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Development of a three-mirror, wide-field sensor, from paper design to hardware

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ABSTRACT

The Landsat Thematic Mapper imagers have provided moderate resolution, multispectral imagery of the Earth for the past 7 years. Yet, the need exists for higher spatial and spectral resolution and better radiometric accuracy. Santa Barbara Research Center has been exploring technology related to the design, tolerance, and alignment of wide-field, all-reflective sensors for multispectral earth observation. The goals of this study were to design an optical system with reduced fabrication risks, to develop a detailed tolerance budget and to demonstrate precision alignment of a laboratory demonstration unit. The telescope is a three-mirror unobscured form that is telecentric and flat field over 15 degrees at F/4.5, and is diffraction-limited at visible wavelengths. A computer-aided alignment approach aligned the telescope to the budgeted tolerance of 0.05 waves rms at 0.6328 microns. Details of the design, tolerance, and alignment of this telescope are described in two earlier papers.[1,2] This paper consolidates the findings of those two and emphasizes the importance of keeping the hardware in mind from very early in the design.

1. OPTICS DESIGN

The telescope is the "reflecting triplet" form of a three-mirror anastigmat. The design used as the starting point was done by L. Cook and R. Kebo of Hughes. This was chosen as being a particularly compact configuration with good performance over wide fields of view and fast f-numbers. Figure 1 shows an isometric plot of the final design and shows the strip field of view. Figures 2 is the diffraction MTF for four field angles and shows the design to be well-corrected with balanced performance across the field. Some of the notable design points are shown in Table 1.

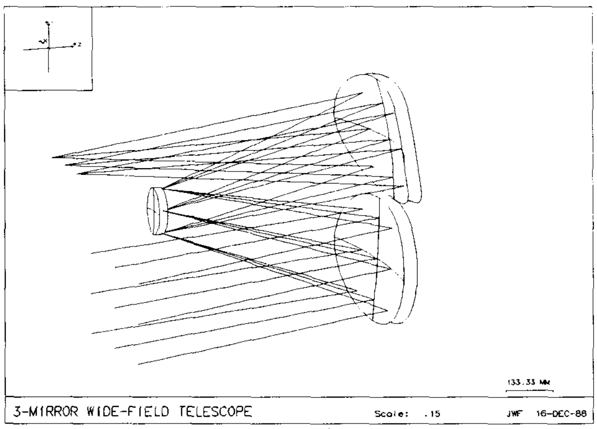


Figure 1. The telescope design is unobscured but retains a common axis for all mirrors

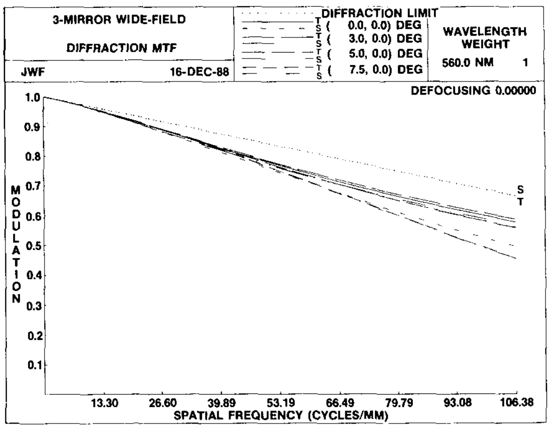


Figure 2. Diffraction MTF shows balanced performance across the field of view

Table 1.
Design Characteristics of the Three-Mirror Telescope

EFL	1.0 meter
F-number	4.5
Field of view	0.6 x 15 degrees
Flat focal plane, telecentric	
Average rms spot size	0.007 mm
Average wavefront error	0.09 waves rms @0.6328 um
Average MTF @20 lp/mm	0.92 (0.94 is diff. lim.)
Average MTF @40 lp/mm	.0.83 (0.87 is diff. lim.)
Aspherics:	
Primary	Conic, 6th order, 8th order
Secondary	Conic, 6th order
Tertiary	Conic, 6th order
Max. Aspheric Departure:	
Primary	0.040 mm
Secondary	<0.001 mm
Tertiary	0.044 mm
Max. Aspheric Slope:	
Primary (@ r=335mm)	13.6 waves/cm
Secondary (@ r=65mm)	0.59 waves/cm
Tertiary (@ r=335mm)	15.9 waves/cm
Parabola (Comparable to Primary)	5.7 waves/cm

1.1 Design attributes that influence the hardware

During the evolution of a design the foremost goal should be to meet the performance requirements. Yet, if such a design is to be more than an academic exercise, then every design decision should be weighted by the influence it has on the eventual hardware. Figure 3 shows the evolution of this design All the forms had nearly equivalent performance. Design A was most compact but had twelve aspherics terms among the three mirrors. Design B had the best performance but was more difficult to mount and baffle from stray light. Design C was chosen as the final design for its best balance in size, performance, fabrication, and alignment. Design D was an F/4.0 version to compare to the others at F/4.5.

An important consideration throughout the design process was the reduction of aspheric terms to reduce the complexity and risk of fabrication. As indicated in Table 1, the final design required only a conic and a 6th-order asphere on each of the mirrors. The primary had an additional 8th-order term that minimally changed the aspheric shape but provided margin in the performance. Asphericity should be judged in terms of sign, magnitude, and slope. The sign of the conic portion of the asphere influences the design of the null corrector that will be needed. Typically, there is little choice in this once the first-order properties of the design have been fixed. The magnitude of the total aspheric departure is an indicator of the amount of glass that will have to be removed from a base spherical surface. This influences the time it will take to fully polish and aspherize the mirror. Finally, aspheric slope should be minimized to help in obtaining a smooth final figure. The best way of reducing this is to avoid unnecessary high-order aspheric terms.

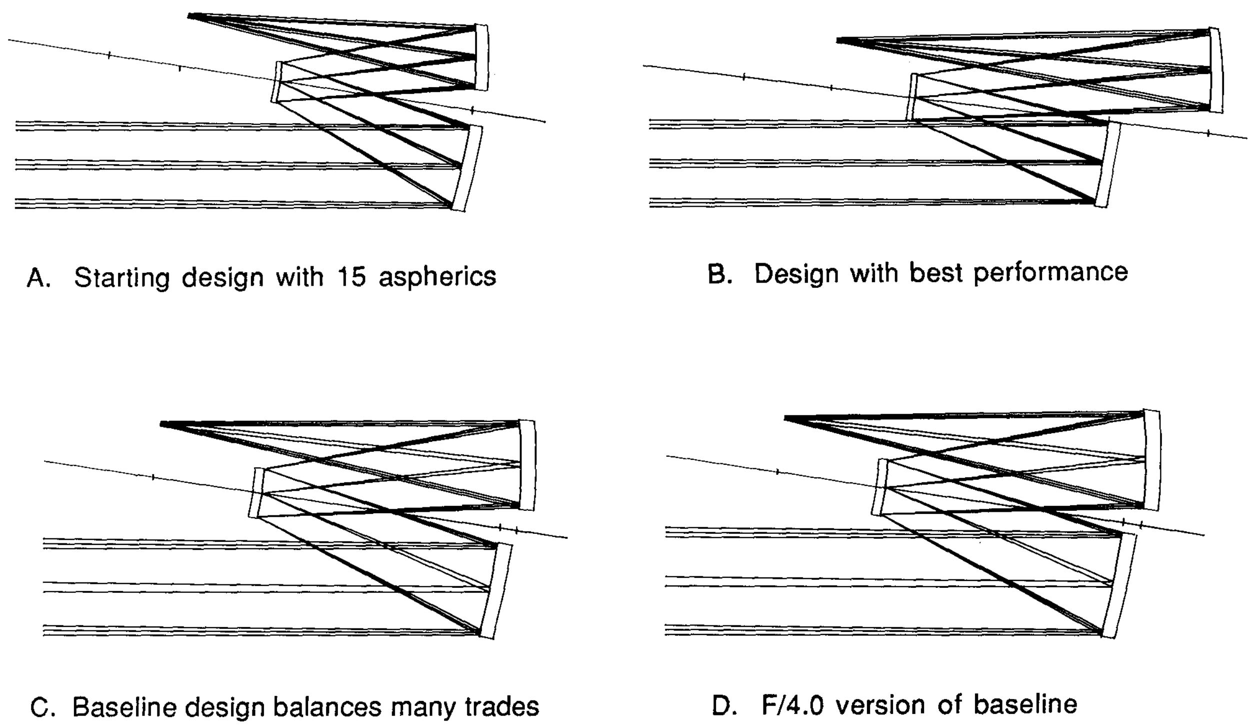


Figure 3. The design evolution was sensitive to a variety of hardware trades.

2. THE ERROR BUDGET AND COMPUTER MODELING

Having a design in hand is an important step, but it is far from having demonstrated a buildable system. The next milestone is to develop a detailed error budget. With precision optical systems, performance is typically close to the diffraction limit. Every tolerance is squeezed, so the error budget must keep track of all factors that affect performance and balance the risk and difficulty between optics and mechanics.

Organization of the error budget is important. It should start with as specific a performance criterion as possibly, then follow the actual flow of the hardware: from design and fabrication, to assembly and operation. Under each major heading, subassemblies should be broken down until every critical dimension has been identified and assigned a tolerance. The tolerances should be distributed so that all are physically obtainable and no single error contribution dominates. This concept is depicted in Figure 4.

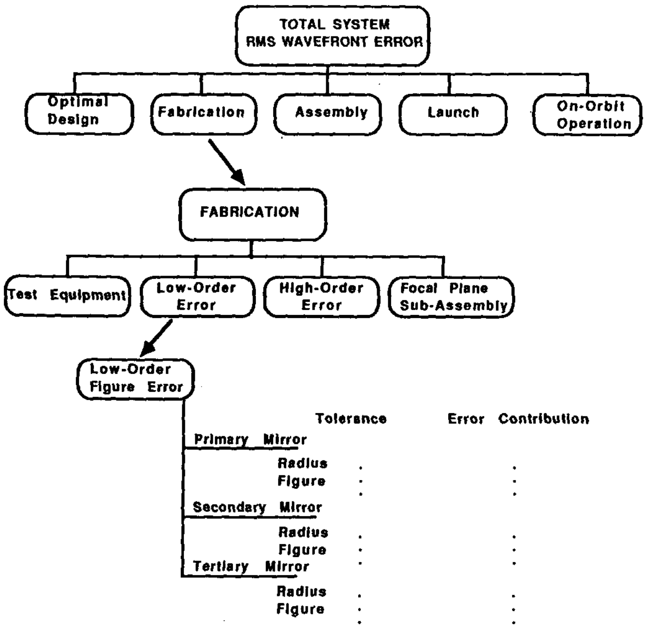


Figure 4. The error budget should follow the flow of the hardware and attempt to balance the distribution of tolerances.

Every tier lower in the error budget should be more amenable to change. On the lowest end, an individual tolerance on a single parameter should not be taken as an absolute. At this level, there is cushion resulting from the statistical combination of all the parameters. At the higher end, however, changes should not occur without a total system reconciliation. Much time and money can be saved if it is realized that system performance will not be jeopardized if a few individual tolerances are exceeded. Indeed, the entire approach assumes that some values will exceed their tolerance while others will come in under tolerance.

Computer modeling is the most effective tool the designer has to anticipate and reduce potential hardware problems. It can save considerable time, dollars, and risk if it is learned, through a paper exercise, what hardware problems might occur and what corrective actions could be applied. Both fabrication and alignment errors should be modeled. Three levels of modeling are appropriate. First a sensitivity analysis that perturbs every parameter a known amount helps identify the "tall poles" that will have to be worried over the most. Second, a worse-case analysis, with compensating parameters, should be conducted. Certain types of fabrication and alignment errors degrade the performance in ways that can be compensated by adjusting other optical elements. Errors such as line of sight and focus are most readily compensated, and others, such as coma and astigmatism can often be compensated, to a degree, while still maintaining overall performance. These worse-case exercises give the designer a feel for how far an individual component might be allowed to exceed a specification and still permit the system performance to be recovered. Finally, a statistical combinations of all tolerances should be examined to ensure a proper balance has been achieved.

Modeling exercises in this project resulted in three significant cost-savings:

1. Fabrication modeling identified specific, low-order errors that could be compensated by rigid-body motions during alignment. These terms included focus, coma, astigmatism, three-theta coma, and spherical aberration. This knowledge allowed us to relax the fabrication tolerances on the

The structure is best seen in the photograph in Figure 5. It consists of a main bulkhead, on which the primary and tertiary mirrors are mounted, and a separate bulkhead for the secondary mirror. These bulkheads are secured to each other through a metering structure that avoids obstructing the light bundle.

Primary and tertiary mirrors are mounted at three points, and each mount constrains two degrees of motions, one radial and one tangential. One mounting point is located near the vertex of the optical surface. This allows tilt adjustments to be made about the mirror vertex, which greatly simplifies the alignment adjustments and modeling. The other two points are radially positioned at opposite "corners" of the mirror. The design of the primary and tertiary mirrors allowed the mounting fixtures to be identical in function and design.

The keys to alignment of primary and tertiary mirrors were their datum surfaces and the precision manufacture of the main bulkhead. The bulkhead's front face was machined flat and incorporates accurately positioned holes that secure tooling balls for positional references. The mechanical alignment was successful in positioning the two mirrors, with respect to their offset nominal settings, to within 0.002 inch and about 1.5 arc-min.

Secondary mirror alignment was aided by use of two reference marks. One was calibrated with respect to the main bulkhead, and the second identified the optical center of the secondary. An alignment telescope was used to extrapolate an axis between these two points.

The quality of the adjustment mechanisms, stability of the structure, and stress-free mounting were verified in practice. During alignment we achieved 0.04 wave P-V repeatability of aberration coefficients and we were able to accurately impart angular motions of less than 15 arc-seconds, which related to a linear motion of the adjustment screws of 0.0004 inches.

4. ALIGNMENT, PUTTING IT ALL TO TEST

The use of computer-aided alignment was motivated by two reasons: the complexity of the optical system and the need for precise results. Manual alignment based on the visual quality of a point image was considered hopeless when faced with aligning three aspheric mirrors, with a total of fifteen degrees of freedom, over a fifteen degree field of view. Geometric techniques employing a Hartmann-type mask and centroiding of the resultant spot image required centroiding accuracies on the order of a micron to achieve the alignment precision. Also, because the fabrication errors eventually would dominate the alignment errors, any approach relying on an ensemble merit function such as rms spot size or rms wavefront error would not work. An interferometric approach was chosen that allowed wavefront data to be decomposed into aberration coefficients. In this way, the alignment errors could be separated from the fixed fabrication errors and high precision could be obtained.

The procedure is actually very straightforward:

1. The goal for the best aligned system is established based on the optimized performance in the presence of errors on the mirror surfaces.

2. Five interferograms are taken across the field of view of the telescope. At each field point, five wavefront sets are measured. Each set is fit to a 15-term Zernike polynomial, and the average of the five data sets is used to define the coefficients that describe the wavefront.

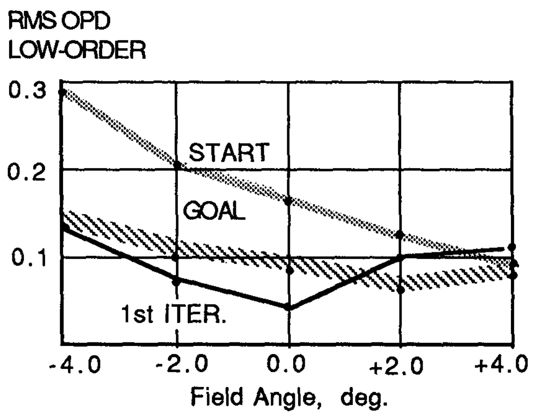
3. These coefficients are defined as INTerferogram files to Code-V.[3]

4. The ALIgnment option of Code-V is run using these interferogram files to describe the current performance and the as-built optical system as the target.

5. Various alignment solutions were attempted in Code-V prior to each iteration. Different combinations of compensators were used to determine the minimum number of alignment motions that would give maximum performance improvement.

The following sequence of figures shows that the alignment goal was met after four iterations. The "Y-axis" of the plots is the value for the rms wavefront error. The "X-axis" indicates the field position of the measurements. Figures 6a through c show the rms of the low-order Zernike fit to the wavefront as a function of field position.

The curve labeled "Goal" is the computer-predicted, best-aligned value. The width of the hatch marks is the 0.055 wave rms acceptance tolerance rss'd with the predicted performance value. The shaded line titled "Start," in Figure 6a, is the value of the measured wavefront after mechanical alignment. The solid black line is the measured data after an alignment cycle had been completed. Table 2 gives highlights of each alignment iteration.



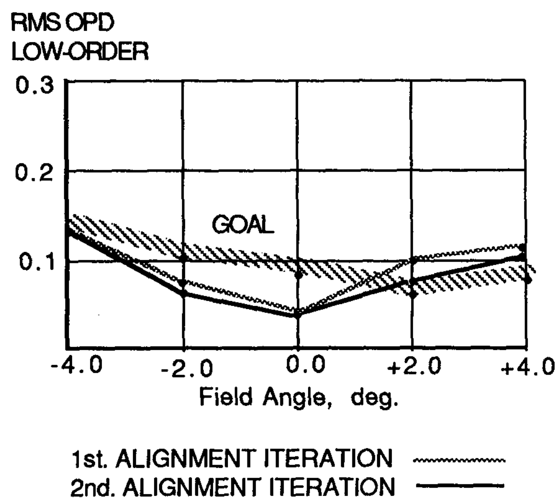


Figure 6.

A. (Upper left) Starting wavefront error and results of first iteration.
B. (Upper right) The second iteration exhibited fine control of the process.
C. (Right) The final iteration shows the result of a different field weighting scheme.

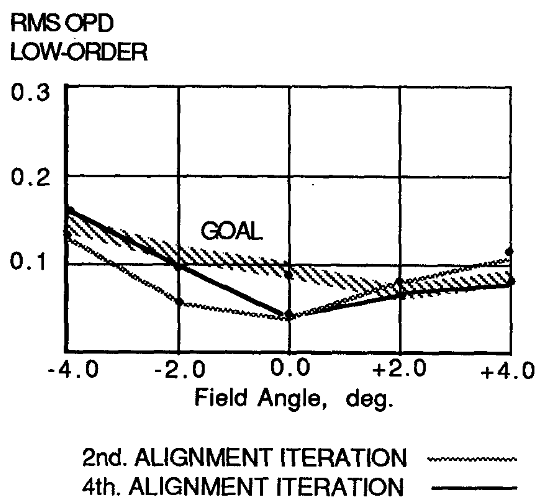


Table 2. Highlights of Alignment Iterations

Iteration 1. This first iteration made the greatest progress. This was the result of applying *five simultaneous rigid-body motions to three optical components.*

Iteration 2. A 15 arc-second tilt of one mirror was predicted to make a small, controlled improvement. Results were as predicted, showing our ability to control the process to the order of 0.02 waves rms.

Iteration 3. A two-axis tilt was applied to the primary mirror. Though there was no statistically significant change of the rms wavefront error, there were changes in the astigmatism terms that were as expected: one went up while the other went down.

Iteration 4. The fourth and final iteration was attempted after a different field-weighting factor was applied to the alignment solution. This brought the entire field, with the minor exception of one field point, to within, or better than the predicted goal. Control of the process was fine enough that the last point could have been recovered.

5. SUMMARY

A three-mirror, unobscured, wide-field telescope with diffraction-limited performance has been designed and toleranced. To demonstrate our ability to assemble such an instrument, a scaled version of the telescope was built. An alignment demonstration was conducted that brought the optical system into alignment to the error-budgeted value of 0.055 waves rms at 0.6328 microns.

The success of this project was due largely to the anticipation of hardware problems very early in the design and tolerance activity. Modeling of fabrication and alignment errors helped relax fabrication tolerances and guided the design of the mounting and adjustment hardware. The end product was a telescope assembly that balanced the difficulty in all contributing disciplines and performed at our highest level of expectation.

6. REFERENCES

1. J.W.Figoski, "Design and tolerance specification of a wide-field, three-mirror, unobscured, high-resolution sensor," Proc. SPIE, vol. 1049, (1989).
2. J.W.Figoski, T.E.Shrode, G.F.Moore, "Computer-aided alignment of a wide-field, three-mirror, unobscured, high-resolution sensor," Proc. SPIE, vol. 1049, (1989).
3. Code-V is a registered trademark of the Optical Research Associates, 550 North Rosemead Blvd., Pasadena, CA, 91107.