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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GEOLOGIC MAPPING OF TUNNELS USING PHOTOGRAMMETRY--CAMERA AND TARGET POSITIONING

by

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Jeffrey A. Coe[1] and Keld S. Dueholm[2]

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ILLUSTRATIONS

ABSTRACT

A photogrammetric method has been developed by the U.S Geological Survey and the U.S. Bureau of Reclamation for use in geologic mapping of tunnels (drifts). The method requires photographing the tunnel walls and roof with a calibrated small-format camera to obtain stereo pairs of photos which are then oriented in an analytical stereo plotter for measurement of geologic features. The method was tested in G-tunnel at Rainier Mesa on the Nevada Test Site. Calculations necessary to determine camera and target positions and problems encountered during testing were used to develop a set of generic formulas that can be applied to any tunnel.

INTRODUCTION

A photogrammetric method for underground geologic mapping of tunnels (drifts) has been developed by the U.S. Geological Survey (USGS) and the U.S. Bureau of Reclamation (USBR). The mapping method consists of: (1) placement of control-point and tie-point targets on tunnel walls (ribs) and roof (back), (2) surveying the three-dimensional coordinates of control-point targets, (3) photographing tunnel walls and roof with a calibrated small-format camera from positions along the tunnel's centerline to obtain blocks of overlapping stereo pairs, (4) orienting the blocks of stereo photos to the surveyed control-point coordinates in an analytical stereo plotter; and (5) stereo measurement of geologic features in the analytical plotter (i.e., digital three-dimensional point collection and calculation of geologic structural parameters).

This report consists of two main sections: (1) A description of generic formulas which can be used to determine camera and target positions for any tunnel, and (2) a discussion of specific calculation examples and testing of the positioning procedures in G-tunnel at Rainier Mesa on the Nevada Test Site.

BACKGROUND

Camera and target positioning takes place from a leveled camera rail that is oriented, via a laser beam from a surveying instrument, along the centerline of a tunnel. The camera is rotated and moved horizontally via a rotating camera mount, developed by G.M. Fairer, U.S. Geological Survey (patent pending, 1986), that slides along the camera rail (Figure 1a.). Targets are placed according to a rotating pyramid beam splitter, developed by G.M. Fairer, U.S. Geological Survey, and M.H. Mckeown and S.C. Beason, U.S. Bureau of Reclamation (patent pending, 1988), that also slides along the rail. The beam strikes the pyramid's angular faces and is projected (at right angles) to the tunnel walls and roof, thereby establishing the correct position for target placement (Figure 1b.). The angle through which the camera is rotated for each exposure, the pyramid rotation angles, and the distance between the exposure positions on the camera rail are calculated and described in this report.

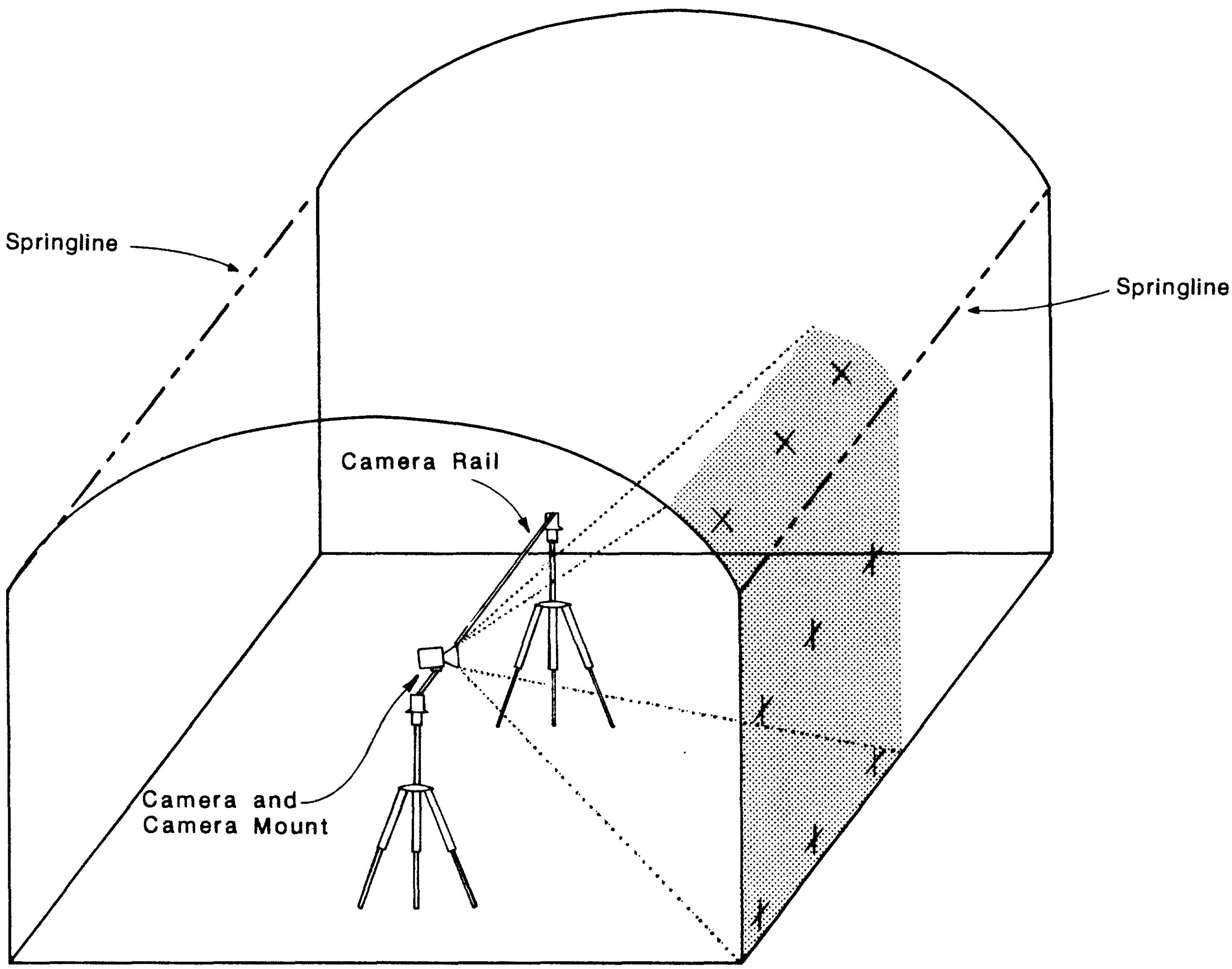


Figure 1a. Diagram of part of a tunnel showing camera mount, targets (+), and camera rail. Hypothetical camera field of view is shown by the patterned area.

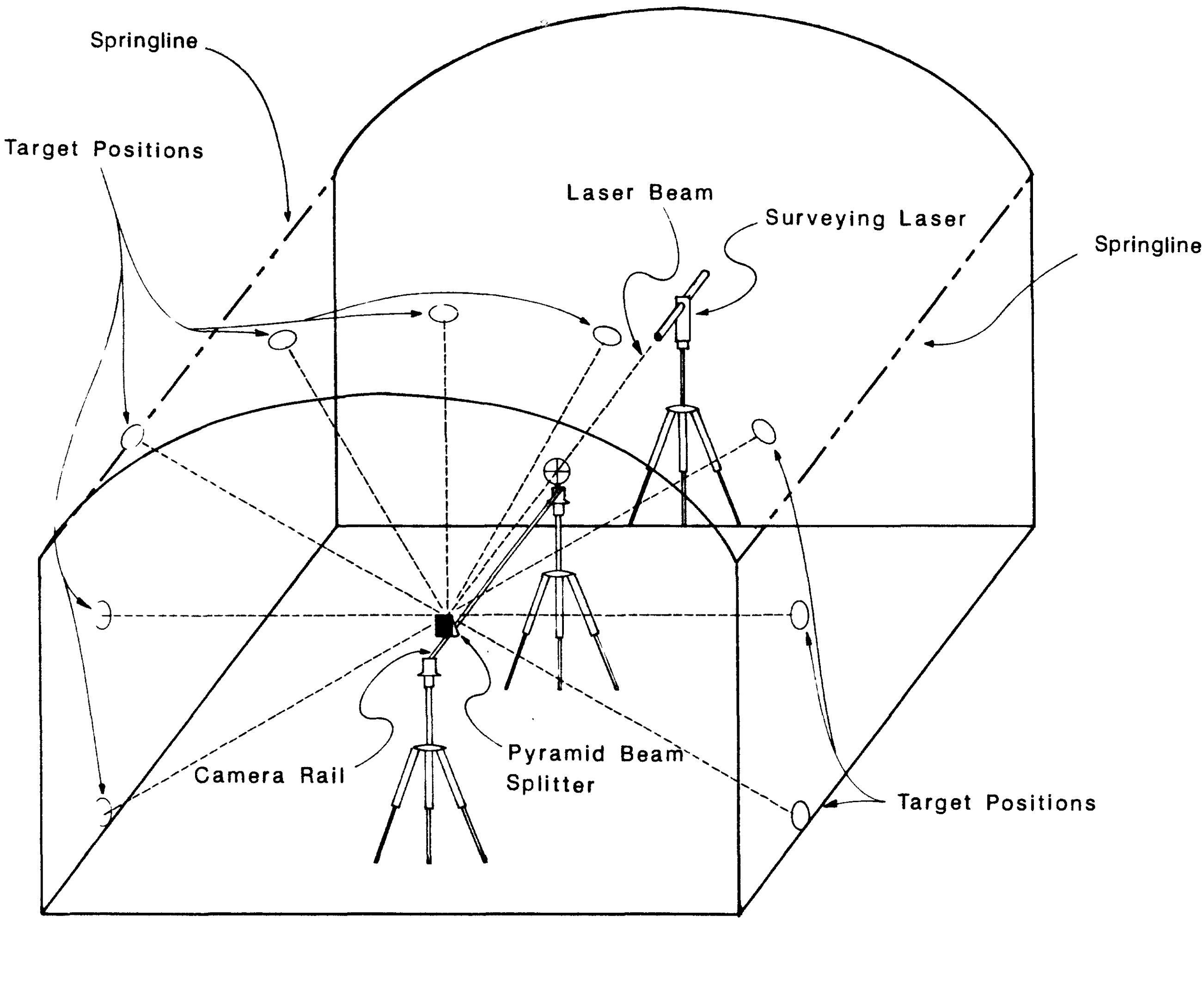


Figure 1b. Diagram of part of a tunnel showing pyramid beam splitter, hypothetical target positions, camera rail, and surveying laser beam.

The following terms, figures, and symbology will be referenced throughout the report.

Camera station: camera location on the horizontal camera rail

Camera position: camera's rotational position while at a camera station

All angles will be referenced from a theoretical plumb line dropped from the camera station (0°) will increase in a clockwise direction.

PHOTOGRAMMETRIC METHODS

The following calculations are based on internal and external camera parameters (fig. 2) and are necessary to determine precise camera position and target placement angles.

Camera Field of View

The camera's linear field of view (fl, fig. 2) is computed based on the following proportion.

$$\frac{c}{D} = \frac{fs}{fl} \qquad fl = \frac{fs * D}{c}$$

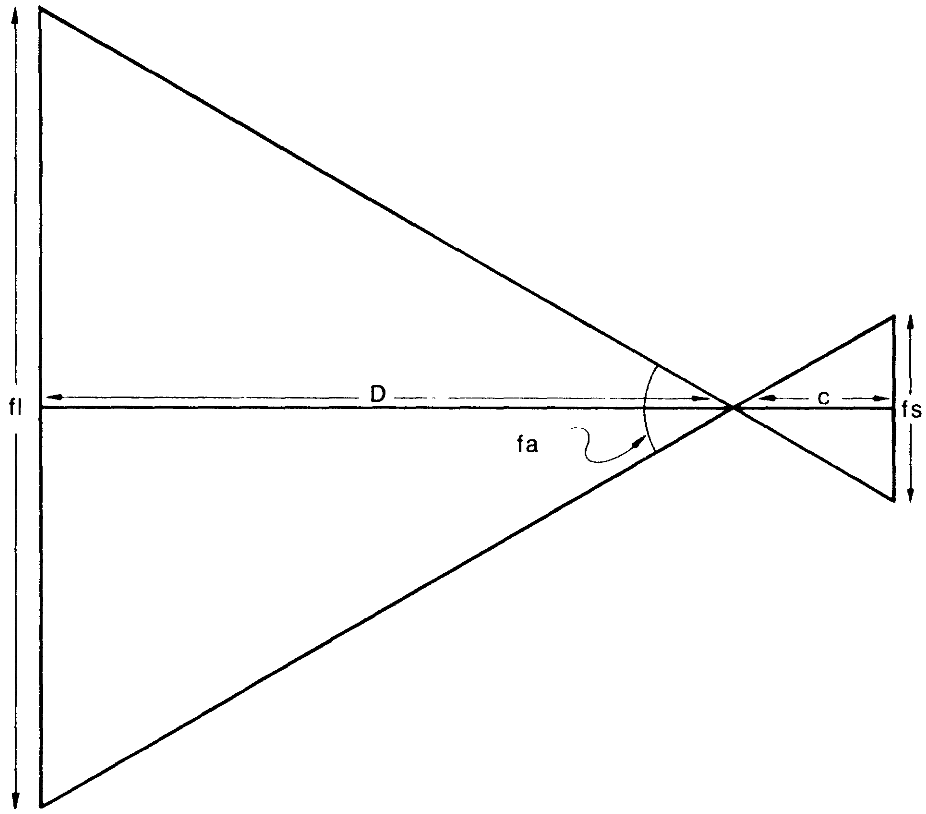
The camera's angular field of view (fa, fig.2) is computed as follows:

$$fa = 2 * \left(\arctan\left(\frac{fs}{2 * c}\right)\right)$$

Distance Between Camera Stations

The shortest distance from the camera to the tunnel walls or roof (Dmin) in the area being photographed is used to compute the distance between camera stations (ds) needed for a minimum of 60 percent overlap in the "down" tunnel direction. By using Dmin to calculate ds, the overlap will never drop below 60 percent. The overlap will be greater than 60 percent in wider and(or) taller areas of the tunnel. The following formula is used to compute the distance between stations:

$$ds = 0.40 \left(Dmin \left(\frac{fs}{c}\right)\right)$$



D = Camera to object distance
c = camera constant (focal length)
fa = camera's angular field of view
fl = camera's linear field of view
fs = camera's image frame size

Figure 2. Two-dimensional view of interior and exterior camera parameters.

Camera Angles

In order to compute the camera angles necessary for complete photo coverage of the walls and roof of the tunnel, the number of camera rotational positions (rp) per camera station, and the percentage of sidelap (ps) required between adjacent photos expressed in degrees (sa), must be determined.

$$sa = ps * fa$$

The camera angles are computed as follows. Multiply the number of camera positions (rp) by the camera's angular field of view (fa), this will yield the maximum possible angular coverage (ma) for each camera-station setup.

$$ma = rp * fa$$

The total amount of sidelap (tas) is computed from (rp) and (sa).

tas = sa * (rp - 1)   (yields tas in degrees)

From ma subtract the total amount of sidelap (tas). This will yield the net angular coverage in degrees (na).

na = ma - tas

Subtract na from 360° and this will give the angular measure that will occur below the camera and cover the floor of the tunnel (@). The angle below the camera (@) should always be less than 180°.

@ = 360° - na

Add (0.5 * fa) to (0.5 * @) to get the angle for the first camera position (cpa(1)).

cpa(1) = (0.5 * fa) + (0.5 * @)

In order to compute the second through the last camera positions at each camera station, the amount of rotation between camera positions (mc) must be computed. The sidelap, in degrees (sa), subtracted from the camera's angular field of view (fa), will yield the correct amount of rotation (mc).

mc = fa - sa

The second (cpa2) through the last (cpa(rp)) camera-position angles, in degrees, are computed:

cpa(i) = cpa(i-1) + mc

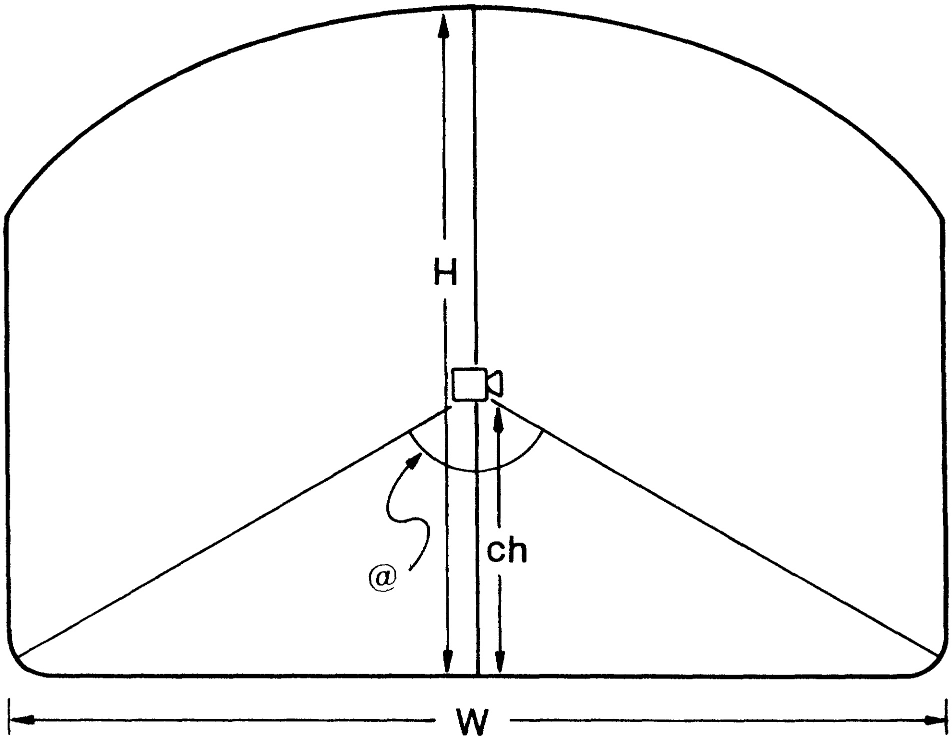
where i = 2, rp

Camera Height

The camera height (ch) is computed based on the tunnel width (W) and the @ angle (fig. 3).

$$\text{Cotangent } (0.5 * @) = \frac{ch}{0.5 * W}$$

ch = (0.5 * W) * (Cotangent (0.5 * @))



ch = camera height
H = floor to roof distance
@ = angle below the camera covering the area on the floor not photographed
W = tunnel width at the floor

Figure 3. Profile of a tunnel looking along the centerline.

Pyramid Angles

Pyramid angles for target placement will vary with different control configurations. A pyramid with the maximum number of angles needed can be used for fewer target placements as long as the camera focal length is held constant. For computational purposes it is assumed that the maximum number of targets needed per stereo model is six, and that they are configured as in figure 4.

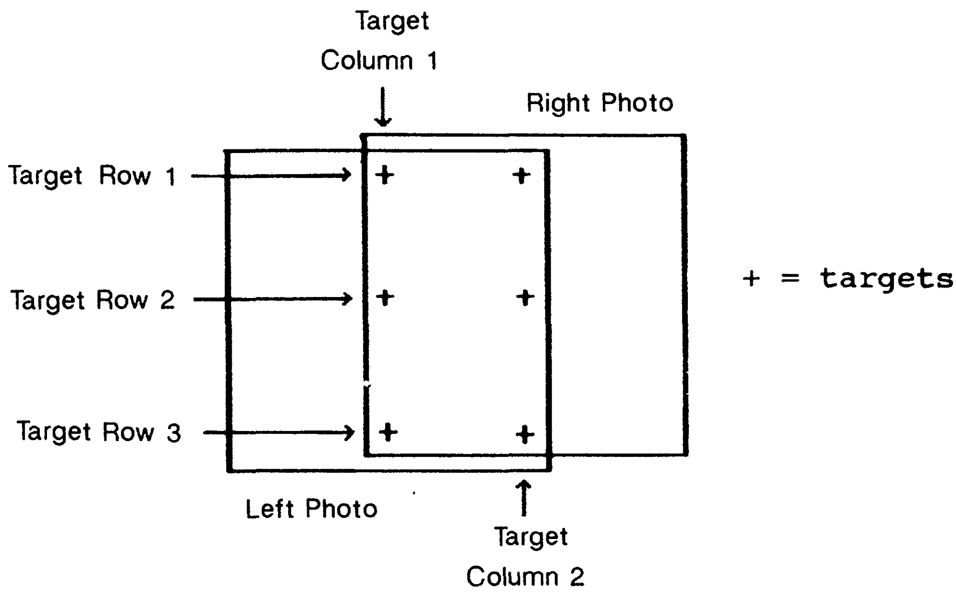


Figure 4. Stereo model with maximum number of targets.

If it is assumed that this stereo pair was taken from camera stations 1 + 2, then target column 1 would have been placed from a pyramid located at camera station 1, and column 2 placed from camera station 2. The number of target "columns" is equal to the number of camera stations.

The total number of target "rows" (tr), needed to cover the perimeter of the tunnel, is determined by the number of camera positions (rp).

$$tr = (2 * rp) + 1$$

tr equals the total number of targets placed from each camera station. The pyramid angles for all targets placed from a camera station are computed as follows.

tpa(j) = target-placement angle for each target row, at each camera station

$$tpa(1) = cpa(1) - (mc/2)$$

$$tpa(j) = tpa(j-1) + (mc/2)$$

where j = 2 to tr

The distance between columns of targets is equal to the distance between camera stations.

Note

The camera height and the distance between camera stations will vary from one tunnel to another, but the camera position and target placement angles will remain constant as long as the focal length of the camera remains the same.

APPLICATION

Calculation Examples

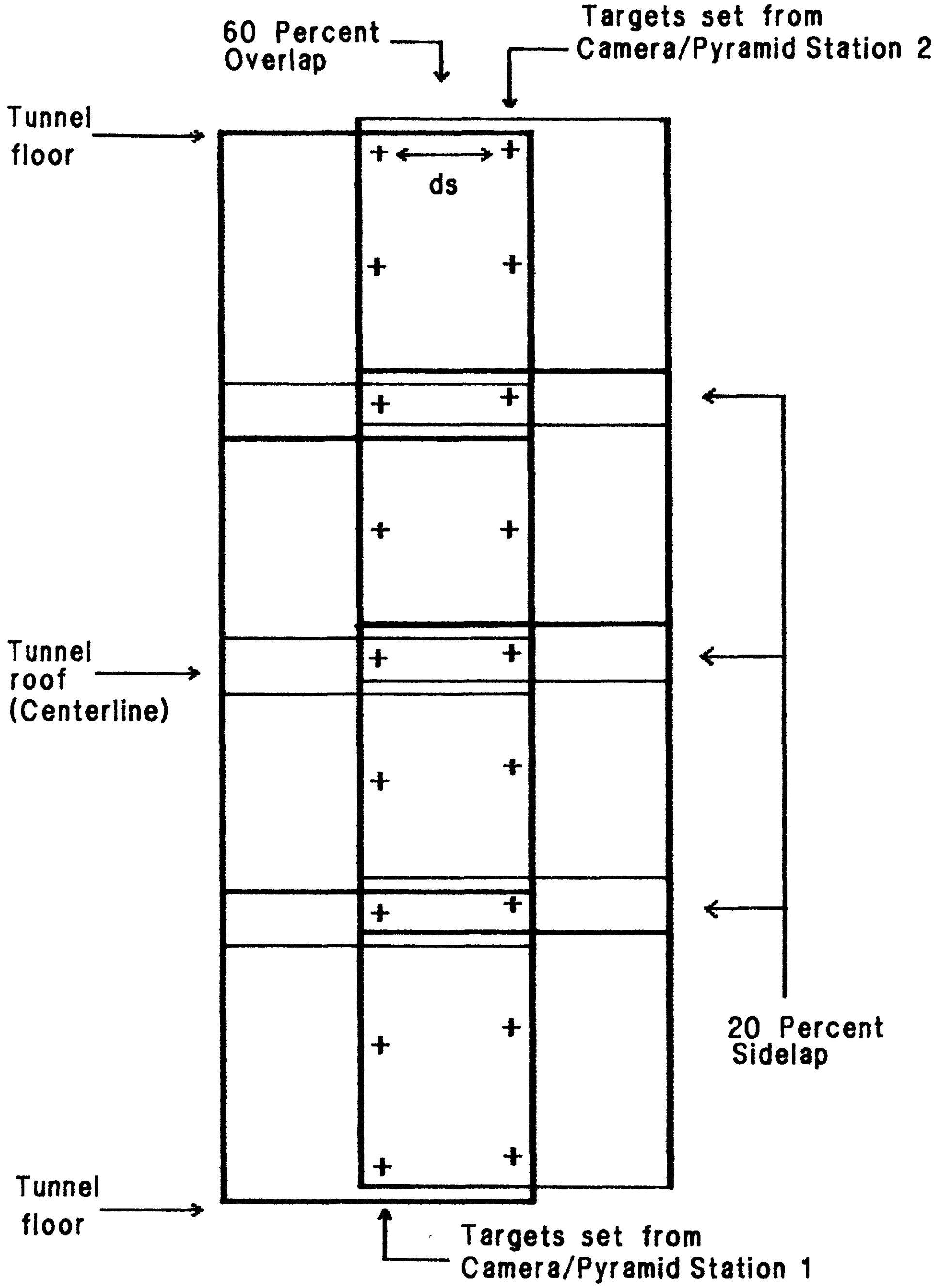
A Rollei 40 mm camera, focused at 3 m, is used for all examples. When focused at this distance the effective focal length is 40.79 mm. The image frame size produced by the Rollei is 55 x 55 mm.

The angular field of view (fa) is computed:

$$fa = 2 * (\arctan(\frac{55 \text{ mm}}{2 * 40.8 \text{ mm}}))$$

$$fa = 68.0^\circ$$

Figure 5 shows the target configuration, using the maximum number of targets needed for prototype testing purposes. The number of targets surveyed and used as control points for production mapping will be signifigantly less. The target and photo positions as shown in figure 5 are desired. The calculated camera angles (cpa(i)) and pyramid angles (tpa(j)) required are shown in figure 6.



+ = targets
ds = distance between stations

Figure 5. Tunnel photo/target configuration derived from two camera stations with four camera positions per station (full periphery projection equivalent, ie, projected onto the theoretically defined tunnel walls and then unfolded).

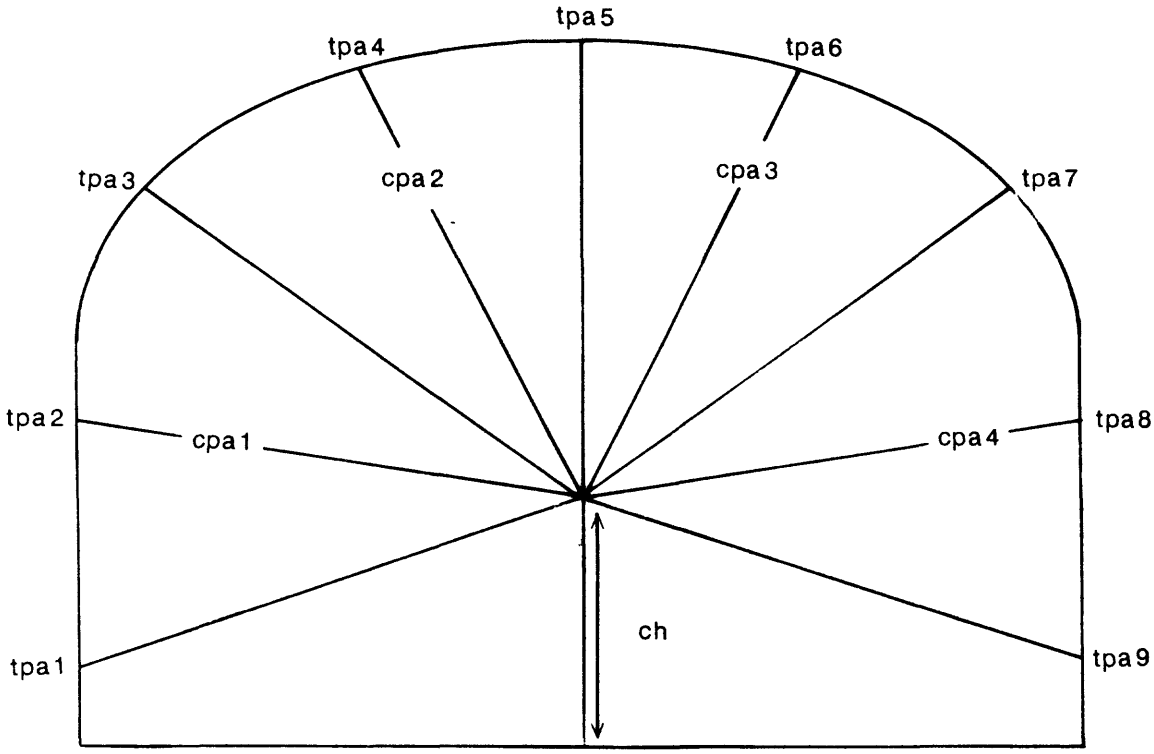


Figure 6. Tunnel cross section showing pyramid and camera angles. (tpa = target placement angle; cpa = camera placement angle; ch = camera height.)

The computation of camera positions was based on the 68° Rollei field of view, 20 percent sidelap (ps) between adjacent photos, and the nominal requirement of 4 camera rotations (rp) per camera station. Sidelap of 20 percent was chosen because 1) it allows for 4 camera rotational positions, rather than 5, which is ideal for multiple stereo pair orientation in the analytical plotter, and 2) it provides sufficient sidelap for reliable stereo coverage.

$$ma = 4 * 68° = 272°$$

$$sa = 0.20 * 68° = 14°$$

$$tas = (4 - 1) * 14° = 42°$$

$$na = 272° - 42° = 230°$$

$$@ = 360° - 230° = 130°$$

First camera position (cpa(1)) = (0.5 * 68°) + (0.5 * 130°) = 99°

$$mc = 68° - 14° = 54°$$

Second camera position (cpa(2)) = 99° + 54° = 153°
Third camera position (cpa(3)) = 153° + 54° = 207°
Fourth camera position (cpa(4)) = 207° + 54° = 261°

As a check:

$$cpa(4) = 360° - cpa(1) = 261°$$

The pyramid angles for target placement are computed as follows:

tr = (4 * 3) - (4 - 1) = 9 target positions per camera station

$$tpa(1) = 99° - (54° / 2) = 72°$$

$$tpa(2) = 72° + (54° / 2) = 99°$$

$$tpa(3) = 99° + (54° / 2) = 126°$$

$$tpa(4) = 126° + (54° / 2) = 153°$$

$$tpa(5) = 153° + (54° / 2) = 180°$$

$$tpa(6) = 180° + (54° / 2) = 207°$$

$$tpa(7) = 207° + (54° / 2) = 234°$$

$$tpa(8) = 234° + (54° / 2) = 261°$$

$$tpa(9) = 261° + (54° / 2) = 288°$$

This target scheme allows for equal angular distances between targets (27°), for the positioning of targets in the center of overlap areas, and for targets at the bottom of each wall to be placed just above the floor (by 7°).

Field Measurements and Calculations

All field measurements described below were performed by USGS and USBR personnel in G-tunnel, August 29 to September 1, 1988. The four parameters that had to be determined in the field were (1) the tunnel width (W), (2) the camera height (ch), (3) shortest distance from the camera to the tunnel roof and walls (Dmin), and (4) the distance between camera/pyramid stations (ds).

Six width measurements were taken approximately 2 m apart in the prototype test area of the tunnel. The mean of these measurements (6.16 m) was used to compute the camera height (ch).

$$ch = (0.5 * 6.16 \text{ m}) * (\text{Cotangent } (0.5 * 130^\circ)) = 1.44 \text{ m}$$

The shortest distance from floor to roof (H) in the test area (3.81 m) was used to find Dmin. Subtracting the camera height from the shortest floor to roof distance yields:

$$Dmin = 3.81 \text{ m} - 1.44 \text{ m} = 2.37 \text{ m}$$

The distance between stations was computed:

$$ds = 0.40 * \left(2.37 \text{ m} * \left(\frac{55 \text{ mm}}{40.8 \text{ mm}}\right)\right) = 1.28 \text{ m}$$

The total distance covered by all six camera/pyramid stations was 6.4 m.

Problems Encountered

Practical

In practice, the tunnel floor is rough and uneven, which makes it difficult to set an accurate camera height. The surveyors' laser (which was set at the correct height at the end of the tunnel) was shot down a large portion of the tunnel (approximately 30 m). The prototype test area occurred in the approximate center of this portion. The laser height (camera height) in the prototype area was not correct because the uneven floor meets the tunnel walls at varying heights. Placing the camera at a theoretical height, calculated from the theoretical tunnel dimensions, throughout the entire tunnel, as opposed to setting the height locally, appears to be the most efficient way of handling this problem.

By design, the G-tunnel width should equal 6.10 m and the height (at the roof centerline) should equal 4.27 m. The theoretical camera height (ch) is computed:

$$ch = (0.5 * 6.10 \text{ m}) * (\text{Cotangent } (0.5 * 130°)) = 1.42 \text{ m}$$

If the tunnel floor is low at the intersection with either wall (i.e., below where the camera field of view hits when the correct camera angle is used) then that portion of that wall would not be photographed. The area not photographed would probably never be more than about 0.2 m. The target-placement angle for the first target above the floor would remain unchanged. If the tunnel floor is high then the first target would be placed at the lowest portion of the wall (not on the floor). In this case, some of the floor would appear in the photo.

Theoretical

The shortest distance parameter (Dmin), which determines the distance between camera stations (ds), which in turn determines the "down" tunnel overlap, should be determined locally to maintain a minimum of 60 percent overlap. Determining this distance locally, however, would require time comsuming measurements and the constant changing of ds.

There are two options possible for determining this distance: (a) determine it locally or (b) use a theoretical distance parameter. These options are presented below but should be thoroughly evaluated before either is chosen.

(a) Local determination would consist of measuring the shortest camera to roof distance (Dmin) for each mining round and using this to compute the distance between camera stations. Care would have to be taken to maintain sufficient overlap between rounds.

(b) A theoretical shortest distance could be used for the entire tunnel. Dmin and ds are computed from the 4.27 m tunnel height as follows:

$$Dmin = 4.27 \text{ m} - 1.42 \text{ m} = 2.85 \text{ m}.$$

$$ds = 0.4 \left(2.85 \text{ m} * \frac{55 \text{ mm}}{40.8 \text{ mm}}\right) = 1.54 \text{ m for 60 percent overlap}$$

The overlap would fall below 60 percent, however, in areas with a low roof and(or) a narrow width. Overlap of 55 percent, although less than ideal, is the smallest overlap acceptable. For 55 percent overlap (ds / fl = 45%) Dmin is calculated as follows:

$$D_{min} = \frac{ds * c}{0.45 * fs} = \frac{1.54\ m * 40.8\ mm}{0.45 * 55\ mm} = 2.54\ m$$

For Dmin = 2.54 m the tunnel height can be no less than 2.54 m + 1.42 m = 3.96 m.

Therefore, if a tunnel with G-tunnel design dimensions can be excavated to within a height of 0.31 m and a width of 1.02 m (no less than a 5.08 m width) this option will work.

To assure that sufficient overlap always exists, photos could be taken with 80 percent overlap. This would account for low and narrow areas (which would still have more than 60 percent overlap), make it possible for the analytical plotter operator to use every other column of photos in "normal" areas, and provide additional perspectives if necessary for mapping of shadowed areas.

ACKNOWLEDGMENT

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