PS04/E.E. Montgomery

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Marshall Space Flight Center AL 35812

26 August 93

Dear Sir:

The Sirius Group is pleased to submit this final report entitled "Laser Power Beaming System Analyses" in partial fulfillment of the requirements of Order No. H-20780D, 1-3-PP-02277(1F). The report includes no inventions or proprietary information, and has been approved for unlimited distribution.

Sincerely yours,

Dr. Glenn W. Zeiders Jr.
President, The Sirius Group

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FINAL REPORT 25 Aug 93

LASER POWER BEAMING SYSTEM ANALYSES

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STATEMENT OF WORK:

A series of developments during the past decade in high power lasers, large segmented telescopes, and adaptive optics, together offer the promise for power beaming from the Earth's surface as a cost-effective means for supplying the energy needs of a variety of space assets. Appropriately configured, the same optical systems should also be able to offer a quality of astronomical imaging heretofore restricted to space-based telescopes.

A Research and Development (R&D) program managed by NASA Marshall Space Flight Center and supported by JPL and industry is presently moving from the planning stage into testing of a complete multi-element adaptive optics subsystem and fabrication of a large telescope truss structure. The technologies represent the most current state of the art, and the efforts will be highly visible; therefore, their success will be critical to the progress of the overall program. It should be understood that they are intended primarily as test vehicles to validate concepts and to familiarize personnel with fabrication procedures, instrumentation, and operation. Many key parameters (segment size, edge sensing, control algorithms, and others) have not been optimized. It is critical that they be identified, their effects be quantified, and means be defined to specify them so that the significance of the tests and their results will not be misinterpreted.

The purpose of this initial effort, part of a much more extensive one to be undertaken to provide technical and planning support of the overall power beaming program, will be specifically to address the risk factors and potential solutions of the unresolved issues associated with the forthcoming Phased Array Mirror, Extendible Large Aperture (PAMELA) and truss telescope projects, and to initiate a detailed plan to identify the critical paths for these and other key program elements.

The contractor shall identify key unresolved issues in the PAMELA test and truss telescope fabrication projects of the NASA laser power beaming program, and shall provide technical and programmatic recommendations for solving these unresolved issues. A recommended selection of development path for the main beam director algorithm will be required. These will require evaluation of the modified multigrid method and the innovative deterministic method proposed by Applied Mathematical Physics Research.

The contractor shall be required to travel to MSFC. The contractor shall submit a final report of his findings and recommendations at the conclusion of the effort.

Dr. Glenn W. Zeiders Jr.
President, The Sirius Group

SUMMARY OF EFFORT

The successful demonstration of the PAMELA adaptive optics hardware and the fabrication of the BTOS truss have been identified by the program office as the two most critical elements of the NASA laser power beaming program, so it was these that received attention during this program. To that end, two trips were made by the contractor to MSFC to familiarize himself with the forthcoming PAMELA tests (especially the instrumentation and the plan prepared by Kaman) and to provide input to the ongoing BTOS truss effort. Meetings were held by the contractor at MSFC with Henry Waite, Gerald Nurre, Sandy Montgomery, Whitt Brantley, John Redmon Jr. and others, and he participated in several BTOS telecons. Detailed analyses were prepared and are attached of the AMP deterministic control scheme and the BTOS truss structure (both the JPL design and a spherical one), and recommendations are given.

Segment Control Techniques

The techniques considered to date in the NASA power beaming program for controlling the individual segments have been based on the use of a Shack-Hartmann sensor for measuring the local slope of the wavefront, then solving Poisson's equation to give the piston displacement.

A variety of iterative approaches (Jacobi, Gauss-Seidel, and successive over-relaxation) have been used for the latter and have proven to be effective for handling high-spatial-frequency disturbances, but their use of the values at nearest neighbors to update the state estimate cause low-frequency errors to be slowly attenuated. The multigrid technique offers promise to effectively circumvent this problem by forming the solution over multiple scales such that even low-frequency disturbances appear to occur over a small scale when viewed from a much larger one. Kaman describes the technique in detail in its 1992 final report, and, of particular interest for implementation with the PAMELA experimental hardware, specifically develops the system of equations needed for use with a 36-element hexagonal array. JPL and Kaman both claim that the multigrid estimator can be accomplished in hardware with a hierarchical controller, but MSFC as the system integrator should independently analyze the problem and define the system requirements -- especially to determine if and how the technique can be realistically extended to > 100,000 elements.

A deterministic alternative proposed by Applied Mathematical Physics Research (AMP) has met with less-than-enthusiastic response from much of the program's control systems community, but I continue to feel that it offers considerable promise and should be explored in more detail. Whereas the ultimate goal of all of the iterative solutions is essentially to converge to a solution which minimizes (in some sense) the edge differences of the segments, the AMP approach requires from the start that the sum of the squares of all of the edge differences at the midpoints be minimized. The resulting equations, one for each independent closed loop through the centers of the segments and the midpoints of abutting edges, involve only the local tilts and the geometry, and they can be cast in the form of a matrix that need be inverted only once to give the required piston displacements. The full solution for a 19-element mirror array was presented in my 1992 final report, and the results for the 36-element PAMELA array are given in Fig. 1 in anticipation of eventual implementation there; both show that, while the original matrices are quite sparse, the final one is not, indicating that the region of influence extends well beyond the nearest neighbors. The matrices would be extremely large if all loops had to be included, and this would have a serious impact on both the electronics and the cabling, so it is of interest to determine the region of influence beyond which tilt data can be neglected; note that a limited range would cause most interior points to have the same set of weighting functions. Fig. 2 gives the weighting functions for determining the center edge difference of symmetrical arrays with 16, 36, and 64 elements (the latter produced 98 X 98 matrices which exceeded the array capabilities of Excel and had to be solved by iteration), and shows that 34 neighboring loops have weighting functions larger than 10% of the maximum while 66 are larger than 3%. The ultimate effects of a particular "cutoff" on Strehl are not immediately apparent, and should probably be deduced numerically using Zernike phase models.

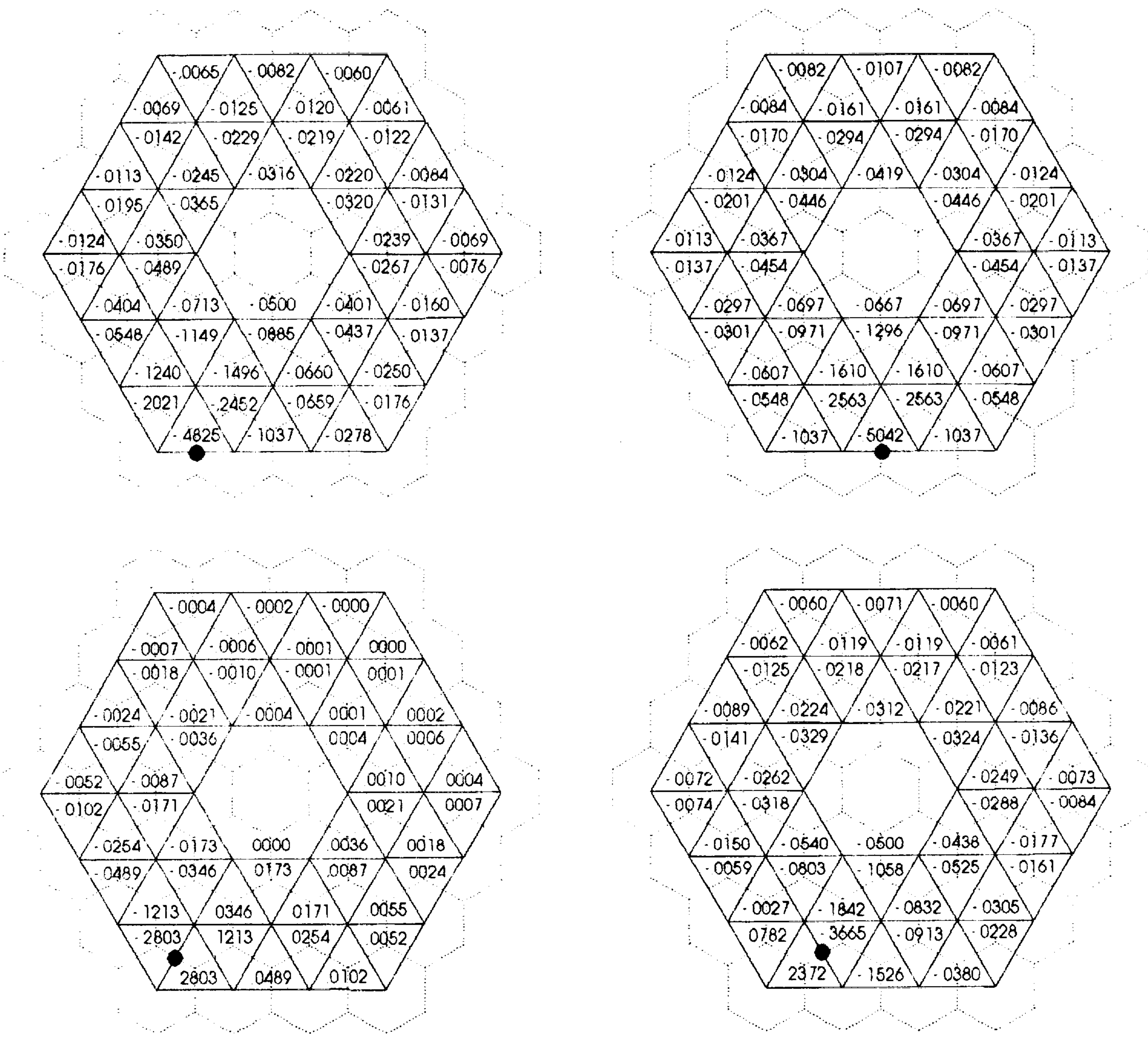
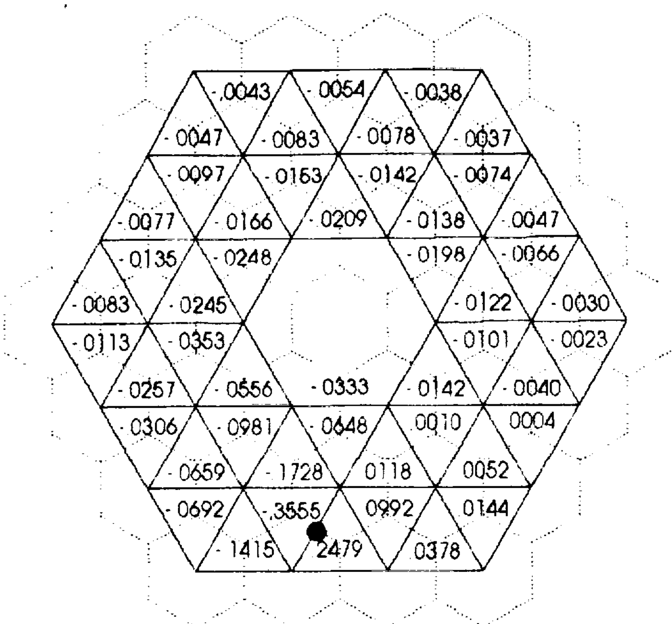


Fig. 1 Deterministic Weighting Functions for 36-Element PAMELA Array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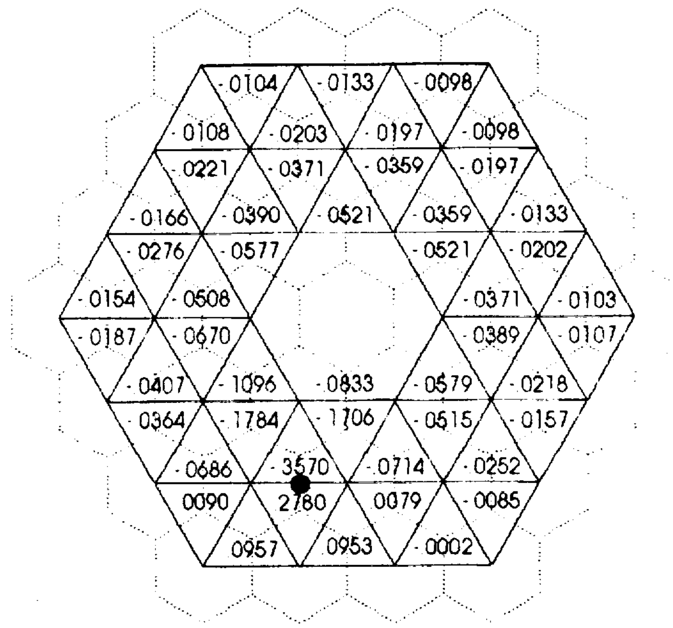
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-.0154 -.0508 -.0371 -.0103
-.0187 -.0670 -.0389 -.0107
-.0407 -.1096 -.0833 -.0579 -.0218
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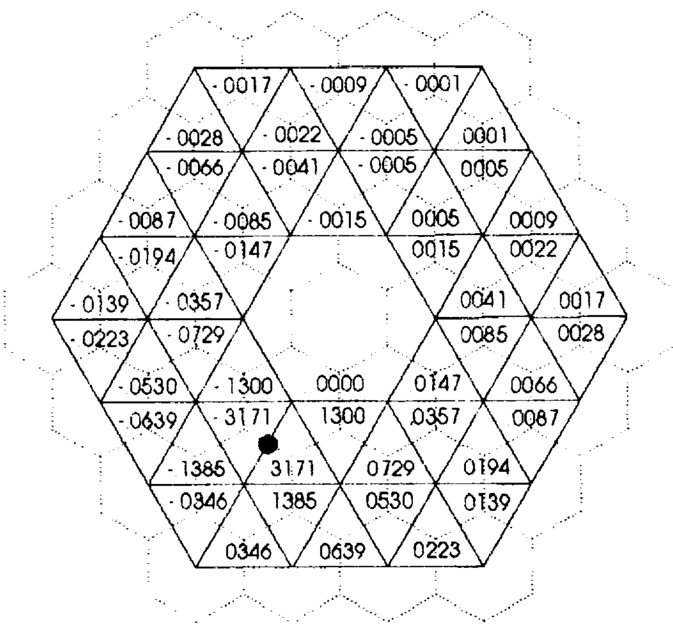
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-.0028 -.0022 -.0005 .0001
-.0066 -.0041 -.0005 .0005
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-.0223 -.0729 .0085 .0028
-.0530 -.1300 .0000 .0147 .0066
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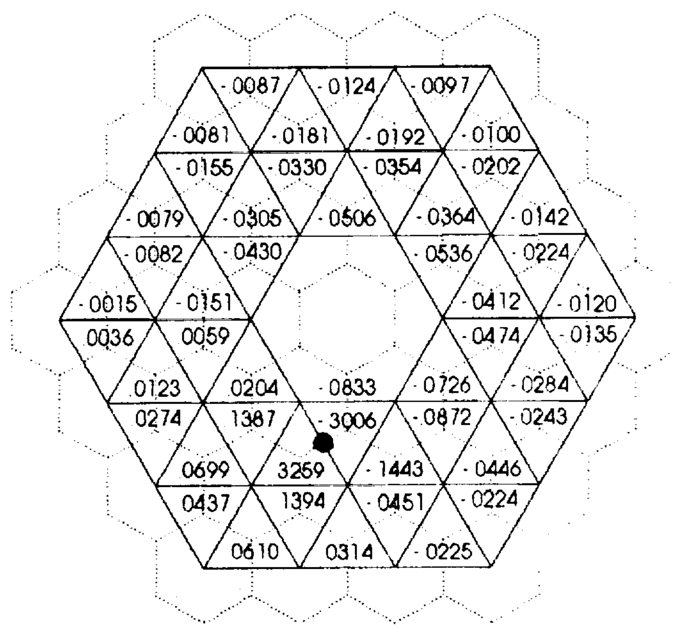
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-.0015 -.0151 -.0412 -.0120
.0036 .0059 -.0474 -.0135
.0123 .0204 -.0833 -.0726 -.0284
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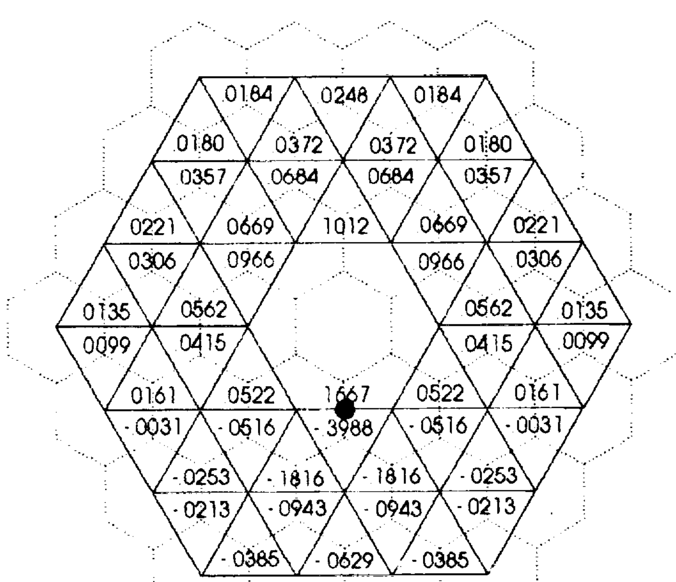
.0610 .0314 -.0225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.0221 .0669 .1012 .0669 .0221
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.0135 .0562 .0562 .0135
.0099 .0415 .0415 .0099
.0161 .0522 .1667 .0522 .0161
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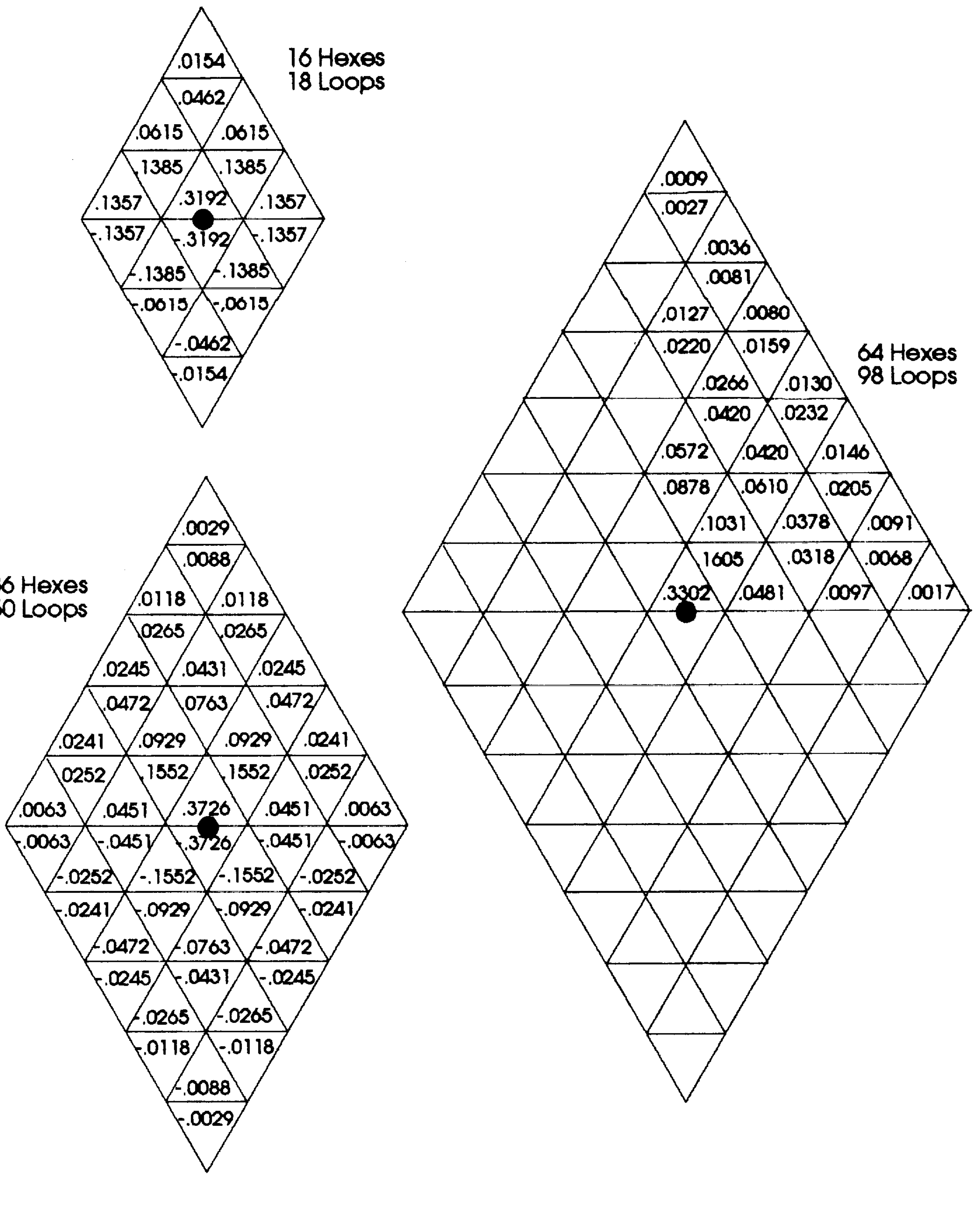

Fig. 2 Path Weighting Functions for Deterministic Control

It is, of course, the distribution of phase itself and not its slope that is important, and additional measurements or other references are needed to supplement the Hartmann data. The iteration schemes rely on edge sensors to establish local edge matching between adjacent segments, while the deterministic approach requires either edge sensors or, preferably, a more global reference from which the piston displacements can be measured. Inductive, capacitive, and optical edge sensors have been or are being specifically developed for this application, but cost and accuracy are key issues that need to be resolved. Accumulation of measurement errors with edge sensors would be a very serious problem in a one-dimensional case, but two-dimensional information propagation should tend to constrain them, and global tilt measurement should further reduce their effect. Global references can be provided mechanically through non-load-bearing auxiliary surfaces and/or electronically through moments of the beacon images at or near the focal plane. Global tilt is usually measured with the zeroth and first moments and corrected with a separate tilt mirror (which acts effectively a mechanical reference) to off load the stroke requirements of the high-frequency actuators; second moments (X^2, Y^2, and XY) are routinely taken at high speed with CCDs in many machine vision applications and could give useful information primarily relating to defocus and astigmatism, but the resulting correction would probably have to made through a global command to the segments -- with piston displacement being measured relative to a mechanical reference.

BTOS Truss Structure

JPL has produced a detailed design of a graphite-epoxy truss structure based upon parallel projection of a regular hexagonal array onto a parabolic surface with the axes of cluster nodes aligned parallel to the projection direction (i.e. normal to the original base plane) and with a uniform truss depth in that direction. In view of the large number of expensive parts (789 struts and 198 cluster nodes) with many different strut lengths and node angles, Sirius has produced a vector-based Excel routine to verify the calculations (the program JPLTRUSS.XLS on the disk that has been provided to the NASA Technical Manager), and it is strongly recommended that MSFC use it to check the blueprints; the nomenclature for that analysis is shown in Fig. 3. Following JPL, the results given in Table I are based on a truss depth of 60", an effective focal length of 596.05" to the upper node surface (11" from the 12M, f/1.25 optical surface to the upper node surface), and a cluster panel face-to-face width of 51.181" (1.3 meters) in the base plane [*note that these dimensions actually result in a maximum diameter of 14.3 meters: 90 cluster panels with a flat-to-flat size of **1.200** meters would have the same area as a 12M aperture with a 1M hole.*] The routine assumes that the axes of all connecting struts at a node pass through a common point to prevent moments from being introduced, "strut lengths" are measured between such nodal points, and cluster angles are measured between the strut axes and the inward cluster axes. It has been found for the nominal design that there are 11 different upper and lower strut lengths varying from 51.181" to 52.347" (519 pieces), 11 diagonal ones from 62.323" to 72.195" (278 pieces), 21 different upper node clusters (108 pieces), and 17 lower ones (90 pieces.)

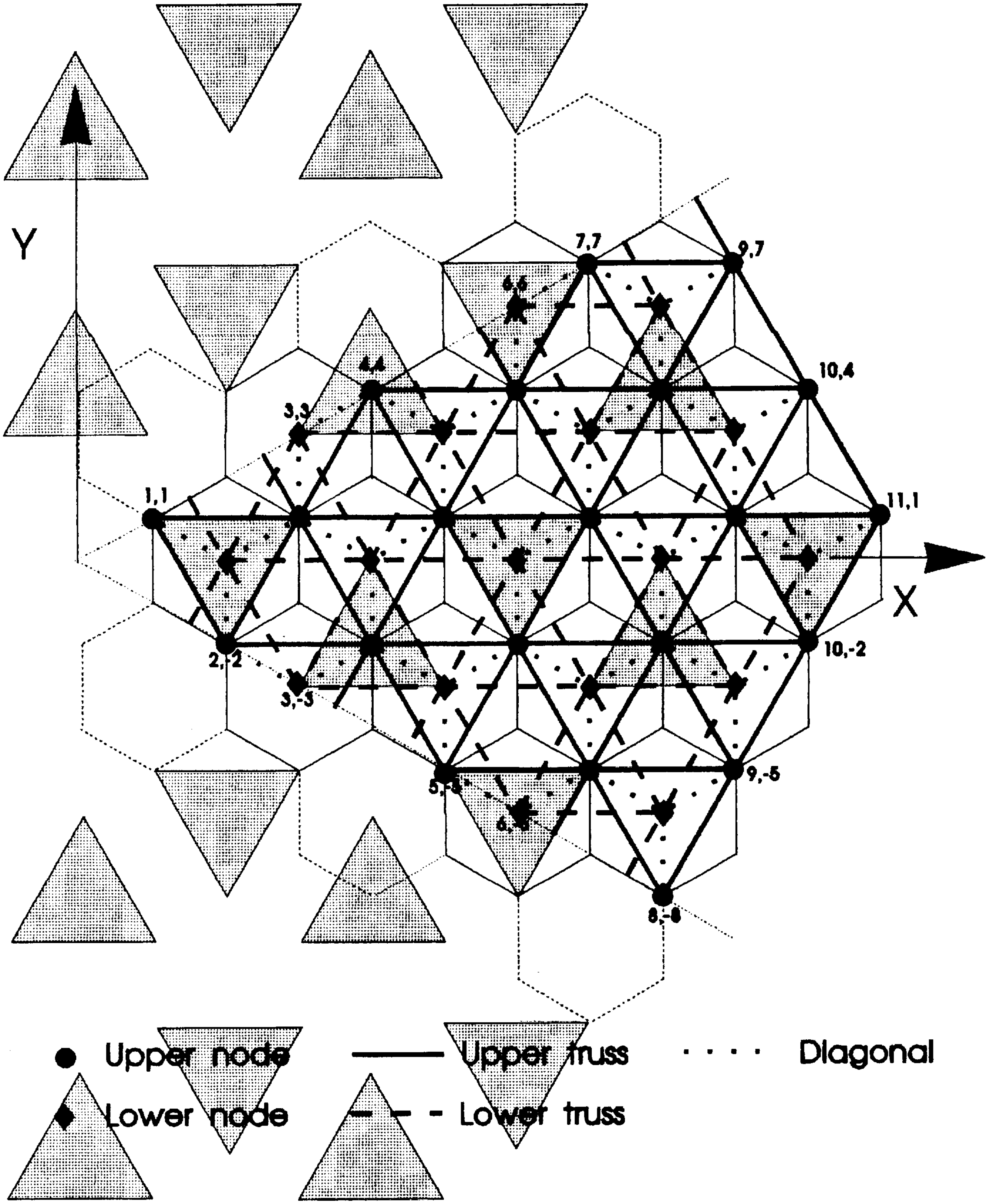

Fig. 3 Nomenclature for Truss Model

TABLE I JPL TRUSS DESIGN

51.181 Cluster face-to-face width in X-Y plane (in)
585.05 Focal length (in)
60 Truss depth (in)

Lower Struts:

		X1	Y1	Z1			X2	Y2	Z2	Length	Angle	#
2	0	51.181	0.000	-58.901	1	3	25.591	44.324	-58.901	51.181	90.000	6
2	0	51.181	0.000	-58.901	3	3	76.772	44.324	-56.704	51.228	92.458	12
2	0	51.181	0.000	-58.901	4	0	102.362	0.000	-55.605	51.287	93.685	6
4	0	102.362	0.000	-55.605	3	3	76.772	44.324	-56.704	51.193	88.770	12
4	0	102.362	0.000	-55.605	5	3	127.953	44.324	-52.309	51.287	93.685	12
4	0	102.362	0.000	-55.605	6	0	153.543	0.000	-50.112	51.475	96.126	6
6	0	153.543	0.000	-50.112	5	3	127.953	44.324	-52.309	51.228	87.542	12
6	0	153.543	0.000	-50.112	7	3	179.134	44.324	-45.717	51.369	94.908	12
6	0	153.543	0.000	-50.112	8	0	204.724	0.000	-42.421	51.756	98.546	6
8	0	204.724	0.000	-42.421	7	3	179.134	44.324	-45.717	51.287	86.315	12
8	0	204.724	0.000	-42.421	9	3	230.315	44.324	-36.928	51.475	96.126	12
8	0	204.724	0.000	-42.421	10	0	255.905	0.000	-32.633	52.127	100.935	6
10	0	255.905	0.000	-32.533	9	3	230.315	44.324	-36.928	51.369	85.092	12
3	3	76.772	44.324	-56.704	5	3	127.953	44.324	-52.309	51.369	94.908	12
5	3	127.953	44.324	-52.309	4	6	102.362	88.648	-52.309	51.181	90.000	6
5	3	127.953	44.324	-52.309	6	6	153.543	88.648	-46.816	51.475	96.126	12
5	3	127.953	44.324	-52.309	7	3	179.134	44.324	-45.717	51.804	97.339	12
7	3	179.134	44.324	-45.717	6	6	153.543	88.648	-46.816	51.193	88.770	12
7	3	179.134	44.324	-45.717	8	6	204.724	88.648	-38.125	51.804	97.339	12
7	3	179.134	44.324	-45.717	9	3	230.315	44.324	-36.928	51.930	98.745	12
9	3	230.315	44.324	-36.928	8	6	204.724	88.648	-38.125	51.228	87.542	12
6	6	153.543	88.648	-46.816	8	6	204.724	88.648	-38.125	51.756	98.546	12
8	6	204.724	88.648	-38.125	7	9	179.134	132.972	-38.125	51.181	90.000	6

Upper Struts:

		X1	Y1	Z1			X2	Y2	Z2	Length	Angle	#
1	1	25.591	14.775	0.386	3	1	76.772	14.775	2.564	51.228	92.458	6
1	1	25.591	14.775	0.386	2	-2	51.181	-29.549	1.465	51.193	91.230	6
3	1	76.772	14.775	2.564	2	4	51.181	59.099	2.564	51.181	90.000	3
3	1	76.772	14.775	2.564	4	4	102.362	59.099	5.860	51.287	93.685	6
3	1	76.772	14.775	2.564	5	1	127.953	14.775	6.958	51.369	94.908	6
3	1	76.772	14.775	2.564	4	-2	102.362	-29.549	4.761	51.228	92.458	6
3	1	76.772	14.775	2.564	2	-2	51.181	-29.549	1.465	51.193	88.770	6
5	1	127.953	14.775	6.958	4	4	102.362	59.099	5.860	51.193	88.770	6
5	1	127.953	14.775	6.958	6	4	153.543	59.099	11.353	51.369	94.908	6
5	1	127.953	14.775	6.958	7	1	179.134	14.775	13.551	51.804	97.339	6
5	1	127.953	14.775	6.958	6	-2	153.543	-29.549	10.254	51.287	93.685	6
5	1	127.953	14.775	6.958	4	-2	102.362	-29.549	4.761	51.228	87.542	6
7	1	179.134	14.775	13.551	6	4	153.543	59.099	11.353	51.228	87.542	6
7	1	179.134	14.775	13.551	8	4	204.724	59.099	19.044	51.475	96.126	6
7	1	179.134	14.775	13.551	9	1	230.315	14.775	22.340	51.930	98.745	6
7	1	179.134	14.775	13.551	8	-2	204.724	-29.549	17.946	51.369	94.908	6
7	1	179.134	14.775	13.551	6	-2	153.543	-29.549	10.254	51.287	86.315	6
9	1	230.315	14.775	22.340	8	4	204.724	59.099	19.044	51.287	86.315	6
9	1	230.315	14.775	22.340	10	4	255.905	59.099	28.932	51.804	97.339	6
9	1	230.315	14.775	22.340	11	1	281.496	14.775	33.327	52.347	102.116	6
9	1	230.315	14.775	22.340	10	-2	255.905	-29.549	27.833	51.475	96.126	6
9	1	230.315	14.775	22.340	8	-2	204.724	-29.549	17.946	51.369	85.092	6
11	1	281.496	14.775	33.327	10	4	255.905	59.099	28.932	51.369	85.092	6
11	1	281.496	14.775	33.327	10	-2	255.905	-29.549	27.833	51.475	83.874	6
4	4	102.362	59.099	5.860	6	4	153.543	59.099	11.353	51.475	96.126	6
6	4	153.543	59.099	11.353	5	7	127.953	103.423	11.353	51.181	90.000	3
6	4	153.543	59.099	11.353	7	7	179.134	103.423	17.946	51.804	97.339	6
6	4	153.543	59.099	11.353	8	4	204.724	59.099	19.044	51.756	98.546	6
8	4	204.724	59.099	19.044	7	7	179.134	103.423	17.946	51.193	88.770	6
8	4	204.724	59.099	19.044	9	7	230.315	103.423	26.735	51.756	98.546	6
8	4	204.724	59.099	19.044	10	4	255.905	59.099	28.932	52.127	100.935	6
10	4	255.905	59.099	28.932	9	7	230.315	103.423	26.735	51.228	87.542	6
7	7	179.134	103.423	17.946	9	7	230.315	103.423	26.735	51.930	98.745	6
9	7	230.315	103.423	26.735	8	10	204.724	147.747	26.735	51.181	90.000	3
2	-2	51.181	-29.549	1.465	4	-2	102.362	-29.549	4.761	51.287	93.685	6
4	-2	102.362	-29.549	4.761	6	-2	153.543	-29.549	10.254	51.475	96.126	6
4	-2	102.362	-29.549	4.761	5	-5	127.953	-73.873	9.156	51.369	94.908	6
4	-2	102.362	-29.549	4.761	3	-5	76.772	-73.873	4.761	51.181	90.000	3
6	-2	153.543	-29.549	10.254	8	-2	204.724	-29.549	17.946	51.756	98.546	6
6	-2	153.543	-29.549	10.254	7	-5	179.134	-73.873	15.748	51.475	96.126	6
6	-2	153.543	-29.549	10.254	5	-5	127.953	-73.873	9.156	51.193	88.770	6
8	-2	204.724	-29.549	17.946	10	-2	255.905	-29.549	27.833	52.127	100.935	6
8	-2	204.724	-29.549	17.946	9	-5	230.315	-73.873	24.537	51.804	97.339	6
8	-2	204.724	-29.549	17.946	7	-5	179.134	-73.873	15.748	51.228	87.542	6
10	-2	255.905	-29.549	27.833	9	-5	230.315	-73.873	24.537	51.287	86.315	6
5	-5	127.953	-73.873	9.156	7	-5	179.134	-73.873	15.748	51.804	97.339	6
7	-5	179.134	-73.873	15.748	9	-5	230.315	-73.873	24.537	51.930	98.745	6
7	-5	179.134	-73.873	15.748	8	-8	204.724	-118.198	23.438	51.756	98.546	6
7	-5	179.134	-73.873	15.748	6	-8	153.543	-118.198	15.748	51.181	90.000	3
9	-5	230.315	-73.873	24.537	8	-8	204.724	-118.198	23.438	51.193	88.770	6

Alignment:

		X1	Y1	Z1			X2	Y2	Z2	Length	Angle	#
1	1	25.591	14.775	0.386	2	0	51.181	0.000	-58.901	66.225	28.500	6
3	1	76.772	14.775	2.564	3	3	76.772	44.324	-56.704	66.225	28.500	6
3	1	76.772	14.775	2.564	4	0	102.362	0.000	-55.605	65.244	26.930	6
3	1	76.772	14.775	2.564	2	0	51.181	0.000	-58.901	68.198	25.676	6
5	1	127.953	14.775	6.958	5	3	127.953	44.324	-52.309	66.225	28.500	6
5	1	127.953	14.775	6.958	6	0	153.543	0.000	-50.112	64.266	27.374	6
5	1	127.953	14.775	6.958	4	0	102.362	0.000	-55.605	68.191	25.282	6
7	1	179.134	14.775	13.551	7	3	179.134	44.324	-45.717	66.225	28.500	6
7	1	179.134	14.775	13.551	8	0	204.724	0.000	-42.421	63.293	27.831	6
7	1	179.134	14.775	13.551	6	0	153.543	0.000	-50.112	70.186	24.888	6
9	1	230.315	14.775	22.340	9	3	230.315	44.324	-36.928	66.225	28.500	6
9	1	230.315	14.775	22.340	10	0	255.905	0.000	-32.633	62.323	28.303	6
9	1	230.315	14.775	22.340	8	0	204.724	0.000	-42.421	71.184	24.526	6
11	1	281.496	14.775	33.327	10	0	255.905	0.000	-32.533	72.185	24.164	6
4	4	102.362	59.099	5.860	5	3	127.953	44.324	-52.309	65.244	26.930	6
4	4	102.362	59.099	5.860	3	3	76.772	44.324	-56.704	68.191	25.282	3
6	4	153.543	59.099	11.353	6	6	153.543	88.648	-46.816	65.244	26.930	6
6	4	153.543	59.099	11.353	7	3	179.134	44.324	-45.717	64.266	27.374	6
6	4	153.543	59.099	11.353	5	3	127.953	44.324	-52.309	70.188	24.888	6
8	4	204.724	59.099	19.044	8	6	204.724	88.648	-38.125	65.244	26.930	6
8	4	204.724	59.099	19.044	9	3	230.315	44.324	-36.928	63.293	27.831	6
8	4	204.724	59.099	19.044	7	3	179.134	44.324	-45.717	71.184	24.526	6
10	4	255.905	59.099	28.932	9	3	230.315	44.324	-36.928	72.185	24.164	6
7	7	179.134	103.423	17.946	8	6	204.724	88.648	-38.125	64.268	27.374	6
7	7	179.134	103.423	17.946	6	6	153.543	88.648	-46.816	71.184	24.526	3
9	7	230.315	103.423	26.735	8	6	204.724	88.648	-38.125	72.185	24.164	6
2	-2	51.181	-29.549	1.465	2	0	51.181	0.000	-58.901	67.210	26.082	6
2	-2	51.181	-29.549	1.465	3	-3	76.772	-44.324	-56.704	65.244	26.930	3
4	-2	102.362	-29.549	4.761	4	0	102.362	0.000	-55.605	67.210	26.082	6
4	-2	102.362	-29.549	4.761	5	-3	127.953	-44.324	-52.308	64.268	27.374	6
4	-2	102.362	-29.549	4.761	3	-3	76.772	-44.324	-56.704	68.198	25.676	6
6	-2	153.543	-29.549	10.254	6	0	153.543	0.000	-50.112	67.210	26.082	6
6	-2	153.543	-29.549	10.254	7	-3	179.134	-44.324	-45.717	63.293	27.831	6
6	-2	153.543	-29.549	10.254	5	-3	127.953	-44.324	-52.308	68.191	25.282	6
8	-2	204.724	-29.549	17.946	8	0	204.724	0.000	-42.421	67.210	26.082	6
8	-2	204.724	-29.549	17.946	9	-3	230.315	-44.324	-36.928	62.323	28.303	6
8	-2	204.724	-29.549	17.946	7	-3	179.134	-44.324	-45.717	70.186	24.888	6
10	-2	255.905	-29.549	27.833	10	0	255.905	0.000	-32.533	67.210	26.082	6
10	-2	255.905	-29.549	27.833	9	-3	230.315	-44.324	-36.928	71.184	24.526	6
5	-5	127.953	-73.873	9.156	5	-3	127.953	-44.324	-52.308	68.198	25.676	6
5	-5	127.953	-73.873	9.156	6	-6	153.543	-88.648	-46.816	63.293	27.831	3
7	-5	179.134	-73.873	15.748	7	-3	179.134	-44.324	-45.717	68.198	25.676	6
7	-5	179.134	-73.873	15.748	8	-6	204.724	-88.648	-38.125	62.323	28.303	6
7	-5	179.134	-73.873	15.748	6	-6	153.543	-88.648	-46.816	68.191	25.282	6
9	-5	230.315	-73.873	24.537	9	-3	230.315	-44.324	-36.928	68.198	25.676	6
9	-5	230.315	-73.873	24.537	8	-6	204.724	-88.648	-38.125	70.186	24.888	6
8	-8	204.724	-118.198	23.438	8	-6	204.724	-88.648	-38.125	68.191	25.282	6

ORIGINAL PAGE IS
OF POOR QUALITY

Strut Angles

Upper & Lower

6	51.101
12	51.228
6	51.287
12	51.193
12	51.287
6	51.475
12	51.228
12	51.388
6	51.706
12	51.287
12	51.475
6	52.127
12	51.388
12	51.388
6	51.101
12	51.475
12	51.604
12	51.193
12	51.604
12	51.930
12	51.228
12	51.706
6	51.101
6	51.228
6	51.193
3	51.101
6	51.287
6	51.388
6	51.228
6	51.193
6	51.193
6	51.388
6	51.604
6	51.287
6	51.228
6	51.228
6	51.475
6	51.930
6	51.388
6	51.287
6	51.287
6	51.604
6	52.347
6	51.475
6	51.388
6	51.388
6	51.475
6	51.475
3	51.101
6	51.604
6	51.706
6	51.193
6	51.706
6	52.127
6	51.228
6	51.930
3	51.101
6	51.287
6	51.475
6	51.388
3	51.101
6	51.706
6	51.475
6	51.193
6	52.127
6	51.604
6	51.228
6	51.287
6	51.604
6	51.930
6	51.706
3	51.101
6	51.193

Alignment

6	66.225
6	66.225
6	65.244
6	68.198
6	66.285
6	64.286
6	69.191
6	66.225
6	63.293
6	70.186
6	66.225
6	62.323
6	71.184
6	72.185
6	65.244
3	69.191
6	65.244
6	64.286
6	70.186
6	65.244
6	63.293
6	71.184
6	72.185
6	64.286
3	71.184
6	72.185
6	67.210
3	65.244
6	67.210
6	64.286
6	68.198
6	67.210
6	63.293
6	69.191
6	67.210
6	62.323
6	70.186
6	67.210
6	71.184
6	68.198
3	63.293
6	68.198
6	62.323
6	69.191
6	68.198
6	70.186
6	69.191

Center

33	51.101
60	51.193
72	51.228
66	51.287
72	51.388
66	51.475
54	51.604
42	51.706
30	51.930
18	52.127
6	52.347
519	11
18	62.323
21	63.293
24	64.286
27	65.244
30	66.225
30	67.210
30	68.198
27	69.191
24	70.186
21	71.184
18	72.185
270	11
789	22

Upper Node Angles

Node	Angles
1,1	92.458, 26.800, 91.230, ., ., ., 91.230, 26.500, 92.458
2,-2	93.685, 25.930, 93.685, 91.230, 26.082, 88.770, 88.770, 26.082, 91.230
3,1	94.908, 25.930, 92.458, 88.770, 28.676, 87.542, 90.000, 26.800, 93.685
4,4	95.126, 25.930, 91.230, 86.315, 25.282, 86.315, 91.230, 25.930, 95.126
4,-2	95.126, 27.374, 94.908, 90.000, 25.676, 86.315, 87.542, 26.082, 92.458
5,1	97.330, 27.374, 93.685, 87.542, 25.282, 85.082, 88.770, 26.900, 94.908
5,-5	97.330, 27.831, 97.330, 91.230, 25.676, 85.082, 85.082, 25.676, 91.230
6,4	98.546, 27.374, 92.458, 85.082, 24.880, 83.874, 90.000, 25.930, 97.330
6,-2	98.546, 27.831, 96.126, 88.770, 25.282, 83.874, 86.315, 26.082, 93.685
7,7	98.745, 27.374, 91.230, 82.661, 24.526, 82.661, 91.230, 27.374, 98.745
7,1	98.745, 27.831, 94.908, 85.315, 24.880, 82.661, 87.542, 26.500, 95.126
7,-5	98.745, 28.303, 98.546, 90.000, 25.282, 82.661, 83.874, 25.676, 92.458
8,4	100.935, 27.831, 93.685, 83.874, 24.526, 81.454, 88.770, 25.930, 98.546
8,-2	100.935, 28.303, 97.330, 87.542, 24.880, 81.454, 85.082, 26.082, 94.908
8,-8	., ., ., 91.230, 25.282, 81.454, 81.454, 25.282, 91.230
9,7	., ., 92.458, 81.454, 24.164, 80.285, 90.000, ., .
9,1	102.116, 28.303, 95.126, 85.082, 24.526, 80.285, 86.315, 25.900, 97.230
9,-5	., ., ., 91.230, 24.880, 80.285, 82.661, 25.676, 93.685
10,4	., ., 94.908, 82.661, 24.164, 79.085, 87.542, ., .
10,-2	., ., ., 88.315, 24.526, 79.085, 83.874, 25.082, 96.126
11,1	., ., ., 90.000, 24.164, 77.884, 85.082, ., .

Lower Node Angles

Node	Angles
2,0	86.315, 25.676, 87.542, 90.000, 26.580, ., 90.000, 26.082, 87.542
3,3	85.082, 25.282, 85.082, 88.770, 26.580, 92.458, 92.458, 26.580, 88.770
3,-3	85.082, 25.676, 88.770, 92.458, 26.800, 92.458, 90.000, 25.676, 85.082
4,0	83.874, 25.282, 86.315, 91.230, 25.930, 93.685, 91.230, 26.082, 86.315
5,3	82.661, 24.880, 83.874, 90.000, 25.930, 94.908, 93.685, 26.580, 87.542
5,-3	86.315, 25.282, 87.542, 93.685, 27.374, 94.908, 90.000, 25.676, 83.874
6,6	81.454, 24.526, 81.454, 88.770, 25.930, 95.126, 95.126, 25.930, 88.770
6,0	81.454, 24.880, 85.082, 92.458, 27.374, 95.126, 92.458, 26.082, 85.082
6,-6	81.454, 25.930, 88.770, 96.126, 27.831, 95.126, 88.770, 25.930, 81.454
7,3	80.285, 24.526, 82.661, 91.230, 27.374, 97.330, 94.908, 26.500, 86.315
7,-3	80.285, 24.880, 86.315, 94.908, 27.831, 97.330, 91.230, 25.676, 82.661
8,6	., 24.164, ., 90.000, 0.000, 98.546, 97.330, 25.282, 87.542
8,0	79.085, 24.526, 83.874, 93.685, 27.831, 98.546, 93.685, 26.082, 83.874
8,-6	., 24.880, 87.542, 97.330, 28.303, 98.546, 90.000, 25.282, .
9,3	., 24.164, ., 92.458, 27.831, 98.745, 96.126, 25.930, 85.082
9,-3	., 24.526, 85.082, 96.126, 28.303, 98.745, 92.458, 25.676, .
10,0	., 24.164, ., 94.908, 28.303, 100.935, 94.908, 26.082, .

(Angles measured from inward vertical. Upper nodes indexed CW, lower CCW.)

Upper Node Summary

3	1,1
3	2,-2
6	3,1
3	4,4
6	4,-2
6	5,1
3	5,-5
6	6,4
6	6,-2
3	7,7
6	7,1
6	7,-5
6	8,4
6	8,-2
3	8,-8
6	9,7
6	9,1
6	9,-5
6	10,4
6	10,-2
6	11,1
108	21

Lower Node Summary

6	2,0
3	3,3
6	3,-3
3	4,0
6	5,3
6	5,-3
3	6,6
6	6,0
6	6,-6
3	7,3
6	7,-3
6	8,6
6	8,0
6	8,-6
6	9,3
6	9,-3
6	10,0
90	17
198	38

TABLE II SPHERICAL TRUSS DESIGN

51.181 Cluster face-to-face width in X-Y plane (in)
586.06 Focal length (in)
60 Truss depth (in)

Lower Chord:

		X1	Y1	Z1			X2	Y2	Z2	Length	AngleV1	AngleV2	AngleH1	AngleH2	#
2	0	53.757	0.000	-58.846	1	3	26.879	46.555	-58.846	53.757	88.770	88.770	119.977	-119.977	6
2	0	53.757	0.000	-58.846	3	3	80.636	46.555	-56.533	53.807	88.768	88.768	59.931	-150.023	12
2	0	53.757	0.000	-58.846	4	0	107.514	0.000	-55.376	53.869	88.767	88.767	0.000	-180.000	6
4	0	107.514	0.000	-55.376	3	3	80.636	46.555	-56.533	53.769	88.770	88.770	120.000	-59.988	12
4	0	107.514	0.000	-55.376	5	3	134.393	46.555	-51.896	53.870	88.767	88.767	59.886	-139.199	12
4	0	107.514	0.000	-55.376	6	0	161.271	0.000	-49.571	54.070	88.763	88.763	0.000	-180.000	6
6	0	161.271	0.000	-49.571	5	3	134.393	46.555	-51.896	53.897	88.768	88.768	120.070	-70.898	12
6	0	161.271	0.000	-49.571	7	3	188.150	46.555	-44.907	53.950	88.765	88.765	59.653	-134.107	12
6	0	161.271	0.000	-49.571	8	0	215.028	0.000	-41.398	54.375	88.756	88.756	0.000	-180.000	6
8	0	215.028	0.000	-41.398	7	3	188.150	46.555	-44.907	53.871	88.767	88.767	120.187	-73.526	12
8	0	215.028	0.000	-41.398	9	3	241.907	46.555	-35.527	54.077	88.763	88.763	59.441	-131.268	12
8	0	215.028	0.000	-41.398	10	0	268.785	0.000	-30.810	54.788	88.746	88.746	0.000	-180.000	6
10	0	268.785	0.000	-30.810	9	3	241.907	46.555	-35.527	53.984	88.765	88.765	120.395	-70.307	12
3	3	80.636	46.555	-56.533	5	3	134.393	46.555	-51.896	53.987	88.765	88.765	-23.888	108.952	12
5	3	134.393	46.555	-51.896	4	6	107.514	93.110	-51.896	53.757	88.770	88.770	100.825	-100.825	6
5	3	134.393	46.555	-51.896	6	6	161.271	93.110	-46.075	54.071	88.763	88.763	40.617	-160.184	12
5	3	134.393	46.555	-51.896	7	3	188.150	46.555	-44.907	54.280	88.760	88.760	-18.946	166.217	12
7	3	188.150	46.555	-44.907	6	6	161.271	93.110	-46.075	53.770	88.770	88.770	106.160	-88.815	12
7	3	188.150	46.555	-44.907	8	6	215.028	93.110	-37.879	54.215	88.758	88.758	45.646	-143.761	12
7	3	188.150	46.555	-44.907	9	3	241.907	46.555	-35.527	54.568	88.751	88.751	-13.888	169.288	12
9	3	241.907	46.555	-35.527	8	6	215.028	93.110	-37.879	53.808	88.769	88.769	108.228	-83.053	12
6	6	161.271	93.110	-46.075	8	6	215.028	93.110	-37.879	54.378	88.756	88.756	-28.638	158.884	12
8	6	215.028	93.110	-37.879	7	9	188.150	139.665	-37.879	53.757	88.770	88.770	95.471	-95.471	6

Upper Chord:

		X1	Y1	Z1			X2	Y2	Z2	Length	AngleV1	AngleV2	AngleH1	AngleH2	#
1	1	25.591	14.775	0.368	3	1	76.772	14.775	2.986	51.228	91.231	91.231	23.977	-169.114	6
1	1	25.591	14.775	0.368	2	-2	51.181	-29.549	1.466	51.193	91.230	91.230	59.960	-150.000	6
3	1	76.772	14.775	2.986	2	4	51.181	59.088	2.986	51.181	91.230	91.230	-108.000	108.000	3
3	1	76.772	14.775	2.986	4	4	102.362	59.088	5.874	51.288	91.233	91.233	-48.904	158.061	6
3	1	76.772	14.775	2.986	5	1	127.953	14.775	6.979	51.371	91.236	91.236	10.865	-173.436	6
3	1	76.772	14.775	2.986	4	-2	102.362	-29.549	4.771	51.228	91.231	91.231	70.770	-136.140	6
3	1	76.772	14.775	2.986	2	-2	51.181	-29.549	1.466	51.188	91.230	91.230	130.883	-69.938	6
5	1	127.953	14.775	6.979	4	4	102.362	59.088	5.874	51.183	91.230	91.230	-113.414	69.877	6
5	1	127.953	14.775	6.979	6	4	153.543	59.088	11.408	51.372	91.235	91.235	-53.145	141.213	6
5	1	127.953	14.775	6.979	7	1	179.134	14.775	13.628	51.611	91.240	91.240	6.533	-175.323	6
5	1	127.953	14.775	6.979	6	-2	153.543	-29.549	10.298	51.288	91.233	91.233	66.341	-131.017	6
5	1	127.953	14.775	6.979	4	-2	102.362	-29.549	4.771	51.229	91.231	91.231	126.641	-75.941	6
7	1	179.134	14.775	13.628	6	4	153.543	59.088	11.408	51.228	91.231	91.231	-115.371	60.797	6
7	1	179.134	14.775	13.628	8	4	204.724	59.088	19.198	51.483	91.237	91.237	-54.821	136.412	6
7	1	179.134	14.775	13.628	9	1	230.315	14.775	22.553	51.863	91.248	91.248	4.646	-176.383	6
7	1	179.134	14.775	13.628	8	-2	204.724	-29.549	18.082	51.374	91.235	91.235	64.288	-128.470	6
7	1	179.134	14.775	13.628	6	-2	153.543	-29.549	10.298	51.288	91.233	91.233	124.070	-70.685	6
9	1	230.315	14.775	22.553	8	4	204.724	59.088	19.198	51.281	91.233	91.233	-116.880	75.686	6
9	1	230.315	14.775	22.553	10	4	255.905	59.088	29.292	51.623	91.241	91.241	-55.620	133.513	6
9	1	230.315	14.775	22.553	11	1	281.496	14.775	33.806	52.403	91.258	91.258	3.886	-177.065	6
9	1	230.316	14.775	22.553	10	-2	255.905	-29.549	28.166	51.488	91.237	91.237	63.815	-127.027	6
9	1	230.316	14.775	22.553	8	-2	204.724	-29.549	18.082	51.376	91.235	91.235	123.076	-67.708	6
11	1	281.496	14.775	33.806	10	4	255.905	59.088	29.292	51.388	91.236	91.236	-117.402	72.335	6
11	1	281.496	14.775	33.806	10	-2	255.905	-29.549	28.166	51.481	91.237	91.237	123.511	-65.833	6
4	4	102.362	59.088	5.874	6	4	153.543	59.088	11.408	51.479	91.237	91.237	29.846	-160.071	6
6	4	153.543	59.088	11.408	5	7	127.953	103.423	11.408	51.181	91.230	91.230	-98.864	98.864	3
6	4	153.543	59.088	11.408	7	7	179.134	103.423	18.082	51.614	91.240	91.240	-38.571	150.270	6
6	4	153.543	59.088	11.408	8	4	204.724	59.088	19.198	51.771	91.244	91.244	20.806	-164.882	6
8	4	204.724	59.088	19.198	7	7	179.134	103.423	18.082	51.193	91.230	91.230	-100.908	80.783	6
8	4	204.724	59.088	19.198	9	7	230.315	103.423	27.041	51.778	91.244	91.244	-43.278	144.640	6
8	4	204.724	59.088	19.198	10	4	255.905	59.088	29.292	52.167	91.254	91.254	15.794	-167.243	6
10	4	255.905	59.088	29.292	9	7	230.315	103.423	27.041	51.230	91.231	91.231	-107.133	83.783	6
7	7	179.134	103.423	18.082	9	7	230.315	103.423	27.041	51.858	91.249	91.249	23.513	-156.196	6
9	7	230.315	103.423	27.041	8	10	204.724	147.747	27.041	51.181	91.230	91.230	-95.606	95.606	3
2	-2	51.181	-29.549	1.466	4	-2	102.362	-29.549	4.771	51.288	91.233	91.233	-23.938	163.928	6
4	-2	102.362	-29.549	4.771	6	-2	153.543	-29.549	10.298	51.479	91.237	91.237	-16.010	168.168	6
4	-2	102.362	-29.549	4.771	5	-5	127.953	-73.873	9.191	51.372	91.235	91.235	43.706	-138.115	6
4	-2	102.362	-29.549	4.771	3	-5	76.772	-73.873	4.771	51.181	91.230	91.230	103.844	-103.844	3
6	-2	153.543	-29.549	10.298	8	-2	204.724	-29.549	18.082	51.769	91.244	91.244	-10.771	171.878	6
6	-2	153.543	-29.549	10.298	7	-5	179.134	-73.873	15.853	51.482	91.237	91.237	40.737	-142.658	6
6	-2	153.543	-29.549	10.298	5	-5	127.953	-73.873	9.191	51.193	91.230	91.230	100.107	-80.846	6
8	-2	204.724	-29.549	18.082	10	-2	255.905	-29.549	28.166	52.165	91.254	91.254	-8.050	173.536	6
8	-2	204.724	-29.549	18.082	9	-5	230.315	-73.873	24.795	51.619	91.241	91.241	51.190	-130.212	6
8	-2	204.724	-29.549	18.082	7	-5	179.134	-73.873	15.853	51.230	91.231	91.231	111.888	-42.108	6
10	-2	255.905	-29.549	28.166	9	-5	230.315	-73.873	24.795	51.292	91.233	91.233	113.067	-77.283	6
5	-5	127.953	-73.873	9.191	7	-5	179.134	-73.873	15.853	51.613	91.240	91.240	-23.731	157.781	6
7	-5	179.134	-73.873	15.853	9	-5	230.315	-73.873	24.795	51.956	91.248	91.248	-22.864	162.486	6
7	-5	179.134	-73.873	15.853	8	-8	204.724	-118.197	23.674	51.776	91.244	91.244	37.086	-150.371	6
7	-5	179.134	-73.873	15.853	6	-8	153.543	-118.197	15.853	51.181	91.230	91.230	97.480	-97.480	3
9	-5	230.315	-73.873	24.795	8	-8	204.724	-118.197	23.674	51.153	91.230	91.230	102.218	-80.751	6

Diagonal:

		X1	Y1	Z1			X2	Y2	Z2	Length	AngleV1	AngleV2	AngleH1	AngleH2	#
1	1	25.591	14.775	0.368	2	0	53.757	0.000	-58.846	67.214	27.508	26.087	59.877	180.000	6
3	1	76.772	14.775	2.986	3	3	80.636	46.555	-56.533	67.214	27.508	26.087	-79.038	-120.023	6
3	1	76.772	14.775	2.986	4	0	107.514	0.000	-55.376	67.236	27.546	26.123	40.882	158.081	6
3	1	76.772	14.775	2.986	2	0	53.757	0.000	-58.846	67.226	27.530	26.108	160.816	29.962	6
5	1	127.953	14.775	6.979	5	3	134.393	46.555	-51.896	67.214	27.508	26.087	-83.288	-109.145	6
5	1	127.953	14.775	6.979	6	0	161.271	0.000	-49.571	67.277	27.618	26.191	36.388	150.161	6
5	1	127.953	14.775	6.979	4	0	107.514	0.000	-55.376	67.261	27.588	26.165	158.678	29.878	6
7	1	179.134	14.775	13.628	7	3	188.150	46.555	-44.907	67.214	27.508	26.087	-85.123	-103.953	6
7	1	179.134	14.775	13.628	8	0	215.028	0.000	-41.398	67.348	27.728	26.282	34.346	150.308	6
7	1	179.134	14.775	13.628	6	0	161.271	0.000	-49.571	67.316	27.688	26.254	154.822	29.747	6
9	1	230.316	14.775	22.553	9	3	241.907	46.555	-35.527	67.214	27.508	26.087	-86.115	-108.985	6
9	1	230.316	14.775	22.553	10	0	268.785	0.000	-30.810	67.423	27.878	26.427	33.088	158.584	6
9	1	230.316	14.775	22.553	8	0	215.028	0.000	-41.398	67.382	27.817	26.377	154.041	29.588	6
11	1	281.496	14.775	33.806	10	0	268.785	0.000	-30.810	67.482	27.986	26.636	153.887	29.340	6
4	4	102.362	59.088	5.874	5	3	134.393	46.555	-51.896	67.238	27.548	26.123	-59.816	131.016	6
4	4	102.362	59.088	5.874	3	3	80.636	46.555	-56.533	67.261	27.588	26.165	180.000	0.000	3
6	4	153.543	59.088	11.408	6	6	161.271	93.110	-46.075	67.236	27.547	26.124	-68.678	-120.186	6
6	4	153.543	59.088	11.408	7	3	188.150	46.555	-44.907	67.278	27.619	26.192	50.706	136.372	6
6	4	153.543	59.088	11.408	5	3	134.393	46.555	-51.896	67.316	27.685	26.254	171.121	18.808	6
8	4	204.724	59.088	19.198	8	6	215.028	93.110	-37.879	67.237	27.548	26.124	-73.524	-113.864	6
8	4	204.724	59.088	19.198	9	3	241.907	46.555	-35.527	67.341	27.728	26.294	45.544	138.572	6
8	4	204.724	59.088	19.198	7	3	188.150	46.555	-44.907	67.381	27.815	26.376	166.287	15.887	6
10	4	255.905	59.088	29.292	9	3	241.907	46.555	-35.527	67.488	27.982	26.533	163.352	18.713	6
7	7	179.134	103.423	18.082	8	6	215.028	93.110	-37.879	67.279	27.621	26.153	59.511	128.568	6
7	7	179.134	103.423	18.082	6	6	161.271	93.110	-46.075	67.281	27.814	26.375	180.000	0.000	3
9	7	230.315	103.423	27.041	8	6	215.028	93.110	-37.879	67.408	27.980	26.531	174.288	6.496	6
2	-2	51.181	-29.549	1.466	2	0	53.757	0.000	-58.846	67.211	27.502	26.082	-120.000	-59.989	6
2	-2	51.181	-29.549	1.466	3	-3	80.636	-46.555	-56.533	67.236	27.546	26.123	0.000	180.000	3
4	-2	102.362	-29.549	4.771	4	0	107.514	0.000	-55.376	67.211	27.502	26.082	-108.102	-80.938	6
4	-2	102.362	-29.549	4.771	5	-3	134.393	-46.555	-51.896	67.277	27.618	26.191	13.829	168.169	6
4	-2	102.362	-29.549	4.771	3	-3	80.636	-46.555	-56.533	67.226	27.530	26.108	133.987	59.885	6
6	-2	153.543	-29.549	10.298	6	0	161.271	0.000	-49.571	67.211	27.502	26.082	-100.004	-80.808	6
6	-2	153.543	-29.549	10.298	7	-3	188.150	-46.555	-44.907	67.338	27.724	26.291	18.923	164.851	6
6	-2	153.543	-29.549	10.298	5	-3	134.393	-46.555	-51.896	67.262	27.581	26.165	138.281	48.851	6
8	-2	204.724	-29.549	18.082	8	0	215.028	0.000	-41.398	67.211	27.502	26.082	-88.214	-88.876	6
8	-2	204.724	-29.549	18.082	9	-3	241.907	-46.555	-35.527	67.422	27.867	26.426	21.440	161.194	6
8	-2	204.724	-29.549	18.082	7	-3	188.150	-46.555	-44.907	67.317	27.687	26.255	142.134	43.474	6
10	-2	255.905	-29.549	28.166	10	0	268.785	0.000	-30.810	67.211	27.502	26.082	-88.588	-80.844	6
10	-2	255.905	-29.549	28.166	9	-3	241.907	-46.555	-35.527	67.384	27.820	26.380	143.573	40.241	6
5	-5	127.953	-73.873	9.191	5	-3	134.393	-46.555	-51.896	67.226	27.530	26.108	-120.116	-70.701	6
5	-5	127.953	-73.873	9.191	6	-6	161.271	-93.110	-46.075	67.338	27.724	26.290	0.000	-180.000	3
7	-5	179.134	-73.873	15.853	7	-3	188.150	-46.555	-44.907	67.227	27.530	26.108	-112.574	-76.831	6
7	-5	179.134	-73.873	15.853	8	-6	215.028	-93.110	-37.879	67.421	27.886	26.423	7.474	173.513	6
7	-5	179.134	-73.873	15.853	6	-6	161.271	-93.110	-46.075	67.262	27.582	26.166	127.888	58.629	6
9	-5	230.315	-73.873	24.795	9	-3	241.907	-46.555	-35.527	67.227	27.531	26.108	-107.989	-70.755	6
9	-5	230.315	-73.873	24.795	8	-6	215.028	-93.110	-37.879	67.318	27.688	26.290	132.787	52.814	6
8	-8	204.724	-118.197	23.674	8	-6	215.028	-93.110	-37.879	67.283	27.583	26.167	-128.376	-65.088	6

Strut Lengths

Upper & Lower

6	53.757
12	53.807
6	53.869
12	53.769
12	53.870
6	54.070
12	53.807
12	53.869
6	54.275
12	53.871
12	54.077
6	54.780
12	53.964
12	53.957
6	53.757
12	54.071
12	54.208
12	53.770
12	54.215
12	54.588
12	53.808
12	54.378
6	53.757
6	51.228
6	51.193
3	51.181
6	51.288
6	51.371
6	51.228
6	51.193
6	51.193
6	51.372
6	51.611
6	51.288
6	51.229
6	51.229
6	51.403
6	51.953
6	51.374
6	51.288
6	51.281
6	51.623
6	52.403
6	51.408
6	51.376
6	51.380
6	51.484
6	51.479
3	51.181
6	51.614
6	51.771
6	51.193
6	51.778
6	52.167
6	51.230
6	51.988
3	51.181
6	51.288
6	51.479
6	51.372
3	51.181
6	51.768
6	51.482
6	51.193
6	52.165
6	51.619
6	51.230
6	51.292
6	51.613
6	51.956
6	51.775
3	51.181
6	51.193

Diagonal

6	67.214
6	67.214
6	67.236
6	67.228
6	67.214
6	67.277
6	67.261
6	67.214
6	67.348
6	67.316
6	67.214
6	67.423
6	67.392
6	67.482
6	67.238
3	67.281
6	67.236
6	67.278
6	67.316
6	67.237
6	67.341
6	67.381
6	67.408
6	67.279
3	67.381
6	67.408
6	67.211
3	67.236
6	67.211
6	67.277
6	67.226
6	67.211
6	67.338
6	67.262
6	67.211
6	67.422
6	67.317
6	67.211
6	67.384
6	67.226
3	67.338
6	67.227
6	67.421
6	67.262
6	67.227
6	67.318
6	67.283

Central

18	51.181
36	51.193
12	51.228
12	51.229
12	51.238
12	51.288
12	51.288
6	51.288
6	51.292
6	51.371
12	51.372
6	51.374
6	51.376
6	51.380
12	51.479
6	51.482
6	51.403
6	51.408
6	51.484
6	51.611
6	51.613
6	51.614
6	51.619
6	51.623
6	51.768
6	51.771
6	51.775
6	51.778
6	51.953
6	51.956
6	51.988
6	52.168
6	52.167
6	52.403
18	53.757
12	53.768
12	53.770
24	53.807
12	53.808
6	53.869
12	53.870
12	53.871
12	53.957
12	53.958
12	53.964
6	54.070
12	54.071
12	54.077
12	54.208
12	54.215
6	54.375
12	54.378
12	54.588
6	54.780
519	54

30	67.211
30	67.214
18	67.226
12	67.227
21	67.236
6	67.237
9	67.261
12	67.262
6	67.263
12	67.277
6	67.278
6	67.279
12	67.316
6	67.317
6	67.318
9	67.338
6	67.340
6	67.341
9	67.381
6	67.392
6	67.384
6	67.421
6	67.422
6	67.423
6	67.408
6	67.409
6	67.482
270	27
780	81

Upper Node Angles

	V	H
1,1	91.231	0.000
	27.508	30.000
	91.230	59.982
	.	.
	.	.
	.	.
	91.230	-119.947
	27.508	-89.954
	91.231	-59.954
2,-2	91.233	0.000
	27.546	29.990
	91.233	59.878
	91.238	119.878
	27.502	149.938
	91.230	179.939
	91.230	-120.061
	27.802	-90.061
	91.230	-60.000
3,1	91.236	0.000
	27.546	29.947
	91.231	59.924
	91.230	120.038
	27.530	150.061
	91.231	-179.988
	91.238	-119.924
	27.808	-89.893
	91.233	-59.838
4,4	91.237	0.000
	27.546	30.000
	91.230	60.061
	91.233	120.246
	27.590	150.104
	91.233	-179.877
	91.230	-119.884
	27.546	-89.632
	91.237	-59.632
4,-2	91.237	0.000
	27.610	29.838
	91.236	59.717
	91.230	119.855
	27.530	149.977
	91.230	179.939
	91.231	-120.139
	27.502	-90.082
	91.231	-59.931
5,1	91.240	0.000
	27.610	29.847
	91.233	59.888
	91.231	120.108
	27.980	150.146
	91.235	-179.989
	91.230	-119.947
	27.908	-89.831
	91.235	-59.678
5,-5	91.240	0.000
	27.724	29.731
	91.240	59.483
	91.230	119.578
	27.530	149.847
	91.235	179.846
	91.235	-120.384
	27.530	-90.384
	91.230	-60.116
6,4	91.244	0.000
	27.619	29.899
	91.231	59.981
	91.235	120.407
	27.885	150.315
	91.237	-179.877
	91.230	-119.670
	27.547	-89.476
	91.240	-59.377
6,-2	91.244	0.000
	27.724	29.989
	91.237	59.908
	91.230	119.878
	27.881	150.082
	91.237	179.938
	91.233	-120.246
	27.802	-90.123
	91.233	-59.814
7,7	91.245	0.000
	27.621	29.987
	91.230	60.278
	91.240	120.756
	27.814	150.487
	91.240	-179.783
	91.230	-119.287
	27.621	-89.024
	91.248	-59.027
7,1	91.248	0.000
	27.726	29.780
	91.235	59.644
	91.258	120.224
	27.886	150.276
	91.240	-179.989
	91.231	-120.817
	27.508	-89.768
	91.237	-59.467
7,-5	91.245	0.000
	27.866	29.538
	91.244	59.159
	91.230	119.984
	27.582	149.932
	91.240	179.845
	91.237	-120.883
	27.530	-90.510
	91.231	-60.045
8,4	91.254	0.000
	27.728	29.750
	91.233	59.873
	91.237	120.418
	27.815	150.483
	91.244	-179.876
	91.230	-119.883
	27.548	-89.318
	91.244	-59.072
8,-2	91.254	0.000
	27.867	29.480
	91.241	59.249
	91.231	119.948
	27.687	150.194
	91.244	179.939
	91.235	-120.410
	27.582	-90.155
	91.235	-59.840
8,-8	.	.
	.	.
	.	.
	91.230	120.000
	27.983	150.625
	91.244	180.620
	91.244	-120.122
	27.883	-90.127
	91.230	-59.902
9,7	.	.
	.	.
	91.231	60.000
	91.244	120.866
	27.980	150.516
	91.249	-179.979
	91.230	-119.489
	.	.
	.	.
9,1	91.259	0.000
	27.870	29.804
	91.237	59.429
	91.236	120.380
	27.817	150.455
	91.240	-179.969
	91.233	-120.135
	27.508	-89.705
	91.241	-59.208
9,-5	.	.
	.	.
	.	.
	91.230	120.000
	27.889	150.488
	91.249	180.267
	91.241	-120.430
	27.531	-90.218
	91.233	-59.592
10,4	.	.
	.	.
	91.235	60.000
	91.241	121.178
	27.982	151.016
	91.254	-179.578
	91.231	-119.468
	.	.
	.	.
10,-2	.	.
	.	.
	.	.
	91.233	120.000
	27.820	150.305
	91.254	179.880
	91.237	-120.084
	27.502	-90.256
	91.237	-59.500
11,1	.	.
	.	.
	.	.
	91.237	120.000
	27.986	150.076
	91.250	-180.576
	91.236	-120.913
	.	.
	.	.

(Angles measured from inward vertical. Upper nodes indexed CW, lower CCW.)

Lower Node Angles

	V	H
2,0	88.767	0.000
	26.100	29.962
	88.769	59.931
	88.778	119.977
	26.087	180.000
	.	.
	88.770	-119.977
	26.082	-89.980
	88.768	-59.931
3,3	88.765	0.000
	26.168	29.885
	88.765	59.771
	88.770	119.794
	26.087	149.908
	88.768	179.888
	88.769	-120.138
	26.087	-90.138
	88.770	-60.023
3,-3	88.765	0.000
	26.100	30.000
	88.770	60.023
	88.768	120.138
	26.123	150.115
	88.768	-179.888
	88.770	-149.882
	26.100	-89.771
	88.765	-59.771
4,0	88.763	0.000
	26.165	29.870
	88.767	59.816
	88.770	120.000
	26.123	150.061
	88.767	-180.000
	88.770	-120.000
	26.082	-89.938
	88.767	-59.946
5,3	88.760	0.000
	26.254	29.795
	88.763	59.583
	88.770	119.770
	26.123	149.962
	88.765	179.988
	88.767	-120.263
	26.087	-90.200
	88.769	-59.953
5,-3	88.760	0.000
	26.168	29.915
	88.769	59.953
	88.767	120.253
	26.191	150.214
	88.765	-179.988
	88.770	-119.770
	26.100	-89.647
	88.763	-59.963
6,6	88.756	0.000
	26.375	29.631
	88.756	59.261
	88.770	119.445
	26.124	149.816
	88.763	179.815
	88.763	-120.554
	26.124	-90.555
	88.770	-60.104
6,0	88.756	0.000
	26.254	29.747
	88.765	59.883
	88.769	120.070
	26.191	150.161
	88.763	-180.000
	88.769	-120.070
	26.082	-89.908
	88.765	-59.853
6,-6	88.756	0.000
	26.166	29.988
	88.770	60.104
	88.763	120.554
	26.290	150.389
	88.763	-179.816
	88.770	-119.445
	26.166	-89.260
	88.756	-59.261
7,3	88.751	0.000
	26.376	29.577
	88.759	59.306
	88.770	119.793
	26.152	150.082
	88.768	179.807
	88.765	-120.416
	26.087	-90.263
	88.767	-59.836
7,-3	88.751	0.000
	26.285	29.703
	88.767	59.836
	88.765	120.416
	26.281	150.361
	88.760	-179.807
	88.770	-119.793
	26.100	-89.521
	88.759	-59.306
8,6	.	.
	26.831	30.000
	.	.
	88.770	120.016
	26.193	150.512
	88.756	180.408
	88.759	-120.217
	26.124	-90.120
	88.769	-59.519
8,0	88.746	0.000
	26.377	29.568
	88.763	59.441
	88.767	120.107
	26.292	150.308
	88.756	-180.000
	88.767	-120.107
	26.082	-89.870
	88.763	-59.441
8,-6	.	.
	26.250	30.000
	88.769	60.248
	88.768	120.947
	26.423	150.690
	88.756	-179.679
	88.770	-119.286
	26.167	-89.982
	.	.
9,3	.	.
	26.633	30.000
	.	.
	88.769	120.513
	26.294	150.860
	88.751	180.555
	88.763	-119.988
	26.087	-89.678
	88.765	-59.039
9,-3	.	.
	26.380	30.000
	88.765	60.086
	88.763	121.027
	26.425	150.953
	88.751	-179.508
	88.769	-119.467
	26.109	-89.986
	.	.
10,0	.	.
	26.536	30.000
	.	.
	88.765	121.015
	26.427	151.164
	88.746	-179.348
	88.765	-119.885
	26.082	-89.104
	.	.

Upper Node Summary

3	1,1
3	2,-2
6	3,1
3	4,4
6	4,-2
6	5,1
3	5,-5
6	6,4
6	6,-2
3	7,7
6	7,1
6	7,-5
6	8,4
6	8,-2
3	8,-8
6	9,7
6	9,1
6	9,-5
6	10,4
6	10,-2
6	11,1
108	21

Lower Node Summary

6	2,0
3	3,3
6	3,-3
3	4,0
6	5,3
6	5,-3
3	6,6
6	6,0
6	6,-6
3	7,3
6	7,-3
6	8,6
6	8,0
6	8,-6
6	9,3
6	9,-3
6	10,0
90	17
198	38

An alternate design is given in Table II based on the same nominal parameters but parallel-projecting the regular hexagonal array onto a spherical front surface, using a constant normal depth to a spherical rear surface, and aligning the axes of the cluster nodes normal to the surfaces (Excel program SPHTRUSS.XLS on the disk.) Spherical surfaces were chosen for computational convenience, and differ from parabolic by less than 0.24" for a 12M f/1.25 optic. This design would now have 54 different upper/lower struts from 51.181" to 54.790" and 27 different diagonals from 67.211" to 67.492", but many of the parts would be the same within standard tolerances. A major advantage of the spherical design would be that the upper mounting plates would all be normal to the cluster axes and could be cast in place, but this is offset somewhat by the small distortion (generally less than 0.5 degrees) of the angles between the flanges.

Both designs suffer from the fact that the mirror cluster plates are not regular hexagons and increase in radial size with distance from the center. It is well known that a spherical or parabolic surface cannot be generated with perfectly-mating regular hexagons, but it is likely that a better design than either of the present two would result if uniform regular hexagons were used and small gaps were allowed between them; a much more repetitive design should be expected to result with the spherical configuration. This could easily be incorporated into the Excel solutions.

With regard to fabrication, JPL has recommended that the holes in the cluster nodes be drilled a fixed distance from the nodal points, resulting in multiple strut lengths with little difference between them; since the angles to the holes vary as much as they do anyway, I would prefer to see that the holes be located so as to minimize the number of strut lengths (i.e., part numbers.) To minimize cumulative errors and recognizing that the basic element of the truss is a tetrahedron (albeit badly skewed with the JPL design), I would further recommend that 40 of them (perhaps those shown shaded in Fig. 3) be rigidly assembled and that they then be connected, either using assembled struts and drilling the holes to produce the proper distance between the nodes or pre-drilling the holes and allowing the epoxy to set after assembly in place.

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The successful demonstration of the PAMELA adaptive optics hardware and the fabrication of the BTOS truss structure have been identified by the program office as the two most critical elements of the NASA power beaming program, so it was these that received attention during this program. Much of the effort was expended in direct program support at MSFC, but detailed technical analyses were also performed and are attached of the AMP deterministic control scheme and the BTOS truss structure (both the JPL design and a spherical one), and recommendations are given.

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