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THERMAL WEAPON SIGHT (TWS) AN/PAS-13* DIFFRACTIVE OPTICS DESIGNED FOR PRODUCIBILITY

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Abstract

The Thermal Weapons Sight (TWS) program is a manportable 3 – 5 micrometer forward-looking-infrared (FLIR) rifle sight. The manportable nature requires that the optics modules be lightweight, low cost and compact while maximizing performance. These objectives were met with diffractive optics. TWS promises to be the first FLIR sensor to incorporate kinoform surfaces in full scale production.

1.0 INTRODUCTION

TWS is a mid-infrared thermal sensing sight being developed for the Army by Hughes Aircraft Company. The program is managed by the U.S. Army Project Manager for Night Vision and Electro-optics (PMNVEO) with technical support provided by CECOM, Night Vision and Electronic Sensors Directorate (NVESD). The technology for this program is based on the use of thermoelectrically cooled second generation PV-HgCdTe MWIR focal plane arrays. The sight will be either hand held or mounted on manportable weaponry (Figure 1). As such, the sight is required to be compact and lightweight. In addition, the battlefield mission requires that the sight provides high optical resolution. The use of diffractive optics has emerged as a powerful design tool which has aided in meeting these criteria.¹ The application of diffractive surfaces to the TWS optical designs has resulted in an overall reduction in lens count while improving performance and lowering cost.

* This work was performed in connection with CECOM contract No. DAAB07-91-K254.

¹ "Optical Element Employing Aspherical & Binary Grating Optical Surfaces." Chungte W. Chen, US Patent: 5,044,706

The TWS program calls for an initial production option up to 6,200 units and is the first large-scale military production program to incorporate diffractive optics into its infrared optics.

The TWS sensor is designed for varying mission scenarios (Figure 2). It can be used as a wide-field-of-view (WFOV) sensor in the Basic Sensor mode without any telescope attachments or with 1 or 3 interchangeable telescopes. The 2× telescope provides the Light Weapon Thermal Sight (LWTS) configuration for lighter weapons in near field engagements. The Medium Weapon Thermal Sight (MWTS) telescope is dual-field-of-view (DFOV) with a 3.3× narrow-field-of-view (NFOV) and a 2× WFOV for mid-range situations. The Heavy Weapon Thermal Sight (HWTS) is intended for long-range operation with a 10× NFOV and a 3.3× WFOV.

The TWS infrared sensor contains a mosaic array of detectors which paints the scene by scanning the image across it. The infrared optics are composed of a re-imaging imager and the 3 application specific telescopes. The visual train paints the display image by scanning a line image of an LED array across the image plane of the eyepiece. (Figure 3.)

2.0 THE USE OF DIFFRACTIVE OPTICS

Figure 4 illustrates how diffractive optical elements (DOE) can provide chromatic correction to an optical system. A conventional lens *without* a diffractive surface will focus light of differing wavelengths at different points due to the inherent dispersion of the lens substrate material. By adding the diffractive surface, the dispersion of the substrate material can be compensated for and the differing wavelengths of light will focus at a common point. Conventional broad wavelength band optical designs employ two or more lens materials with different powers and dispersion characteristics to balance the chromatic aberrations. This would generally result in a greater number of lenses in the design to provide chromatic correction than that required for the basic geometrical correction. With the simple addition of a diffractive surface, the color correction can be accomplished with the minimum number of lenses.

The diffractive elements used on TWS are surface-relief circularly symmetric gratings with very high diffraction efficiency. This is created by reducing a continuous phase profile (Figure 5-a) into discrete 2π increments located along a common surface (Figure 5-b). This analog type of surface relief profile is commonly known as a kinoform and is theoretically capable of achieving 100 percent diffraction efficiency at its functional wavelength. The TWS kinoform surface relief profiles are formed by single-point precision diamond machining methods.

3.0 THE TWS DIFFRACTIVE DESIGNS

A diffractive optic was used in each of the TWS IR optical designs for simplification and/or to improve its performance. Table 1 compares the modulation transfer function (MTF) of the diffractive designs against the conventional. In general, the MTF of the diffractive design out-performs its conventional counterpart.

The utilization of a diffractive optic element reduced the number of optical lens elements required in the IR imager from 5 to 3 (Figure 6). As an added benefit, the overall MTF was improved, the distortion was cut in half and the sensitivity of the lenses to positional tolerances was reduced. The geometrical aberration (H-TanU) curves of the conventional and diffractive imager are shown in Figure 7 and Figure 8 respectively. The top, middle and bottom curves in each are the H-TanU curves corresponding to the full field, 70 percent field and on-axis, respectively. Note that the diffractive design demonstrates much better chromatic as well as higher order aberration correction.

The design principles for the TWS re-imaging imager that consists of refractive optical elements and DOE are:

1. The primary lateral color, secondary lateral color, and coma are self-corrected through the symmetry principle, wherein the front and rear groups are symmetric with respect to the intermediate image plane.
2. The axial color of the entire system is corrected by a DOE in the second group. This DOE also corrects the high-order chromatic aberrations, such as spherochromatism and chromatic coma. Because this DOE is positive, it contributes to the overall system power, unlike a classical flint glass. Using the DOE for chromatic aberration significantly reduces the intrinsic aberrations of each element and, therefore, that of the entire optical system.
3. The spherical aberration and coma of the front and rear groups are corrected by using an aspherical surface or by bending the lenses.
4. The astigmatism is corrected by placing the lens elements in the proper positions with adequate optical power distribution.
5. The DOE and germanium significantly reduce the field curvature, as compared to the conventional equivalent.

Likewise, the incorporation of a diffractive surface in the LWTS telescope design eliminated one lens element while improving performance (Figure 9). This is attributed to the germanium-DOE, which has similar dispersion characteristics to a silicon lens but with a higher index of refraction. Therefore, the low-order, high-order aberrations and field curvature are significantly reduced. The objective portion of this design is also more compact.

Unlike the IR imager and the LWTS telescope, the number of optical elements remained the same in the MWTS diffractive NFOV and WFOV telescope designs (Figure 10) but performance benefits were achieved. The significant improvement in the MWTS image quality is also attributed to the germanium-DOE element, as described for the LWTS case. The MWTS NFOV diffractive design, on average, picked up 15 absolute MTF points over the conventional design! The MWTS WFOV also made gains.

For the HWTS telescope (Figure 11), replacing the CaF_2 objective secondary with a diffractive ZnS lens element allowed the Si objective primary to be simplified from an asphere to a sphere. The combination of ZnS and a DOE creates an Abbe number about the same as that of the CaF_2 lens. Indeed, the combination of ZnS and a DOE has optical characteristics even better than the CaF_2 lens, such as higher index of refraction to reduce aberrations with a tunable Abbe number for better chromatic aberration correction. This permitted the Si objective to be fabricated with less costly conventional polishing. The difference between precision diamond machining the ZnS kinoform rather than the Si objective results in an overall cost savings. Si is difficult to diamond machine and tool wear is significant due to its inherent hardness. For equivalent 1.0 inch diameter parts, more than 30 ZnS lenses can be diamond machined without replacing the tool compared to only 1 Si lens. Thus, ZnS provides significant savings in tooling. In addition, the predicted MTF performance is enhanced especially for the WFOV. (See Table 1.)

4.0 HARDWARE EXAMPLES

Figure 12 describes the first prototype imager used to validate the performance of precision diamond machined diffractive designs for TWS-type applications.² The kinoform element required a $14 \cdot 2\pi$ zones (Figure 12a). Figure 12b shows these zones as fabricated on the lens. The success of achieving the required analog pattern is exhibited in the profilometer trace of the surface (Figure 12c).

Another kinoform example can be easily seen on the second lens of the HWTS telescope. The zones on this ZnS piece are quite evident in the cutaway view of the telescope (Figure 13).

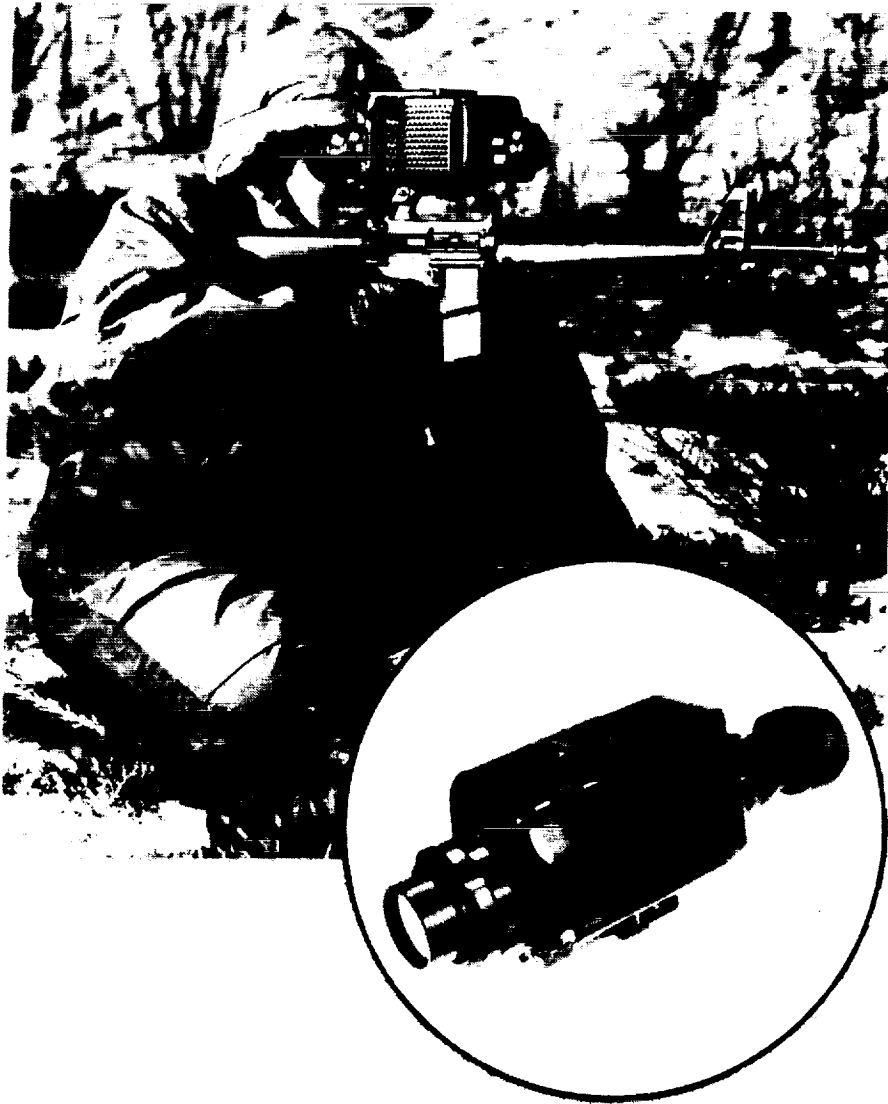
² "The Use of Diffractive Optical Element in 3 - 5 Micrometer Optical System," Chungte W. Chen, J. Steven Anderson, presented at IRIS Specialty Group on Passive Sensors, February 1992

5.0 TWS TEST DATA

Preliminary MTF tests have been conducted on the first optical modules produced in the development production prove-out (DPPO) phase of the TWS program. Tables 2 – 5 compare the MTF test data of each module against the nominal design value and the predicted performance due to manufacturing tolerances. Note that some of the variations in MTF test values may be related to the test accuracy. (The better MTF stations are only accurate to 3 percent.) However, the trend of all tested values match closely with the predicted performance. These results verify with multiple cases that the diffractive optic model predictions are accurate.

6.0 CONCLUSION

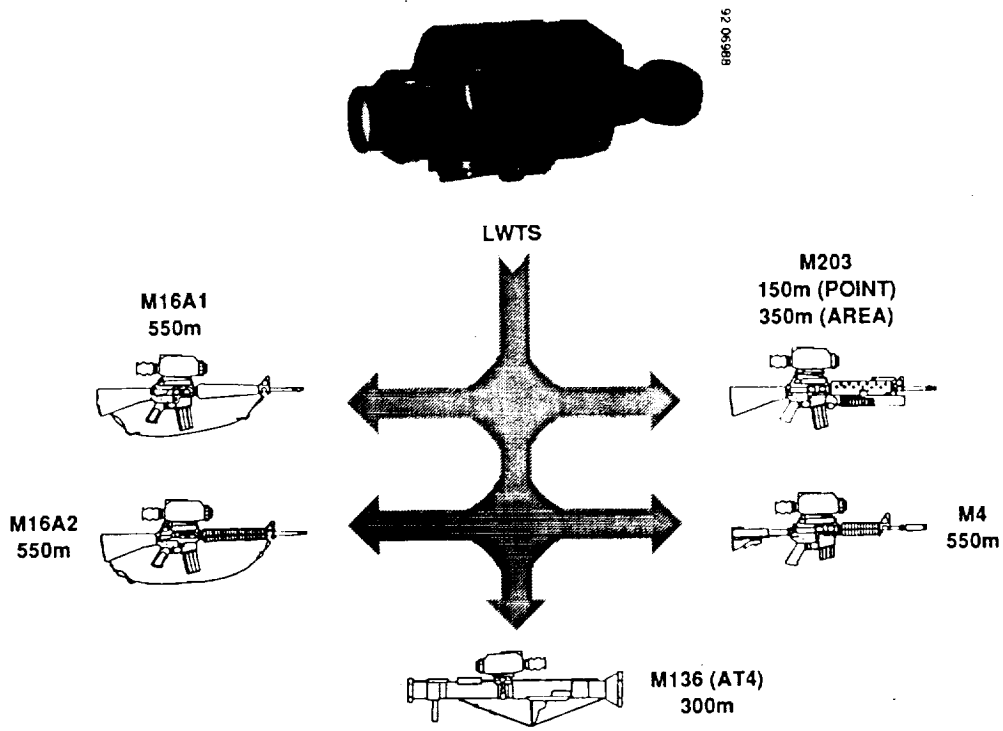
The use of diffractive optics has been successful in achieving the optical design goals. TWS boasts optical systems that are lighter, more compact, and lower cost than their conventional counterparts while attaining significant performance gains. The technology of precision diamond machining kinoforms has now been realized. The Thermal Weapons Sight is blazing a vivid path in the deployment of diffractive IR optical sights.



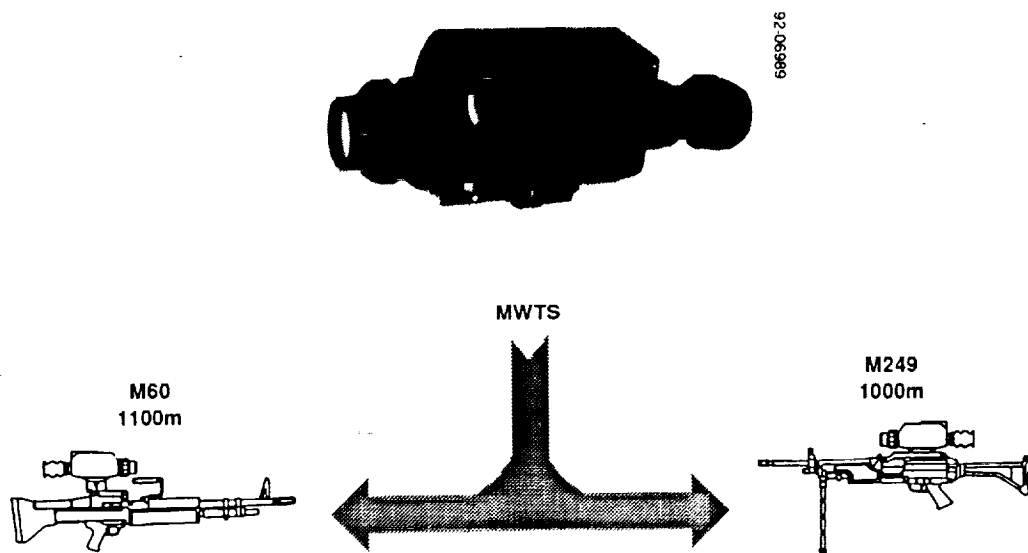
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Figure 1: THERMAL WEAPON SIGHT (AN/PAS-13). *The TWS, shown here in its LWTS configuration, is lightweight in all configurations for manportable mobility.*



(a) LWTS



(b) MWTS

Figure 2: TWS WEAPON APPLICATIONS. *The TWS is designed to meet all thermal imaging needs of the Infantry squad. A full complement of mounting brackets and electronic reticles are available for a wide variety of weapons.*

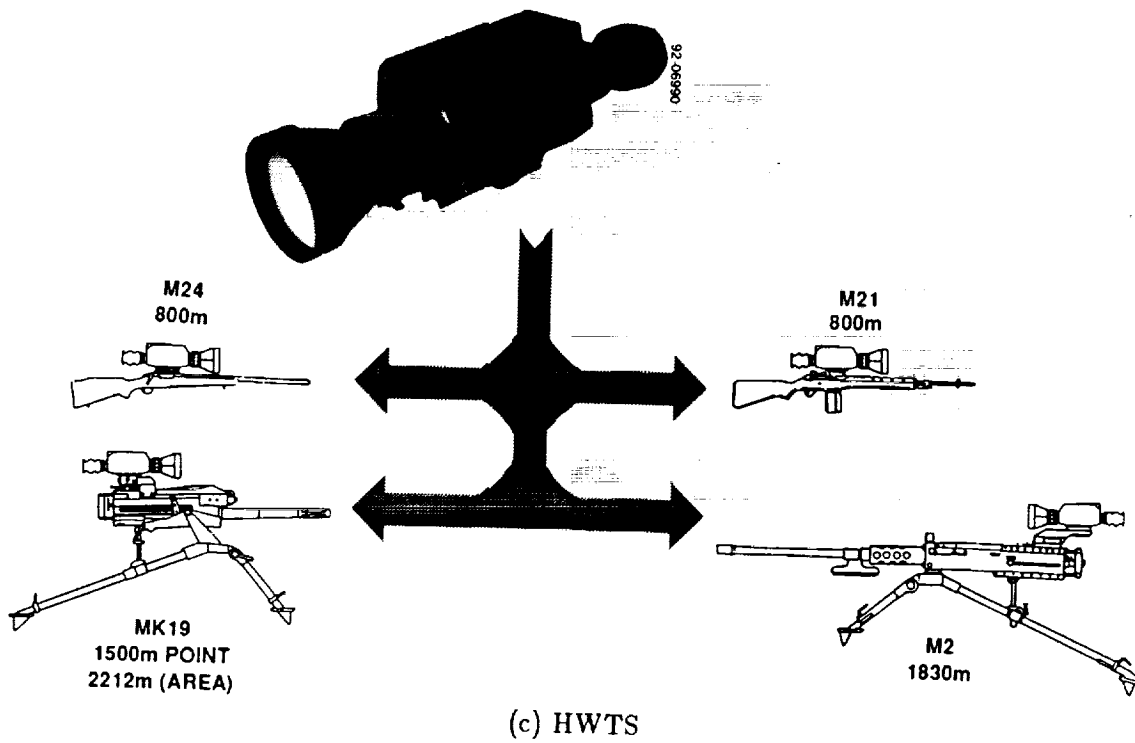


Figure 2: TWS WEAPON APPLICATIONS (Continued).

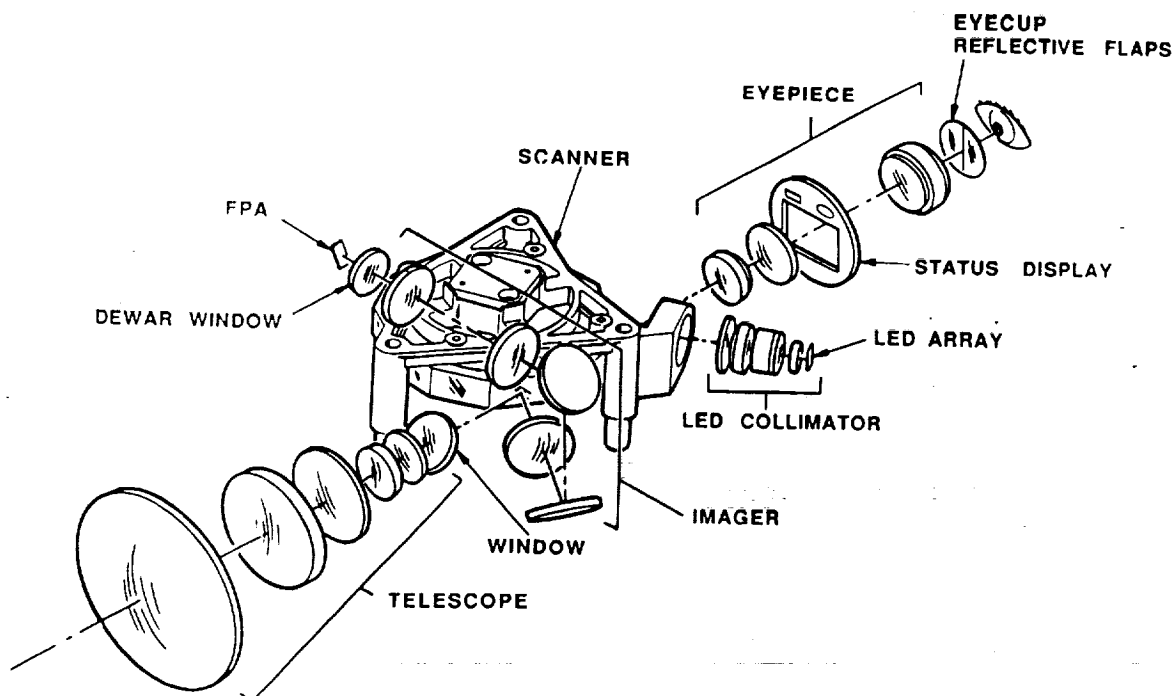


Figure 3: TWS OPTICAL DESIGN. Different facets of the same polygon wheel are used for both the IR and visible scans.

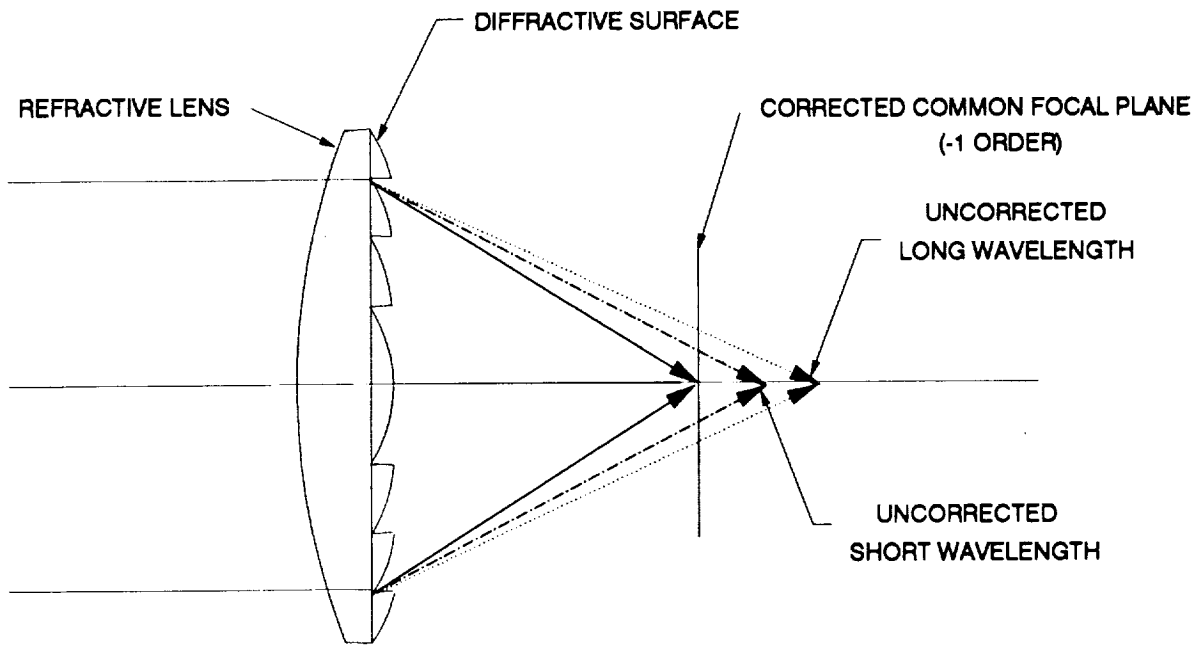


Figure 4: DIFFRACTIVE COLOR CORRECTION. The diffractive surface creates a common focus for the short and long spectral wavelengths.

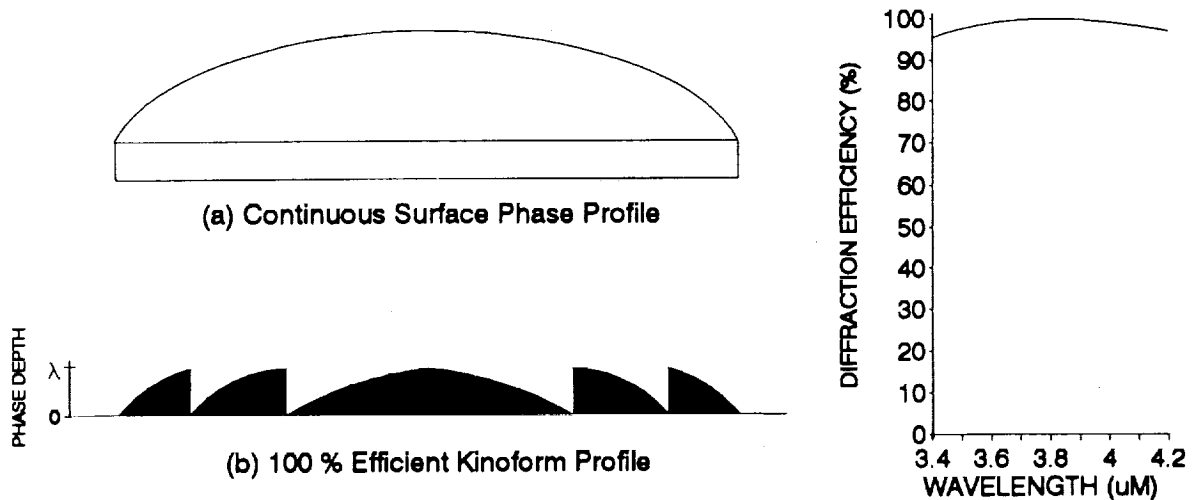


Figure 5: KINOFORM SURFACE RELIEF PROFILE. Diffractive surfaces are the reduction of continuous surface phase profiles into 2π increments. Diffraction efficiency peaks at the reference wavelength.

TABLE 1.

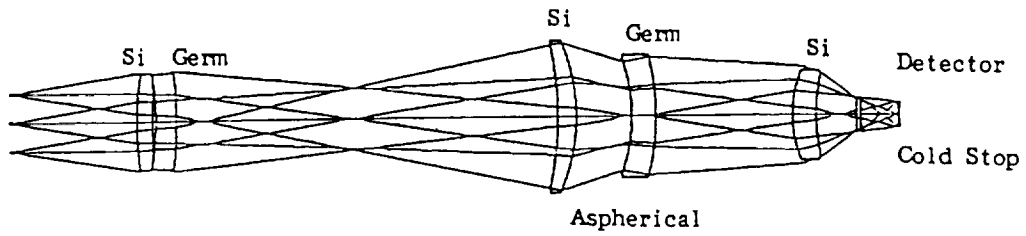
MTF COMPARISON BETWEEN CONVENTIONAL DESIGN
AND DIFFRACTIVE DESIGN

FIELD	IMAGER		HWTS WFOV		HWTS NFOV		MWTS WFOV		MWTS NFOV		LWTS	
	C	D	C	D	C	D	C	D	C	D	C	D
0.25 VER	.79	.78	.73	.80	.73	.73	.75	.79	.62	.80	.71	.71
0.25 HOR	.77	.74	.60	.77	.64	.68	.72	.75	.56	.73	.64	.69
0.75 VER	.71	.72	.60	.77	.76	.80	.74	.79	.61	.65	.62	.61
0.75 HOR	.63	.75	.43	.70	.39	.47	.69	.64	.36	.56	.49	.71

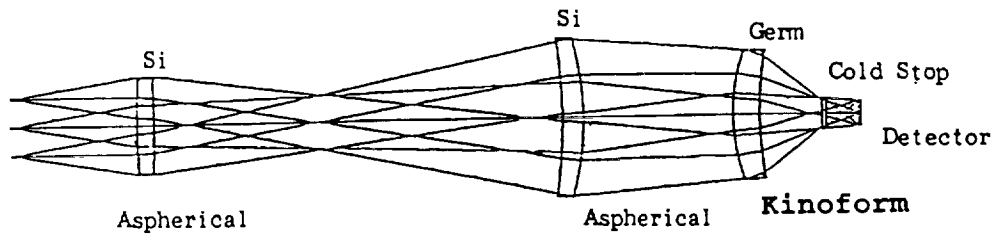
C: CONVENTIONAL DESIGN,

D: DIFFRACTIVE DESIGN

MTF AT 23.3 LP/MM



(a) Conventional Design



(b) Diffractive Design

Figure 6: TWS DIFFRACTIVE IR IMAGER. *Diffractive optics create a 40 percent reduction in lens count, cut distortion in half and relax fabrication tolerances.*

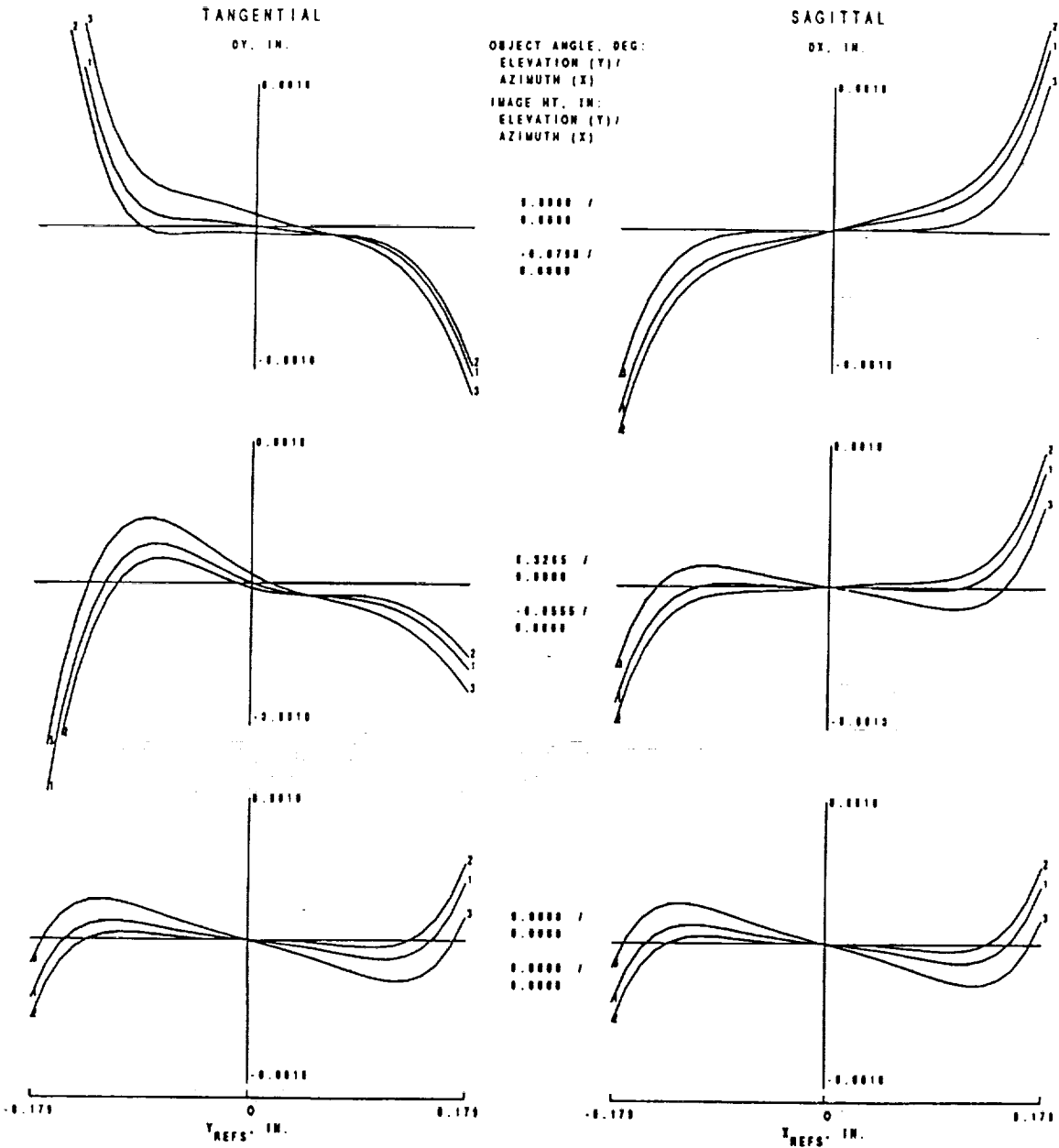


Figure 7: CONVENTIONAL IMAGER PERFORMANCE. *The H-TanU curves of the conventional imager exhibit chromatic aberration.*

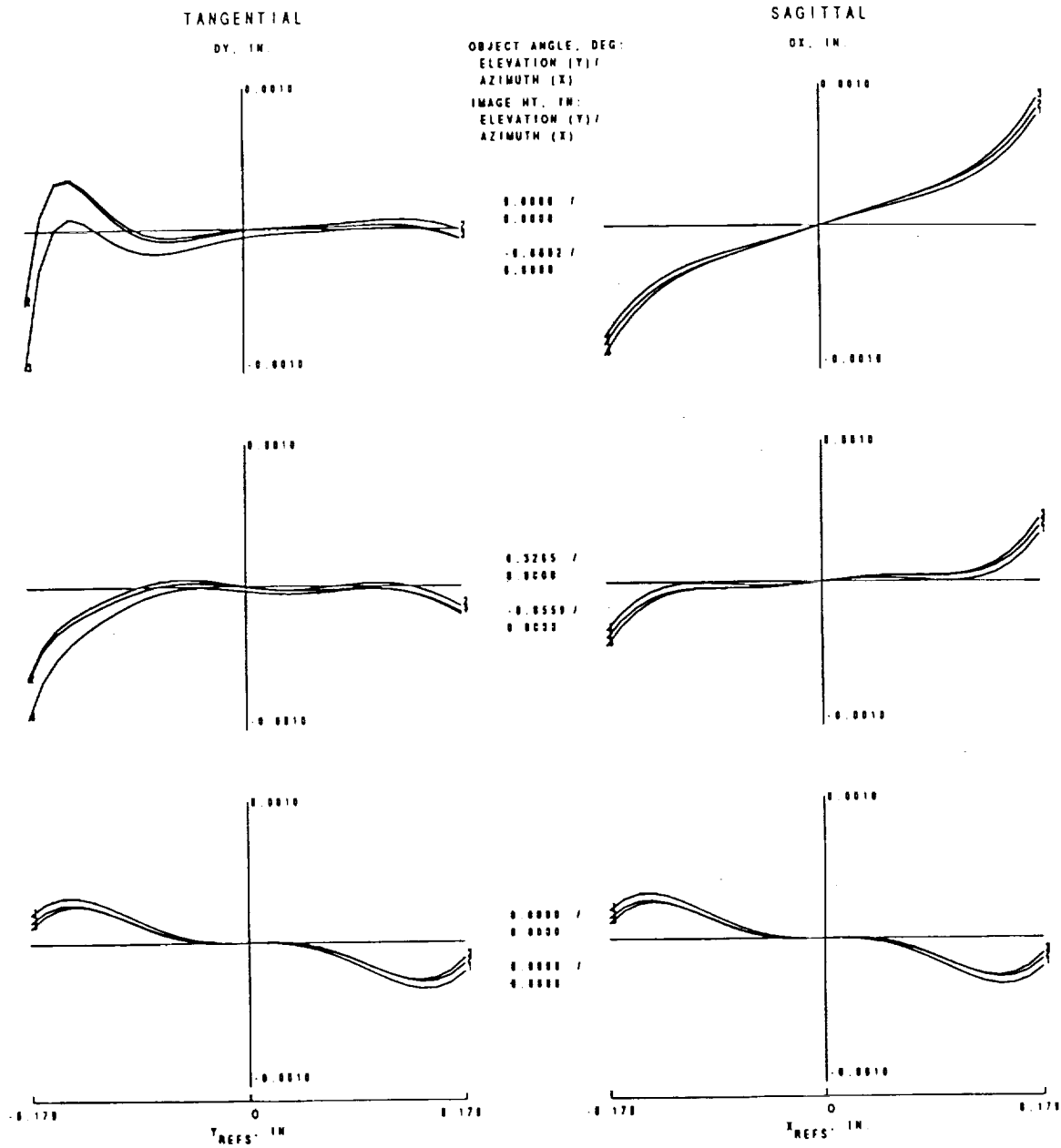
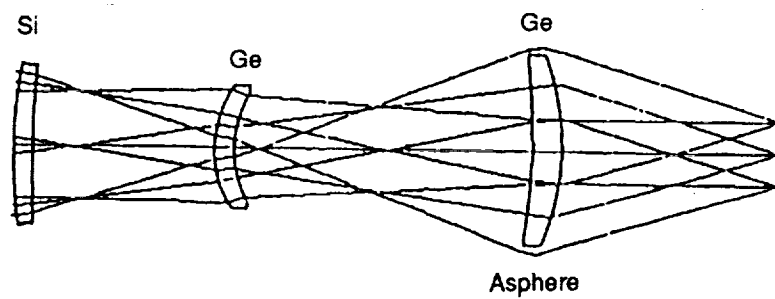
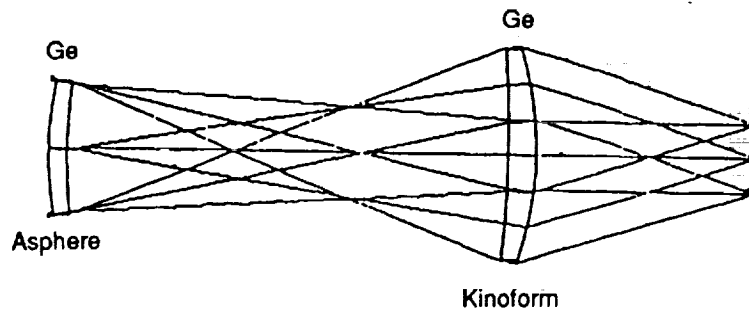


Figure 8: DIFFRACTIVE IMAGER PERFORMANCE. *The diffractive imager chromatic aberrations are well corrected and the geometrical aberrations are less than the conventional design.*

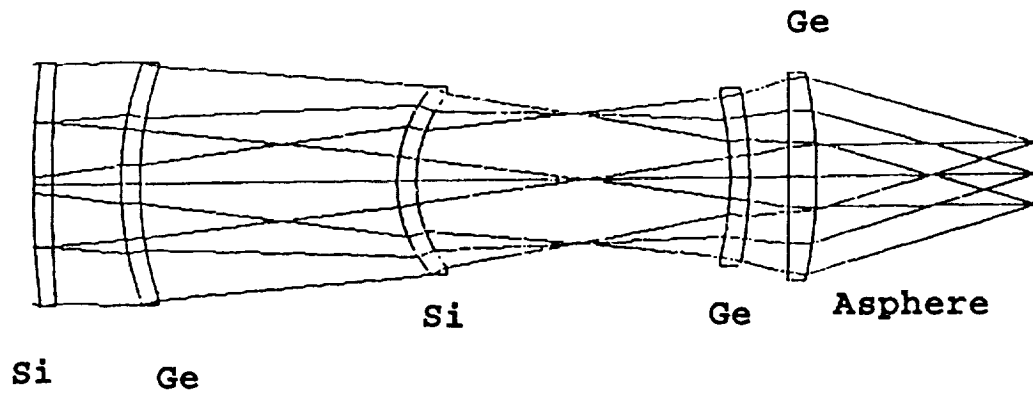


(a) Conventional design

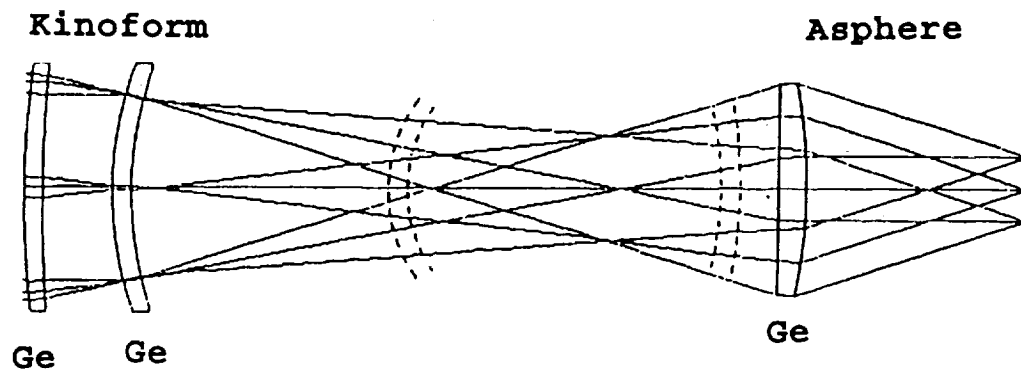


(b) Diffractive Design

Figure 9: LWTS DIFFRACTIVE TELESCOPE. *The LWTS diffractive telescope has 33 percent fewer lenses and is more compact.*

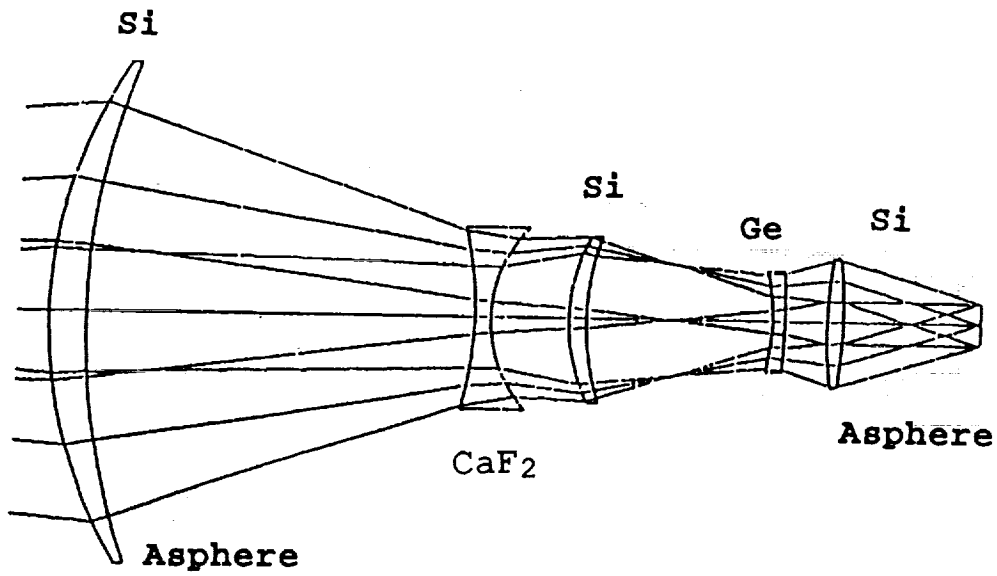


(a) Conventional Design (WFOV View)

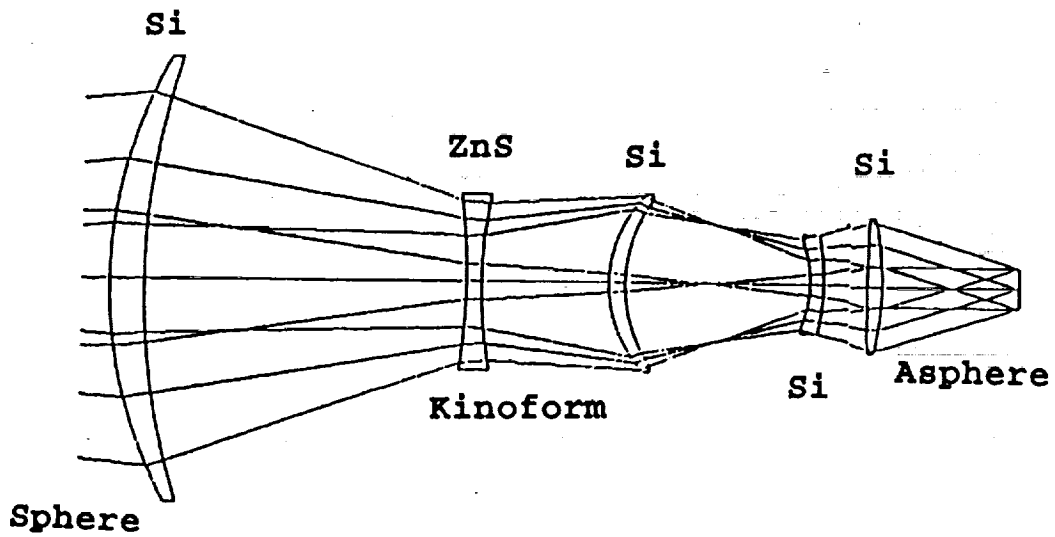


(b) Diffractive Design (NFOV View)

Figure 10: MWTS DIFFRACTIVE TELESCOPE. *The MWTS diffractive telescope provides substantial MTF improvement through better chromatic correction.*

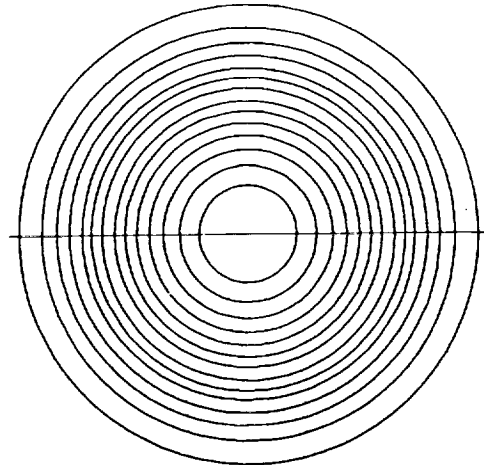


(a) Conventional Design



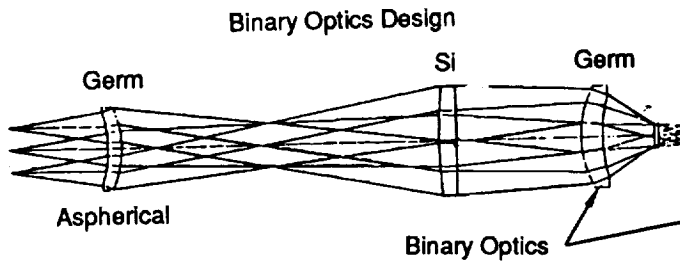
(b) Diffractive Design

Figure 11: HWTS DIFFRACTIVE TELESCOPE. *The HWTS diffractive telescope provides enhanced producibility and imagery.*



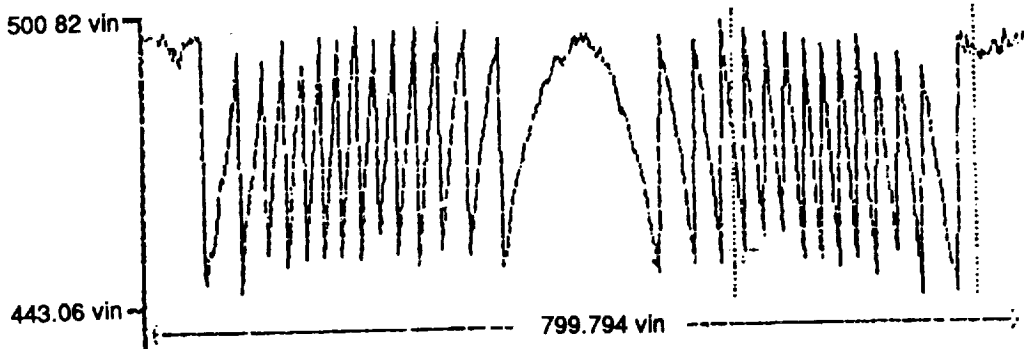
(NOT TO SCALE)

a. Diffractive imager 2π zones (14)



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b. Kinoform Surface



b. Kinoform Profile Measurement

Figure 12: TWS PROTOTYPE IR IMAGER. *The diffractive lens is composed of 14 precision diamond machined zones with a depth of 1.28 micrometers.*



Figure 13: HWTS DIFFRACTIVE TELESCOPE. *The ZnS kinoform on the second lens of the telescope can be seen in this cut-away view.*

TABLE 2. SUMMARY OF MTF DATA FOR IR IMAGER

FIELD	DESIGN	DESIGN & TOLERANCES	TEST RESULTS
On-Axis	0.83	0.79	0.82
0.5 Elevation	0.80	0.79	0.80

Spatial Frequency 0.296 lp/mrad
Vertical Bar Reponse

TABLE 3. SUMMARY OF MTF DATA FOR LWTS TELESCOPE

FIELD	DESIGN	DESIGN & TOLERANCES	TEST RESULTS
On-Axis	0.72	0.69	0.72
0.5 Elevation	0.73	0.7	0.68
0.5 Azimuth	0.74	0.71	0.73

Spatial Frequency 0.6 lp/mrad
Vertical Bar Response

TABLE 4. SUMMARY OF MTF DATA FOR MWTS TELESCOPE

FIELD	DESIGN	DESIGN & TOLERANCES	TEST RESULTS
On-Axis	0.83	0.82	0.83
0.5 Elevation	0.83	0.82	0.79
0.5 Azimuth	0.7	0.68	0.66

WIDE FIELD OF VIEW

Spatial Frequency 0.6 lp/mrad
Vertical Bar Response

FIELD	DESIGN	DESIGN & TOLERANCES	TEST RESULTS
On-Axis	0.82	0.8	0.81
0.5 Elevation	0.81	0.79	0.82
0.5 Azimuth	0.78	0.76	0.71

NARROW FIELD OF VIEW

Spatial Frequency: 1.0 lp/mrad
Vertical Bar Response

TABLE 5. SUMMARY OF MTF DATA FOR HWTS TELESCOPE

FIELD	DESIGN	DESIGN & TOLERANCES	TEST RESULTS
On-Axis	0.74	0.71	0.74
0.5 Elevation	0.75	0.73	0.67
0.5 Azimuth	0.59	0.56	0.63

WIDE FIELD OF VIEW

Spatial Frequency 1.0 lp/mrad
Vertical Bar Response

FIELD	DESIGN	DESIGN & TOLERANCES	TEST RESULTS
On-Axis	0.81	0.72	0.72
0.5 Elevation	0.81	0.72	0.71
0.5 Azimuth	0.71	0.63	0.67

NARROW FIELD OF VIEW

Spatial Frequency: 1.0 lp/mrad
Vertical Bar Response