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ERDA CONTRACT NO. E(04-3)-1109

MASTER SOLAR PILOT PLANT Phase I

DETAILED DESIGN REPORT

Collector Subsystem
Research Experiment

(CDRL No. 6)
(Approved)

31 August 1976

MN ONLY

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Honeywell

ERDA Contract No. E(04-3)-1109

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**SOLAR PILOT PLANT
PHASE I**

DETAILED DESIGN REPORT

Collector Subsystem Research Experiment

CDRL Item No. 6

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FOREWORD

This is the final submittal of the Solar Pilot Plant Collector Subsystem Experiment Detailed Design Report (DDR) per CDRL Item 6 of ERDA Contract E (04-3) 1109.

It incorporates those changes to the 18 May 1976 initial submittal required by ERDA. Changes are indicated by a bar in the margin.

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COLLECTOR SUBSYSTEM DDR AGENDA

18 MAY 1976

8:30	Opening Remarks	L. Ball
8:45	Program Overview and Summary	L. Ball
8:50	Design Status Against Plan	L. Ball
9:00	Experiment Objectives	R. Parker
9:15	Heliostat Mechanical Design	R. Snyder/ J. Arnold
11:00	Experiment and Heliostat Electrical- Design	R. Younski
LUNCH		
2:30	System Analysis	H. Ross
3:30	Engineering Model Tests and Plans	R. Parker
3:45	Experimental Model Test Plans	R. Parker
4:00	Executive Review Session	L. Ball

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**SOLAR PILOT PLANT
PRELIMINARY DESIGN
COLLECTOR SUBSYSTEM
DETAIL DESIGN REVIEW**

Collector Subsystem

Program Overview

CONCEPTUAL DESIGN REFRESHER

The conceptual design approved was the tilt-tilt configuration which provided low cost and high performance.

The concept review proceeded through three meetings and, after a parametric trade study, was approved at the 17 December 1975 meeting.

The concept evolved from an azimuth-elevation to a tilt-tilt configuration through trade-off studies performed using a computer program which considered cost, stiffness, flexure, and other technical parameters. From a conceptual standpoint, the tilt-tilt approach with square mirror modules was the best. This is the heliostat concept that has been detailed.

Other concept highlights include:

- Two speed motor control
- Battery prime power
- Hard line simplex serial data link
- Open loop real time command/control
- Use of tallest building in facility
- Locations to simulate maximum range and maximum angular rate

These features have all been implemented in the detail design.

Collector Subsystem

Program Overview

PROGRAM PLAN

The Program Plan is a low risk low cost approach which meets schedule and performance constraints.

The Program Plan details the sequential steps of performing the experiment. The engineering model has the purpose of avoiding hardware risk by trying before buying all significant hardware.

Specific checkpoints provide for review and approval prior to continuing to the next step or milestone. The test of the Engineering Model assures both the experimental equipment and heliostat hardware perform about as planned prior to making commitments for remaining hardware.

The summary constraint diagram shows the interrelationship of the steps or checkpoints so it is easily seen that the bulk of the remaining work is assembly and test oriented.

PROGRAM PLAN
LEVEL 1 SUMMARY CONSTRAINTS

PROGRAM CONSTRAINTS
LEVEL 2 CONTROL LEVEL

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Collector Subsystem

Program Overview

SRE OBJECTIVES AND PROGRAM FOR ACCOMPLISHMENT

The objectives of the Collector Subsystem Solar Research Experiment (SRE) are to: (1) design and evaluate heliostat and tracking and control concepts, (2) to assess environmental effects on the heliostat, and (3) to simulate pilot plant daily operation.

The SRE is intended to assure the pilot plant design is a low risk economical approach through comparison of different designs. To obtain this assurance, the SRE will result in the design, build, and test of four heliostats. These units will be used to validate or modify the design and requirements as appropriate to finalize a design for the pilot plant.

The program for accomplishing the objectives includes demonstration of planned assembly and calibration techniques, evaluation of expected tracking errors versus actual errors, measurement and analysis of environmental effects. Also, day-to-day operations are planned.

Checkout and evaluation of the test set up, data taking machinery, and recording techniques are planned as well.

Using the measured values, comparisons with predictions will be made to draw conclusions regarding areas necessary to redesign for the pilot plant.

Thus, it can be seen that outputs from the SRE will include:

- Test methods.
- Test results and data.
- Designs and associated analysis.
- Design tools.
- Assembly methods.
- Test hardware.

as well as functional heliostats.

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Collector Subsystem

Program Overview

DESIGN STATUS AGAINST PLAN

The collector design is proceeding on schedule. Certain critical decisions are based on engineering model tests.

The preparation and release of drawings is essentially complete as shown on the chart. Certain revisions will be made in the drawings to reduce the cost or to improve performance.

All drawings prepared to date have been submitted for approval and have been approved in a timely fashion. The drawings in general have not been changed after submittal. The design definition is sufficiently described on drawings and specifications so that DDR approval should be forthcoming.

COLLECTOR SUBSYSTEM RESEARCH EXPERIMENT
DESIGN DOCUMENTATION

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COLLECTOR SUBSYSTEM RESEARCH EXPERIMENT DESIGN DOCUMENTATION

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COLLECTOR SUBSYSTEM RESEARCH EXPERIMENT DESIGN DOCUMENTATION

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Collector Subsystem

Collector Subsystem Research Experiment

METHOD OF EVALUATING PERFORMANCE

Collector Subsystem performance is best demonstrated by a combination of analytical techniques and obtaining test data at the appropriate assembly level.

Collector Subsystem Research Experiment Detail Specification, Part I, DS YG8112A1, establishes the performance, design, development, and test requirements for the CSRE. The current revision of this specification is included in Appendix 2.

The illustration lists performance parameters and means for assessing them.

**SRE
TEST EVALUATION MATRIX**

PARAMETER	DESIGN GOAL	EVALUATED BY
TRACKING PERFORMANCE	2 MR (6.9 ARC-MIN)/ AXIS 1σ	ANALYSIS AND TEST
REDIRECTED ENERGY	95 PERCENT IN APERATURE	ANALYSIS AND TEST
SURFACE REFLECTANCE	> 80 PERCENT	TEST
FUNCTIONAL PERFORMANCE		
SLEW RATES	>7 MR (0.4 DEG)/SEC	ANALYSIS AND TEST
ANGULAR FREEDOM	—	ANALYSIS AND TEST
AUTO TRACKING	—	ANALYSIS AND TEST
OFFSET POINTING	—	ANALYSIS AND TEST
INITIALIZATION	—	ANALYSIS AND TEST
ENVIRONMENTAL EFFECTS	4.4 TO 54.5°C (+40 TO 130°F) 13.5 M/S (30.2 MPH)	ANALYSIS AND TEST

Collector Subsystem

Collector Subsystem Research Experiment

CONFIGURATION OF THE COLLECTOR SUBSYSTEM EXPERIMENT

The equipment complex described is needed to provide the functions essential to conducting the Collector Subsystem Research Experiment.

The equipment to be evaluated during the research experiment, as well as major support items, is functionally illustrated.

The control center block to the left contains the computer subsystem and the weather station receive modem. The computer subsystem includes the H-516 processor, ASR-35 keyboard, printer, magnetic tape decks and the RS232C input/output. The processor operates under software control in real time to service four heliostats, the photodetector array, the weather station and peripherals. An internal real time clock provides one second interrupts to synchronize sun position computations. The ASR-35 provides operator interface for command or data entry and print-outs of command responses, squawks and logs. The magnetic tape decks provide for program loading and data storage. The RS232C input/output performs series parallel conversions and data formatting. This control center will be located in the north-east corner of Building E-2.

Each heliostat contains four 10 sq m (107.6 sq ft) facets mounted in a tilt-tilt gimbal arrangement. Heliostats are installed with the frame axis normal to the line-of-sight to the target. The engineering model is trailer mounted. Reflector positioning can be achieved under manual control or commanded from the processor via a serial data line. A sync indicator enables the operator to maintain matched frame linear actuator extensions when driving under manual control. The command decode module properly routes the 8 command bits to the frame and mirror module drive controllers. The up/down counter generates an error signal when a difference exists between the encoder pulse count and the controller commanded pulse count. This digital error signal is converted to an analog servo amplified drive signal which in turn causes the dc motors to rotate until the error signal is nulled. Appropriate drive trains position the reflectors about two axes. A second up/down counter in the frame drive system detects failure of one of the linear actuator drives and generates a servo amplifier inhibit. Initialization switches sense this commanded orientation and generate a drive stop command. A limit switch on the frame drive prevents over riding the linear actuator operating range.

The photodetector array consists of 224 light intensity detectors in a 14 x 16 vertical and horizontal matrix. The detectors are spaced 30.5 cm (1 ft) on center. Five other photodetectors sense the ambient light intensity for background suppression.

The matrix sensor analog outputs are processed by a time division multiplexer followed by a differential amplifier to reestablish ground reference. An analog to digital conversion prepares the intensity data for serial digital transmission to the processor when commanded. The

processor computes image centroid coordinates from the intensity data, as a measure of the pointing error to be removed by calibration. This intensity data is also stored on magnetic tape for off-line intensity map generation. The array is installed on the roof of Building E-2 and is capable of being pointed toward heliostats located at any azimuth heading. The array is equipped with an auxiliary lightning protection device tied into the primary building lightning protection system.

A photographic reference grid hung on the side of Building E-2 provides for photographing the redirected image from the reflector.

The weather station can be located at each heliostat site in turn. It provides sensors of barometric pressure for atmospheric refraction connection; wind speed and direction; ambient, two absolute and one differential structural temperature; and insulation.

The data is transmitted to the processor via a modem for storage on magnetic tape. The equatorial mount continually positions the pyrheliometer to track the sun.

Details of the equipment configuration can be found in the Solar Collector Subsystem Baseline Definition Summary of Appendix 15.

Computer and Software details are contained in Appendix 7.

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Collector Subsystem

Collector Subsystem Research Experiment

ARRANGEMENT OF THE SRE TEST SITES

The Aerospace Division complex will be used for mirror module and heliostat testing because it offers (1) a centrally located tall structure for redirected image sensor mounting, (2) an available central control facility within the same building, (3) clear lines-of-sight for all equipment test sites, and (4) economic and convenience factors.

The illustration shows the relative locations of Building E-2 and the mirror module and experimental model heliostat test sites. The central control facility is located in the northeast corner of Building E-2. The target areas consist of both a photodetector array and a photographic reference grid capable of being pointed toward each test site.

Experimental heliostat site selection was based on several criteria:

1. Unrestricted insolation from one half hour after true sunrise to one half hour before true sunset at all times during the year was a primary concern. All sites satisfy this criteria.
2. Performance evaluation of heliostats located in north, east or west and south field sites to exercise the frame and mirror module drives over total travel.
3. Testing heliostats at the maximum, mean, and minimum line-of-sight ranges.
4. Minimum off-normal azimuth angle lines-of-sight.
5. Avoidance of redirecting solar rays into normal pedestrian and vehicle traffic.
6. Maximum use of existing facilities and services.

Since the heliostat installations are now temporary, each site can be activated with minimum disturbance to existing facilities and landscaping, thereby minimizing unproductive costs.

Alternating current power can be supplied to the N site from Building E-1, to the E site from Plant 1, and to the S site from Plant 5.

The mirror module test sites were located to the north of Building E-2 to take advantage of the contrast offered by redirecting an image onto the shaded north building face. The line-of-sight ranges are equal to the 338.9 m (1112 ft) focal lengths and 146.9 m (482 ft) minimum range for the pilot plant configuration.

RESEARCH EXPERIMENT SITE PLAN

Collector Subsystem

Mechanical Configuration of Experimental Heliostat

HELIOSTAT ASSEMBLY DESCRIPTION

The experimental heliostats reflect the parametric design results.

The research experiment heliostat is a tilt-tilt gimbal configuration with 40 square meters of mirror surface. The unit has four square mirror assemblies spaced five meters on centers. Heliostat weight at outer axis bearings is estimated at 3,450 Kg (7,600 lbs).

Each mirror assembly supports 2.5 mm (0.098 in) second surfaces mirrors with a built in focal length of 339 meters (1,112 ft). The support structures are steel skinned prism shapes using various core configurations. Stub shafts at each end interface bearings and drive components.

A gear box and spur gear nested in the frame rail drive one center mirror assembly. The other three are slaved with a rigid tie rod and crank arm system which provides full circle range and face-down stowage.

The I-beam frame has pivot pins located at the center of gravity of the rotating mass. Angle sections and 3 mm (0.118 in) plates provide the stiffness required under one "g" loading at high 1.31 rad (75 deg) gimbal angles.

Two synchronous linear actuators control frame twist and provide the 1.83 rad (105 deg) of rotation freedom required to allow use of a common heliostat in any field location (pilot plant). Three common motor assemblies drive two actuators and the mirror drive.

Reinforced concrete footings control rocking modes as well as support the heliostat weight. The Engineering model is trailer mounted.

ENGINEERING MODEL HELIOSTAT ASSEMBLY AND ALIGNMENT

0 376-530 B

1. Engineering Model Trailer
2. Frame Bearing Assembly
3. Post Support Assembly
4. Reinforced Frame Assembly
5. Mirror Module Bearing Assembly
6. Mirror Module with Spur Gear
7. Mirror Module without Spur Gear

8. Reflective Surface
9. Speed Reduction Assembly
10. Motor/Encoder Assembly
11. Crank Arm Assembly
12. Tie Rod Assembly
13. Tie Rod Adjustment
14. Linear Actuator Assembly
15. Shims As Required

0 576-42 B

Collector Subsystem

Mechanical Configuration of Experimental Heliostat

MIRROR MODULE ASSEMBLY

Design requirements for mirror module assemblies for use in the Solar Research Experiment have been established. Two assemblies have been fabricated by Honeywell using locally available materials and techniques for early evaluation. Two separate designs and fabrication contracts have been completed with speciality lightweight structural fabrication companies.

BASIC REQUIREMENTS

Detail overall dimensions and requirements have been established for mirror module assemblies by Honeywell Drawing No. 34026575. A copy of this drawing has been included in the data package given to each design review attendee. The significant requirements have been outlined in Table 1.

PLYWOOD MIRROR MODULE

The initial mirror module was constructed as soon as the basic design concept was conceived. It utilized 1.9 cm (0.75 in) marine grade plywood as the structural elements and was covered with 0.64 cm (0.25 in) masonite for the exterior surface. A 677.9 meter (2224 feet) spherical radius was formed using a templet and hand tools. Complete contour data will be presented in the test results section. Table 1 compares this mirror module with significant requirements and other mirror module assemblies.

VARIABLE FOCUS MIRROR MODULE

In order to have the capability of evaluating focus of the mirror, one mirror module was fabricated to incorporate this feature. The module was standard size, fabricated from bar joist structural steel. The mirror was only 1.8 x 1.8 meters (6 x 6 feet) since this was the largest size 4.8 millimeter (3/16 in) mirrors could be obtained. Detail contour data for one particular adjustment of the focus for this unit will be presented with test results. Table 1 compared this mirror module with significant requirements and other mirror module assemblies.

PARSONS CORPORATION MIRROR MODULES

Two mirror modules have been designed and fabricated by Parsons Corp. to the requirements of Honeywell Drawing 34026575. These two units have been received and are undergoing test and evaluation. The significant data on these mirror modules are contained in Table 1 with test results presented in that section. A detail design review was held on 23 March 1976. Representatives of Honeywell and Sandia Corp. attended. These mirror modules used flat aluminum honeycomb covered with aluminum clad steel skin. The contour for the mirrors was cast over the flat honeycomb using a pre-machined male contour

TABLE 1. MIRROR MODULE DEFINITION

	Design Requirements Per 34026575	Plywood Mirror Module	Variable Focus Mirror Module	Parsons Mirror Module	Brunswick Mirror Module
Type of Reflective	2.5 to 3.0 mm (0.098 to 0.12 in) float glass mirrors	3.0 mm float (0.12 in) glass mirror	4.8 mm (0.19 in) float glass mirror	2.5 mm (0.98 in) float glass mirrors	3.0 mm (0.12 in) float glass mirrors
Mirror Surface Size	10 sq m (107.6 sq ft) multiple pieces of glass allowed 3.18 x 3.18 m (125 x 125 in.)	10 sq m (107.6 sq ft) using 9 pieces of glass 3.18 x 3.18 m (125 x 125 in.)	3.25 sq m (35 sq ft) single piece of glass (125 x 125 in. - 10 sq m frame)	10 sq m (107.6 sq ft) using 16 pieces of glass 3.18 x 3.18 m (125 x 125 in.)	10 sq m (107.6 sq ft) using 9 pieces of glass 3.18 x 3.18 m (125 x 125 in.)
Mirror Surface Contour Spherical Radius Allowable Tolerance	677.9 m (2224.1 ft) 0.4 mm (0.016 in) deviation with not more than 8 mm/m (0.001 in./ft) deviation	677.9 m (2224.1 ft) (see test data)	N/A	677.9 m (2224.1 ft) (see test data)	677.9 m (2224.1 ft) (see test data)
Mirror Reflectivity	>80%	85% - 90%	-	-	-
Design Loads					
Max Load	9.76 kg/m ² (2 lbs/ft ²)	-	-	9.76 kg/m ² (2 lbs/ft ²)	9.76 kg/m ² (2 lbs/ft ²)
Torque	68.4 kg-m (7500 in.-lbs)	-	-	68.4 kg-m (7500 in.-lbs)	68.4 kg-m (7500 in.-lbs)
Weight	249.5 kg (550 lbs)	374.2 kg (825 lbs)	510.3 kg (1125 lbs)	340.2 kg (750 lbs)	317.5 kg (700 lbs)
Maximum Stress					
Skim	(good practice)	-	-	129.2 kg/cm ² (1837 psi)	92.7 kg/cm ² (1318 psi)
Shear	(good practice)	-	-	386.1 kg/cm ² (5492 psi) in aluminum honeycomb	0.0773 kg/cm ² (1.1 psi) in foam 0.014 kg/cm ² (0.2 psi) in foam with torsion beam 12 kg/cm ² (17 psi) in beam
Maximum Rotation Under Load	1.0 mrad (3.4 arc-min)	-	-	0.7 mrad (2.4 arc-min)	3.8 mrad (13.0 arc-min) for foam only 1.0 mrad (3.4 arc-min) for foam w/beam

tool and EPON 828 and Versamid semirigid potting material. Mirrors were attached using EPON 828 and DTA. Excellent results have been obtained to date on these units.

BRUNSWICK CORPORATION MIRROR MODULES

Two mirror modules have been designed and fabricated by Brunswick Corp. to the requirements of Honeywell Drawing 34026575. These two units have been received and are undergoing test and evaluation. The significant data on these mirror modules are contained in Table 1 with test results presented in that section. A detail design review was held on 22 March 1976. Representatives of Honeywell attended. Two variations of the same basic configurations have been designed and fabricated by Brunswick. Both use steel exterior skin structures laminated to a rigid foam. One unit has an additional beam through the rotational axis to carry most of the torsion load.

Brunswick attempted to fabricate the contour without extensive tooling and the results have not been good. It is anticipated that with adequate tooling the contour of these units can be controlled. Major emphasis on testing these units will be on structural properties.

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Collector Subsystem

Mechanical Configuration of Experimental Heliostat

HELIOSTAT INNER AXIS DRIVE

Spur gears provide low backlash and high efficiency while the tie rod system allows continuous 360 degree rotation.

The heliostat inner axis is driven by a motor/encoder assembly identical to those used on the linear actuators. The motor drives a two stage 1600:1 reductor designed by Spiroid Division of Illinois Tool Works. The final stage is a 10.1:1 spur gear pass which allows high preloading [136 kg (300 pounds)] for a backlash control with a small (3 percent) reduction in drive efficiency. The large spur gear [40.6 cm (16 inch pitch diameter)] is secured to the stub shaft of one mirror module. The four mirror modules are driven synchronously by a crank arm and tie rod system.

The eight crank arms are secured to the ends of the 10.16 cm (4 inch) diameter stub shafts using a 69.8 mrad (4 degree) tapered sleeve. This approach allows quick assembly and removal of crank arms as well as adjustment of mirror module toe-in. The 60.96 cm (24 inch) crank arm length was selected to keep errors resulting from tie rod buckling within acceptable limits. The crank arm section is designed to control bending in two axes as well as twist.

The junction between crank arms and tie rods is provided by rod end ball joints. The spherical bearing surface of these units is a glass-filled, injection-molded nylon with molybdenum disulfide for lubricity. The 1.27 cm (1/2 inch) units selected have a radial load capacity of 3175 kg (7000 pounds) and are used in color coded left and right hand versions.

The tie rods (reference Honeywell Drawing 34026608) are made from rolled welded seam tubing and weigh approximately 24.9 kg (55 pounds) with rod ends. The cross-section area is sized for simple compressive spring rate. The diameter is sized to limit lateral deflection under combinations of one "g" and end loading [158.8 kg (350 pounds)]. The tubular design also makes them insensitive to outer gimbal elevation angle. With one left and one right hand rod end, the tie rods are also "turnbuckles" which are adjusted for proper length at the top-dead-center position of the crank arms.

Differentials between tie rod and frame temperatures will be monitored during the research experiments to determine the exact values of differential expansion which must be considered. Both steady state and transient conditions will be monitored.

A preliminary analysis shows that lock-up at top-dead-center (crank arm horizontal) is not possible due to the high mechanical advantage of the crank arm and the compliance of the tie rod. A momentary lag and then jump will occur as the mirrors pass through these positions.

Reflective white paint and matching of thermal time constants will be used to control differential temperatures.

Natural mass imbalances in both the mirror modules and tie rod system are used to oppose each other to provide a net balanced condition for the inner axis as seen at the spur gear.

HELIOSTAT INNER AXIS DRIVE (SPUR GEAR COVER REMOVED FOR CLARITY)

0576-25

Collector Subsystem

Mechanical Configuration of Experimental Heliostat

HELIOSTAT OUTER AXIS DRIVE

Linear screw actuators provide a rigid, repeatable drive system with adequate backlash control. Actuator mounting geometry is common for all heliostats in the field.

The heliostat outer axis drive consists of two linear actuators described by Drawing 34026598. Two actuator types have been developed for use on the engineering model heliostat. One is a ball screw jack, the other a machine screw unit. Two screws are used to compensate for the lack of torsional rigidity over the frame's 15.5 m (51 ft) length. The selected attachment geometry for the actuators is based on the following considerations:

- Operating range of 1.8 rad (105 degrees) makes one geometry suitable for any field location.
- Screw length of 182.9 cm (72 inch) allows maximum use of 365.9 cm (144 inches) standard length.
- Standard backlash values for screw/nut and fittings are within error budget allotment.
- Easy access to gear box and motor assemblies for initial alignment and maintenance
- Post twist eliminated by symmetrical mount
- Ground clearance for tip of cover tube.

Actuator vendors are:

Pow-R-Jac Division
Limitorque Corp.
King of Prussia, Pa.

Ball Screw
Actuator

Vendor P/N 01-504-0110-4

Templeton, Kenly & Co.
Broadview, Illinois

Machine Screw
Actuator

Vendor P/N C-2518020

Two actuator types are being evaluated because of similar cost/performance potential. The machine screw has good self-locking capability (due to low efficiency) and fewer parts. The ball screw has high efficiency and better side load capability. A comparison of actuators is provided in Honeywell Technical Coordination Letter (TCL) No. SRE-19.

Screw actuators were selected for the heliostat outer axis drive for the following reasons:

- Inherent stiffness
- Low backlash
- No spring preload required

- Accuracy and repeatability
- Life
- Standard commercial parts requiring minimum modification
- Require only one gear pass

Each actuator is driven by a motor/encoder assembly (reference Honeywell Drawing 34026612).

Potential problem areas are:

- Life of rubber bellows under solar radiation
- Side loading due to frame deflections (machine screw)
- Marginal self-locking under oscillatory wind loads (ball screw).

HELIOSTAT FRAME DRIVE

0876-560

Collector Subsystem

Mechanical Configuration of Experimental Heliostat

HELIOSTAT FRAME AND SUPPORT

Standard structural shapes are used to reduce labor and cost. Box sections provide torsional rigidity required to control bearing loads.

The heliostat frame, approximately 3.6 m (12 feet) wide by 15.5 m (51 feet) long, is fabricated from standard structural shapes per AISC standards. Although this approach adds more than 453.6 kg (1000 pounds) to the frame over the bar joist concept a cost reduction is realized through fewer pieces, fewer welds and less labor.

Stiffness and deflection are the primary design criteria for the I-beams while stress is more important in the pivots and angle braces. Stiffness requirements originate from budgeted pointing error under wind load and bearing moment loads when the frame is tilted at high angles.

The frame is built to commercial tolerances of ± 0.635 cm ($\pm 1/4$ inch) except for location of mounting holes for the mirror module bearing supports and pivot pin locations. Tolerances of ± 0.159 cm ($\pm 1/16$ inch) are required here to control alignment of the axes.

The 4.92 cm (1-15/16 in) diameter pivot pins support the entire heliostat weight and are located at the center of gravity to minimize drive system loads.

The torsional compliance of the frame about its pivot axis (end-to-end) allows alignment of mirrors without undue residual stress or drive loads. The linear actuators provide the required stiffness for pointing accuracy.

Stress and deflection analysis of the frame has been completed using the STARDYNE computer program.

The angle braces are sized to resist column buckling at high gimbal angles.

The support posts are made from 20.32 cm (eight inch) standard channel sized to resist bending under operational wind loads. The "split post" approach facilitates high gimbal angles and symmetrical support for the actuators. The slab size is controlled by allowable soil bearing pressures due to combined weight and overturning moment due to wind.

The analysis of the foundation and posts is documented in TCL No. SRE-35.

TABLE 1. HELIOSTAT WEIGHT ESTIMATE

<u>Item</u>	<u>Metric (Kg)</u>	<u>English (lbs)</u>
Frame	1,783	3,923
Mirror Modules (4)	1,309	2,880
Inner Drive	289	636
Bearing Supports (8)	<u>67</u>	<u>148</u>
Total	3,448	7,587

HELIOSTAT FRAME

0576-90

Collector Subsystem

Mechanical Configuration of Experimental Heliostat

MECHANICAL ANALYSIS OF EXPERIMENT HELIOSTAT

Mechanical analysis provides a high probability of early operational success, cost effective design and a foundation for future development.

Extensive analysis work has been performed on the Engineering Model design. A large portion was developed during the parametric analysis effort and continued through the detail design phase.

An overview of areas investigated is shown below.

Aerodynamic Loading (Ref: TCL SRE-66)

Wind forces at 13.5 m/s (30.2 mph) and worst case gimbal angles.

- Total Moment (wind l to outer axis) 346 kg-M (30,000 in.-lbs)
- Total Drag (wind l to outer axis) 298 kg (658 lbs)
- Total Lift (wind l to outer axis) 368 kg (810 lbs)

Total Drag Force at 54 m/s (120 mph) 488 kg (1,074 lbs)

(Storage position, wind velocity perp to heliostat outer axis)

(NOTE: Moments are peak values of oscillatory plus center of pressure components. These are used for sizing structural stiffness. Motor torque requirements are based on center of pressure effects only. All values include wind shear effects.)

Structural Analysis

- STARDYNE

Deflection and stress under wind loads (planned for submittal by 8/30/76)

Deflection and stress under "q" loading at variable gimbal angles (see Appendix 3)

- Other (Ref: TCL SRE-69)

Thermally induced stress

Column loading analysis

Reinforced concrete analysis

Torsion stiffness analysis

{ Frame braces
Tie rods
Actuators
Support posts

Drive System Analysis (Ref: TCL SRE 67 and 68)

Bearing loads and life.

Friction torque load on motor

Wind torque loads on motor

Variable "g" torque loads on motor (imbalance effects)
Torque loads due to thermal effects
Reflected inertia
Motor power requirements
Reduction ratio of linear actuator drive

Thermal Analysis

Pointing (toe-in) error due to differential thermal expansion.
(Ref: TCL SRE-65)

Tie rod stress due to differential expansion. (Ref: TCL SRE-69)

Study of sensitivity to changes in solar heating and ambient temperature. (Ref: TCL No. SRE-36)

Mass Properties Analysis (Ref: TCL SRE-70)

Weight estimate
Center of gravity
Mass moment of inertia reflected at motor
Actuator imbalance versus gimbal angle
Mirror drive balancing

Pointing Error Analysis (Ref: TCL SRE-65)

Spring rate effects
Manufacturing and assembly tolerances
Backlash effects
Bearing runout and fit effects
Thermal effects
Alignment resolution
Mass imbalance effects
 Inner axis mm versus tie rods and crank arms
 Actuator imbalance

Soil Loading Analysis (Ref: TCL SRE-35)

Shear modulus effects
Vertical spring rates
Rocking spring rates
Bearing pressure

Collector Subsystem

Mechanical Configuration of Experimental Heliostat

ADHESIVE BONDING

Honeywell's successful experience with adhesive bonding of small glass optical equipments has identified the design parameters needed for reliable joining. This experience now needs testing to extrapolate from small to large surface glass bonding.

Substrate Parameters. Establish the surface preparation (cleaning, chromate films, etc) for adhesive bonding and resistance to corrosive deterioration.

Adhesive Selection. The selected adhesive must be adhesively and cohesively strong to withstand many thermal expansions and contractions without failure of adhesive or glass substrate.

Joint Configuration. The glass substrate must be free of physical defects (act as stress risers/concentrations) conducive of failure (i.e., crack propagation).

Test Plan. Prepare and expose actual size adhesive bonded test coupons to test conditions (e.g., thermal cycling, moisture) representative of the Heliostat outdoor environment.

I. FAILURE MECHANISMS:

A. Mirror (Glass):

1. Compressive Loading (Buckling): Occurs at temperature below the adhesive's curing temperature.
2. Tensile Loading: Occurs at temperature above the adhesive's curing temperature

B. Adhesive:

1. Thermal cycle loading exceeds the adhesive's adhesive or cohesive strength (shear failures)

C. Steel (Honeycomb)

1. Moisture attacks (deteriorates) the surface, resulting in failure of the adhesive at bond line.

II. ADHESIVE BONDING PARAMETERS:

A. Substrates:

1. Thermal Expansion Coefficients (destructive)
2. Silver-Backing: Resist to moisture and adhesive solvents.
3. Surface Finish: Compatible with environment and adhesive.... long life requirement

C. Joint Configuration:

1. Glass: Ground and polished edges.
2. Adhesive:
 - (a) Controlled bond-line thickness--to accommodate thermal expansion stress [Glass-Beads 0.038 cm (0.015" dia)]
 - (b) Solid Fill: Prevent water traps--Freezing--Glass Failure

B. Adhesives:

1. Epoxies (3M-2216)	High Strength
2. Polyurethanes (TBD)	Low Elong.
3. Silicones	
GE RTV 11	
GE RTV 560	Low Strength
DC RTV 93-076	High Elog.

D. Testing:

1. Glass/Adhesive/Steel: Sample strips: 254 cm x 107 cm (1" x 42") Adhesive bonded
Thermal Cycle: -17.7° to +60°C (0° to +140°F) for seven days. Lap Shear specimens made to appraise damage to adhesive.
2. Mirror: 7.6 cm x 7.6 cm (3" x 3") Mirror pieces exposed to moisture, appraise protective methods to silver.

Collector Subsystem

Mechanical Configuration of Experimental Heliostat

HELIOSTAT IMPROVEMENT AREAS

Heliostat design may be improved through continued design engineering effort resulting in improved assembly performance and cost.

Several areas of potential redesign have been identified. These areas generally have not been sufficiently explored to assure high cost reduction. Performance impact of each change must be assessed before implementation of the change. Several changes are sufficiently simple they may be implemented on the three experimental models.

Honeywell will continue investigation and continue identification of areas of change to improve performance cost and delivery.

0876-561

PART NUMBER	B BORE +0.0000 -0.0005	D OUTSIDE DIAMETER +0.0000 -0.0005	W BALL WIDTH +0.000 -0.002	T RACE WIDTH ±0.005	O SHOULDER DIAMETER REF	BALL DIA REF	M ⁰	E GROOVE DIA +0.000 -0.010	LOAD RATINGS (LBS)			NO-LOAD BREAKAWAY TORQUE (IN.-LBS)	APPROX WEIGHT (LBS)
									STATIC LIMIT		DYNAMIC OSCILLATING RADIAL LOAD		
									RADIAL LBS	AXIAL LBS			
NH88	0.5000	1.0000	0.500	0.390	0.642	0.813	9	0.878	17900	2100	10400	1 TO 15	0.070

OPERATING TEMPERATURE RANGE -85°F TO 325°F

NOTE 1 - CONCENTRICITY OUTSIDE DIAMETER "D" AND GROOVE DIAMETER E TO BORE "B" 0.005 TIR

NOTE 2 - BEARINGS LISTED ON THIS PAGE ARE ALSO APPROVED FOR PROCUREMENT TO MIL-B-8842 AND MILITARY STANDARDS MS21233 AND MS21232

MATERIALS

DESIGNATION	BALL	RACE	LINERS
CATALOG NO.	CRES 440C, AMS 5630 R/C 55-62	CRES 17-4PH, AMS 5643 R/C 26-35	TEFLON* DURALINER BONDED TO RACE ID NO LUB REQUIRED

FIGURE 1. SPHERICAL PIVOT

TABLE 1. POTENTIAL AREAS OF REDESIGN AND ASSOCIATED RATIONALE

	<u>Rationale</u>
1. Mirror Module	
<ul style="list-style-type: none"> • Reduce overall dimension from 317.5 cm to 305 cm (125 in to 120 inches) 	Reduced Cost Improved Delivery
<ul style="list-style-type: none"> • Increase cell size of honeycomb mirror module core material 	Reduced Cost Reduced Weight
<ul style="list-style-type: none"> • Reduce supplementary structure 	Reduced Weight Reduced Cost Improved Assembly
2. Mirror Module Drive	
<ul style="list-style-type: none"> • Increased use of castings: motor housing and cover, gearbox crank arms, spur gear, bearing supports 	Reduced Cost Reduced Weight Reduced Machining for higher volume production
<ul style="list-style-type: none"> • Increased use of self aligning parts: spherical pivot on gear box, frame bearings (see Figure 1) 	Reduced Cost (possible), Reduced Assembly time Relaxed Tolerances
<ul style="list-style-type: none"> • Increased use of standard parts: hex bolts, nuts 	Reduced Cost Improved Delivery
<ul style="list-style-type: none"> • Use constant diameter tie rods between mirror modules 	Improved Delivery Improved Assembly
<ul style="list-style-type: none"> • Replace four point contact rolling element with spherical sleeve bearings 	Reduced Cost
FRAME DRIVE	
<ul style="list-style-type: none"> • Replace cast iron housing with cast aluminum 	Reduced Cost
<ul style="list-style-type: none"> • Incorporate motor adapters and pivots into housing casting 	Reduced Cost Improved Delivery Improved Assembly
<ul style="list-style-type: none"> • Use single ended input shaft on actuator 	Reduced Cost Improved Life
<ul style="list-style-type: none"> • Delete shimming operations 	Reduced Cost Improved Assembly
<ul style="list-style-type: none"> • Replace pillow block and bearing with spherical rod end on actuator at frame 	Reduced Cost Improved Assembly
<ul style="list-style-type: none"> • Delete or reduce boot costs by adhesive or dry film lubricant respectively 	Reduced Cost Improved Assembly
<ul style="list-style-type: none"> • Replace pillow blocks with sleeve bearings 	Reduced Cost Improved Assembly
POSTS	
<ul style="list-style-type: none"> • Replace actuator support weldment with Iron casting 	Reduced Cost Improved Assembly

Collection Subsystem

System Analysis

AERODYNAMICALLY INDUCED STATIC MOMENT COEFFICIENT

Worst-case testing indicates a $C_m = 0.16$. Theoretical value induced by lift gives $C_m = 0.30$.

Table 1 provides a few representative data points from applicable testing for heliostat configurations. All data has been converted to a common denomination, Moment Coefficient, C_m .

Very limited data is available which gives flat plate loading in the presently configured heliostat configuration. Reference 1 data may be the best empirical data we have at the present because the Moment Coefficients are constant with varying speeds, the plate was near the ground surface, thereby incorporating the ground stream flow and the Reynold's number is near Honeywell's configuration (3.0×10^6). The wind tunnel tests from Reference 2 has some wall effects included and the moments were determined from 8 pressure taps on each of 3 panels in tandem, perpendicular to the tunnel flow.

Analytical studies involve only free stream drag/lift and turbulent wake studies. The theoretical C_m should be approximately 25 percent of the maximum lift coefficient, C_L or $0.25 \times 1.17 = 0.30$ where $C_L = 1.17$ is the theoretical value at large Re. Test results show $C_L = 1.23$ due to smaller Re and surface shear.

In conclusion, realistic empirical results indicate a worst-case Moment Coefficient due to steady state aerodynamic loads of $C_m = 0.16$ as compared to a possible theoretical value of 0.30. A value of 0.50 was used for design load calculations thus providing a reasonable margin.

TABLE 1. HELIOSTAT MOMENT COEFFICIENT DUE TO STEADY AERODYNAMIC LOADS

DERIVED CM	WIND VEL (M/S)/(MPH)	EQUIVALENT MOMENT ON 3.18 X 3.18 M ² (KG-M)/ FT - #	α	ACTUAL TEST CONFIGURATION	REF
0.147	9/20	24/173	37° 646 MR	3.7 X 3.7 M ² (40 X 40 FT ²) HELIO-STAT FRONTAL WIND VEL	1
0.151	17.9/40	97/700	37° 646 MR	3.7 X 3.7 M ² (40 X 40 FT ²) HELIO-STAT FRONTAL WIND VEL	1
0.159	16.9/60	231/1668	37° 646 MR	3.7 X 3.7 M ² (40 X 40 FT ²) HELIO-STAT FRONTAL WIND VEL	1
0.10	13.5/30	37/266	45° 785 MR	FIRST PLATE OF HELIOSTAT FIELD OTHER PLATE'S CM WERE LESS DUE TO FLOW INTERFERENCES MOMENT DERIVED FROM EIGHT PRESSURE TAPS, WIND TUNNEL, RE = 2.6 X 10 ⁴	2
0.30	N/A	N/A	N/A	THEORETICAL VALUE BASED ON WORST-CASE LIFT COEFFICIENT C _L = 1.23	1,2,3

REFERENCES:

1. NSF GRANT (MAY 74 - SEPT 75) G1-39456 "DESIGN, FABRICATION AND TEST OF A HELIOSTAT FOR A CENTRAL RECEIVER SOLAR THERMAL POWER PLANT, SEPT 1975
2. HONEYWELL "TECHNICAL PROPOSAL FOR SOLAR TEST FACILITY HELIOSTAT ARRAY AND CONTROL SYSTEM", 1 DEC 1975
3. HOERNER, DR. ING. S.F. "FLUID-DYNAMIC DRAG", 1965

Collector Subsystem

Configuration Of Power And Control System

OVERALL OPERATION OF THE HELIOSTAT ELECTRONICS

The Heliostat Electronics provides the means to accept and execute commands from the Heliostat Control Computer and contains the controls to prevent self inflicted damage when attempting to administer a potentially harmful set of commands.

A block diagram of the Heliostat Electronics for the SRE is shown in the figure. Basic operation is as follows.

Heliostat gimbal control is centered around the counter control circuitry and an up/down counter. Incremental update information in the form of an 8-bit serial digital word from the Heliostat Control Computer is received by a Universal Asynchronous Receiver Transmitter (UART) which performs a serial to parallel data conversion. The attitude change command bits are gated into the up/down counter by the counter control circuitry. The output of the counter is converted to an analog signal by a D/A converter and becomes the error signal to the analog servo amplifier. The gimbal torque motor is driven in accordance with the sign and magnitude of the error signal. As the motor shaft is driven, an incremental encoder on the shaft produces an output pulse for every revolution of the motor shaft. The encoder output pulses are fed to the counter control circuitry and are used to update the up/down counter. When the counter output reaches zero, the servo stops driving.

Two sets of control electronics are required, one each for the inner and outer axes. Both axes share a common communications receiver, timing control generator, and power supply.

For the outer axis, a two motor drive system is used, one for each ball screw. This requires that a pair of output power amplifiers be used, an extra incremental encoder is needed, plus some added circuitry to maintain speed sync between the two outer gimbal motors.

A switching arrangement will allow the gimbal motors to be driven in a manual fashion directly from the Heliostat battery without any control electronics. This can be used for tests requiring only coarse positioning or to stow the heliostat in the event of a control loop failure.

The encoder resolution and the gear ratio between the motor shaft and the gimbal load determine the minimum step of the load. Effective gear ratio is 16000/1 for both axes. For a single pulse per turn encoder, load step size is, therefore:

$$\frac{6.28 \text{ rad/step}}{16000} = 0.39 \text{ mrad (81 arc-sec)/step}$$

which is consistent with the accuracy requirement for fine tracking.

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HELIOSTAT ELECTRONICS

The high speed slew requirement of 5.2 mr/sec (0.3 deg/sec) is provided for by the setting of a second bit in the command word which will allow 15 counts to be entered into the up/down counter. Fifteen counts correspond to a $15 \times 0.39 \text{ mr} = 5.89 \text{ mr}$ (1215 arc-sec) step at the load which can be metered out under full windload in 0.76 seconds. For computer updates every second, controlled slew is 5.89 mr per second.

In the event that the outer axis is inadvertently commanded to drive to a position beyond its stops, limit switches will disable the drive to prevent the heliostat from damaging itself. Stops are not required on the inner axis.

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Collector Subsystem

Configuration of Power and Control System

HELIOSTAT COMMUNICATIONS INTERFACE

The Heliostat Communications Interface accepts serial digital data from the Heliostat Control Computer and converts it to a form that can be used by the Heliostat Electronics.

A schematic diagram of the Heliostat Communications Interface is shown in the figure. A standard 8820 differential line receiver used as an input buffer accepts serial digital data from the computer and passes it on to the receiver section of the UART. Terminals shown at the left of the UART Block are the data input terminal and the control inputs required to define receiver operation. The receiver clock frequency of 76.8 KHz provides for operation at 4800 BAUD. The Data Ready and Data Ready Reset lines are used by the counter control circuitry to control data flow. The data outputs RR1 through RR8 contain the Heliostat update information in the format shown and are acted upon by the counter control circuitry as required.

HELIOSTAT COMMUNICATIONS INTERFACE

Collector Subsystem

Configuration of Power and Control System

HELIOSTAT TIMING GENERATOR

The Heliostat Timing Generator provides the timing control signals required by the Heliostat Electronics.

A schematic of the Heliostat Timing Generator is shown in the figure. A 1.536 MHz crystal controlled oscillator signal is divided by a factor of 20 to provide a 76.8 kHz clock signal to the UART. The UART clock rate is 16X the data rate which allows for data reception at 4800 baud. Crystal control provides the accuracy and stability required to synchronize the Heliostat receiver to the computer transmitter.

The 76.8 kHz is further counted down to 9.6 kHz, the intermediate frequencies of which are combined to provide four clocks for use by the counter control circuitry.

TIMING GENERATOR
HELIOSTAT ELECTRONICS

Collector Subsystem

Configuration Of Power And Control System

HELIOSTAT COUNTER CONTROL/COUNTER OPERATION

The counter control circuitry updates the up/down counter with information from the Heliostat Control Computer and the motor shaft incremental encoder.

A schematic diagram of the counter control circuitry and the up/down counter is shown in the figure. Asynchronous counter update information can originate with the computer or the incremental encoder. The counter control circuitry continuously cycles between the UART and the encoder outputs to allow the update information to be read into the counter. The capacity of the up/down counter is 8-bits to provide some reserve capacity beyond the 15 count maximum input requirement. Counter control cycle time is 104 μ sec.

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HELIOSAT COUNTER CONTROL/UP-DOWN COUNTER

Collector Subsystem

Configuration Of Power And Control System

HELIOSTAT DIGITAL-TO-ANALOG CONVERTER OPERATION

The Heliostat digital-to-analog converter transforms the digital output of the up/down counter to a bipolar analog signal for use by the servo amplifier.

The Heliostat D/A converter is a Burr Brown DAC-CB1-V which is a 12-bit complementary binary input converter. The converter is connected for complementary offset binary operation to provide the required analog outputs. Since only 8-bits are required to read the up/down counter, the 4 LSB's of the converter are fixed to a 1 input. The converter input/output for the 8-bits used, is shown in the table.

HELIOSTAT D/A CONVERTER OPERATION

M S B	INPUT CODE								OUTPUT VOLTS
0	0	0	0	0	0	0	0		+9.922
0	1	1	1	1	1	1	1		+0.078
0	1	1	1	1	1	1	1		0.000
1	0	0	0	0	0	0	0		-0.078
1	1	1	1	1	1	1	1		-10.000

Collector Subsystem

Configuration Of Power And Control System

HELIOSTAT SERVO OUTPUT AMPLIFIER OPERATION

A linear H switch power amplifier provides an efficient method to supply the high bidirectional linear output currents required to operate the servo motor.

A schematic of the Heliostat Servo Output Amplifier is shown in the figure. The amplifier consists of a pair of solid state switches and a pair of linear power output stages connected to opposite ends of the load (motor winding). The sign of the input signal determines which amplifier/switch pair is chosen. When a pair is chosen, the switch ties one end of the motor winding to ground while the other end is driven by the linear amplifier. When the opposite pair is chosen, the switch/linear input terminals are reversed. This permits bidirectional motor currents to be supplied from a single positive voltage power supply (+24 volt battery) without the losses associated with generating the high current negative voltage required by a more conventional power amplifier stage.

A schematic of the Heliostat Servo Amplifier is shown in the figure. An operational amplifier stage with a gain of 14.3 v/v provides for the proper scaling of the servo. Two comparators, with thresholds set at ± 0.75 the analog weight of the D/A LSB (0.85 volts), sample the scaling amp output. At levels beyond 0.85 volts, the FET is switched on to provide the full input to the follow-on power amplifier. At levels below 0.85 volts, the FET is switched off and no signal is allowed to pass. With the FET turned off, loop offset voltage is prevented from reaching the power amp. Power dissipation is, therefore, reduced and a potential limit cycle situation between loop offset and the LSB of the D/A converter is eliminated.

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Configuration of Power and Control System

HELIOSTAT SERVO OUTPUT AMP SMALL SIGNAL SIMULATION

A small signal simulation of the Heliostat Servo Output amplifier confirms stable closed loop operation.

The equivalent circuit for the simulation is shown in the figure. The model is for a linear simulation of the op amp and the three level shifting and power output transistors. The op amp model considers input R, output R, and voltage gain and uses a single pole low frequency corner for response purposes. All higher frequency breaks occur at 1 MHz and higher and are of no consequence. The transistor models are modified H parameter common base equivalents taking into account input resistance, output resistance, current gain, collector to base transistion capacitance, and base to emitter diffusion capacitance. The values shown are nominal values for an output operating current of one ampere.

A Bode plot of the open loop gain and phase calculations is shown.

Phase margin is $>\frac{\pi}{2}$ rad (90 deg). Gain margin is >60 db. Breadboard test data tends to verify these numbers in that no ringing was observed in square wave response tests on the amplifier.

HELIOSTAT SERVO OUTPUT AMPLIFIER
 SMALL SIGNAL EQUIVALENT CIRCUIT
 SERVO OUTPUT AMPLIFIER
 VALUES SHOWN ARE NOMINAL CASE FOR $I_0 = 1$ AMPERE
 PHASE MARGIN > 90 DEGREES; GAIN MARGIN > 60 DB; BANDWIDTH 250 Hz
 CLOSED LOOP GAIN 10 V/V

PHASE MARGIN $> \frac{\pi}{2}$ RAD (90°); GAIN MARGIN > 60 DB; BANDWIDTH 250 Hz

Collector Subsystem

Configuration of Power and Control System

HELIOSTAT INCREMENTAL ENCODER OPERATION

The Heliostat Incremental Encoder generates an output pulse for each turn of the motor shaft with pulses denoting clockwise rotation appearing on one output line and pulses denoting CCW rotation appearing on another line.

A schematic diagram of the encoder and a picture of the "coded" disc used by the encoder is shown in the figure. The disc is mounted on the motor shaft with the edge allowed to rotate through two optical pairs. The optical pairs are TIL 148's which consist of an IRED and a photodiode. When the hole in the disc appears between the optical pair, an output is generated by the phototransistor. This output is latched up by an LM 111 comparator with hysteresis whose output is wired to interface directly with T²L.

The key to determining direction of rotation lies in the fact that the holes in the disc are offset with respect to the positioning of the optical pairs. This results in a time sequence for the outputs of the optical pairs during disc rotation that reverses when the rotation of the disc is reversed. This is used by the encoder logic to generate the output pulse on the proper output line. The logic is so arranged that the disc can be reversed at any time without having the encoder lose a pulse.

Collector Subsystem

Configuration Of Power And Control System

HELIOSTAT SERVO MOTOR SIZING ANALYSIS

Based on the predicted wind load, the Inland Motor Model T1806 will supply the output torque and slew rate required for proper operation.

The motor current I_M of a DC servo motor is given by

$$1. \quad I_M = \frac{V_M - \dot{\theta}_L N K_V}{R_M}$$

where: V_M = Motor Terminal Voltage in volts

$\dot{\theta}_L$ = Load speed in rads/sec (deg/sec)

N = Gear ratio

K_V = Back EMF in volts/rad/sec (volts/deg/sec)

R_M = Motor resistance in ohms

Also, the available motor torque T_M can be found from

$$2. \quad T_M = I_M K_M - T_F$$

where: K_M = Motor Torque sensitivity in kg m (ft lbs)/amp

T_F = Motor Friction in kg m (ft lbs).

from which the load torque T_L becomes:

$$3. \quad T_L = T_M E N$$

where: E = Gear Train Efficiency.

Combining 1, 2 and 3 and solving for $\dot{\theta}_L$, the speed that the motor will run at under load becomes:

$$4. \quad \dot{\theta}_L = \frac{V_M E N K_M - R_M (T_L + E N T_F)}{E N^2 K_M K_V}$$

The power in the motor W_M can be found from:

$$5. \quad W_M = V_M I_M$$

Substituting 1. in 5. produces:

$$6. \quad W_M = \frac{V_M^2 - V_M \dot{\theta}_L N K_V}{R_M}$$

Motor efficiency E_M is defined as:

$$7. \quad E_M = \frac{W_L}{W_M}$$

where: W_L = watts delivered to the load

$$\text{and, } W_L = K T_L \dot{\theta}_L$$

where: K = scaling factor to convert kg m rad/sec (ft lb deg/sec) to watts and equals 2.987×10^{-3} (2.367×10^{-2} .)

The T1806-C motor spec lists the following parameters:

Volts at Peak Torque	: 14.7
Peak Torque	: 71.9 gm [100 oz-in (0.52 lb-ft)]
Back EMF, K_V	: 0.105 volts/rad/sec (0.0018 volts/deg/sec)
Torque Sensitivity, K_M	: 10.73 g-m/amp (0.0776 ft lb/amp)
Motor Resistance, R_M	: 2.2 ohms
No Load Speed	: 130 rads/sec (7448 deg/sec)
Amps At Peak Torque	: 6.7 amps
Motor Friction	: 21.6 gm [3 oz in (0.15625 ft lbs)]
Max. Winding Temp.	: 155°C (311°F)

The remaining parameters complete the definition of the system:

	<u>Outer Axis per Actuator</u>	<u>Inner Axis</u>
Load, Wind and Unbalance	71.5 kg-m(517 ft-lbs)max	32.9 kg-m (238 ft lbs)
Gear Ratio	16000/1	16000/1 max.
Gear Efficiency	0.5	0.2

Based on the above derivations and data, the values appearing in the two tables were calculated for varying load conditions. Temperature rise calculations are based upon a thermal resistance of 5°C/watt (9°F/watt). The data shows the motor to be quite capable of meeting the 5.2 mrad/sec (0.3°/sec) slew requirement at the maximum expected load.

OUTER AXIS SERVO MOTOR CALCULATIONS

T_L kgm (FT LB)	$\dot{\theta}_L$ (RAD/SEC)	$\dot{\theta}_L$ (DEG/SEC)	W_M (WATTS)	MECH. WATTS OUT	E_F (%)	DELTA T RISE (°C) /°F
0 (0)	0.008486	0.4862	2.96	0	0	15/59
13.8 (100)	0.008275	0.4741	5.33	2.24	42.1	27/80.6
27.7 (200)	0.008064	0.4620	7.69	4.37	56.9	38/100.4
55.3 (400)	0.007642	0.4378	12.4	8.22	66.0	87/188.6
71.5 (517)	0.00740	0.4237	15.2	10.37	68.2	76/168.8
83.0 (600)	0.00722	0.4137	17.16	11.75	68.5	87/188.6
96.8 (700)	0.00701	0.4016	19.50	13.31	68.2	97/206.6
110.6 (800)	0.0068	0.3895	21.90	14.75	67.4	109/228.2
124.5 (900)	0.00659	0.3774	24.23	16.08	66.3	121/249.8
138.3 (1000)	0.00637	0.3653	26.63	17.29	64.9	133/271.4
152.1 (1100)	0.00616	0.3532	29.00	18.39	63.4	145/293
166.0 (1200)	0.00595	0.3411	31.37	19.38	61.8	157/314.6

INNER AXIS SERVO MOTOR CALCULATIONS

T_L kgm (FT LB)	$\dot{\theta}_L$ (RAD/SEC)	$\dot{\theta}_L$ (DEG/SEC)	W_M (WATTS)	MECH. WATTS OUT	E_F (%)	DELTA T RISE (°C) /°F
0 (0)	0.008487	0.4862	2.95	0	0	15/59
13.8 (100)	0.00796	0.4650	8.87	5.50	62.0	44/111.2
27.7 (200)	0.00743	0.4258	14.79	10.08	68.1	74/165.2
32.9 (238)	0.00723	0.4142	17.05	11.66	68.4	85/185
41.5 (300)	0.00690	0.3955	20.72	14.04	67.8	104/219.2
48.4 (350)	0.00664	0.3804	23.68	15.76	66.6	118/244.4
55.3 (400)	0.00637	0.3653	26.64	17.29	64.9	133/271.4
62.2 (450)	0.00611	0.3502	29.60	18.65	63.0	148/298.4
69.2 (500)	0.00584	0.3351	32.55	19.83	60.9	163/325.4

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Collector Subsystem

Configuration of Power and Control System

HELIOSTAT POWER CONSUMPTION ANALYSIS

Based on an average 12 hour operating day, the heliostat will consume 0.72 percent of the power generated by its contribution to the system.

An estimate of the power required by a Heliostat for a normal operating day is given in the table, backup of which is provided in Appendix 1. The 189 watt hour estimate is the value actually required by the Heliostat Electronics. If a battery is to supply this power, approximately 20 percent more power will have to be supplied to the battery than can be drawn from it. Finally, assuming a 60 percent ac to dc conversion efficiency factor in a trickle charger supplying recharge current to the battery from an ac line, the total ac power (Phac) required by the Heliostat becomes:

$$Phac = \frac{(189.32)(1.2)}{0.6}$$

$$= 379 \text{ watt hrs.}$$

If we assume that the Pilot Plant will generate 10 Mw for 10 hrs from 1905 Heliostats on an average day, each Heliostat will generate:

$$\frac{\text{Watt hrs}}{\text{Heliostat}} = \frac{(10 \times 10^6 \text{ watts})(10 \text{ hrs})}{1905}$$

$$= 52493$$

$$\frac{\text{Power Required}}{\text{Power Generated}} = \frac{379}{52493}$$

$$= 0.0072$$

$$= 0.72\%$$

ESTIMATED POWER REQUIREMENTS FOR HELIOSTAT OPERATION

Fixed Power	14.98 watts x 12 hr	= 179.76 watt hrs
Outer Axis Tracking	0.0215 $\frac{\text{watt hr}}{\text{deg}}$ x 90 deg	= 1.935 watt hrs
Outer Axis Slew	0.0100 $\frac{\text{watt hr}}{\text{deg}}$ x 180 deg	= 1.800 watt hrs
Inner Axis Tracking	0.0215 $\frac{\text{watt hr}}{\text{deg}}$ x 90 deg	= 1.935 watt hrs
Inner Axis Slew	0.00863 $\frac{\text{watt hr}}{\text{deg}}$ x 450 deg	= 3.884 watt hrs
Total watt hrs for Average day		= 189.32 watt hrs
At 24 volts, current requirements		= 7.89 amp hrs

Collector Subsystem

Configuration of Power and Control System

HELIOSTAT MANUAL OPERATION

A switching arrangement, by which the gimbal torque motors may be driven directly from the battery without the need for any Heliostat Control Electronics, will allow for coarse gimbal positioning tests and provide the means to stow the Heliostat in the event of a control loop failure.

A schematic of the switching arrangement is shown in the figure. Single pole double throw switches permit a motor drive signal from either the servo output amplifier or the 24 volt battery. A center off three position return to center switch will permit a reversing of the battery across the motor terminals to allow for driving in both directions. Both axes can be driven simultaneously in either direction.

Synchronization of the outer axis motors is accomplished by the operator keeping "zeroed" a 20-0-20 microameter tied between two pots which are mounted at the extreme ends of the gimbal. A rheostat is provided to adjust the speed of the motors. Coarse mode scaling is $2.3 \mu\text{a}/\text{degree}$. High resolution scaling is $8 \mu\text{a}/\text{degree}$.

0576-438

Collector Subsystem

Configuration of Power and Control System

OUTER AXIS TWO MOTOR SYNCHRONIZING ELECTRONICS OPERATION

The outer axis synchronizing electronics will keep the two outer axis motor drives tracking to within a maximum angular difference of two LSB pulse weights [0.78 mr (162 arc-seconds)].

The motors used to drive the heliostat axes are dc servo motors whose speed is a function of the applied load. Since two motors are required for the outer axis drive, some means must be provided to keep the two drives tracking within some limits. This is accomplished in the following manner.

Two incremental encoders are used for the outer axis, one for each motor drive. The outputs of the encoders are synchronized to the heliostat electronics timing and are gated into an up/down counter. Each pulse to the counter carries a weight of 0.39 mr (81 arc-seconds) of gimbal angle movement. Should the counter output differ by two counts from its zero output value, a signal is generated to remove 24 volt power from the amplifier driving the leading motor to allow the lagging motor to catch up. Leading and lagging are determined by the method by which encoder pulses are clocked into the counter and by the polarity of the servo error signal which is sensed by a comparator. When the lagging motor moves within 1 count of the leading motor, power is restored to both drives. As explained in the section on initialization, the counter output and the position of the two gimbal drives are automatically reset every time initialization of the heliostat is commanded.

Removal of the +24 volts from the servo output amplifier is the fail safe way of stopping the leading motor, since even a short circuit malfunction in the output amplifier cannot continue to drive the motor when commanded to stop. The outer axis limit switches are wired in series with this 24 volt line for the same reason.

OUTER AXIS 2 MOTOR SYNCHRONIZER

0576-458

Collector Subsystem

Configuration of Power and Control System

INITIALIZATION OPERATION

The initialization function will be self-contained at the Heliostat, requiring only the setting of a single bit in the data word to command the start of the function.

The receipt by the Heliostat of a "1" for the initialization bit causes two things to immediately happen: (1) it sets the servo error counter to zero which opens the computer controlled loop by means of the threshold detector in the servo amp, and (2) it switches control of the gimbal motor to the initialization switches. The initialization switches provide the signal and signal sense (polarity) to drive the gimbal to the initialization position. The initialization switches cause the drive signal to be removed when the initialization position is reached.

The initialization position detector is made up of a pair of switches each of which is mechanically adjustable in position. The adjustments are used to set the 0.19 mr (40 arc-second) dead zone which defines the initialization position. Two initialization switches are required on the outer axis, one for each motor drive. Each outer axis switch also has an extra pair of poles. The outputs of these switch poles are combined with the initialization bit to provide a preset to the outer axis synchronizing counter. This provides for an automatic reset of the synchronizing electronics and the positions of the extreme ends of the outer axis every time the heliostat is initialized. No such synchronization is needed for the inner axis and the extra switch poles, logic, and second initialization switch are not required.

INITIALIZATION MECHANIZATION

Collector Subsystem

Configuration Of Support Elements

OVERALL OPERATION OF DATA COLLECTION SYSTEM

The Calibration Array in conjunction with a 240 channel multiplexer and the heliostat control computer provides the means to record size, shape and intensity information of the reflected beam, and also the data to be able to calculate the beam energy centroid for calibration purposes.

The calibration array consists of 224 analog photodetectors mounted on a rectangular grid 4.9 meters (16 feet) wide by 4.3 meters (14 feet) high. Grid line spacing is 0.3 meter (1 foot). The outputs of the photodetectors are fed to a 240 channel analog multiplexer where they are sequentially switched to a common output bus. The analog output of the multiplexer is digitized by an 8-bit analog to digital converter and is outputted in parallel to the Universal Asynchronous Receiver Transmitter (UART). The UART formats the data with start, stop and parity bits and transmits it serially to the Heliostat control computer via a line driver and twisted shielded pair. At the computer, another UART receives the serial digital data and converts it back to parallel form where it can be read by the computer at high speed and can be recorded or processed as desired. The entire array is read out by a single command from the computer.

Five photo detectors set 5.3 meters (17.5 feet) below the array provide a measure of background. The outputs of these detectors are averaged, inverted, and summed with the outputs of the array photo detectors to suppress array background and enhance the signal to background ratio.

Since the detector outputs are analog levels of incident power, information on size, shape, and intensity are contained in a data block. Centroid calculations are computed from intensity level information and the distance from which the intensity level was measured with respect to some reference point about which the centroidal axis is to be calculated. Since the intensity level is contained in the analog output, and since the array is fixed with a known grid spacing, all the information is present in order to be able to calculate the energy centroid of the beam.

DATA COLLECTION SYSTEM

0576-358

Collector Subsystem

Configuration Of Support Elements

ARRAY PHOTODETECTOR OPERATION

The TIL99 phototransistor operated in the short circuit mode at an effective zero bias eliminates the problems associated with the leakage currents and β of the phototransistor, thereby, providing for a long term stable monitor.

A schematic diagram of the photodetector circuit is shown in the figure on the facing page. Each photo transistor has its own amplifier packaged with it on the array. By operating the phototransistor across the input terminals of the operational amplifier, the feedback causes the device to operate in the short circuit mode and prevents the collector-base junction from operating at a voltage larger than the offset voltage of the op amp (2 mv maximum).

The leakage current I_L of a PN junction is the sum of three currents and is given by:

$$I_L = I_D + I_G + I_S$$

where

I_D = diffusion current due to diffusion of minority carriers across the junction

I_G = charge generation current due to impurity ions in the depletion layer

I_S = surface leakage current

The contribution due to I_D can be found from the classic diode equation which is given by:

$$I = I_D \left(e^{\frac{qV}{MKT}} - 1 \right)$$

where

q = electron charge (1.60199×10^{-19})

V = junction voltage

M = scaling constant (1 to 2 depending on construction)

K = Boltzmann's constant (1.38032×10^{-23})

T = absolute temperature in degrees Kelvin.

By evaluating the equation at $V = 10$ volts where the TIL99 is specified and at $V = 0.002$ volt, the maximum voltage at which it will be operated, that part of the leakage current due to I_D is found to be reduced by a minimum of 92.5 percent.

The calculation of the charge generation current I_G depends on several physical parameters not available for the TIL99. However, extrapolation of a curve showing a plot of I_G versus voltage* shows that the contribution of I_G at 0.002 volt will be reduced to ≈ 0.6 percent that of I_G at 10 volts.

Surface leakage current I_S results from the resistance path across the junction and as such is directly proportional to the applied voltage. Comparing 0.002 volts to 10 volts, this component becomes vanishingly small. Based on a total leakage current made up of one-third diffusion current and two-thirds charge generation current, the maximum leakage current at 0.002 volts is $(7.5\%)(0.33) + (0.6\%)(0.66)$ or 2.9 percent of that at 10 volts. Spec for the TIL99 at 10 volts is 100 nanoamps at 25°C (77°F). Since both diffusion and charge generation currents are bulk currents, they follow the general rule of doubling every 10 degrees celcius (18 deg Fahrenheit) increase in junction temperature. At 125°C (257°F), the maximum junction operating temperature, maximum leakage is:

$$\begin{aligned} I_{L_{\max}} &= 2^{10} (0.0029) (100 \times 10^{-9} \text{ amp}) \\ &= 297 \text{ nanoamps} \end{aligned}$$

Signal current I is given by:

$$I = I_{SO} KAR$$

where

I_{SO} = solar insolation incident on active area of the phototransistor in mw/cm^2

K = factor to modify spectral response of the transistor compared to sunlight (≈ 0.26)

A = active area of chip [nom 0.076 cm square (0.030 in square)]

R = responsivity of chip (500 $\mu\text{a/mw}$)

Nominal signal current I at one sun incident input is:

$$\begin{aligned} I &= (100 \text{ mw/cm}^2) (0.26) (0.076 \text{ cm})^2 (500 \mu\text{a/mw}) \\ &= 75 \mu\text{a} \end{aligned}$$

* Motorola High Speed Switching Transistor Handbook, Second Edition, Page 50.

Compared to a leakage current of less than $0.3 \mu\text{a}$, conclude that leakage currents are no problem.

Note that in the equation for I no transistor β term is included. This is because the device is being operated as a diode and hence, no β multiplier is used. Since K and R are basic physical constants, the main variable is A , which has been found to vary ≈ 3 to 1. The variable is accounted for by selecting compensating resistors in the amplifier so that all amplifiers have the same scale factor. Scale factor has been chosen at 1 volt per sun and amplifier saturation occurs at approximately 14 suns input.

PHOTODETECTOR CIRCUIT

0576-348

Collector Subsystem

Configuration of Support Elements

PACKAGING FOR ENVIRONMENT

The photodetector amplifier, packaged in a PVC tube glued at both ends, and the cal array-computer interface electronics, contained in a package on stand-offs with access through the baseplate, provides effective weatherproofing for outdoor operation.

Two elements of the calibration and monitor system have to be packaged for outdoor operation. They are, (1) the photo detector amplifier which is mounted on the calibration array grid, and (2) the array computer interface electronics which sits on the roof at the base of the array.

The phototransistor of the photodetector amplifier is hermetically sealed in a T018 can. The accompanying amplifier is mounted on a PC board in a PVC tube. By capping the ends of the tube and gluing all openings with PVC cement, an effective weatherproof seal is made.

The cover for the interface electronics package has no access holes. Input and output are made through connectors, the edges of which are sealed with RTV. The package sits on a set of legs ≈ 0.2 meters (8 inches) high.

SENSOR PACKAGING

A7604-086

CALIBRATION ARRAY ELECTRONICS PACKAGING

Collector Subsystem

Configuration of Support Elements

MULTIPLEXER OPERATION

A 240 channel analog multiplexer, an A/D converter, and a UART provide the means to efficiently transfer all array data to the Heliostat control computer for analysis and storage.

For the Research Experiment, the calibration and monitoring array will be mounted on the roof of Building E2 which is the tallest building at the Aero-Florida facility, while the Heliostat control computer will be placed on the first floor of E2, some 76 meters (250 feet) away. In all, at least 229 different signals will be sent from the array to the computer. In order to accomplish this, a 240 channel analog multiplexer at the array will sequentially commutate the signals to a single output line. The signal will be digitized by an 8-bit A/D converter and transmitted in serial fashion to the computer by a UART and a line driver over a twisted shielded pair.

The analog multiplexer is designed around the Harris Semiconductor HI 506A-5 which is a 16 channel single ended analog integrated circuit. To avoid leakage problems the switches are arranged in a two tiered fashion with 16 input channels for each output channel as shown in the diagram. Fifteen input chips are provided for a total input capacity of $16 \times 15 = 240$ channels of which 229 are assigned, resulting in 11 spares. The design can accommodate another input chip providing another 16 input channels if desired. Timing for control of the multiplexer is derived from a 1.536 MHz crystal controlled oscillator, which was designed to provide the accuracy and stability required to synchronize the UART transmitter with the computer input receiver.

To partially compensate for single ended switching, an array common line is returned to provide the low input to the differential amplifier at the multiplexer output.

The A/D converter is a Hybrid Systems ADC 540-8 which is an 8-bit converter with a 3 μ sec convert time. At a scaling of 1 volt/sun, the LSB of the converter at 39 mv corresponds to a resolution of 0.039 suns. Digital output is in parallel. The UART is a standard integrated chip which formats the 8-bit data word with start, stop, and parity bits, and transmits the data in serial fashion. Transmission rate is 9600 BAUD. The line driver is the standard 8830 differential driver.

The array computer interface electronics transmits data in a block upon receipt of a single data request from the computer. Sequence time is 1.67 ms per channel resulting in a time to transmit a complete data block of $(1.67 \text{ ms})(229) = 0.382$ seconds.

CALIBRATION ARRAY MULTIPLEXER

Collector Subsystem

Configuration of Support Elements

SUNMETER OPERATION AND DATA

A simple inexpensive circuit with no moving parts provides a measure of relative incident energy throughout the day.

For varying input incidence angles, the output of a phototransistor follows the "cosine law", i.e., the output signal is proportional to the cosine of the angle made by the incident ray with the chip normal. By summing the output of two wide angle sensors set in a plane at $\pm \frac{\pi}{3}$ rad (± 60 deg) to the normal, signals entering over a π rad (180 deg) input angle can theoretically be measured with a scaling variation of less than ± 7 percent without tracking or moving parts. See diagram on facing page.

A schematic diagram of the Sunmeter which uses this principle, is shown in the figure. TIL99 phototransistors are used with their T018 cans cutback as far as possible and sealed with a thin flat plate glass input window to provide as wide a field of view as possible. The devices track their cosine curves quite well to 1.2 rad (70 deg) incidence angles. The output of the summing amp feeds a pen recorder to provide a continuous hard copy of the data. Sample reproductions of the output data are shown. A continuous set of data has been recorded beginning on 23 February 1976.

SIMPLE FIXED SUNMETER

Collector Subsystem

Configuration Of Support Elements

BACKGROUND SUPPRESSION

Array background suppression can be effectively implemented by summing the inverted output of a photo detector amplifier set apart from the array with the signals sensed by the array photodetectors.

Since the output of an array photodetector is the sum of the signal from the reflected beam and the background energy incident on the array, background light will tend to mask the signal from the reflected beam. By monitoring the background with a set of photodetectors set apart from the array, the background signal level which typically averages 0.2 suns, can be electrically subtracted from the array photodetector outputs, thereby enhancing the signal to background ratio.

Large off-axis scatter signals from the heliostat could overlap the background monitor causing an error in the background correction signal. However, off-axis scatter measurements made on small mirror samples with a collimated beam at Aero-Florida and a laser at S&R in Minneapolis show the scatter component beyond 8.7 mr (0.5°) from the reflection angle to be less than one part per thousand. Data from these measurements is shown plotted on the facing page. The background monitor for the research experiment will be placed 5.3 meters (17.5 feet) below the array which corresponds to 17.5 mr (1.0°) offset angle from the array at a heliostat distance of 305 meters (1000 feet).

To further insure a good measurement of the background level, the background monitor will consist of 5 photodetector amplifiers spread across the width of the array, the outputs of which will be together and used as the background suppression signal.

Collector Subsystem

System Analysis

POINTING ACCURACY DEMONSTRATED BY ERROR ANALYSIS

A pointing error of 1.15 mr (4.0 arc-min), during winds of 13.5 m/s (30.2 mph) and with maximum temperature differentials, is predicted by the error analysis.

The calculated pointing error of 1.15 mr (4.0 arc-min) 1 sigma is within the specified value of 2 mr (7 arc-min). The analysis was done for the worst case windloads of 13.5 m/s (30 mph) and maximum temperature differentials between the most sensitive members of the structure.

Error rotation inputs are defined in three basic computational frames per Figure 1:

The O_n frame, fixed in the mounting posts at the outer axis bearings.

The I_n frame, fixed to the outer gimbal (frame) at the inner axis (mirror module) bearings.

The M_n frame fixed in the mirror module.

Pointing errors in the mirror module frame are related to error rotations in the error frames by the equations:

$I_2 + M_2 + O_2 \cos \phi + O_3 \sin \phi$ about the inner gimbal axis

$M_1 + (I_1 + O_1) \cos \theta - (I_3 + O_3 \cos \phi + O_2 \sin \phi) \sin \theta$ about an axis perpendicular to the inner axis and the mirror normal.

Errors are grouped for analysis into windspeed dependent errors, temperature differential dependent errors, gravity dependent errors, and independent errors.

Scale factors are developed for wind, temperature differentials and gravity induced errors in the storyboard entitled "Deterministic Errors". The scale factors are then multiplied by the assumed windspeed and aerodynamic coefficients, temperature differentials and gravity direction to obtain the angular errors tabulated in Table 1. Note that in determining the total errors for each type forcing function input, the errors are summed for each axis.

Nondeterministic errors, discussed in some detail in the storyboard by that title, are summarized in Table 2. Note that in determining the total errors of this type that the RSS of the error is about each axis.

A summation of all error sources is presented in Table 3. Note that in calculating the total errors about the M_{t1} or M_{t2} axes, the sum of the wind, temperature, and gravity induced errors is used. The RSS of the deterministic errors is used.

The specific assumed conditions affecting the wind and gravity dependent errors were zero inner and outer gimbal angles (mirror normal vertical) and end-on wind (wind per perpendicular to the outer axis and in the horizontal plane) at 13.5 m/s (30 mph).

The same type calculation rerun for edge-on wind resulted in a total pointing error of 2.1 mr (7.2 arc-sec) 3 sigma.

0876-557

HELIOSTAT COMPUTATIONAL FRAMES

TABLE 1. DEPENDENT ERROR SOURCES FOR ZERO INNER AND OUTER GIMBAL ANGLES AND 30 MPH, END-On WIND

Source	Driver	3 Sigma Errors in mr/arc-sec about Indicated Axis					
		O_2	O_3	O_1/I_1	I_3	M_1	I_2/M_2
Frame	Wind			0.034/7.0	0.001/0.2		0.009/1.9
Windup	Wind						
Servo	Wind			0.24/49.5			
Mirror Module	Wind					0.124/25.6	0.124/25.6
Sum of Wind		0	0	0.274/56.5	0.001/0.2	0.124/25.6	0.133/27.4
Crankarm	Temp						0.9/3.3
Frame	Temp				0.18/37.1		
Support Posts	Temp	0.02		0.2/41.2			
Sum of Temp		0.02		0.2/41.2	0.18/37.1		0.9/3.3
Frame	Gravity			0.25/51.6			0.085/17.5

TABLE 2. INDEPENDENT ERROR SOURCES

3σ Errors - Millirads/ Arc-Sec							
Source	Distrib.	O_2	O_3	O_1/I_1	I_3	M_1	I_2/M_2
Foundation	Random Walk	0.031/6.4		0.010/2.1			
Mirror Not l	Norm.					0.450/92.8	
Stub Shaft Coning	Norm.					0.040/8.25	
Out. Axis Align	Flat	0.160/33	0.160/33				
θ not l φ Axis	Norm.				0.310/63.9		
Ball Screw Lead	Norm.			0.130/26.8			
Backlash	Norm.			0.180/37.1			0.540/111.4
Quantization	Flat			0.100/20.6			0.100/20.6
Gear Tooth-Tooth	Norm.			0.140/			0.540/111.4
Encoder	Norm.						
Command Lag	Flat			0.050/10.3			0.050/10.3
Computer	Norm.			0.340/70			0.340/70
Crankarm Play	Norm.						0.210/43.3
Bearing R.O./Fit	Norm.	0.002/0.41		0.40/82.5	0.40/82.5		
Initial Defocus	Norm.					0.707/145.8	0.707/145.8
Total RSS 3σ	Norm.	0.163/33.6	0.160/33	0.446/92	0.313/64.6	0.839/173	1.120/231

TABLE 3. SUMMATION OF ERRORS

Source	Errors in Millirads/Arc-Sec									
	3 σ						3 σ		1 σ	
	O_2	O_3	O_1/I_1	I_3	M_1	I_2/M	M_{T1}	M_{T2}	M_{T1}	M_{T2}
Wind			0.274/ 56.5	0.001/ 0.21	0.124/ 25.6	0.131/ 27.0	0.398/ 82.1	0.131/ 27.0	0.398/ 82.1	0.131/ 27.0
Temperature	0.02/ 4.1		0.2/ 41.2	0.18/ 37.1		0.9/ 185.6	0.2/ 42.2	0.92/ 185.6	0.2/ 42.2	0.92/ 185.6
Gravity			0.25/ 51.6			0.085/ 17.5	0.25/ 51.6	0.085/ 17.5	0.25/ 51.6	0.085/ 17.5
Independent	0.163/ 33.6	0.160/ 33.0	0.446/ 92.0	0.313/ 64.6	0.839/ 173.0	1.120/ 231.0	0.95/ 196.0	1.130/ 233.1	0.317/ 65.4	0.377/ 77.8
RSS/Axis							1.08/ 222.8	1.45/ 299.0	0.60/ 123.8	0.99/ 204.2
Total RSS							1.81/ 373.3		1.15/ 237.2	

Collector Subsystem

System Analysis

DETERMINISTIC ERRORS

Scale factors for computing pointing errors as a function of wind-speed, temperature differentials, and gravity deflections are derived and discussed.

Outer gimbal angular deflections due to windloads were determined using a detailed structural model of the frame and the "STARDYNE" program*. The results of the analysis can be related to windspeed (V) and Lift (C_L), Drag (C_D) and Moment (C_m) coefficients by the following matrix equations:

End-on wind (wind perpendicular to outer axis and horizontal)

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} 0.707E-5 & 1.44E-4 & 1.88E-5 \\ 3.05E-5 & 3.02E-5 & 3.34E-5 \\ 0.72E-5 & 0.82E-6 & 1.34E-5 \end{bmatrix} \begin{bmatrix} C_L V^2 \\ C_D V^2 \\ C_m V^2 \end{bmatrix}$$

Edge-on wind (wind along outer axis)

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} 4.85E-4 & 0.66E-5 & 1.37E-4 \\ 1.54E-4 & 4.58E-5 & 0.615E-3 \\ 1.8E-5 & 2.55E-4 & 0 \end{bmatrix} \begin{bmatrix} C_L V^2 \\ C_D V^2 \\ C_m V^2 \end{bmatrix}$$

Windload coefficients as a function of the angle of attack of the wind** are summarized in the following table.

	0.44π	-0.33π	-0.22π	-0.11π	0	$+0.11\pi$	$+0.22\pi$	$+0.33\pi$	$+0.44\pi$
Angle of Attack Rad (Deg)	(-80)	(-60)	(-40)	(-20)	(0)	(20)	(40)	(60)	(80)
Lift Coefficient C_L	0.2	0.7	0.6	0.4	-0.1	-0.6	-0.6	-0.8	-0.4
Drag Coefficient C_D	1.4	1.0	0.6	0.2	0.1	0.2	0.6	1.0	1.4
Moment Coefficient C_m	-0.3	-0.3	-0.4	-0.5	-0.3	0.5	0	-0.2	-0.25

* Memo: Johnson to Snyder, 1, December 1975, "Structural Analysis of the Tilt-Tilt Heliostat".

** Memo: Snyder to Parker, 10 October 1975, "Comparison of Moment Coefficients from Hopkins Analysis and S&R Testing".

The actual frame angular deflections are then computed for a specific wind direction (end-on or edge-on) and angle of attack (a function of the gimbal angles). For the specific case of edge-on wind, and with zero degree inner and outer gimbal angles, the angle of attack is zero giving $C_L = -0.1$, $C_D = +0.1$, and $C_m = -0.3$ from the table. For a wind-speed of 13.5 m/s (30 mph), the frame rotations are then computed from the matrix equation to be:

$$\begin{array}{lll} I_1 = -0.08 \text{ mr,} & I_2 = -0.176 \text{ mr,} & I_3 = 0.021 \text{ mr.} \\ (-16.5 \text{ arc-sec}) & (-36 \text{ arc-sec}) & (4.3 \text{ arc-sec}) \end{array}$$

For end-on wind the rotations are:

$$\begin{array}{lll} I_1 = -0.034 \text{ mr,} & I_2 = -0.009 \text{ mr,} & I_3 = -0.001 \text{ mr.} \\ (-7 \text{ arc-sec}) & (-1.9 \text{ arc-sec}) & (-0.21 \text{ arc-sec}) \end{array}$$

Inner axis windup due to wind torques occurs about the I_2/M_2 axis during maximum [13.4 m/s (30 mph)] windload conditions. The total angular deflection is 1 mr (206 arc-sec). It consists of 0.28 mr (41.2 arc-sec) twist and 0.20 mr (41.2 arc-sec) bend of the crank arm, 0.42 mr (86.6 arc-sec) tie rod compression, and 0.10 mr (20.6 arc-sec) gear deflection. This deflection is caused only by edge-on winds and is related to both the wind velocity and wind torque moment coefficient, C_m . The moment coefficients are related to the wind angle of attack in the above table. $\Delta I_2/M_2 = C_m V^2 2.22 \times 10^{-3} \text{ mr (0.458 arc-sec)}$ where C_m is the moment coefficient and V is the wind speed in mph. With zero degree inner and outer gimbal angles, the angle of attack is 0 degree. From the table above, $C_m = -0.3$ and for edge-on winds the deflection about $I_2/M_2 = 0.3 \times 900 \times 2.22 \times 10^{-3} = 0.60 \text{ mr (123.8 arc-sec)}$. For end-on winds the deflection will be zero.

The servo loop gains are specified to allow no more than $4 \times 10^{-4} \text{ rads (0.023 deg)}$ hangoff with 13.5 m/s (30 mph) winds. Although it is expected the loop gains can ultimately be set to give significantly stiffer loops (see section on Loop Simulation Results), this figure is used in the analysis. The hangoff angle is calculated as $0.89 \times 10^{-3} C_m V^2 \text{ mr (0.184 } C_m V^2 \text{ arc-sec)}$. The calculation for 13.5 m/s (30 mph) winds and for $C_m = -0.3$ (0,0 gimbal angles give zero angle of attack) gives a deflection of $-0.24 \text{ mr (-49.5 arc-sec)}$. For end-on winds $I_1 = -0.24 \text{ mr (-49.5 arc-sec)}$ and $I_2 = 0$. For edge-on winds $I_2 = 0.24 \text{ mr (49.5 arc-sec)}$ and $I_1 = 0$.

Mirror module deflections due to windloads are specified to be less than $1.4 \times 10^{-3} \text{ rads (0.08 deg)}$ in a 13.5 m/s (30 mph) wind. End-on winds will cause about the same forces on all mirror facets while edge-on winds primarily distort the mirror module on the windward end. Edge-on deflections, rms'd for all four facets then =

$$\sqrt{\frac{\delta_1^2}{4}} = \frac{\delta_1}{2} \quad \text{where } \delta_1 \text{ is the deflection of a single facet due to edge-on wind.}$$

It seems reasonable to assume the deflection increases with the distance from the center of the mirror. For this type error distribution

the one sigma reflection will equal 0.79 the three sigma or maximum value. Around the zero degree inner and outer gimbal angle position, the primary distortion force is due lift and the deflection for end-on winds is calculated as $C_L V^2 \times 1.95 \times 10^{-3}$ mr (0.2 arc-sec). C_m , for 0,0 gimbal angles and therefore zero angle of attack, is 0-1. For 13.5 m/s (30 mph) winds, assuming equal distribution of deflections about M_1 and M_2 , the M_1 and M_2 rotation is $0.707 \times -0.1 \times 900 \times 1.95 \times 10^{-3} = -0.124$ mr (-25.6 arc-sec), three sigma or -0.098 mr (-20.2 arc-sec), one sigma, for end-on winds. The M_1 and M_2 rotation is -0.062 mr (-12.8 arc-sec) three sigma, or $-.047$ mr (-9.7 arc-sec) one sigma for edge-on winds.

Temperature differentials between the crank arm pivot points along the frame and connecting rods cause deflections of the mirror module relative to the control module. A crank arm length of 0.6 meter (2 ft) and connecting rod lengths of 5 meters (16.4 ft), together with a temperature coefficient of expansion for steel of 10.5×10^{-6} m/m°C gives a peak deflection of 1.75×10^{-4} rads/°C (9.72×10^{-5} rad/°F) for the mirror module farthest from the control module, 0.875×10^{-4} rad/°C (4.86×10^{-5} rad/°F) for adjacent modules and 0 for the control module. Taking the rms value of these to provide a single temperature coefficient gives a scale factor of 0.9×10^{-4} rads/°C (5.00×10^{-5} rad/°F) of temperature differential about the M_2 axis. A maximum temperature differential of 10°C (18°F) is expected between the side rails and crank arms.

Temperature differentials between the long side rails result in rotations about the I_3 frame axis. The two outermost mirror module pivots are 7.5 meters (24.6 ft) from the centerline and the two innermost are 2.5 meters (8.2 ft). The thermal travel acts over a mirror module length of 3.2 m (10.5 ft) and the coefficient of exp = 10.5×10^{-6} /°C giving a scale factor of $10.5 \times 10^{-6} \times 7.5/3.2 = 2.3 \times 10^{-5}$ rads/°C (1.28×10^{-5} rad/°F) for the outer pair and 0.78×10^{-5} rads/°C (4.33×10^{-6} rad/°F) for the inner pair. Taking the rms value of these gives a composite coefficient for the heliostat of 1.8×10^{-5} rads/°C (1.00×10^{-5} rad/°F). A maximum of 10°C (18°F) is expected between the two rails.

Change in relative length of the two support posts causes a rotation about the O_2 axes. For steel posts 2 meters (6.5 ft) long spaced 10 meters (32.8 ft) apart the scale factor is 2×10^{-6} rads/°C (1.11×10^{-6} rad/°F). A maximum 10°C (18°F) temperature differential is expected between the posts.

Change in temperature across the cross-section of the posts causes a rotation about the O_1 axis. For steel posts 2 meters (6.5 ft) long and 0.3 meter (1 ft) wide the scale factor is 6.7×10^{-5} rads/°C (3.72×10^{-5} rad/°F). A maximum 3°C (5.4°F) temperature differential is expected across the cross-section of the support posts.

Frame deflections due to gravity were derived from the STARDYNE analysis. A reasonable fit to the data is obtained using:

$$I_1 = 2.5E-4 \cos \phi \text{ mr}$$

$$I_2 = 8.5E-5 \cos \phi \text{ mr}$$

where ϕ is the frame off level angle.

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Collector Subsystem

System Analysis

NON-DETERMINISTIC ERRORS

Foundation structural build, and computer errors are described and quantified.

Foundation errors occur about the O_1 and O_2 axis and are the result of the foundation settling and shifting as a function of time. It is assumed these errors have a random walk characteristic; that is, the expected error magnitude varies as the square root of time. It is further assumed that 10 times a year, through the continual calibration of the heliostat, these errors are reset to zero. Measurements on the specific slab, loading and ground conditions will have to be made before accurate estimates can be made. A value of 100 microrads (20.6 arc-sec) per year about the O_2 axis and 30 microradians (6.2 arc-sec) per year about the O_1 have been allotted to this source. At 0.1 year the expected values are then 31 and 10 microradians (6.4 and 2.1 arc-sec) about the O_2 and O_1 axes, respectively. Rotations about the vertical axis, O_3 are assumed negligible.

Initial alignment of the nominal mirror normal relative to the inner axis can be held to a maximum of 0.45 milliradians (92.8 arc-sec). This is taken as a 3 sigma value and should have a normal distribution throughout the field of heliostats. It occurs only about the M_1 axis since errors about M_2 are taken out by the initial calibration.

Stub shaft coning is due to the misalignment of the two stub shafts on each end of the mirror module. They determine the axis of rotation of the mirror modules. This is controlled by print tolerances to be 0.08 mr (16.5 arc-sec) peak-to-peak or 0.04 mr (8.25 arc-sec) 3 sigma. It has a normal distribution. This occurs about M_1 and M_3 .

The bearing mounts for the outer axis in the support posts are adjustable for alignment of the axis. The major residual error is determined by the resolution of the adjustment which has a maximum error of 0.16 mr (33 arc-sec). Since the error is equally likely to fall anywhere between 0 and 0.16, it has a flat distribution. This outer axis alignment error occurs about the O_2 and O_3 axis.

Non-orthogonality of inner and outer axis is a rotational error about I_3 . This error is held to 0.31 mr (63.9 arc-sec) 3 sigma by the build and assembly tolerances. It has a normal distribution for all the heliostats in the field.

Ball screw lead error is matched (by a selection process) and compensated for in the computer to less than 0.008 cm/m (0.001 in./ft) of travel for a travel of 1 m (± 3 feet). Operation on a radius arm of 0.6 m (2 feet) results in a rotational error of 0.000125 rads (25.8 arc-sec) maximum if both screws have the same magnitude and sign for all the facets. If the sign is opposite the outboard facet rotates 0.0001875 rad (38.7 arc-sec) and the inboard facets 0.0000625 rads (12.9 arc-sec).

Taking the rms of all the facets for both conditions gives 0.00013 rads (26.8 arc-sec) 3 sigma. This is an O_1/I_1 input.

Backlash is controlled by manufacturing tolerances. The inner-gimbal backlash, O_1/I_1 , is 0.54 mr (111.4 arc-sec) 3 sigma (I_2/M_2). The value for the outer axis drive has not been finalized but is expected to be 0.18 mr (37.1 arc-sec) 3 sigma. The error will most likely not be distributed between 0 and $\pm$ maximum, but will tend to be concentrated at the maximum value, the sign being dependent on wind direction and/or mass unbalance. Contributing backlash sources are rod end, spur gears, and reducer assembly.

Quantization errors occur about the O_1/I_1 and I_2/M_2 axes. The command resolution is 0.39 mr (81 arc-sec) giving a peak error of 0.2 mr (41.25 arc-sec) and having a flat distribution.

Gear tooth-to-tooth machining tolerances control these errors to 0.54 mr (111.4 arc-sec) 3 sigma about O_1/I_1 axes. Estimates of I_2/M_2 put this error at 0.14 mr (28.9 arc-sec) 3 sigma. The distribution is normal.

The encoders are mounted in the gear train so that one revolution of the encoder equals one quanta step at the load [0.388 mr (80 arc-sec)]. The equivalent pointing error of the load is therefore negligible.

Command time lag introduces errors about the O_1/I_1 and I_2/M_2 axes. The maximum command rate is one step/second. The maximum command rate during normal operation is 0.35 rad/hr (20 deg/hr) or 0.1 mr/sec (20.6 arc-sec/sec). The commands are issued to position the heliostat for the minimum error over the time interval so that a maximum error of 0.5 mr (10.3 arc-sec) is expected. The distribution is flat.

Computer errors occur about the O_1/I_1 and I_2/M_2 axes. Errors in the time standard, temperature input, pressure input, algorithm accuracy and least significant bit contribute to these terms. The error is 0.34 mr (70 arc-sec) 3 sigma with a normal distribution.

Crank arm play between the drive and driven axes results in error rotations about the I_2/M_2 axis. The play is toleranced at 0.0127 cm (0.005 in) maximum and with a 0.6 m (2 ft) crank arm gives a 0.21 mr (43.3 arc-sec) 3 sigma error. Windloads and/or mass unbalance tend to maintain this error at the maximum values.

Bearing runout/fit is held to a tolerance of 0.00254 cm (0.001 inch). For the inner axis with a 0.6 m (2 ft) crank arm, this gives a 0.04 mr (8.25 arc-sec) 3 sigma, normally distributed, error about the O_1/I_1 and I_3 axes. The outer axis, having 10 meters (32.8 ft) between bearings, has only 0.0025 mr (0.52 arc-sec) 3 sigma, errors about the O_2 and O_3 axes.

The reflective surface deviation from the desired parabolic shape due to build tolerances is set at 1 mr (206 arc-sec) maximum or 0.707 mr (145.8 arc-sec) around the M_1 or M_2 axes. It is assumed this will have a normal distribution over the surface of the mirror.

Collector Subsystem

System Analysis

CONTROL LOOPS GIVE STABLE OPERATION

Torque motors with position feedback provide efficient, simple control loops that give stable operation with digital commands during tracking and slewing modes and with large windloads.

Stable operation was demonstrated using

- Position feedback from the motor shaft
- Structural load resonance
- Quantized commands and feedback
- Multiple and three state loops
- 0.4 rad/hr (23 deg/hr) and 0.005 rad/sec (0.3 deg/sec) command rates
- Wind loads up to 115 kg-m (834 pound-foot)

The gear ratio was selected to deliver an 0.39 mr (81 arc-sec) load motion for one revolution of the motor. The resulting gear ratio of 16,000:1 effectively decouples load torques from the motor. With position feedback from the motor, the control loop is essentially independent of load dynamics. Motor back emf provides the damping required to give stable loop operation, so that the loop electronics need provide only a power amplification function.

Simplicity and economy are characteristic of the resulting design shown in Functional block diagram form in Figure 1. The electronics convert the quantized error signal to a power drive to the torque motor (Inland No. NT1911). The motor drives the load through the gear train. Digital output of either load or motor shaft position is subtracted from the command angle input to generate the error signal.

The first configuration simulated used an electronics gain giving 13.4 m/s (30 mph) wind load torque for each step [0.39 mr (81 arc-sec)] of error signal. Stable, well damped response was indicated with feedback from either the load or motor shaft. With feedback from the motor shaft, the loop gain was increased until the 0.39 mr (81 arc-sec) quantization of error signal produced saturated motor torque. This results in three state operation -0, + stall torque or -stall torque output. This loop was run with command rates of 0.4 rad/hr (23 deg/hr) and 0.005 rad/s (0.3 deg/s) and with up to 13.4 m/s (30 mph) wind loads. No indication of instability was noted.

Printout of a typical outer gimbal run showing response to step 115 kg-m (834 lb-ft) wind torque and 6 mr (1238 arc-sec) step command inputs is presented in Figure 2. Feedback from motor shaft, three state loop gain and a 13 Hz load resonance were used for this run. The oscillation of load position is due to ringing of the load spring-mass system.

FIGURE 1. FUNCTIONAL BLOCK DIAGRAM

0576-111

SYMBOL-BLOCK #
 + = 99 QUANTIZED INPUT COMMAND
 * = 50 MOTOR SHAFT POSITION
 x = 68 QUANTIZED MOTOR SHAFT POSITION
 □ = 40 MIRROR POSITION

FIGURE 2. SIMULATION RESULTS SHOWING HIGH GAIN LOOP RESPONSE TO STEP 115 kg-m (834#-FT) WIND TORQUE AND 6 MR STEP COMMAND INPUTS

Collector Subsystem

System Analysis

SIMULATION RESULTS DEMONSTRATE LOOP PERFORMANCE

Inner and outer axis transient response to various combinations of command inputs, windloads, and loop gains demonstrate satisfactory response times and stability.

The table below describes the loop inputs and gains used for various transient response runs. The figures show the simulation results for selected runs.

Collector Subsystem

Engineering Model Test Plans and Data

OBJECTIVES OF THE TEST PROGRAM

Two comprehensive plans have been prepared for the test program to ensure satisfaction of the test objectives.

A document titled, Solar Collector Subsystem Engineering Model Plan, No. 376-13639, 5 March 1976, was prepared, coordinated, and submitted. This document establishes a plan to control the assembly and test process for the engineering model heliostat, as well as associated facilities, tooling, auxiliary equipment, and test equipment. A similar document was prepared for the heliostats. It is described later.

The engineering model is one of four heliostats to be assembled during the CSRE. The configuration of this heliostat and associated mirror modules will reflect drawing releases during the detail design phase, initially. Alternate mechanizations for a given function will be incorporated for comparative evaluation, i.e., mirror modules supplied by various manufacturers, second surface mirror and first surface film reflectors, acme thread and ball screw linear actuators, as examples. The configuration at the completion of the research experiment will reflect use of this heliostat as a test bed. Trailer mounting this heliostat increases its utility because it can be positioned to simulate any pilot plant heliostat location in the array for position sensitive effect evaluation. Further, this mounting configuration also lends itself to induced environmental condition evaluation.

Use of this heliostat in the manner prescribed in the engineering model plan will yield:

- Data for presentation at Detail Design Review and later reporting which establishes concept feasibility, demonstrates function, supports design analyses, defines design margins and quantifies ambient environmental influences.
- Selection of a mirror module design from candidates evaluated and data to satisfy technical concerns over use of honeycomb.
- Provision and evaluation of facilities, tooling, auxiliary equipment, test equipment, software, methods and processes to be employed in the assembly and test of three experimental heliostats.
- A test bed heliostat to support experimental heliostat research. (i.e., Try before buy)

These objectives will be attained on a schedule consistent with program major milestones and within allocated cost.

COLLECT DATA

- . ESTABLISH CONCEPT FEASIBILITY
- . DEMONSTRATE FUNCTION
- . SUPPORT DESIGN ANALYSIS
- . DEFINE DESIGN MARGINS
- . QUANTITY AMBIENT ENVIRONMENTAL INFLUENCES

EVALUATE DESIGNS

- . MIRROR MODULES
- . REFLECTOR
- . LINEAR ACTUATOR

EVALUATE

- . FACILITIES
- . TOOLING
- . AUXILIARY EQUIPMENT
- . TEST EQUIPMENT
- . SOFTWARE
- . METHODS AND PROCESSES

PROVIDE TEST BED

Collector Subsystem

Engineering Model Test Plans and Data

HIGHLIGHTS OF ENGINEERING MODEL TESTING

The engineering model heliostat tests will evaluate subassemblies, processes, and procedures as well as provide insight into best tests for experimental H/S testing.

The more significant operations inherent to build and test of the engineering model mirror modules and heliostat are:

Primary

- Evaluation of two built-up mirror modules (MM3B and MM3P) manufactured by Brunswick and Parsons, respectively. MM3B employs 3 mm (0.12 in) float glass, second surface mirrors, while MM3P incorporated 2.5 mm (0.098 in) float glass.
- Evaluation of the engineering model heliostat operated both in manual and computer controlled modes at several sites selected for the experimental heliostats.

Secondary

- Evaluation of Mirror Module 1 (MM1) consisting of a plywood, contoured frame supporting 3 mm (0.12 in) float glass, second surface mirrors.
- Evaluation of Mirror Module 2 (MM2) consisting of a steel frame configured to provide variable focus of a 0.48 cm (3/16 in) float glass, stiffened mirror assembly measuring 3 1/3 m² (6 x 6 feet).
- Evaluation of a film first surface reflector applied over the glass on a type 3 mirror module.

Pedestrians and auto traffic will be protected by a combination of restricting access to potential illumination areas, covering mirrors, and stationing test personnel with manual position control capability at the heliostat site during heliostat operating periods. During periods of nonoperation, the reflective surfaces will be covered or positioned so that redirected solar energy cannot be a safety hazard.

The application of quality assurance measures will be consistent with research experimentation.

The test team will insure that data is not compromised by excessively inaccurate test equipment.

Dedicated data books logged out to the test teams will be used for all manual data recording. Periodic data book audits will be conducted by the Program Manager. Bulk data will be stored on magnetic tape. Processed data will be recorded on printed paper. Photographic techniques will be employed for redirected image recording.

ERDA approval of the engineering model heliostat design documentation⁰ is required prior to release for fabrication of the heliostat or components. The program manager insures that approval is secured.

Test results will be compared to analytical findings and documented in a test report.

ENGINEERING MODEL TEST HIGHLIGHTS

Primary

Evaluate

- Two Built-Up Mirror Modules
- Heliostat in Manual and Computer Controlled Modes

Secondary

- Plywood Contoured Mirror Module
- Steel Frame Variable Focus Mirror Module
- Film First Surface Reflector

Test Status

- Tests of MM1 and 2 Essentially Complete
- Electronic BB Tests 80 Percent Complete
- H/S Assembly and Test 20 Percent Complete

Collector Subsystem

Engineering Model Test Plans and Data

TEST OF MIRROR MODULES

A mirror module can be adequately characterized by measurement of focal length, redirected image shape with sun at various off-axis angles, contour under applicable loads, and weight.

A mirror module test range has been established at the Aerospace Division complex in St. Petersburg, Florida. The illustration on Page 10 shows the location of the minimum and maximum line of sight (LOS) range sites. Benchmarks have been surveyed and installed to enable precise measurement of reflector location while redirecting an image onto either the photodetector array or photographic reference grid installed on Building E-2.

Focal length is set at the maximum LOS range site in the case of variable focus MM2 or measured in the case of the other fixed focal length mirror modules. The redirected image long axis coinciding with the diagonal of the square 10 m^2 (108 ft^2) reflector decreases in length by about 0.12 m per 30.5 m (0.4 ft per 100 ft) when the reflector is moved in a direction away from the target and toward a point at the nominal 339 m (1112 ft) focal length. Moving the reflector in the same direction but away from the focal point causes the long axis dimension to increase at a rate of about 0.69 m per 30.5 m (2.25 ft per 100 ft). This distinct change in rate of image size change per unit of range enables fairly precise measurement of focal length.

Redirected image shape data for all mirror modules is taken at both sites during a six hour period centered around mid-day. Image intensity maps are printed off line from data sensed by the photodetector array. These maps, as well as photographic image data, are compared to analytic characterizations. A computer program is used to account for the influence of sun angle, slant range and target skew on the image shape.

Each mirror module in turn is mounted on a mobile A frame gantry to facilitate relocation and sun tracking.

The contour of the glass is measured with the mirror module in a horizontal orientation and clamped at the axle. Data is taken with the mirror shaded, exposed to solar loading, and loaded with sand bags to simulate wind pressure. The mirror module is then repositioned to the vertical orientation and the contour is remeasured.

Each mirror module is weighed.

Following completion of mirror evaluation, a film reflector will be installed over the glass surface. Redirected images produced by this reflector will be evaluated.

During the course of mirror module testing the photodetector array and control room complex will be installed. Functional checks will be made on the H-516, ASR-35, magnetic tape decks, RS232 I/O, photodetector array, and H-516 interface. Software to control these elements will also be developed during this period. This software will be debugged, as well as off line software to produce intensity maps.

ENGINEERING MODEL MIRROR MODULE TEST PLAN

<u>Parameter</u>	Mirror Module*				
	<u>1</u>	<u>2</u>	<u>3P</u>	<u>3B</u>	<u>3F</u>
Focal length					
Redirected image shape at 1112 ft and 480 ft LOS from 9 AM to 3 PM to investigate:	X		X	X	
• Focus Quality	X	X	X	X	X
• Off Axis Aberrations	X	X	X	X	X
• Scatter	X	X	X	X	X
• Intensity Centroid Location		X	X	X	X
• Intensity Map		X	X	X	X
• Cleanliness Effects	X	X	X	X	X
Contour deviation as a function of:					
• Orientation (g-sensitivity)	X	X	X	X	
• Wind (simulated load)	X	X	X	X	
• Ambient Temperature and Solar Load	X	X	X	X	
• Time (creep, aging, etc.)	X	X	X	X	
Weight	X	X	X	X	

*SYMBOLS

- 1 Wood structure manufactured by Honeywell.
- 2 Variable focus steel structure manufactured by Honeywell.
- 3P Built-up honeycomb structure manufactured by Parsons.
- 3B Built-up foam structure manufactured by Brunswick.
- 3F Either 3P or 3B paved with reflective film.

Collector Subsystem

Engineering Model Test Plan and Data

HELIOSTAT ASSEMBLY AND ALIGNMENT

Assembly and alignment process is easily accomplished to ready the heliostat for its intended function.

The engineering model heliostat assembly and alignment process consists of the following steps. Items required in support of each step are also listed.

<u>Operation</u>	<u>Support Items</u>
1. Weigh each element prior to installation	Scale
2. Assemble bearings to frame <ul style="list-style-type: none">• 4 outer axis pillow blocks• 2 linear actuator inter-face pillow blocks	Hand tools
3. Assemble frame to posts on trailer	Mobile crane Cable yokes (2 each)
4. Level frame and secure to trailer	Guy wires (4)
5. Assemble spur gear 40.6 cm (16 in) pitch diameter to one (driven) mirror module	Carpenter level and straight edge
6. Assemble bearing and support assemblies to mirror modules (1 of 8 unique for gear box)	
7. Assemble mirror modules with bearing/support assemblies to frame. Shim interface between frame and MM supports as required to prevent binding of bearings	"A" frame mobile hoist 1.27 cm (1/2 inch) diameter tooling pin
8. Temporarily secure MM to frame to prevent rotation (mirror modules have built in imbalance)	Safety cables
9. Assemble gear box to driven MM support assembly. Set spring preload and stops	Measure spring compression (count turns)

Operation

Support Items

10. Assemble motor/encoded set and associated electronics	
11. Install 8 crank arms, set $\frac{\pi}{4}$ rad (45 deg) nom from mirror and secure taper locks	
12. Assemble tie rod and rod ends to crank arms	"A" frame mobile hoist
13. Adjust the rod length (to prevent binding at top dead center)	
14. Assemble and align linear actuators and associated electronics and set initialization and limit switches	Mirror module leveling and alignment bar [actuator weight 45.5 kg (100 pounds) maximum]
15. Shim 2 center mirror modules	
16. Level frame stub shaft axes	Manometer*
17. Set mirror module toe-in and set initialization switch	Mirror module leveling and adjustment bar. Mirror module adjusting bar
18. Balance Heliostat outer axis	Force gauge
19. Balance heliostat inner axis	Force gauge

As a part of the process tooling and adjustment range adequacy will also be verified.

Conclusion: Assembly has been sufficiently defined to proceed through DDR.

*Manometer is a fluid filled open ended flexible tube used to sense local level at the center of the frame stub shaft axes while adjusting the trailer leveling jacks.

ENGINEERING MODEL HELIOSTAT ASSEMBLY AND ALIGNMENT

0376-5308

1. Component Weight	11. Crank Arm Assembly
2. Frame Bearing Assembly	12. Tie Rod Assembly
3. Frame to Post Assembly	13. Tie Rod Adjustment
4. Level Frame	14. Linear Actuator Assembly and Alignment, Initialization and Limited Adjustment
5. Spur Gear to Mirror Module Assembly	15. Shim and Center Mirror Modules
6. Mirror Module Bearing Assembly	16. Level Frame Axes
7. Mirror Module to Frame Assembly	17. Set Mirror Module Toe-In and Initialization Switch
8. Secure Mirror Module	18. Balance Outer Gimbal
9. Gear Box Assembly	19. Balance Inner Gimbal
10. Motor/Encoder Assembly	

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Collector Subsystem

Engineering Model Test Plans and Data

TEST OF HELIOSTAT IN MANUAL MODE

Functional checkout and characterization establish a baseline for later comparison.

Prior to operating the heliostat in the tracking mode certain tests will be performed while operating in a local manual control mode, as follows:

Verify function of manual controller, frame drive, mirror module drive, limit switches, initialization switches, and power loss detector.

Stabilize frame support, trailer, etc. (base).

Characterize frame and mirror module drives.

Verify initial mirror module toe-in adjustment.

Inspect mirror for cleanliness and clean if indicated.

If the results of sun tracking tests in the computer controlled mode indicate the need for error source testing, selected measurements from the following list will be made, as appropriate:

Measure structure static binding and twist deflections as a function of:

- Combinations of frame and mirror module rotational angles (g-sensitivity)
- Ambient temperature change
- Time (creep, wear, aging)

Determine effect on contour and rotational error, that is, windup, of 1 each inner and 1 each outer mirror module of:

- Combinations of frame and mirror module rotational angles (g-sensitivity)
- Ambient temperature change
- Wind (simulate with weights)
- Time (creep, aging, wear)

Periodically inspect to determine the combined residual effects of natural wind, humidity, rain, dust, salt air, sand, electrical storms, hail, wear and aging.

ENGINEERING MODEL
HELIOSTAT TEST PLAN - MANUAL MODE

Evaluate Drive Systems:

- Gimbal Travel Range
- Turning Rate (High and Low)
- Frame CG Trim
- Mirror Module/Drive CG Trim
- Torque Capability (Loaded)
- Backlash, Crank Arm Play and Bearing Runout/Fit
- Encoder Angular Accuracy
- Control Loop Dynamic Response, Stability, Resonances
- Self-Induced Vibrations

Test Initialization Switches Adjustment Stability

Check Mirror Module Toe-In Adjustment Stability

Measure structure static bending and twist deflections as a function of:

- Orientation (g-sensitivity)
- Ambient Temperature
- Loads (dead weight)
- Time (creep, wear, aging, etc.)

Check inner and outer mirror contour and windup as a function of:

- Orientation (g-sensitivity)
- Ambient Temperature
- Wind (simulated load)
- Time (creep, wear, aging, etc.)

Evaluate combined residual effect of natural wind, humidity, rain, dust, salt air, sand, electrical storms, hail, wear, and aging in normal operations.

Collector Subsystem

Engineering Model Test Plan and Data

TEST OF HELIOSTAT IN AUTO MODE

Insight into expected heliostat array performance can be obtained by evaluating the performance of a single trailer mounted heliostat at several sites within the array.

Following installation of the heliostat electronics associated with operation under computer control, the meteorological station and associated H-516 interface, the equipment complex will be tested, as follows:

1. Verify function of motor controller operated under computer control and associated interface, meteorological station and H-516 interface.
2. Verify software functions.
 - Site initialization constants
 - Sun vector calculation (real time)
 - Refraction correction
 - Heliostat address, command and calibration
 - Mode control
 - Initialization
 - Return to stowage
 - Offset pointing
 - Tracking
 - Rotational nonlinearity calculations for jack screws
 - Meteorological data processing
 - Operator interface
 - Data storage for later reevaluation
 - Statistical pointing accuracy correlation with
 - Meteorological data
 - Structural conditions
 - Data plotting
3. Demonstrate control parameters.
 - Return to stowage in 15 minutes
 - Emergency defocus 52.4 mr (3 deg) in 1.2 seconds
 - Frame position command scale factor and uncompensated nonlinearity

4. Characterize heliostat electronics parameters including power consumption as a function of.
 - Modes
 - Ambient wind
5. Verify battery sizing.
6. Operate in tracking mode from 1/2 hour after sunrise to 1/2 hour before sunset. At intervals offset point to reference grid on side of E-2 and photograph image.
7. Verify MM toe-in adjustment adequacy. Readjust if necessary.
8. Determine pointing accuracy and pattern shape as a function of
 - Time of day (short term)
 - Ambient wind
 - Ambient temperature
 - Day to day (long term)
9. Verify base stability.

If the results of Item 6 tests indicate the need for error source testing, the following measurement will be made if appropriate.

10. Measure structure motion as a function of ambient wind (steady state and gusts).

The tests outlined in Items 6 through 9 will be repeated at each site selected for the experimental heliostats.

ENGINEERING MODEL
HELIOSTAT TEST PLAN - AUTO MODE

Function Integrity

Redirected image position and shape from 1/2 hour after sunrise to 1/2 hour before sunset from four field locations:

- Focus Quality
- Off Axis Aberrations
- Scatter
- Intensity Centroid Location
- Intensity Map
- Cross Axis Coupling
- Cleanliness Effects
- Calibration Coefficients
- Pointing Accuracy
- Performance Sensitivity to
 - Time of Day (Short Term)
 - Ambient Wind
 - Ambient Temperature
 - Solar Loading (Including thermal differentials produced by shading and blocking)
 - Day to Day (Long Term)

Control Parameters:

- Return to Stowage in 15 minutes
- Emergency Defocus - 0.05 rad (3 degrees) in 12 seconds
- Frame Position Command Scale Factor and Uncompensated Nonlinearity

Electronics Parameter Characterization

Structure deflection as a function of ambient wind (steady State and gusts)

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Collector Subsystem

Engineering Model Test Plans and Data

ANALYSIS OF MIRROR MODULE TEST DATA

The plywood mirror module served as an adequate vehicle for test technique development. The variable focus mirror module requires further evaluation and the Parsons build up mirror modules are exhibiting satisfactory performance.

To date four mirror modules have been tested. The results of these tests are summarized in the tabulation. Raw data is included in Appendix 11.

MM1 served as a vehicle for developing the techniques to be employed in testing the remaining mirror modules. Environmental exposure, that is, primarily temperature and moisture, created stress in the wooden frame which caused five of the nine mirror facets to fracture. Testing of this mirror module has been suspended.

MM2 testing is currently in process. Further, contour measurements and redirected pattern studies are planned. The low intensity of the redirected image when testing at the 339 m (1112 ft) range has hindered focus pattern studies. This phenomenon is a function of mirror area, that is, 3.3 m^2 (36 sq ft) as opposed to the baseline 10 m^2 (108 sq ft) mirror, and the low reflectance of the 4.8 mm (0.19 in) glass.

Limited testing of the mirror modules supplied by Parsons has been accomplished. These mirror modules are performing well.

ENGINEERING MODEL MIRROR MODULE TEST DATA SUMMARY

Parameter	Mirror Module			
	MM1	MM2	MM3P (SN P01)	MM3P (SN P05)
Focal Length	<304.8m (1000 ft) over all 152.4-182.9m (500-600 ft) along axle >304.8m (1000 ft) normal to axle	Variable	Close to nominal 342.9 m (1112 ft)	Close to nominal 342.9 m (1112 ft)
Redirected Image Shape	Per analytical model as modified by contour deviation	Per analytical model	Per analytical model	TBD
Contour Deviation				
Manufacturing Accuracy and Short Term Aging	2 to 1 deviation after 2 month natural environment exposure	0.53 cm (0.021 inch) max deviation (9 data points)	0.0381 cm (0.015 inch) max deviation (52 data points)	0.0889 cm (0.035 inch) max deviation (52 data points)
G-Sensitivity	No data	TBD	TBD	TBD
Wind Sensitivity (Simulated Load)	No data - mirror fractured while attempting measurement	TBD	0.020 cm (0.008 inch) max deviation at 4.75 g/m ² (2 lbs/sq ft) and no full solar load. (22 data points)	TBD
Solar Load Sensitivity	>0.0762 cm (0.030 inch)	TBD	See wind sensitivity	0.015 cm (0.006 inch) max deviation partial to full solar load (11 data points)
Weight	381.8 kg (842 lbs)	510 kg (1125 lbs)	301.5 kg (665 lbs)	316.5 (698 lbs)

Collector Subsystem

Experimental Model Test Plans

OBJECTIVES OF THE TEST PLANS

A comprehensive plan has been prepared to insure satisfaction of the experimental model test objectives.

Consistent with definition of the engineering model test program, a document titled, Solar Collector Subsystem Experimental Model Plan, No. 576-13699, 3 May 1976, has been prepared. This document establishes a plan to control the test process for the experimental model heliostats.

Three experimental model heliostats will be assembled during the CSRE. These heliostats and associated mirror modules will be built in the configuration(s) approved at DDR.

Testing these heliostats per the experimental model plan will yield data as shown on the chart.

EXPERIMENTAL MODES
TEST OBJECTIVES

GATHER DATA IN SUPPORT OF:

- CONFIRMING FEASIBILITY AND PERFORMANCE OF HELIOSTAT AND CONTROL SYSTEM
- UPDATING PILOT PLANT PRELIMINARY DESIGN
- SUPPORT ELEMENT EVALUATION
- OPERATING INSTRUCTION VALIDATION
- ANALYSIS BY OTHER AGENCIES

Collector Subsystem

Experimental Model Test Plans

HIGHLIGHTS OF EXPERIMENTAL MODEL TESTING

The experimental test program through evaluation of mirror module samples, mirror modules, and three heliostats under natural and induced environments will yield an adequate performance evaluation of the Collector Subsystem.

The more significant operations inherent to the experimental model heliostat and mirror module test program are identified in the illustration. Highlights of this sequence are:

- Pre and post heliostat installation test of a minimum of two mirror modules to evaluate consistency of manufacturing processes and effects of environmental exposure and aging. These mirror modules will be evaluated in the same manner as those for the engineering model.
- Heliostat assembly and alignment. This operation will be performed in the same manner as it was performed for the engineering model heliostat, except as follows:
 - Concrete foundations rather than trailer
 - Survey and frame axis alignment normal to LOS
 - Test sample mirror modules installed in inner and outer positions
 - Initial measurements for foundation stability evaluation
 - Toe-in angles set for LOS slant range as follows:

Field Location	LOS Range (m/ft)	mr/deg (Toe in Angle)	
		Inner	Outer
N	147/482	8.64/0°29'42"	25.9/1°29'06"
E	246/806	5.17/0°17'47"	15.5/0°53'20"
S	314/1030	4.04/0°13'54"	12.1/0°41'42"

- Functional checkout of heliostat elements performed in same manner as engineering model heliostat.

- Periodic performance evaluation of each heliostat to establish a performance baseline and determine the residual effects from use and environmental exposure.
- Extended daily operation of each heliostat to evaluate day to day performance and develop the heliostat calibration technique.
- Induced thermal forcing function testing to evaluate influence on pointing accuracy and redirected pattern shape.
- Wind testing to evaluate steady state wind influences on pointing accuracy and pattern shape.
- Evaluating of minor module samples representative of reflector and support structure materials and processes under extended natural environmental exposure.

Completion milestone dates for each operation are also shown in the illustration.

The safety, quality assurance and customer involvement considerations outlined for the engineering model test program also apply to the experimental model test program.

Instructions covering normal operation will be validated during the test program.

Extrapolation techniques will be applied to relate actual test results over the actual exposure range to predict results over the application range.

Computer programs will be employed to predict mirror module and heliostat redirected pattern shape as a function of sun, reflector and target geometry. Test results will be compared to analytical findings.

EXPERIMENTAL MODEL OPERATION SEQUENCE AND SCHEDULE

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Collector Subsystem

Experimental Model Test Plane

PERFORMANCE EVALUATION OF HELIOSTATS

Periodic performance evaluation of the heliostat drive systems, optics, pointing accuracy and base stability establishes a baseline and enables detection of deviations from this baseline.

These tests will be performed on each heliostat before, after and at appropriate intermediate intervals during extended daily operation, thermal test, and wind test to determine the residual effects from use and these environmental exposures.

1. Characterize frame and mirror module drives.
2. Recheck initialization switch adjustment and mirror module toe-in angles.
3. Measure foundation stability.
4. Operate in tracking mode from 1/2 hour after sunrise to 1/2 hour before sunset. At 15 minute intervals offset point to reference grid on side of E-2 and photograph image.
5. Determine pointing accuracy and pattern shape as a function of:
 - Time of day (short term)
 - Ambient environment
6. At the completion of the final performance evaluation test, inspect the heliostat for the combined residual effects of natural wind, humidity, rain, dust, salt air, sand, electric storms, etc.

EXPERIMENTAL MODEL
HELIOSTAT PERFORMANCE EVALUATION TEST PLAN

CONFORMANCE TO DESIGN DOCUMENTATION

COMPONENT WEIGHTS

FUNCTIONAL INTEGRITY

DRIVE SYSTEMS:

- GIMBAL TRAVEL RANGE
- TURNING RATE (HI & LO)
- FRAME CG TRIM
- MIRROR MODULE/DRIVE CG TRIM
- TORQUE CAPABILITY (LOADED)
- BACKLASH, CRANK ARM PLAY & BEARING RUNOUT/FIT
- ENCODER ANGULAR ACCURACY
- CONTROL LOOP DYNAMIC RESPONSE, STABILITY, RESONANCES
- SELF INDUCED VIBRATIONS
- FRAME POSITION COMMAND SCALE FACTOR & UNCOMPENSATED NONLINEARITY
- POWER CONSUMPTION AS A FUNCTION OF:
 - GIMBAL ANGLE
 - MODE
 - AMBIENT WIND

REDIRECTED IMAGE POSITION & SHAPE FROM 1/2 HOUR AFTER SUNRISE TO 1/2 HOUR BEFORE SUNSET FROM THREE FIELD LOCATIONS:

- FOCUS QUALITY
- OFF AXIS ABERRATIONS
- SCATTER
- INTENSITY CENTROID LOCATION
- INTENSITY MAP
- CROSS AXIS COUPLING
- CLEANLINESS EFFECTS
- CALIBRATION COEFFICIENTS
- POINTING ACCURACY
- PERFORMANCE SENSITIVITY TO
 - TIME OF DAY (SHORT TERM)
 - AMBIENT WIND
 - SOLAR LOADING
 - DAY TO DAY (LONG TERM)

FOUNDATION STABILITY

INITIALIZATION SWITCH AND MIRROR MODULE TOE-IN ADJUSTMENT STABILITY

COMBINED EFFECT OF NATURAL WIND, HUMIDITY, RAIN, DUST, SALT, AIR, SAND, ELECTRICAL STORMS, HAIL, WEAR, AGING.

Collector Subsystem

Experimental Model Test Plans

HELIOSTAT EXTENDED DAILY OPERATION

The heliostat calibration technique can be effectively evaluated and refined by collecting and analyzing compensation data for north, east and south field heliostats over a two-month interval.

These tests will be performed on each heliostat to evaluate day to day performance and develop the heliostat calibration technique. The photodetector array and weather station will be relocated periodically to service each heliostat in turn.

1. Operate the heliostat serviced by the photodetector array in the closed loop tracking mode from 1/2 hour after sunrise to 1/2 hour before sunset.
2. Evaluate pointing correction data to refine the calibration compensation model to reduce the combined effect of at least the following systematic error sources:
 - Foundation settling and shifting
 - Mirror module normal not perpendicular to inner axis
 - Stub shaft coning
 - Outer axis alignment
 - Non-orthogonality of inner and outer axle
 - Ball screw
 - Gear
 - Encoder error
3. Further evaluate the day to day pointing correction data to determine if a periodic pattern exists. If a cyclic pattern exists, refine the calibration compensation model to reduce this source of pointing error or isolate and correct the error cause.
4. In conjunction with items 2 and 3, determine the calibration interval required to maintain acceptable pointing accuracy.
5. From intensity maps reduced from the data collected in item 1, determine adequacy of toe-in adjustment and optics quality. Readjust toe-in if indicated.
6. Operate the remaining heliostats in the open loop tracking mode from 1/2 hour after sunrise to 1/2 hour before sunset, maintaining the redirected image on the appropriate side of E-2. Input normal pointing corrections, if required. Periodically photograph the redirected image. From these pattern photographs, determine adequacy of toe-in adjustment and optics quality.

EXPERIMENTAL MODEL
HELIOSTAT EXTENDED DAILY OPERATION
TEST PLAN

Closed loop tracking from 1/2 hour after sunrise to 1/2 hour before sunset from three field locations for approximately two months:

- Systematic Error Compensation
- Periodic Error Compensation
 - Solar Load Sensitive
 - Ambient Temperature Sensitive
 - G-Sensitive
- Pattern Shape
 - Off Axis Aberrations
 - Cross Axis Coupling
 - Toe-In Adjustment
- Calibration Interval
- Calibration Array Size

Collector Subsystem

Experimental Model Test Plans

HELIOSTAT THERMAL TEST

Evaluation of heliostat performance in terms of pointing accuracy and redirected image shape while exposed to natural and induced thermal environments will provide a basis for predicting heliostat performance over the application temperature range.

While each operating heliostat in turn will be locally monitored by the meteorological station to establish correlations between thermal conditions and performance, a single heliostat will be subjected to the more rigorous thermal evaluation described below:

1. Install thermocouples at appropriate locations on the heliostat structure to monitor temperature gradients across thermally sensitive members, as well as ambient conditions.
2. Operate the heliostat in the closed loop tracking mode.
3. Induce thermal forcing functions using selected heating with thermal blankets, transient induction by sun shade remove or other appropriate technique.
4. Evaluate the data to determine the effect on pointing accuracy and pattern shape of:
 - Ambient temperature
 - Thermal gradients
 - Differential thermal time constants
 - Solar isolation
 - Cloud passage
5. If indicated, investigate improving thermal performance using techniques such as selective paint color, insulation and screening.

EXPERIMENTAL MODEL
HELIOSTAT THERMAL TEST PLAN

Closed loop tracking with induced thermal forcing functions to evaluate influence on pointing accuracy and pattern shape of:

- Ambient temperature
- Thermal gradients
- Differential thermal time constants
- Solar isolation
- Cloud passage

Collector Subsystem

Experimental Model Test Plans

HELIOSTAT WIND TEST

Evaluation of heliostat performance in terms of pointing accuracy and redirected image shape while exposed to natural wind environments will provide a basis for predicting heliostat performance in the application environment.

Data recorded by the National Oceanic and Atmospheric Administration at the Tampa International Airport indicates that natural wind sustained velocities sampled over a one minute interval reached the 11.2 to 13.0 m/s (25 to 29 mph) range on nine separate days during the May 1975 to February 1976 time frame. This weather station, located approximately 24,000 m (15 miles) from the CSRE test site, records data representative of the natural environment anticipated during experimental heliostat testing.

Each operating heliostat in turn will be locally monitored by the meteorological station to establish correlations between wind conditions and performance.

1. Operate the heliostat in the closed loop tracking mode.
2. Evaluate the data to determine the effect on pointing accuracy and pattern shape of:
 - Wind velocity
 - Wind direction with respect to major axes
 - Mirror module and frame attack angle.

EXPERIMENTAL MODEL
HELIOSTAT WIND TEST PLAN

CLOSED LOOP TRACKING WITH NATURAL WIND TO EVALUATE INFLUENCE ON
POINTING ACCURACY AND PATTERN SHAPE OF:

- STEADY STATE WIND VELOCITY
- WIND DIRECTION
- FRAME ATTACK ANGLE
- MIRROR MODULE ATTACK ANGLE

Collector Subsystem

Experimental Model Test Plans

TEST OF MIRROR MODULE SAMPLES

Evaluation of the optical properties of small samples representative of mirror module reflector will provide a basis for predicting mirror module optical performance.

Samples representative of mirror module reflectors and support structure materials and processes will be subjected to extended natural environmental exposure to determine the residual effect of the environments and aging, as follows:

1. Fabricate reference and test samples.
2. Evaluate samples to determine:
 - Total spectral reflectance
 - Adhesion
 - Off axis scatter
3. Retain reference samples in a protected benign environment.
4. Expose the test samples to normal environment.
5. Periodically reevaluate both reference and test samples to measure changes in Item 2 parameters.

The tabulated reflectance data was measured at ERC. Spectral reflectance plots for each test sample are included in Appendix 10.

SPECTRAL REFLECTANCE

Cary 14 Spectrometer With Tungsten Source

Range 0.3 to 2.5 μm
(1.18×10^{-7} to 9.84×10^{-7} in)

MIRRORED GLASS REFLECTORS

Perf Group	Ref No.	Composition	Manufacturer	Visual Range		Infrared Range	
				R (%)	Wavelength ($\mu\text{m/in}$)	R (%)	Wavelength ($\mu\text{m/in}$)
1	9	0.0071 cm (0.028 inch), 2nd surface, silvered, laminated glass reinforcement	ASG Glass/Gardner Mirror	96	0.65/ 2.56×10^{-7}	98	1.7/ 6.70×10^{-7}
	11	0.229 cm (0.090 inch), 2nd surface, silvered, low iron	ASG Glass/Gardner Mirror	96	0.55/ 2.17×10^{-7}	94	1.6/ 6.30×10^{-7}
2	10	0.25 to 0.30 cm (0.098 to 0.118 in), 2nd surface, silvered	ASG Glass/Gardner Mirror	92	0.50/ 1.97×10^{-7}	84	1.7/ 6.70×10^{-7}
	8	0.0071 cm (0.028 in), 2nd surface, vapor deposited aluminum, laminated glass reinforcement	ASG Glass/Gardness Mirror	86	0.55/ 2.17×10^{-7}	94	1.8/ 7.09×10^{-7}
FILM REFLECTORS							
1	7	Chrome on 0.005 cm (0.002 in) polyester	Coating Products, Inc.	93	0.5/ 1.97×10^{-7}	95	1.6/ 6.30×10^{-7}
2	2	Oxidized SiO on aluminum	Schjeldahl	88	0.65/ 2.56×10^{-7}	95	1.3/ 5.12×10^{-7}
	1	Series emittance tape	Schjeldahl	82	0.65/ 2.56×10^{-7}	98	2.2/ 8.66×10^{-7}
3	4	Type G4J05 0.005 cm (0.002 in) aluminum on teflon, 2nd surface	Schjeldahl	81	0.7/ 2.76×10^{-7}	46 ⁽¹⁾	1.7/ 6.70×10^{-7}
4	3	Gold on flexible plastic	Schjeldahl	76	0.7/ 2.76×10^{-7}	98	1.8/ 7.09×10^{-7}
	5	G405600 Aluminum - Mylar on teflon	Schjeldahl	66	0.65/ 2.56×10^{-7}	84	2.2/ 8.66×10^{-7}
	6	UV screening Tedlar on metallized Mylar	DuPont	65	0.7/ 2.76×10^{-7}	88	2.2/ 8.66×10^{-7}

(1) See Appendix 10

Appendix 1

HELIOSTAT POWER CONSUMPTION ANALYSIS

MOTOR POWER FOR FINE TRACKING

Based on the equations given in the section on the analysis for motor sizing, the following table shows the final motor conditions as a function of wind load for a one-step input where the LSB equals $1/2 V_M$ maximum.

Outer Axis

T_L Ft-Lb	$\dot{\theta}_L$ Rad/Sec	$\dot{\theta}_L$ Deg/Sec	W_M	Mech Watts Out	Eff	ΔT Rise
0	0.00411	0.2355	1.48	0	0	7.4
258	0.00357	0.2043	4.54	2.50	55%	22.7
* 517	0.00302	0.1730	7.60	4.23	56%	38.0
1000	0.00200	0.1147	13.32	5.43	41%	66.6

Inner Axis

T_L Ft-Lb	$\dot{\theta}_L$ Rad/Sec	$\dot{\theta}_L$ Deg/Sec	W_M	Mech Watts Out	Eff	ΔT Rise
0	0.00411	0.2355	1.48	0	0	7.4
119	0.00348	0.1955	5.00	2.75	55%	25.0
* 238	0.00285	0.1636	8.52	4.60	54%	42.6
500	0.00147	0.0844	16.28	4.99	31	81.4

*Full Load Condition.

Note that at 0.5 full load conditions, ultimate slew speed for either axis is 0.2 degree/second. This value will be used as the final value for both axis.

To calculate the motor power requirements from a zero starting speed, Table 1 is given. It shows the calculations for motor speed, current, power, accumulated travel, etc., as a function of time. Calculations are for a load = $1/2$ maximum load, final speed = 0.2 degree/second, a motor time constant of 13.3 ms and a $V_M = 1/2 V_M$ maximum (LSB = $1/2 V_M$ maximum).

TABLE 1. MOTOR CONDITIONS FROM STARTUP FOR FINE TRACKING

Time MS	$\frac{-t}{1-e^{-t/13.3 \text{ ms}}}$ Fraction of Full Speed	Shaft Speed Deg/Sec	Shaft Travel Arc-Sec	Accum Travel Arc-Sec	I_M Amps	W_M Watts	Cons Power Watt Sec	Acc Motor Power Watt Sec	Supply 2 X MP Watt Sec
0	0	0							
2	0.14	0.028	0.10	0.10	3.15	23.18	0.0464	0.0464	
4	0.26	0.052	0.288	0.388	2.81	20.63	0.0412	0.0876	
6	0.36	0.072	0.446	0.835	2.51	18.48	0.0369	0.1246	
8	0.45	0.09	0.583	1.418	2.26	16.62	0.0332	0.1578	
10	0.53	0.106	0.705	2.124	2.03	14.95	0.030	0.188	
12	0.59	0.118	0.806	2.93	1.84	13.58	0.027	0.214	
14	0.65	0.130	0.893	3.823	1.67	12.41	0.025	0.2397	
16	0.70	0.14	0.972	4.795	1.54	11.33	0.023	0.262	
18	0.74	0.148	1.037	5.832	1.42	10.44	0.021	0.283	0.566
20	0.78	0.156	1.094	6.92	1.13	8.29	0.083	0.366	0.732
22	0.81	0.162	1.145	8.07					
24	0.83	0.166	1.181	9.25					
26	0.85	0.170	1.21	10.46					
28	0.88	0.176	1.245	11.70	0.899	6.53	0.065	0.431	0.862
30	0.90	0.18	1.28	12.98					
32	0.91	0.182	1.30	14.29					
34	0.92	0.184	1.32	15.60					
36	0.93	0.186	1.33	16.94	0.768	5.64	0.68	0.499	1.0
38	0.94	0.188	1.35	18.29					
40	0.95	0.19	1.36	19.65					
42	0.96	0.192	1.37	21.0					
44	0.96	0.192	1.37	22.40	0.675	4.96	0.00984	0.00496	
46	0.97	0.194	1.39	23.79					
48	0.97	0.194	1.40	25.18					
50	0.98	0.196	1.40	26.6					
∞-2 ms	1.0	0.2	1.44						
<u>0.72 arc-sec</u> ms									

Step Size = 81 arc-seconds. 81 arc-seconds - 26.6 arc-seconds left to be at full speed.

$$\frac{54.4 \text{ arc-sec}}{0.72 \text{ arc-sec}} = 75.5 \text{ ms. Total step time} = 50 + 75.5 = 125 \text{ ms.}$$

$$\text{Total motor power} = 0.499 \text{ watt/sec} + (75.5 \text{ ms}) \frac{0.00496 \text{ watt/sec}}{\text{msec}} =$$

$$0.499 + 0.371 = 0.870 \text{ watt seconds/step.}$$

$$\text{Power Supply power} = 2 \times 0.870 = 1.74 \text{ watt seconds/step.}$$

Convert to degrees.

$$\begin{aligned} \text{Supply power} &= \left(\frac{1.74 \text{ watt sec}}{81 \text{ arc-sec}} \right) \left(\frac{3600 \text{ arc-sec}}{\text{degree}} \right) \\ &= \frac{77.37 \text{ watt sec}}{\text{degree}} \end{aligned}$$

In terms of watt hours/degree

$$\begin{aligned} \text{Supply Power} &= \frac{\frac{77.37 \text{ watt sec}}{\text{degree}}}{\frac{3600 \text{ sec}}{\text{hour}}} \\ &= 0.0215 \text{ watt hrs/deg} \end{aligned}$$

For 90 degree tracking

$$\begin{aligned} \text{Supply Power} &= \left(\frac{0.0215 \text{ watt hours}}{\text{degrees}} \right) 90 \text{ degrees} \\ &= 1.93 \text{ watt hours} \end{aligned}$$

In terms of current this is

$$\begin{aligned} \text{Amp hours} &= \frac{1.93 \text{ watt hours}}{24 \text{ volts}} \\ &= 0.0806 \text{ amp hours/90 degrees} \end{aligned}$$

MOTOR POWER TO SLEW

Table 2 shows the motor conditions from startup for the slew mode for the conditions of load = 1/2 maximum load, and final speed = 0.45 degree/second.

TABLE 2. MOTOR CONDITIONS FROM STARTUP FOR SLEW CONDITIONS

Time MS	$1 - e^{-\frac{t}{RC}}$ $\frac{-t}{13.3 \text{ ms}}$ Fract Speed	Shaft Speed Deg/Sec	Shaft Travel (Av Vel) _T Arc-Sec	Accum Travel Arc-Sec	I _M Amps	W _M Watts	Consum Power Watt Sec	Accum Motor Power Watt Sec
2	0.14	0.063	0.227	0.227	6.26	92	0.184	0.184
4	0.26	0.117	0.648	0.875	5.48	80.6	0.161	0.345
6	0.36	0.162	1.00	1.875	4.82	70.9	0.141	0.487
8	0.45	0.202	1.31	4.185	4.25	62.6	0.125	0.612
10	0.53	0.24	1.59	5.775	3.74	54.9	0.11	0.722
12	0.59	0.26	1.80	7.575	3.35	49.2	0.098	0.820
14	0.65	0.29	1.98	9.555	3.01	44.3	0.088	0.908
16	0.70	0.31	2.16	11.175	2.60	39.4	0.077	0.987
18	0.74	0.33	2.30	14.105	2.41	35.5	0.071	1.05
20	0.78	0.35	2.52	16.535	1.74	25.7	0.257	1.31
22	0.81	0.36	2.55	19.085				
24	0.83	0.37	2.62	21.705				
26	0.85	0.38	2.70	24.405				
28	0.88	0.39	2.77	27.175	1.21	17.88	0.179	1.49
30	0.90	0.40	2.84	30.015				
32	0.91	0.41	2.91	32.925				
34	0.92	0.41	2.95	35.875				
36	0.93	0.42	2.99	38.865	0.88	12.98	0.156	1.65
38	0.94	0.42	3.02	41.885				
40	0.95	0.43	3.06	44.945				
42	0.96	0.43	3.10	48.045				
44	0.96	0.43	3.10	51.145	0.683	10.05	0.131	1.78
46	0.97	0.44	3.13	54.275				
48	0.97	0.44	3.17	57.445				
50	0.98	0.44	3.17	60.615				
52	0.98	0.44	3.17	63.340	0.683	10.05	0.131	1.78
54	0.98	0.44	3.17	66.515				
56	0.98	0.44	3.17	69.690				
58	0.99	0.45	3.24	72.93				
60	0.99	0.45	3.24	76.17	0.683	10.05	0.131	1.78
62	0.99	0.45	3.24	79.41				
64	0.99	0.45	3.24	82.65				

If in the command set we had a total of 15 81 arc-second steps, the final 14 would be metered out at the maximum rate of 0.45 degree/sec.

$$(81 \text{ arc-seconds}) 14 = 1134 \text{ arc-seconds}$$

$$0.45 \text{ degree/second} = 1620 \text{ arc-seconds/second}$$

$$\text{To meter out the final 14 would require } \frac{1134 \text{ arc-sec}}{1620 \frac{\text{arc-sec}}{\text{sec}}} = 0.7 \text{ sec}$$

$$\text{To meter out the total 15 would require } 0.700 + 0.06 = 0.760 \text{ second.}$$

$$\text{Power to deliver 14 would be } (10.05 \text{ watts}) (0.70 \text{ sec}) = 7.035 \text{ watt sec.}$$

$$\text{Power required to deliver 15 would be } 7.035 + 1.78 = 8.815 \text{ watt sec}$$

which is $\frac{8.815 \text{ watt sec}}{1215 \text{ arc-sec}}$.

$$\text{Per degree it is: } \left(\frac{8.815 \text{ watt sec}}{1215 \text{ arc-sec}} \right) \frac{3600 \text{ arc-sec}}{\text{degree}} = \frac{26.12 \text{ watt sec}}{\text{deg}}$$

$$\text{In watt hours it is: } \frac{26.12 \text{ watt sec}}{3600 \frac{\text{deg sec}}{\text{hr}}} = \frac{0.007255 \text{ watt hour}}{\text{degree}}$$

$$\text{In Amp hours it is: } \frac{0.007255 \text{ watt hr}}{24 \text{ volt deg}} = \frac{3.023 \times 10^{-4} \text{ Amp hours}}{\text{degree}}$$

If we were to do an emergency slew controlled by the heliostat, that is, avoid the start stop every second using the computer, a little less power would be required. We would essentially run at the 10.05 watt level all the time except for one start up power level of ≈ 1.5 watt second.

At 0.45 degree/second which is 1620 arc-second/second, one degree would require

$$\frac{\frac{3600 \text{ arc-sec}}{\text{deg}}}{\frac{1620 \text{ arc-sec}}{\text{sec}}} = \frac{2.22 \text{ Sec}}{\text{deg}}$$

$$\text{At 10.05 watts, this is } (10.05) 2.22 = \frac{22.31 \text{ watt sec}}{\text{degree}}$$

which is 0.006197 watt hours/degree which is 2.58×10^{-3} amp hours/degree.

For a 180 degree slew, this would amount to

$$\text{Power} = (180 \text{ degrees}) \frac{0.006197 \text{ WH}}{\text{degree}} + \frac{1.5 \text{ watt sec}}{3600 \frac{\text{sec}}{\text{Hr}}}$$

= 1.115 watt hours

= 0.0465 amp hours

For a 270 degree slew power would be

Power = (270) (0.006197) + 0.000416

= 1.6736 watt hours

= 0.0697 amp hours

In summary,

Power at 1/2 load during fine tracking = 0.0215 watt hour/degree

Power at 1/2 load during comp cont slew = 0.00775 watt hour/degree

Power at 1/2 load during Helio cont slew = 0.006197 watt hour/degree

FIXED POWER ESTIMATES FOR HELIOSTAT ELECTRONICS

The following estimates assume the use of low power Schottky T^2L .

	<u>+5V</u> ma	<u>+15V</u> ma	<u>-15V</u> ma	<u>+24V</u> ma
1. Communications Interface, 1 per system				
(est) 1.1 Line Receiver	10	0	0	0
1.2 UART	<u>20</u>	<u>0</u>	<u>7</u>	<u>0</u>
Total per subsystem, system	30	0	7	0
2. Osc and Clock Generator, 1 per system				
(est) 2.1 Flip-Flops (8)	32	0	0	0
2.2 Assorted Gate Chips (3)	<u>11</u>	<u>0</u>	<u>0</u>	<u>0</u>
Total per subsystem, system	43	0	0	0
3. Counter Control, Up/Down Counter, 2 per system				
(est) 3.1 4 bit up/down counters (2)	30	0	0	0
3.2 Assorted Chips (10)	<u>36</u>	<u>0</u>	<u>0</u>	<u>0</u>
Total per subsystem	66	0	0	0
Total per system	132	0	0	0
4. D/A Converters, 2 per system				
4.1 Burr Brown DAC-80 (1)	<u>20</u>	<u>25</u>	<u>25</u>	<u>0</u>
Total per subsystem	20	25	25	0
Total per system	40	50	50	0

	<u>+5V</u> ma	<u>+15V</u> ma	<u>-15V</u> ma	<u>-24V</u> ma
5. Scaling and Threshold Amp, 2 per system				
5.1 Op Amps (3)	0	5.25	5.25	0
5.2 Bias Resistors	<u>0</u>	<u>0.15</u>	<u>0.15</u>	<u>0</u>
Total per subsystem	0	5.4	5.4	0
Total per system	0	10.8	10.8	0
6. Power Amp, 3 per system				
6.1 "OFF" Condition				
6.1.1 Leakage, Power Transistors (4)	0	0	0	8
6.1.2 Op Amps (2)	<u>0</u>	<u>3.5</u>	<u>3.5</u>	<u>0</u>
Total per subsystem	0	3.5	3.5	8
Total per system	0	10.5	10.5	24
6.2 "ON" Condition				
6.2.1 R _B Output switch (1)	0	0	0	10
6.2.2 R _B Output Switch driver (1)	0	4	0	0
6.2.3 R _B Output Linear Output Trans (1)	0	0	0	16
6.2.4 Quasi Linear Driver IC (1)	0	0	0	4.6
6.2.5 Op Amps (2)	0	3.5	3.5	0
6.2.6 Leakage Power Trans (2)	<u>0</u>	<u>0</u>	<u>0</u>	<u>4</u>
Total per subsystem	0	7.5	3.5	34.6
Total per system	0	22.5	10.5	103.8
7. Encoder, 3 per system				
7.1 Optical Pair Bias (2)	0	10	0	0
7.2 Assorted gates and Inv chips (4)	7.4	0	0	0
7.3 One Shots (6)	66	0	0	0
7.4 Op Amps (2)	<u>0</u>	<u>10.2</u>	<u>8.2</u>	<u>0</u>
Total per subsystem	73.4	20.2	8.2	0
Total per system	220.2	60.6	8.2	0
8. Manual Controller				
(est) 8.1 UART (1)	20	0	7	0
8.2 Associated Logic Chips (4)	<u>14.4</u>	<u>0</u>	<u>0</u>	<u>0</u>
Total per subsystem	34.4	0	7	0
Fixed System Totals				
Power Amp Off, No Manual Controller	465	131.9	93.5	24 ma
	2.325	2.025	1.41	0.576 w

Low voltage power totals = $2.325 + 2.025 + 1.41 = 5.76$ watts.

Assume 40 percent conversion efficiency, low voltage power requirements at battery levels = $5.76/0.4 = 14.4$ watts. Including 0.576 watts for power amp leakage, total fixed power = $14.4 + 0.576 + 14.98$ Power Amp "ON" power. During slew on a per amplifier basis,

$$+15V \text{ power} = (0.0075) 15 = 0.1125 \text{ watt}$$

$$-15V \text{ power} = (0.0035) 15 = \underline{0.0525} \text{ watt}$$

$$\text{Total} \quad 0.165 \text{ watt}$$

At 40 percent efficiency, battery drain = $164/0.4 = 0.4125$ watts. +24V power = $(0.0346) (24) = 0.83$ watt. To this add 10 percent of slew power for Amp Sat or 1 watt. Total power amp power during slew = $0.41 + 0.83 + 1.0 = 2.24$ watts.

$$\text{Gimbal slew time/degree} = \frac{1 \text{ degree}}{0.45 \frac{\text{deg}}{\text{sec}}} = 2.2 \text{ sec/deg} = 6.17 \times 10^{-4} \text{ hr/deg.}$$

$$\begin{aligned} \text{Amp power for one degree on inner axis} &= \left(\frac{2.24 \text{ watts}}{\text{Amp}} \right) \left(\frac{6.17 \times 10^{-4} \text{ hr}}{\text{degree}} \right) 1 \text{ amp} \\ &= \underline{\underline{1.328 \times 10^{-3} \text{ watt hours}}} \\ &\quad \text{degree} \end{aligned}$$

Total power to slew inner axis = $0.00725 + 0.001382 = 0.00863$ watt hours/deg. Amp power for one degree on outer axis is 2X inner (2 amps) or

$$\frac{2 \times 1382 \times 10^{-3} \text{ watt hrs}}{\text{degree}} = \underline{\underline{2.764 \times 10^{-3} \text{ watt hrs}}} \\ \text{degree}$$

Total power to slew outer axis = $0.00725 + 0.002764 = 0.0100$ watt hour/degree.

Appendix 2
(CSRE DS-I)

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CSRE
DETAIL SPECIFICATION

PART I OF I

DS YG 8112A1

THIS DETAIL SPECIFICATION IS FOR

CONTRACT No. LC 403127

COLLECTOR SUBSYSTEM RESEARCH EXPERIMENT

SIGNATURES		DATE
ORIGINATOR	S. K. STEPHENSON	9-12-75
ACCEPTOR	S. K. STEPHENSON	
APPROVED BY	R. S. PARKER	

REVISIONS

LTR.	DESCRIPTION	APPROVAL	DATE
A	Change to Replanned Program Consistent with SRE Objectives.	<i>LP Ball</i> 1/16/76	1/16/76
B	Incorporated S&RC Comments Per P.E.L. No. C-18, 17 February 1976	<i>LP Ball</i>	3/11/76
C	Incorporated S&RC Comments Per P.E.L. No. C-26, 23 March 1976	<i>Relgman</i>	4-14-76

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COLLECTOR SUBSYSTEM RESEARCH EXPERIMENT

1.0 SCOPE

This specification establishes the performance, design, development, and test requirements for the Collector Subsystem Research Experiment (CSRE). The CSRE is an experimental system of computer controlled tracking reflectors used to determine focusing and pointing capabilities. A photo detector array is included along with computer software and peripherals.

2.0 APPLICABLE DOCUMENTS

The following documents, of latest issue form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of this specification, the contents of this specification shall be considered a superseding requirement.

- a. Interstate Commerce Commission Shipping Standards and Regulations.
- b. Standards of the American Institute of Steel Construction.
- c. Specifications for Aluminum Structures of the Aluminum Association.
- d. American Concrete Institute Standards.
- e. Standards of the National Electrical Manufacturing Association.

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3.0 REQUIREMENTS

3.1 Collector Subsystem Research Experiment Definition

The CSRE shall consist of an array of 4 heliostats to reflect the solar rays to a simulated receiver. The basic heliostat design requires a reflective surface which is mounted on a tracking support such that solar rays will be reflected onto a simulated fixed receiver continuously during sunlight hours. The heliostat may employ sensors, electronics, and drive mechanisms as required to direct the reflected rays of the sun onto the simulated receiver as well as provide auxiliary functions for other modes of operation and non-operational positionings. A design goal is that all heliostats be interchangeable regardless of position in the concentrating field.

A central computer controller, software, and associated peripherals provides computation of apparent sun position, processing of photo detector array data, heliostat command instructions, mode control, and control of heliostat communications.

Grid mounted photo detector array provides for periodic calibration of the heliostat and re-directed image mapping by relaying beam intensity data to the control computer.

Components of the experimental system are as follows:

- a. LG 8016A1 - Heliostat - An assembly of tracking solar reflectors mounted on a common set of two degree-of-freedom gimbals with drive trains, motors, and motor control electronics.
- b. BG 8251A1 - Computer, Heliostat Control - A central processor with associated peripheral equipment used to command heliostat to specified pointing vectors.
- c. LG 8015A1 - Photo Detector Array - A set of detectors used to measure heliostat re-directed beam intensity. This device functions both as a receiver simulator and calibration array.

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- d. QG 8172A1 - Software, Heliostat Control - A set of computer programs and subroutines used to command a heliostat and provide interface for operator and other equipment.
- e. - Support Services - The equipment, facilities, and instrumentation required for the experiment.

3.1.1 Collector Subsystem Research Experiment Diagram

Figure 1 shows a functional diagram of heliostats of the CSRE and its interfaces with the other subsystems.

3.1.2 Interface Definition

The interfaces between the Collector Subsystem and other subsystems are as follows.

3.1.2.1 Collector Positioning/Sun Movement/Receiver

Heliostat positioning during normal operations shall continuously or incrementally follow the sun and adjust the attitude of the reflective surfaces to position the reflected image on the receiver. Normal operations are defined as operation in the tracking mode during the time interval between one-half hour after true sun-rise and one-half hour before true sun-set.

3.1.2.2 Collector Controls/Master Controls

Heliostat controls shall be responsive to signals from a master control system.

3.1.2.3 Collector Foundation/Site

Heliostat support structure/foundations shall be designed and installed to maximize experimental data and yet not degrade the Collector Subsystem performance, Paragraph 3.2.1, while operating in anticipated experiment environments.

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I.E. - Interface Electronics

COLLECTOR SUBSYSTEM RESEARCH
EXPERIMENT INTERFACES

FIGURE 1

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3.1.2.4 Collector Subsystem/Prime Power

The CSRE shall be supplied with 115V rms, 60 Hz, single phase prime power.

3.2 Characteristics

3.2.1 Performance

The heliostats shall reflect the direct insolation as projected on the heliostat onto the receiver simulator, shall permit modifications to adjust power loads, and shall be rapidly controllable for emergency defocusing or stowage in the event of need.

- a. Reflective surfaces shall direct 95% of the re-directed insolation into the simulated receiver cavity with a 3.5 x 7.0 meter pattern measured perpendicular to the beam between 10 AM and 2 PM only, at a slant range of 1100 ft. The reflectance of the surface shall be as high as practical with a goal of 90% of the direct reflectance when measured by Cary Model 14 reflectometer or equivalent equipment. The surface life shall be sufficient to satisfy needs of research experiment. Total heliostat reflector area shall be approximately 40 m².
- b. Structural support shall be consistent with the requirements of Paragraph 3.2.5.
- c. The drive system shall adjust the position of the reflective surfaces to achieve specified receiver solar flux pattern throughout daily and seasonal variations. As a goal, the per axis pointing, tracking, or following accuracy shall be two milliradians (16') in the presence of the environmental disturbances defined in Paragraph 3.2.5. The drive shall have capability for survival, defocusing and maintenance operations that will allow reflective surfaces to be placed in stowage within 15 minutes and remove solar flux from the receiver within 12 seconds for 3 degree travel.

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- d. The Control System shall provide for all required operating modes which may include but are not necessarily limited to:
1. Initialization
 2. Offset pointing
 3. Tracking or following
 4. Emergency shutdown
 5. Manual control of single units
 6. Fail Safe
 7. Return to stowage
 8. Limit control
 9. Calibration and check-out
- e. The local heliostat controls shall meet applicable standards and be installed in suitable weathertight enclosure. These controls shall include limit of gimbal travel, and gimbal initialization attitude, as well as the logic to self command, the stowage mode, and gimbal drive inhibit.
- f. A suitable foundation design shall be provided for the proper stable support of the components of all heliostats.

3.2.2 Physical Characteristics

- a. The maximum heliostat weight shall be less than 5 tons but will be governed by cost, transportation and servicing constraints, structural requirements, and power consumption of the drive components.
- b. Shape limitations will be constrained only by the collector field layout, shadowing and blocking restraints, and servicing functions.
- c. The heliostat design shall provide a specified stored or "safe" position(s) which may be used during periods of maintenance, high winds, at night or in stormy weather.

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3.2.3 Reliability

Consideration shall be given in the heliostat design to achieving adequate reliability by providing operating margins and utilizing standard parts and conservative design practice.

3.2.4 Maintainability

- a. The reflective surfaces shall be readily cleaned without degradation. Water, ice, dust, or other degrading conditions such as bird droppings on the reflective surfaces should cause no permanent damage to the reflective characteristics. The entire heliostat should be designed such that potential maintenance points can be easily reached and components such as electronic units, motors, drives, etc., readily replaced.
- b. Elements subject to wear or damage should be easily inspected, serviced or replaced, or shall be designed for adequate life.
- c. The heliostats should be serviceable by personnel of normal skills and should require a minimum of specialized equipment and tools.

3.2.5 Environmental Conditions

Consideration shall be given in the heliostat design to normal ambient conditions of temperature variations from -20 degrees C to 60 degrees C (goal), humidity, rain, ice, hail, and sand storms. Consideration shall be given in the design of electrical and control components to minimizing damage caused by electrical disturbances or by currents expected during severe thunder storms. The heliostats shall be designed to withstand sustained winds up to 13.5 m/s and gusts with rms velocity of 13.5 m/s in an operational mode, and withstand sustained winds of 25 m/s and gusts with rms velocity of 38 m/s in a non-operational mode.

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3.3 Design and Construction

Design and construction standards compatible with the end use shall be employed.

3.3.1 Materials, Processes, and Parts

To the maximum extent possible, standard materials and processes shall be employed. Avoidance of highly stressed components and unusual materials is desired. As far as practical, off-the-shelf components used in industry should be employed.

3.3.2 Electrical Transients

The heliostat operation shall not be adversely affected by reasonable external or internal electrical transients. Components of the collector subsystem shall be protected, as required, against environments as specified in Paragraph 3.2.5.

3.3.3 Product Marking

The major elements in the heliostats shall be marked with suitable identification.

3.3.4 Workmanship

The heliostat and all associated items shall be fabricated and assembled in accordance with the modern engineering, shop, and field practices consistent with cost and performance requirements.

3.3.5 Interchangeability

Components with standard tolerances, where available, shall be used to permit interchangeability for servicing. Satisfactory replacement parts shall be available for the period of the contract.

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3.3.6 Safety

The heliostats shall be designed to minimize safety hazards to operating and service personnel and the public. Electrical supplies shall be adequately insulated and grounded. Moving elements shall be shielded as necessary to avoid entanglements.

Safeguards will be provided to protect personnel and the public from radiation damage to personnel. Shields, fences, and area denial and warning shall be considered.

3.4 Documentation

3.4.1 Characteristics And Performance

Equipment functions, normal operating characteristics, limiting conditions, test data, and performance curves, where applicable shall be documented.

3.4.2 Instructions

Instructions shall cover assembly, installation, alignment, adjustment, checking, lubrication, and maintenance. Operating instructions shall be prepared for startup, routine and normal operations, regulation and control, shutdown, and emergency conditions.

The operating instructions shall be submitted and approved six weeks prior to starting of tests in accordance with SOW requirements.

3.4.3 Construction

Good commercial practice shall be utilized in the design and construction of this experimental equipment. Layout drawings or sketches shall be prepared to show the equipment construction. Engineering data, wiring diagrams, and parts lists shall be prepared. Changes made to the design shall be incorporated into that documentation prior to completion of test activity.

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3.5 Logistics

3.5.1 Maintenance

Necessary maintenance shall be performed under supervision of engineering personnel familiar with the equipment.

3.5.2 Supply

Not applicable.

3.5.3 Facilities And Facility Equipment

Laboratory assembly and field test facilities shall be provided as necessary.

3.6 Personnel And Training

3.6.1 Personnel

The program shall be staffed primarily with engineering personnel commensurate with program funding.

3.6.2 Training

Not applicable.

3.7 Precedence

The order of precedence regarding importance of heliostat requirements characteristics for this development is as follows:

- a. Performance
- b. Capability
- c. Cost (dollars/square meter) of heliostat. (While the cost of prototype mirror modules is not of overriding importance, it is desirable that the design be such that comparable units could eventually be mass-produced in large numbers at low cost.)

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4.0 QUALITY ASSURANCE PROVISIONS

4.1 General

A test program at system level shall be conducted to validate the design for the solar pilot plant. System level testing will be conducted at Aero Florida. The system will consist of four heliostat subassemblies, a structure including photo-detector arrays, and H516 computer with associated peripherals.

4.2 Responsibility For Tests

Honeywell Aero will be responsible for conducting the system tests. A test plan shall be prepared to ensure the test program accomplishes the Research Experiment objectives.

4.3 Quality Conformance

The program shall be executed in accordance with the program Quality Plan.

4.3.1 Inspection

A design conformance verification consisting of a customer witnessed comparison of hardware to build documentation shall be accomplished.

4.4 Test Requirements

Testing shall be conducted to allow evaluation of design in attaining the performance specified in Paragraph 3.2. The testing shall include as a minimum.

4.4.1 Tracking Performance

The tracking system performance shall be tested under actual operating conditions.

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4.4.2 Mechanical Integrity

Mechanical integrity shall be evaluated by subjecting the heliostat to natural environments. Wind and temperature environments will also include induced environments.

4.4.3 Optical Performance

Optical performance will be evaluated through measurements of surface contours, beam quality, reflectivity, focal length, over a range of operational attitudes and environment.

5.0 PREPARATION FOR DELIVERY

Upon completion of the Research Experiment, the deliverable hardware shall be capable of being disassembled to the extent necessary to prepare for shipment.

6.0 NOTES

Not applicable.

10.0 NOT APPLICABLE

Appendix 3
STRUCTURAL ANALYSIS

NOMENCLATURE

This nomenclature is applicable to complete STARDYNE analysis.

The complete card image of all input data has been included for reference purposes. An explanation of this data is too involved for this report. Control Data publishes a STARDYNE Users Manual with complete details.

Deflection tables start with a title giving the conditions under which data is applicable. The maximum rotation and translation is listed. The table gives translation and rotation for each mode as follows:

- X1 Translation in the X1 Axis - Units of inches
- X2 Translation in the X2 Axis - Units of inches
- X3 Translation in the X3 Axis - Units of inches
- X4 Rotation about the X1 Axis - Units of Radians
- X5 Rotation about the X2 Axis - Units of Radians
- X6 Rotation about the X3 Axis - Units of Radians

The axis location is shown in a computer graphics plot of the system. Positive directions are shown and the right-hand sign convention was used. These plots also show mode numbers with respect to beams.

SECTION I

BAR JOIST CONFIGURATION
(CANTILEVER END ONLY)

COORDINATE REFERENCE FRAME

DISPLACEMENT CASE 1

MRI/STARDYNE FINITE ELEMENT MODEL PROJECTION ON X3-X1 PLANE CASE NO. 1

DISPLACEMENT CASE 2

MRI/STARDYNE FINITE ELEMENT MODEL PROJECTION ON X3-X1 PLANE CASE NO. 2

DISPLACEMENT CASE 3

ONE G LOAD AT 75 DEGREES
(BOTTOM CANTILEVER)
BAR JOIST CONFIGURATION

MRI/STARDYNE FINITE ELEMENT MODEL PROJECTION ON X3-X1 PLANE CASE NO. 3

		CARD IMAGE																								
		1	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80				
CARD NO		*****																						CARD TYPE		
2		* * SOLAR ENERGY HELIOSTAT FRAME STRUCTURAL ANALYSIS																* * *	X	* *						
3		* * PRELIMINARY ANALYSIS OF SINGLE CANTILEVER END																* * *	X	* *						
4		* * * ADDED X SPACES AND ALLOWED MOMENTS ON RODS																						* * *		* *
5	MATLG	1	STEEL										30.E6	.3	.28	9.F-6				.02	MATLG					
6	END																							END		
7	NODE	1	0.										0.	0.				0.	NODE							
8		2	0.										10.	0.				0.	NODE							
9		3	0.										20.	0.				0.	NODE							
10		4	0.										30.	0.				0.	NODE							
11		5	0.										40.	0.				0.	NODE							
12		6	0.										50.	0.				0.	NODE							
13		7	0.										60.	0.				0.	NODE							
14		8	0.										70.	0.				0.	NODE							
15		9	0.										80.	0.				0.	NODE							
16		10	0.										90.	0.				0.	NODE							
17		11	0.										100.	0.				0.	NODE							
18		12	0.										108.	0.				0.	NODE							
19		13	0.										0.	12.9				0.	NODE							
20		14	0.										10.	12.9				0.	NODE							
21		15	0.										30.	12.9				0.	NODE							
22		16	0.										50.	12.9				0.	NODE							
23		17	0.										70.	12.9				0.	NODE							
24		18	0.										90.	12.9				0.	NODE							
25		19	0.										100.	12.9				0.	NODE							
26		20	0.										108.	12.9				0.	NODE							
27		21	4.9										0.	0.				0.	NODE							
28		22	4.9										20.	0.				0.	NODE							
29		23	4.9										40.	0.				0.	NODE							
30		24	4.9										50.	0.				0.	NODE							
31		25	4.9										60.	0.				0.	NODE							
32		26	4.9										80.	0.				0.	NODE							
33		27	4.9										100.	0.				0.	NODE							
34		28	4.9										108.	0.				0.	NODE							
35		29	4.9										0.	12.9				0.	NODE							
36		30	4.9										10.	12.9				0.	NODE							
37		31	4.9										20.	12.9				0.	NODE							
38		32	4.9										30.	12.9				0.	NODE							
39		33	4.9										40.	12.9				0.	NODE							
40		34	4.9										50.	12.9				0.	NODE							
41		35	4.9										60.	12.9				0.	NODE							
42		36	4.9										70.	12.9				0.	NODE							
43		37	4.9										80.	12.9				0.	NODE							
44		38	4.9										90.	12.9				0.	NODE							
45		39	4.9										100.	12.9				0.	NODE							
46		40	4.9										108.	12.9				0.	NODE							
47		41	0.										40.	12.9				0.	NODE							
48		42	40.										0.	12.9				0.	NODE							
49		43	40.										0.	0.				0.	NODE							
50		44	4.9										90.	14.45				0.	NODE							
51		45	4.9										108.	14.45				0.	NODE							
52		46	2.45										90.	12.9				0.	NODE							
53		47	2.45										108.	12.9				0.	NODE							
54		48	2.45										90.	14.45				0.	NODE							

CARD NO	1	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	CARD TYPE
55			49			2.45				108.				14.45								NODE
56			50			0.				90.				14.45								NODE
57			51			0.				108.				14.45								NODE
58			52			2.45				90.				20.45								NODE
59			53			2.45				108.				20.45								NODE
60			54			2.45				100.				25.45								NODE
61			55			4.9				10.				0.								NODE
62	END																					END
63	RESTG		1			111111																RESTG
64			13			111111																RESTG
65			21			111111																RESTG
66			29			111111																RESTG
67			42			111111																RESTG
68			43			111111																RESTG
69	END																					END
70	WGHT		54			350.		350.		350.												WGHT
71	END																					END
72	BEAMG		1		1	2	21	1	1													BEAMG
73			2		2	3	21	1	1													BEAMG
74			3		3	4	21	1	1													BEAMG
75			4		4	5	21	1	1													BEAMG
76			5		5	6	21	1	1													BEAMG
77			6		6	7	21	1	1													BEAMG
78			7		7	8	21	1	1													BEAMG
79			8		8	9	21	1	1													BEAMG
80			9		9	10	21	1	1													BEAMG
81			10		10	11	21	1	1													BEAMG
82			11		11	12	21	1	1													BEAMG
83			12		13	14	29	1	1													BEAMG
84			13		14	15	29	1	1													BEAMG
85			14		15	41	29	1	1													BEAMG
86			15		41	16	29	1	1													BEAMG
87			16		16	17	29	1	1													BEAMG
88			17		17	18	29	1	1													BEAMG
89			18		18	19	29	1	1													BEAMG
90			19		19	20	29	1	1													BEAMG
91			20		1	13	2	1	2													BEAMG
92			21		1	14	2	1	2													BEAMG
93			22		14	3	2	1	2													BEAMG
94			23		3	15	2	1	2													BEAMG
95			24		15	5	2	1	2													BEAMG
96			25		5	16	2	1	2													BEAMG
97			26		34	6	16	1	2													BEAMG
98			27		16	7	2	1	2													BEAMG
99			28		7	17	2	1	2													BEAMG
100			29		17	4	2	1	2													BEAMG
101			30		9	18	2	1	2													BEAMG
102			31		18	11	2	1	2													BEAMG
103			32		11	39	19	1	2													BEAMG
104			33		11	20	2	1	2													BEAMG
105			34		20	12	2	1	2													BEAMG
106			35		21	55	1	1	1													BEAMG
107			36		22	23	1	1	1													BEAMG
108			37		23	24	1	1	1													BEAMG

*** STARDYNE 3.0 INPUT ***

CARD NO	CARD IMAGE																						CARD TYPE
	1	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80		
109				38		24		25		1	1	1										BEAMG	
110				39		25		26		1	1	1										BEAMG	
111				40		26		27		1	1	1										BEAMG	
112				41		27		28		1	1	1										BEAMG	
113				42		29		30		13	1	1										BEAMG	
114				43		30		31		13	1	1										BEAMG	
115				44		31		32		13	1	1										BEAMG	
116				45		32		33		13	1	1										BEAMG	
117				46		33		34		13	1	1										BEAMG	
118				47		34		35		13	1	1										BEAMG	
119				48		35		36		13	1	1										BEAMG	
120				49		36		37		13	1	1										BEAMG	
121				50		37		38		13	1	1										BEAMG	
122				51		38		39		13	1	1										BEAMG	
123				52		39		40		13	1	1										BEAMG	
124				53		21		29		31	1	2										BEAMG	
125				54		21		30		31	1	2										BEAMG	
126				55		30		22		31	1	2										BEAMG	
127				56		22		32		31	1	2										BEAMG	
128				57		32		23		31	1	2										BEAMG	
129				58		23		34		31	1	2										BEAMG	
130				60		34		25		31	1	2										BEAMG	
131				61		25		36		31	1	2										BEAMG	
132				62		36		26		31	1	2										BEAMG	
133				63		26		38		31	1	2										BEAMG	
134				64		38		27		31	1	2										BEAMG	
135				66		27		40		31	1	2										BEAMG	
136				67		40		28		31	1	2										BEAMG	
137				68		21		2		1	1	2										BEAMG	
138				69		2		22		1	1	2										BEAMG	
139				70		22		4		1	1	2										BEAMG	
140				71		4		23		1	1	2										BEAMG	
141				72		23		6		1	1	2										BEAMG	
142				73		6		25		1	1	2										BEAMG	
143				74		25		8		1	1	2										BEAMG	
144				75		8		26		1	1	2										BEAMG	
145				76		26		10		1	1	2										BEAMG	
146				77		10		27		1	1	2										BEAMG	
147				78		27		12		1	1	2										BEAMG	
148				79		12		28		1	1	2										BEAMG	
149				80		29		14		13	1	2										BEAMG	
150				81		14		31		13	1	2										BEAMG	
151				82		31		15		13	1	2										BEAMG	
152				83		15		33		13	1	2										BEAMG	
153				84		33		16		13	1	2										BEAMG	
154				85		16		35		13	1	2										BEAMG	
155				86		35		17		13	1	2										BEAMG	
156				87		17		37		13	1	2										BEAMG	
157				88		37		18		13	1	2										BEAMG	
158				89		18		39		13	1	2										BEAMG	
159				90		39		20		13	1	2										BEAMG	
160				91		20		40		13	1	2										BEAMG	
161				92		23		43		21	1	3										SUPPORT	
162				93		5		23		21	1	3										SUPPORT	

*** ONE G LOAD IN X3 DIRECTION (DOWN)

STATIC DEFLECTIONS FOR OUTPUT VECTOR 1

*MAXIMUM ROTATION IS AT NODE 37 *DOF = 4 VALUE = -.904029E-03

*MAXIMUM TRANSLATION IS AT NODE 28 *DOF = 3 VALUE = -.709761E-01

NODE	***** TRANSLATIONS *****			***** ROTATIONS (RADIAN) *****		
	X1	X2	X3	X4	X5	X6
2	-.3207149E-03	-.5464544E-03	-.1043348E-02	-.1970872E-03	.7472829E-04	.7997616E-04
3	-.1537305E-02	-.1666944E-02	-.3821218E-02	-.3582057E-03	.2298743E-03	.1313920E-03
4	-.2461498E-02	-.2587561E-02	-.8108892E-02	-.4823081E-03	.1897461E-03	.2104459E-04
5	-.2350670E-02	-.3322271E-02	-.1325863E-01	-.5370258E-03	.2917371E-03	.4809747E-04
6	-.3518929E-02	-.3856221E-02	-.1915465E-01	-.6901075E-03	.4757845E-03	.9709516E-04
7	-.3809485E-02	-.4446694E-02	-.2703552E-01	-.8307554E-03	.6051041E-03	-.1947216E-04
8	-.3428940E-02	-.4797681E-02	-.3539098E-01	-.8420366E-03	.3843977E-03	-.3840906E-04
9	-.3146062E-02	-.5152306E-02	-.4393358E-01	-.8728495E-03	.4916998E-03	-.1982078E-04
10	-.2996248E-02	-.5269035E-02	-.5284424E-01	-.8990999E-03	.4326154E-03	-.1219085E-04
11	-.2883842E-02	-.5393080E-02	-.6180177E-01	-.8886215E-03	.4451597E-03	-.9493321E-05
12	-.2821367E-02	-.5392652E-02	-.6888045E-01	-.8823070E-03	.4281765E-03	-.6501462E-05
14	.2713704E-03	.5706706E-03	-.1247785E-02	-.2100576E-03	.8769826E-04	-.7696022E-04
15	.2513948E-02	.2575109E-02	-.7916074E-02	-.4696150E-03	.3202088E-03	-.2347064E-04
16	.3576866E-02	.3849201E-02	-.1965202E-01	-.6849567E-03	.4658972E-03	-.1013520E-03
17	.3523258E-02	.4800800E-02	-.3522238E-01	-.8535016E-03	.4788953E-03	.3710274E-04
18	.3059747E-02	.5264386E-02	-.5297207E-01	-.8880253E-03	.4489323E-03	.2043323E-04
19	.2835205E-02	.5271409E-02	-.6178213E-01	-.8822921E-03	.4354305E-03	.2004897E-04
20	.2704039E-02	.5276857E-02	-.6887651E-01	-.8868026E-03	.4305233E-03	.1495857E-04
22	.4439691E-03	-.1383632E-02	-.4618762E-02	-.3778601E-03	.2169595E-04	.1055545E-04
23	-.2326496E-02	-.3063384E-02	-.1466271E-01	-.6678202E-03	.2795846E-03	.7702918E-04
24	-.2496370E-02	-.3711533E-02	-.2187285E-01	-.7128410E-03	.4463517E-03	-.4338109E-05
25	-.2523273E-02	-.4359183E-02	-.2888386E-01	-.7411586E-03	.3972193E-03	.7383450E-05
26	-.2729737E-02	-.5123216E-02	-.4587489E-01	-.9022571E-03	.4166431E-03	.6003623E-05
27	-.2780168E-02	-.5365557E-02	-.6389894E-01	-.8890883E-03	.4354015E-03	.3642204E-05
28	-.2821124E-02	-.5365859E-02	-.7097611E-01	-.8819975E-03	.4280310E-03	.5931246E-05
30	.1375498E-03	.4726475E-03	-.1721625E-02	-.2679105E-03	.5826438E-04	.3452108E-04
31	-.4172056E-03	.1325928E-02	-.4834430E-02	-.3586492E-03	.1621599E-03	-.2098380E-04
32	.8530139E-03	.2358006E-02	-.9007518E-02	-.4864942E-03	.1339361E-03	-.1796131E-03
33	.2360160E-02	.3032867E-02	-.1462858E-01	-.6286685E-03	.2654938E-03	-.6872148E-04
34	.2508848E-02	.3843579E-02	-.2135339E-01	-.7124163E-03	.4256108E-03	.1177606E-05
35	.2578296E-02	.4349185E-02	-.2888506E-01	-.7884076E-03	.3968438E-03	-.9193705E-05
36	.2675971E-02	.4861463E-02	-.3709844E-01	-.8566981E-03	.4116454E-03	-.1201177E-04
37	.2848410E-02	.5118327E-02	-.4596808E-01	-.9040285E-03	.4140805E-03	-.2410207E-04
38	.3060400E-02	.5358816E-02	-.5503358E-01	-.9034559E-03	.4551237E-03	-.1553904E-05
39	.2869564E-02	.5366083E-02	-.6398450E-01	-.8822387E-03	.4447060E-03	.2414253E-04
40	.2705994E-02	.5370662E-02	-.7097211E-01	-.8687339E-03	.4281503E-03	.1889947E-04
41	.2385377E-02	.3217633E-02	-.1327962E-01	-.5910933E-03	.2795011E-03	-.4264244E-04
44	.3711487E-02	.6732597E-02	-.5503415E-01	-.8856390E-03	0.	.1942364E-04
45	.3366886E-02	.6741328E-02	-.7097281E-01	-.8856601E-03	0.	.2040698E-04
46	.3060049E-02	.5314291E-02	-.5400485E-01	0.	0.	0.
47	.2795029E-02	.5321050E-02	-.6992760E-01	0.	0.	0.
48	.3712264E-02	.6685013E-02	-.5400513E-01	-.8846220E-03	.4207494E-03	.1941852E-04
49	.3367817E-02	.6692542E-02	-.6992795E-01	-.8846457E-03	.4276415E-03	.1937896E-04
50	.3713083E-02	.6635976E-02	-.5297249E-01	-.8836050E-03	0.	.2056812E-04
51	.3368716E-02	.6645027E-02	-.6887739E-01	-.8836314E-03	0.	.1940652E-04
52	.6237486E-02	.1199401E-01	-.5400816E-01	-.8850424E-03	.4214608E-03	.1692790E-04
53	.5932899E-02	.1199931E-01	-.6993264E-01	-.8842782E-03	.4269229E-03	.1689490E-04
54	.8190657E-02	.1642042E-01	-.6286157E-01	0.	.4244925E-03	.1542501E-04
55	-.1985172E-03	-.3874995E-03	-.1377197E-02	-.2490338E-03	.3605378E-04	-.3449197E-04

ONE G LOAD IN X3 DIRECTION (DOWN)

X - BOTTOM OF JOIST
• - TOP OF JOIST

X3
DEFL
(MILS)

70

60

50

40

30

20

10

10 20 30 40 50 60 70 80 90 100 110

BEAM LENGTH - INCH

Pivot Point Deflection:
62.8 mils

*** ONE G LOAD WITH HELIOSTAT TILTED TO 75 DEG (TOP CANTILEVER) ***

STATIC DEFLECTIONS FOR OUTPUT VECTOR 2

*MAXIMUM ROTATION IS AT NODE 54 *DOF = 5 VALUE = .651068E-02

*MAXIMUM TRANSLATION IS AT NODE 54 *DOF = 1 VALUE = .285893E+00

***** TRANSLATIONS ***** ROTATIONS (RADIAN) *****

NODE	X1	X2	X3	X4	X5	X6
2	-.3865248E-03	-.1271838E-03	.5386139E-03	.9431538E-04	.2731056E-03	.1348416E-03
3	-.2604986E-02	.4150711E-03	.1755969E-02	.1235160E-03	.2436388E-03	.2376726E-03
4	-.4004980E-02	.7128752E-03	.2531160E-02	-.1234851E-04	.1664751E-02	-.3201991E-04
5	-.4344852E-03	.2027125E-02	.7132068E-03	-.4093378E-03	.2062339E-02	-.8061512E-03
6	.1021882E-01	.3104954E-02	-.3575274E-02	-.1251306E-03	.1847904E-02	-.1383990E-02
7	.2736549E-01	.4477168E-02	-.1605092E-02	.2050256E-03	.2651431E-02	-.2004524E-02
8	.4966523E-01	.5140927E-02	-.1407343E-02	-.1162586E-03	.4347037E-02	-.2427580E-02
9	.7540524E-01	.5964972E-02	-.3234573E-02	-.2188050E-03	.4418397E-02	-.2689919E-02
10	.1029003E+00	.6040548E-02	-.5498362E-02	-.2346025E-03	.5565265E-02	-.2783114E-02
11	.1311758E+00	.6261669E-02	-.8011980E-02	-.2781214E-03	.5891788E-02	-.2914893E-02
12	.1549915E+00	.6247786E-02	-.1037124E-01	-.3044490E-03	.6152390E-02	-.3001402E-02
14	-.3885223E-04	.3153526E-03	.6634234E-03	.7504478E-04	.3513503E-03	.1269611E-04
15	.1936850E-02	.3232999E-02	.5666806E-03	-.1141841E-03	.6658684E-03	-.3448249E-03
16	.3165146E-01	.7637038E-02	-.1826140E-02	-.8153357E-04	.1693251E-02	-.2689055E-02
17	.9428069E-01	.1030950E-01	-.2969244E-02	-.2278179E-04	.3695980E-02	-.3584644E-02
18	.1708798E+00	.1175806E-01	-.4661729E-02	-.3163861E-03	.5523519E-02	-.3802223E-02
19	.2074981E+00	.1176868E-01	-.8603067E-02	-.3236677E-03	.5877222E-02	-.3507054E-02
20	.2348447E+00	.1177711E-01	-.1037682E-01	-.1888652E-03	.6116447E-02	-.3387799E-02
22	-.2979167E-02	-.5320217E-03	-.3763260E-02	-.2990818E-03	.5284197E-03	.2610893E-03
23	-.4421303E-03	-.2716709E-02	-.9259861E-02	-.1569272E-03	.1897332E-02	-.7560786E-03
24	.9791579E-02	-.4294733E-02	-.1062146E-01	-.4330131E-03	.1830321E-02	-.1408292E-02
25	.2773055E-01	-.5872341E-02	-.1815187E-01	-.7781345E-03	.2827234E-02	-.2068329E-02
26	.7537971E-01	-.7735165E-02	-.2925008E-01	-.4411950E-03	.4743403E-02	-.2651711E-02
27	.1315248E+00	-.8185725E-02	-.3765939E-01	-.3722876E-03	.5917172E-02	-.2917940E-02
28	.1549896E+00	-.8187153E-02	-.4050035E-01	-.3442822E-03	.6157169E-02	-.2940124E-02
30	-.9478665E-04	.2454573E-03	-.1591450E-02	-.2193219E-03	.3291522E-03	.1159859E-03
31	-.1865738E-02	.3208221E-03	-.3671082E-02	-.1987803E-03	.7576427E-03	.8164512E-04
32	-.7697012E-04	-.1784247E-03	-.5617344E-02	-.1855011E-03	.1635095E-03	-.5013004E-03
33	.9272004E-02	-.1072710E-02	-.7928609E-02	-.3474021E-03	.1360014E-02	-.1445631E-02
34	.3116331E-01	-.2184555E-02	-.1204722E-01	-.4599371E-03	.1482568E-02	-.2655588E-02
35	.6025666E-01	-.3978967E-02	-.1708994E-01	-.5470080E-03	.2822437E-02	-.3146752E-02
36	.9390029E-01	-.4356130E-02	-.2301058E-01	-.6317265E-03	.3357782E-02	-.3562442E-02
37	.1313828E+00	-.5620704E-02	-.2946406E-01	-.6104177E-03	.5057720E-02	-.3925642E-02
38	.1708879E+00	-.5633879E-02	-.3446000E-01	-.3275207E-03	.5286243E-02	-.3784531E-02
39	.2066835E+00	-.5642120E-02	-.3691749E-01	-.3306453E-03	.5838774E-02	-.3503281E-02
40	.2348409E+00	-.5658068E-02	-.4049314E-01	-.4866682E-03	.6141704E-02	-.3527258E-02
41	.9358081E-02	.5465437E-02	-.8910390E-03	-.1296193E-03	.1464541E-02	-.1422434E-02
44	.1803140E+00	-.5130976E-02	-.3446303E-01	-.3862050E-03	0.	-.3422507E-02
45	.2443671E+00	-.5136395E-02	-.4049433E-01	-.2860627E-03	0.	-.3669421E-02
46	.1708854E+00	.3061365E-02	-.1956406E-01	0.	0.	0.
47	.2348398E+00	.3059937E-02	-.2543437E-01	0.	0.	0.
48	.1803132E+00	.3566857E-02	-.1956434E-01	-.3260851E-03	.6116756E-02	-.3688307E-02
49	.2443673E+00	.3565612E-02	-.2543423E-01	-.3262919E-03	.6172698E-02	-.3424545E-02
50	.1803144E+00	.1226575E-01	-.4660101E-02	-.2659652E-03	0.	-.3423344E-02
51	.2443673E+00	.1226754E-01	-.1037481E-01	-.3665211E-03	0.	-.3669357E-02
52	.2169276E+00	.5522445E-02	-.1956496E-01	-.3257776E-03	.6245799E-02	-.3835539E-02
53	.2813800E+00	.5523434E-02	-.2543530E-01	-.3263154E-03	.6331055E-02	-.3326025E-02
54	.2858930E+00	.7153646E-02	-.2282791E-01	0.	.6510685E-02	-.3575776E-02
55	-.3375967E-03	-.7079666E-04	-.1118249E-02	-.2030429E-03	.2559642E-03	.1571971E-03

TOP CANTILEVER BEAM
ONE G LOAD AT 75 DEG.
X - Bottom of Joist
• - Top of Joist

X1
Defl.
(mils)

240

220

200

180

160

140

120

100

80

60

40

20

PIVOT POINT DEFLECTION:

286 mils

10 20 30 40 50 60 70 80 90 100 110

ONE G LOAD AT 75 DEG TOP CANTILEVER BEAM

X - Bottom of Joint
• - Top of Joint

46 1473

X3
Defl
(mils)

PIVOT POINT DEFLECTION: 22.8 mils

* * * ONE G LOAD WITH HELIOSTAT TILTED TO 75 DEG (BOTTOM CANTILEVER)

S T A T I C D E F L E C T I O N S

FOR OUTPUT VECTOR 3

*MAXIMUM ROTATION IS AT NODE 54 *DOF = 5 VALUE = -.629097E-02

*MAXIMUM TRANSLATION IS AT NODE 54 *DOF = 1 VALUE = -.281654E+00

***** TRANSLATIONS ***** ROTATIONS (RADIAN) *****

NODE	X1	X2	X3	X4	X5	X6
2	.2205208E-03	-.1556610E-03	-.1078651E-02	-.1963277E-03	-.2344262E-03	-.9344594E-04
3	.1808387E-02	-.1277892E-02	-.3733832E-02	-.3089232E-03	-.1246559E-03	-.1696641E-03
4	.2730914E-02	-.2052197E-02	-.6728322E-02	-.2372942E-03	-.1566538E-02	.4291259E-04
5	-.7822218E-03	-.3746732E-02	-.7575876E-02	.1313732E-03	-.1911336E-02	.8310465E-03
6	-.1204021E-01	-.5100934E-02	-.6339175E-02	-.2320691E-03	-.1601638E-02	.1434246E-02
7	-.2931828E-01	-.6778777E-02	-.1238849E-01	-.6350246E-03	-.2338229E-02	.1994445E-02
8	-.5144005E-01	-.7624207E-02	-.1691103E-01	-.3195796E-03	-.4148073E-02	.2407700E-02
9	-.7703364E-01	-.8631806E-02	-.1950545E-01	-.2329819E-03	-.4163893E-02	.2679659E-02
10	-.1044511E+00	-.8767800E-02	-.2185342E-01	-.2307716E-03	-.5341344E-02	.2776804E-02
11	-.1326685E+00	-.9053127E-02	-.2397661E-01	-.1818291E-03	-.5661374E-02	.2909979E-02
12	-.1564519E+00	-.9039022E-02	-.2528125E-01	-.1522331E-03	-.5930766E-02	.2998037E-02
14	.1793136E-03	-.1997346E-04	-.1309277E-02	-.1837706E-03	-.3059577E-03	-.5253072E-04
15	-.6356303E-03	-.1900127E-02	-.4664040E-02	-.1288886E-03	-.5001283E-03	.3326765E-03
16	-.2980007E-01	-.5644692E-02	-.8345748E-02	-.2730000E-03	-.1452102E-02	.2636595E-02
17	-.9245705E-01	-.7824607E-02	-.1526186E-01	-.4189906E-03	-.3448104E-02	.3603848E-02
18	-.1692960E+00	-.9033210E-02	-.2275661E-01	-.1432558E-03	-.5291152E-02	.3812799E-02
19	-.2060306E+00	-.9040196E-02	-.2337536E-01	-.1330067E-03	-.5651843E-02	.3517431E-02
20	-.2334451E+00	-.9045808E-02	-.2527366E-01	-.2701438E-03	-.5893608E-02	.3395542E-02
22	.3208965E-02	-.1841461E-03	.1372589E-02	.1035014E-03	-.5171899E-03	-.2556258E-03
23	-.7620641E-03	.1131101E-02	.1670443E-02	-.1887365E-03	-.1752619E-02	.7959489E-03
24	-.1108370E-01	.2373643E-02	-.6999303E-03	.6404657E-04	-.1599290E-02	.1406046E-02
25	-.2903659E-01	.3616027E-02	.3201585E-02	.3945108E-03	-.2621633E-02	.2072151E-02
26	-.7679262E-01	.5083388E-02	.5505231E-02	-.2581329E-04	-.4527749E-02	.2654818E-02
27	-.1329638E+00	.5408513E-02	.4585296E-02	-.8790451E-04	-.5691808E-02	.2919826E-02
28	-.1564498E+00	.5409785E-02	.3763113E-02	-.1122396E-03	-.5935620E-02	.2943194E-02
30	.1659824E-03	-.8149264E-06	.7003373E-03	.8065143E-04	-.2989946E-03	-.9811781E-04
31	.1649792E-02	.3654783E-03	.1168781E-02	.1314348E-04	-.6737087E-03	-.9250634E-04
32	.5184901E-03	.1398929E-02	.9550524E-03	-.6630828E-04	-.9418412E-04	.4083326E-03
33	-.8050385E-02	.2642522E-02	.3568575E-03	.2200332E-04	-.1222595E-02	.1410061E-02
34	-.2986473E-01	.4173992E-02	.9947044E-03	.9119041E-04	-.1262272E-02	.2656198E-02
35	-.5892213E-01	.6230105E-02	.2139031E-02	.1389282E-03	-.2617031E-02	.3141993E-02
36	-.9251520E-01	.6872424E-02	.3808422E-02	.1882996E-03	-.3144714E-02	.3556225E-02
37	-.1299085E+00	.8269950E-02	.5670980E-02	.1424925E-03	-.4843392E-02	.3913167E-02
38	-.1693039E+00	.8407602E-02	.5974626E-02	-.1401081E-03	-.5050671E-02	.3783727E-02
39	-.2051982E+00	.8419605E-02	.3799111E-02	-.1260015E-03	-.5608594E-02	.3515777E-02
40	-.2334403E+00	.8437923E-02	.375974E-02	.3701153E-04	-.5920093E-02	.3537040E-02
41	-.8123410E-02	-.3799990E-02	-.5982490E-02	-.1763306E-03	-.1319871E-02	.1400363E-02
44	-.1783929E+00	.8615768E-02	.5977349E-02	-.7220172E-04	0.	.3432560E-02
45	-.2426244E+00	.8625706E-02	.3758803E-02	-.1723549E-03	0.	.3679984E-02
46	-.1693015E+00	-.3106878E-03	-.8388851E-02	0.	0.	0.
47	-.2334396E+00	-.3057615E-03	-.1076015E-01	0.	0.	0.
48	-.1783918E+00	-.1066944E-03	-.8388713E-02	-.1317952E-03	-.5898976E-02	.3698358E-02
49	-.2426242E+00	-.1015525E-03	-.1076048E-01	-.1316007E-03	-.5951350E-02	.3434576E-02
50	-.1783925E+00	-.8830972E-02	-.2275846E-01	-.1913887E-03	0.	.3433990E-02
51	-.2426236E+00	-.8828073E-02	-.2527613E-01	-.9084651E-04	0.	.3679402E-02
52	-.2136991E+00	.6856525E-03	-.8389664E-02	-.1323204E-03	-.6027651E-02	.3844301E-02
53	-.2783091E+00	.6874106E-03	-.1076183E-01	-.1313870E-03	-.6110080E-02	.3334770E-02
54	-.2816535E+00	.1345564E-02	-.9709243E-02	0.	-.6290967E-02	.3583760E-02
55	.2348442E-03	-.1297731E-03	.4054117E-03	.7414302E-04	-.2373028E-03	-.1750501E-03

46 1473

K&E 10 X 10 TO 1/2 INCH • 7 1/2 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.

XI
(mils)

BOTTOM CANTILEVER BEAM
ONE G LOAD AT 75 DEG
X - BOTTOM OF JOIST
• - TOP OF JOIST

260
240
220
200
180
160
140
120
100
80
60
40
20

10 20 30 40 50 60 70 80 90 100 110

Pivot Point Defl
282 mils

ONE G LOAD AT 75 DEG
 BOTTOM CANTILEVER BEAM
 X - BOTTOM OF JOIST
 . - TOP OF JOIST

X3

(MILS)

PIVOT POINT

DEFLECTION = 9.7 MILS

40

30

20

10

0

10

20

30

40

50

60

70

80

90

100

110

BEAM LENGTH

SECTION II

CANTILEVER BEAM
 10-25 LBS/FT WIDE FLANGE AND
 10-25 LBS/FT WIDE FLANGE WITH
 1/8 INCH PLATES

DISPLACEMENT CASE 1

ONE G LOAD IN -X3 DIRECTION
10. INCH - 25 LB/FT WIDE
FLANGE

MRI/STARDYNE FINITE ELEMENT MODEL PROJECTION ON X3-X1 PLANE CASE NO. 1

DISPLACEMENT CASE 2

ONE G LOAD AT 75 DEGREES
(TOP CANTILEVER)
10 INCH - 25 LB/FT WIDE
FLANGE

MRI/STARDYNE FINITE ELEMENT MODEL PROJECTION ON X3-X1 PLANE CASE NO. 2

DISPLACEMENT CASE 3

MRI/STARDYNE FINITE ELEMENT MODEL. PROJECTION ON X3-X1 PLANE CASE NO. 3

*** STARDYNE 3.0 INPUT ***

		CARD IMAGE																						
		1	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80		
CARD NO		*****																						CARD TYPE
2	*** RUN 5 ***																							X
3	*** SOLAR ENERGY HELIOSTAT FRAME STRUCTURAL ANALYSIS ***																							X
4	*** PRELIMINARY ANALYSIS OF CANTILEVER END USING WIDE FLANGE ***																							X
5	*** SELECTED WIDE FLANGE IS 10 INCH - 25 LB/FT ***																							
6	MATLG 1 STEEL 30.E6 .3 .28 9.E-6 .02																							MATLG
7	END																							END
8	NODE 1						0.				10.					0.							NODE	
9	2						0.				20.					0.							NODE	
10	3						0.				30.					0.							NODE	
11	4						0.				40.					0.							NODE	
12	5						0.				50.					0.							NODE	
13	6						0.				60.					0.							NODE	
14	7						0.				70.					0.							NODE	
15	8						0.				80.					0.							NODE	
16	9						0.				90.					0.							NODE	
17	10						0.				100.					0.							NODE	
18	11						0.				108.					0.							NODE	
19	12						40.				0.					-5.29							NODE	
20	13						40.				0.					5.29							NODE	
21	14						0.				0.					0.							NODE	
22	15						0.				90.					5.29							NODE	
23	16						0.				108.					5.29							NODE	
24	17						0.				40.					5.29							NODE	
25	18						0.				40.					-5.29							NODE	
26	19						0.				92.					8.79							NODE	
27	20						0.				106.					8.79							NODE	
28	21						0.				100.					9.29							NODE	
29	50						-10.				0.					0.							NODE	
30	51						-10.				0.					5.29							NODE	
31	52						-10.				0.					-5.29							NODE	
32	END																							END
33	RESTG 12						111111																RESTG	
34	13						111111																RESTG	
35	14						111111																RESTG	
36	END																							END
37	WGHT 21 350. 350. 350.																							WGHT
38	END																							END
39	BEAMG 1 14 1 50 1 1																							BEAMG
40	2 11 1 1 2 1 50 1 1																							BEAMG
41	12 9 15 14 1 2																							BEAMG
42	13 11 16 14 1 2																							BEAMG
43	14 4 17 14 1 2																							BEAMG
44	15 4 18 14 1 2																							BEAMG
45	16 12 18 51 1 3																							BEAMG
46	17 13 17 52 1 3																							BEAMG
47	END																							END
48	BPROP1 1 7.36 .373 133. .13.7 .85 .85																							BPROP
49	BPROP2 1 5.762 10.08																							BPROP
50	BPROP6 2																							BPROP
51	BPROP1 3 .527 .00618 .110 .110 .85 .85																							BPROP
52	BPROP2 3 2.3 2.3																							BPROP
53	END																							END
54	TRIAB 1 19 20 21 1-1 1.																							TRIAB

CARD NO	1	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	CARD TYPE
55	END																					END
56	QUADB	1			15			16		20			19		1	1	1.14			-2		QUADB
57	END																					END
58	ENDGEOM																					ENDGE
59	*** STATIC INERTIA LOAD FOR HELIOSTAT WITH 10 INCH WF BEAM ***																					***
60	STATIC	0			0			-2														STATI
61	*** ONE G LOAD IN X3 DIRECTION (DOWN) (10-25 WF) ***																					***
62	ACCEL	-1																				ACCEL
63	END																					END
64	END CASE																					END C
65	*** ONE G LOAD AT 75 DEG (TOP CANTILEVER) (10-25WF) ***																					***
66	ACCEL	-1			-.9659					.2588												ACCEL
67	END																					END
68	END CASE																					END C
69	*** ONE G LOAD AT 75 DEG (BOTTOM CANTI) (10-25WF) ***																					***
70	ACCEL	-1			.9659					.2588												ACCEL
71	END																					END
72	END CASE																					END C
73	ALL DONE																					ALL D
74	OPTION								1							1				60		OPTIO
75	BEAM	0			0			0												500.		BEAM
76	TPLATE				1			1		1		1					0			500.		TPLAT
77	QPLATE				1			1														QPLAT
78	ENDMODEL																					ENDMO

*** ONE G LOAD IN X3 DIRECTION (DOWN) (10-25 WF) ***

S T A T I C D E F L E C T I O N S FOR OUTPUT VECTOR 1

*MAXIMUM ROTATION IS AT NODE 11 *DOF = 4 VALUE = -.572350E-03

*MAXIMUM TRANSLATION IS AT NODE 11 *DOF = 3 VALUE = -.440307E-01

NODE	***** TRANSLATIONS: *****			***** ROTATIONS (RADIAN) *****		
	X1	X2	X3	X4	X5	X6
1	-.1713723E-13	.8730539E-15	-.6710380E-03	-.1155288E-03	.9069674E-04	.2247732E-14
2	-.3572611E-13	.1746108E-14	-.2421956E-02	-.2166331E-03	.1813935E-03	.2903289E-15
3	-.1371528E-13	.2619162E-14	-.5111092E-02	-.3038294E-03	.2720902E-03	-.5872210E-14
4	.9093420E-13	.3524958E-14	-.8601949E-02	-.3776343E-03	.3627870E-03	-.1623817E-13
5	.3146014E-12	.3281947E-14	-.1276336E-01	-.4387485E-03	.3627870E-03	-.2801537E-13
6	.6474849E-12	.3028436E-14	-.1747143E-01	-.4876226E-03	.3627870E-03	-.3808127E-13
7	.1072471E-11	.2774926E-14	-.2260634E-01	-.5247730E-03	.3627870E-03	-.4643594E-13
8	.1572448E-11	.2521416E-14	-.2805343E-01	-.5507163E-03	.3627870E-03	-.5307939E-13
9	.2130289E-11	.2262079E-14	-.3370322E-01	-.5659689E-03	.3627870E-03	-.5801160E-13
10	.2720062E-11	-.4680187E-05	-.3942856E-01	-.5717441E-03	.3627870E-03	-.5978804E-13
11	.3202965E-11	-.8424337E-05	-.4403072E-01	-.5723496E-03	.3627870E-03	-.6081888E-13
15	.1919143E-02	.2993976E-02	-.3370322E-01	-.5659689E-03	.3627870E-03	-.5801160E-13
16	.1919143E-02	.3019305E-02	-.4403072E-01	-.5723496E-03	.3627870E-03	-.6081888E-13
17	.1919143E-02	.1997685E-02	-.8601949E-02	-.3776343E-03	.3627870E-03	-.1623817E-13
18	-.1919143E-02	-.1997685E-02	-.8601949E-02	-.3776343E-03	.3627870E-03	-.1623817E-13
19	.3188897E-02	.5009167E-02	-.3485334E-01	0.	.3627870E-03	-.6944105E-13
20	.3188897E-02	.5020661E-02	-.4288720E-01	0.	.3627870E-03	-.7169740E-13
21	.3370291E-02	.5302659E-02	-.3944500E-01	0.	.3627870E-03	-.7127419E-13

*** ONE G LOAD AT 75 DEG (TOP CANTILEVER) (10-25WF) ***

STATIC DEFLECTIONS FOR OUTPUT VECTOR 2
 *MAXIMUM ROTATION IS AT NODE 11 *DOF = 5 VALUE = .390881E-01
 *MAXIMUM TRANSLATION IS AT NODE 21 *DOF = 1 VALUE = .489349E+00

NODE	***** TRANSLATIONS *****			***** ROTATIONS (RADIANS) *****		
	X1	X2	X3	X4	X5	X6
1	-.7634469E-03	.6311699E-04	-.2117188E-03	-.3762941E-04	.1311045E-03	.9725369E-04
2	-.1506103E-02	.1262340E-03	-.7806867E-03	-.7161988E-04	.2622089E-03	-.5516769E-05
3	-.2035126E-03	.1893510E-03	-.1671183E-02	-.1021051E-03	.3933134E-03	-.3131545E-03
4	.5217214E-02	.2524680E-03	-.2848823E-02	-.1292187E-03	.5244178E-03	-.8305026E-03
5	.1655197E-01	.2524680E-03	-.4240666E-02	-.1450351E-03	.8120083E-02	-.1403570E-02
6	.3303673E-01	.2524680E-03	-.5773984E-02	-.1576837E-03	.1571575E-01	-.1861862E-02
7	.5354794E-01	.2524680E-03	-.7417767E-02	-.1672982E-03	.2331141E-01	-.2210221E-02
8	.7701051E-01	.2524680E-03	-.9142344E-02	-.1740123E-03	.3090708E-01	-.2453490E-02
9	.1023978E+00	.2524680E-03	-.1091938E-01	-.1779597E-03	.3850274E-01	-.2596514E-02
10	.1285023E+00	.2512567E-03	-.1271597E-01	-.1794543E-03	.3882795E-01	-.2623235E-02
11	.1495671E+00	.2502877E-03	-.1415890E-01	-.1796110E-03	.3908812E-01	-.2643008E-02
15	.3060773E+00	.1193875E-02	-.1091938E-01	-.1779597E-03	.3850274E-01	-.2596514E-02
16	.3563433E+00	.1200430E-02	-.1415890E-01	-.1796110E-03	.3908812E-01	-.2643008E-02
17	.7991385E-02	.9360348E-03	-.2848823E-02	-.1292187E-03	.5244178E-03	-.8305026E-03
18	.2443044E-02	-.4310989E-03	-.2848823E-02	-.1292187E-03	.5244178E-03	-.8305026E-03
19	.4465342E+00	.1825611E-02	-.1128000E-01	0.	.3865340E-01	-.2915987E-02
20	.4875165E+00	.1828585E-02	-.1379998E-01	0.	.3901683E-01	-.2937614E-02
21	.4893487E+00	.1917310E-02	-.1272022E-01	0.	.3886304E-01	-.2942143E-02

* * * ONE G LOAD AT 75 DEG (BOTTOM CANTI) (10-25WF) * * *

S T A T I C D E F L E C T I O N S FOR OUTPUT VECTOR 3

*MAXIMUM ROTATION IS AT NODE 11 *DOF = 5 VALUE = -.389003E-01

*MAXIMUM TRANSLATION IS AT NODE 21 *DOF = 1 VALUE = -.487604E+00

***** TRANSLATIONS ***** ROTATIONS (RADIAN) *****

NODE	X1	X2	X3	X4	X5	X6
1	.7634469E-03	-.6311699E-04	-.1356105E-03	-.2216828E-04	-.8415982E-04	-.9725369E-04
2	.1506103E-02	-.1262340E-03	-.4729177E-03	-.4050940E-04	-.1683196E-03	.5516769E-05
3	.2035126E-03	-.1893510E-03	-.9743185E-03	-.5515702E-04	-.2524795E-03	.3131545E-03
4	-.5217214E-02	-.2524680E-03	-.1603546E-02	-.6624482E-04	-.3366393E-03	.8305026E-03
5	-.1655197E-01	-.2524680E-03	-.2365651E-02	-.8206118E-04	-.7932305E-02	.1403570E-02
6	-.3303673E-01	-.2524680E-03	-.3269230E-02	-.9470979E-04	-.1552797E-01	.1861862E-02
7	-.5354794E-01	-.2524680E-03	-.4283275E-02	-.1043243E-03	-.2312363E-01	.2210221E-02
8	-.7701051E-01	-.2524680E-03	-.5378112E-02	-.1110385E-03	-.3071930E-01	.2453490E-02
9	-.1023978E+00	-.2524680E-03	-.6525407E-02	-.1149858E-03	-.3831497E-01	.2596514E-02
10	-.1285023E+00	-.2536792E-03	-.7692258E-02	-.1164804E-03	-.3864017E-01	.2623235E-02
11	-.1495671E+00	-.2546482E-03	-.8631401E-02	-.1166372E-03	-.3890034E-01	.2643008E-02
15	-.3050839E+00	.3558071E-03	-.6525407E-02	-.1149858E-03	-.3831497E-01	.2596514E-02
16	-.3553499E+00	.3623623E-03	-.8631401E-02	-.1166372E-03	-.3890034E-01	.2643008E-02
17	-.6998036E-02	.9796712E-04	-.1603546E-02	-.6624482E-04	-.3366393E-03	.8305026E-03
18	-.3436392E-02	-.6029030E-03	-.1603546E-02	-.6624482E-04	-.3366393E-03	.8305026E-03
19	-.4448837E+00	.7671344E-03	-.6760086E-02	0.	-.3846562E-01	.2915987E-02
20	-.4858659E+00	.7701089E-03	-.8398431E-02	0.	-.3882905E-01	.2937614E-02
21	-.4876042E+00	.8273465E-03	-.7696511E-02	0.	-.3867527E-01	.2942143E-02

DISPLACEMENT CASE 1

ONE G LOAD -X3 DIRECTION
 10 INCH - 25 LB/FT WIDE
 FLANGE WITH 1/8 PLATE BOTH
 SIDES FROM NODE 4 THROUGH
 NODE 11

MRI/STARDYNE FINITE ELEMENT MODEL PROJECTION ON X3-X1 PLANE CASE NO. 1

DISPLACEMENT CASE 2

MRI/STARDYNE FINITE ELEMENT MODEL PROJECTION ON X3-X1 PLANE CASE NO. 2

MRI/STARDYNE FINITE ELEMENT MODEL PROJECTION ON X3-X1 PLANE CASE NO. 3

*** STARDYNE 3.0 INPUT ***

CARD NO		CARD IMAGE																CARD TYPE					
		1	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	
2	*** RUN 6 ***																						X
3	*** SOLAR ENERGY HELIOSTAT FRAME STRUCTURAL ANALYSIS ***																						X
4	*** PRELIMINARY ANALYSIS OF CANTILEVER END USING WIDE FLANGE ***																						X
5	*** SELECTED WIDE FLANGE IS 10 INCH - 25 LB/FT ***																						X
6	*** 0.125 INCH PLATES ON EACH SIDE OF WF FOR 60 INCHES ***																						
7	MATLG 1 STEEL 30.E6 .3 .28 9.E-6 .02																						MATLG
8	END																						END
9	NODE 1																						NODE
10	2																						NODE
11	3																						NODE
12	4																						NODE
13	5																						NODE
14	6																						NODE
15	7																						NODE
16	8																						NODE
17	9																						NODE
18	10																						NODE
19	11																						NODE
20	12																						NODE
21	13																						NODE
22	14																						NODE
23	15																						NODE
24	16																						NODE
25	17																						NODE
26	18																						NODE
27	19																						NODE
28	20																						NODE
29	21																						NODE
30	50																						NODE
31	51																						NODE
32	52																						NODE
33	END																						END
34	RESTG 12																						RESTG
35	13																						RESTG
36	14																						RESTG
37	END																						END
38	WGHT 21 350. 350. 350.																						WGHT
39	END																						END
40	BEAMG 1 14 1 50 1 1																						BEAMG
41	2 4 1 1 2 1 50 1 1																						BEAMG
42	5 11 4 1 5 1 50 1 4																						BEAMG
43	12 9 15 14 1 2																						BEAMG
44	13 11 16 14 1 2																						BEAMG
45	14 4 17 14 1 2																						BEAMG
46	15 4 18 14 1 2																						BEAMG
47	16 12 18 51 1 3																						BEAMG
48	17 13 17 52 1 3																						BEAMG
49	END																						END
50	BPROP1 1 7.36 .373 133. 13.7 .85 .85																						BPROP
51	BPROP2 1 5.762 10.08																						BPROP
52	BPROP6 2																						BPROP
53	BPROP1 3 .527 .00618 .110 .110 .85 .85																						BPROP
54	BPROP2 3 2.3 2.3																						BPROP

CARD NO

CARD NO	1	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80
55	RPROP1	4		9.67		33.8		148.		32.		.85		.85							
56	RPROP2	4		5.762		10.08															
57	END																				
58	TRIAB	1		19		20		21		1-1		1.									
59	END																				
60	QUADB	1		15		16		20		19		1	1	1.14		-2					
61	END																				
62	ENDGEOM																				
63	*** STATIC INERTIA LOAD FOR HELIOSTAT WITH 10-25WF WITH PLATES) ***																				
64	STATIC	0		0		-2															
65	*** ONE G LOAD IN X3 DIRECTION (DOWN) (10-25 WF WITH 1/8 PLATE) ***																				
66	ACCEL	-1						1													
67	END																				
68	END CASE																				
69	*** ONE G LOAD AT 75 DEG (TOP CANTILEVER) (10-25WF WITH 1/8 PLATE) ***																				
70	ACCEL	-1		-.9659				.2588													
71	END																				
72	END CASE																				
73	*** ONE G LOAD AT 75 DEG (BOTTOM CANTI) (10-25WF WITH 1/8 PLATE) ***																				
74	ACCEL	-1		.9659				.2588													
75	END																				
76	END CASE																				
77	ALL DONE																				
78	OPTION							1							1		60				
79	BEAM		0		0		0										500.				
80	TPLATE				1		1		1		1					0	500.				
81	QPLATE				1		1														
82	ENDMODEL																				

CARD TYPE

BPROP
 BPROP
 END
 TRIAB
 END
 QUADB
 END
 ENDGEOM

 STATI

 ACCEL
 END
 END C

 ACCEL
 END
 END C

 ACCEL
 END
 END C
 ALL D
 OPTIO
 BEAM
 TPLAT
 QPLAT
 ENDMO

*** ONE G LOAD IN X3 DIRECTION (DOWN) (10-25 WF WITH 1/8 PLATE) ***

S T A T I C D E F L E C T I O N S FOR OUTPUT VECTOR 1

*MAXIMUM ROTATION IS AT NODE 11 *DOF = 4 VALUE = -.584091E-03

*MAXIMUM TRANSLATION IS AT NODE 11 *DOF = 3 VALUE = -.455706E-01

***** TRANSLATIONS ***** ROTATIONS (RADIAN) *****

NODE	X1	X2	X3	X4	X5	X6
1	-.176475E-13	.7744343E-15	-.7158997E-03	-.1231063E-03	.9639186E-04	.2315396E-14
2	-.3681036E-13	.1548869E-14	-.2581972E-02	-.2306917E-03	.1927837E-03	.3030712E-15
3	-.1421137E-13	.2323303E-14	-.5445592E-02	-.3232727E-03	.2891756E-03	-.6036973E-14
4	.9342527E-13	.3136380E-14	-.9159296E-02	-.4013657E-03	.3855675E-03	-.1669956E-13
5	.2877650E-12	.2879423E-14	-.1352910E-01	-.4591951E-03	.3855675E-03	-.2188796E-13
6	.5302161E-12	.2596390E-14	-.1841462E-01	-.5051800E-03	.3855675E-03	-.2632376E-13
7	.8132525E-12	.2313357E-14	-.2370044E-01	-.5399301E-03	.3855675E-03	-.3000503E-13
8	.1129329E-11	.2030324E-14	-.2927729E-01	-.5640555E-03	.3855675E-03	-.3293180E-13
9	.1470865E-11	.1762479E-14	-.3504194E-01	-.5781657E-03	.3855675E-03	-.3510596E-13
10	.1828924E-11	-.3511746E-05	-.4088004E-01	-.5835143E-03	.3855675E-03	-.3616485E-13
11	.2120124E-11	-.6321143E-05	-.4557064E-01	-.5840910E-03	.3855675E-03	-.3636189E-13
15	.2039652E-02	.3058497E-02	-.3504194E-01	-.5781657E-03	.3855675E-03	-.3510596E-13
16	.2039652E-02	.3083520E-02	-.4557064E-01	-.5840910E-03	.3855675E-03	-.3636189E-13
17	.2039652E-02	.2123225E-02	-.9159296E-02	-.4013657E-03	.3855675E-03	-.1669956E-13
18	-.2039652E-02	-.2123225E-02	-.9159296E-02	-.4013657E-03	.3855675E-03	-.1669956E-13
19	.3389138E-02	.5112717E-02	-.3621441E-01	0.	.3855675E-03	-.3736613E-13
20	.3389138E-02	.5124091E-02	-.4440475E-01	0.	.3855675E-03	-.3843075E-13
21	.3581922E-02	.5411729E-02	-.4089549E-01	0.	.3855675E-03	-.3812458E-13

*** ONE G LOAD AT 75 DEG (TOP CANTILEVER) (10-25WF WITH 1/8 PLATE)***

STATIC DEFLECTIONS FOR OUTPUT VECTOR 2

*MAXIMUM ROTATION IS AT NODE 21 *DOF = 6 VALUE = -.173078E-02

*MAXIMUM TRANSLATION IS AT NODE 20 *DOF = 1 VALUE = .110563E+00

***** TRANSLATIONS

***** ROTATIONS (RADIAN) *****

NODE	X1	X2	X3	X4	X5	X6
1	-.8038275E-03	.6717697E-04	-.2233290E-03	-.3959046E-04	.1325784E-03	.1021576E-03
2	-.1579367E-02	.1343539E-03	-.8220989E-03	-.7525824E-04	2.2651567E-03	-.7016275E-05
3	-.1890880E-03	.2015309E-03	-.1757751E-02	-.1071370E-03	3.3977351E-03	-.3323648E-03
4	.5552972E-02	.2687079E-03	-.2993064E-02	-.1353604E-03	4.5303134E-03	-.8787311E-03
5	.1573215E-01	.2687079E-03	-.4438840E-02	-.1503266E-03	5.6141354E-03	-.1137072E-02
6	.2822515E-01	.2687079E-03	-.6018080E-02	-.1622275E-03	6.6979574E-03	-.1342499E-02
7	.4251644E-01	.2687079E-03	-.7700922E-02	-.1712209E-03	7.7817794E-03	-.1497738E-02
8	.5811778E-01	.2687079E-03	-.9459077E-02	-.1774645E-03	8.8656014E-03	-.1605513E-02
9	.7456814E-01	.2687079E-03	-.1126584E-01	-.1811162E-03	9.9494233E-03	-.1668547E-02
10	.9139013E-01	.2677990E-03	-.1309161E-01	-.1825004E-03	10.9895209E-03	-.1688121E-02
11	.1049234E+00	.2670720E-03	-.1455743E-01	-.1826497E-03	11.1021599E-02	-.1689486E-02
15	.7959059E-01	.1226813E-02	-.1126584E-01	-.1811162E-03	9.9494233E-03	-.1668547E-02
16	.1103277E+00	.1233289E-02	-.1455743E-01	-.1826497E-03	10.1021599E-02	-.1689486E-02
17	.9358330E-02	.9847643E-03	-.2993064E-02	-.1353604E-03	5.303134E-03	-.8787311E-03
18	.2747614E-02	-.4473486E-03	-.2993064E-02	-.1353604E-03	5.303134E-03	-.8787311E-03
19	.8636640E-01	.1868649E-02	-.1163225E-01	0.	.9949973E-03	-.1727293E-02
20	.1105631E+00	.1871593E-02	-.1419273E-01	0.	.1058360E-02	-.1729207E-02
21	.1007080E+00	.1961777E-02	-.1309561E-01	0.	.1033387E-02	-.1730784E-02

* * * ONE G LOAD AT 75 DEG (BOTTOM CANTI) (10-25WF WITH 1/8 PLATE) * * *

STATIC DEFLECTIONS FOR OUTPUT VECTOR 3
 *MAXIMUM ROTATION IS AT NODE 21 *DOF = 6 VALUE = .173078E-02
 *MAXIMUM TRANSLATION IS AT NODE 16 *DOF = 1 VALUE = -.109272E+00

NODE	***** TRANSLATIONS *****			***** ROTATIONS (RADIAN) *****		
	X1	X2	X3	X4	X5	X6
1	.8038275E-03	-.6717697E-04	-.1472207E-03	-.2412934E-04	-.8268593E-04	-.1021576E-03
2	.1579367E-02	-.1343539E-03	-.5143300E-03	-.4414777E-04	-.1653719E-03	.7016275E-05
3	.1890880E-03	-.2015309E-03	-.1060897E-02	-.6018894E-04	-.2480578E-03	.3323648E-03
4	-.5552972E-02	-.2687079E-03	-.1747788E-02	-.7238652E-04	-.3307437E-03	.8787311E-03
5	-.1573215E-01	-.2687079E-03	-.2563824E-02	-.8735276E-04	-.4145657E-03	.1137072E-02
6	-.2822515E-01	-.2687079E-03	-.3513326E-02	-.9925364E-04	-.4983877E-03	.1342499E-02
7	-.4251644E-01	-.2687079E-03	-.4566429E-02	-.1082470E-03	-.5822097E-03	.1497738E-02
8	-.5811778E-01	-.2687079E-03	-.5694846E-02	-.1144906E-03	-.6660316E-03	.1605513E-02
9	-.7456814E-01	-.2687079E-03	-.6871870E-02	-.1181424E-03	-.7498536E-03	.1668547E-02
10	-.9139013E-01	-.2696167E-03	-.8067901E-02	-.1195266E-03	-.7899512E-03	.1688121E-02
11	-.1049234E+00	-.2703438E-03	-.9029933E-02	-.1196758E-03	-.8220292E-03	.1689486E-02
15	-.7853487E-01	.3562652E-03	-.6871870E-02	-.1181424E-03	-.7498536E-03	.1668547E-02
16	-.1092720E+00	.3627413E-03	-.9029933E-02	-.1196758E-03	-.8220292E-03	.1689486E-02
17	-.7302606E-02	.1142168E-03	-.1747788E-02	-.7238652E-04	-.3307437E-03	.8787311E-03
18	-.3803338E-02	-.6516326E-03	-.1747788E-02	-.7238652E-04	-.3307437E-03	.8787311E-03
19	-.8461218E-01	.7776931E-03	-.7112330E-02	0.	-.7954276E-03	.1727293E-02
20	-.1088089E+00	.7806368E-03	-.8791174E-02	0.	-.8587904E-03	.1729207E-02
21	-.9885403E-01	.8393339E-03	-.8071897E-02	0.	-.8338177E-03	.1730784E-02

46 1473

K&E
10 X 10 TO 1/2 INCH • 7/8 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.

ONE G LOAD AT 75 DEG
TOP CANTILEVER
(10-25 WF)

X - w/o 1/2 in. plate
• - w/ 1/8 in. plate

XI
Defl.
(mils)

150
140
130
120
110
100
90
80
70
60
50
40
30
20
10

10 20 30 40 50 60 70 80 90 100 110

Pivot Point Deflection:
X - 489 mils
• - 101 mils

46 1473

K-E 10 X 10 TO 1/2 INCH • 7/8 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.

SECTION II-

PROTOTYPE FRAME, MOUNTING POSTS, OUTER DRIVE
AND SIMULATED MIRROR MODULES.

10 INCH - 25 LB/FT WITH ADDED TORSIONAL STIFFENERS
AT MIRROR MOUNTING POINTS

Note: Actuators between frame and mounting posts not loaded. This causes frame to rotate approximately -10 milliradians about X2 axis. This will be revised on later runs. Relative deflections of beams under loads are still applicable.

ONE G LOAD IN X3 DIRECTION (DOWN) COMPLETE FRAME

DISPLACEMENT CASE 1

MRI/STARDYNE FINITE ELEMENT MODEL PROJECTION ON X2-X3 PLANE CASE NO. 1

CARD NO	1	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	CARD TYPE
55	551					62.5				494.54				-10.1875								NODE
56	552					62.5				494.54				-11.1875								NODE
57	553					62.5				494.54				-12.1875								NODE
58	554					62.5				494.54				-13.1875								NODE
59	555					62.5				494.54				-51.6875								NODE
60	556					62.5				494.54				-60.1875								NODE
61	557					62.5				494.54				-68.1875								NODE
62	558					62.5				494.54				-77.1875								NODE
63	559					62.5				494.54				-86.1875								NODE
64	560					62.5				505.46				.8125								NODE
65	561					62.5				505.46				-10.1875								NODE
66	562					62.5				505.46				-21.1875								NODE
67	563					62.5				505.46				-32.1875								NODE
68	564					62.5				505.46				-43.1875								NODE
69	565					62.5				505.46				-51.6875								NODE
70	566					62.5				505.46				-60.1875								NODE
71	567					62.5				505.46				-68.6875								NODE
72	568					62.5				505.46				-77.1875								NODE
73	569					62.5				505.46				-86.4125								NODE
74	570					62.5				300.				-86.4125								NODE
75	580					52.5				94.54				-41.				JC NODE				NODE
76	581					52.5				100.00				-41.				OUTER				NODE
77	582					52.5				105.46				-41.				AXIS				NODE
78	583					52.5				494.54				-41.				ACCUT				NODE
79	584					52.5				500.00				-41.				MOUNT				NODE
80	585					52.5				505.46				-41.				NODES				NODE
81	586					52.5				300.00				-86.4125				JC NODE				NODE
82	FND																					END
83	RESTG	509				111111																RESTG
84		519				111111																RESTG
85		559				111111																RESTG
86		569				111111																RESTG
87	FND																					END
88	WGHT	190				421.5			421.5		421.5											WGHT
89		191				449.5			449.5		449.5											WGHT
90		192				449.5			449.5		449.5											WGHT
91		193				421.5			421.5		421.5											WGHT
92		240				22.			22.		22.											WGHT
93		290				421.5			421.5		421.5											WGHT
94		291				449.5			449.5		449.5											WGHT
95		292				449.5			449.5		449.5											WGHT
96		293				421.5			421.5		421.5											WGHT
97		581				108.2			108.2		108.2											WGHT
98		584				108.2			108.2		108.2											WGHT
99	FND																					END
100	BEAMG	100				171			100		306	1	1									BEAMG
101		101	106			100			101		306	1	1									BEAMG
102		107	114			106			107		306	1	2									BEAMG
103		115	120			114			115		306	1	1									BEAMG
104		121	140			120			121		306	1	2									BEAMG
105		141	146			140			141		306	1	1									BEAMG
106		147	154			146			147		306	1	2									BEAMG
107		155	160			154			155		306	1	1									BEAMG
108		161				160			170		306	1	1									BEAMG

*** STARDYNE 3.0 INPUT ***

CARD NO	CARD IMAGE																					CARD TYPE
	1	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	
163	*****																					BEAMG
164	*****																					BEAMG
165	*****																					BEAMG
166	*****																					BEAMG
167	*****																					BEAMG
168	*****																					BEAMG
169	*****																					BEAMG
170	*****																					BEAMG
171	*****																					BEAMG
172	*****																					BEAMG
173	*****																					BEAMG
174	*****																					BEAMG
175	*****																					BEAMG
176	*****																					BEAMG
177	*****																					BEAMG
178	*****																					BEAMG
179	*****																					BEAMG
180	*****																					BEAMG
181	*****																					BEAMG
182	*****																					BEAMG
183	*****																					BEAMG
184	*****																					BEAMG
185	*****																					BEAMG
186	*****																					BEAMG
187	*****																					BEAMG
188	*****																					BEAMG
189	*****																					BEAMG
190	*****																					BEAMG
191	*****																					BEAMG
192	*****																					BEAMG
193	*****																					BEAMG
194	*****																					BEAMG
195	*****																					BEAMG
196	*****																					BEAMG
197	*****																					END
198	BPROP1	1		7.35				.373		133.			13.7		.85			.8510-25WF			BPROP	
199	BPROP2	1		5.762				10.08													BPROP	
200	BPROP1	2		9.67				33.5		148.2			32.0		.85			.8510-25WF			BPROP	
201	BPROP2	2		5.762				10.08										W/1/8 PL			BPROP	
202	BPROP1	3		7.45				.604		124.			6.79		.85			.85S10-25.4			BPROP	
203	BPROP2	3		4.661				10.													BPROP	
204	BPROP1	4		2.65				.033		38.8			.606		.85			.8510-9 JR			BPROP	
205	BPROP2	4		2.69				10.													BPROP	
206	BPROP1	5		.53				.00618		.11			.11		.85			.851.5X1.5			BPROP	
207	BPROP2	5		2.3				2.3										3/16			BPROP	
208	BPROP4	5		0.				0.		5.46			0.		0.			5.46ANGLE			BPROP	
209	BPROP1	6		.53				.00618		.11			.11		.85			.85			BPROP	
210	BPROP2	6		2.3				2.3													BPROP	
211	BPROP4	6		0.				0.		-5.46			0.		0.			0.37			BPROP	
212	BPROP1	7		.53				.00618		.11			.11		.85			.85			BPROP	
213	BPROP2	7		2.3				2.3													BPROP	
214	BPROP4	7		0.				0.		-5.46			0.		0.			-5.46			BPROP	
215	BPROP1	8		6.777				1.3778		.6889			.6889		.89			.89 1.9355			BPROP	
	BPROP							.936										BAR			BPROP	

*** STARDYN 3.0 INPUT ***

CARD NO		CARD IMAGE																CARD TYPE			
1	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	
217	BPROP4	8		0.		0.		0.		0.		0.		0.		4.4					BPROP
218	BPROP1	9		21.59		.4785		63.3		7.4		.85		.85		.85		FRAME			BPROP
219	BPROP4	9		0.		0.		0.		4.0		0.		0.		0.		PIVOT			BPROP
220	BPROP1	10		6.63		.4765		63.3		7.4		.85		.85		.85		POST			BPROP
221	BPROP2	10		2.45		0.		0.		0.		0.		0.		0.					BPROP
222	BPROP1	11		17.46		.622		4.99		45.9		.85		.85		.85		NM BRG			BPROP
223	BPROP4	11		0.		0.		5.04		0.		0.		0.		0.		SUPP			BPROP
224	BPROP1	12		.75		.5664		.0039		.5625		.85		.85		.85					BPROP
225	BPROP4	12		4.1		0.		0.		4.1		0.		0.		0.					BPROP
226	BPROP1	13		.75		.5664		.0039		.5625		.85		.85		.85					BPROP
227	BPROP4	13		-4.1		0.		0.		-4.1		0.		0.		0.					BPROP
228	BPROP1	14		.516		39.26		37.38		1.88		.85		.85		.85					BPROP
229	BPROP4	14		-14.		0.		0.		0.		0.		0.		0.					BPROP
230	BPROP1	15		12.57		25.13		12.57		12.57		.89		.89		.89					BPROP
231	BPROP2	15		0.		0.		0.		0.		0.		0.		0.					BPROP
232	BPROP1	16		1.227		.24		.12		.12		.89		.89		.89					BPROP
233	BPROP4	16		0.		0.		0.		4.31		0.		0.		-9.68					BPROP
234	BPROP6	17		1																	BPROP
235	END																				END
236	ENDGEOM																				ENDGE
237	***																				***
238	STATIC	0				0		-2													STATI
239	***																				***
240	ACCEL	-1																			ACCEL
241	END																				END
242	END CASE																				END C
243	ALL DONE																				ALL D
244	OPTION							1							1		60				OPTIO
245	BEAM	0				0		0									500.				BEAM
246	TITLE1																				TITLE
247	TITLE2																				TITLE
248	TITLE3																				TITLE
249	ENDMODEL																				ENDMO

PREPARED BY HONEYWELL INC. - AERO DIVISION PAGE NO.
 CHECKED BY SOLAR RESEARCH EXPERIMENT PROGRAM REPORT NO.
 DATE LG8106A HELIOSTAT-STATIC HO-IZ. POSIT. MODEL NO.

*** HORIZONTAL POSITION UNDER ONE G LOAD

STATIC DEFLECTIONS FOR OUTPUT VECTOR 1
 *MAXIMUM ROTATION IS AT NODE 250 *DOF = 5 VALUE = -.116487E-01
 *MAXIMUM TRANSLATION IS AT NODE 230 *DOF = 3 VALUE = -.917128E+00

NODE	***** TRANSLATIONS *****			***** ROTATIONS (RADIAN) *****		
	X1	X2	X3	X4	X5	X6
100	.6739310E-01	-.2477090E-02	.6913412E+00	-.1750919E-03	-.1062275E-01	.3790749E-04
101	.6701224E-01	-.2477090E-02	.6896375E+00	-.1806345E-03	-.1050775E-01	.3779596E-04
102	.6664085E-01	-.2477090E-02	.6878215E+00	-.1982219E-03	-.1039275E-01	.3601248E-04
103	.6629566E-01	-.2477091E-02	.6857701E+00	-.2283706E-03	-.1027775E-01	.3255704E-04
104	.6599338E-01	-.2477091E-02	.6833550E+00	-.2715971E-03	-.1016275E-01	.2742966E-04
105	.6575073E-01	-.2477091E-02	.6804431E+00	-.3284180E-03	-.1004774E-01	.2063033E-04
106	.6558444E-01	-.2477092E-02	.6768956E+00	-.3903497E-03	-.9932742E-02	.1215904E-04
107	.6548202E-01	-.2477729E-02	.6726240E+00	-.4699139E-03	-.9859729E-02	.8778111E-05
108	.6540727E-01	-.2478366E-02	.6675809E+00	-.5543102E-03	-.9786716E-02	.6623205E-05
109	.6534795E-01	-.2479003E-02	.6616251E+00	-.6531477E-03	-.9713703E-02	.5694322E-05
110	.6529178E-01	-.2479640E-02	.6545089E+00	-.7670354E-03	-.9640690E-02	.5991463E-05
111	.6523346E-01	-.2479914E-02	.6462626E+00	-.8773494E-03	-.9717283E-02	.6122436E-05
112	.6516774E-01	-.2480197E-02	.6369276E+00	-.9654305E-03	-.9793876E-02	.7472452E-05
113	.6508242E-01	-.2480475E-02	.6268233E+00	-.1031888E-02	-.9870470E-02	.1004151E-04
114	.6496531E-01	-.2480744E-02	.6161629E+00	-.1077330E-02	-.9947063E-02	.1382962E-04
115	.6478037E-01	-.2482434E-02	.6050707E+00	-.1112603E-02	-.1006126E-01	.2196695E-04
116	.6453530E-01	-.2494114E-02	.5937398E+00	-.1125733E-02	-.1017546E-01	.2585354E-04
117	.6427263E-01	-.2485705E-02	.5823891E+00	-.1117236E-02	-.1028966E-01	.2548939E-04
118	.6403484E-01	-.2487475E-02	.5712321E+00	-.1087629E-02	-.1040386E-01	.2087451E-04
119	.6386446E-01	-.2489155E-02	.5604775E+00	-.1037428E-02	-.1051807E-01	.1200889E-04
120	.6380399E-01	-.2490835E-02	.5503285E+00	-.9671499E-03	-.1063227E-01	-.1107463E-05
121	.6384796E-01	-.2492099E-02	.5410068E+00	-.8898401E-03	-.1061995E-01	-.6717578E-05
122	.6393491E-01	-.2493342E-02	.5324933E+00	-.8061767E-03	-.1060764E-01	-.9704608E-05
123	.6403862E-01	-.2494625E-02	.5244485E+00	-.7167685E-03	-.1059532E-01	-.1006855E-04
124	.6413285E-01	-.2495888E-02	.5181269E+00	-.6222246E-03	-.1058301E-01	-.7809409E-05
125	.6419137E-01	-.2497152E-02	.5123767E+00	-.5231540E-03	-.1057070E-01	-.2927181E-05
126	.6418796E-01	-.2498415E-02	.5076492E+00	-.4201657E-03	-.1055838E-01	.4578133E-05
127	.6410180E-01	-.2497120E-02	.5039327E+00	-.3178217E-03	-.1059195E-01	.1077449E-04
128	.6397913E-01	-.2495825E-02	.5012663E+00	-.2126010E-03	-.1062552E-01	.1188056E-04
129	.6387085E-01	-.2494531E-02	.4995669E+00	-.1051124E-03	-.1065909E-01	.7896332E-05
130	.6382787E-01	-.2493236E-02	.4991541E+00	.4035094E-05	-.1069265E-01	-.1178183E-05
131	.6389273E-01	-.2492013E-02	.4997462E+00	.1134086E-03	-.1067775E-01	-.9994048E-05
132	.6402137E-01	-.2490791E-02	.5014295E+00	.2215813E-03	-.1066284E-01	-.1393160E-04
133	.6416498E-01	-.2499548E-02	.5041844E+00	.3279443E-03	-.1064794E-01	-.1299083E-04
134	.6427480E-01	-.2498346E-02	.5080030E+00	.4318884E-03	-.1063303E-01	-.7171739E-05
135	.6430619E-01	-.2499528E-02	.5128546E+00	.5343031E-03	-.1063745E-01	.4018765E-07
136	.6427702E-01	-.2490710E-02	.5187135E+00	.6326836E-03	-.1064188E-01	.4939551E-05
137	.6421042E-01	-.2491892E-02	.5255364E+00	.7264060E-03	-.1064631E-01	.7526349E-05
138	.6412952E-01	-.2493075E-02	.5332735E+00	.8148662E-03	-.1065073E-01	.7800584E-05
139	.6405744E-01	-.2494257E-02	.5410692E+00	.8974553E-03	-.1065516E-01	.5762255E-05
140	.6401730E-01	-.2495439E-02	.5512614E+00	.9735642E-03	-.1065958E-01	.1411361E-05
141	.6406642E-01	-.2496944E-02	.5614825E+00	.1045160E-02	-.1054429E-01	-.9895857E-05
142	.6420474E-01	-.2498448E-02	.5723213E+00	.1096514E-02	-.1042899E-01	-.1642803E-04

PREPARED BY HONEYWELL INC. - AFRO DIVISION PAGE NO.
 CHECKED BY SOLAR RESEARCH EXPERIMENT PROGRAM REPORT NO.
 DATE LG8106A HELIOSTAT-STATIC, HORIZ. POSIT. MODEL NO.

* * * HORIZONTAL POSITION UNDER ONE G LOAD

STATIC DEFLECTIONS FOR OUTPUT VECTOR 1

*MAXIMUM ROTATION IS AT NODE 250 *DOF = 5 VALUE = -.116487E-01

*MAXIMUM TRANSLATION IS AT NODE 230 *DOF = 3 VALUE = -.917128E+00

***** TRANSLATIONS ***** ROTATIONS (RADIAN) *****

NODE	X1	X2	X3	X4	X5	X6
143	.6438450E-01	-.2500013E-02	.5835731E+00	.1127109E-02	-.1031370E-01	-.1818515E-04
144	.6455796E-01	-.2501537E-02	.5950277E+00	.1136428E-02	-.1019841E-01	-.1516723E-04
145	.6467737E-01	-.2503062E-02	.6064699E+00	.1123955E-02	-.1008311E-01	-.7374262E-05
146	.6469497E-01	-.2504587E-02	.6176791E+00	.1089174E-02	-.9967818E-02	.5193754E-05
147	.6461212E-01	-.2504417E-02	.6284603E+00	.1044041E-02	-.9891041E-02	.1062894E-04
148	.6448504E-01	-.2504248E-02	.6386878E+00	.9777443E-03	-.9814263E-02	.1403998E-04
149	.6433397E-01	-.2504079E-02	.6481468E+00	.8896762E-03	-.9737486E-02	.1542689E-04
150	.6417915E-01	-.2503910E-02	.6566166E+00	.7792274E-03	-.9660709E-02	.1478965E-04
151	.6402382E-01	-.2504616E-02	.6637536E+00	.6651313E-03	-.9733891E-02	.1576022E-04
152	.6386578E-01	-.2505322E-02	.6698292E+00	.5660854E-03	-.9807074E-02	.1533074E-04
153	.6371904E-01	-.2506028E-02	.6749880E+00	.4814805E-03	-.9880256E-02	.1350123E-04
154	.6359759E-01	-.2506734E-02	.6793743E+00	.4107076E-03	-.9953439E-02	.1027168E-04
155	.6353811E-01	-.2506754E-02	.6830340E+00	.3395278E-03	-.1006926E-01	.2113197E-05
156	.6355150E-01	-.2506773E-02	.6860559E+00	.2824589E-03	-.1018508E-01	-.4301638E-05
157	.6362032E-01	-.2506792E-02	.6885783E+00	.2389843E-03	-.1030090E-01	-.8972822E-05
158	.6372713E-01	-.2506811E-02	.6907346E+00	.2085876E-03	-.1041672E-01	-.1190036E-04
159	.6385450E-01	-.2506831E-02	.6926530E+00	.1907523E-03	-.1053254E-01	-.1308424E-04
160	.6398499E-01	-.2506850E-02	.6944566E+00	.1849618E-03	-.1064836E-01	-.1252447E-04
170	.6408518E-01	-.2506850E-02	.6959350E+00	.1848957E-03	-.1064836E-01	-.1252447E-04
171	.6769636E-01	-.2477090E-02	.6927406E+00	-.1750258E-03	-.1062275E-01	.3790749E-04
190	-.3395417E-01	-.6051991E-03	.6913374E+00	-.1757646E-03	-.1062575E-01	.2088089E-04
191	-.3764588E-01	.6742380E-02	.5503246E+00	-.9700919E-03	-.1063883E-01	.2064804E-04
192	-.3767274E-01	-.1178158E-01	.5512578E+00	.9728174E-03	-.1065710E-01	.2094857E-04
193	-.3760671E-01	-.4272163E-02	.6944529E+00	.1853014E-03	-.1065143E-01	.2112222E-04
200	.6743795E-01	-.5264055E-02	-.7218831E+00	-.1764372E-03	-.1062876E-01	.4401120E-05
201	.6739561E-01	-.5264054E-02	-.7236054E+00	-.1630120E-03	-.1074529E-01	.4535916E-05
202	.6734356E-01	-.5264054E-02	-.7254504E+00	-.2016318E-03	-.1086182E-01	.6342664E-05
203	.6726509E-01	-.5264054E-02	-.7275411E+00	-.2328131E-03	-.1097835E-01	.9821362E-05
204	.6714347E-01	-.5264053E-02	-.7300057E+00	-.2770726E-03	-.1109488E-01	.1497201E-04
205	.6696198E-01	-.5264053E-02	-.7329775E+00	-.3349266E-03	-.1121141E-01	.2179461E-04
206	.6670391E-01	-.5264053E-02	-.7365952E+00	-.4068916E-03	-.1132794E-01	.3028917E-04
207	.6638175E-01	-.5264674E-02	-.7409467E+00	-.4753348E-03	-.1140152E-01	.3370533E-04
208	.6603135E-01	-.5265295E-02	-.7450783E+00	-.5636098E-03	-.1147510E-01	.3593917E-04
209	.6566451E-01	-.5265916E-02	-.7521316E+00	-.6633257E-03	-.1154868E-01	.3699069E-04
210	.6529308E-01	-.5266534E-02	-.7592539E+00	-.7780914E-03	-.1162226E-01	.3685988E-04
211	.6492133E-01	-.5266750E-02	-.7677160E+00	-.8891484E-03	-.1154520E-01	.3672099E-04
212	.6456139E-01	-.5266963E-02	-.7771729E+00	-.9777017E-03	-.1146814E-01	.3449944E-04
213	.6423407E-01	-.5267175E-02	-.7874024E+00	-.1044360E-02	-.1139108E-01	.3019523E-04
214	.6396021E-01	-.5267388E-02	-.7981847E+00	-.1089733E-02	-.1131402E-01	.2380836E-04
215	.6380364E-01	-.5269481E-02	-.8094052E+00	-.1124677E-02	-.1120297E-01	.8882635E-05
216	.6377179E-01	-.5271575E-02	-.8208555E+00	-.1137174E-02	-.1109192E-01	-.1136244E-05
217	.6381559E-01	-.5273680E-02	-.8323180E+00	-.1127742E-02	-.1098088E-01	-.6248271E-05
218	.6388598E-01	-.5275761E-02	-.8435757E+00	-.1096897E-02	-.1086983E-01	-.6453446E-05

.PREPARED BY . HONEYWELL INC. - AFRO DIVISION .PAGE NO.
 .CHECKED BY . SOLAR RESEARCH EXPERIMENT PROGRAM .REPORT NO.
 .DATE . LG8106A HELIOSTAT-STATIC, HORIZ. POSIT. .MODEL NO.

*** HORIZONTAL POSITION UNDER ONE G LOAD

S T A T I C D E F L E C T I O N S F O R O U T P U T V E C T O R 1
 *MAXIMUM ROTATION IS AT NODE 250 *DOF = 5 VALUE = -.116487E-01
 *MAXIMUM TRANSLATION IS AT NODE 230 *DOF = 3 VALUE = -.917128E+00

***** TRANSLATIONS ***** ROTATIONS (RADIAN) *****

NODE	X1	X2	X3	X4	X5	X6
219	.6393389E-01	-.5277854E-02	-.8544173E+00	-.1045155E-02	-.1075879E-01	-.1751771E-05
220	.6391025E-01	-.5279947E-02	-.8546362E+00	-.9730338E-03	-.1064774E-01	.7856756E-05
221	.6380850E-01	-.5281556E-02	-.8740287E+00	-.8978462E-03	-.1066209E-01	.1161668E-04
222	.6368098E-01	-.5283165E-02	-.8826330E+00	-.8160596E-03	-.1067644E-01	.1303442E-04
223	.6355094E-01	-.5284774E-02	-.8903861E+00	-.7282830E-03	-.1069078E-01	.1210997E-04
224	.6344185E-01	-.5286383E-02	-.8972312E+00	-.6351255E-03	-.1070513E-01	.8843340E-05
225	.6337714E-01	-.5287992E-02	-.9031174E+00	-.5371960E-03	-.1071948E-01	.3234519E-05
226	.6338022E-01	-.5289600E-02	-.9080002E+00	-.4351035E-03	-.1073383E-01	-.4716489E-05
227	.6346873E-01	-.5288716E-02	-.9118621E+00	-.3334645E-03	-.1070162E-01	-.1110600E-04
228	.6359568E-01	-.5287831E-02	-.9146885E+00	-.2286907E-03	-.1066941E-01	-.1240277E-04
229	.6371012E-01	-.5286947E-02	-.9164511E+00	-.1213913E-03	-.1063721E-01	-.8606792E-05
230	.6376115E-01	-.5286062E-02	-.9171279E+00	-.1217514E-04	-.1060500E-01	.2819273E-06
231	.6370432E-01	-.5285144E-02	-.9166976E+00	.9751968E-04	-.1062170E-01	.9129843E-05
232	.6358548E-01	-.5284225E-02	-.9151717E+00	.2062610E-03	-.1063840E-01	.1268586E-04
233	.6345753E-01	-.5283307E-02	-.9125629E+00	.3134399E-03	-.1065510E-01	.1094998E-04
234	.6337340E-01	-.5282388E-02	-.9088898E+00	.4184473E-03	-.1067180E-01	.3922196E-05
235	.6338091E-01	-.5284078E-02	-.9041672E+00	.5222210E-03	-.1066868E-01	-.4465655E-05
236	.6345932E-01	-.5285768E-02	-.8984225E+00	.6222055E-03	-.1066556E-01	-.1026004E-04
237	.6358271E-01	-.5287458E-02	-.8916965E+00	.7177917E-03	-.1066244E-01	-.1346097E-04
238	.6372515E-01	-.5289148E-02	-.8840364E+00	.8083706E-03	-.1065931E-01	-.1406843E-04
239	.6386069E-01	-.5290838E-02	-.8754952E+00	.8933332E-03	-.1065619E-01	-.1208243E-04
240	.6396340E-01	-.5292528E-02	-.8661321E+00	.9720705E-03	-.1065307E-01	-.7502967E-05
241	.6398038E-01	-.5294776E-02	-.8559156E+00	.1045491E-02	-.1076764E-01	.2952432E-05
242	.6391339E-01	-.5297025E-02	-.8450641E+00	.1098421E-02	-.1088221E-01	.9288897E-05
243	.6380364E-01	-.5299274E-02	-.8337850E+00	.1130344E-02	-.1099677E-01	.1150643E-04
244	.6369230E-01	-.5301523E-02	-.8222910E+00	.1140743E-02	-.1111134E-01	.9605027E-05
245	.6362058E-01	-.5303772E-02	-.8107999E+00	.1129102E-02	-.1122590E-01	.3584693E-05
246	.6362965E-01	-.5306021E-02	-.7995348E+00	.1094905E-02	-.1134047E-01	-.6554576E-05
247	.6372025E-01	-.5306738E-02	-.7886934E+00	.1050097E-02	-.1141752E-01	-.1111611E-04
248	.6385038E-01	-.5307455E-02	-.7784036E+00	.9839052E-03	-.1149457E-01	-.1445989E-04
249	.6400785E-01	-.5308173E-02	-.7688824E+00	.8957194E-03	-.1157162E-01	-.1658590E-04
250	.6418050E-01	-.5308890E-02	-.7603527E+00	.7849309E-03	-.1164867E-01	-.1749415E-04
251	.6435457E-01	-.5309492E-02	-.7531609E+00	.6703842E-03	-.1157513E-01	-.1691620E-04
252	.6451739E-01	-.5310093E-02	-.7470359E+00	.5708874E-03	-.1150159E-01	-.1524330E-04
253	.6465801E-01	-.5310695E-02	-.7418304E+00	.4858314E-03	-.1142805E-01	-.1247544E-04
254	.6476547E-01	-.5311297E-02	-.7374029E+00	.4146073E-03	-.1135451E-01	-.8612633E-05
255	.6480148E-01	-.5311278E-02	-.7337068E+00	.3428904E-03	-.1123784E-01	.9214925E-06
256	.6475086E-01	-.5311258E-02	-.7306540E+00	.2852845E-03	-.1112117E-01	.8711966E-05
257	.6463106E-01	-.5311239E-02	-.7281061E+00	.2412731E-03	-.1100451E-01	.1475879E-04
258	.6445952E-01	-.5311220E-02	-.7259295E+00	.2103397E-03	-.1088784E-01	.1906196E-04
259	.6425365E-01	-.5311201E-02	-.7239963E+00	.1919678E-03	-.1077117E-01	.2162148E-04
260	.6403091E-01	-.5311181E-02	-.7221832E+00	.1856409E-03	-.1065451E-01	.2243735E-04
270	.6385141E-01	-.5311181E-02	-.7206993E+00	.1855748E-03	-.1065451E-01	.2243735E-04

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 CHECKED BY SOLAR RESEARCH EXPERIMENT PROGRAM REPORT NO.
 DATE LGH106A HELIOSTAT-STATIC, HORIZ. POSIT. MODEL NO.

PREPARED BY HONEYWELL INC. - AERO DIVISION PAGE NO.
 CHECKED BY SOLAR RESEARCH EXPERIMENT PROGRAM REPORT NO.
 DATE LGH106A HELIOSTAT-STATIC, HORIZ. POSIT. MODEL NO.

*** HORIZONTAL POSITION UNDER ONE G LOAD
 S T A T I C D E F L E C T I O N S FOR OUTPUT VECTOR 1
 *MAXIMUM ROTATION IS AT NODE 250 *DOF = 5 VALUE = -.116487E-01
 *MAXIMUM TRANSLATION IS AT NODE 230 *DOF = 3 VALUE = -.917128E+00
 ***** ROTATIONS (RADIAN) *****

MODE	X1	X2	X3	X4	X5	X6
271	.6747316E-01	-.5264055E-02	-.7204729E+00	-.1763711E-03	-.1062976E-01	.4401120E-05
290	-.3395417E-01	-.3522357E-02	-.7218859E+00	-.1757646E-03	-.1062575E-01	.2088089E-04
291	-.3764588E-01	.3996190E-02	-.8646402E+00	-.9700919E-03	-.1063883E-01	.2064804E-04
292	-.3767274E-01	-.1456774E-01	-.8661361E+00	.9728174E-03	-.1065710E-01	.2094857E-04
293	-.3760671E-01	-.7081418E-02	-.7221869E+00	.1853014E-03	-.1065143E-01	.2112222E-04
300	.6529347E-01	-.4928137E-02	-.6427930E+00	-.7665104E-03	-.1161474E-01	.3211427E-04
301	.6529335E-01	-.4608093E-02	-.5266385E+00	-.7549294E-03	-.1156033E-01	.3318848E-04
302	.6529424E-01	-.4282099E-02	-.4112621E+00	-.7433484E-03	-.1145845E-01	.4008251E-04
303	.6529462E-01	-.3790284E-02	-.2971413E+00	-.7317674E-03	-.1130855E-01	.5279635E-04
304	.6529403E-01	-.3212746E-02	-.1848344E+00	-.4541470E-03	-.1109317E-01	.5766564E-04
305	.6529344E-01	-.2699978E-02	-.7493722E-01	-.1765265E-03	-.1082793E-01	.3984214E-04
306	.6529305E-01	-.2508966E-02	-.5024883E-02	.3926752E-05	-.1062855E-01	.1608785E-04
307	.6529274E-01	-.2459547E-02	.6323725E-01	-.1740092E-03	-.1043012E-01	-.1704777E-05
308	.6529227E-01	-.2569157E-02	.1659231E+00	-.4477568E-03	-.1016629E-01	-.1421009E-04
309	.6529180E-01	-.2703711E-02	.2662229E+00	-.7215044E-03	-.9952248E-02	-.8693636E-05
310	.6529179E-01	-.2728302E-02	.3647170E+00	-.1328871E-03	-.9803371E-02	.2639617E-05
311	.6529179E-01	-.2665101E-02	.4514442E+00	-.7442699E-03	-.9702193E-02	.8864884E-05
312	.6529179E-01	-.2565197E-02	.5584347E+00	-.7556526E-03	-.9648153E-02	.9982167E-05
313	.1892745E-01	-.2526013E-02	-.3259285E-02	-.5111372E-03	-.1056677E-01	.1283329E-03
314	.1879205E-01	-.2524666E-02	-.2705179E-02	.8417952E-03	-.1054309E-01	-.1458653E-03
350	.6418055E-01	-.5489319E-02	-.6436273E+00	.7732381E-03	-.1164109E-01	-.1822580E-04
351	.6418061E-01	-.5668877E-02	-.5272095E+00	.7615453E-03	-.1158649E-01	-.1731178E-04
352	.6418066E-01	-.5830986E-02	-.4115723E+00	.7498526E-03	-.1148431E-01	-.1475207E-04
353	.6418071E-01	-.5959309E-02	-.2971943E+00	.7381598E-03	-.1133399E-01	-.1054669E-04
354	.6418028E-01	-.5803559E-02	-.1846399E+00	.4602294E-03	-.1111808E-01	.7163090E-05
355	.6417984E-01	-.5747786E-02	-.7444115E-01	.1822989E-03	-.1085219E-01	.4945814E-04
356	.6417956E-01	-.5304188E-02	-.4422251E-02	.1644174E-05	-.1065233E-01	.9013379E-04
357	.6417914E-01	-.4708050E-02	.6399145E-01	.1810406E-03	-.1045317E-01	.9125728E-04
358	.6417864E-01	-.3835484E-02	.1664019E+00	.4570351E-03	-.1018837E-01	.7966555E-04
359	.6417808E-01	-.3159568E-02	.2674174E+00	.7330295E-03	-.9973532E-02	.5192815E-04
360	.6417835E-01	-.2794057E-02	.3661205E+00	.7445790E-03	-.9824073E-02	.2394556E-04
361	.6417862E-01	-.2646046E-02	.4635717E+00	.7561285E-03	-.9722491E-02	.8428279E-05
362	.6417888E-01	-.2590882E-02	.5602469E+00	.7676779E-03	-.9668224E-02	.5376311E-05
363	.1787855E-01	-.5313494E-02	-.2435640E-02	-.6629368E-03	-.1061511E-01	.1815967E-03
364	.1606478E-01	-.5315314E-02	-.2155277E-02	.8375761E-04	-.1055431E-01	.3105731E-03
400	.6377369E-01	-.5290090E-02	-.8111767E+00	.2213574E-04	-.1059161E-01	-.1065351E-06
401	.6378623E-01	-.5270851E-02	-.7053276E+00	.5644662E-04	-.1058389E-01	.4935357E-05
402	.6379877E-01	-.5174042E-02	-.5995271E+00	.9075750E-04	-.1058121E-01	.1540761E-04
403	.6381131E-01	-.4945358E-02	-.4937281E+00	.1250684E-03	-.1058293E-01	.3131021E-04
404	.6380535E-01	-.4497760E-02	-.3877855E+00	.1285238E-03	-.1060703E-01	.5587234E-04
405	.6379939E-01	-.3869223E-02	-.2815934E+00	.1319793E-03	-.1063216E-01	.6749791E-04
406	.6379551E-01	-.3424925E-02	-.2124310E+00	.1342253E-03	-.1064876E-01	.6811729E-04
407	.6379184E-01	-.2994364E-02	-.1431594E+00	.1364713E-03	-.1066536E-01	.6327097E-04

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 CHECKED BY SOLAR RESEARCH EXPERIMENT PROGRAM REPORT NO.
 DATE LGR10AA HELIOSTAT-STATIC, HORIZ. POSIT. MODEL NO.

*** HORIZONTAL POSITION UNDER ONE G LOAD

STATIC DEFLECTIONS FOR OUTPUT VECTOR 1

***MAXIMUM ROTATION IS AT NODE 250 *DOF = 5 VALUE = -.116487E-01

***MAXIMUM TRANSLATION IS AT NODE 230 *DOF = 3 VALUE = -.917128E+00

***** TRANSLATIONS ***** ROTATIONS (RADIAN) *****

NODE	X1	X2	X3	X4	X5	X6
408	.6378568E-01	-.2440612E-02	-.3637630E-01	.1399268E-03	-.1069045E-01	.4514242E-04
409	.6377972E-01	-.2132228E-02	.7065567E-01	.1433822E-03	-.1071447E-01	.1407730E-04
410	.6379176E-01	-.2108050E-02	.1778304E+00	.1085454E-03	-.1071619E-01	-.7038026E-05
411	.6380379E-01	-.2236759E-02	.2850040E+00	.7370864E-04	-.1071355E-01	-.1661905E-04
412	.6381583E-01	-.2403597E-02	.3921296E+00	.3887187E-04	-.1070592E-01	-.1466577E-04
500	.1304456E-01	.8896331E-02	-.1047041E-02	-.6623164E-03	.3176945E-03	-.3479661E-02
501	.9811785E-02	.2844735E-02	-.4287335E-03	-.4389610E-03	.2703407E-03	-.2336762E-02
502	.7097717E-02	-.7742846E-03	-.8092965E-03	-.2200305E-03	.2233844E-03	-.1193862E-02
503	.4897982E-02	-.2009414E-02	-.6887302E-03	-.5524870E-05	.1768255E-03	-.5096293E-04
504	.3111357E-02	-.1716011E-02	-.5530526E-03	.2875623E-04	.1456290E-03	-.3069176E-04
505	.1994321E-02	-.1340140E-02	-.4480337E-03	.5243463E-04	.1163619E-03	-.1941555E-04
506	.1134595E-02	-.8809707E-03	-.3423405E-03	.4835560E-04	.8743875E-04	-.8139342E-05
507	.5150745E-03	-.4744876E-03	-.2320848E-03	.4436194E-04	.5870164E-04	-.5501233E-05
508	.1381910E-03	-.1495453E-03	-.1211495E-03	.2916574E-04	.3034360E-04	-.2863000E-05
510	.1339832E-01	-.1348912E-01	-.7625681E-03	.5339255E-03	.3014911E-03	.3229379E-02
511	.1028916E-01	-.8169273E-02	-.6675387E-03	.4242210E-03	.2636198E-03	.2148533E-02
512	.7597751E-02	-.4280463E-02	-.5713799E-03	.2737378E-03	.2251793E-03	.1067687E-02
513	.5333300E-02	-.2271250E-02	-.4740918E-03	.8247583E-04	.1861694E-03	-.1315924E-04
514	.3439997E-02	-.1644754E-02	-.3701707E-03	.5230581E-04	.1569738E-03	-.2823422E-04
515	.2231490E-02	-.1229459E-02	-.2965157E-03	.4557800E-04	.1269451E-03	-.1818392E-04
516	.1290127E-02	-.8686261E-03	-.2221864E-03	.3949145E-04	.9646968E-04	-.8133611E-05
517	.5388796E-03	-.4391617E-03	-.1508748E-03	.4328487E-04	.6570570E-04	-.5497360E-05
518	.1611653E-03	-.1650775E-03	-.7885552E-04	.3116274E-04	.3445724E-04	-.2860984E-05
550	.1208727E-01	.7633497E-02	-.7875207E-03	-.3325221E-03	.2920922E-03	-.3550880E-02
551	.9102259E-02	.4674814E-02	-.6849500E-03	-.2110408E-03	.2514564E-03	-.2403703E-02
552	.8852924E-02	.4469399E-02	-.6755603E-03	-.2012463E-03	.2478249E-03	-.2299414E-02
553	.4438495E-02	.2073518E-02	-.4762207E-03	-.4365786E-04	.1739738E-03	-.1093497E-03
554	.2708002E-02	.1624472E-02	-.3685819E-03	-.3854993E-04	.1419069E-03	-.1089337E-03
555	.1660938E-02	.1240314E-02	-.2944446E-03	-.4670676E-04	.1075826E-03	-.7267495E-04
556	.8920249E-03	.8553531E-03	-.2206330E-03	-.4259989E-04	.7645983E-04	-.3641619E-04
557	.4803197E-03	.4974091E-03	-.1534179E-03	-.4346897E-04	.4963306E-04	-.2521121E-04
558	.4848546E-04	.1509414E-03	-.7706595E-04	-.2959640E-04	.2295990E-04	-.1260560E-04
560	.1409036E-01	.5445929E-03	-.1026055E-02	.2393782E-03	.3252972E-03	-.1218085E-02
561	.1075909E-01	.2192350E-02	-.9146249E-03	.7701306E-04	.2796793E-03	-.8475362E-03
562	.7935619E-02	.2453366E-02	-.8020755E-03	-.1493705E-04	.2329702E-03	-.4769873E-03
563	.5631951E-02	.2084214E-02	-.6883917E-03	-.3647211E-04	.1851700E-03	-.1064383E-03
564	.376128E-02	.1637942E-02	-.5556860E-03	-.3717753E-04	.1568321E-03	-.1091348E-03
565	.2485335E-02	.1259920E-02	-.4500631E-03	-.4767804E-04	.1320976E-03	-.7277597E-04
566	.1467955E-02	.8566465E-03	-.3437659E-03	-.4332608E-04	.1042642E-03	-.3641714E-04
567	.6978106E-03	.4755369E-03	-.2330482E-03	-.4293249E-04	.7381671E-04	-.2461368E-04
568	.2001104E-03	.1533990E-03	-.1216562E-03	-.2944801E-04	.4015965E-04	-.1281022E-04
580	.3395544E-02	-.1476340E-02	.4478782E-03	.1394650E-04	.1565587E-03	-.3859457E-04
581	.3585763E-02	-.1476697E-02	.1065992E-02	.3381432E-04	.1573556E-03	-.3099133E-04

.PREPARED BY . HONEYWELL INC. - AERO DIVISION .PAGE NO.
 .CHECKED BY . SOLAR RESEARCH EXPERIMENT PROGRAM .REPORT NO.
 . DATE .LG8105A HELIOSTAT-STATIC. HORIZ. POSIT. .MODEL NO.

*** HORIZONTAL POSITION UNDER ONE G LOAD

STATIC DEFLECTIONS FOR OUTPUT VECTOR 1

*MAXIMUM ROTATION IS AT NODE 250 *DOF = 5 VALUE = -.116487E-01

*MAXIMUM TRANSLATION IS AT NODE 230 *DOF = 3 VALUE = -.917128E+00

***** TRANSLATIONS ***** ROTATIONS (RADIANS) *****

NODE	X1	X2	X3	X4	X5	X6
582	.3733137E-02	-.1477048E-02	.1321897E-02	.6049725E-04	.1581524E-03	-.2290783E-04
583	.2930444E-02	.2813794E-02	.1247420E-02	-.3510486E-04	.1495610E-03	-.1074439E-03
584	.3502829E-02	.2813983E-02	.1103551E-02	-.2290809E-04	.1553941E-03	-.1041593E-03
585	.4072492E-02	.2814167E-02	.9826539E-03	-.3061242E-04	.1612272E-03	-.1064467E-03

3-52

DEFLECTION OF MAIN FRAME BEAM (FRONT BEAM)

3-53

3-54

DEFLECTION CURVE CENTER CROSS BEAM

Appendix 4

IMAGE ANALYSIS

Sun images reflected from a parabolic mirror as projected onto a broad-side surface located at the focal point (target) have been shown* to consist of two parts:

1. A true-shape image of the mirror linearly scaled in size by $1-\cos\theta$, where θ is the angle between the mirror axis and the sun.
2. A pattern of circles around each point on the mirror image of radius EF where E is half the sun's subtended angle (.00465 rads) and F is the focal length (distance to the tower).

Circular mirror pattern shapes are sketched for several different values of θ in Figure 1. It is convenient to think of the patterns as composed of four circles having diameters defined by:

$$\begin{aligned} D_S &= 2EF && \text{sun's image} \\ D_M &= (1-\cos\theta)D_M && \text{mirror image} \\ D_I &= D_M + D_S && \text{total image outer diameter} \\ D_C &= D_M - D_S && \text{total image core diameter} \end{aligned}$$

In equation form:

$$\begin{aligned} D_I &= (1-\cos\theta)D_M + 2EF \\ D_C &= (1-\cos\theta)D_M - 2EF \end{aligned}$$

Outer image diameter is of particular interest to the research experiment since it, together with computation errors of the offset facets and pointing errors, defines the desired size of the target array.

The core diameter is of uniform intensity and for $D_M < D_S$ is constant at maximum value. For $D_M > D_S$ the core intensity is still uniform but of decreasing magnitude with increasing D_M .

The scaled mirror image size part of the equation is seen to be a function only of θ and is, therefore, only weakly related to distance from the target. The sun image portion of the equation is dependent only on the sun's subtended angle and is directly proportional to distance from the target.

* Memo, W. H. Egli to J. C. Powell, 3/4/75, "Performance of Off-Axis Low Aperture Reflectors", S&RC/R.

FIGURE 1. CIRCULAR MIRROR IMAGES

FIGURE 2. POCE SITE IMAGES - $10M^2$ SQUARE FACET

Mirror shapes other than circular do not result in nice simple equations, but are just as easily sketched. Image shapes expected from a 10m^2 square mirror at the extremes of the POCE field and for the extremes of θ are sketched to scale in Figure 2. The image rotates about its center on the broadside target plane the same amount as the plane defined by the sun, mirror normal, and target vectors rotates away from vertical.

Total specular reflectance, by taking into account the spectral distribution of the sun's energy, gives a true picture of reflector efficiency.

Reflectance figures can be misleading unless the total (sun's) specular reflectance is used. The example below shows how a mirror, having a maximum reflectance as high as 0.9, has an effective (total specular) reflectance of only 0.68 even though its reflectance appears to track the sun's spectral distribution.

Spectral distribution of the sun's energy per unit wavelength is plotted in Figure 3.* Reflectance below 0.3 and above 2.0 microns is of little benefit since 98% of the sun's energy falls within this band, as shown by the cumulative distribution in Figure 4.

Reflectance of a 1/4 inch silvered second surface mirror is plotted in Figure 5.** When this is multiplied by the sun's irradiance, the reflected spectral distribution per unit wavelength of Figure 6 is obtained. Integrating Figure 6 gives the cumulative reflected energy of Figure 7 showing a total specular reflectance (mirror efficiency) of 68%.

Silicon photo transistors are being used in the experiment calibration array. They have a peak spectral response at .9 microns and taper off to zero below .5 and above 1.1 microns. While they are useful for obtaining relative intensity measurements for determining spot size, the mirror total reflectance should be periodically measured (to determine mirror efficiency). If significant variations are noted, we might also want to periodically measure the mirror reflectance versus wavelength to aid in evaluation.

Cost tradeoffs should use the total specular reflectance of the reflectors. If manufacturer's data is used, the same model for the sun's spectral irradiance must be used. It appears there is considerable latitude possible here; i.e., time of day and elevation above sea level can make significant differences.

* Handbook of Geophysics and Space Environments, Air Force Cambridge Research Labs, Office of Aerospace Research, U. S. Air Force, 1965.

** Design fabrication and testing of a heliostat for a central receiver solar thermal power plant - Final Report by University of Houston and McDonnell Douglas Astronautics Co. under a national science foundation grant for period 5/74 to 9/75.

Angles between facet axes and the sun, important because they define the maximum available power and off-axis aberration of a heliostat, vary between 0 and 74 degrees.

Cosines of facet axes to sun angles, calculated for the POCE field geometry over the course of a day and a year, were found to:

1. Be significantly larger in the North field quadrant.
2. Be significantly larger for inner rings.
3. Have an average yearly value of .78.
4. Be nearly normally distributed; 68% > .73, 95% > .45, 99% > .30.
5. Have a range of 1.0 to 0.28.

Loss of available power and defocusing due to the POCE site geometry is demonstrated in Figure 1. Here the average yearly cosines for the heliostats are plotted v.s. field position. The significantly higher values for the inner rings compared to the outer rings is due to the higher tower line of sight for the inner circles.

The effect of radial distance from the tower (or tower height) on the cumulative distribution of the cosines is demonstrated in Figure 2. This curve, together with the field geometry is used to compute the cumulative distribution of the cosines for the entire field, shown in Figure 3. These plots are useful for weighing the effects of apertures or targets not capable of receiving the worst case images.

The POCE field geometry had a tower height of 120 meters maximum heliostat radial distance from the tower of 305 meters and a minimum radial distance of 46 meters.

The cosines were calculated each hour for one hour after sunrise to one hour before sunset for three days of the year; equinox, summer solstice and winter solstice. Average yearly values for a particular heliostat were calculated by averaging the values for each hour and the three days.

Appendix 5

COORDINATE TRANSFORMATIONS

Mirror pointing errors are related to error rotations occurring about the three error measurement frames in the heliostat by the equations:

$$\text{Error about } \hat{x}_{11} = M_1 + (I_1 + O_1) C\theta - (I_3 + O_3 c\phi + O_2 s\phi)$$

$$\text{Error about } \hat{y}_{11} = I_2 + M_2 + O_2 c\phi + O_3 s\phi$$

where

$\hat{y}_{11}$ is the unit direction vector along the inner gimbal axes

$\hat{z}_{11}$ is the unit vector along the mirror normal

$$\hat{x}_{11} = \hat{y}_{11} \times \hat{z}_{11} .$$

Error equations are developed by determining the rotation of the mirror caused by small error rotations about the heliostat frames:

O_n fixed in the mounting posts

I_n fixed in the outer gimbal

M_n fixed in the mirror.

The direction cosines of the mirror normal measured on the inner axis are related to the base cosines in an errorless heliostat by the matrix equation

$$|n_m| = |\theta| |\phi| |n_b| \text{ or } |n_b| = |\phi|^T |\theta|^T |n_m|$$

where

$|\phi|$ is the rotation matrix due to the outer gimbal angle

$|\theta|$ the matrix due to the inner gimbal angle.

If we include the error rotations we get

$$|n'_m| = |M| |\theta| |I| |\phi| |O| |n_b| .$$

Combining the two above equations gives:

$$|n'_m| = |M||\theta||I||\phi||O||\phi|^T|\theta|^T|n_m|.$$

M, O, and I are error rotations about the three axis of each triad which for small angles ($\cos \gamma = 1$ and $\sin \gamma = \gamma$) reduces to:

$$(\gamma) = \begin{vmatrix} 1 & \gamma_3 & -\gamma_2 \\ -\gamma_3 & 1 & \gamma_1 \\ \gamma_2 & -\gamma_1 & 1 \end{vmatrix}$$

The transformation group $|\phi||O||\phi|^T$ then is:

$$|\phi||O||\phi|^T = \begin{vmatrix} 1 & (O_3 \cos \phi - O_2 \sin \phi) & -(O_3 \sin \phi + O_2 \cos \phi) \\ -(O_3 \cos \phi + O_2 \sin \phi) & 1 & O_1 \\ (O_3 \sin \phi + O_2 \cos \phi) & -O_1 & 1 \end{vmatrix}$$

which is the matrix representation of the rotational error vector $\hat{O}$ transformed through a rotation ϕ .

Let

$$|\phi||O||\phi|^T = O'$$

another small angle transformation matrix.

Then

$$|n'_m| = |M||\theta||I||O'|||\hat{\epsilon}|^T|n_m|$$

But

$$|\hat{I}||\hat{O}'| = \begin{vmatrix} 1 & +(I_3 + O_3') & -(I_2 + O_2') \\ -(I_3 + O_3') & 1 & (I_1 + O_1') \\ (I_2 - O_2') & -(I_1 + O_1') & 1 \end{vmatrix}$$

which is the matrix representation of the sum of the two rotation vectors $\hat{I}$ and $\hat{O}'$ - another small angle rotation matrix.

Then

$$|n'_m| = |M||\theta||I + O'|||\theta|^T|n_m|$$

But

$|M||\theta||I + O'||\theta|^T$ is exactly the same form as was $|I||\phi||O||\phi|^T$ so that it is the matrix representation of the error rotation vector $\hat{I} + \hat{O}'$ transformed through the rotation θ and summed with the error rotation vector $\hat{M}$.

Functionally, the above can be represented as shown in Figure 1, where the error vector $\hat{O}_n$ is transformed through ϕ , summed with $\hat{I}_n$, transformed through θ and summed with $\hat{M}_n$.

Let the resulting matrix, itself a small angle rotation matrix, be $|\beta|$ and defining the error matrix $|\epsilon| = |n'_m| - |n_m|$, then:

$$|\epsilon| = |\beta||n_m| - |I||n_m| = \begin{vmatrix} 0 & \beta_3 & -\beta_2 \\ -\beta_3 & 0 & \beta_1 \\ \beta_2 & -\beta_1 & 0 \end{vmatrix} |n_m|$$

which in vector form is:

$$\hat{\epsilon} = \hat{\beta} \times \hat{n}_m$$

The rotation vectors $\hat{O}$, $\hat{I}$ and $\hat{M}$ and the mirror normal $\hat{n}$ can be transformed to any convenient computation frame. The target frame is a particularly useful one since the error rotation about the target direction can be dropped and the two remaining cosines are the cross-course and elevation errors in the target frame.

Figure 1. HELIOSTAT POINTING-ERROR FLOW-DIAGRAM

Functional relationships between the coordinate frames used in the analysis and control of the heliostats are defined in Figure 2. From left to right the rotations r , w , i , $Lg + \Omega t + 90^\circ$ and Lt define the transformations from inertial to local vertical-north space and give the direction cosines of the sun direction vector. The rotation H gives the base frame for a specific heliostat in terms a cross-course, up, and (cross-course) X (up) frame. E is the elevation angle to the target and provides the transformation to the target frame. The N transformation zeros the sun's cosine on the $\hat{x}$ axis, S zeros the sun's cosine on the $\hat{y}$ axis and F is a 90 degree rotation to realign the inertial frame x axis and the sun's direction vector. The ϕ and θ rotations are the heliostat gimbal angles and provide the transformation from the base frame to the mirror.

The circle diagram of Figure 3 provides a summary of the functional diagram. The numbers within the small circles represent the frame, the letters (on the inside of the large circles) are rotation angles and the x , y or z notations outside the circle define the axes about which the rotations occur.

Matrixes relating the frame adjacent to a rotation can be written using the diagram key. For instance, by inspection:

$$\begin{vmatrix} x_{10} \\ y_{10} \\ z_{10} \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & c\phi & s\phi \\ 0 & -s\phi & c\phi \end{vmatrix} \begin{vmatrix} x_6 \\ y_6 \\ z_6 \end{vmatrix}$$

Vector direction cosines can also be defined using the diagram. For example:

$$s_1 \hat{x}_6 + s_2 \hat{y}_6 + s_3 \hat{z}_6 = s_1 \hat{x}_{10} + (s_2 c\phi + s_3 s\phi) \hat{y}_{10} + (s_3 c\phi - s_2 s\phi) \hat{z}_{10}$$

FIGURE 2. COMPUTATIONAL FRAMES

The equations for computing cross-course and elevation errors at the target are derived as follows:

For $\hat{T}$ = Unit Director Vector to Tower

$\hat{X}$ = Unit Sun vector

$\hat{n}$ = Unit Mirror Normal Vector

$$\hat{T} = - [\hat{S} - (\hat{S} \cdot \hat{n}) \hat{n}] + (\hat{S} \cdot \hat{n}) \hat{n}$$

$$\hat{T} = - [\hat{S} - 2(\hat{S} \cdot \hat{n}) \hat{n}]$$

converting to matrix equations

$$(\hat{S} \cdot \hat{n}) \hat{n} = nn^T S$$

so that

$$T = - [I - 2nn^T] S \quad \text{similarly} \quad S = - (I - 2nn^T) T$$

$$\text{Let } T' = - [I - 2n'n'^T] S$$

where $n' = n + \delta n$ and δn is small compared to $\hat{n}$

$$\text{then } T' = - (I - 2 [n + \delta n] [n + \delta n]^T) S = -S + 2 (nn^T + n\delta n^T + \delta n n^T + \delta n \delta n^T) S$$

but $\delta n \delta n^T$ is second order small

$$\text{therefore } T' = -S + 2 (nn^T + n\delta n^T + \delta n n^T) S = - (I - 2 [nn^T + n\delta n^T + \delta n n^T]) S$$

$$\text{Let } \epsilon T' = T - T' = -S + 2nn^T S + S - 2nn^T S - 2 (n\delta n^T + \delta n n^T) S$$

$$\text{or } \epsilon T' = -2 (n\delta n^T + \delta n n^T) S$$

$$\epsilon T' = -2 (n\delta n^T + \delta n n^T) (-I + 2nn^T)^T$$

$$= -2 (-n\delta n^T + 2n\delta n^T nn^T - \delta n n^T + 2\delta n n^T nn^T)^T$$

But since $\delta n^T n = 0$ and $n^T n = I$

$$\epsilon T' = -2 (-n\delta n^T - \delta n n^T + 2\delta n n^T) = -2 (\delta n n^T - n\delta n^T)^T$$

$$\epsilon T' = 2 (n\delta n^T - \delta n n^T)^T$$

(1)

Since $n\delta n^T$ and $\delta n n^T$ are symmetric with equal diagonals

$n\delta n^T - \delta n n^T$ is a skew symmetric rotation matrix, $[\psi]$, and is small angle since all terms are multiplied by δn or δn^T .

$\epsilon T' = 2 (\psi)T$ which in vector notation gives

$$\hat{\epsilon T} = 2 \hat{\psi} \times \hat{T}$$

letting $\delta \hat{n} = \hat{\phi} \times \hat{n}$ and expanding $n\delta n^T - \delta n n^T$ gives ψ , the elements of which are the rotation vector $\hat{\phi} = [\hat{\phi} - (\hat{\phi} \cdot \hat{n})\hat{n}]$ which can be recognized as the component of the rotation vector $\hat{n}$ so that

$$\hat{\epsilon T}' = 2 [\hat{\phi} - (\hat{\phi} \cdot \hat{n})\hat{n}] \times \hat{T} \quad (2)$$

If we compute the error in the target frame where $T = 0\hat{x}$ and $1\hat{y}$ and $0\hat{z}$

$$\frac{\epsilon T'}{2} = [-\phi_3 + (n \cdot \phi)n_3] \hat{c} + 0 \hat{a} + [\phi_1 - (n \cdot \phi)n_1] \hat{c} \times \hat{a}$$

and the miss distances at the target are:

$2R (\phi_3 + (n \cdot \phi)n_3)$ cross course error and

$2R (\phi_1 - (n \cdot \phi)n_1)$ perpendicular to cross course and along course.

Where R is the slant range to the target.

Appendix 6

HELIOSTAT DRAWING LIST

The following drawings are available upon request to Honeywell Aerospace Division, 13350 US Highway 19, St. Petersburg, Florida, 33733.

LG8016A1 Rev -	Heliostat Assembly
34026594 Rev 2	Mirror Module, Plywood
34026577 Rev 1	Mirror Module, Adjustable Focus
34026575 Rev 2	Mirror Module, Built Up Structure
34026613 Rev -	Spur Gear
34026612 Rev -	Motor/Encoder Assembly
34026615 Rev -	Bearing Support Assembly
34026579 Rev -	Crank Arm Detail Assembly
34026600 Rev 1	Taper Lock
34026608 Rev -	Tie Rod Detail Assembly
34026616 Rev -	Retainer Detail Assembly - Bearing
34026614 Rev 1	Frame Detail Assembly - I Beam
34026617 Rev -	Housing Detail Assembly - Motor
34026571 Rev -	Foundation and Support Assembly
34026598 Rev 4	Linear Actuator - Heliostat
34026578 Rev -	Trailer Assembly
34026568 Rev -	Frame Calibration Array

The following drawings are available but are not part of package:

34026581	Spring Support Detail Assembly
34026582	Pivot Block
34026583	Motor Adapter
34026584	Motor Shaft
34026587	Shoulder Washer

Appendix 7

COMPUTER AND SOFTWARE

The computer used for the research experiment is the Honeywell Model 516. This computer features 16K of memory, a real time clock and standard input/output options.

An ASR-35 teletypewriter has been selected for the printer/keyboard requirement. The keyboard will be used for operator inputs to the system to input data and command various modes and data printouts. The printer will be used to display command responses, squawks and operating logs. The ASR-35 is a device with many years of reliability history.

A magnetic tape unit will be used to load programs and record data obtained in the research experiment. Such recorded data can be retrieved for post-test data reduction and analysis.

The RS232C input/output performs serial/parallel conversions and data formatting at the H-516 interface.

These equipments are illustrated in Figure 7-1.

The SRE Software provides operator interface, data recording, command output, and computation of vector direction cosines. Both scratchpad and permanent memory are used. FORTRAN higher order language was used so the program is adaptable.

The Software Specification QG8172A1 defines all functional characteristics of the software. Sun position is computed and corrected for atmospheric refraction. Mirror normal vector is computed from the sum of all commands issued to each of the three heliostats.

Computational errors are sufficiently small that they may be neglected. Open and closed loop tracking (with array) is required in the software. Input constants, such as target position heliostat position, etc. are maintained in memory which is easily altered via a patch routine. Thus allowing use of heliostat at various locations. Other modes include initialization, offset pointing, stowage, and data recording.

A listing for the program follows.

FIGURE 7-1. COMPUTER AND SOFTWARE

HELIOSTAT SOFTWARE

FORTRAN ONLY

1 C HELIOSTAT CONTROL SOFTWARE 4/29/76

2 C

3 C

4 C UP, EAST, NORTH HELIOSTAT CENTERED COORDINATE FRAME.

5 C BASE DISTANCE MEASURED HORIZONTALLY IN FEET FROM THE MIRROR SURFACE

6 C TO A POINT (C) AT THE SAME LEVEL BELOW THE TARGET.

7 C HEIGHT MEASURED VERTICALLY IN FEET FROM POINT (C) TO THE TGT CENTROID

8 C AZIMUTH MEASURED CLOCKWISE FROM TRUE NORTH IN DEGREES TO THE

9 C BASELINE AIMED AT THE TARGET FROM THE HELIOSTAT.

10 C HELIOSTAT OUTER AXIS NON-RIGHT TRIANGLE FIXED LEGS ARE 34 IN. AND

11 C 43.32436 IN. RESULTING IN A REFERENCE SCREW LENGTH OF 63.12687

12 C IN. AND A REFERENCE ANGLE OF 108.8532 DEG. WHEN THE OUTER AXIS HOME.

13 C THE CAL ARRAY IS 14, 16 (ROWS, COLUMNS) AND IS INPUT BY COLUMNS.

14 C

15 C DIMENSION M(4), B(8), H(8), A(8), GINNER(4), GOUTER(4), GOUT(4)

16 C DIMENSION DC1(4), DC2(4), DC3(4), SDC1(4), SDC2(4), SDC3(4)

17 C DIMENSION ASIN(4), ACOS(4), SASIN(4), SACOS(4), KC(4)

18 C DIMENSION C(16)

19 C COMMON /DATA/ ICRA, ICAL(14, 16), IWERT(16)

20 C REAL JULDAT, LATI, LONG, NORTH, MINS

21 C NAUTICAL ALMANAC CONSTANTS. UPDATE ANNUALLY EACH JANUARY 1.

22 C DATA YEAR/76., JULDAT/2442777.5/, GHAA/6.5867/

23 C LOCAL GEODETIC COORDINATES

24 C DATA LATI/27.8928/, LONG/82.7258/

25 C

26 C DATA SF1/.01185/, SF2/.17775/, SF3/2.25E-2/, SF4/3.375E-1/

27 C DATA SF5/.01375/, SF6/.20625/

28 C DATA DTORAD/1.745329E-2/, RTODEG/57.29578/

29 C DATA C(1), C(2), C(3), C(4), C(5), C(6), C(7), C(8), C(9), C(10), C(11),

30 C + C(12), C(13), C(14), C(15), C(16)

31 C + /-7.5, -6.5, -5.5, -4.5, -3.5, -2.5, -1.5, -.5, .5, 1.5, 2.5, 3.5, 4.5, 5.5,

32 C + 6.5, 7.5/

33 C SITE INITIALIZATION

34 C

35 C D=JULDAT-2415020.

36 C T=D/36525

37 C ARGPGE=281.2208+4.70684E-5*D+4.53E-4*T**2

38 C TEMP=.9856003*(D-YEAR*360.)-5.183904*YEAR

39 C ANMEAN=(TEMP+358.4758-5.686E-3-1.5E-4*T**2)*DTORAD

40 C ECLPIN=(23.45229-1.30125E-2*T)*DTORAD

41 C AMDOT=1.720279E-2

42 C RLAT=LATI*DTORAD

43 C SLAT=SIN(RLAT)

44 C CLAT=COS(RLAT)

45 C SINCL=SIN(ECLPIN)

46 C CINCL=COS(ECLPIN)

47 C OMEG= GHAA*15.+LONG*2.7379E-3-LONG

48 C DELVER=0.

49 C DELHOR=0.

50 C REFRAC=.0149

51 C

52 C

53 C DO 20 I=1, 4

54 C M(I)=5

55 C CALL SSWTCH(I, J)

56 C IF (J.EQ. 2) GO TO 20

57 C WRITE(1, 10) I

```

57      READ(1,15)      B(I),H(I),A(I),B(I+4),H(I+4),A(I+4)
58 C
59      10 FORMAT(48H ENTER BASE, HEIGHT, AZ, BASE, HEIGHT, AZ OF HS ,I1//)
60      15 FORMAT(F7.1,F6.1,F8.3,F7.1,F6.1,F8.3)
61 C
62      20 CONTINUE
63      IENBHS=0
64      IFLAG=0
65      MESSAGE=0
66      ICALF=0
67 C
68 C
69      DO 30 I=1,4
70      ELEV=ATAN2(H(I),B(I))
71      ASIN(I)=SIN(A(I)*DTORAD)
72      ACOS(I)=COS(A(I)*DTORAD)
73      DC1(I)=SIN(ELEV)
74      DC2(I)=COS(ELEV)*ASIN(I)
75      DC3(I)=COS(ELEV)*ACOS(I)
76      ELEV=ATAN2(H(I+4),B(I+4))
77      SASIN(I)=SIN(A(I+4)*DTORAD)
78      SACOS(I)=COS(A(I+4)*DTORAD)
79      SDC1(I)=SIN(ELEV)
80      SDC2(I)=COS(ELEV)*SASIN(I)
81      SDC3(I)=COS(ELEV)*SACOS(I)
82      30 CONTINUE
83 C
84      CALL INIDAP
85      WRITE(1,35)
86      READ(1,40) DAYS,HOURS,MINS
87      25 FORMAT(30H ENTER GMT DAYS, HOURS, MINS )
88      40 FORMAT(3F4.0)
89      SECS=59.
90 A      OCP, .0020
91 C
92      W=(ARGPGE+4.70684E-5*(DAYS+.71))*DTORAD
93      SINW=SIN(W)
94      COSW=COS(W)
95      IENBHS=1
96 C
97      100 IF (IFLAG.EQ. 0) GO TO 200
98      IFLAG=0
99      WRITE(8)DAYS,HOURS,MINS,SECS,M,B,H,A,GINNER,GOUTER,GOUT,DC1,DC2,
100      +DC3,SDC1,SDC2,SDC3,AZSUN,ELSUN,RELSUN,REFRAC,DELVER,DELHOR,
101      +ICAL,IWEAT
102 C
103 A      OCP :104
104      DO 150 IP=1,4
105      CALL SSWTCH(IP,IX)
106      IF (IX.EQ. 2) GO TO 150
107      WRITE(1,180) HOURS,MINS,IP, M(IP),GOUT(IP),GINNER(IP),AZSUN,
108      +RELSUN,DELVER,DELHOR
109      150 CONTINUE
110      180 FORMAT(1H ,2F3.0,2I3,4F9.4,2F8.2//)
111      190 CONTINUE
112 A      SKS :104

```


113 GO TO 190
114 195 CONTINUE
115 A OCP 4
116 C
117 200 IF (MESSAGE .EQ. 0) GO TO 210
118 MESSAGE=0
119 WRITE(1,205) IHS,M(IHS),HOURS,MINS,SECS
120 205 FORMAT(4H HS ,I1,6H MODE ,I1,6H TIME ,3F3.0)
121 207 CONTINUE
122 A SKS :104
123 GO TO 207
124 208 CONTINUE
125 A OCP 4
126 C
127 210 CONTINUE
128 A INA :1004
129 GO TO 100
130 213 CONTINUE
131 ICAR=
132 IF (ICAR .EQ. :310) GO TO 214
133 GO TO 100
134 214 READ(1,215) IHS,MODE
135 215 FORMAT(2I1)
136 IF(IHS-1) 100,220,230
137 220 IF(IHS-5) 225,100,100
138 225 IF(MODE-1) 100,230,230
139 230 IF(MODE-6) 240,100,100
140 240 M(IHS)=MODE
141 MESSAGE=1
142 GO TO 100
143 C
144 C INTERRUPT BLOCK PRORTI
145 A DAC,PRORTI
146 C UPDATE GREENWICH MEAN TIME
147 250 SECS=SECS+1.
148 TIME=HOURS+MINS/60.+SECS/3600.
149 IF (SECS .LT. 60.) GO TO 320
150 SECS=0.
151 MINS=MINS+1.
152 A LDA :377
153 302 CONTINUE
154 A OTA :0115
155 GO TO 302
156 304 CONTINUE
157 ICALF=1
158 IFLAG=1
159 IF (MINS .LT. 60.) GO TO 305
160 MINS=0.
161 HOURS=HOURS+1.0
162 IF (HOURS .LT. 24.) GO TO 305
163 HOURS=0.
164 DAYS=DAYS+1.
165 C
166 C COMPUTE SUNS ORBITAL POSITION
167 305 AM=AMMEAN+AMDOT*(DAYS+TIME/24.)
168 AE=0

```
169 DO 310 I=1,3
170 310 AE=AM+.01672*SIN(AE)
171 TEMP1=COS(AE)
172 TEMP2=1-.01672*TEMP1
173 COSV=(TEMP1-.01672)/TEMP2
174 SINW=(.99986*SIN(AE))/TEMP2
175 EQUAT=COSV*COSW-SINV*SINW
176 TEMP=COSV*SINW+SINV*COSW
177 EASTI=TEMP*CINCL
178 POLAR=TEMP*SINCL
179 C COMPUTE EARTH FIXED POINTING VECTOR TO SUN
180 320 OMEGA=(OMEG+15.*(DAYS*6.57098E-2+TIME))*DTORAD
181 SINO=SIN(OMEGA)
182 COSO=COS(OMEGA)
183 TEMP=COSO*EQUAT+SINO*EASTI
184 UP=CLAT*TEMP+SLAT*POLAR
185 EAST=COSO*EASTI-SINO*EQUAT
186 NORTH=CLAT*POLAR-SLAT*TEMP
187 TEMP=SQRT(EAST**2+NORTH**2)
188 AZSUN=RTODEG*ATAN2(EAST,NORTH)
189 ELSUN=RTODEG*ATAN2(UP,TEMP)
190 RELSUN= ELSUN+REFRAC*TEMP/UP
191 DCS1=SIN(RELSUN*DTORAD)
192 TEMP=COS(RELSUN*DTORAD)
193 DCS2=TEMP*SIN(AZSUN*DTORAD)
194 DCS3=TEMP*COS(AZSUN*DTORAD)
195 C
196 IF (IENBHS.EQ.0) GO TO 900
197 C
198 DO 600 I=1,4
199 IK=M(I)
200 GO TO (430,440,450,460,470),IK
201 C CLOSED LOOP TRACK OF PRIMARY TGT, MODE 1
202 430 H(I)=H(I)-DELVER
203 ELEV=ATAN2(H(I),B(I))
204 TEMP=SQRT(H(I)*H(I)+B(I)*B(I))
205 A(I)=A(I)-ATAN2(DELHOR,TEMP)*RTODEG
206 TEMP=A(I)*DTORAD
207 ASIN(I)=SIN(TEMP)
208 ACOS(I)=COS(TEMP)
209 DC1(I)=SIN(ELEV)
210 TEMP=COS(ELEV)
211 DC2(I)=TEMP*ASIN(I)
212 DC3(I)=TEMP*ACOS(I)
213 C OPEN LOOP TRACK OF PRIMARY TGT, MODE 2
214 440 V1=DCS1+DC1(I)
215 V2=DCS2+DC2(I)
216 V3=DCS3+DC3(I)
217 AS=ASIN(I)
218 AC=ACOS(I)
219 GO TO 475
220 C OPEN LOOP TRACK OF SECONDARY TGT, MODE 3
221 450 V1=DCS1+SDC1(I)
222 V2=DCS2+SDC2(I)
223 V3=DCS3+SDC3(I)
224 AS=SASIN(I)
```

```

225     AC=SACOS(I)
226     GO TO 475
227 C POINT AT SECONDARY TGT, MODE 4
228     460 V1=SDC1(I)
229     V2=SDC2(I)
230     V3=SDC3(I)
231     AS=SASIN(I)
232     AC=SDCOS(I)
233     GO TO 475
234 C HOME, MODE 5
235     470 KC(I)=1
236     GOUTER(I)=63.12687
237     GOUT(I)=0.
238     GINNER(I)=180.
239     GO TO 600
240 C COMPUTE RESULTANT NORMALIZED HELIOSTH POINTING VECTOR
241     475 TEMP=SQRT(V1*V1+V2*V2+V3*V3)
242     R1=V1/TEMP
243     TEMP1=V2/TEMP
244     TEMP2=V3/TEMP
245 C ROTATE TO RADIAL COORDINATES
246     R2=-TEMP1*AC+TEMP2*AS
247     R3=-TEMP1*AS-TEMP2*AC
248 C COMPUTE GIRNAL ANGLES
249     THETA=ATAN2(-R3,SQRT(R1*R1+R2*R2))
250     PHI=ATAN2(R2,R1)*RTODEG
251 C COMPUTE SCREW LENGTH
252     SCREW=SQRT(3033.-2946.056*COS(1.899847-THETA))
253 C FORMAT OUTER AXIS COMMAND. POSITIVE COMMANDS LENGTHEN SCREW
254 C AND ROTATE OUTER AXIS AWAY FROM THE TARGET.
255     ITEMP=(GOUTER(I)-SCREW)/SF1
256     IF (ITEMP) 510,555,520
257     510 KC(I)=2
258     SIGNUM=1.0
259     ITEMP=-ITEMP
260     GO TO 525
261     520 SIGNUM=-1.0
262     KC(I)=0
263     525 IF (ITEMP-15) 530,540,540
264     530 KC(I)=KC(I)+8
265     GOUTER(I)=GOUTER(I)+SF1*SIGNUM
266     GO TO 550
267     540 KC(I)=KC(I)+4
268     GOUTER(I)=GOUTER(I)+SF2*SIGNUM
269     550 TEMP=(3033.-GOUTER(I)*GOUTER(I))/2946.056
270     TEMP1=SQRT(1.-TEMP*TEMP)
271     GOUT(I)=108.8532-ATAN2(TEMP1,TEMP)*RTODEG
272 C FORMAT INNER AXIS COMMAND. POSITIVE COMMANDS CAUSE A POSITIVE
273 C ROTATION ABOUT AN AXIS DIRECTED RADially OUTWARD FROM THE TARGET.
274     555 ITEMP=(PHI-GINNER(I))/SF3
275     KC(I)=KC(I)+16
276     IF(ITEMP) 560,600,570
277     560 KC(I)=KC(I)-16
278     SIGNUM=-1.0
279     ITEMP=-ITEMP
280     GO TO 575

```

```
281 570 SIGNUM=1.0
282 575 IF (ITEMP-15) 580,590,590
283 580 KC(I)=KC(I)+64
284 GINNER(I)=GINNER(I)+SF3*SIGNUM
285 GO TO 600
286 590 KC(I)=KC(I)+32
287 GINNER(I)=GINNER(I)+SF4*SIGNUM
288 600 CONTINUE
289 C
290 C ISSUE HELIOSTAT COMMANDS
291 610 CONTINUE
292 A LDA,=KC
293 A OTA,0105
294 GO TO 610
295 620 CONTINUE
296 A LDA,=KC
297 A OTA,0106
298 GO TO 620
299 630 CONTINUE
300 A LDA,=KC
301 A OTA,0130
302 GO TO 630
303 640 CONTINUE
304 A LDA,=KC
305 A OTA,0131
306 GO TO 640
307 C
308 C COMPUTE CAL ARRAY CENTROID
309 645 CONTINUE
310 IF (ICALF.EQ.0) GO TO 730
311 650 IF (ICRAY.NE.37417) GO TO 645
312 ICALF=0
313 TEMP1=0.
314 TEMP2=0.
315 DO 710 I=1,14
316 TEMP=0.
317 DO 705 J=1,16
318 TEMP=TEMP+FLOAT(ICAL(I,J))
319 TEMP1=TEMP1+TEMP
320 710 TEMP2=TEMP2+TEMP*C(I+1)
321 IF (TEMP1.EQ.0.) GO TO 730
322 DELVER=-TEMP2/TEMP1
323 C
324 TEMP2=0.
325 DO 720 J=1,16
326 TEMP=0.
327 DO 715 I=1,14
328 715 TEMP=TEMP+FLOAT(ICAL(I,J))
329 720 TEMP2=TEMP2+TEMP*C(J)
330 DELHOR=TEMP2/TEMP1
331 GO TO 900
332 730 DELVER=0.
333 DELHOR=0.
334 C
335 C COMPUTE WEATHER DATA AND REFRACTION CORRECTION
336 C
```

```
337 900 CONTINUE
338 C   INTERRUPT RETURN J
339 A   LDA, J
340 A   JMP*, J
341     END
```

0 FORTTRAN ERRORS
\$FN-24-32 41204082-614 A


```

342 C CALRAY
343   DIMENSION C(16)
344   COMMON IHR5, IMINS, ISECS, ICAL(14,16), IWERT(16)
345   DATA C(1), C(2), C(3), C(4), C(5), C(6), C(7), C(8), C(9), C(10), C(11),
346   +      C(12), C(13), C(14), C(15), C(16)
347   +/-7.5, -6.5, -5.5, -4.5, -3.5, -2.5, -1.5, -.5, .5, 1.5, 2.5, 3.5, 4.5, 5.5,
348   + 6.5, 7.5/
349 C
350   CALL INIT
351   WRITE(1,35)
352   READ(1,40) IHR5, IMINS, ISECS
353   35 FORMAT(24H ENTER HOURS, MINS, SECS)
354   40 FORMAT(I3, I3, I3)
355 A   OCP :0020
356   45 WRITE(1,50) IHR5, IMINS, ISECS
357   50 FORMAT(6H TIME , I2, 1H:, I2, 1H:, I2, 1H: /)
358   CALL CALSAM
359   TEMP1=0.
360   TEMP2=0.
361   DO 110 I=1,14
362     TEMP=0.
363     DO 105 J=1,16
364       105 TEMP=TEMP+FLOAT(ICAL(I,J))
365       TEMP1=TEMP1+TEMP
366     110 TEMP2=TEMP2+TEMP*C(I+1)
367     IF (TEMP1 .EQ. 0.) GO TO 130
368     DELVER=-TEMP2/TEMP1
369 C
370   TEMP2=0.
371   DO 120 J=1,16
372     TEMP=0.
373     DO 115 I=1,14
374       115 TEMP=TEMP+FLOAT(ICAL(I,J))
375     120 TEMP2=TEMP2+TEMP*C(J)
376     DELHOR=TEMP2/TEMP1
377     GO TO 140
378   130 DELVER=0.
379     DELHOR=0.
380   140 WRITE(1,150) DELVER, DELHOR
381   150 FORMAT(8H DELVER=, F8, 2, 8H DELHOR=, F8, 2, 10H /)
382     GO TO 45
383   160 CONTINUE
384   END

```

* ERROR NOT SUBPROG RECORD 384

****3612

1 FORTRAN ERRORS
\$FN-24-32 41204082-614 A

Appendix 8

BREADBOARD TEST DATA

A breadboard of the Heliostat Servo Output Amplifier was built to check operation. Measured data on static threshold, signal swing, switching time margins, and output rise and fall time are presented. Signal swing and switching data were taken with a bipolar square wave as an input and with the amplifier driving a 15 ohm resistive load. Short term operating tests to full saturation into a 4 ohm load (± 5 amperes) were run with no apparent difficulty. No output ringing or tendency toward oscillation was noted. All tests were run at room temperature. The data shows that the amplifier will perform its expected function.

HELIOSTAT SERVO OUTPUT AMPLIFIER BREADBOARD TEST DATA

<u>Measured Point</u>	<u>Signal Swing (Volts) or Time (ms)</u>	
	<u>Inverting Side</u>	<u>Non-Inverting Side</u>
Op Amp Output, Non Sat Output	+5.5V to -13.5V	+5.25V to -13.5V
Op Amp Output, Sat Output	+13.5V to -13.5V	+13.5V to -13.5V
Darlington Driver Base, Non Sat Output	+1.3V to -8V	+1.3V to -8V
Darlington Driver Base, Sat Output	+1.3V to -8V	+1.3V to -8V
Darlington Output Base, Non Sat Output	+0.7V to -0.4V	+0.7V to -0.4V
Darlington Output Base, Sat Output	+0.8V to -0.4V	+0.8V to -0.4V
Base 2N2222A, Non Sat Output	+5.25V to -1.2V	+5.25V to -1.2V
Base 2N2222A, Sat Output	+6.0V to -1.2V	+6.0V to -1.2V
Collector 2N2222A, Non Sat Output	+24V to 22.5V	24V to 22.5V
Collector 2N2222A, Sat Output	5.5V to 24V	5.5V to 24V
Base, PNP	24V to 24V- V_{BE}	24V to 24V- V_{BE}
Collector, PNP	0 to 24V	0 to 24V
Emitter, Linear Output	-0.3V to 24V	-0.3V to 24V
Cp Amp Slew Rate, Pos. Going Signal	19V in 6 ms	19V in 6.7 ms
Op Amp Slew Rate, Neg. Going Signal	19V in 5.3 ms	19V in 7 ms

SWITCHING TIME MARGINS, BASE COLLECTOR DARLINGTON DRIVER TRANSISTOR

$V_{BC}=0$ Neg. Going, $V_{CE}=0$ Pos. Going, Non Sat. Output	4 ms	5 ms
$V_{BC}=0$ Neg. Going, $V_{CE}=0$ Pos. Going, Sat. Output	1.0 ms	3 ms
$V_{BC}=0$ Pos. Going, $V_{CE}=0$ Neg. Going, Going to 0, Non Sat Output	5 ms	4.2 ms
$V_{BC}=0$ Pos. Going, $V_{CE}=0$ Neg. Going, Going to 0, Sat. Output	2.5 ms	1.0 ms

SWITCHING TIME MARGINS, BASE COLLECTOR DARLINGTON OUTPUT TRANSISTOR

$V_{EC}=0$ Neg. Going, $V_{CE}=0$ Pos. Going, Non Sat. Output	4.4 ms	5.5 ms
$V_{EC}=0$ Neg. Going, $V_{CE}=0$ Pos. Going, Sat Output	1.0 ms	3 ms
$V_{BC}=0$ Pos. Going, $V_{CE}=0$ Pos. Going, Going to 0, Non Sat Output	5 ms	4.5 ms
$V_{BC}=0$ Pos. Going, $V_{CE}=0$ Pos. Going, Going to 0, Sat Output	3.5 ms	2.5 ms
Output Square Wave Risettime Non Sat Output		0.05 ms
Output Square Wave Risettime Sat Output		0.1 ms
Output Square Wave Falltime Non Sat Output		0.05 ms
Output Square Wave Falltime Sat Output		0.1 ms

Output Square Wave Time Threshold Non Sat Output	7 ms oneside, 6 ms otherside
Output Square Wave Time Threshold Sat Output	3.5 ms oneside, 2.5 ms otherside.

Static Threshold: ± 30 mv

Appendix 9

SERVO SIMULATION

The model used in the simulation of the heliostat loop is shown in the figure. It includes quantization of the input commands and position feedback, torque motor saturation limiting, load spring rate and damping, and worm gear friction.

Parameter values used for the analysis are summarized in the table below.

The simulation uses the "analog continuous systems simulator". This permits application of various input commands and load torques in combination or individually and provides stability verification under these conditions. Outputs from any block within the loop can be obtained.

LOOP PARAMETERS USED IN SIMULATION

	<u>Symbol</u>	<u>Units</u>	<u>Inner Axis</u>	<u>Outer Axis One Motor</u>
Torque Motor				
Max Stall Torque	T_M	lb-ft	0.52	1.04
Gain	K_M	lb-ft/V	$2.17\epsilon-2$	$4.34\epsilon-2$
Elec Time Const	T_M	sec	$1.3\epsilon-3$	$1.3\epsilon-3$
Damping (BEMF)	K_B	lb-ft-sec	$3.91\epsilon-3$	$7.82\epsilon-3$
Inertia	J_M	lb-ft-sec ²	$5.21\epsilon-5$	$1.04\epsilon-4$
Quantization		arc-sec	81	81
Gear Ratio	N	-	$1.6\epsilon4$	$1.6\epsilon4$
Gear Efficiency	E	-	0.25	0.25
Gear Inertia at Motor	J_G	lb-ft-sec ²	3×10^{-8}	2.86×10^{-5}
Load				
Inertia	J_L	lb-ft-sec ²	$7.32\epsilon2$	$2.67\epsilon3$
Spring Rate	K_L	lb-ft/rad	$6.25\epsilon5$	$1.75\epsilon7$
Damping	D_L	lb-ft-sec	$2.67\epsilon3$	$2.70\epsilon4$
Torque				
Wind	T_W	lb-ft	208	834
Mass Unbalance	T_U	lb-ft	30	200
Friction	T_F	lb-ft	2	2

GIMBAL CONTROL LOOP MODEL USED IN SIMULATION

0576-39B

Appendix 10

MIRROR MODULE REFLECTANCE MEASUREMENTS

SPECTRAL REFLECTANCE

Cary 14 Spectrometer With Tungsten Source

Range 0.3 to 2.5 mm

MIRRORED GLASS REFLECTORS

Perf Group	Ref No.	Composition	Manufacturer	Peak Reflectance			
				Visual Range		Infrared Range	
				R (%)	Wavelength (μm)	R (%)	Wavelength (μm)
1	9	0.028 inch, 2nd surface, silvered, laminated glass reinforcement	ASG Glass/Gardner Mirror ↓	96	0.65	98	1.7
	11	0.090 inch, 2nd surface, silvered, low iron		96	0.55	94	1.6
2	10	0.098 to 0.118 inch, 2nd surface, silvered	ASG Glass/Gardner Mirror ↓	92	0.50	84	1.7
	8	0.028 inch, 2nd surface, vapor deposited aluminum, laminated glass reinforcement		86	0.55	94	1.8

FILM REFLECTORS

1	7	Chrome on 0.002 inch polyester	Coating Products, Inc.	93	0.5	95	1.6
2	2 1	Oxidized SiO on aluminum Series emittance tape	Schjeldahl ↓	88	0.65	95	1.3
				82	0.65	98	2.2
3	4	Type G4005 0.002 inch aluminum on teflon, 2nd surface		81	0.7	46 ⁽¹⁾	1.7
4	3	Gold on flexible plastic	DuPont ↓	76	0.7	98	1.8
	5	G405600 Aluminum - Mylar on teflon		66	0.65	84	2.2
	6	UV screening Tedlar on metalized Mylar		65	0.7	88	2.2

(1) See Appendix

REFLECTANCE

D. JOHNSON/TFL

3-22-76

Series Emittance Tape (Schjeldahl)
(1)

REFLECTANCE

D. JOHNSON/TFL

3-22-76

Series Emittance Tape (Schjeldahl)
(1)

REFLECTANCE

D. JOHNSON / TEL

3-22-76

Oxidized SiO_2 on Aluminum (Schjeldahl)
(2)

REFLECTANCE

D. JOHNSON / TEL

3-22-76

Oxidized SiO_2 on Aluminum (Schjeldahl)
(2)

REFLECTANCE

Gold (Schjeldahl)
(3)

D. JOHNSON/TFL
3-22-76

REFLECTANCE

Gold (Schjeldahl)
(3)

D. JOHNSON/TFL
3-22-76

100
90
80
70
60
50
40
30
20
10

The measured reflectances for sample No. 4 indicate an apparent discrepancy at 0.7 μ m. The spectrometer operates in different modes in the visible and infrared ranges. In the visible the source is filtered, and it does not heat the sample. In the infrared the source is not filtered, so it irradiates the sample with much more energy. This heats the sample, and apparently increases absorption by the Teflon layer which is optically before the Al rear surface. This seems to account for the lower measured reflectance. The scans were repeated several times to determine the cause of the discrepancy. The operator could observe the reflectance decrease with time at 0.7 μ m when measuring in the infrared mode. This is a point to note in application of the rear surface material.

64005 (SCHNEIDER)
(4)

REFLECTANCE

D. JOHNSON / TFL
3-24-76

100
90
80
70
60
50
40
30
20
10

64005 (SCHNEIDER)
(4)

REFLECTANCE

D. JOHNSON / TFL
3-24-76

Solar Mirror Metall. G405600 (Schjeldahl)
(5)

REFLECTANCE

JENNISON/TFL

3-22-76

Solar Mirror Metall. GA05600 (Schjeldahl)
(5)

REFLECTANCE

JENNISON/TFL

3-22-76

metallized Mylar laminate
(6)

REFLECTANCE

D. JOHNSON / TFL

3-22-76

metallized Mylar laminate
(6)

REFLECTANCE

D. JOHNSON / TFL

3-22-76

CHROME ON .002" POLYESTER (7)
 REFLECTANCE
 D. JOHNSON/TFL
 3-24-76

CHROME ON .002" POLYESTER (7)
 REFLECTANCE
 D. JOHNSON/TFL
 3-24-76

REFLECTANCE

D. JOHNSON/TFL

3-22-76

#10

REFLECTANCE

D. JOHNSON/TFL

3-22-76

#10

$\lambda (\mu)$

REFLECTANCE

D. JOHNSON / TEL

#11 REAR SURF MIRROR

3-29-76

$\lambda (\mu)$

REFLECTANCE

D. JOHNSON / TEL

#11 REAR SURF MIRROR

3-29-76

Appendix 11

PLYWOOD FRAME FIXED FOCUS MIRROR MODULE

(TYPE MM1)

TEST DATA

A7603-031

FIGURE 1. PLYWOOD FRAME FIXED FOCUS MIRROR MODULE (TYPE MM1)

A7603-034

FIGURE 2. MM1 REDIRECTING BEAM ON BUILDING E-2

FIGURE 3. MM1 VIEWED FROM ROOF OF BUILDING E-2

FIGURE 4. MM1 REDIRECTED PATTERN

RANGE: APPROXIMATELY 500 FEET

DATE: 2 MARCH 1976

TIME: 1440 HOUR EST

MIRROR MODULE: 1

DATE: -

SURFACE ORIENTATION: HORIZ

CONDITIONS: ALL: NO ADDED MASS LOAD

○ 4/27/76 1400-1500 HREDST FULL

SOLAR LOAD $\approx 90^\circ\text{F}$ AMBIENT

□ 4/29/76 1500-1600 HREDST FULL

SOLAR LOAD $\approx 90^\circ\text{F}$ AMBIENT

△ 5/4/76 0730-0830 HREDST NO

SOLAR LOAD

$\approx 75^\circ\text{F}$ AMBIENT

DESIGN
NOMINAL?

FIGURE 5. CONTOUR DATA

MIRROR MODULE: 1

DATE: 5/4/76

SURFACE ORIENTATION: HORIZ

CONDITIONS: ALL: NO ADDED MASS LOAD

○ 0830-0930 HR EDST
PARTIAL SHADE

□ 1000-1100 HR EDST
PARTIAL SHADE

FIGURE 6. CONTOUR DATA

MIRROR MODULE: 1

DATE: 4/28/76

SURFACE ORIENTATION: HORIZ

CONDITIONS:

ALL: NO ADDED MASS LOAD
PARALLEL SHADE

□ RUN 1 0930-1030 HR EST

○ RUN 2 1030-1130 HR EST

FIGURE 7. CONTOUR DATA

FIGURE 8. MM1 SURFACE FRACTURES
(TOP EDGE RAISED)

STEEL FRAME VARIABLE FOCUS MIRROR MODULE

(TYPE MM2)

TEST DATA

FIGURE 9. STEEL FRAME VARIABLE FOCUS MIRROR MODULE (TYPE MM2)

FIGURE 10. MM2 REDIRECTING BEAM ON TARGET

3	3	3	3	3	1	2	3	3	3	3	3	2	2	3	3
3	2	3	2	3	3	2	2	3	2	2	3	2	3	3	2
2	3	3	2	2	3	3	2	2	3	3	3	3	2	2	2
3	3	1	3	2	2	2	2	3	2	2	3	2	3	3	3
3	1	3	3	2	3	2	3	3	3	3	3	3	3	2	3
2	3	3	3	2	3	3	3	2	3	2	2	3	3	3	2
3	2	3	3	3	4	3	2	2	3	2	1	3	3	2	3
2	3	3	2	3	3	2	2	3	3	3	2	3	3	2	3
3	3	3	3	1	3	2	3	2	3	2	3	2	3	3	3
3	2	3	2	3	2	3	3	3	3	2	3	2	3	3	2
4	3	2	3	2	3	3	2	2	3	3	2	3	3	3	3
2	2	3	3	3	3	3	3	2	3	3	3	2	3	2	3
2	3	3	3	3	3	3	2	2	3	3	3	3	2	3	3
2	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3

Background Light
(1 = 0.04 suns)

3	3	3	3	3	2	2	3	3	3	3	3	3	2	3	3
3	2	3	2	3	3	2	2	3	2	3	4	4	4	3	2
2	3	3	2	2	3	3	2	2	4	5	9	10	8	5	2
3	3	1	3	2	2	2	2	3	4	8	15	16	15	11	5
3	1	3	3	2	3	2	3	4	7	15	23	24	20	12	5
2	3	3	3	2	3	3	3	4	9	18	26	27	22	13	4
3	2	3	3	3	4	3	3	4	10	10	23	24	20	9	4
2	3	3	2	3	3	2	3	5	10	15	14	18	12	5	3
3	3	3	3	1	3	2	3	3	7	10	12	10	7	4	3
3	2	3	2	3	2	3	3	4	5	6	7	4	3	3	2
4	3	2	3	2	3	3	2	3	3	4	3	3	3	3	3
2	3	3	3	3	3	3	3	2	3	3	3	2	3	2	3
2	3	3	3	2	3	3	2	2	3	3	3	3	2	3	3
2	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3

Redirected Pattern
Sample 1
Height 8 ft Width 8 ft

3	3	3	3	3	1	2	3	4	4	4	3	2	2	3	3
3	2	3	2	3	3	3	3	6	7	7	5	2	3	3	2
2	3	3	2	2	3	4	6	11	15	13	10	4	2	2	2
3	3	1	3	2	3	5	11	21	22	18	13	5	3	3	3
3	1	3	3	2	4	5	16	25	28	22	13	5	3	2	2
2	3	3	3	3	4	9	18	25	26	20	10	4	3	3	2
3	2	3	3	3	5	9	15	20	21	8	5	3	3	2	3
2	3	3	2	3	4	6	11	15	13	9	3	3	3	2	3
3	3	3	3	1	4	5	7	8	8	4	3	2	3	3	3
3	2	3	2	3	2	4	4	5	3	2	3	2	3	3	2
4	3	2	3	2	3	3	2	3	3	3	2	3	3	3	3
2	3	3	3	3	3	3	3	2	3	3	3	2	3	2	3
2	3	3	3	3	3	3	2	2	3	3	3	3	2	3	3
2	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3

Redirected Pattern
Sample 2
Height 9 ft Width 7 ft

FIGURE 11. MM2 BEAM ON PHOTODETECTOR ARRAY
RANGE: APPROXIMATELY 500 FT DATE: 28 APRIL 1976

MIRROR MODULE: 2

DATE: 5/7/76

SURFACE ORIENTATION: HORIZ

CONDITIONS: NO ADDED MASS LOAD
MORNING, HAZY, NOT SHADED

FIGURE 12. CONTOUR DATA

BUILT UP PANEL FIXED FOCUS MIRROR MODULE

(Type MM3P)

SN PO 1

TEST DATA

[illegible]

Background Light
Time: 9.26 AM EDST
(1 = 0.04 suns)

0	0	0	0	0	0	0	C	0	0	0	1	0	0	1	1
0	0	0	0	0	0	0	C	0	0	1	1	3	5	3	1
0	0	0	0	0	0	1	C	0	1	3	9	3	11	7	2
0	0	0	0	0	0	0	0	1	3	11	19	20	19	12	5
0	0	0	1	0	1	0	1	2	10	20	29	31	24	13	4
0	1	0	1	0	0	1	1	6	17	29	36	34	25	12	1
1	0	1	0	1	1	1	2	15	29	17	38	31	19	7	1
0	0	1	0	1	1	0	7	16	27	34	25	24	12	2	1
0	0	0	0	0	1	0	7	13	23	25	22	23	5	1	1
0	0	1	0	0	0	0	3	9	14	15	10	3	1	1	0
1	0	0	0	0	0	1	0	2	4	2	1	1	1	1	1
0	0	0	1	0	1	1	1	0	1	1	1	0	1	0	1
0	0	0	0	0	1	1	0	0	1	0	1	0	0	0	0
0	0	1	0	1	1	0	0	1	1	1	0	0	1	1	1

Redirected Pattern
Sample 1
Height 9 ft Width 8 ft
Time: 9:28 AM EDT

0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0	1	0	1	1	0	0
0	0	0	0	0	0	0	1	3	4	2	1	0	0	1
0	0	0	1	0	1	1	9	13	12	8	3	1	0	0
0	0	0	1	0	3	11	18	22	18	12	4	1	1	0
1	0	1	1	2	11	20	30	33	26	7	4	0	0	1
0	0	1	0	6	17	23	39	39	28	15	1	1	0	1
0	0	0	2	7	28	37	43	36	22	9	1	0	0	1
0	0	1	5	16	27	37	36	23	15	4	1	0	0	0
1	1	0	6	14	21	28	18	15	5	1	0	1	1	0
0	0	0	3	9	14	17	12	4	1	1	0	0	1	0
0	0	0	1	2	4	3	1	1	1	0	1	0	0	0
0	0	1	0	1	1	1	1	0	1	1	0	0	1	0

Redirected Pattern
Sample 2
Height 9 ft Width 8 ft
Time: 9:30 AM EDT

11-14

TIME 10:21:55*

1	1	0	1	0	0	0	0	1	0	0	1	0	0	1	1
1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
0	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0
1	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1
1	0	0	1	0	1	0	0	1	1	1	0	1	1	0	0
0	1	1	1	0	0	1	1	0	1	0	0	0	1	1	0
1	0	1	1	1	1	1	0	0	1	0	0	0	0	0	1
0	1	1	0	1	1	0	0	1	1	1	0	1	0	0	1
0	1	0	1	0	1	0	0	0	0	0	0	0	1	1	1
0	0	1	0	1	0	0	0	1	0	0	0	0	0	1	0
1	1	0	1	0	0	1	0	0	1	1	0	1	1	1	1
0	0	0	1	0	1	1	1	0	1	1	0	0	1	0	1
0	1	1	1	0	1	1	0	0	1	1	1	1	0	0	0
0	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1

Background Light
Time 10:20 AM EDST
(1 = 0.04 suns)

DELVER= -0.88 DELHOR= -0.09

ENTER HOURS, MINS, SECS
TIME 0: 0: 0

1	1	2	3	4	2	5	6	5	4	4	3	1	0	1	1
1	1	3	3	7	8	8	5	9	5	5	4	1	1	0	0
1	2	5	6	9	10	11	10	9	10	8	6	4	1	0	0
2	4	2	9	6	10	9	10	13	10	9	8	4	2	1	1
2	1	8	11	9	13	5	13	13	12	11	8	7	4	0	0
1	5	7	11	11	11	13	13	12	13	10	7	6	4	1	0
2	4	8	10	12	14	13	11	10	12	4	4	5	3	1	1
1	3	6	5	10	12	14	11	11	11	10	5	5	2	1	1
1	2	4	6	2	9	9	11	8	9	5	5	2	2	2	1
1	0	3	1	5	5	7	7	8	7	5	3	1	1	1	0
1	1	1	2	2	4	5	3	4	3	3	1	2	1	1	1
0	0	0	1	1	2	3	3	1	2	2	1	1	1	0	1
0	1	1	1	0	1	1	0	1	1	1	1	1	0	1	0
0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1

Redirected Pattern
Height >11 ft Width 14 ft
Time 10:45 AM EDST

DELVER= 1.29 DELHOR= -0.59

FIGURE 14. MM3P (SN P01) BEAM ON PHOTODETECTOR ARRAY
RANGE: APPROXIMATELY 1100 FT DATE: 13 MAY 1976

MIRROR MODULE: 3P (SN PO 1)

DATE: 5-11-76

SURFACE ORIENTATION: HORIZ

CONDITIONS:

- NO ADDED MASS LOAD, NO SOLAR LOAD
EARLY MORNING
- LOADED 2 LB/FT² --
1400-1500 HR EDT.
FULL SOLAR LOAD

FIGURE 15. CONTOUR DATA

MIRROR MODULE: 3P (SN P01)

DATE: 5-11-76

SURFACE ORIENTATION: Horiz

CONDITIONS:

1. No Load 10:30-11:30 HR

2. Partial Solar Load 12:00-13:00 HR

3. Full Solar Load 13:00-14:00 HR

FIGURE 16. CONTOUR DATA

MIRROR MODULE: 3P (SN POI)

DATE: 5-11-76

SURFACE ORIENTATION: HORIZ

CONDITIONS: NO ADDED MASS LOAD

0930-1030HR EDT

PARTIAL SOLAR LOAD

FIGURE 17. CONTOUR DATA

MIRROR MODULE: 3P (SD POI)

DATE: 5-11-76

SURFACE ORIENTATION: Horiz

CONDITIONS: NO ADDED MASS LOAD

0830-0930 HR EDST

PARTIAL SOLAR LOADING

FIGURE 18. CONTOUR DATA

BUILT UP PANEL FIXED FORMS MIRROR MODULE

(Type MM3P)

SN PO 5

TEST DATA

MIRROR MODULE: 3P (SN POS)

DATE: 5-12-76

SURFACE ORIENTATION: HORIZ

CONDITIONS: NO ADDED MASS LOAD

0900 - 1000 HR EDT

PARTIAL SOLAR LOAD

FIGURE 19. CONTOUR DATA

MIRROR MODULE: 3P (SN POS)

DATE: 5-12-76

SURFACE ORIENTATION: HORIZ

CONDITIONS: NO ADDITIONAL MASS LOAD

○ 0930-1030 HR EDST
PARTIAL SOLAR LOAD

□ 1330-1430 HR EDST
FULL SOLAR LOAD

FIGURE 20. CONTOUR DATA

MIRROR MODULE: 3P (SN POS)

DATE: 5-12-76

SURFACE ORIENTATION: HORIZ

CONDITIONS: NO ADDITIONAL MASS LOAD

1430-1500 HZ EDST

FULL SOLAR LOAD

FIGURE 21. CONTOUR DATA

MIRROR MODULE: 3P (SN P05)

DATE: 5-12-76

SURFACE ORIENTATION: Horiz

CONDITIONS: NO ADDITIONAL SOLAR LOAD

1500 - 1600 HR EST

FULL SOLAR LOAD

FIGURE 22. CONTOUR DATA

Appendix 12

RESEARCH EXPERIMENT HELIOSTAT LOCATION

HELIOSTAT SOUTH TEST SITE
103C FT LOS 163 DEG AZ

HELIOSTAT NORTH TEST SITE
482 FT LOS 10 DEG AZ

HELIOSTAT EAST TEST SITE
806 FT LOS 90 DEG AZ

MIRROR MODULE MAXIMUM RANGE TEST SITE
1112 FT LOS 27 DEG AZ

MIRROR MODULE MINIMUM RANGE TEST SITE
482 FT LOS 3 DEG AZ

Appendix 13

TWO TECHNIQUES FOR REDIRECTED IMAGE CHARACTERIZATION

Photographic image recording provides an alternate method to verify photodetector light intensity data, a means to record images larger than the array and enables simultaneous image recording from multiple heliostat or mirror module sites.

The illustration shows the photodetector array and photographic reference grids installed on the north side of Building E-2.

Light intensity data sensed by the array of photodetectors is periodically transferred to the processor and stored on magnetic tape under software control. An off line computer program processes this data to generate an intensity map as illustrated. The map is produced on a line printer using character over prints to achieve a representation of six intensity levels.

The grid lines on the photographic reference grid are on one foot vertical and horizontal centers. The redirected image on the grid is photographed from a camera site in front of the grid.

Benchmarks referenced to the target area on Building E-2 have been installed at the two mirror module test sites. These benchmarks facilitate precise definition of reflector to target geometry. Heliostat sites will be precisely located using survey techniques. Sun position is established by recording date and time when an image sample is taken.

A computer program has been developed to predict the redirected pattern shape for mirror modules and heliostats as a function of the sun to reflector to target geometry. Comparison of image data, either from an intensity map or photograph, with the prediction, enables evaluation of performance parameters such as off axis aberrations, scatter and cross-axis coupling and focus quality.

0376-10

INTENSITY MAP

A7604-076

RESEARCH EXPERIMENT REDIRECTED IMAGE CHARACTERIZATION

Appendix 14

GATHERING METEOROLOGICAL DATA FOR PERFORMANCE CORRELATION

Climatronics Corporation has supplied a fully integrated meteorological measuring system for the research experiment. Performance parameters of this system are:

Wind Speed

Range: 0-44.7 meters/sec (0-100 mph)
or
0-22.35 meters/sec (0-50 mph)
Accuracy: System ± 0.5 mph or 2 percent
Distance Constant: 2.44 meters max (8 feet)

Wind Direction

Range: 0-540°
Accuracy: ± 2 percent system
Distance Constant: 2.44 meters max (8 feet)
Damping Ratio: 0.4 to 0.6

Temperature #1 - Ambient

Range: -34 to +50°C
Accuracy: $\pm 0.2^\circ\text{C}$
Linearity: $\pm 0.2^\circ\text{C}$

Temperature #2 - Structure

Range: 0 to 100°C
Accuracy: $\pm 0.2^\circ\text{C}$
Linearity: $\pm 0.2^\circ\text{C}$

Temperature #3 - Structure

Range: 0 to 100°C
Accuracy: $\pm 0.2^\circ\text{C}$
Linearity: $\pm 0.2^\circ\text{C}$

Temperature #4 - Differential Structure

Range: $\pm 10^\circ\text{C}$ from temp. probe #3
Accuracy: ± 5 percent of Δt

Solar Radiation

Sensor Type: Eppley Normal Incidence Pyroheliometer

Field of View: $5^{\circ}43'30''$

Sensitivity: 8 microvolts per watt meter⁻² approx.

Temperature: ± 1 percent over ambient temperature range -20 to $+40^{\circ}\text{C}$
dependence

Linearity: ± 0.5 percent from 0-2800 watts meter⁻²

Response time: 1 second (1/e signal)

Barometric Pressure

Range: 9.14 to 1066 Mb

Linearity: $\pm 0.3\%$

Sensitivity: $\pm 0.2\%$

Hysteresis: With 0.2%

Repeatability: Within 0.2%

Op. Temp. Range: -34°C to 82°C

Temp. Error: $\pm 0.0045\%/^{\circ}\text{C}$ max.

The pyroheliometer is installed on an equatorial mount to track the sun. Data from the weather station is transmitted to the processor via an FSK modem and is stored on magnetic tape.

The Research Experiment Weather Station test set-up is shown in Figure 1.

Figure 1

Figure 2 defines the actual signal interconnects within the experimental set-up.

EXPERIMENTAL TEST PROGRAM - ENVIRONMENTAL INTERFACES

Figure 2

Solar Collector Subsystem BASELINE DEFINITION SUMMARY

NOT AUTHORIZED FOR PUBLIC RELEASE

REVISION B: 15 July 1976

Solar Collector Subsystem BASELINE DEFINITION SUMMARY

Prepared By:

R.S. Parker
Principal Investigator

Approved By:

L.P. Ball
Program Manager

CONTRACT NO. LC403127 WITH
HONEYWELL INC.
ENERGY RESEARCH CENTER

Honeywell

AEROSPACE DIVISION
ST. PETERSBURG, FLORIDA

1

BASELINE COLLECTOR SUBSYSTEM

Honeywell's baseline collector subsystem is comprised of 1) a computer controlled open loop simplex serial data command scheme, 2) battery powered motors with batteries trickle charged, 3) four facet tilt-tilt low profile heliostats and 4) periodic calibration of each heliostat using a tower mounted sensor array.

2

3

SYSTEM BASELINE DESIGN

The baseline design is maintained for the pilot plant and commercial scale power generation systems. Power rating is defined at 2 PM on winter solstice. Where no other data is provided pilot plant uses same data as commercial scale.

4

BASELINE DESIGN

	COMMERCIAL	PILOT PLANT
NAMEPLATE CAPACITY	130MW(e)	15MW(e)
2PM DEC 21 NET POWER	100MW(e)	10MW(e)
TOWER HEIGHT	445M	130M
FIELD OD	1890M	550M
NUMBER OF HELIOSTATS	16,800	1680
HELIOSTAT SIZE	40M ²	40M ²
TURBINE CYCLE (FROM RCVR)	120 BAR/510°C	100 BAR/510°C
TURBINE CYCLE (FROM STORAGE)	60 BAR/280°C	---
STORAGE TYPE	PHASE CHANGE	---
STORAGE CAPACITY	TO BE DETERMINED	42MWH(e)
RECEIVER	CAVITY	---
COOLING	DRY	---
LOCATION	INYOKERN	---

5

360 DEGREE HELIOSTAT FIELD LAYOUT

Heliostat field layout studies have shown a tower-south-of-center, non-uniform field can efficiently redirect energy to a circular steam generator atop the tower. The heliostat field completely surrounds the tower with the outer south boundary approximately 450 feet from the tower base and the north edge 1350 feet from the tower. The field outer perimeter is elliptic with an eccentricity of approximately 0.6. This perimeter shape was chosen because heliostat field studies showed tracking efficiency is optimal for elliptic field boundaries.

The heliostat spacing is based on an analysis of shadowing and blocking of adjacent heliostats. The spacing chosen has a minimal amount of shadowing and blocking annual energy losses. The heliostats can be packed relatively dense close to the tower, and spaced farther apart farther out in the field. The spacing also varies somewhat with azimuth position. Heliostats in the south field can be spaced closer together than those in the north or east.

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COLLECTOR SUBSYSTEM DATA

The collector subsystem described encompasses the heliostat (from helios = sun and stat = stationary) array, computer command and control scheme and special facilities. Specification requirements are also summarized.

CHARACTERISTIC	RESEARCH EXPERIMENT	PILOT PLANT
IDENTIFICATION NO.	YGB112A1	T80
HELIOSTAT ARRAY		
TYPE	TILT-TILT, 4 FACET	TILT-TILT, 4 FACET
QUANTITY	1 ENGINEERING MODEL 3 RESEARCH MODELS	1680 OPERATIONAL MODELS
TOTAL REFLECTOR AREA	160 M ² (1634 FT ²)	67,200 M ²
ORIENTATION	OA TARGET LOS	OA TARGET LOS
BEAM ELEVATION ANGLE	0.04 TO 1.18 RAD (2.5 TO 67.8 DEG)	0.36 TO 1.18 RAD (20.7 TO 67.8 DEG)
LOS RANGE	18.3 TO 338 M (60 TO 1110 FT)	128 TO 338 M (420 TO 1110 FT)
TURNING RATE	23 DEG/HR MAX	23 DEG/HR MAX
TRACKING REPOSITION	1080 DEG/HR	1080 DEG/HR
COMPUTER SUBSYSTEM		
PROCESSOR	HS16	T80
PERIPHERALS	MAGTAPE DECK (2 EA) ASR-35 TTY RS232C I/O (8 CH)	T80
SOFTWARE	FORTRAN SUFFICIENT FOR EXPERIMENT	HIGHER ORDER LANGUAGE SIZED FOR PILOT PLANT
COMMUNICATIONS	INDIVIDUAL SERIAL DATA LINKS	SERIAL DATA BUS
POWER DISTRIBUTION	LOCAL BATTERY WITH OFF-LINE RECHARGE	13.8K VRMS, 60 HZ, STEPDOWN TO 115 VRMS FOR ON-LINE BATTERY CHARGE
SPECIAL TEST FACILITIES		
RECEIVER & CALIBRATION ARRAY SIMULATOR	BILL BOARD ATOP BLDG E-2 WITH PHOTODETECTOR ARRAY FOR INTENSITY MAP & CENTROID LOCATION	T80
WEATHER DATA	METEOROLOGICAL CLUSTER	T80
PERFORMANCE		
TRACKING PERIOD	1/2 HR AFTER TRUE SUNRISE TO 1/2 HR BEFORE TRUE SUNSET	1/2 HR AFTER TRUE SUNRISE TO 1/2 HR BEFORE TRUE SUNSET
FAR FIELD POINTING	2 MR/AXIS (10) MIRROR NORMAL	2 MR/AXIS (10) MIRROR NORMAL
OPTICS	1 MR TOTAL (10)	1 MR TOTAL (10)
REDIRECTED PATTERN	95% WITHIN 3.5 M X 7 M	95% WITHIN 3.5 M X 7 M
1110 FEET		
10 AM TO 2 PM		
SURFACE REFLECTANCE (INITIAL)	>80%	>90% (GOAL)
RETURN TO STOWAGE	<15 MIN	<15 MIN
EMERGENCY DEFOCUS MAX TIME	<12 SEC/3 rd TRAVEL	<12 SEC/3 rd TRAVEL

SUMMARY DESCRIPTION

SOLAR COLLECTOR SUBSYSTEM

HELIOSTAT ASSEMBLY

The first heliostat assembly has been built and is now undergoing extensive tests at Honeywell facilities in St. Petersburg, Fla. Major assembly items are shown and identified with key numbers.

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1. Foundation
2. Frame Bearing Assembly
3. Post Support Assembly
4. Reinforced Frame Assembly
5. Mirror Module Bearing Assembly
6. Mirror Module with Spur Gear
7. Mirror Module without Spur Gear

8. Reflective Surface
9. Speed Reduction Assembly
10. Motor Encoder Assembly
11. Crank Arm Assembly
12. Tie Rod Assembly
13. Tie Rod Adjustment
14. Linear Actuator Assembly
15. Electronics

TECHNICAL DATA
 7600 LBS GIMBALED WEIGHT
 8950 LBS ON FOUNDATION
 1100 FT FIXED FOCAL LENGTH
 ± 360 DEG MIRROR ROTATION
 105 DEG FRAME ROTATION
 LENGTH OA 60 FT
 HEIGHT 8.5 FT
 WIDTH 12.5 FT

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HELIOSTAT DATA

The details of the experimental and pilot plant heliostats are given. The service life of 30 years for the pilot plant assumes that proper maintenance is performed.

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CHARACTERISTIC	RESEARCH EXPERIMENT		PILOT PLANT
	ENGINEERING MODEL	EXPERIMENTAL MODEL	
IDENTIFICATION NO	LG8018A1-EM	LG8018A1	TBD
GIMBAL ORDER	TILT-TILT	TILT-TILT	TILT-TILT
MIRROR MODULES	TYPE 1 TYPE 2 TYPE 3	COMBINATION: 4 EA TYPE 3 TBD	4 EA TYPE 3
FOUNDATION	TRAILER	CONCRETE	CONCRETE
ENVELOPE LENGTH	18.4 M (60.4 FT)	18.4 M (60.4 FT)	18.4 M (60.4 FT)
WIDTH	4.5 M (14.7 FT)	4.5 M (14.7 FT)	4.5 M (14.7 FT)
HEIGHT	TBD	4.8 M (15.8 FT)	4.8 M (15.8 FT)
ANGULAR RANGE - FRAME	+30, -75 DEG	+30, -75 DEG	+30, -75 DEG
MM	±180 DEG	±180 DEG	±180 DEG
WEIGHT STEEL	4009 Kg (8950 lbs)	4059 Kg (8950 lbs)	4060 Kg (8950 lbs)
GLASS	225 KG (495 LBS)	225 KG (495 LBS)	225 KG (495 LBS)
CONCRETE	NONE	6501 KG (14,500 LBS)	6501 KG (14,500 LBS)
SHIPPING WEIGHT	TBD	TBD	TBD
FINISH	WHITE PAINT	WHITE PAINT	WHITE PAINT
POWER	LOCAL BATTERY WITH OFF LINE RECHARGE	LOCAL BATTERY WITH OFF LINE RECHARGE	115 VRMS, 60 HZ, 10 - WATTS
SIGNAL (COMMAND)	INDIVIDUAL RS232 SERIAL DATA LINK	INDIVIDUAL RS232 SERIAL DATA LINK	SERIAL DATA BUS
SERVICE LIFE	2 YEARS	2 YEARS	30 YEARS
ENVIRONMENT			
TEMPERATURE	4°C TO 55°C (40°F TO 130°F)	4°C TO 55°C (40°F TO 130°F)	-20°C TO 60°C (-4°F TO 140°F)
WIND			
OPERATE			
SUSTAINED	AMBIENT PLUS 13.5 M/SEC INDUCED	AMBIENT PLUS 13.5 M/SEC INDUCED	13.5 M/SEC (30 MPH)
GUST			TBD
NON-OPERATING			TBD
SUSTAINED			TBD
GUST			TBD

SUMMARY DESCRIPTION

HELIOSTAT

13

MIRROR MODULE DATA

Several mirror modules were designed, built and tested. The first column describes a prototype fixed focus unit. The second column describes a variable focus unit designed to test center pull effects. The third column describes a foam core unit. The last column describes a honeycomb core unit which was selected for the 4 research experiment heliostats.

CHARACTERISTIC	TYPE			
	1	2	3B	3P
IDENTIFICATION NO.	34026594	34026577	34026575B	34026575P
REFLECTIVE SERVICE TYPE	FLOAT GLASS 2ND SURFACE MIRROR	FLOAT GLASS 2ND SURFACE MIRROR	FLOAT GLASS 2ND SURFACE MIRROR	FLOAT GLASS 2ND SURFACE MIRROR
THICKNESS	3 MM (0.118 INCH)	4.8 MM (0.19 INCH)	3 MM (0.118 INCH)	2.5 MM (0.098 INCH)
AREA	9 PCS EA 1.05 X 1.05 M (13.46 X 3.46 FT)	9 PCS EA 1.05 X 1.05 M (13.46 X 3.46 FT)	9 PCS EA 1.05 X 1.05 M (13.46 X 3.46 FT)	18 PCS EA 0.79 X 0.79 M (12.6 X 2.6 FT)
MOUNT	BOND TO SUPPORT STRUCTURE	BOND TO STIFFENER MECHANICALLY FASTENED TO SUPPORT STRUCTURE	BOND TO SUPPORT STRUCTURE	BOND TO SUPPORT STRUCTURE
SPHERICAL RADIUS	677.9 M (2224 FT)	ADJUSTABLE	677.9 M (2224 FT)	677.9 M (2224 FT)
FOCAL LENGTH	338.9 M (1112 FT)	ADJUSTABLE	338.9 M (1112 FT)	338.9 M (1112 FT)
REFLECTANCE	~ 83%	< 8%	~ 83%	~ 90%
CONTOUR CONTROL	SUPPORT STRUCTURE	CENTER PULL AGAINST RING RESTRAINT	SUPPORT STRUCTURE	SUPPORT STRUCTURE
OVERALL LENGTH	3.58 M (11.75 FT)	3.58 M (11.75 FT)	3.58 M (11.75 FT)	3.45 M (11.32 FT)
WIDTH	3.18 M (10.42 FT)	3.18 M (10.42 FT)	3.18 M (10.42 FT)	3.06 M (10.07 FT)
THICKNESS	0.22 M (0.72 FT)	0.25 M (0.82 FT)	0.20 M (0.67 FT)	0.20 M (0.67 FT)
MIRROR SUPPORT STRUCTURE	3/4 INCH FIR PLYWOOD FRAME WITH 1/4 INCH MASONITE SKIN	STEEL BAR JOIST FRAME WITH 7/2 INCH DIA FOCUSING RING AND 1/4 INCH FIBER GLASS CORE IN PAPER CORE HONEYCOMB STIFFENER	TRIANGULAR SANDWICH BUILT-UP PANEL SKIN MATERIAL-STEEL CORE MATERIAL-FOAM	RECTANGULAR SANDWICH BUILT-UP PANEL SKIN MATERIAL- ALUMINUM CLAD STEEL CORE MATERIAL - ALUMINUM
SUPPORT SHAFTS	CARBON STEEL W/ NICKEL PLATED BEARING SURFACES	CARBON STEEL W/ NICKEL PLATED BEARING SURFACES	ALUMINUM MACHINING	ALUMINUM MACHINING
SUPPORT BEARING DIAMETER	102 MM (4 INCH) BORE	102 MM (4 INCH) BORE	102 MM (4 INCH) BORE	102 MM (4 INCH) BORE
WEIGHT (ESTIMATED)	340 KG (750 LBS)	319 KG (700 LBS)	268 KG (590 LBS)	272 KG (600 LBS)
IMBALANCE	0 KG-M	0 KG-M	18.7 KG-M (135 FT-LB)/MAX	18.7 KG-M (135 FT-LB)/MAX
SHIPPING WEIGHT	TBD	TBD	TBD	TBD
FINISH	WHITE PAINT ON NON- FUNCTIONAL SURFACES	WHITE PAINT ON NON- FUNCTIONAL SURFACES	WHITE PAINT ON NON- FUNCTIONAL SURFACES	WHITE PAINT ON NON- FUNCTIONAL SURFACES

SUMMARY DESCRIPTION

MIRROR MODULE

DRIVE SYSTEMS DATA

The 4 mirror modules on each heliostat are ganged together and driven by a single motor working through a 16000 to 1 speed reducer. The outer frame is driven by two screw jacks driven by independent motors which are synchronized through control electronics.

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CHARACTERISTIC	INNER AXIS	OUTER AXIS
DRIVER TRAIN ELEMENTS	DC SERVO MOTOR WITH ENCODER GEAR BOX SPUR GEAR CRANK ARM/MM STUB SHAFT TIE ROD CRANK ARM/MM STUB SHAFT (WITH 90° OFFSET FOLLOWING DRIVE TRAIN)	2 EA SYNCHRONIZED DRIVE TRAINS: DC SERVO MOTOR WITH ENCODER WORM GEAR BALL NUT BALL SCREW FRAME
MOTOR-TO-LOAD REDUCTION RATIO	16000:1	16000:1
MOTOR TORQUE REQD UNDER 13.5 M/S SUSTAINED WIND	0.0102 KG-M (0.074 FT-LBS)	0.0090 KG-M (0.065 FT-LBS)
MAX TORQUE AT GIMBAL AXIS UNDER 13.5 M/S SUSTAINED WIND	32.9 KG-M (238 FT-LBS)	142.7 KG-M TOTAL (1032 FT-LBS TOTAL)
MAX POWER REQD AT MOTOR SHAFT	8.45 WATTS	7.34 WATTS EACH MOTOR
MAX ELECT PWR REQD TO MOTOR	33.8 WATTS	30 WATTS EACH MOTOR
AVAILABLE MOTOR TORQUE	0.0205 KG-M (0.148 FT-LBS)	0.0180 KG-M (0.130 FT-LBS)
MAX SLEW RATE CAPABILITY	0.005 RAD/SEC (0.3 DEG/SEC)	0.005 RAD/SEC (0.3 DEG/SEC)
ENCODER RESOLUTION	1 PULSE PER MOTOR REVOLUTION	1 PULSE PER MOTOR REVOLUTION
WEIGHT	272 KG (600 LBS)	90.7 KG (200 LBS)
SHIPPING WEIGHT	TBD	TBD
FINISH	WHITE PAINT	PROTECTIVE COVER

SUMMARY DESCRIPTION

DRIVE SYSTEMS

17

FRAME AND POST DATA

The frame and post are described. The I-Beam frame consists of two wide flange rails braced and reinforced to accept moment loads. The split channel type posts allow frame cross members to drop between them at high frame angles.

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IDENTIFICATION NO.	34026572
FRAME OVERALL WIDTH LENGTH DEPTH	3.5 M WIDE (11.6 FT) 15.7 M LONG (51.5 FT) 0.4M DEEP (1.33 FT)
SHIPPING WEIGHT MATERIAL	TBD HIGH STRENGTH LOW ALLOY STRUCTURAL STEEL
CONSTRUCTION SUPPORT BEARING (4)	I-BEAMS 1 15/16 PILLLOW BLOCK
WEIGHT FINISH	1361 KG (3000 LBS) WHITE PAINT
SUPPORT (2 EA) HEIGHT MATERIAL WEIGHT SHIPPING WEIGHT FINISH	FRAME AXIS 2.29 M (7.5 FT) ABOVE FOUNDATION TOP 2 EA TWIN STEEL U CHANNELS 181 KG (400 LBS) TBD WHITE PAINT
FOUNDATION	REINFORCED CONCRETE PER LOCAL SOIL CONDITIONS

SUMMARY DESCRIPTION

FRAME, SUPPORT AND FOUNDATION

19

CALIBRATION ARRAY DATA

The calibration array and its sensors are described. The array configuration is sized sufficient to measure reflected insolation (sun energy) at all times of day. All sensor data is scaled and input to the command computer to allow bias correction of heliostat commands.

20

CHARACTERISTIC	RESEARCH EXPERIMENT	PILOT PLAN
IDENTIFICATION NO.	LG8015A1	TBD
FUNCTION	CENTROID LOCATION AND INTENSITY MAPPING	CENTROID LOCATION
OVERALL HEIGHT	4.8 M (15.75 FT)	TBD
WIDTH	5.1 M (16.67 FT)	TBD
SENSOR		
TYPE	TIL 99 PHOTO TRANSISTOR	TIL 99 PHOTO TRANSISTOR
QUANTITY	224 ARRAY & 5 BACKGROUND	TBD
LOCATION	0.3 M (1 FT) ON VERT AND HORIZ CENTERS IN 4.28 X 4.88 M (14 X 16 FT) ARRAY	TBD
FIELD OF VIEW	+0.39 RAD (+22.5 DEG)	TBD
EXPECTED BACKGROUND	1.5 SUNS	1.5 SUNS
SIGNAL TO BACKGROUND RATIO	2.6 TO 1	2.6 TO 1
POWER	115 VRMS, 60 HZ, 10 -WATTS	115 VRMS, 60 HZ, 10 -WATTS
SIGNALS	STROBE AND TDM SERIAL DATA LINK	STROBE AND TDM SERIAL DATA LINK

**SUMMARY
DESCRIPTION**

**INSOLATION
DETECTOR
ARRAY**

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