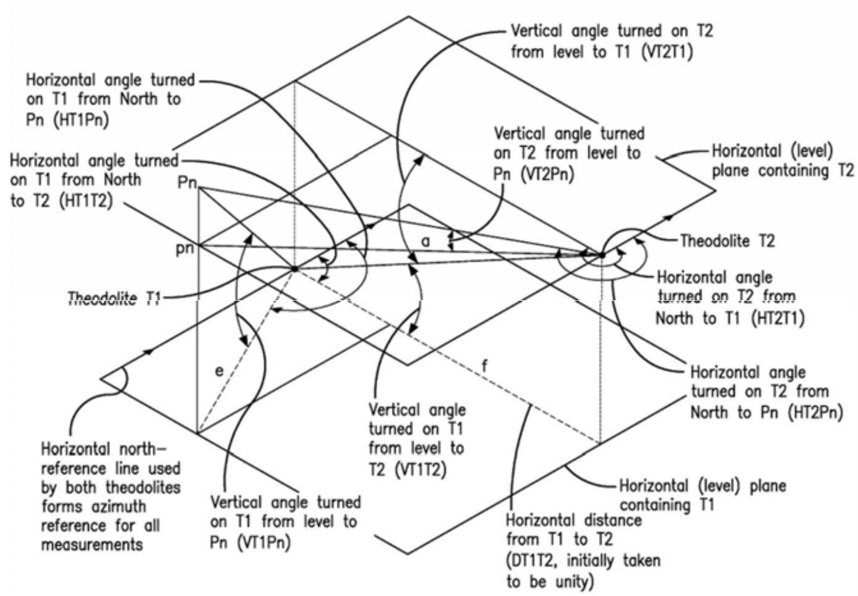

Figure 13
Perspective view of the theodolites and point Pn

After determining the x, y, and z coordinates for the points P1 and P2 along the path of the laser beam, the azimuth and elevation of the line they define may be computed. This is a simple matter of converting a vector quantity from a Cartesian to polar coordinate system. Figure 14 illustrates the conversion from Cartesian coordinates to polar coordinates. The magnitude of the distance between the points P1 and P2 is the square root of the sum of the squares of the delta values, or DP1P2 = Sqrt[(Delta X)^2 + (Delta y)^2 + (Delta Z)^2]. The azimuth of the line P1P2 is the arctangent of the delta x and delta y values, or Atn(Delta y / Delta x). The elevation angle is computed by taking the arctangent of the delta z value divided by the magnitude of the vector in the horizontal plane, or Atn[Delta z / Sqrt((Delta x)^2 + (Delta y)^2)].

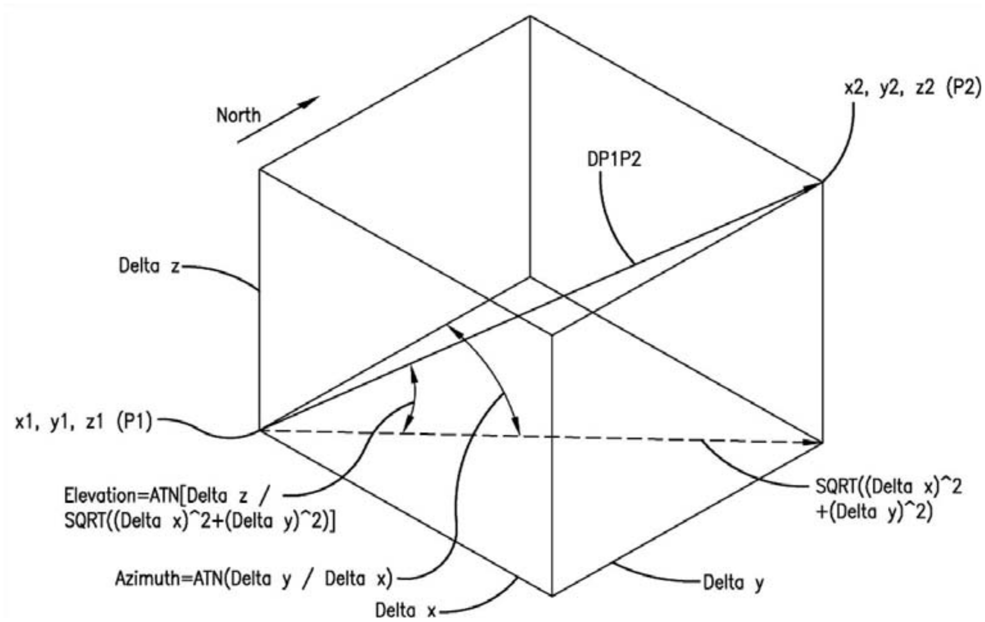

Figure 14
Perspective view of P1, P2, and the conversion from Cartesian coordinates

As previously mentioned, because the distance from theodolite T1 to T2 is a constant and assumed to be unity, the x, y, and z coordinates of any point Pn are scaled proportionally to that distance. However, by taking measurements of two points (P1 and P2) that are a known distance apart, one may compute a scale constant. The scale constant is equal to the known fixed distance divided by the computed P1 to P2 distance. When the scale factor is applied to subsequent Pn measurements, the x, y, and z coordinates may be output in the measured unit; for example: inches, feet, meters, etc. Additionally, theodolites T1 and T2 may be used to measure angles to a point Pn for which geodetic survey location data is known such as an easting, northing, and altitude. The computed x, y, and z coordinate information for the initial point Pn may be applied as offsets to the measurements of other points. In that case, the subsequent x, y, and z coordinates are output in terms of easting, northing, and altitude.
The computations described may be performed manually or automated via a spreadsheet or computer program. The tabular nature of repetitive measurements lends itself easily to a spreadsheet format. A description of a spreadsheet specifically prepared for these computations is discussed in the Operational section of this report.

BEAMS CALIBRATION

For accuracy and ease of use, the BEAMS laser apparatus should be mechanically and optically calibrated. Typically, this operation need only be performed once unless it is suspected that the apparatus was subjected to rough handling or conditions that could affect calibration. It is also possible to use the apparatus in the absence of calibration by measuring its out-of-calibration magnitude and applying offsets to the resultant computed elevation and azimuth. Additionally, it is possible to make pairs of measurements then compute the average elevation and azimuth to remove the bias. These two methods will be described later in this document in the Alternative Measurement Techniques section.

Mechanical Calibration

To calibrate the laser apparatus, the mandrel is inserted in the bore of a tube or fixture. The tube may be, but not need be, the tube for which it is desired to measure the elevation and azimuth. The mandrel may be inserted into the bore until the handle is near the end of the tube. The action of the spring loaded plungers on the lobe assemblies aligns the axis B of the mandrel with the axis C of the bore (fig. 4). The laser (42) is then mechanically adjusted so that the laser housing is aligned with axis B of the mandrel (18) and therefore axis C of the bore (14). The laser (42) is mechanically adjusted by centering the laser aperture (62) on axis C of the bore (14). A dial indicator with a magnetic base affixed to the outside of the tube (fig. 15) or similar instrument may be used to measure the run-out of the laser aperture (62) as the apparatus is rotated in the bore using the handle (68). The laser apparatus is rotated in 180-deg increments noting the dial indicator readings at each position. Adjustments are made to the position of the laser (42) in two axes that are orthogonal to axis C of the bore until the run out of the laser aperture is substantially zero. The adjustments are made by loosening fasteners [64 (fig. 7) and moving the third support member (52) along axes R and G (fig. 8). Adjustments may also be made by loosening fasteners [48 (fig. 7)] and moving the second support member (44) along axis D (fig. 8). Movement of the second support member (44) along axis D and movement of the third support member (52) along axis R is generally movement in the vertical direction, but the third support member (52) may provide finer control of motion. Movement of the second support member (44) along axis B (fig. 8) may be needed to ensure that the laser (42) is tightly encased between the support member [36 (fig. 4) and the third support member (52).

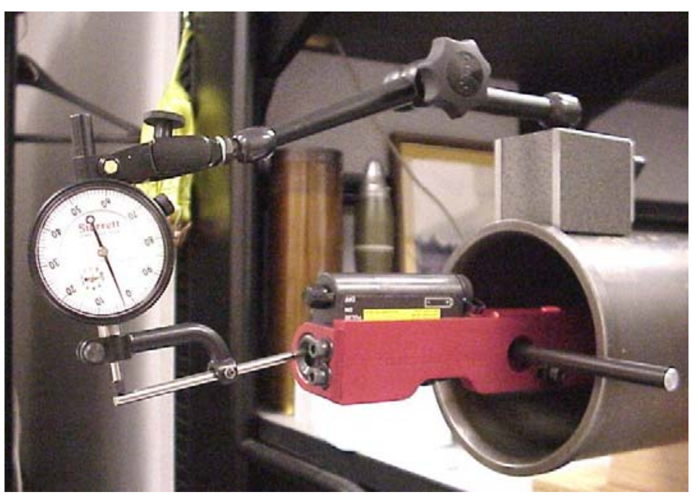

Figure 15
Dial indicator used to measure run-out of laser aperture

Laser Calibration

The previously described adjustments align the laser aperture with axis C of the bore. Additionally, the laser beam itself must be aligned. Referring to figure 16, the laser beam may be imaged on any convenient reflective surface that will serve as a screen. The center I of the first laser spot is noted. The laser apparatus is then rotated in the bore or fixture 180 deg and the center J of the second laser spot is noted. Any motion of the laser spot may be offset by adjusting the two angular controls [74 and 76 (fig. 4)] on the laser. The controls are used to move the laser spot half the distance from the second spot (J) location to the first spot (I) location. For example, in figure 16, the controls may be used to move the laser horizontally to the left a distance of b/2 and vertically downward a distance of c/2. This process may be repeated until there is no apparent motion of the laser spot at which time the laser beam will be coaxial with axis C of the bore.

Alignment of the laser beam may be verified by moving the reflective surface to another location along the laser beam and repeating the process. It may be possible that if the laser aperture is not centered on the apparatus, some laser beam motion will always be observed. In that case, the relative motion of the laser spot will be substantially the same at any two distances indicating that the laser beam is parallel to axis C of the tube (12). This is an acceptable condition.

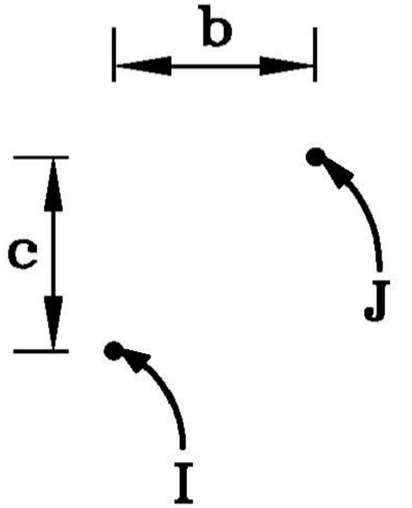

Figure 16
Example of laser spot motion from I to J after 180-deg rotation of laser apparatus

To accurately determine the first and second positions of the laser spot, an optical instrument, for example a theodolite, placed next to the apparatus may be used (fig. 17). Figure 18 shows a view through the theodolite telescope viewing the laser spots when the apparatus is rotated through 180 deg. The double reticle lines represent 30 arc-seconds and it can be seen that the center of the beam is well within those marks at the two positions.

Figure 17
Theodolite placed adjacent to laser apparatus during calibration

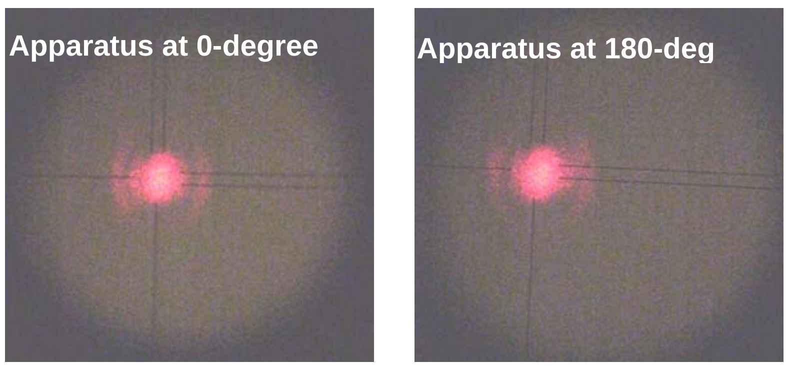

Figure 18
Laser spot viewed through theodolite showing no motion at the calibration positions

BEAMS OPERATION

Setup and Measurements

After completion of the calibration process, the laser apparatus may be used to measure the elevation and azimuth of a tube bore. Referring to figure 19 with the tube (12) positioned at the elevation and azimuth of interest, the laser beam (20) extends as a projection of bore axis C and is viewed on any convenient reflective surface (16) at laser spot point H. Two theodolites (78 and 80) are situated so they may directly view the laser spot H and each other. The figure shows the theodolites as flanking each side of the beam. In practice, the positioning of the theodolites is not critical. Excellent measurement results have been achieved with theodolites flanking the beam to the rear of the weapon or to the front of the weapon. The use of translucent screens permit the theodolites to be placed forward of the screens themselves. Additionally, the theodolites do not have to be placed symmetrically about the laser beam. Measurements with one theodolite in front of the weapon and the other to the flank have also produced excellent results. Distances between the theodolites and screens may also be widely varied to suit the particular measurement. Distances between the theodolites and weapon of closer than 2 m and as far as 20 m were demonstrated to produce excellent results. The limitations are largely based upon the resolution of the theodolites and their minimal focusing distances. A typical BEAMS setup is shown in figure 20 where a translucent screen was used at the first location to permit the theodolites to be placed in front of it. The figure is enhanced showing the tetrahedron in-space formed between the two theodolites and two screens.

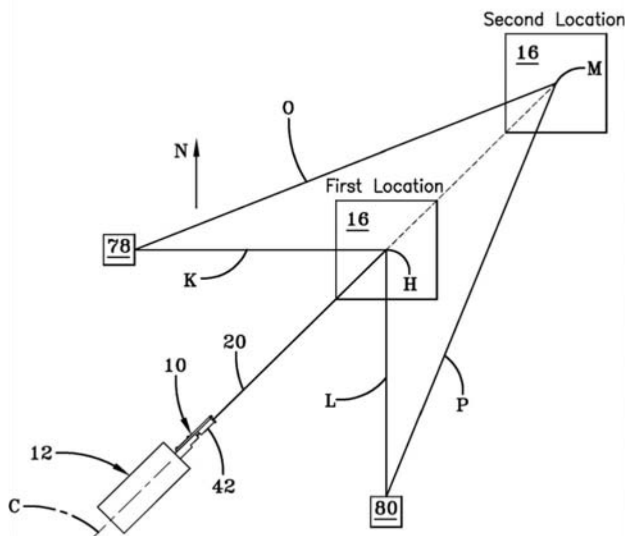

Figure 19
Block diagram of laser apparatus, theodolite, and screen set up

Figure 20
Typical BEAMS setup depicting the tetrahedron formed by theodolites and screens
(Laser line and spots enhanced for clarity.)

Citing figure 19, theodolites 78 and 80 are referenced to a common angular system such as north denoted by arrow N. All horizontal measurements are referenced to this angle. Additionally, the theodolites are each referenced to the local horizontal plane using conventional methods described previously in the Theodolite Apparatus section. At each theodolite, measurements are made of the horizontal and vertical angles to the opposing theodolite. Additionally, at each theodolite, measurements are made of the horizontal and vertical angles between the theodolite and the laser point H along lines K and L, respectively. The reflective surface (16) is then placed at a second location, which may be further or closer along the laser beam path than the first location. In figure 19, the second location is further away from the laser than the first location. At the second location, the laser beam makes a spot or point M on the screen (16). Horizontal and vertical angular measurements of spot M are made from the theodolites along lines O and P, respectively. Note that although measurements may be made to the point further from the laser first, when entering data into the spreadsheet, the data gathered for the point closest to the laser must be entered as the “P1” point.

There are now three sets of angular data. They are:

- The horizontal and vertical angles of the theodolites measured to each other
- The horizontal and vertical angles measured from each theodolite to point H
- The horizontal and vertical angles measured from each theodolite to point M

From these three sets of angular data, one may compute the three-dimensional positions of the points H and M referenced to an orthogonal coordinate system in which the reference direction N and the horizontal are the principal axes and having dimensions that are proportional to the horizontal distance between the theodolites. The computation of these parameters was described in detail in the Computation Component section.

Alternative Measurement Techniques

As mentioned in the calibration paragraphs, it is possible to use the laser apparatus in the absence of prior calibration. This can be accomplished in two ways:

- Quantify and subtract the bias from measurements or
- Make measurement pairs to null the bias

Both approaches are similar in that the laser beam is observed on a pair of screens at points H and M and the horizontal and vertical angles are measured from each theodolite as per figure 19. The laser apparatus is rotated 180 deg in the bore without altering the bore’s position. The laser is observed on the screens a second time and horizontal and vertical measurements are again made. The elevation and azimuth for each pair of measurements is computed and the elevation and azimuth deltas between the two laser positions are determined. The elevation and azimuth bias corrections are computed by dividing the deltas in half. These corrections may be applied to subsequent measurements. Alternatively, the bias may be nullified by always making pairs of measurements with the laser apparatus rotated 180 deg between measurements. The average of the two elevation and azimuth values will yield the corrected elevation and azimuth of the bore. The disadvantage to this approach is that it doubles the number of measurements that must be made. It also has the disadvantage of potentially disturbing the position of the weapon when the laser apparatus is rotated.

For either of these alternative techniques, the assumption is made that the magnitude of the out-of-calibration condition of the laser fixture is small in comparison to the error in estimating a 180-deg rotation of the apparatus itself. By using the handle of the apparatus as a guide and an index mark on the face of the tube, bore rotation error may be kept to a minimum.

Spreadsheet Computations

The BEAMS spreadsheet was created using Microsoft® Office Excel® 2003 for two reasons. First, Excel® is a convenient development environment to automate the required equations and second, the resultant product is highly portable for use on many personal computer platforms. This makes it well suited to running on a laptop computer to collect and reduce data in a field environment. The spreadsheet makes use of many embedded features of Excel® including the Analysis ToolPak Add-In. This feature must be enabled to support two visual basic routines developed specifically for the spreadsheet. These are DMStoDec, which converts data in the degrees, minutes, and seconds format into decimal degrees and the inverse DegToDMS, which converts decimal degrees to degrees, minutes, and seconds format. Therefore, for the spreadsheet to operate properly from the Excel® Tool menu select Add-Ins and be sure the Analysis ToolPak is checked as shown in figure 21. Additionally, when the Excel® application is launched the Enable Macros feature must be selected.

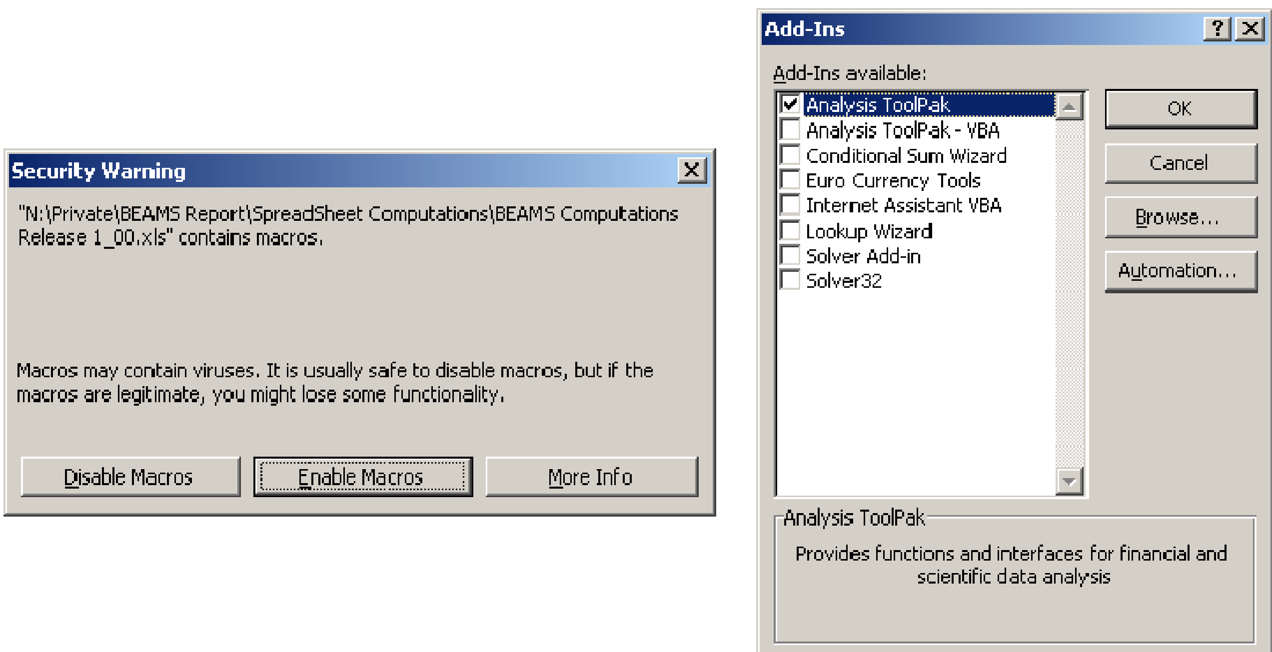

Figure 21
Excel® enabled macros and add-ins menu dialog boxes

The BEAMS spreadsheet is a workbook composed of five separate worksheets. The worksheets are:

- BEAMS title sheet
- Instructions and terms
- Setup and calibration data
- Data
- Graphs

Due to the complex nature of the workbook, all of the cells with the exception of those that require data entry are protected. Attempting to alter the content of protected cells is highly discouraged as it may render the entire workbook unusable. Screen captures of each of the sheets are presented for reference in appendix A. The title workbook provides information on the developer of the spreadsheet and its release version. The instructions and terms workbook consists of a highly condensed version of this document, which can be used as a reference for the operator. It also includes a list of terms and abbreviations for each of the columns in the workbook. These terms are also listed in this document in the individual worksheet sections.

Setup and Calibration Data Worksheet

The setup and calibration data worksheet shown in figure A-3 (app A) is the first sheet that requires operator input. Operator input is only required in cells which are shaded green. Data entry columns incorporate a mouse-over help feature as shown in figure 22.

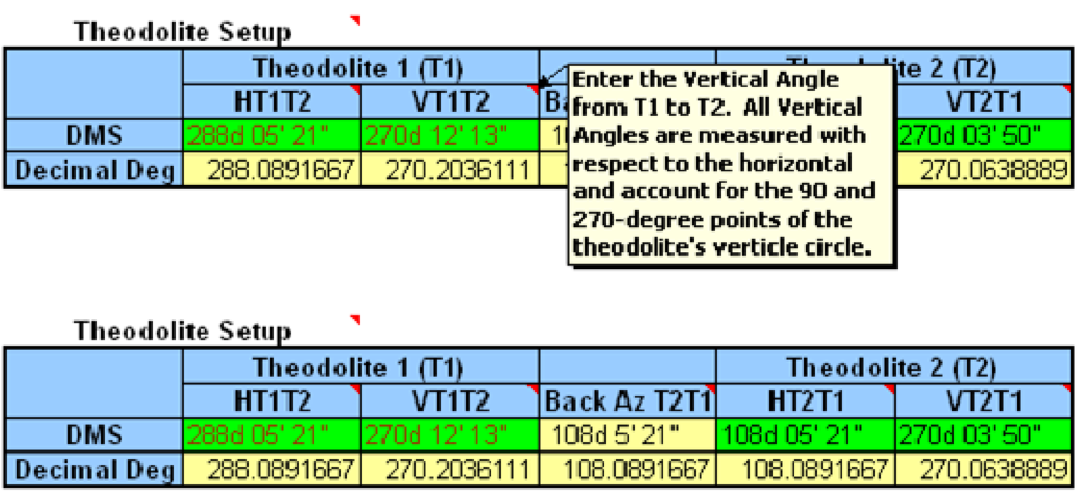

Figure 22
Theodolite setup showing mouse-over help and data entry

As previously described in the Computation Component section, the horizontal and vertical angles between theodolite T1 and T2 must be measured. It is not critical which theodolite is designated T1. It is, however, critical that once it is designated that all subsequent measurements are made following the same naming convention. In a typical setup, theodolite T1 is leveled and oriented to an azimuth reference. The azimuth reference may come from a separate theodolite that is positioned on a survey control point and has its azimuth reference oriented to a known distant aim point reference. Theodolite T1 then sights to T2 to orient it on a proper azimuth. When the horizontal angle from T1 to T2 (HT1T2) and the vertical angle (VT1T2) are entered into the spreadsheet, the spreadsheet will compute and display the back-azimuth from T2 to T1. That is the horizontal angle from T1 to T2 minus 180-degrees. This is the azimuth value which is set on T2 when it observes T1. That angle (HT2T1) along with the vertical angle (VT2T1) is entered into the spreadsheet. These four values on the setup and calibration worksheet will be applied to all entries made on the setup and calibration and data worksheets. If the theodolites are moved or re-oriented, a new workbook should be used for the new values. It is critical that the proper data entry format be observed. All angular data entries in the spreadsheet are in degrees, minutes, and seconds and are of the form

D[DD]d$MM’$SS”

where:

D	Single digit in degrees and [DD] is an optional digit(s)
d	Delimiter indicating degrees
$	Space
MM	Two digits of arc-minutes
‘	Delimiter, single quite, indicating arc-minutes
SS	Two digits of arc-seconds
“	Delimiter, double quote, indicating arc-seconds

As the data is entered into the spreadsheet in degrees, minutes, and seconds, the cell below the entry (fig. 22) displays the value converted to decimal degrees.

The BEAMS may be used as a purely angular measurement system or may be optionally calibrated for distance as mentioned previously. If a distance calibration is not required, no further data entry is needed on the setup and calibration data worksheet.

When the distance calibration is performed, all resulting three-dimensional computations in the spreadsheet will be scaled by that known distance to yield actual X, Y, and Z distances rather than relative measurements. In either case, all three-dimensional references are made with respect to T1 as the 0, 0, 0 origin. The process for entering angular measurement data for the calibration or actual tube positioning is exactly the same. The only difference is whether the data is entered on the setup and calibration worksheet or the data worksheet. Each worksheet has four major sections namely:

- Data input and output — Where inputs cells are green, output cells are tan
- Angular data — Where output cells are tan
- Data for theodolite — Where output cells are light yellow
- Data for theodolite — Where output cells are yellow

Data Worksheet

Since there is a high degree of commonality between the two worksheets, the following paragraphs will focus on the data worksheet. The reader will see that the same applies to the more streamlined setup and calibration worksheet. When viewing the spreadsheets, the green color cells require data input. Tan color cells indicate outputs that are used by or computed for both theodolites. Light yellow color cells are data outputs computed from the horizontal and vertical angles measured by theodolite one. Yellow color cells are data outputs computed from the horizontal and vertical angles measured by theodolite two.

Data Input and Output

Each BEAMS elevation and azimuth computation requires sighting to and making angular measurements at two points along the laser beam or known distance baseline, P1 and P2. Point P1 is located closer to the laser or in the case of the calibration distance baseline on the setup and calibration worksheet, the point closest to the line from T1 to T2. On the data worksheet, each data point is consecutively numbered from P1 to P30 and each pair numbered from 1 to 15. The pair numbers are used to reference data on subsequent portions of the data worksheet as will be explained in the following paragraphs. If more than 15 pairs of data points are needed, it will be necessary to open another BEAMS workbook.

For each point (Pn), the horizontal and vertical angles (HT1 and VT1) measured from T1 along with the associated angles (HT2 and VT2) measured from T2 are entered into the appropriate cells. The process is then repeated for the P2 measurements. When making measurements, it is critical that the surface upon which the laser is viewed remains stationary while both theodolites make measurements of that point. If this data is entered in the calibration and setup worksheet, the calibration distance should also be entered. The spreadsheet then computes the data shown in table 1. Figure A-4 (app A) illustrates examples of data entries and outputs of the worksheet.

Table 1
Definitions for setup and calibration worksheet and data worksheet output

Meas Dif X	Difference in X value computed for each theodolite. X is measured perpendicular to the north-south reference line with values increasing to the right. On the setup and calibration worksheet, the value will be a percentage of the T1 to T2 distance. It will also be a percentage on the data worksheet unless the calibration information was entered in the setup and calibration worksheet. Ideally, the difference in computing the location of Pn based upon T1 or T2 data should be zero. In reality, small errors will be present in the measurements that will show up as difference values. Acceptable measurements will have difference values on the order of 10^{-4} to 10^{-15} dependent upon the distance between the theodolites or less than 0.25 mm if distance scaling is used.
Meas Dif Y	Difference in Y value computed for each theodolite. Y is measured parallel to the north-south reference line with values increasing in a northerly direction. See Meas Dif X for additional information.
Meas Dif Z	Difference in Z value computed for each theodolite. Z is measured perpendicular to the horizontal plane with values increasing in the upward direction. See Meas Dif X for additional information.
Dif DP1P2	Difference in the computed distances from P1 and P2 for each theodolite. This is the difference in magnitude of the vectors between P1 and P2 when computed using data for each theodolite. It may be scaled or a percentage of the distance between the theodolites and is ideally zero.
AvgHP1P2	Average horizontal angle between P1 and P2. This is the azimuth of the laser which is coincident with the bore azimuth. It is displayed in decimal degrees and mils where there are 6400 mils in 360 deg.
AvgVP1P2	Average vertical angle between P1 and P2. This is the elevation of the laser which is coincident with the bore azimuth. It is displayed in decimal degrees and mils.

Common Angular Data

The BEAMS angular data displays the horizontal and vertical angles for the eight data values entered in the input output section converted to decimal degrees. It also displays the three angles A, E, and F of the horizontal triangle (fig. 12) in decimal degrees, where A is the horizontal angle turned on T1 from T2 to Pn, E is the horizontal angle turned on T2 from T1 to Pn, and F is the horizontal angle turned at Pn from T1 to T2. These intermediate data outputs are used in other sections of the workbook and are a convenient reference in the event troubleshooting of the setup becomes necessary. Figure A-5 (app A) illustrates examples of data output from the worksheet.

Data for Theodolite 1

This section of the worksheet uses the horizontal and vertical angles measured by T1 and the range information established by the horizontal angle on T2 for computations. It outputs the distance from T1 to point Pn; the x, y, and z coordinate of Pn; the component distance along each cardinal axis of the distance between P1 and P2; the magnitude of the distance; and the horizontal and vertical angles between P1 and P2 for each of the 15 data pair entries in the input section. A detailed definition of these values is shown in table 2. These values averaged with the corresponding values in the data for the Theodolite 2 section of the worksheet are used to compute the values in the output section.

Table 2
Definitions for data for theodolite 1 worksheet output

DT1	Distance measured from T1 to Pn. The distance is measured along the line from T1 to Pn. The value will be a percentage or an actual distance dependent upon the setup and calibration worksheet.
XT1	Distance measured from T1 to Pn in the X direction. The X direction and percentage or scaled distance conventions follow those previously described.
YT1	Distance measured from T1 to Pn in the Y direction. The Y direction and percentage or scaled distance conventions follow those previously described.
ZT1	Distance measured from T1 to Pn in the Z direction. The Z direction and percentage or scaled distance conventions follow those previously described.
DXP1P2	Distance measured from P1 to P2 in the X direction. The X direction and percentage or scaled distance conventions follow those previously described.
DYP1P2	Distance measured from P1 to P2 in the Y direction. The Y direction and percentage or scaled distance conventions follow those previously described.
DZP1P2	Distance measured from P1 to P2 in the Z direction. The Z direction and percentage or scaled distance conventions follow those previously described.
DP1P2	Distance measured from P1 to P2. The distance is measured along the line from P1 to P2. The percentage or scaled distance conventions follow those previously described.
HP1P2	Horizontal angle between P1 and P2. This is the azimuth of the laser which is coincident with the bore azimuth. It is displayed in decimal degrees and mils, where there are 6400 mils in 360 deg.
VP1P2	Vertical angle between P1 and P2. This is the elevation of the laser which is coincident with the bore azimuth. It is displayed in decimal degrees and mils.

In the event the elevation and azimuth in the output section don't agree with the expected value, these intermediate data outputs are useful in determining at which theodolite a poor measurement may have been made. Figure A-6 (app A) illustrates examples of data output from the worksheet.

Data for Theodolite 2

This section of the worksheet performs the same function as previously described for theodolite one. The difference is that it uses the horizontal and vertical angles measured by T2 and the range information established by the horizontal angle on T1 for computations. It also makes use of two additional pieces of information, so that its output is reflected back to the origin of T1 rather than T2. To do this, the spreadsheet incorporates two additional columns, namely, T2T1 Z Dif and ZT2 + Zdif. The first column (T2T1 Z Dif) contains the magnitude of the difference in height from T2 to T1. This is required as the theodolites are not operating in the same horizontal plane. The second column (ZT2 + Zdif) is the corrected height value for T2. As with all distance parameters, these may be a percentage or an actual distance dependent upon the setup and calibration worksheet. Figure A-7 (app A) illustrates examples of data output from the worksheet.

Graphical Data Worksheet

The graph worksheet provides a three-dimensional graphic representation of each of 15 pairs of data points entered in the data worksheet. The origin for the three axes is T1 and the data is normalized to the distance of the point furthest from the origin. By operating the three slider controls it is possible to rotate the graph so the data points may be viewed at any angle. A slider control is also included to provide a zoom feature so the closely grouped points may be expanded for better viewing. Figure A-8 (app A) illustrates examples of the plotted data.

Implementation of the three-dimensional graphics and rotation was based upon Andy Pope's three-dimensional XY-Scatter Chart (ref. 8). It uses sine and cosine functions to create a rotation matrix, which operates on the x, y, and z values computed in the data worksheet. It also generates the coordinate axis and outer “cage” boundary of the graphics. When the Visual Basic ScrollBar controls are adjusted, the rotation matrix changes the apparent three-dimensional position of the data points, axis, and cage. This foreshortening presents the illusion that the graph is turning in three-dimensions. Excel® does not support automatic generation of labels for the data points in the chart. To generate the labels for the data points and coordinate axes, Rob Bovey’s XY Chart Labeler V7.0 (ref. 9) was used.

This author modified the original three-dimensional XY-Scatter Chart format to normalize the data so a wide range of points could be accommodated within the cage boundary. The scatter chart was also modified so that data point pairs are connected by lines. Additionally, it was modified to include the zoom feature so close-set data points could be seen more clearly.

Making Measurements

Prior to using the theodolite to measure angles, the telescope should be focused to eliminate parallax. Accurate measurements will be difficult to achieve if parallax is present. Parallax is removed by bringing the focus of the eyepiece and the focus of the objective lens to the plane of the reticle. This can be accomplished by pointing the telescope toward the sky or a neutral background and rotating the eyepiece until the reticle crosshairs become distinct lines. The telescope can then be pointed to a well-defined distant point. While viewing the crosshairs, adjust the telescope focusing ring to bring the distant point into sharp focus. Adjust the instrument horizontally to center the vertical crosshair on the distant point. Move your eye horizontally back and forth across the eyepiece and note the position of the reticle relative to the distant point. If the crosshair remains fixed on the distant point, the parallax has been removed. If not, adjust the eyepiece slightly to bring the crosshairs into sharper focus, refocus the telescope, and repeat the process until there is no apparent motion.

To achieve high quality results with BEAMS, maintaining consistent theodolite operation is paramount. This is true for both instrument setup and when sighting to the laser spots for measurements. This can be particularly challenging when more than one theodolite operator is viewing the laser spots. Although it may be intuitive to sight to the edge of a laser spot, more consistent results will be achieved if the reticle is centered on the spot. This is true because the angle of obliquity between the line of the laser, the attitude of the screen, and the line-of-sight of the theodolite will vary as measurements are made. Thus, the spot will appear to be almost circular at some positions, becoming more elliptical at others, to almost a line when the angle of incidence of the laser beam and the screen or the theodolite approaches 90 deg. Figure 23 clearly shows the difference in the laser spot appearance as seen through a theodolite with the incident laser at near zero and at near 90 deg to the line of sight.

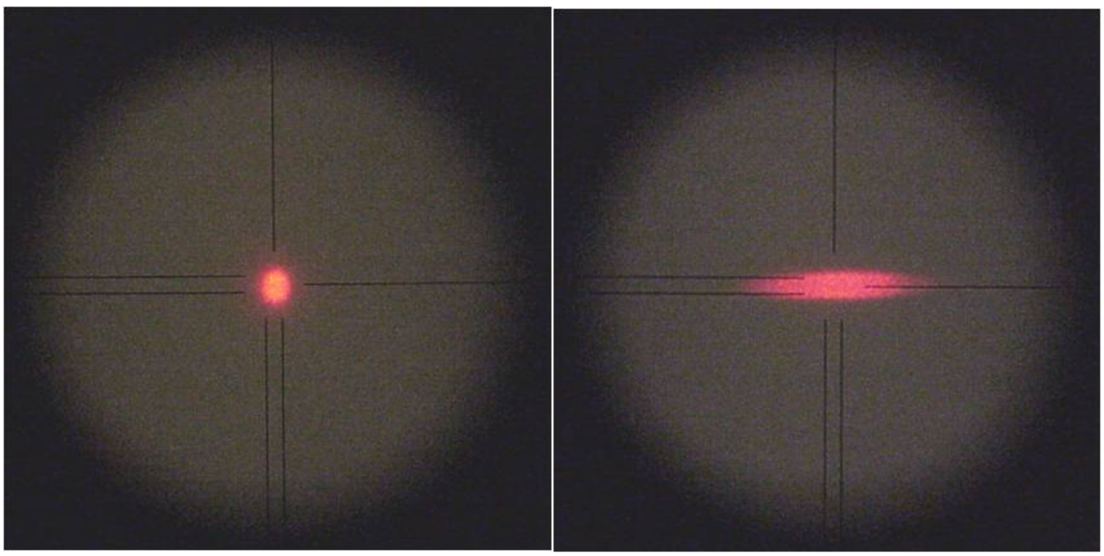

Figure 23
Views through the theodolite of a laser spot at near 0-deg incidence angle on the left and near 90-deg incidence on the right

Dependent upon how the screens are mechanically held in position it is neither always possible nor desirable to maintain them perpendicular to the laser beam. This would be contingent upon the positioning of the theodolites and their view of the screens at various elevations and azimuths of the weapon bore. Prior to the actual collection of data, it is good practice to verify that both theodolites can observe the screens at the extreme elevations and azimuths at which the weapon will be pointed for testing. When positioning the screens, they must remain stable while the laser spot positions are measured. Any motion of a screen during the theodolite measurements will invalidate the data.

Typical BEAMS setups on a variety of weapon platforms and measurement conditions have yielded pointing accuracy measurements between 0.1 and 0.05 mils (~20 to 10 arc-seconds).

BEAMS APPLICATIONS

A total of four laser apparatus were produced for mortar applications. Two are equipped with lobes for the 60, 81, and 120-mm mortar systems. The other two have lobes only for the 81-mm mortars. The 120 and 81-mm have been used extensively for in-house pointing accuracy measurements on several mortar platforms. These include:

- M95 Mortar Fire Control System (MFCS) on the M1064 tracked 120-mm mortar carrier
- MFCS on the dismounted 120-mm mortar (MFCS-D)
- 81-mm M253 Inconel® mortar
- 81-mm M253 steel mortar

Technical reports concerning these efforts are currently in-press.

The 81-mm only laser apparatuses were made for the Naval Surface Warfare Center (NSWC), Crane Division, Crane, Indiana to support their 81-mm fire control work. One of those units was used by NSWC's contractor, Teledyne Scientific Company, Thousand Oaks, California to verify their weapon pointing efforts.

The Office of the Project Manager (PM) for Towed Artillery Systems (TAS) at Picatinny Arsenal became aware of BEAMS and independently pursued developing a laser apparatus for their 105-mm M119A2 towed howitzer. With assistance from this author, they were able to achieve reliable and extremely repeatable pointing measurements on the M119A2 howitzer. Based upon the highly positive results, the PM has elected to use BEAMS for their bid-sample testing of inertial navigation systems for the howitzer. The PM Office in conjunction with this author has trained personnel from the Yuma Test Center (YTC), Yuma Proving Ground (YPG), Yuma, Arizona in the operation of BEAMS. Testing was conducted August through November 2009. Additionally, the Office of the PM for Light Armored Vehicles (PM LAV) at the Tank Automotive and Armaments Command (TACOM), Warren, Michigan have elected to use BEAMS for testing of their newly integrated inertial navigation system for the 120-mm mortar. The system was tested for Foreign Military Sales (FMS).

CONCLUSIONS

Current weapon pointing measurement methods employed at Government Proving Grounds make use of cumbersome mechanical fixtures or techniques that are highly dependent upon the skill of the theodolite operator. The processes can require repeated relocating and leveling of the theodolite to "wiggle-in" on the single proper azimuth line of the weapon. Additionally, properly identifying and sighting to the proper measurement points themselves may be highly subject to error. All of this leads to a measurement process that can be extremely tedious and time consuming to perform and can still result in error.

The Bore Elevation and Azimuth Measurement System (BEAMS) has proven itself to be a low-cost technique to verify in a field-test environment that the elevation and azimuth pointing accuracy requirement of a weapon's fire control system is met. Interchangeable lobes allow for use with any weapon tube caliber to include both smooth-bore mortars and rifled artillery cannons. The eye-safe laser provides a projection of the tube axis and its associated mechanical and optical adjustments allow the laser beam to be made concentric with the actual tube axis. These features facilitate measurement and/or removal of bias from the fixture. The BEAMS uses dual theodolites and conventional geodetic survey procedures to make three-dimensional measurements of the laser's position. The use of two or more theodolites to establish the three-dimensional coordinates of a point has been used successfully for decades in the aerospace and shipbuilding industries. From the measurements of the laser's position, the weapon tube elevation and azimuth can be computed with exceptional accuracy. The computations may be performed in a spreadsheet or the use of dedicated computer software. By automating the computations in an Excel® spreadsheet, they become extremely portable and can be taken to the field to reduce data in real time to verify the bore position. Because BEAMS makes two measurements of the laser's position, all the measurements are effectively scaled to the same coordinate system. Therefore, the use of a calibrated scale bar or other length standard to establish accurate lengths is not necessary. However, if a length standard is used, the subsequent XYZ coordinates may be scaled into real world distance measurements.

The BEAMS was evaluated on numerous mortar and artillery platforms and has provided excellent measurement results on all of them. PMs have realized the value of BEAMS measurements in removing human error from evaluation of the performance of their fire control systems. The BEAMS has raised the standards by which pointing accuracy measurements are made.

RECOMMENDATIONS

Because of the accuracy achieved with the Bore Elevation and Azimuth Measurement System (BEAMS), it is possible to make additional types of weapon measurements. This could include relative motion of various weapon components before and after firing to verify mechanical alignments are maintained.

The BEAMS has proven itself simple and reliable to use; however, the process may be further automated. By employing digital theodolites or total stations, the horizontal and vertical angles measured to each laser point may be automatically entered in to a spreadsheet or dedicated computer program.

It is highly recommended that further implementations of the BEAMS be explored to fully evaluate its potential for making accurate engineering measurements in a test environment.

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APPENDIX A
BEAMS EXCEL® SPREADSHEET SCREEN CAPTURES

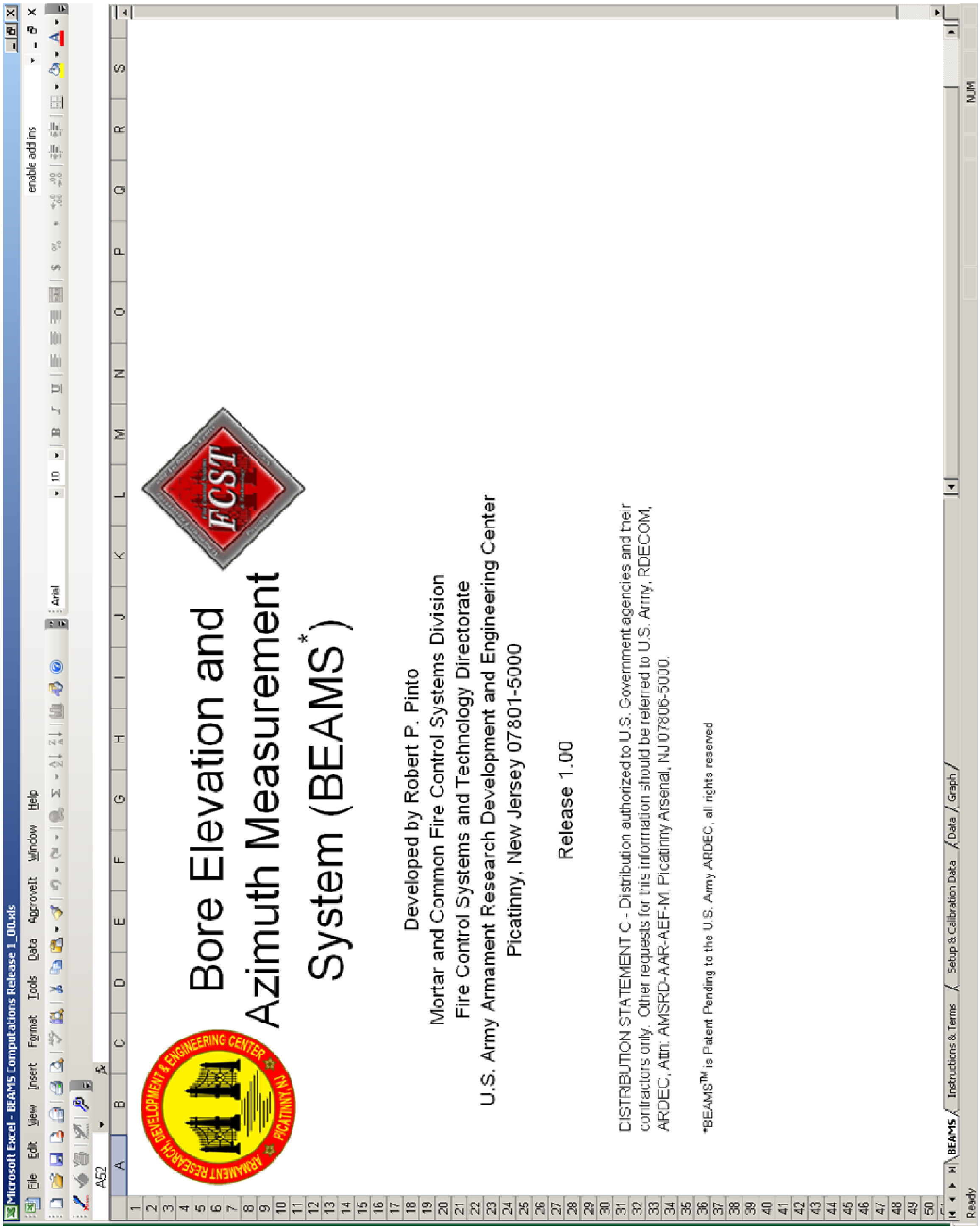


Figure A-1
BEAMS workbook title page

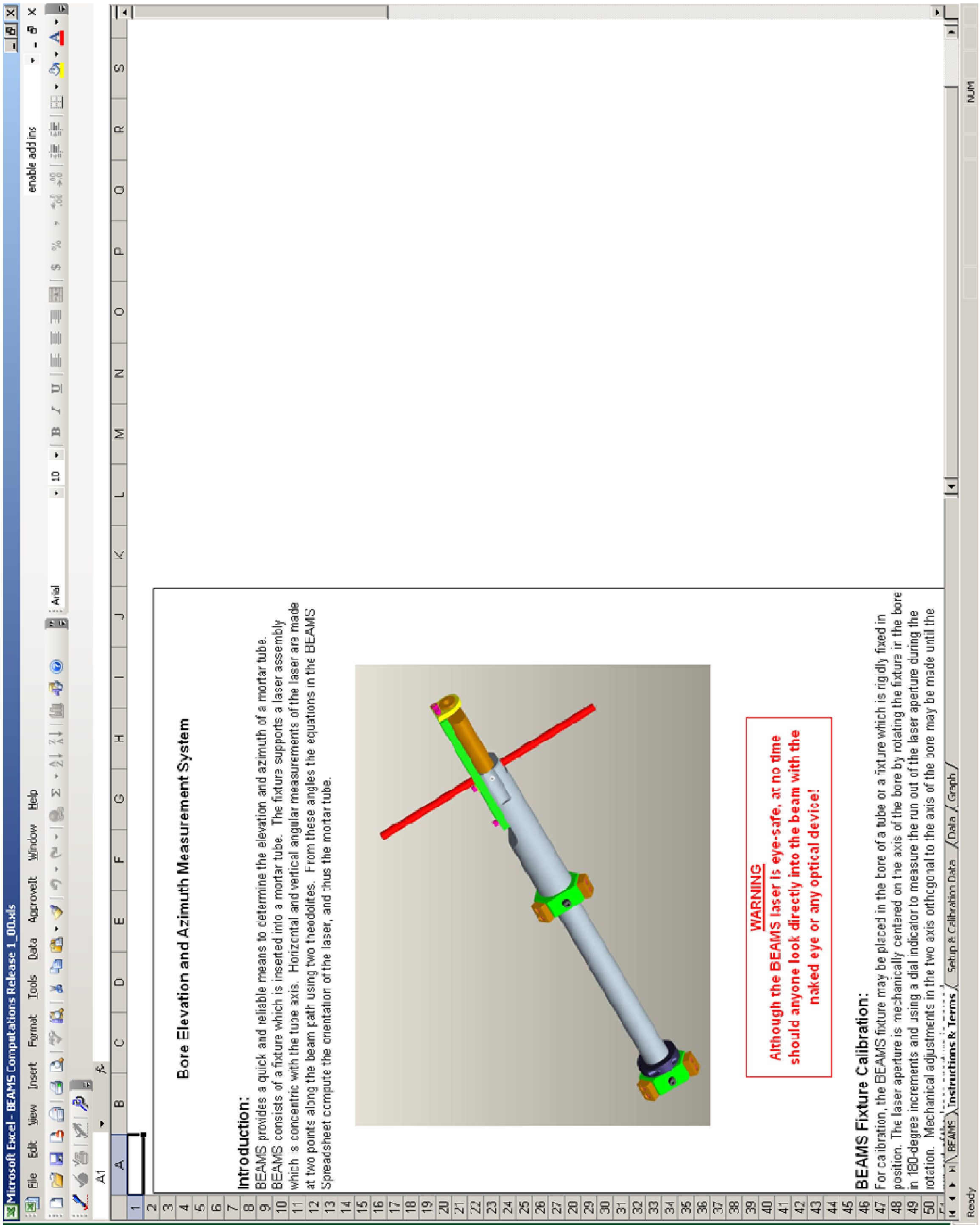


Figure A-2
BEAMS instructions and terms worksheet

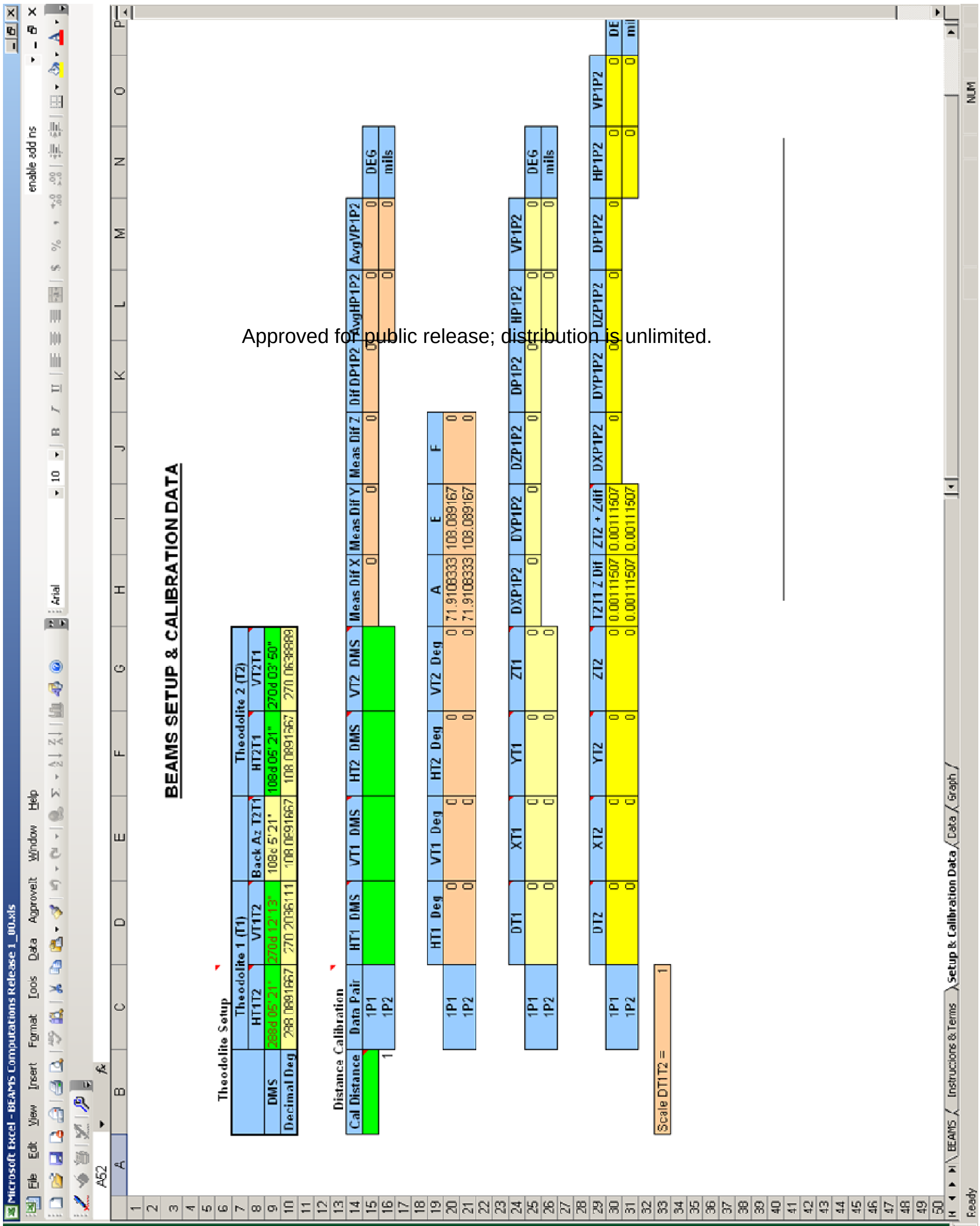
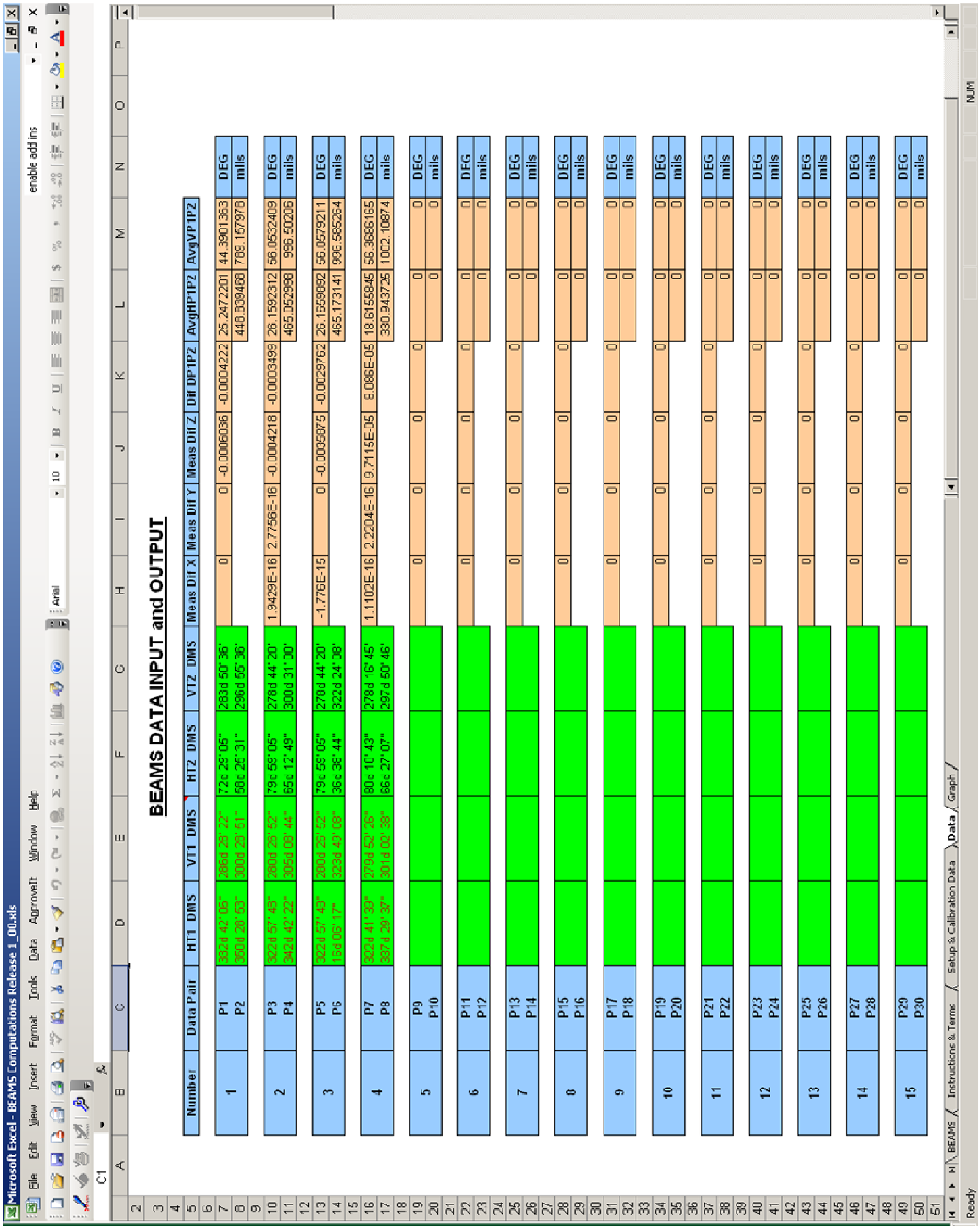
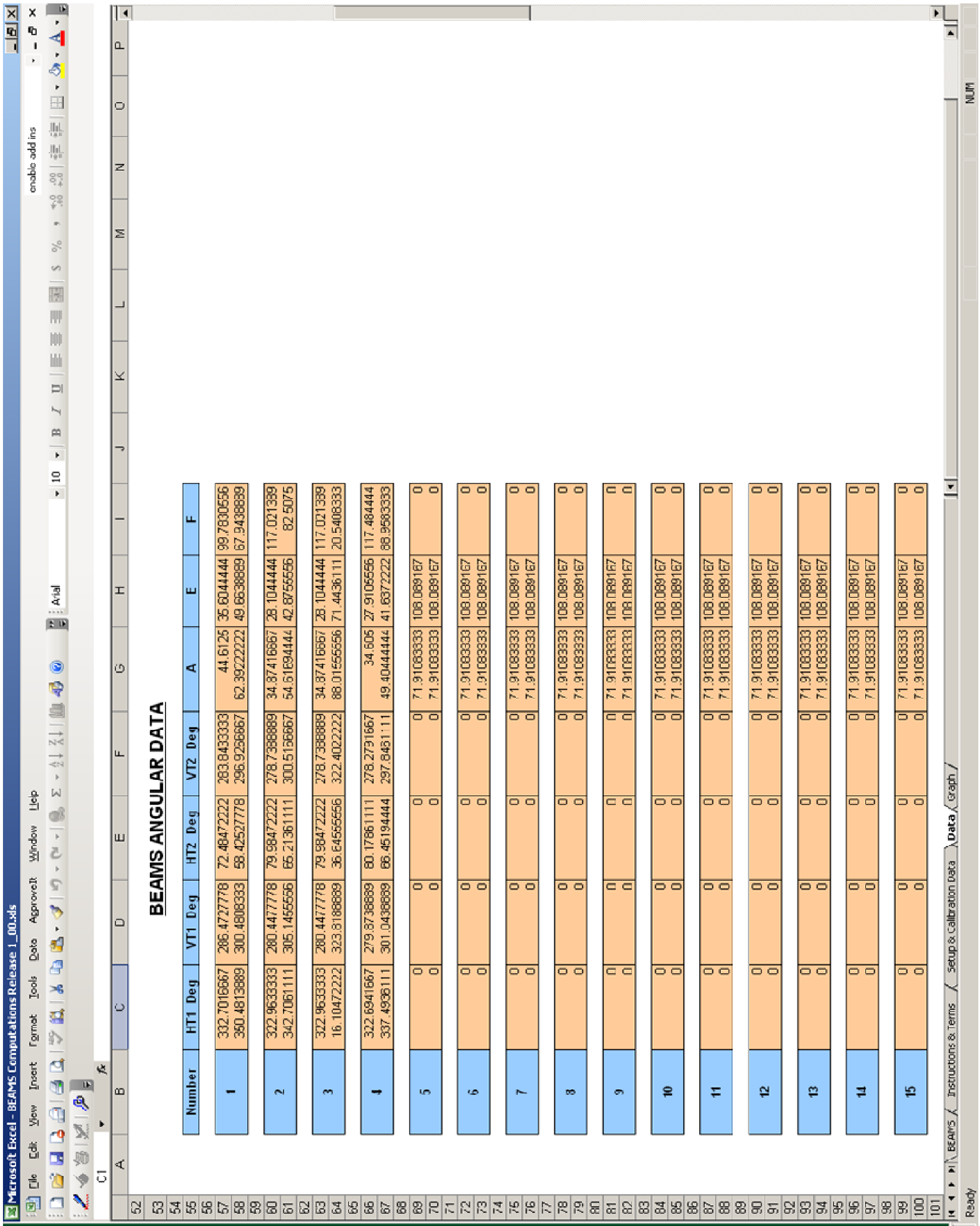


Figure A-3
BEAMS Calibration and setup worksheet



Number	Data Pair	HT1 DMS	VT1 DMS	HT2 DMS	VT2 DMS	Meas Dif X	Meas Dif Y	Meas Dif Z	Dif DP1P2	AvgHP1P2	AvgVP1P2	
1	P1	332d 42' 05"	286d 28' 22"	72c 29' 05"	283d 50' 36'	0	0	-0.0006036	-0.0004222	25.2472201	44.3901363	DEG
	P2	350d 28' 53"	300d 28' 51"	58c 25' 31"	296d 55' 36'					448.839468	789.157976	mils
2	P3	322d 57' 43"	280d 28' 52"	79c 59' 05"	278d 44' 20'	1.9429E-16	2.7756E-16	-0.0004218	-0.0003499	26.1592312	56.0532409	DEG
	P4	342d 42' 22"	305d 09' 44"	65c 12' 49"	300d 31' 30'					465.052988	996.50206	mils
3	P5	322d 57' 43"	200d 28' 52"	79c 59' 05"	270d 44' 20'	-1.776E-15	0	-0.0035075	-0.0029762	26.1559092	56.0579211	DEG
	P6	15d 06' 17"	323d 40' 08"	36c 38' 44"	322d 24' 38'					465.173141	996.585264	mils
4	P7	322d 41' 33"	279d 52' 26"	80c 10' 43"	278d 16' 45'	1.1102E-16	2.2204E-16	9.7115E-05	8.086E-05	18.6155845	56.3686165	DEG
	P8	337d 29' 37"	301d 02' 38"	66c 27' 07"	297d 50' 46'					330.943725	1002.10874	mils
5	P9					0	0	0	0	0	0	DEG
	P10									0	0	mils
6	P11					0	0	0	0	0	0	DEG
	P12									0	0	mils
7	P13					0	0	0	0	0	0	DEG
	P14									0	0	mils
8	P15					0	0	0	0	0	0	DEG
	P16									0	0	mils
9	P17					0	0	0	0	0	0	DEG
	P18									0	0	mils
10	P19					0	0	0	0	0	0	DEG
	P20									0	0	mils
11	P21					0	0	0	0	0	0	DEG
	P22									0	0	mils
12	P23					0	0	0	0	0	0	DEG
	P24									0	0	mils
13	P25					0	0	0	0	0	0	DEG
	P26									0	0	mils
14	P27					0	0	0	0	0	0	DEG
	P28									0	0	mils
15	P29					0	0	0	0	0	0	DEG
	P30									0	0	mils

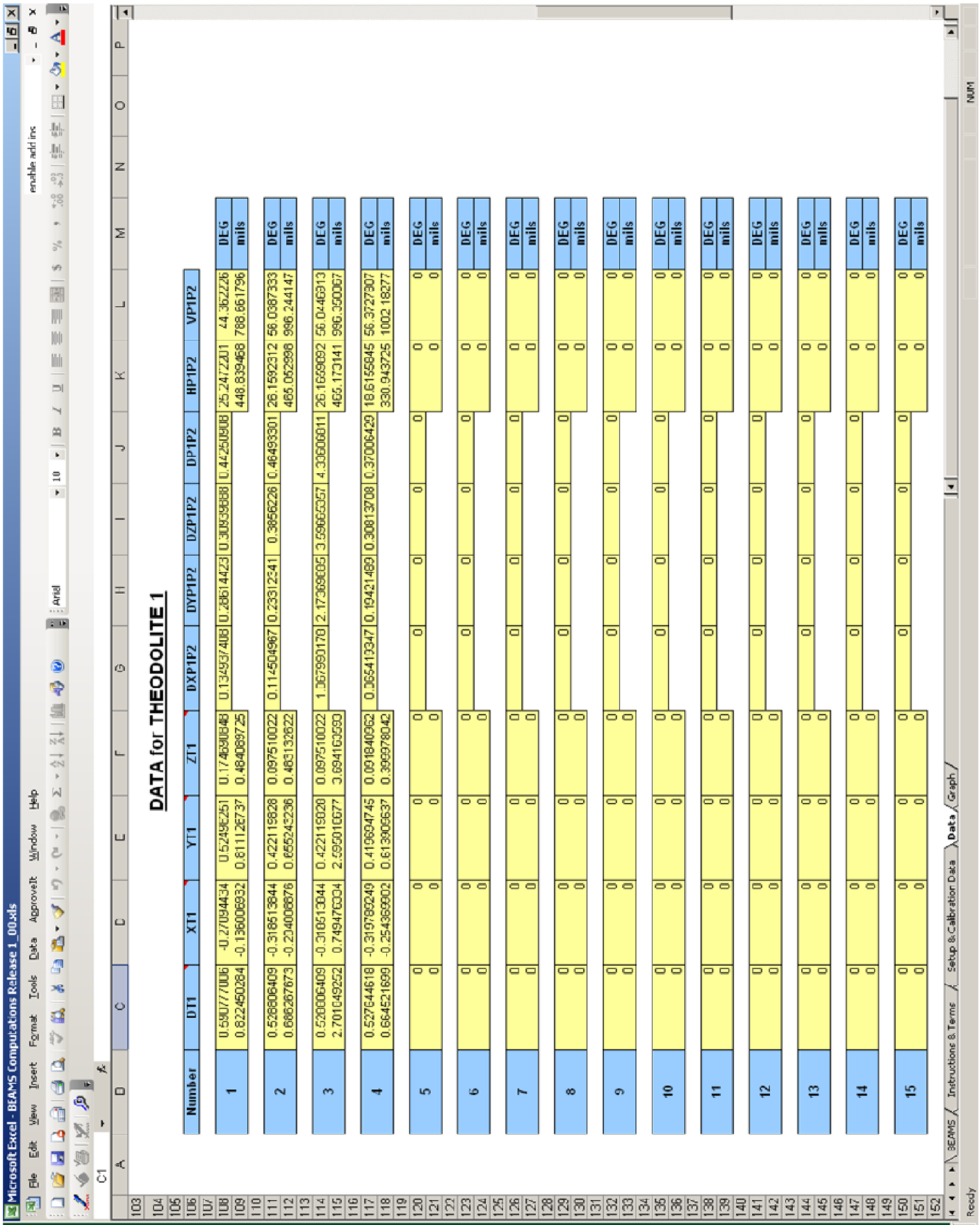
Figure A-4
BEAMS data input and output worksheet



BEAMS ANGULAR DATA

Number	HT1 Deg	VT1 Deg	HT2 Deg	VT2 Deg	A	E	F
1	332.7016667	286.4727778	72.48472222	283.8433333	44.6125	35.6044444	99.7830556
	350.4813889	300.4808333	58.42527778	296.9256667	62.39222222	49.6638889	67.9438889
2	322.9633333	280.4477778	79.98472222	278.7338889	34.87416667	28.1044444	117.021389
	342.7061111	305.1455556	65.21361111	300.5156667	54.61694444	42.8755556	82.5075
3	322.9633333	280.4477778	79.98472222	278.7338889	34.87416667	28.1044444	117.021389
	16.10472222	323.8188889	36.64555556	322.4022222	88.01555556	71.4436111	20.5408333
4	322.6941667	279.8738889	80.17861111	278.2731667	34.605	27.9105556	117.484444
	337.4936111	301.0438889	66.45194444	297.8461111	49.40444444	41.6372222	88.9583333
5	0	0	0	0	71.91083333	108.089167	0
	0	0	0	0	71.91083333	108.089167	0
6	0	0	0	0	71.91083333	108.089167	0
	0	0	0	0	71.91083333	108.089167	0
7	0	0	0	0	71.91083333	108.089167	0
	0	0	0	0	71.91083333	108.089167	0
8	0	0	0	0	71.91083333	108.089167	0
	0	0	0	0	71.91083333	108.089167	0
9	0	0	0	0	71.91083333	108.089167	0
	0	0	0	0	71.91083333	108.089167	0
10	0	0	0	0	71.91083333	108.089167	0
	0	0	0	0	71.91083333	108.089167	0
11	0	0	0	0	71.91083333	108.089167	0
	0	0	0	0	71.91083333	108.089167	0
12	0	0	0	0	71.91083333	108.089167	0
	0	0	0	0	71.91083333	108.089167	0
13	0	0	0	0	71.91083333	108.089167	0
	0	0	0	0	71.91083333	108.089167	0
14	0	0	0	0	71.91083333	108.089167	0
	0	0	0	0	71.91083333	108.089167	0
15	0	0	0	0	71.91083333	108.089167	0
	0	0	0	0	71.91083333	108.089167	0

Figure A-5
BEAMS angular data worksheet



DATA for THEODOLITE 1

Number	DT1	XT1	YT1	ZT1	DXP1P2	DYP1P2	DZP1P2	DP1P2	HP1P2	VP1P2	
1	0.590777006	-0.27094434	0.52496251	0.174690848	0.134937408	0.28614423	0.30939888	0.44250908	25.2472201	44.362226	DEG
	0.822450284	-0.136006932	0.811126737	0.484089725					448.839468	788.661796	mils
2	0.528806409	-0.318513844	0.422119828	0.097510022	0.114504967	0.23312341	0.3856226	0.46493301	26.1592312	56.0387333	DEG
	0.686267673	-0.234008876	0.655243236	0.483132622					465.052998	996.244147	mils
3	0.528806409	-0.318513844	0.422119828	0.097510022	1.367993178	2.17369685	3.59665357	4.33606811	26.1659092	56.0446913	DEG
	2.701049252	0.749476334	2.595010677	3.694163593					465.173141	996.350067	mils
4	0.527644618	-0.319789249	0.419694745	0.091840962	0.365419347	0.19421489	0.30813708	0.37006429	18.6155845	56.3727307	DEG
	0.664521699	-0.254369902	0.613909637	0.399978042					330.943725	1002.18277	mils
5	0	0	0	0	0	0	0	0	0	0	DEG
	0	0	0	0					0	0	mils
6	0	0	0	0	0	0	0	0	0	0	DEG
	0	0	0	0					0	0	mils
7	0	0	0	0	0	0	0	0	0	0	DEG
	0	0	0	0					0	0	mils
8	0	0	0	0	0	0	0	0	0	0	DEG
	0	0	0	0					0	0	mils
9	0	0	0	0	0	0	0	0	0	0	DEG
	0	0	0	0					0	0	mils
10	0	0	0	0	0	0	0	0	0	0	DEG
	0	0	0	0					0	0	mils
11	0	0	0	0	0	0	0	0	0	0	DEG
	0	0	0	0					0	0	mils
12	0	0	0	0	0	0	0	0	0	0	DEG
	0	0	0	0					0	0	mils
13	0	0	0	0	0	0	0	0	0	0	DEG
	0	0	0	0					0	0	mils
14	0	0	0	0	0	0	0	0	0	0	DEG
	0	0	0	0					0	0	mils
15	0	0	0	0	0	0	0	0	0	0	DEG
	0	0	0	0					0	0	mils

Figure A-6
BEAMS data for theodolite 1 worksheet

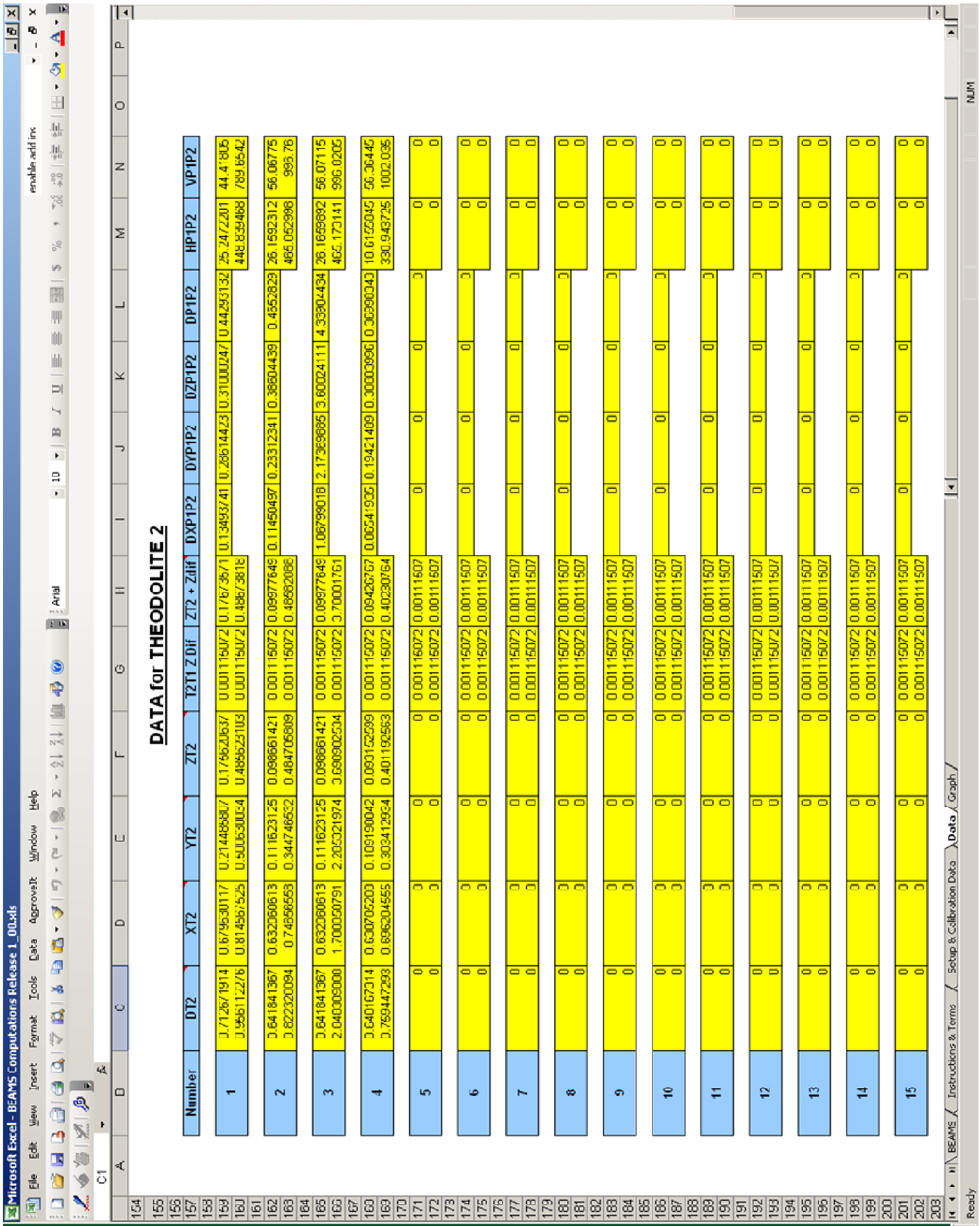


Figure A-7
BEAMS data for theodolite 2 worksheet

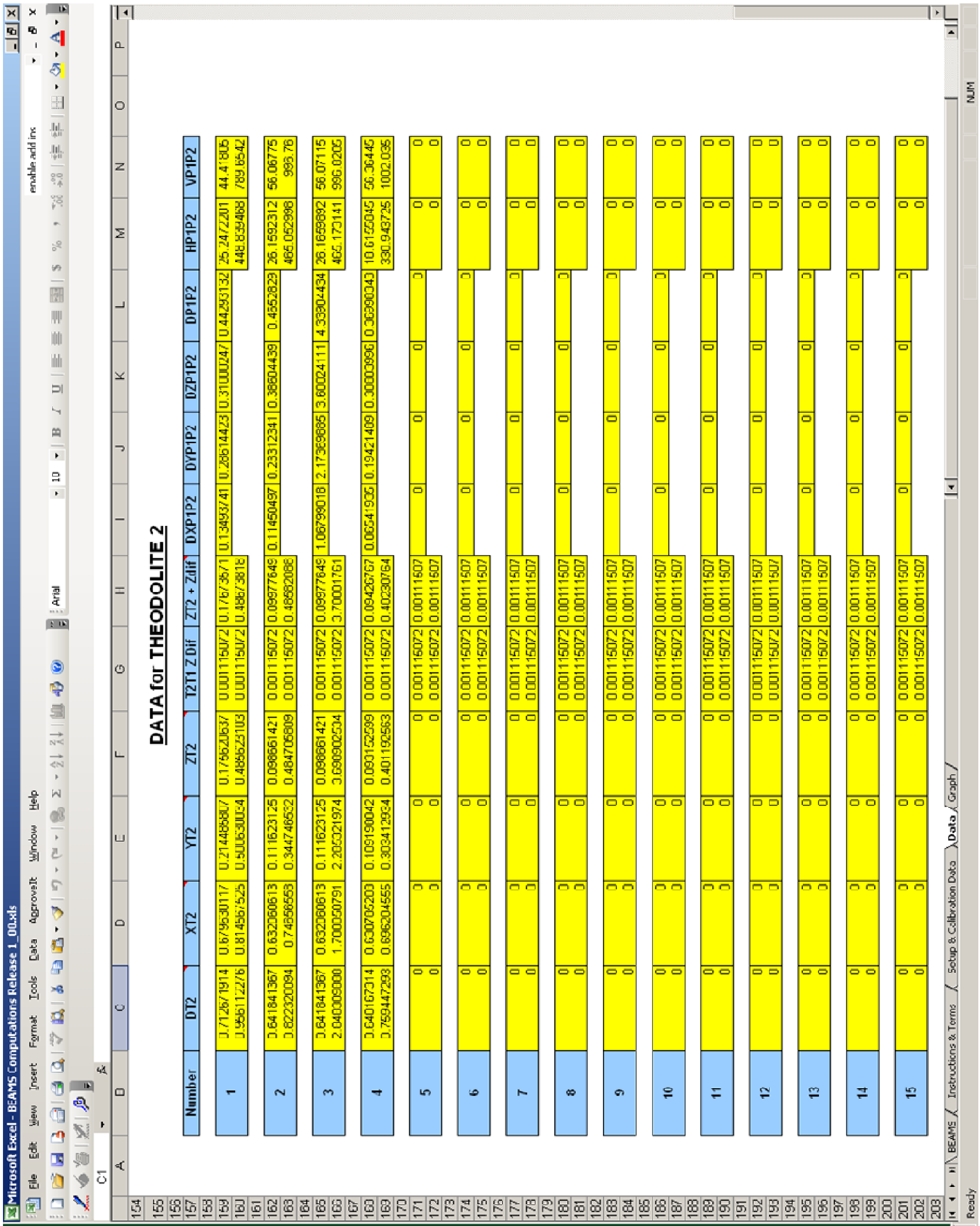


Figure A-8
BEAMS data plot worksheet

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