CHARA Technical Report

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The 3D Layout of the CHARA Array

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1. INTRODUCTION

The CHARA Array will employ five 1-m size, alt-azimuth style telescopes at a site on Mount Wilson in southern California. The telescopes will be housed separately and operated remotely from a central laboratory. Light from each telescope will be directed by subsequent flat mirrors through vacuum pipes to additional optics and instrumentation at the central laboratory.

One of the constraints imposed on the light paths of the array is that no differential polarization effects can be introduced (See Appendix D of the Proposal and Technical Report 28): differential polarization will reduce the measured visibilities, often to nearly zero, making the array unusable. To avoid this problem it is necessary to ensure that each light beam uses the same number, orientation and order of reflections. This is somewhat difficult to arrange since each input beam comes from a telescope in a different position on the mountain. Furthermore, since the mountain top is not even approximately a plane, the two dimensional solution given in Appendix D of the proposal must be extended to the third dimension. A configuration is required which takes into account each telescope position, the symmetry requirement, the positions of the existing structures on the site, and the many other requirements listed below.

As the following analysis shows, the solution to this problem is highly coupled and complex: moving one telescope or mirror causes a 'ripple-down' affect on all other light paths and mirrors. This technical report will describe the current state of the '3D problem'.

2. REQUIREMENTS

Here follows a list of the requirements to be met by the positioning of the telescopes and relay mirror system:

- The telescopes should be placed as close as possible to the optimum UV coverage points, keeping in mind the terrain and the other constraints listed below.
- Each light beam must undergo the same number of reflections, in the same order, and have identical angles of incidence on each mirror.

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- The number of reflections must be kept to a minimum.
- No light pipes should overlap or cross if possible.
- The terrain profiles must be measured beneath each light pipe and the minimum and maximum heights of the pipe tabulated. If a light pipe is too high off the ground the structure required to support it may be prohibitively expensive.
- The pipes should be arranged so that the minimum number of trees need to be removed.
- The height of each mirror must be kept as close as possible to zero feet. Each mirror represents a change in the light beam direction within the vacuum system and therefore it's mounting pier will undergo substantial atmospheric pressure.
- The amount of force produced in this manner at each mirror point in the light pipe must be calculated.
- Mirrors must have enough clearance to allow space for a mount.
- Mirrors can not be placed in the BCL/OPLE in any position that will interfere with another subsystem (for example, the optical tables at the end of the OPLEs).
- All of the light pipes must enter the BCL/OPLE building through the pre-existing 'break-out' boxes.
- Each light-pipe must terminate on one of the pre-existing inertial pads within the BCL/OPLE.
- Enough room for future expansion of the system, for example more light pipes, should be left.
- The light pipes must not hit the concrete edge of the BCL/OPLE main slab.
- No light pipe can go through an existing building.
- Telescope 1 and 2 light pipes must go beneath the existing road near the 60″ telescope building.
- The parallel light pipes (like those for the two southern telescopes) must be approximately 2 feet apart, center to center.
- The telescopes piers themselves should be placed as close as possible to the current terrain height.
- The analysis should provide positions and unit vectors for each of the light beam paths and all of the mirrors for each telescope.
- The 'vacuum boxes' containing the mirrors should be kept as similar as possible to reduce design and construction costs.

3. PARAMETERIZATION

At a recent meeting the nomenclature for the telescopes was changed from the simple numbering of the telescopes (Telescopes 1 through 7), to a system based on which arm of the Y the telescopes are in (S1, S2, N1, N2 and so on). Unfortunately most of the analysis and coding for the solution of the '3D problem' were completed before this change. Therefore I will continue to use the old notational system for this report. Table 1 shows how the new and old names correspond.

TABLE 1. Telescope names.

Old Name	New Name
T1	S1
T2	S2
T3	S3
T4	E1
T5	W1
T6	W2
T7	E2

The telescope and mirror numbering system is shown in Figure 1. This configuration of light pipes meets the criteria that each light beam undergo the same number and orientation of reflections. However, the exact positioning of each mirror still needs to be determined in three dimensions.

Rather than use north, east and height parameters I shall use a standard Cartesian frame (x, y, z) where x is east, y is north and z is height. Along with this Cartesian frame are the unit vectors $\hat{\imath}, \hat{\jmath}$ and $\hat{k}$ in the x, y and z directions. The origin of the reference frame used is the same as that used by the survey team that produced the map of the mountain. The raw data from that survey along with subsequent surveys, was used to produce a number of matrices of terrain heights in regular grids of 50, 10, 5, 2 and 1 feet. The larger grids were used for debugging (as they consumed less memory and took less time to run through the analysis software), while the smaller grids were used in the final output of the solution. The positions of roads and existing buildings were taken from the initial survey data and added to the parameter file used as input to the analysis program.

In each optical chain the first six reflections are within the telescope system itself and are identical in each system. Thus the first mirror included in this analysis will be mirror number 7 in each line. The center point of each mirror will be written $P_{T,M}$ where T is the telescope number and M is the mirror number. Thus the first mirror in the beam path for T1 will be $P_{1,7}$, which reflects the vertical beam leaving the telescope optical chain into the first light pipe path. The mirrors at positions $P_{1,8}$ and $P_{1,9}$ bounce the beam along the next two pieces of light-pipe while the final mirror included in this analysis, $P_{1,10}$, reflects the beam out of the final light pipe into the correct POP line, which is terminated at the position O_1. Each mirror also requires a unit vector $\hat{m}_{T,M}$, defining the unit vector normal to the mirror surface, and each light pipe direction also has a unit vector $\hat{l}_{M_1,M_2}$. Since the beam propagation directions in each arm of the array must be identical, only four mirror unit vectors and three light pipe unit vectors are required.

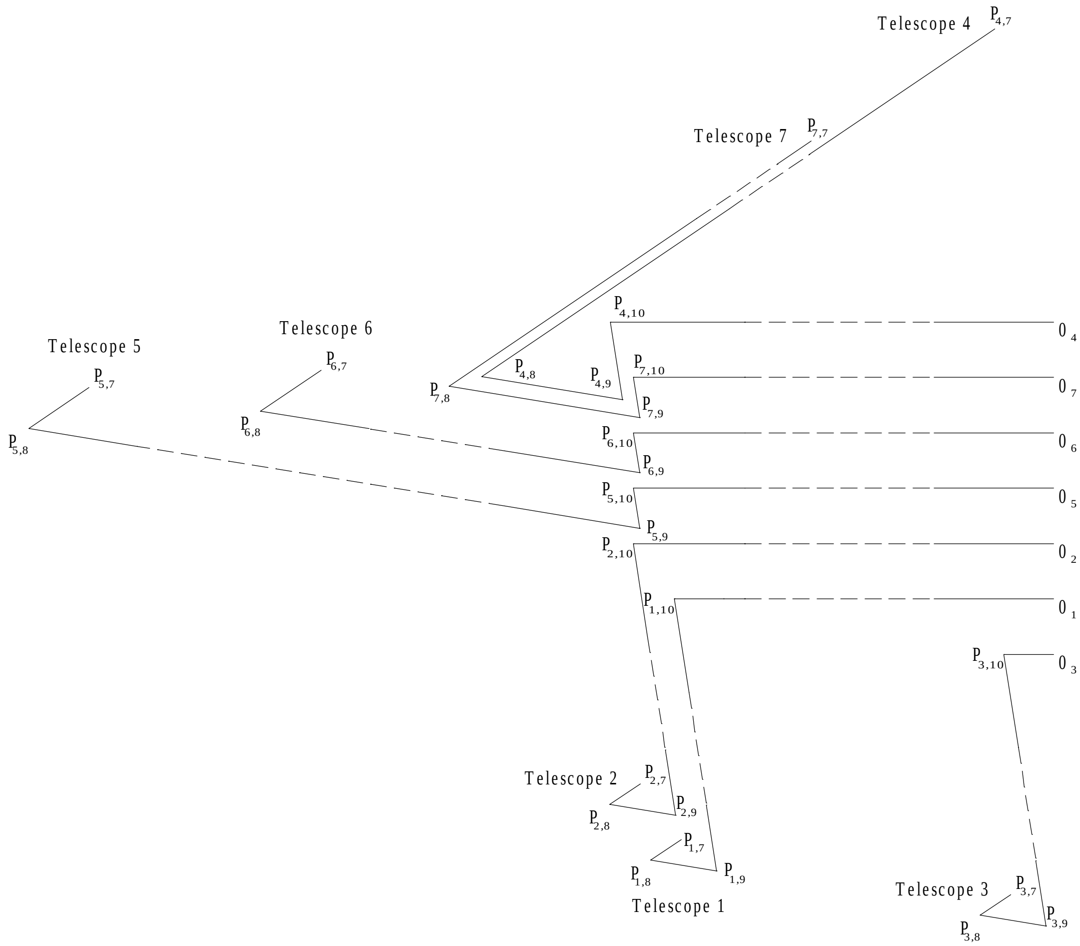

FIGURE 1. The numbering scheme for the telescopes and mirrors in the optical lines.

Given that all the mirror positions have been calculated, the light pipe unit vector for the line between point 7 and 8 will be given by

$$\hat{\imath}_{7,8} = \frac{P_{T,7} - P_{T,8}}{|P_{T,7} - P_{T,8}|} \tag{1}$$

where, since each arm is identical in this respect, T =1, 2, 3, 4, 5, or 6. Similarly,

$$\hat{\imath}_{8,9} = \frac{P_{T,8} - P_{T,9}}{|P_{T,8} - P_{T,9}|} \tag{2}$$

and

$$\hat{\imath}_{9,10} = \frac{P_{T,9} - P_{T,10}}{|P_{T,9} - P_{T,10}|}. \tag{3}$$

All of the final beam directions will be in the POP line which is due east, or in vector form

$$\hat{o} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}. \tag{4}$$

The mirror vectors, which will again be identical in each arm, will be the vector average of the light pipe vectors:

$$\hat{\mathrm{m}}_7 = \frac{\hat{\mathrm{l}}_{7,8} + \hat{\mathrm{k}}}{2}, \tag{5}$$

$$\hat{\mathrm{m}}_8 = \frac{\hat{\mathrm{l}}_{8,9} - \hat{\mathrm{l}}_{7,8}}{2}, \tag{6}$$

$$\hat{\mathrm{m}}_9 = \frac{\hat{\mathrm{l}}_{9,10} - \hat{\mathrm{l}}_{8,9}}{2} \quad \text{, and} \tag{7}$$

$$\hat{\mathrm{m}}_{10} = \frac{\hat{\mathrm{o}} - \hat{\mathrm{l}}_{9,10}}{2}. \tag{8}$$

Finally, the light pipe line between mirror M_1 and M_2 for telescope T can either be written

$$P_T(t) = t\, P_{T,M_1} + (1-t)\, P_{T,M_2}, \text{ for } 0 \le t \le 1, \tag{9}$$

or equivalently as

$$P_T(t) = P_{T,M_1} + t\, \hat{\mathrm{l}}_{M_1,M_2}, \text{ for } 0 \le t \le |P_{T,M_1} - P_{T,M_2}|. \tag{10}$$

4. INPUT PARAMETERS

Before exact positions for the telescopes, mirrors and light pipes can be found many input parameters are required, including:

- The position and size of the BCL/OPLE building.
- The positions of the break-out panels in the BCL/OPLE building.
- The position and sizes of the inertial slabs within the BCL/OPLE building.
- The position and size of the 100″ and 60″ domes.
- A first guess at the positions and height above current ground level for each of the telescope number 7 mirrors.
- The height above the floor of the final mirror number 10 of each telescope line.
- The position of the end of the POP line O_T for each telescope.

along with a number of other parameters as set out in Section 5. These parameters are supplied to the program in a text file. Another input file supplies data concerning other existing buildings on the site while a third input file lists the positions and types of trees along the light pipe lines. Example input files are given in Appendices A, B and C.

5. ANALYSIS

The approach used for the analysis of the array geometry is as follows:

1. Establish as soon as possible the unit vectors $\hat{l}_{7,8}$, $\hat{l}_{8,9}$ and $\hat{l}_{9,10}$.
2. With these vectors defined, adjust the telescope and mirror positions in each telescope line so that each segment in each line are parallel to these vectors.
3. Check the solution for possible problems, for example, passing through a nearby building or not passing through a break-out panel.
4. Produce an output file listing the final positions of each telescope and mirror, along with warning messages concerning any potential problems found.
5. Produce output files for use in displaying the solution using the 2D and 3D CAD software. These output files are either test files containing Cartesian coordinates of the mirror and telescope positions or a BasicCAD program for drawing curtain elements in the 3D-CAD program.

Of course, it is not possible to check for every conceivable problem within the software and the output files must be examined and visualized using the CAD software so that the solution can be checked for errors. The steps used to find a solution are described in the following sections.

5.1. Establish unit vector $\hat{\mathbf{l}}_{7,8}$

Since T4 feeds directly into the first long light pipe it will be used to define the unit vector $\hat{l}_{7,8}$. The position $P_{4,7}$ is defined in the input parameter file. The terminating end of this light pipe, $P_{4,8}$, must also be defined in the input parameter file in terms of the x and y positions and the height of the beam above the slab floor. Given these two points $\hat{l}_{7,8}$ can be calculated using Equation 1.

5.2. Locate point $P_{5,8}$

The long light pipe defining the unit vector $\hat{l}_{8,9}$ runs between points $P_{5,8}$ and $P_{5,9}$, an so in order to find $\hat{l}_{8,9}$ we must first establish the position of $P_{5,8}$. The position of $P_{5,7}$ is set in the input parameter file, and we already have the unit vector $\hat{l}_{7,8}$ from step 2 above, so all that is required is the length of the first light pipe segment on T5, $t_{5,7,8}$, which must also be set in the input parameter file. The position of point $P_5, 8$ is then given by

$$P_{5,8} = P_{5,7} + t_{5,7,8}\,\hat{l}_{7,8}. \tag{11}$$

5.3. Establish unit vector $\hat{\mathbf{l}}_{8,9}$

The unit vector $\hat{l}_{8,9}$ requires the point $P_{5,8}$ found in step 2, and the termination of this long light pipe run at point $P_{5,9}$, which must, to a first approximation, be defined in the input parameter file. Given these two positions $\hat{l}_{8,9}$ can be calculated using Equation 2.

5.4. Locate points $P_{2,8}$ and $P_{2,9}$

The final light pipe unit vector requires points $P_{2,9}$ and $P_{2,10}$. The position of $P_{2,9}$ is calculated as follows. The input parameter file must specify the lengths of the two short light pipe runs $t_{2,7,8}$ and $t_{2,8,9}$. Then $P_{2,8}$ can be calculated based on the $P_{2,7}$ position in the input parameter file via

$$P_{2,8} = P_{2,7} + t_{2,7,8}\,\hat{\mathrm{l}}_{7,8} \tag{12}$$

and $P_{2,9}$ via

$$P_{2,9} = P_{2,8} + t_{2,8,9}\,\hat{\mathrm{l}}_{8,9}. \tag{13}$$

5.5. Establish unit vector $\hat{\mathbf{l}}_{9,10}$

The y and z coordinates of position $P_{2,10}$ must be the same as the POP termination point O_2 defined in the input parameter file. The x coordinate must be set independently within the input parameter file. Along with the position $P_{2,9}$ calculated in step 4, $\hat{\mathrm{l}}_{9,10}$ can now be found using Equation 3.

5.6. Locate points $P_{5,9}$ and $P_{5,10}$

With the three unit vectors now known it is necessary to move point $P_{5,9}$ and to locate $P_{5,10}$ so that all of the T5 light pipes are parallel to the unit vectors. $P_{5,9}$ must lie on the light pipe defined by $\hat{\mathrm{l}}_{8,9}$ and so

$$P_{5,9} = P_{5,8} + t_{5,8,9}\,\hat{\mathrm{l}}_{8,9}. \tag{14}$$

Similarly the point $P_{5,10}$ can be written

$$P_{5,10} = P_{5,9} + t_{5,9,10}\,\hat{\mathrm{l}}_{9,10}, \tag{15}$$

which after substituting using Equation 14 gives

$$P_{5,10} = P_{5,8} + t_{5,8,9}\,\hat{\mathrm{l}}_{8,9} + t_{5,9,10}\,\hat{\mathrm{l}}_{9,10}. \tag{16}$$

We also know that the point $P_{5,10}$ must lie on the POP line defined by O_5 and $\hat{\mathrm{o}}$ and so

$$P_{5,10} = O_5 - t_O\,\hat{\mathrm{o}}. \tag{17}$$

Combining Equations 14 and 16 we get

$$P_{5,8} + t_{5,8,9}\,\hat{\mathrm{l}}_{8,9} + t_{5,9,10}\,\hat{\mathrm{l}}_{9,10} = O_5 - t_O\,\hat{\mathrm{o}} \tag{18}$$

which can be written in the matrix form

$$\mathcal{T}\mathcal{M} = \mathcal{P} \tag{19}$$

where

$$\mathcal{T} = (t_{5,8,9}, t_{5,9,10}, t_O), \tag{20}$$

$$\mathcal{P} = O_5 - P_{5,8}, \text{ and} \tag{21}$$

$$\mathcal{M} = \begin{pmatrix} \hat{\mathrm{l}}_{8,9} \\ \hat{\mathrm{l}}_{9,10} \\ \hat{\mathrm{o}} \end{pmatrix}. \tag{22}$$

This can be solved for the vector $\mathcal{T}$ and the points $P_{5,9}$ and $P_{5,10}$ calculated using Equations 14 and (15). If any of the lengths $t_{5,8,9}, t_{5,9,10}$, or t_O are found to be negative some form of error has occurred and the input parameters must be adjusted.

5.7. Locate points $P_{4,9}$ and $P_{4,10}$

We now use a similar method to find locations for the points $P_{4,9}$ and $P_{4,10}$. The point $P_{4,9}$ must lie on the $\hat{\mathrm{l}}_{89}$ light pipe and so

$$P_{4,9} = P_{4,8} + t_{4,8,9}\,\hat{\mathrm{l}}_{8,9}, \tag{23}$$

and since $P_{4,10}$ must lie on the light pipe line defined by $\hat{\mathrm{l}}_{9,10}$

$$\begin{aligned} P_{4,10} &= P_{4,9} + t_{4,9,10}\,\hat{\mathrm{l}}_{9,10} && (24)\\ &= P_{4,8} + t_{4,8,9}\,\hat{\mathrm{l}}_{8,9} + t_{4,9,10}\,\hat{\mathrm{l}}_{9,10}. && (25) \end{aligned}$$

$P_{9,10}$ must also lie on the POP line defined by O_4 and $\hat{\mathrm{o}}$ and so

$$P_{4,10} = O_4 + t_O\,\hat{\mathrm{o}}. \tag{26}$$

Combining Equations 25 and 26 we get

$$P_{4,8} + t_{4,8,9}\,\hat{\mathrm{l}}_{8,9} + t_{4,9,10}\,\hat{\mathrm{l}}_{9,10} = O_4 + t_O\,\hat{\mathrm{o}} \tag{27}$$

which can be solved as in the previous step for $t_{4,8,9}, t_{4,9,10}$ and t_O and the values for $P_{4,9}$ and $P_{4,10}$ can be calculated. Once again if these lengths are negative an error of some kind has occurred and no solution is possible with the current set of input parameters.

5.8. Locate point $P_{1,10}$

The final point in the telescope 1 optical line, $P_{1,10}$, is defined to lie a distance d along the x axis to the west of the final telescope 2 point $P_{2,10}$. The line defining the last light pipe for T2 can be written

$$P(t) = P_{2,9} + t\,\hat{\mathrm{l}}_{9,10}. \tag{28}$$

The plane containing the POP line for T1, the z axis, and parallel to the plane $y = 0$, is

$$(P(t) - O_1).\hat{\mathrm{j}} = 0 \tag{29}$$

and this plane and line intersect when

$$t = \frac{O_{1,y} - P_{2,9,y}}{\hat{\mathrm{l}}_{9,10,\hat{\mathrm{j}}}} \tag{30}$$

where $O_{1,y}$ and $P_{2,9,y}$ are the y coordinates of O_1 and $P_{2,9}$ respectively and $\hat{\mathrm{l}}_{9,10,\hat{\mathrm{j}}}$ is the $\hat{\mathrm{j}}$ component of $\hat{\mathrm{l}}_{9,10}$. The point $P_{1,10}$ is then given by

$$P_{1,10} = \begin{pmatrix} P_{2,9,x} + t\,\hat{\mathrm{l}}_{9,10,\hat{\mathrm{i}}} - d \\ O_{1,y} \\ P_{2,9,z} + t\,\hat{\mathrm{l}}_{9,10,\hat{\mathrm{k}}} \end{pmatrix}. \tag{31}$$

Note that the height of this point will not be the same as defined in the parameter file as the height of the POP line O_1. It is likely that this point could be forced to be the same height as the other POP lines: the angular change in the long length of light pipe will be very small and will probably not cause any polarization problems.

5.9. Locate points $P_{1,7}$, $P_{1,8}$ and $P_{1,9}$

Although the position of the first mirror in the T1 line $P_{1,7}$ is set in the input parameter file, it is still necessary to find positions for points $P_{1,8}$ and $P_{1,9}$ while still keeping the light pipes between them parallel to the unit vectors $\hat{l}_{7,8}$ and $\hat{l}_{8,9}$. Two methods have been used to do this. The first keeps $P_{1,7}$ exactly as defined in the parameter file and solves for positions $P_{1,8}$ and $P_{1,9}$. The second approach forces the lengths of the light pipes in the $\hat{l}_{7,8}$ and $\hat{l}_{8,9}$ directions to be the same as those for T2 while moving $P_{1,7}$. Both options will be described below.

5.9.1. Option 1 for Step 9

The point $P_{1,7}$ is forced to be the same as set out in the input parameter file so $P_{1,8}$ can be written

$$P_{1,8} = P_{1,7} + t_{1,7,8}\,\hat{l}_{7,8}. \tag{32}$$

The point $P_{1,9}$ is then given by

$$\begin{aligned} P_{1,9} &= P_{1,8} + t_{1,8,9}\,\hat{l}_{8,9} && (33)\\ &= P_{1,7} + t_{1,7,8}\,\hat{l}_{7,8} + t_{1,8,9}\,\hat{l}_{8,9}. && (34) \end{aligned}$$

Similarly $P_{1,10}$, calculated in step 8, must also be related to $P_{1,9}$ via

$$\begin{aligned} P_{1,10} &= P_{1,9} + t_{1,9,10}\,\hat{l}_{9,10} && (35)\\ &= P_{1,7} + t_{1,7,8}\,\hat{l}_{7,8} + t_{1,8,9}\,\hat{l}_{8,9} + t_{1,9,10}\,\hat{l}_{9,10} && (36) \end{aligned}$$

which can be solved for $t_{1,7,8}$, $t_{1,8,9}$ and $t_{1,9,10}$, allowing us to calculate $P_{1,8}$ and $P_{1,9}$ from Equations 32 and 34.

5.9.2. Option 2 for Step 9

While the the method above does produce valid positions the light pipes along the $\hat{l}_{7,8}$ and $\hat{l}_{8,9}$ directions were often very long and resulted in unworkable configurations. Another approach is to force the $\hat{l}_{7,8}$ and $\hat{l}_{8,9}$ light pipes to have the same lengths as T2 (see step 4 above). Thus, we have

$$\begin{aligned} P_{1,8} &= P_{1,7} + t_{2,7,8}\,\hat{l}_{7,8}, && (37)\\ P_{1,9} &= P_{1,8} + t_{2,8,9}\,\hat{l}_{8,9} && (38)\\ &= P_{1,7} + t_{2,7,8}\,\hat{l}_{7,8} + t_{2,8,9}\,\hat{l}_{8,9} \text{ and} && (39)\\ P_{1,10} &= P_{1,9} + t\,\hat{l}_{9,10} && (40)\\ &= P_{1,7} + t_{2,7,8}\,\hat{l}_{7,8} + t_{2,8,9}\,\hat{l}_{8,9} + t\,\hat{l}_{9,10}. && (41) \end{aligned}$$

This gives an equation for $P_{1,7}$ in terms of $P_{1,10}$:

$$P_{1,7} = P_{1,10} - t_{2,7,8}\,\hat{l}_{7,8} - t_{2,8,9}\,\hat{l}_{8,9} - t\,\hat{l}_{9,10} \tag{42}$$

and all that is required is a value for t that places T1 as close as possible to the required position in the parameter file. If we consider only the x axis we have

$$t_x = \frac{P_{1,10,x} - t_{2,7,8}\, l_{7,8,\hat{\imath}} - t_{2,8,9}\, l_{8,9,\hat{\imath}} - P_{1,7,x}}{l_{9,10,\hat{\imath}}} \tag{43}$$

with a similar expression for t_y in the y axis. A final value for t is found by averaging these two, that is,

$$t = \frac{t_x + t_y}{2}. \tag{44}$$

The points $P_{1,7}$, $P_{1,8}$ and $P_{1,9}$ are then calculated using Equations 38, 39, and 42.

Since this method forces the small light pipes of T1 and T2 to be identical it is the method used as of the writing of this report. The final telescope position will not be the same as that in the input parameter file, but it will not have moved by much.

5.10. Locate points $P_{3,7}$, $P_{3,8}$ and $P_{3,9}$

Similar options exist for T3, although once again forcing $P_{3,7}$ to be exactly as specified in the input parameter file can cause rather unworkable solutions. The x value of $P_{3,10}$ must be specified in the input parameter file while the y and z values must be the same as the POP line O_3, also defined in the parameter file. A method analogous to that set out for T1 can then be employed to find points $P_{3,7}$, $P_{3,8}$ and $P_{3,9}$.

5.11. Telescope 6 light pipes.

The beginning and end points of the light pipes for T6 are specified in the input parameter file. The starting point $P_{6,7}$ is entered as a 'first guess' while only the x coordinate of $P_{6,10}$ is required, since the y and z components will be the same as the POP line defined by O_6.

We begin by forcing the length of the light pipe between $P_{6,9}$ and $P_{6,10}$ to be the same as that for T5 and so

$$P_{6,9} = P_{6,10} - t_{5,9,10}\, \hat{l}_{9,10}. \tag{45}$$

We now need to find values for $t_{6,8,9}$ and $t_{6,7,8}$ that bring the point $P_{6,7}$ as close as possible to the required x and y positions set out in the input parameter file. Once again we want to find an expression for relating the two end points of the light pipe;

$$P_{6,8} = P_{6,9} - t_{6,8,9}\, \hat{l}_{8,9} \tag{46}$$

$$P_{6,7} = P_{6,8} - t_{6,7,8}\, \hat{l}_{7,8} \tag{47}$$

$$= P_{6,9} - t_{6,8,9}\, \hat{l}_{8,9} - t_{6,7,8}\, \hat{l}_{7,8}. \tag{48}$$

The x and y parts of this equation form a set of simultaneous equations that can be solved for $t_{6,8,9}$ and $t_{6,7,8}$ and the values for $P_{6,8}$ and $P_{6,9}$ can then be calculated. Note that this method forces T6 to be in the exact x and y coordinates requested but modifies the z coordinate.

5.12. Telescope 7 light pipes.

Once again, since it is desirable to keep as many of the parts of the light pipes the same as possible, we begin by forcing the last two lines of T7 to be the same length as those for T4. The x coordinate of $P_{7,10}$ is set in the parameter file, along with the y and z coordinates, which must be the same as the POP termination point O_7. Thus we have

$$P_{7,9} = P_{7,10} - t_{4,9,10}\, \hat{\mathrm{l}}_{9,10} \tag{49}$$

and

$$P_{7,8} = P_{7,9} - t_{4,8,9}\, \hat{\mathrm{l}}_{8,9}. \tag{50}$$

All that is left is to find a value for $t_{7,7,8}$ that places T7 as close as possible to the x and y positions in the parameter file. As for locating T1 we split the equation

$$P_{7,7} = P_{7,8} - t_{7,7,8}\, \hat{\mathrm{l}}_{7,8} \tag{51}$$

into the x and y parts

$$t_x = \frac{P_{7,8,x} - P_{7,7,x}}{l_{7,8,\hat{\mathrm{i}}}} \tag{52}$$

$$t_y = \frac{P_{7,8,y} - P_{7,7,y}}{l_{7,8,\hat{\mathrm{j}}}} \tag{53}$$

and form the mean

$$t_{7,7,8} = \frac{t_x + t_y}{2}. \tag{54}$$

The position $P_{7,7}$ can then be calculated using Equation 51. An option here is to force the z coordinate of $P_{7,7}$ to be the same as that set in the parameter file. This means that the light pipes will not be perfectly parallel, in reality none of them will be 'perfect', but it allows us to control the height of this telescope above the ground. Unfortunately the light pipe for T4 must pass through the dome for T7 and so the flexibility in height is severely limited in practice.

6. TESTING FOR ERRORS IN THE SOLUTION

Once the '12 step program' set out in Section 5 has been completed and positions for all of the mirrors have been found, the solution should be tested against the criteria listed in Section 2. The '3D' program performs the following tests:

- Calculates the mirror vectors as per Equations 6, 7, 8, and 8.
- Calculate the height of each mirror above (or below) the current terrain.
- Calculate the center of each vacuum chamber. The vacuum chambers are assumed to be cylindrical with the center at the mean position of the mirrors centers. The size of this chamber is set in the parameter file for each telescope input and output. An offset for the center of the chamber along the y axis is also continued in the input parameter file for fine adjustment of the chamber position.

- Calculate the atmospheric force acting on each of these vacuum boxes.
- For each telescope check that the termination points are on the correct inertial slab.
- For each telescope check that the light pipe exits the building within the correct break-out panel.
- For telescopes 1 and 2 ensure that the light pipes do not pass through the 100″ dome.
- For each telescope check that each part of the optical chain is parallel, to within some specified tolerance (nominally 1 degree), to the vectors $\hat{l}_{7,8}$, $\hat{l}_{8,9}$ or $\hat{l}_{9,10}$.
- For each light pipe check that the length is neither negative or ridiculously long.
- For each telescope check that the final point $P_{T,10}$ lies on the POP line defined by O_T and $\hat{o}$.
- Check if any of the mirror positions are either very low, actually underground or too high. The maximum height is set in the software itself.
- Check the long light pipe runs against the tree data and list the trees that are too close. Unfortunately, since the tree data at this time is incomplete, this check has been temporarily disabled in the software.
- Calculate and list the final baselines created by the solution telescope positions.

7. RESULTS

The modeling program was run using a 1 foot grid for the terrain, and after several iterations and adjustments, a solution was found that meets most of the criteria. Some problem areas still exist, for example clearance for the light pipes near the BCL/OPLE building and near the main intersection of roads near the 60″ dome, however, the positions of the telescopes need to be fixed in order for work to continue on the design of the telescope enclosures. Furthermore, the remaining problems are all for dimensional sizes of the order of 1 foot, and it is unlikely that the precision of either the terrain map or the buildings themselves is good enough to solve these problems using this model. Solutions will have to be found 'on the ground'.

Figure 2 shows a rendering of the entire mountain top as viewed from the south, including most of the existing structures (in brown). The 100″ dome is the large building in the center, behind which lies the BCL/OPLE. It is clear from this figure that T3 lies almost completely below the current terrain, while T2 is only slightly below ground. The light pipes from T1 and T2 go below ground almost exactly where the main road intersection near the 60″ dome. It is also possible to see that T7 is rather high above the current terrain. This sort of rendered image has proved invaluable in testing the results of the 3D model.

The data for each of the seven telescopes are given in Table 2, which contains the following information:

1. The positions of the center of each of the relay mirrors. These positions are in the same coordinate frame as that used by the surveyors and have been written in the same (x, y, z) format as used in the software, that is, the position for east is written first, then north and finally the height above sea level.

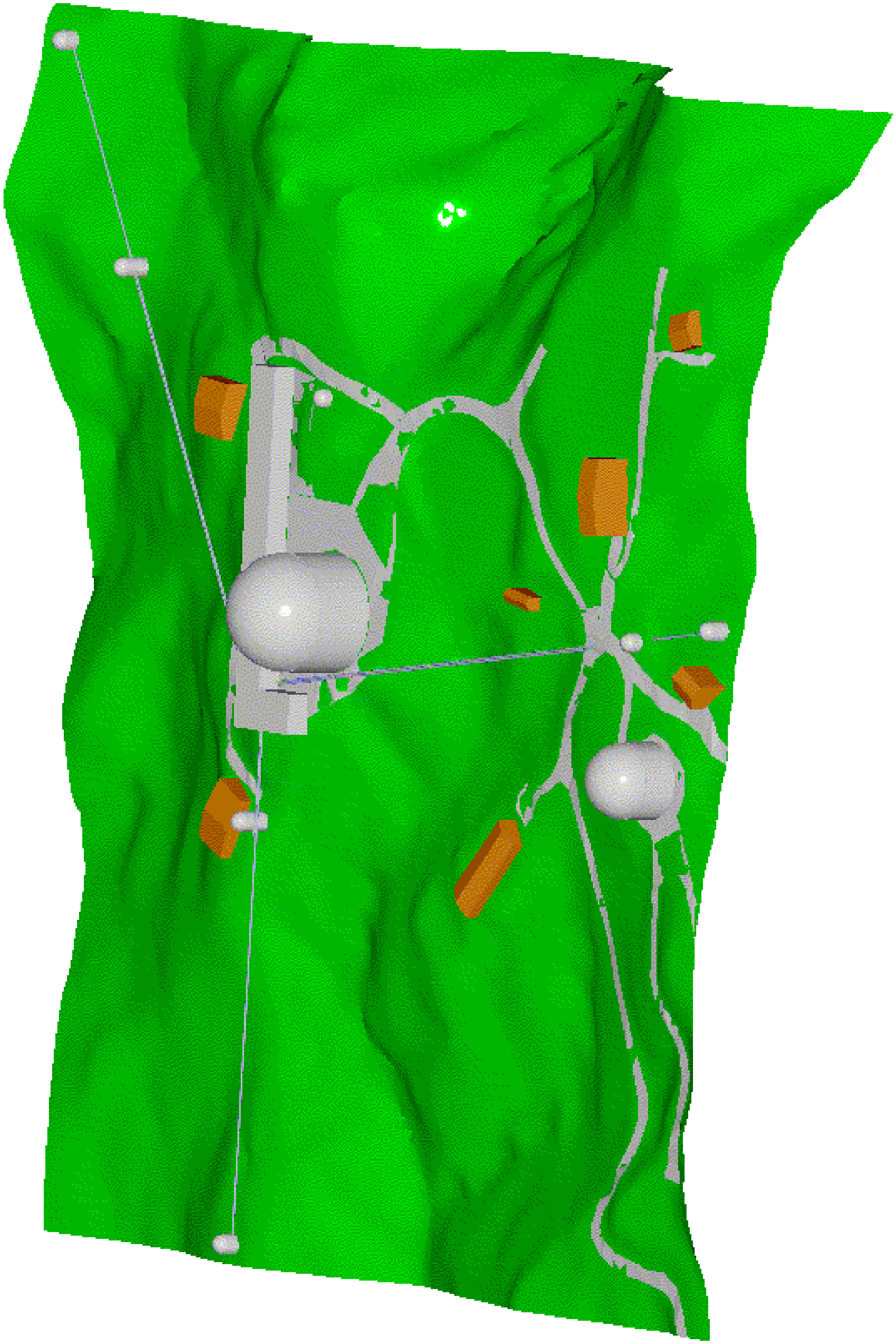

FIGURE 2. Rendering of final solution as viewed from the south.

2. Following each mirror position is the height of the mirror center above (or below) the current terrain. Note that for the mirrors inside the BCL/OPLE building these heights are from the the existing inertial slab.

3. The heading for the light pipe leaving the telescope. This is the number of degrees from north (clockwise) that the 'front' of the telescope pier must face. The telescope base plate design is shown in Figure 3 which defines the 'front' of the telescope pier. Note that the vertical beam leaving the telescope is not in the middle of this framework. Room must be left for a second light pipe to run through some of these piers, for example on T2 and T7. An example of this is shown in Figure 4. In all cases except telescopes 4 and 7, the light pipes leave the pier towards the BCL/OPLE through the front of the pier. The headings listed for T4 and T7 are for the 'front' of the pier: the light pipes themselves on these two telescopes exit in the opposite direction.

4. The slope of the light pipe leaving the telescope pier. All light pipes go up as they leave the telescope domes. The greatest slope is for T5 at nearly 6 degrees.

5. The total length of vacuum path from mirror number 7 to mirror number 10.

6. The position at which the light pipe intersects the BCL/OPLE building is then listed in the absolute coordinates.

7. For telescopes 1 and 2, the distance of the light pipe from the 100$''$ dome is also listed.

Table 3 gives the final values for the unit vectors defined in Section 3. Since all of the mirrors should, in theory, point in the same direction only one set of vectors are listed for all telescopes.

With the positions of the telescopes and light pipes it is possible to calculate all possible baselines, and these are listed in Table 4. These baselines were found by finding the distance between the number 7 mirrors in each telescope. Since the actual height of each telescope above mirror 7 is yet to be determined these baselines are only approximate. The bearing given for each baseline was calculated from the (x, y) position of the mirrors only.

Table 5 shows the atmospheric pressure created at each mirror point. This was calculated by assuming a 10 inch diameter pipe and performing a simple vector addition of the unit vectors defining the light pipe directions into and out of each mirror. In many cases multiple mirrors will be contained in the same vacuum box, however, these figures give some idea of the forces involved.

Due to the coupled nature of the 3D problem it was not a trivial problem to keep each of the sets of parallel light pipes the same distance apart. If it is determined that this is a problem small adjustments can be made in the solution to force a constant separation. The separations of these light pipes determined by the solution as of the writing of this report are listed in Table 6.

Due to time constraints, and the fact that the results of this analysis were not available when the BCL/OPLE was being designed, the inertial slabs on which the long light pipes terminate are not in the ideal locations for the mirror positions determined in this solution. Nevertheless, all mirror centers are within the bounds of the inertial slabs as shown in Figure 5. The vacuum boxes that go around these mirrors will hang over the edge of the slab in the case of T4, but it should still be possible to attach the enclosure firmly to the inertial slab.

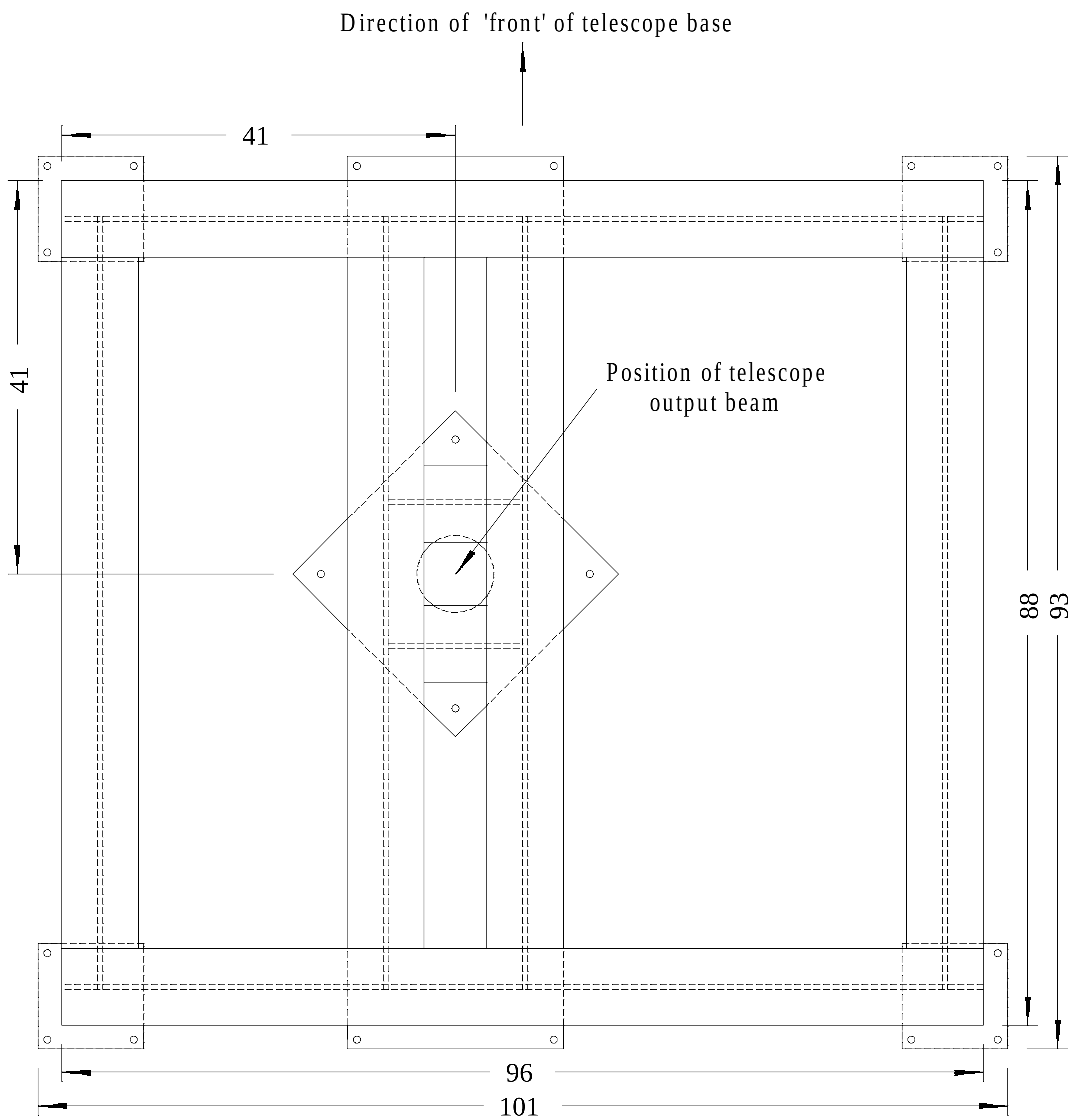

FIGURE 3. Telescope base defining the 'front' of the base and position of telescope output beam. More detail on the dimensions of this unit can be found in the telescope machine shop drawings. Scale 1:20.

TABLE 2. Telescope and light pipe positions.

T1 (S1)	Mirror 7 Center/Height	4270493.8613E, 4194174.3243N, 5670.9401H / 4.91 ft
	Mirror 8 Center/Height	4270492.8277E, 4194173.6241N, 5671.0014H / 4.71 ft
	Mirror 9 Center/Height	4270493.4821E, 4194173.5174N, 5671.0708H / 4.78 ft
	Mirror 10 Center/Height	4270395.4563E, 4194803.5200N, 5683.1297H / 1.63 ft
	Light Pipe Heading/Slope/Length	351°.16 / 1°.08 / 639.61 ft
	Passes through BCL/OPLE	4270397.48E, 4194790.54N, 5682.88H
	100″ Dome Clearance	3.14 ft
T2 (S2)	Mirror 7 Center/Height	4270474.7200E, 4194284.4900N, 5673.0488H / -3.00 ft
	Mirror 8 Center/Height	4270473.6864E, 4194283.7898N, 5673.1101H / -2.96 ft
	Mirror 9 Center/Height	4270474.3408E, 4194283.6831N, 5673.1795H / -2.89 ft
	Mirror 10 Center/Height	4270393.1560E, 4194805.4500N, 5683.1667H / 1.67 ft
	Light Pipe Heading/Slope/Length	351°.16 / 1°.08 / 530.06 ft
	Passes through BCL/OPLE	4270395.48E, 4194790.54N, 5682.88H
	100″ Dome Clearance	5.11 ft
T3 (S3)	Mirror 7 Center/Height	4270640.9493E, 4194733.2880N, 5681.7542H / -6.34 ft
	Mirror 8 Center/Height	4270639.9157E, 4194732.5878N, 5681.8155H / -6.41 ft
	Mirror 9 Center/Height	4270640.5701E, 4194732.4812N, 5681.8848H / -6.25 ft
	Mirror 10 Center/Height	4270630.1500E, 4194799.4500N, 5683.1667H / 1.67 ft
	Light Pipe Heading/Slope/Length	351°.16 / 1°.08 / 69.70 ft
	Passes through BCL/OPLE	4270631.54E, 4194790.54N, 5683.00H
T4 (E1)	Mirror 7 Center/Height	4270902.3700E, 4195179.0900N, 5651.3750H / 1.50 ft
	Mirror 8 Center/Height	4270367.5000E, 4194816.7500N, 5683.1000H / 1.60 ft
	Mirror 9 Center/Height	4270367.9885E, 4194816.6704N, 5683.1517H / 1.65 ft
	Mirror 10 Center/Height	4270367.8672E, 4194817.4500N, 5683.1667H / 1.67 ft
	Light Pipe Heading/Slope/Length	55°.88 / 2°.81 / 648.11 ft
	Passes through BCL/OPLE	4270379.50E, 4194824.88N, 5682.39H
T5 (W1)	Mirror 7 Center/Height	4269917.6400E, 4194882.5400N, 5635.4688H / 1.50 ft
	Mirror 8 Center/Height	4269916.8131E, 4194881.9798N, 5635.5178H / 1.58 ft
	Mirror 9 Center/Height	4270366.4649E, 4194808.7098N, 5683.1512H / 1.65 ft
	Mirror 10 Center/Height	4270366.3388E, 4194809.5200N, 5683.1667H / 1.67 ft
	Light Pipe Heading/Slope/Length	99°.25 / 5°.97 / 459.89 ft
	Passes through BCL/OPLE	4270357.15E, 4194810.23N, 5682.16H
T6 (W2)	Mirror 7 Center/Height	4270276.5000E, 4194835.1600N, 5671.7809H / 12.73 ft
	Mirror 8 Center/Height	4270264.5070E, 4194827.0355N, 5672.4922H / 13.32 ft
	Mirror 9 Center/Height	4270365.1261E, 4194810.6398N, 5683.1512H / 1.65 ft
	Mirror 10 Center/Height	4270365.0000E, 4194811.4500N, 5683.1667H / 1.67 ft
	Light Pipe Heading/Slope/Length	235°.88 / 2°.81 / 117.83 ft
	Passes through BCL/OPLE	4270357.15E, 4194811.94N, 5682.31H
T7 (E2)	Mirror 7 Center/Height	4270722.4283E, 4195059.8115N, 5661.6496H / 10.52 ft
	Mirror 8 Center/Height	4270360.7828E, 4194814.8200N, 5683.1000H / 1.60 ft
	Mirror 9 Center/Height	4270361.2713E, 4194814.7404N, 5683.1517H / 1.65 ft
	Mirror 10 Center/Height	4270361.1500E, 4194815.5200N, 5683.1667H / 1.67 ft
	Light Pipe Heading/Slope/Length	55°.88 / 2°.81 / 437.34 ft
	Passes through BCL/OPLE	4270375.63E, 4194824.88N, 5682.22H

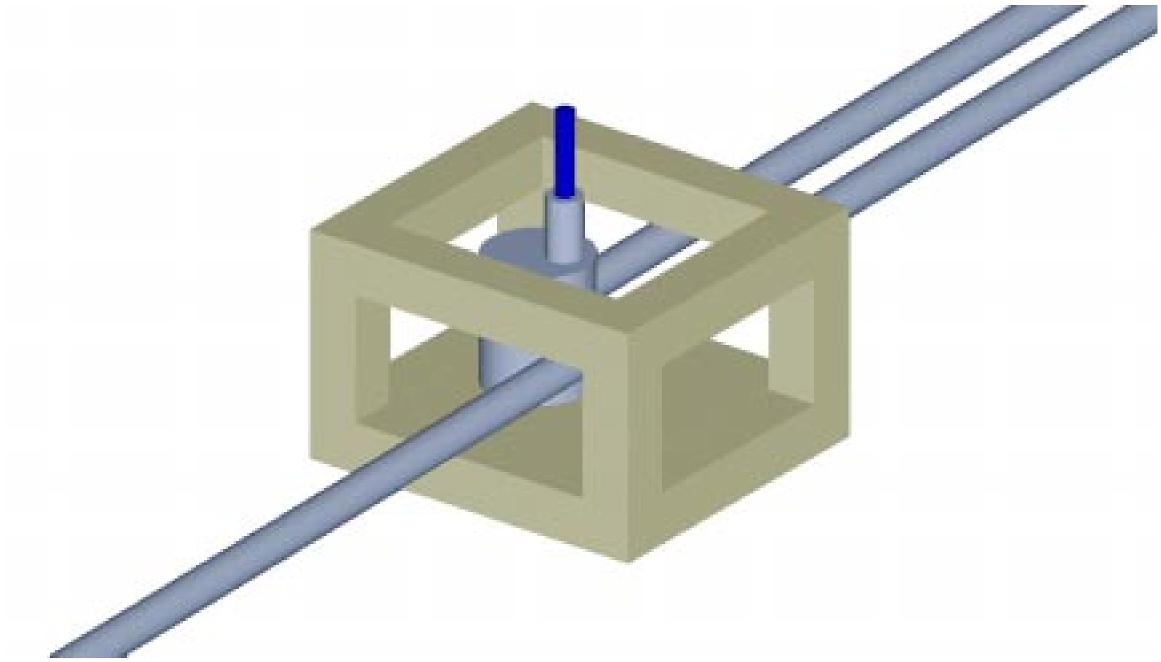

FIGURE 4. Rendering of the pier for T2 showing the light pipe for T1 also passing through the telescope pier.

TABLE 3. Unit vectors.

Light Pipe	$l_{7,8}$	(-0.8269, -0.5602, 0.0490)
	$l_{8,9}$	(0.9816, -0.1600, 0.1040)
	$l_{9,10}$	(-0.1537, 0.9879, 0.0189)
Mirror	m_7	(-0.4135, -0.2801, 0.5245)
	m_8	(0.9043, 0.2001, 0.0275)
	m_9	(-0.5677, 0.5739, -0.0425)
	m_{10}	(0.5769, -0.4940, -0.0095)

TABLE 4. Baselines.

Telescopes	Length		Bearing
T1-T2	111.84 ft	34.09 m	350.1
T4-T7	216.13 ft	65.88 m	236.5
T3-T7	337.14 ft	102.76 m	14.0
T5-T6	363.79 ft	110.88 m	97.5
T3-T6	378.55 ft	115.38 m	285.6
T2-T3	478.67 ft	145.90 m	20.3
T6-T7	499.42 ft	152.22 m	63.3
T3-T4	517.69 ft	157.79 m	30.4
T1-T3	578.09 ft	176.20 m	14.7
T2-T6	585.26 ft	178.39 m	340.2
T1-T6	695.67 ft	212.04 m	341.8
T4-T6	714.44 ft	217.76 m	241.2
T3-T5	740.00 ft	225.55 m	281.7
T2-T7	814.01 ft	248.11 m	17.7
T2-T5	818.18 ft	249.38 m	317.0
T5-T7	824.50 ft	251.31 m	77.6
T1-T5	913.71 ft	278.50 m	320.9
T1-T7	914.56 ft	278.76 m	14.5
T2-T4	991.80 ft	302.30 m	25.5
T4-T5	1028.54 ft	313.50 m	253.2
T1-T4	1084.81 ft	330.65 m	22.1

TABLE 5. Atmospheric pressure.

Mirror	Pressure	Direction Vector
M7	1592.7 lbs	(-0.5709, -0.3867, 0.7242)
M8	2037.6 lbs	(0.9759, 0.2160, 0.0296)
M9	1777.7 lbs	(-0.7022, 0.7100, -0.0526)
M10	1670.3 lbs	(0.7595, -0.6504, -0.0124)

TABLE 6. Parallel light pipes.

Telescopes	Distance
T1 & T2	1.98 ft
T4 & T7	2.19 ft
T5 & T6	1.70 ft

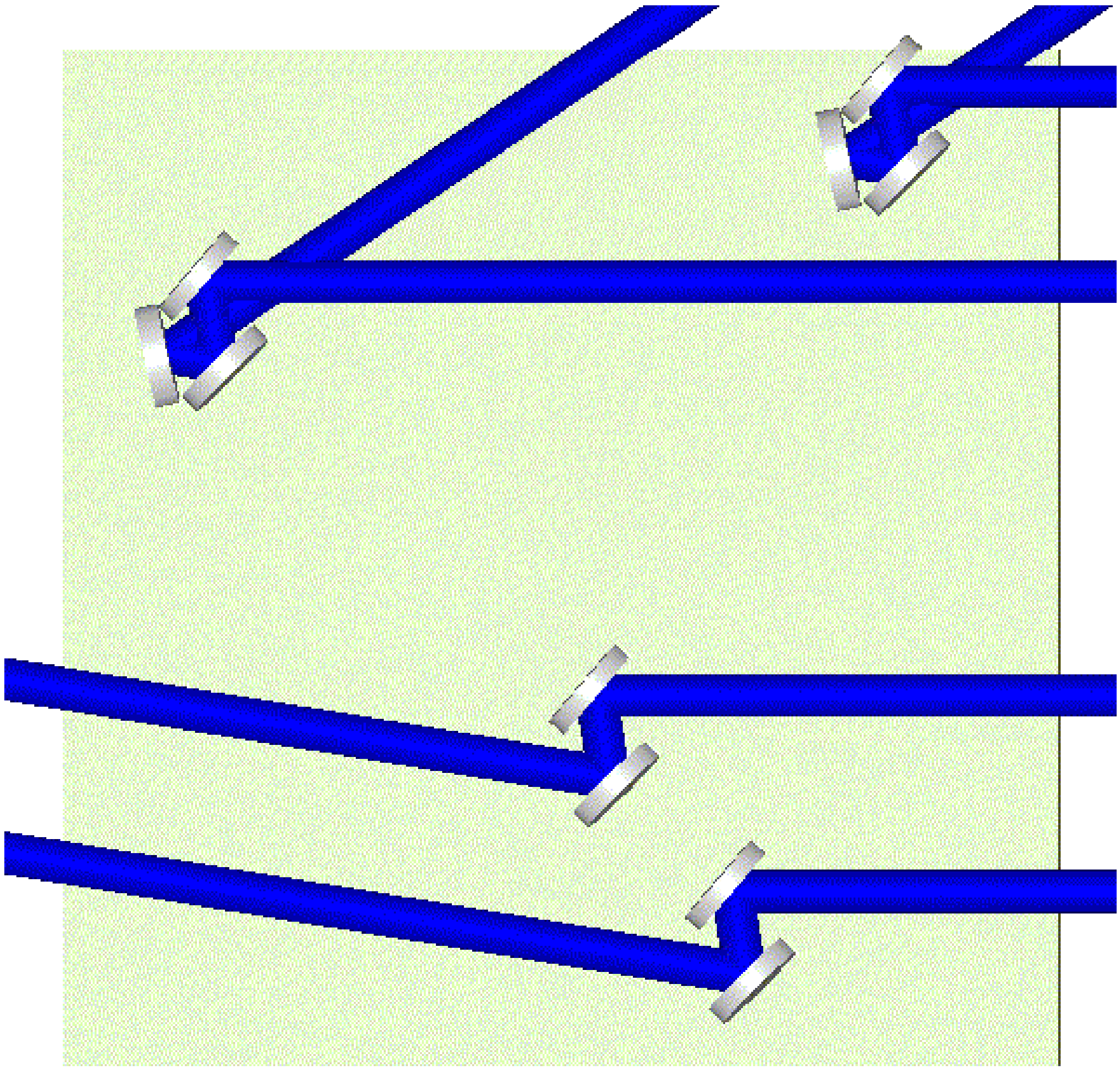

FIGURE 5. Rendering of the inertial slab for termination of East and West arms.

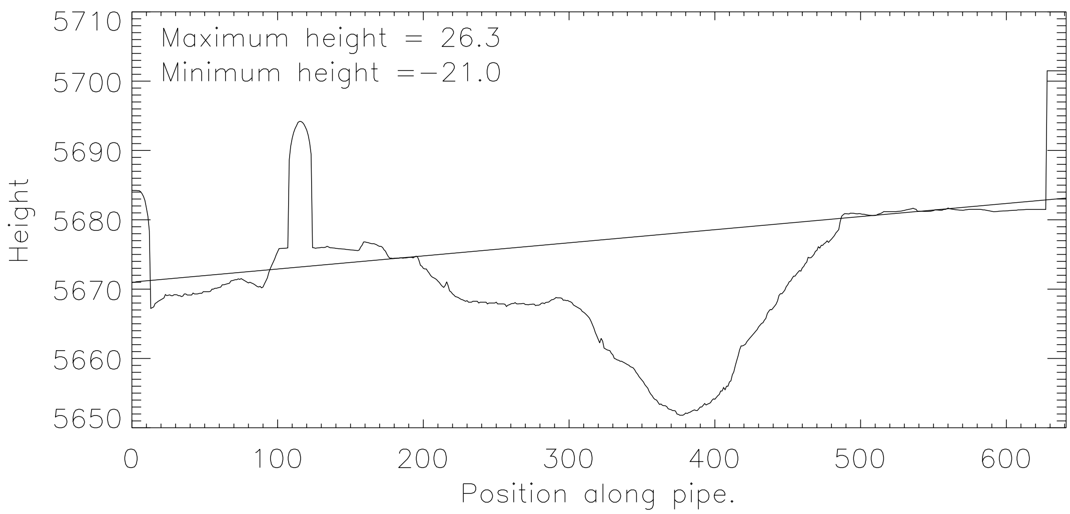

FIGURE 6. Light pipe cross-section for T1.

Figures 6, 7, and 8 show a cross-section along the light pipe for each telescope. The terrain is also plotted along with a minimum and maximum height above the current terrain. Note that the domes themselves have been added, as part of the terrain, so in most cases the minimum height is with respect to the dome ceiling, not the current terrain.

Finally, Figure 9 shows a plan of the area near the BCL/OPLE and 100″ dome. The existing break-out panels in the BCL/OPLE are shown as dark areas in the walls, and the inertial slabs inside the BCL/OPLE have been shown. While the light pipes for telescopes 1 and 2 do pass very close to the dome, they do not pass through it. Note that the maps supplied by the surveyor's only gave the position of the outside of the dome catwalk (shown as a solid think line). The position of the outside of the dome itself was measured by hand on the site and is shown as a thin circle. The light pipe for T4 comes very close to the edge of the break-out panel, but no way has been found as yet to move it further to the west without interfering too much with other aspects of the solution. It is probably not an insurmountable problem, and this is one of measurements that are close the resolution limit of the terrain and building data.

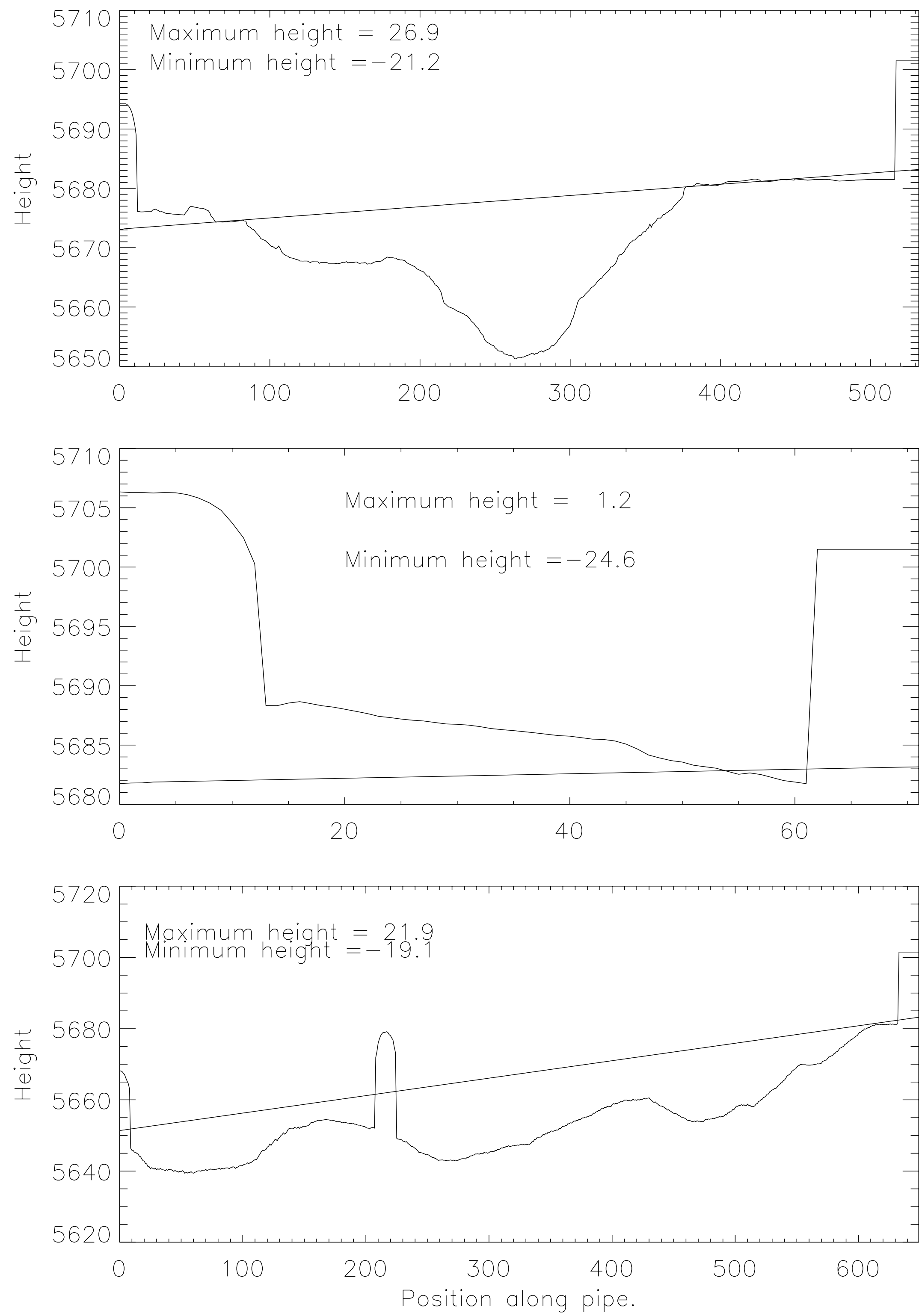

FIGURE 7. Light pipe cross-section for T2 (top), T3 (middle), and T4 (bottom).

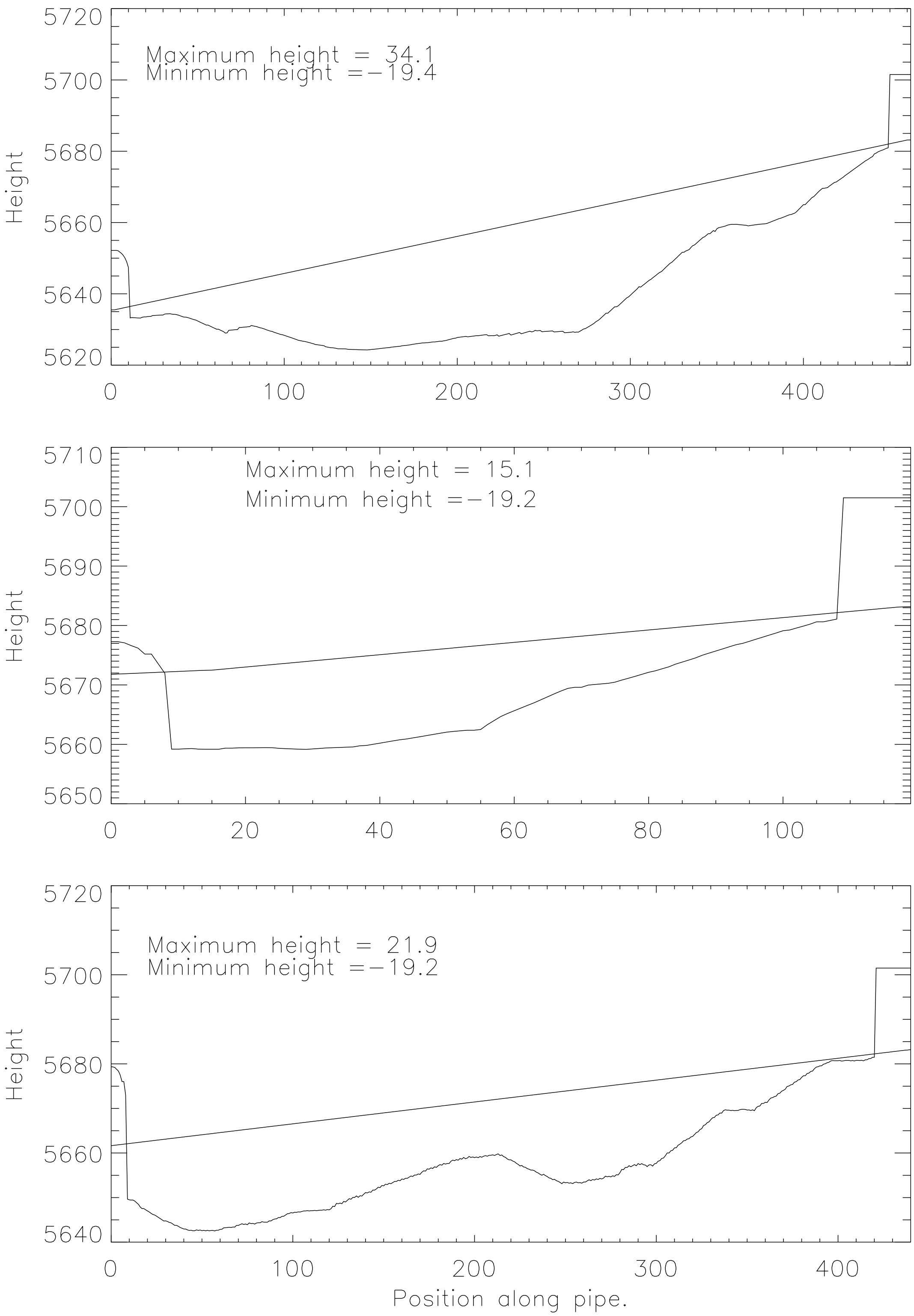

FIGURE 8. Light pipe cross-section for T5 (top), T6 (middle), and T7 (bottom).

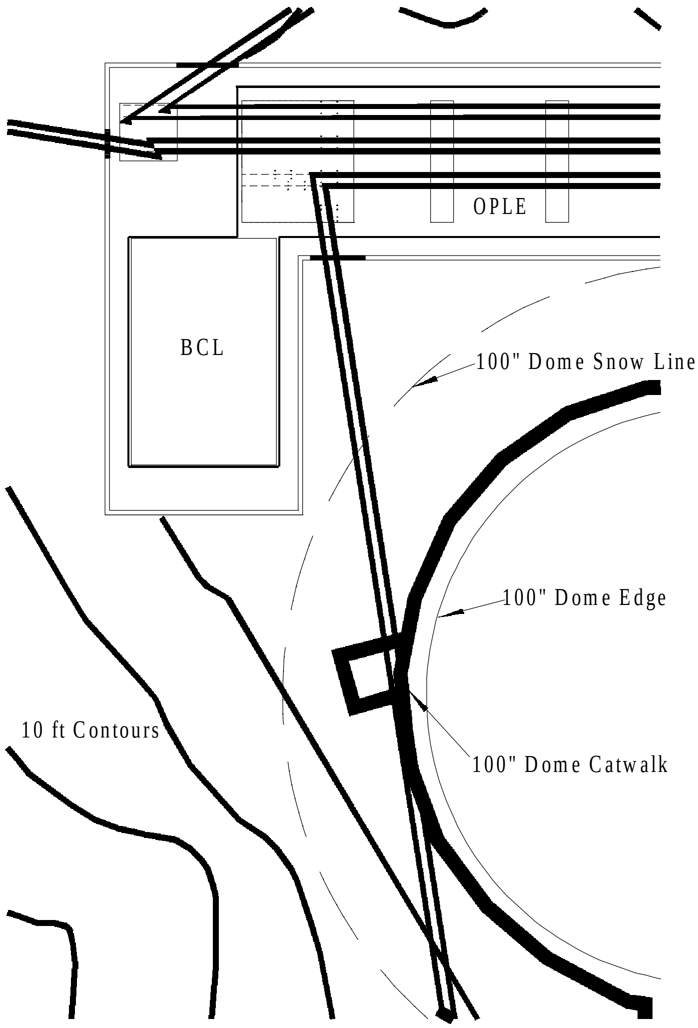

FIGURE 9. Plot showing break-out panel locations and 100″ dome edge and snow line.

A. EXAMPLE PARAMETER FILE

Here is an example parameter file as used by the '3D' program as input. This is the input parameters as they were used to generate the solution set out in this report.

```
#
# Parameter file for 3D model
#

# First of all, the floor height in the OPLE/BCL
5681.5

# Now a description of the BCL building
# Lower left corner
#4270361.00 4194746.38 # Original
4270357.14 4194746.39 # Point from Pafford
```

```
# Inside Corner
#4270395.34 4194790.54 # Original
4270391.5 4194790.52 # Point from Pafford

# Top right corner
#4270665.50 4194824.88 # Original
4270661.58 4194824.82 # Point from Pafford

# The positions of the ‘break out’ panels
# For T1 & T2
#4270396.73 4194790.54 4270406.04 4194790.54 # Original
4270392.88 4194790.54 4270402.19 4194790.54 # Calculated
# For T3
#4270633.88 4194790.54 4270639.41 4194790.54 # Original
4270630.03 4194790.54 4270635.56 4194790.54 # Calculated
# For T4
#4270373.41 4194824.88 4270384.09 4194824.88 # Original
4270369.56 4194824.88 4270380.24 4194824.88 # Calculated
# For T5
#4270361.00 4194808.30 4270361.00 4194813.30 # Original
4270357.15 4194808.30 4270357.15 4194813.30 # Calculated

# The positions of the Inertial Slabs
# For T1 & T2
#4270384.84 4194797.17 4270404.16 4194818.26 # Original
4270380.99 4194797.17 4270400.31 4194818.26 # Calculated
# For T3
#4270631.16 4194797.17 4270641.50 4194818.26 # Original
4270627.31 4194797.17 4270637.65 4194818.26 # Calculated
# For T4 & T5
#4270363.59 4194807.80 4270373.41 4194817.80 # Original
4270359.74 4194807.80 4270369.56 4194817.80 # Calculated

# The 100" dome center, radius and height
4270463.00 4194715.00 50.436667 50.0

# The 60" dome center, radius and height
4270363.00 4194237.75 32.557 30.0

# TELESCOPE NUMBER 1

#X,Y and delta Z
#4270484.23 4194177.10 1.5 # NEW COORDS FROM CADMAN
#4270491.90 4194174.97 1.5 # Moved 25.75 ft south along pipe line
  # From Solution position.
#4270488.21 4194151.67 1.5 # Moved 25.75 ft south along pipe line
  # From Cadman position
#4270491.96 4194174.96 1.5 # Moved 25.75 ft south along pipe line
  # From Solution position.
4270493.87 4194174.38 1.5 # Moved 25.75 ft south along pipe line
  # From Solution position.
          # And then to East for T1,T2 OPLE swap.

# Distance on X axis between T1&T2 light pipes in feet
#2.0
-2.0 # Now negative as OPLE lines for T1 & T2 are swapped

# X,Y and delta Z for beginning of POP
# 4270653.0 4194805.45 1.6666667 # Original
#4270649.15 4194805.45 1.6666667 # Calculated
```

```
4270649.81 4194803.52 1.6666667 # Calculated and swapped with T2

# Unit vector describing POP direction
1 0 0

# Radius height and offset of start vacuum box
1.25 3.0 0.16666667

# Radius, height and Y offset for end vacuum box
1.0 2.5 0.0

# TELESCOPE NUMBER 2

#X,Y and delta Z
#4270480.00 4194263.49 -3.0 # NEW COORDS FROM CADMAN
# 4270474.76 4194284.18 -3.0 # Moved 84.83 ft north along pipe line
    # From Solution position.
#4270471.11 4194260.88 -3.0 # Moved 84.83 ft north along pipe line
  # From Cadman position
#4270476.72 4194284.49 -3.0 # Moved 84.83 ft north along pipe line
  # From Solution position
4270474.72 4194284.49 -3.0 # Moved 84.83 ft north along pipe line
  # From Solution position
  # And moved to West for OPLE swap with T1

# X position of P10
# 4270399.00 # Original
#4270395.15 # Calculated
4270393.156 # Calculated and moved for T1/T2 OPLE swap.

# Lengths of first two parts of light pipes (t78, t89)
#1.0 0.66666667 # THIS CAUSES BEAMS TO HIT MIRRORS!
#1.5 0.66666667 # Works but needs to be compressed a bit
1.25 0.66666667 # Works but needs to be compressed a bit

# X,Y and delta Z for beginning of POP
# 4270653.0 4194803.52 1.6666667 # Original
#4270649.15 4194803.52 1.6666667 # Calculated
4270649.81 4194805.45 1.6666667 # Calculated and swapped with T1

# Unit vector describing POP direction
1 0 0

# Radius and height of start vacuum box
1.25 3.0 0.16666667

# Radius, height and Y offset for end vacuum box
1.0 2.5 0.0

# TELESCOPE NUMBER 3

#X,Y and delta Z NEW COORDS FROM CADMAN
4270637.78 4194716.18 -9

# X position of P10
# 4270634.0 # Original
4270630.15 # Calculated

# X,Y and delta Z for beginning of POP
# 4270653.66 4194799.45 1.6666667 # Original
4270649.81 4194799.45 1.6666667 # Calculated
```

```
# Unit vector describing POP direction
1 0 0

# Radius and height of start vacuum box
1.25 3.0 0.16666667

# Radius, height and Y offset for end vacuum box
1.0 2.5 0.0

# TELESCOPE NUMBER 4

#X,Y and delta Z ORIGINAL COORDS
#4270913.0 4195175.0 1.5 # Original
4270902.37 4195179.09 1.5 # New Pafford points

# Position and height of end of light pipe P8
# 4270366.0 4194814.0 1.5 # Original
# 4270362.15 4194814.0 1.5 # Calculated But too spread out
# 4270362.0 4194814.75 1.6 # Calculated
4270367.5 4194816.75 1.6 # Calculated

# X,Y and delta Z for beginning of POP
# 4270653.66 4194815.52 1.6666667 # Original
# 4270649.81 4194815.52 1.6666667 # Calculated
4270649.81 4194817.45 1.6666667 # Calculated Swapped with T7

# Unit vector describing POP direction
1 0 0

# Radius and height of start vacuum box
1.0 3.0 0.0

# Radius, height and Y offset for end vacuum box
1.0 2.5 0.125

# TELESCOPE NUMBER 5

#X,Y and delta Z NEW COORDS FROM CADMAN
4269917.64 4194882.54 1.5

# First guess at X,Y and delta Z for P9
# 4270367.0 4194809.0 1.3 # Original
4270363.15 4194809.25 1.3 # Calculated

# Length of first part of light pipe
1.0

# X,Y and delta Z for beginning of POP
# 4270653.66 4194809.52 1.6666667 # Original
4270649.81 4194809.52 1.6666667 # Calculated

# Unit vector describing POP direction
1 0 0

# Radius and height of start vacuum box
1.25 3.0 0.0

# Radius, height and Y offset for end vacuum box
1.0 2.5 0.0
```

```
# TELESCOPE NUMBER 6

#X,Y and delta Z
4270276.50 4194835.16 1.5

# X for P10
# 4270369.00 # Original
# 4270365.15 # Calculated
4270365 # Moved to west to make room for vacuum box

# X,Y and delta Z for beginning of POP
# 4270653.66 4194811.45 1.6666667 # Original
4270649.81 4194811.45 1.6666667 # Calculated

# Unit vector describing POP direction
1 0 0

# Radius and height of start vacuum box
1.0 3.0 0.0

# Radius, height and Y offset for end vacuum box
1.0 2.5 0.0

# TELESCOPE NUMBER 7
# 4270726.00 4195060.00 1.5 # Original
4270722.15 4195060.00 1.5 # Moved to west by 3.85

# X for P10
4270361.15

# X,Y and delta Z for beginning of POP
# 4270653.66 4194817.45 1.6666667 # Original
# 4270649.81 4194817.45 1.6666667 # Calculated
4270649.81 4194815.52 1.6666667 # Calculated Swapped with T4

# Unit vector describing POP direction
1 0 0

# Radius and height of start vacuum box
1.0 3.0 0.0

# Radius, height and Y offset for end vacuum box
1.0 2.5 0.125
```

B. EXAMPLE BUILDING FILE

The building file contains a list of building types and positions. An example building parameter as it was at the time of writing this report is listed below.

```
#
# File containing data about the various buildings on Mount Wilson
#

# The Cadman House
HOUSE 4270242 4194865 4270293 4194839 4270259 4194899 4270310 4194872 10.0

# The Berkeley House
HOUSE 4270593 4194871 4270640 4194866 4270597 4194911 4270644 4194907 10.0
```

```
# The Galley
HOUSE 4270489 4194415 4270502 4194413 4270494 4194448 4270507 4194447 10.0

# The Shed near the 60"
HOUSE 4270428 4194169 4270448 4194158 4270444 4194197 4270464 4194186 12.0

# Our house
HOUSE 4270731 4194203 4270760 4194211 4270724 4194230 4270753 4194238 10.0

# Museum
#HOUSE 4269936 4194331 4269977 4194361 4269873 4194415 4269913 4194444 10.0

# Shed near rubbish bins
HOUSE 4270290 4194445 4270310 4194467 4270224 4194506 4270248 4194527 10

# Mike's House
#HOUSE 4270637 4194114 4270680 4194121 4270631 4194147 4270675 4194155 10.0

# Cadman's Office
HOUSE 4270563 4194295 4270627 4194297 4270562 4194318 4270627 4194320 15

# The walking bridge
#HOUSE 4270473 4194467 4270483 4194466 4270489 4194636 4270498 4194635 1
```

C. EXAMPLE TREE FILE

Finally the tree parameter files contains a list of tree type and positions. Only a subset of the current tree parameter file is listed below.

```
#
# Tree Data File compiled by build_trees /bin/sh script
#
# X (East)    Y (North)   Z      Type
4270396.670 4194824.359 5683.490 CON
4270397.350 4194830.837 5683.458 CON
4270400.021 4194712.963 5681.668 CON
4270460.138 4194840.949 5681.179 CON
4270497.244 4194837.325 5681.515 CON
4270496.592 4194839.503 5680.772 CON
4270412.890 4194716.360 5681.779 CON
4270372.331 4194714.215 5675.133 CON
4270361.178 4194748.947 5679.933 CON
4270366.587 4194735.931 5679.245 CON
4270589.969 4194879.027 5674.388 CON
4270591.585 4194878.442 5674.356 CON
4270640.794 4194870.149 5674.400 CON
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