This document is a new chapter (4.5) to be added to NOAA Manual NOS NGS 3 (hereinafter referred to simply as NOS 3). This new chapter provides an alternative method to normal leveling techniques for crossing rivers, valleys, highways, or other barriers.

Authors:
Steven Breidenbach
John Ellingson
Kendall L. Fancher
Charles Geoghegan
Tim Hanson
Dave Zenk

4.5 Instructions for Theodolites

In 2014, the National Geodetic Survey developed an alternate observing routine suitable for performing river/valley crossings. This alternate routine uses commonly available modern electronic theodolites. The routine addresses sources of error (atmospheric refraction, Earth's curvature, pointing and collimation) which are a function of long-sighting distances and unbalanced shots encountered during river/valley crossings. The routine also addresses instrument and observer errors associated with the use of theodolite instruments. The routine employs the fundamental procedures necessary for a precise crossing: double centering of measurements, multiple observations of targets and simultaneous reciprocal observations. The routine is presented here for use (with suitable theodolites) in crossings of up to 2 kilometers (1.2 miles) in length and up to first-order precision.

4.5.1 Instruments and Setups

Instrument. Suitable theodolites for this observing procedure must have: (1) a telescope that can be plunged, allowing for observations in both direct and reverse mode (2) automatic vertical circle indexing and (3) a minimal instrument least count of 0.1 to 1.0 arcseconds, depending on the desired leveling order and class and crossing width (see Table 4-4).

A measurement procedure known as double centering is used in this routine. Double centering consists of plunging the instrument's telescope between individual measurements and taking measurements to targets in both direct and reverse mode. The mean of two measurements taken this way is self-corrected for any collimation error.

This observing routine relies on the ability to measure precise vertical angles referenced to zenith ("zenith angles"). An error source occurs when a theodolite is not perfectly leveled, creating a misalignment between the instrument's vertical axis and the plumb line. Instruments with automatic tilt-axis compensation self-correct for this potential error source. Theodolite instruments suitable for this routine must have properly functioning automatic vertical-axis compensation.

The least count of an instrument is the smallest measurement increment directly displayed by the instrument. The least count is typically a smaller value than the standard deviation achieved by the measurements taken with the instrument. Table 4-4 identifies minimal least count requirements for instruments dependent on the desired order/class of leveling and crossing width.

Table 4-4.-Instrument Least Count Requirement

	Order/Class of Leveling				
	1/1	1/2	2/1	2/2	3
Crossing Width (meters)	Least Count (seconds)				
100 - 300	0.1	0.5	1.0	1.0	1.0
300 - 600	0.1	0.5	0.5	1.0	1.0
600 - 1000	0.1	0.1	0.5	0.5	1.0
1000 - 1500	0.1	0.1	0.5	0.5	1.0
1500 - 2000	0.1	0.1	0.1	0.5	0.5

The standard deviation of a given set of zenith angle measurements is influenced by both the achievable precision of the instrument and the ability of the observer to accurately point on a target. Table 4-5 represents standard deviations, based on the order and class of leveling being conducted and the width of the crossing, which if achieved should promote a successful crossing routine. Before attempting a crossing routine, you should verify your ability to achieve the standard deviations with your instrument by sighting a well-defined target at your intended crossing width under good sighting conditions, measuring eight sets of direct and reverse mode zenith angles, and then computing the standard deviation of the complete set.

Table 4-5.-Standard Deviation Recommendations

	Order/Class of Leveling				
	1/1	1/2	2/1	2/2	3
Crossing Width (meters)	Standard Deviation (seconds)				
100 - 300	1.4	2.2	3.1	3.9	6.2
300 - 600	1.1	1.4	2.3	2.8	4.2
600 - 1000	0.8	1.1	1.7	2.3	3.4
1000 - 1500	0.7	0.8	1.4	2.0	2.8
1500 - 2000	0.6	0.7	1.1	1.7	2.5

Target Assembly. The target assemblies recommended for this technique (see Figure 4-24) are essentially the same as used for other methods (see Figure 4-9). Each target assembly consists of a target column with two attached targets and an adapter on the foot plate for mounting to a tribrach and tripod. You should construct a set of target assemblies to meet your local needs using materials and methods that are practical and available. Each target assembly consists of four basic parts; a column, foot plate, and two targets. Most machine shops can fabricate target assemblies for this routine using commercially available materials.

The target column should be made of straight, rigid metal stock at least 0.8 meter long. The metal stock should allow for permanent mounting of sighting targets and a foot plate.

Figure 4-24. - Example of recommended target assembly.

The foot plate (see Figure 4-25) provides for mounting of the target assembly to a tribrach and tripod. Ideally, it should be at least 0.5 inches thick and 0.5 inches wider and longer than the bottom of the target column to allow approximately 0.25 inches of foot plate extension surrounding the target column. At its center, the foot plate should have a 5/8-11 inch tapped hole to accommodate a rotating tribrach adapter.

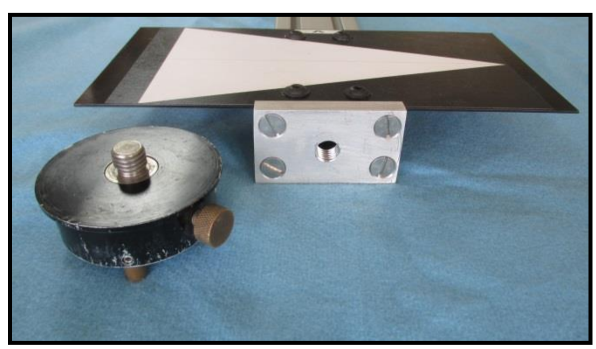

Figure 4-25. –Foot plate with 5/8-11 inch tapped hole and rotating tribrach adapter.

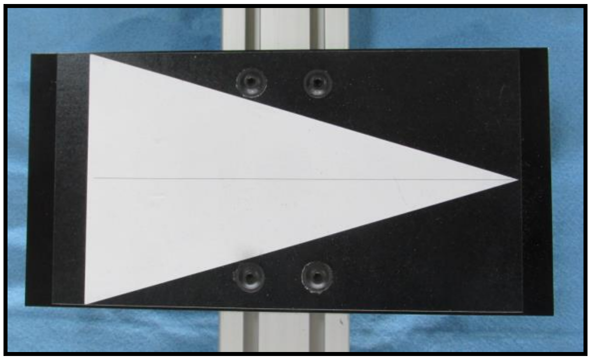

Figure 4-26. –Target, affixed to target column.

Targets (see Figure 4-26) can be constructed of sheet metal or a durable plastic material. Each target should be a 6-inch by 12-inch black rectangle with a 5-inch by 10-inch white isosceles triangle. Each triangle point should be set back from the edge of the rectangle approximately 1 inch to foster good sighting contrast and to protect the target point from incidental damage in handling. Targets should be affixed to the target column with the base of the isosceles triangle perpendicular to the target column. The triangle points should be separated by a distance of at least 0.6 meters and no more than 1.0 meter. It is important to securely attach the targets to the target column to ensure they do not move during field measurements.

After the targets have been attached to the target column, the separation distance between them must be measured to a precision of 0.0001 meter. The separation distance between targets does not have to be the same value for both target assemblies. See Appendix D for how this distance can be readily measured using a digital leveling system. You must measure target separation distances immediately before and after each use to confirm the targets did not shift during observations.

Each target assembly should be uniquely identified to eliminate confusion about which target assemblies were used in a survey or on which side of the crossing they were placed. Each target assembly should have a unique number, letter, or color. Ideally, you should be able to see the identity marking through the telescope eyepiece during the field observations.

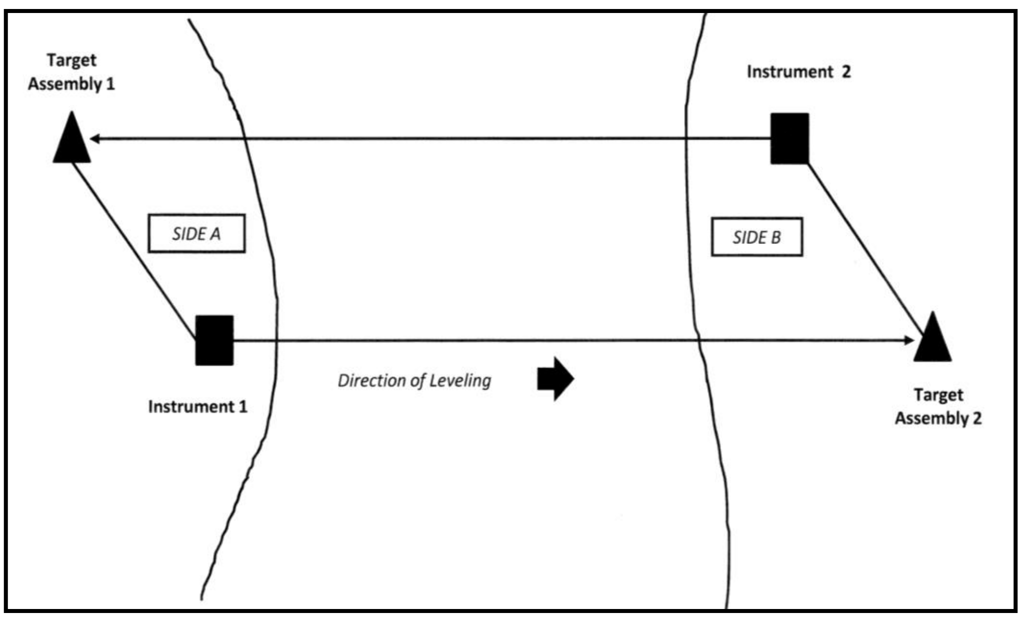

Figure 4-27. - Instrument and target assembly setup.

Equipment Setups. Two theodolites and two target assemblies are required for this routine. Each theodolite is set up directly across from a target assembly on the opposite side of the crossing. Observations from instruments to target assemblies should be balanced, or as equal in length as possible, and over similar terrain and conditions. A correct configuration of instrument setups is illustrated in Figure 4-27. Target assemblies should be set up near a benchmark, ideally within one setup, included in the level line associated with the crossing.

Prior to conducting a crossing routine, position each target assembly such that its upper target is above and its lower target is below the intercept of the horizontal line of sight for the level instruments located on either side of the crossing.

Both target assemblies should be located in similar environmental conditions i.e., both in full sun or full shade. The theodolite instruments should be shaded during the observations. Place tripods firmly in the ground to ensure there is no movement of the target assemblies during the crossing routine. The lower target triangle point for both sides of crossing will be treated as a temporary benchmark, so the target assembly must remain stable throughout the crossing routine.

Immediately before beginning a crossing routine, conduct double-run leveling for the leveling order and class associated with the crossing routine, between the nearby bench mark and the bottom target triangle point on both sides A and B of the crossing (See chapter 3.7.5 "Leveling to Awkward Control Points.") When measuring directly to a feature, such as a triangle point with a digital level, the reticle of the level instrument being used must be coincident with its horizontal line of sight, or a systematic error source will be introduced into the measurement. Appendix E provides specific instructions for checking a digital level to ensure the reticle is coincident with the horizontal line of sight.

4.5.2 Observing Routine

One running of the crossing routine includes a minimum of eight sets of observations from both instrument setups to their respective nearby target assemblies and eight sets of simultaneous reciprocal observations from both instrument setups to their respective distant target assemblies. You must record all associated metadata on the appropriate form. (See Appendix C for an example observing form for this new procedure). Take beginning and ending temperature information at the height of the target assemblies. For a complete crossing, two independent runnings are required. Leaving the target assemblies in place, break down the instrument setups, and reset them in the same location before beginning the second running. You should only attempt the crossing routine when environmental conditions are conducive to favorable results. (See subchapter 4.2, "Environmental Conditions").

1. Each observer should set their instrument up in a safe and secure location, so that lines of sight to both target assemblies are clear and unobstructed and measurements can be taken from a comfortable observing height. The instrument should be shaded from the sun. You must set up each instrument so that its horizontal line of sight intercepts or falls somewhere between the upper and lower targets of both side A and side B target assemblies. For the most precise results, the angular difference between upper and lower targets should be between 100 and 250 arcseconds and target separation distance should not exceed 1.0 meter. This is possible at sighting distances of 2.0 kilometers or less.

2. Record beginning information metadata (see Table 4-6).

3. Remove parallax and sharply focus on targets. With the telescope in direct pointing mode, observe zenith angles to the nearby upper and lower targets. Plunge the scope and rotate the instrument to put the telescope in reverse pointing mode and repeat the zenith angle observations. This completes one set of zenith angles. At a minimum, observe eight sets of zenith angles with the telescope in direct and reverse mode to the nearby targets. With the telescope in direct pointing mode, observe zenith angles to the opposite side upper and lower targets. Plunge the scope, rotating the instrument to put the telescope in reverse pointing mode and repeat the zenith angle observations. At a minimum, observe eight sets of zenith angles with the telescope in direct and reverse mode to the opposite side targets. Targets should be observed in a logical pattern. Be sure each observer follows the same observing pattern. Observers must synchronize sets of zenith angle measurements taken to opposite side targets to within one minute of each other to adequately correct for the effects of refraction. Failure to synchronize measurements may result in failure of the crossing routine. Record associated metadata for each set of measurements (see Table 4-6).

4. Record ending information metadata (see Table 4-6).

5. Reset both instrument setups and conduct a second running, following steps 1 through 4. The target assemblies should not be reset.

6. At the completion of the second running, verify the target assemblies did not settle during the crossing routine. Recheck the target assembly plumbing bubbles, etc.

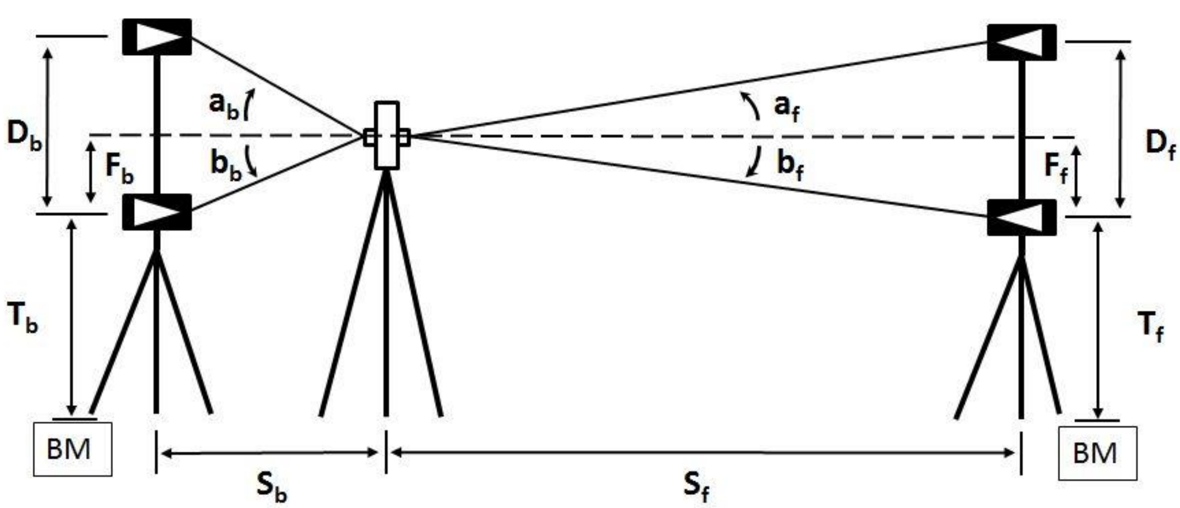

Figure 4 -28. Computational components

4.5.3 Computation Sequence

1. For the first running and for both sides of the crossing, compute a backsight target intercept height F_b and a backsight stadia distance S_b, (see figure 4 -28):

a. Using measured zenith angles, compute elevation angle a_b to upper targets and depression angle b_b to bottom target for each set of measurements.

b. Compute distance F_b, from the lower target triangle point to the intercept of the horizontal line of sight using the formula:

$$F_b = D_b\,(b_b/(b_b - a_b))$$

c. Compute backsight stadia distance S_b using the formula:

$$S_b \approx D_b/(b_b - a_b)$$

This formula is an approximation, but is suitable for computing the stadia distance when using small tilt angle values.

2. For the first running and for both sides of the crossing, compute a foresight target intercept height F_f and a foresight stadia distance S_f, (see figure 4-28):

a. Using measured zenith angles, compute elevation angle a_f to upper targets and depression angle b_f to bottom target for each set of measurements.

b. Compute distance F_f, from the lower target triangle point to the intercept of the horizontal line of sight using the formula:

$$F_f = D_f\,(b_f/(b_f - a_f))$$

Compute foresight stadia distance S_b using the formula:

$$S_f \approx D_f/(b_f - a_f)$$

3. For both side A and side B of the first running, combine target intercept heights F along with leveled height differences T to compute a section height difference H between bench marks:

$$H = (T_b + F_b) - (F_f + T_f)$$

and combine stadia distances S for a mark-to-mark stadia distance:

$$S = S_b + S_f$$

4. Mean the two height differences and stadia distances computed in step 3, computing an average height difference and stadia distance for the section between bench marks for the first running.

5. Compute an average section height difference and stadia distance for the second running by completing steps 1 through 4.

6. Check the mean height differences of the first and second runnings computed in steps 4 and 5 to make sure they meet section closure requirements for the leveling order and class being undertaken, as explained in section 3.7.7. If the height differences do not meet closure requirements, additional runnings will be necessary, as described in detail in section 3.7.7.

7. Create an Elevation Difference file (HGZ) for the river crossing, and merge it with the HGZ file associated with the level line being continued through the crossing.

Table 4-6.- Required Metadata

When to Record	Required metadata
Before Measurements	Side of Instrument setup (A or B)
Before Measurements	Level line number
Before Measurements	Date of observations
Before Measurements	Start time of observations
Before Measurements	5-Digit Weather Code
Before Measurements	Observer and Recorder names
Before Measurements	Temperature and temperature units
Before Measurements	Instrument model and serial number
Before Measurements	BM stamping and SSN (side A and B)
Before Measurements	Target Assembly identifier and separation distances (side A and B)
Before Measurements	Leveled Height diff. from BM to lower target (side A and B)
During Measurements	Time at start of each set of measurements
During Measurements	Target being observed for each set of measurements (lower/upper)
During Measurements	Instrument face (D or R) for each set of measurements
During Measurements	Zenith angles (Degrees, minutes and seconds)
After Measurements	5-Digit Weather Code
After Measurements	Ending time
After Measurements	Ending temperature and temperature units

Appendix D –
Instructions for Measuring Target Separations Using a Digital Leveling System

Purpose

This appendix describes how a digital leveling system consisting of a digital bar-code level and a one-piece staff can be used to measure the separation distance between target assembly target triangle points to a precision of +/- 0.0001 meters.

Specific Instructions

Set up a level staff on top of a turning pin using the brace poles. Be sure the turning pin and staff are secure and will not move throughout the entire procedure.

Secure a target assembly with tribrach onto a fixed-leg tripod, taking care to finely plumb the target column. Locate the target assembly less than one meter to the side of the level staff and perpendicular to the intended instrument line of sight.

Set up the level approximately 5 meters away so that the distances from the level to the staff and from the level to the target assembly are close to the same length.

The target assembly should be set up to conveniently sight both the upper and lower targets (as shown in Figures D-1 and D-2 respectively).

Figure D-1. Sighting on the upper target triangle point.

Step 1 – Upper Target Staff Reading

By trial and error, sight the upper target triangle point as finely as possible. Adjust the tripod legs first, and later use the foot screws of the level to raise and lower the instrument line of sight. Once the triangle target point has been finely bisected with the horizontal crosshair of the level, rotate the level to read the adjacent staff. Record the staff reading. Repeat this entire step at least three times to be sure you have obtained consistent sighting of the target point and rod readings. Average the readings to obtain a staff reading for the upper target.

Figure D-2. Sighting on the lower target triangle point.

Step 2 – Lower Target Staff Reading

By trial and error, sight the lower target triangle point as finely as possible. At first, adjust the tripod legs, and later use the foot screws of the level to raise and lower the line of sight. Once the target point has been finely bisected with the horizontal crosshair of the level, rotate the level to read the adjacent bar-code staff. Record the staff reading. Repeat this entire step at least three times to be sure you have obtained consistent sighting of the target point and rod readings. Average the readings to obtain a staff reading for the lower target.

Step 3 – Computing Target Separation

Subtract the staff reading of the lower target from the staff reading of the upper target. This height difference represents the target separation distance. The value should be recorded to 0.00001 meters.

Step 4 – Target Separation Distance

Repeat setups 1 through 3 after resetting the turning pin and finely plumbing the level staff. This second separation distance should agree with the first distance recorded to +/- 0.0001 meter. If it does, the mean of these two measured distances is the final separation distance. The final separation distance should be recorded for use in future computations. If it does not, you must repeat steps 1 through 4.

Appendix E.
Instructions for Verification of Instrument Reticle Coincidence with Horizontal Line of Sight

This appendix describes a procedure for verifying that an instrument's reticle is coincident with its horizontal line of sight. When measuring directly to a feature, such as a target triangle point, the horizontal crosshair of the level instrument's reticle must be coincident with its horizontal line of sight. If not, a systematic error source will be introduced into the measurement.

Specific Instructions

Step 1 – Construct a suitable adapter.
Install a footplate using instructions provided in chapter 4.5.1, "Instruments and Setups," onto the top of one of the two target assembly columns (see figure E-1). Place an invar strip parallel to the edge of the back side of the target column and near its center. Drill two small-diameter holes through the invar strip and target column. Secure the invar strip to the target column using two self-tapping metal screws appropriately sized for the drill holes.

Step 2 – Identify an "edge."
Approximately at the midpoint on an invar strip, arbitrarily select a top or bottom edge of a black stripe or block. Mark this "edge" so it can be identified for future measurements. The edge has a unique and precise digital value recognized by the level instrument. It will be repeatedly observed optically and digitally with the strip both erect and inverted. Through an iterative process, the instrument's horizontal crosshair will be checked, and if necessary, aligned to the edge.

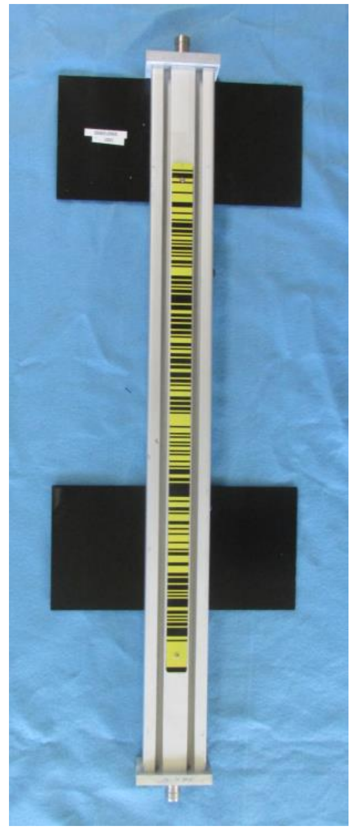

Figure E-1. Sighting target with invar strip attached.

Step 3 – Set up the equipment.
Mount the target assembly to a tribrach and tripod. Take care to finely plumb the invar strip. Adjust the tripod height so the midpoint of the invar strip is at a comfortable observing height. Set up the level instrument nearby. The instrument will need to be adjusted up or down very precisely. An adjustable-height instrument stand would be a good choice here, however a standard tripod and the instrument's footscrews can also be used.

Step 4 – Sight on the invar strip.

Point the instrument on the invar strip, adjusting it up or down so the horizontal crosshair intercepts the edge identified in step 2. Take time to be as precise as possible. When you are satisfied with the pointing, read the rod digitally, and record the value. Repeat this two more times, and calculate the standard deviation. Repeat as necessary until the standard deviation of the series of readings meets an acceptable tolerance of 0.0001m. Determine the average value of the series of readings.

Step 5 – Invert the invar strip and sight on the edge identified in step 2.

Without moving the tripod and tribrach setup, invert the target assembly and remount it in the tribrach. Set the level to read an "inverted" rod and repeat step 4.

Step 6 – Check for misalignment.

Compare the erect and inverted average values. Half of the difference between these two values is the amount of misalignment in the horizontal crosshair with the instrument's line of sight. If the misalignment is less than 0.0001 meter, the check is complete and no adjustment is necessary. If the misalignment exceeds 0.0001 meter, then an adjustment of the horizontal crosshair will be necessary.

Step 7 – Adjust the horizontal crosshair.

Using the instrument footscrews, adjust the instrument up or down while taking a series of test readings until the mean height determined in step 6 is displayed. Once this is accomplished, use the appropriate tool and the manufacturer's instructions to adjust the horizontal crosshair to the edge identified in step 2. Check the new alignment by repeating steps 4 and 5.

Observing Form for Optical Total Station
River Crossing Routine

Optical Total Station River Crossing Routine	Side:		Page __of __

Level Line #	Date	Start Time:	Start 5 digit Weather Code:
Observer:		Recorder:	
Instrument model	Instrument serial#	Temperature units:	Beginning Temperature :
BM Stamping:	BM SSN#	BM Stamping:	BM SSN#
Target Assembly #	Target Sep.	Target Assembly #	Target Sep.
Height diff. - BM to Target Assembly lowe		Height diff. - BM to Target Assembly lower	

Backsight (nearby target assembly)

Set #	Target	Face	Time	Zenith Angle Deg.	Min.	Sec.
1	Lower	D				
		R				
	Upper	R				
		D				
2	Upper	D				
		R				
	Lower	R				
		D				
3	Lower	D				
		R				
	Upper	R				
		D				
4	Upper	D				
		R				
	Lower	R				
		D				
5	Lower	D				
		R				
	Upper	R				
		D				
6	Upper	D				
		R				
	Lower	R				
		D				
7	Lower	D				
		R				
	Upper	R				
		D				
8	Upper	D				
		R				
	Lower	R				
		D				

Foresight (opposite side target assembly)

Set #	Target	Face	Time	Zenith Angle Deg.	Min.	Sec.
1	Lower	D				
		R				
	Upper	R				
		D				
2	Upper	D				
		R				
	Lower	R				
		D				
3	Lower	D				
		R				
	Upper	R				
		D				
4	Upper	D				
		R				
	Lower	R				
		D				
5	Lower	D				
		R				
	Upper	R				
		D				
6	Upper	D				
		R				
	Lower	R				
		D				
7	Lower	D				
		R				
	Upper	R				
		D				
8	Upper	D				
		R				
	Lower	R				
		D				

Mean Z angle upper target		Mean Z angle upper target	
Mean Z angle lower target		Mean Z angle lower target	
Lower target deflection angle	radians:	Lower target deflection angle	radians:
Upper target elevation angle	radians:	Upper target elevation angle	radians:
DH - lower target to Intercept		DH - lower target to Intercept	
Stadia dist. - Inst. To Target		Stadia dist. - Inst. To Target	
End Time:	Temperature units:	Ht diff lower to lower target	
End weather code:	Ending Temp:	Ht diff BM to BM	

Comments: