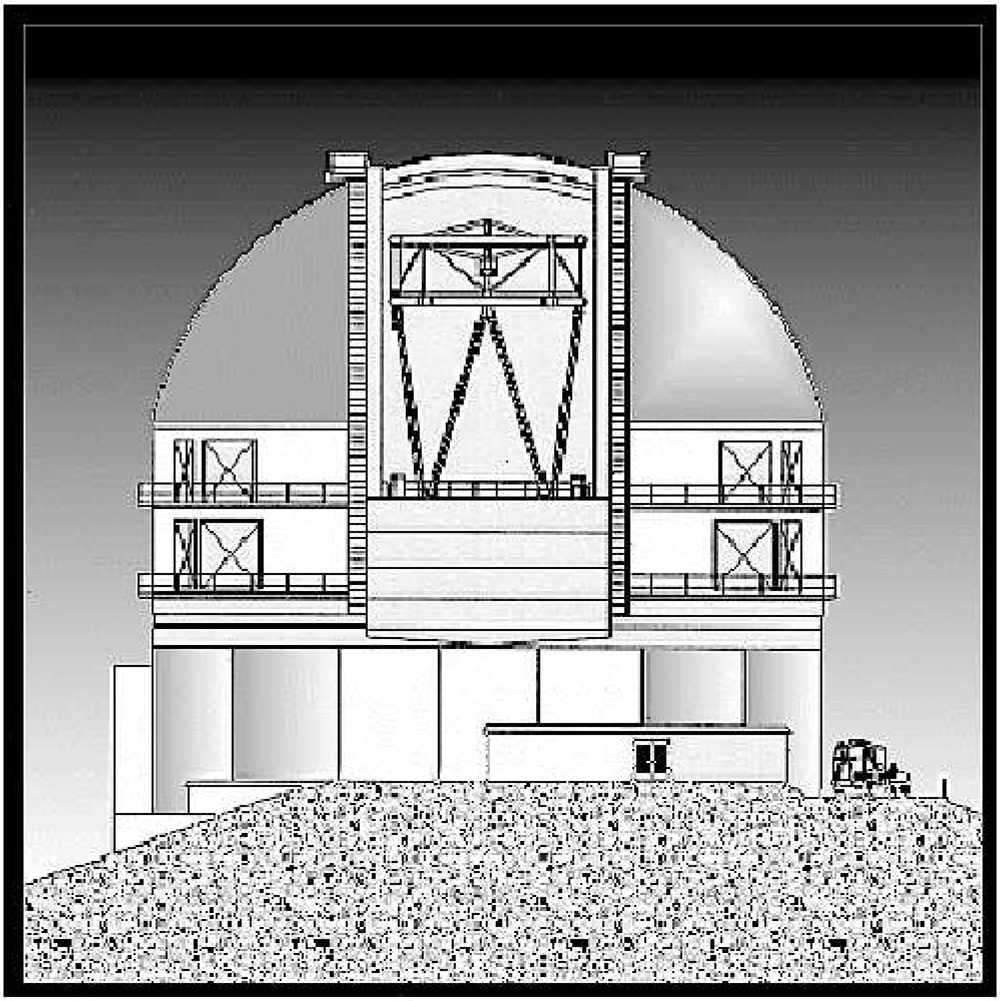
GEMINI
8-M Telescopes Project

SPE-O-G0063
Version 1.0

Description of Algorithms to Control Primary Mirror Position



L. Stepp
Optics Group

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GEMINI PROJECT OFFICE 950 N. Cherry Ave. Tucson, Arizona 85719
Phone: (520) 318-8545 Fax: (520) 318-8590

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1. Introduction

To maintain optical alignment at all telescope orientations, the M1 Support System must define the position and orientation of the primary mirror relative to the rest of the telescope. The control functions for this are provided by the Primary Mirror Control System (PCS). The purpose of this document is to explain the operation of the M1 Support System in defining the mirror position, and to describe the associated functions required of the PCS.

2. Coordinate System

The coordinate system used in this document is a right handed Cartesian system, and it is consistent with the coordinate system used in many other Gemini documents, including the PCS PDR documents[1]. The origin of the coordinate system is at the vertex of the primary mirror. The X-axis is parallel to the telescope elevation axis. The positive Y-axis points to the zenith when the telescope is horizon pointing. The Z-axis is coincident with the optical axis, positive towards the secondary mirror. Figure 1 illustrates the coordinate system.

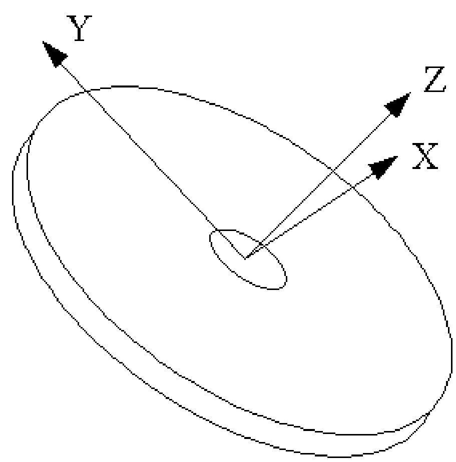

Figure 1. The coordinate system used in this document.

Rx, Ry and Rz are small angle rotations about the X, Y and Z axes respectively. Unless otherwise indicated, coordinates in this document are stated in meters.

3. Arrangement of the hydraulic zones

Reference 2 describes the philosophy of the Gemini M1 Support System, and compares it to the mirror support philosophies used in several other large telescopes. In the Gemini system, the position and orientation of the mirror are controlled by systems of interconnected hydraulic cylinders, called hydraulic whiffletrees because of their functional similarity to mechanical whiffletree mirror supports. Theses are divided into X-definers, lateral supports and axial supports.

The x-definers are arranged in a single hydraulic zone. The lateral supports are divided into two hydraulic zones. The axial supports have six zones that can be connected in three different configurations, by means of computer controlled valves. The three axial support configurations are :

1. Standard Three-zone
2. Alternate Three-zone
3. Six-zone

In the Standard Three-zone Configuration, the six axial zones are connected in three pairs consisting of: 4 & 5; 6 & 7; and 8 & 9. In the Alternate Three-zone Configuration, the three axial zones are: 5 & 6; 7 & 8; and 9 & 4. The three-zone configurations are kinematic, the six-zone configuration is overconstrained. The hydraulic zones of the axial and lateral supports are illustrated in Figure 2. The numbering of the zones treats X first (X-definers), then Y (lateral supports) and then Z (axial supports). Within each system, the zones are numbered in counterclockwise order starting from the + X-axis.

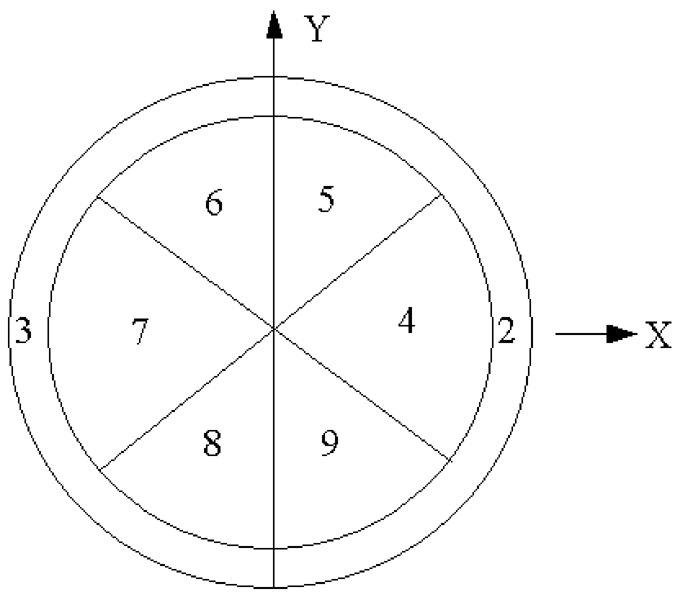

Figure 2. Arrangement of the hydraulic zones. Zone 1 is the X-definers (not shown); zones 2 and 3 are lateral supports; zones 4-9 are axial supports.

4. Control of Mirror Position

4.1. Standard three-zone configuration

The six whiffletree zones (three axial, two lateral and the X-definers) control the six orthogonal degrees of freedom. Adjusting the fluid volumes in the six zones, by means of the master cylinders, can move the mirror in the six Cartesian degrees of freedom: X, Y, Z, Rx, Ry, and Rz. However, there is not a one-to-one correspondence between actuation of individual master cylinders and the individual degrees of freedom.

The "axial" supports act perpendicular to the curved back of the mirror. The resultant of these support forces is aligned with the optical axis, but the individual support forces are not. Each axial support mechanism is connected to the mirror through a flexure column, which allows small transverse movements of the mirror relative to the supports. These flexures all point to the center of curvature of the optical surface, 28.8 meters above the mirror vertex. Therefore, the instant center for small lateral movements is at the center of curvature.

The lateral supports are linked to the mirror around the outer edge; each lateral support linkage is attached to the edge of the mirror along the thickness midline. The line of action of each support is essentially tangent to the midsurface of the mirror. The resultant of all the lateral support forces points in the + Y direction and passes through the center of mass of the mirror, which is located at (0, 0, 0.048).

The lateral supports are divided by the Y-axis into two zones, left and right as viewed when horizon pointing. The resultant of the support forces in a single zone points in the + Y direction and passes through a point approximately 4 meters from the optical axis in either the + or - X direction.

The lateral support constrains mirror motion in either the + or - Y direction. The constraint is applied by the linkages, which allow small amounts of motion in orthogonal directions. In total, the lateral support constraints act as two Y-direction constraints at the locations (3.9, 0.0, 0.048) and (-3.9, 0.0, 0.048).

The X-Definers are very similar to the lateral supports, but apply a constraint in the + or - X Direction. As in the lateral supports, this constraint is applied in line with the center of mass of the mirror, at an effective position of (0.0, 0.0, 0.048). When the mirror is rotated in tip or tilt by means of the axial supports, without changing the fluid volumes in the lateral supports and X-definers, the mirror actually rotates about its center of mass rather than about the vertex of the optical surface.

Table 1 shows the fluid volume changes in the six hydraulic zones required to produce motion of the optical surface in each of the six Cartesian degrees of freedom. A plus sign indicates the movement of the zone is in the positive coordinate direction, for example, in the + Z direction for the axial support zones.

Desired Motion: 1 mm or 1 mRad in positive direction	X-Definers	Lateral Zones		Axial Zones		
	1	2	3	4-5	6-7	8-9
X Translation	61.666			-6.218	6.218	
Y Translation		78.963	78.963	-3.590	-3.590	7.180
Z Translation				90.975	90.975	90.975
Rotation about X		-3.800	-3.800	103.400	103.400	-206.80
Rotation about Y	-16.500			-179.100	179.100	
Rotation about Z		313.900	-313.900			

Table 1. Fluid volume changes in milliliters required to produce individual motions in the six Cartesian degrees of freedom, with the axial support arranged in the Standard Three-zone Configuration.

4.2. Control of Mirror Position -- Alternate Three-zone configuration

The Alternate Three-Zone Configuration will only be used if experiments performed in the observatory show that it works better than the Standard Three-Zone Configuration in resisting wind buffeting of the primary mirror (this would depend on the typical patterns of wind pressure variation across the mirror). Table 2 shows the fluid volume changes required to produce motion in each of the six degrees of freedom with the support arranged in the Alternate Three-zone Configuration.

Desired Motion: 1 mm or 1 mRad in positive direction	X-Definers	Lateral Zones		Axial Zones		
	1	2	3	5-6	7-8	9-4
X Translation	61.666				6.218	-6.218
Y Translation		78.963	78.963	-7.180	3.59	3.590
Z Translation				90.975	90.975	90.975
Rotation about X		-3.800	-3.800	206.800	-103.400	-103.400
Rotation about Y	-16.500				179.100	-179.100
Rotation about Z		313.900	-313.900			

Table 2. Fluid volume changes in milliliters required to produce individual motions in the six Cartesian degrees of freedom, with the axial support arranged in the Alternate Three-zone Configuration.

4.3. Six-Zone Configuration

The Six-Zone Configuration will be used in high-wind conditions, to provide additional resistance to mirror deformation. Table 3 shows the fluid volume changes required to produce motion in each of the six degrees of freedom with the support arranged in the Six-zone Configuration. This information is expressed in matrix form in Appendix A.

Desired Motion: 1 mm or 1 mRad in positive direction	X-Definers	Lateral Zones		Axial Zones					
	1	2	3	4	5	6	7	8	9
X Translation	61.67			-4.15	-2.07	2.07	4.15	2.07	-2.07
Y Translation		78.96	78.96		-3.59	-3.59		3.59	3.59
Z Translation				45.49	45.49	45.49	45.49	45.49	45.49
Rotation about X		-3.80	-3.80		103.40	103.40		-103.4	-103.4
Rotation about Y	-16.50			-119.4	-59.70	59.70	119.40	59.70	-59.70
Rotation about Z		313.90	-313.9						

Table 3. Fluid volume changes in milliliters required to produce individual motions in the six Cartesian degrees of freedom, with the axial support arranged in the Six-zone Configuration.

It can be seen that the information in Tables 1 and 2 can be derived from the information in Table 3. In fact, the control of each of the three modes should be by means of the matrix in Appendix

A. Each of the six axial zones has its own master cylinder unit (MCU), so a combined zone in a three zone mode (for example, zone 4-5) has two MCUs. Fluid volume changes should be divided equally between the two MCUs. As a result, Appendix A applies to all three modes.

5. The position sensors

The hydraulic systems are designed to be stiff, however they are not infinitely stiff. For example, without compensation the mirror will decenter about half a millimeter as the telescope moves from zenith to horizon. Therefore, the hydraulics are not used as the position reference. Position sensors attached to the mirror cell are used to provide that reference. Effectively, the mirror position is defined by the position sensors rather than by "hard points".

The locations and orientations of the position sensors have been chosen to satisfy the following philosophical principles:

- The sensors are mounted at locations having minimum flexure from changing gravity orientation
- The lines of action of the sensors are aligned with the directions of motion of the mirror produced by fluid volume changes in individual hydraulic zones
- The sensors must give true readings in the presence of temperature changes
- The sensors should be symmetric about X = 0 and Y = 0 planes

Following these principles has led to: (1) using sensors that are not perfectly aligned with the coordinate directions, and (2) having more sensors than degrees of freedom to be measured. The reasons are explained below.

Tilt of the primary mirror has a large effect on telescope pointing, so to maintain pointing accuracy the position sensors that measure this tilt must be located at points on the mirror cell having minimum deflection from gravity loading. The best locations are directly above the attachment points of the four bipods that support the cell. Finite-element analysis indicates that these four points have equal deflection relative to the telescope structure from zenith-pointing gravity, and their deflections have symmetry about the x = 0 plane at all zenith angles. Position sensors at these four locations are used to measure motions in Z, Rx and Ry. The sensors are perpendicular to the back of the mirror, that is, they point towards the center of curvature. Therefore, they are insensitive to motions caused by the lateral supports and X-definers.

Thermal expansion must be considered when choosing the locations for the sensors to measure lateral motion. It is not practical to locate position sensors on the optical axis. We have located the lateral sensors at the outer edge of the mirror. Radial-direction sensors at the outer edge of the mirror are subject to relative thermal expansion between the steel mirror cell and the zero-expansion mirror. Sensors tangential to the edge of the mirror can give a true measure of the relative motion of that side of the mirror, unaffected by temperature changes, but another sensor is needed on the opposite side to distinguish between lateral motion and rotation about the optical axis.

Another factor affecting lateral sensor location is the relative distortion of the mirror from horizon-pointing gravity loads. The lateral support has been designed to minimize the deflections of the optical surface in the direction normal to the surface, however finite-element analysis indicates the shearing deflection in the "plane" of the mirror has a magnitude of almost 10 microns at the horizon. This means that if the Y-direction lateral sensors were located at the sides (at 3 o'clock and 9 o'clock positions), they would not represent the true location of the optical axis when the telescope is horizon pointing.

As a result of these considerations, the Y-direction position of the mirror is measured in a radial direction at two points on opposite sides of the mirror (at 6 o'clock and 12 o'clock when horizon pointing) with the position of the optical axis given by the average of the two readings. These sensors are oriented tangent to the mirror curvature, therefore they are inclined approximately 8 degrees relative to the Y-axis. The X-direction position and mirror rotation about the Z-axis are indicated by two sensors at the same 6 o'clock and 12 o'clock positions, oriented parallel to the X-axis.

The locations and orientations of the position sensors are shown in Figure 3. The positive direction for each sensor is the direction generally in the positive direction for the associated Cartesian coordinate. For example, sensors 5 through 8 indicate a positive change when the mirror moves in the + Z direction.

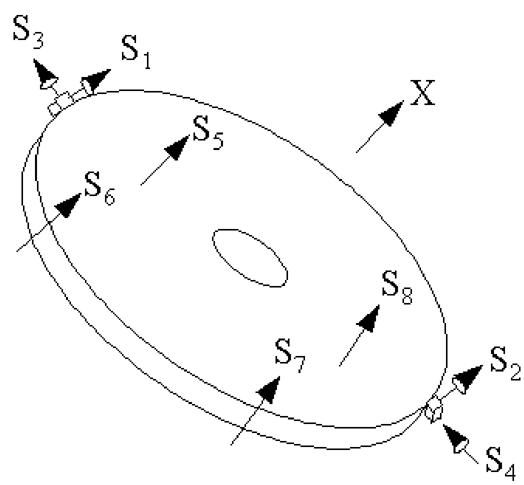

Figure 3. Locations of the position sensors. In each case the arrow points in the positive direction for the sensor.

5.1. Effects caused by thermal expansion

Sensors 3 and 4 are influenced by relative thermal expansion between the mirror and cell. The position of the center of the mirror can be determined by taking the average of the two readings. The magnitude of the relative expansion is given by the difference of the two readings. The relative expansion indicated by ΔS_4-ΔS_3 is about 105 micrometers per degree C.

Note, however, that because of the angle of the contact surfaces for sensors 3 and 4, a Z translation will cause both sensors to change readings. The average of the two readings will still indicate the position of the center of the mirror, but the difference between the readings is influenced both by temperature and Z translation.

5.2. Diagnostic calculations

Because there are 8 position sensors to measure 6 degrees of freedom, the redundant sensor information can be used for diagnostic purposes, for example, to indicate a fault in one of the sensors. Two calculations can be performed to indicate a fault condition.

$$\Delta S_4 - \Delta S_3 - 0.071(\Delta S_5 + \Delta S_6 + \Delta S_7 + \Delta S_8) - 0.000105(\Delta T) = 0$$

where the sensor readings are expressed in meters, and ΔT in degrees C; and

$$\Delta S_5 - \Delta S_6 + \Delta S_7 - \Delta S_8 = 0$$

The first equation relates to an apparent relative expansion of the mirror diameter. The second relates to an apparent flexure of the mirror. If either of these equations departs from zero by more than a certain criterion value, a fault condition should be indicated. It is possible that cell flexure with zenith angle might make it necessary to compare the second equation to an expression that is a function of zenith angle instead of zero.

5.3. Conversion from sensor readings to orthogonal coordinates

The eight sensor readings can be related to the six coordinate directions. Calculations are simplified if a 6 x 6 conversion matrix can be used. Therefore, we will combine sensor readings 3 and 4, and sensor readings 7 and 8. Appendix B gives the conversion matrix from coordinates to sensor readings and Appendix C gives the conversion matrix from sensor readings to coordinates.

6. Change of mirror position with zenith angle

The axis of the Cassegrain Rotator is defined as the optical axis, and as the telescope orientation changes this axis tilts relative to the M1 Cell Structure. To stay in alignment with the Cassegrain Rotator as the zenith angle changes, the mirror must tilt and decenter relative to the cell. Specifically, as zenith angle increases, the mirror must move in the +Y direction and rotate in the -Rx direction.

The relative tilt of the Cassegrain Rotator axis has been calculated by finite-element analysis, and these results will be verified by measurements in the telescope. The correct position and orientation of the mirror as a function of zenith angle will be stored in a look-up-table (LUT). The information in the LUT will be in terms of the position sensor readings required at a particular zenith angle. As the telescope orientation changes, the PCS will drive the master cylinders to maintain the position sensor readings specified in the LUT for the current zenith angle. This is the only aspect of the control that is "closed loop". The primary mirror will not be moved in response to measurements of image motion or optical aberrations. These will be controlled by movements of the secondary mirrors.

The magnitude of mirror movement between zenith and horizon is calculated to be 200 micrometers in the +Y direction, and -15 arc seconds in the Rx direction. The required movement of the mirror vertex relative to the position sensors is equal to these values times the sine of the zenith angle. For example, at a zenith distance of 30 degrees the mirror would be shifted 100 micrometers in Y and rotated -7.5 arc seconds in Rx compared to its position at zenith. The actual values in the LUT may also contain corrections for cell flexure.

The amount of hydraulic fluid that must be displaced to maintain the correct mirror position as a function of zenith angle depends on the mirror motion described above, plus the amount of fluid required to overcome the sag of the supports from elastic deformation under the mirror weight. The lateral supports will sag under horizon-pointing gravity approximately 400 micrometers; this will vary as the sine of the zenith angle. A more exact prediction of this value will be made at the end of the design process.

7. Calibrations

The numerical values stated in this report have been calculated based on nominal sizes of components and finite-element analysis of mechanical deflections. They will need to be recalibrated based on measurements made in the assembled telescope. The affected numbers include:

- The values in Tables 1-3
- The constants in the first equation in section 5.2
- (Possibly) the right side of the second equation in section 5.2
- The amount of mirror movement with zenith angle
- The amount of fluid that must be moved to compensate for horizon-pointing gravity sag
- The values in the matrices in Appendices A and B

8. Acknowledgments

This report relied heavily on the work of Earl Pearson, who derived the matrices on which it is based, and who has provided advice and review during its writing.

9. References

1. J. Maclean, "Gemini Primary Mirror Control System - Preliminary Package Software Design Description," Gemini Specification SPE-C-G0064, December 5, 1995.
2. L. Stepp, E. Huang and M. Cho, "Gemini Primary Mirror Support System", SPIE Proceedings 2199, ed. L. Stepp, Kona, Hawaii, March, 1994.

Appendix A
Matrix Equation to Calculate Fluid Volume Changes to Accomplish Specified Position Changes

$$
\begin{bmatrix} \Delta V1 \\ \Delta V2 \\ \Delta V3 \\ \Delta V4 \\ \Delta V5 \\ \Delta V6 \\ \Delta V7 \\ \Delta V8 \\ \Delta V9 \end{bmatrix}
=
\begin{bmatrix}
61.67 & 0 & 0 & 0 & -16.50 & 0 \\
0 & 78.96 & 0 & -3.80 & 0 & 313.90 \\
0 & 78.96 & 0 & -3.80 & 0 & -313.90 \\
-4.15 & 0 & 45.49 & 0 & -119.40 & 0 \\
-2.07 & -3.59 & 45.49 & 103.40 & -59.70 & 0 \\
2.07 & -3.59 & 45.49 & 103.40 & 59.70 & 0 \\
4.15 & 0 & 45.49 & 0 & 119.40 & 0 \\
2.07 & 3.59 & 45.49 & -103.40 & 59.70 & 0 \\
-2.07 & 3.59 & 45.49 & -103.40 & -59.70 & 0
\end{bmatrix}
\begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \\ \Delta Rx \\ \Delta Ry \\ \Delta Rz \end{bmatrix}
$$

where:

$\Delta V1$ = the change in fluid volume in hydraulic zone 1, in liters
Movements ΔX, ΔY and ΔZ are in meters
Rotations ΔRx, ΔRy and ΔRz are in radians

Rotation angles ΔRx, ΔRy and ΔRz are assumed to be small.

Appendix B
Matrix Equation to Calculate Sensor Readings From Coordinate Values

$$
\begin{bmatrix} \Delta S_1 \\ \Delta S_2 \\ \dfrac{\Delta S_3 + \Delta S_4}{2} \\ \Delta S_5 \\ \Delta S_6 \\ \dfrac{\Delta S_7 + \Delta S_8}{2} \end{bmatrix}
=
\begin{bmatrix}
1.000 & 0 & 0 & 0 & -0.100 & -4.100 \\
1.000 & 0 & 0 & 0 & -0.100 & 4.100 \\
0 & 0.9899 & 0 & 0.39 & 0 & 0 \\
-0.063 & -0.063 & 0.996 & 1.818 & -1.818 & 0 \\
0.063 & -0.063 & 0.996 & 1.818 & 1.818 & 0 \\
0 & 0.063 & 0.996 & -1.818 & 0 & 0
\end{bmatrix}
\begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \\ \Delta Rx \\ \Delta Ry \\ \Delta Rz \end{bmatrix}
$$

where:

ΔSn = change in reading in sensor number n, in meters
Movements ΔX, ΔY and ΔZ are in meters
Rotations ΔRx, ΔRy and ΔRz are in radians

Rotation angles ΔRx, ΔRy and ΔRz are assumed to be small.

Some of the zero values are not precisely zero, but they have been omitted because they are significantly smaller than the other values in the table.

Appendix C
Matrix Equation to Calculate Coordinate Values From Sensor Readings

$$
\begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \\ \Delta Rx \\ \Delta Ry \\ \Delta Rz \end{bmatrix}
=
\begin{bmatrix}
-0.498 & 0.498 & 0 & -0.030 & 0.030 & 0 \\
0 & 0 & 0.996 & -0.055 & -0.055 & 0.110 \\
0 & 0 & 0 & 0.251 & 0.251 & 0.502 \\
0 & 0 & 0.035 & 0.136 & 0.136 & -0.271 \\
0.173 & -0.173 & 0 & -0.274 & 0.274 & 0 \\
0.122 & 0.122 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} \Delta S_1 \\ \Delta S_2 \\ \dfrac{\Delta S_3 + \Delta S_4}{2} \\ \Delta S_5 \\ \Delta S_6 \\ \dfrac{\Delta S_7 + \Delta S_8}{2} \end{bmatrix}
$$

where:

Movements ΔX, ΔY and ΔZ are in meters
Rotations ΔRx, ΔRy and ΔRz are in radians
ΔSn= change in reading in sensor number n, in meters

Rotation angles ΔRx, ΔRy and ΔRz are assumed to be small.