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Optical Tolerance analyses for the Far-ultraviolet Imaging Spectrograph onboard KAISTSAT-4

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The Far-ultraviolet IMaging Spectrograph (FIMS) is a spectrograph optimized for the observations of diffuse emissions in far-ultraviolet wavebands. FIMS is the main payload of first Korean scientific satellite, KAISTSAT-4, which will be launched in 2002. Extensive tolerance study of FIMS optical system has been performed, including decentering and tilt of the optical elements and manufacturing figure errors of parabolic-cylinder collecting mirror and ellipsoidal grating. We describe the tolerance analyses and its results.

1. Introduction

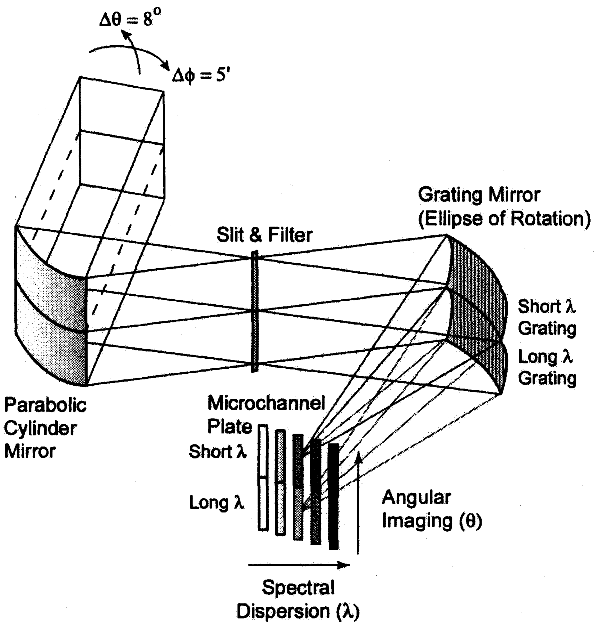

Figure 1. FIMS schematic diagram

FIMS is a dual (short wavelength band: 900–1150Å, long wavelength band: 1335–1750Å) imaging spectrograph, optimized for faint diffuse radiation by employing an off-axis parabolic cylinder mirror in front of a slit that guides lights to a diffraction grating. The reflective grating is an ellipse of rotation providing angular resolution. The FIMS design is derived from the two flight-proven EURD instruments[1)]. The cylindrical-source method provides twice the grasp and field of standard spectrographs, even with fast (f/2.2) optics. The imaging performance allows for a large field with imaging resolution (arc minute scales) similar to other important interstellar all-sky surveys.

The schematic diagram of the FIMS optics and the optical specifications are shown in figure 1 and table 1, respectively.

Table 1. FIMS Optical Specifications

Parameters	Short Wave Band	Long Wave band
Band Pass	900–1150Å	1335–1750Å
FOV	4°×5′	8°×5′
Spectral Resolution	1.4Å @ 1035Å	2.2Å @ 1550Å
Spatial Resolution	5′–10′	5′–10′
Grasp	0.6×10^{-4} cm^{2}sr	1.25×10^{-4} cm^{2}sr
Mirror Figure	Off-axis Parabolic Cylinder	
Mirror Focal Length	125 mm (f/2.2)	
Slit to Grating	177.4 mm	
Grating to Detector	170.0 mm	
Grating Figure	Ellipse of Rotation $(z/A)^2+(x/A)^2+(y/C)^2=1$	
Ellipse Axis A	180.0 mm	
Ellipse Axis C	242.6 mm	
Ruling Constant G	2250/mm	3000/mm
Diffraction Order	-2	-1
Mirror Coating	B_4C	MgF_2
Grating Coating	B_4C	MgF_2
Photocathode	KBr	CsI + Grid
Fixed Filter	MgF_2	CaF_2

2. Tolerance Analysis

The objective of the tolerance analysis is to determine the tolerance margins that can be specified for optical and mechanical elements and assemblies, which will still provide adequate optical performance. The analysis begins with performance specifications, which also are called system requirements. A maximum change is found for each optical parameter that causes at least one of the specifications to go just outside its limits. The analysis ends with error budget table on the optical and mechanical system[2].

The optical performance characteristics and the performance criteria, which are obtained from the scientific mission objectives, are shown in table 2. The coordinate system used for the tolerance analysis is shown in figure 2.

Table 2. Performance Criteria

Performance	Criteria	Requirements
Spectral Resolution	<1.8Å at 1035 Å <3.0Å at short wave band	From OVI emission line detection limit
Spatial Resolution	<10′	Same spatial resolution as ϕ
Bore Sight Error in θ	<±1°	Half of FOV overlap
View angle θ width	99% width <4°	Half of FOV overlap
Bore Sight Error in ϕ	<±2.5′	Half of FOV overlap
View angle ϕ width	99% width <10′	Half of FOV overlap
Wavelength Shift	<30Å	~ 1/10 shift in a band

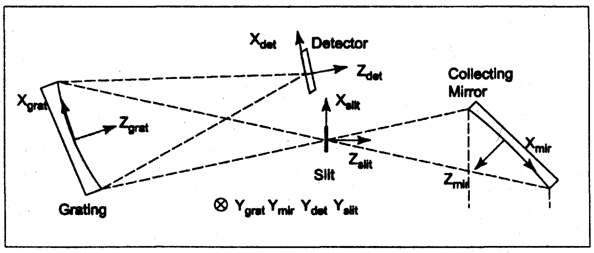

Figure 2. Coordinate systems for tolerance analysis.

Since the main objective of the FIMS is to observe diffuse radiation from interstellar medium, the isotropic incident rays are assumed to calculate the spectral resolution degradation, the bore sight errors, the view angle changes and wavelength shift while changing the individual optical parameters.

Table 3. FIMS sensitivity table*

		Spat. Res.	θ shift	ϕ shift	ϕ width
Mirror	ΔZ	×	×	±0.12	×
	ΔX	×	×	±0.14	±0.36
	ΔY	×	×	×	×
	R_Z	±24	×	×	±31
	R_X	±23	±45	±25	±40
	R_Y	×	×	±1.3	±15
	ΔF	×	×	±3.00	±5.00
Grating		Spec. Res.	Spat. Res.	θ shift	λ shift
	ΔZ	±0.25	×	×	×
	ΔX	±0.53	×	×	×
	ΔY	±3.75	±1.90	±3.00	×
	R_Z	±35	±18	Δ	×
	R_X	±41	±23	±32	×
	R_Y	±18	×	×	±25
	ΔA	±0.22	×	×	×
	ΔC	×	±3.68	×	×
	Rul. Tilt	×	×	±129	×
	Rul. Const.	±79	×	×	±64
Detector		Spec. Res.	Spat. Res.	θ shift	λ shift
	ΔZ	±0.42	×	×	×
	ΔX	×	×	×	±2.40
	ΔY	±5.40	×	±3.00	×
	R_Z	±61	×	×	×
	R_X	×	×	×	×
	R_Y	±160	×	×	×

*Units are mm and arcmin for linear and angular dimensions, respectively.

For the spatial resolution it is assumed that the incident rays have random ϕ angles and the spatial resolutions are calculated at 5 points y = [0, 6, 12, -6, -12] mm on detector plane, which correspond to incident angle θ = [0, 2, 4, -2, -4] degree if there is no bore sight error in θ direction.

The maximum changes found for each parameter are shown in table 3. The symbols × in the table represent that the optical performances are not sensitive to changes of corresponding parameters. It is noticeable that the spectral resolution and the wavelength shift are mainly related with the grating, while the bore sight and field of view in the ϕ direction depend on the mirror.

It is found from the analysis that the following tolerance pairs are coupled and that one of them can be used to compensate of the other. Detail analyses of the compensators are performed and the results are used as an input for the error budget analysis.

- For mirror, translation along X and rotation about Y
- For grating, translation along X and rotation about Y
- For grating, translation along Y and rotation about X
- For grating, curvature error ΔA and translation along Z

3. Error Budgets

The goal of the error budget analysis is to find allowable tolerances for each parameter so that none of the parameter changes will dominate the performance degradation. For some parameters the present manufacturing or alignment techniques cannot provide the tolerance limits. In that case the compensator is used to mitigate the performance degradation.

Method commonly used for error analyses include root of the sum of the square (r.s.s.) estimates and computer generated Monte Carlo (random simulation) analyses. The root of the sum of the squares of the parameter sensitivities allows crude estimates of how the performance margins can be apportioned to arrive at an error budget that considers the effects of randomness as a first approximation.

Table 4 and table 5 show the results of error budget analysis. The allowed ranges for adjustment and adjuster resolution for the mirror and the grating are shown in the tables.

The most serious manufacturing limit is found for the radius of curvature A of the ellipsoidal grating, since the manufacturing precision would be at most ±1 mm for the curvature of the ellipsoidal or equivalent toroidal grating. A compensation study has been performed to find if there is any optical parameter, which may compensate the performance degradation due to the grating curvature error. It is found that the degradation of the spectral resolution due to tolerance of curvature A of grating can be compensated adjusting the detector position or the grating position.

Image quality variation due to ellipsoidal curvature error is insensitive to the curvature change and to the grating or detector position change to compensate the curvature error. About 1.5–2 mm of space along Z direction for the linear adjustment of the grating or detector is required to compensate about ±1 mm error of the grating curvature.

The limit (1.3′) on the Y-axis rotation of mirror, R_Y, which is obtained from ϕ width constraint, is difficult to achieve. The fine linear translation along X-axis of the mirror can be used to compensate the ϕ shift error due to R_Y error, while the adjustment around Y-axis is used to adjust the degradation of ϕ width.

The precision of the grating center alignment is about the same order as the tolerance limits of ΔX and ΔY. Thus, rotations of the grating about Y and X-axes are used to compensate the performance degradation due to the grating center misalignments, ΔX and ΔY, respectively.

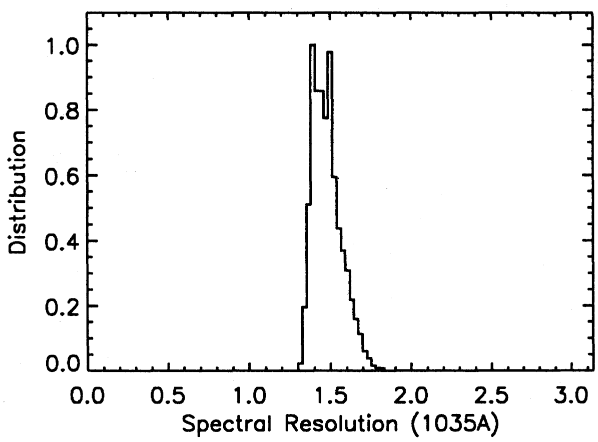

Figure 3. An example of Monte Carlo simulation results for parabolic distribution: Spectral resolution probability distribution.

Monte Carlo simulation is used to give an accurate appraisal of the probability of success for an assigned set of tolerances. For each Monte Carlo cycle, all of the parameters are randomly set using one of three statistical distributions, modified Gaussian distribution, uniform distribution, and parabolic distribution. Figure 3 shows an example that the spectral resolutions are within the performance criteria.

References

1) Bowyer, S., Edelstein, J., & Lampton, M. 1998, Astrophysical Journal, 485, 523
2) Ginsberg, R. H., 1981, Optical Engineering, 1981, 20(2), 175

Table 4. Error Budgets-Mirror Adjuster Requirements

	Range	Resolution	Comments
ΔZ	±2 mm	10μm	- To compensate ΔF, allowed range ~ 2mm - Resolution < (sensitivity)/ $\sqrt{2}$ /(5 = precision scaling factor)
ΔX	±2 mm	10μm	- To compensate ΔF, allowed range ~ 2mm - Same resolution as ΔZ, Resolution < (sensitivity)/10.
ΔY	NA	Fixed	- ΔY does not change any optical performances.
R_Z	±2°	4′	- Allowed range ~ ΔZ assuming lateral dimension is 50mm (=arctan(2/50)). - Resolution = (sensitivity)/6 = 58μm assuming lateral dimension is 50mm.
R_X	±2°	4′	- Allowed range ~ ΔZ assuming lateral dimension is 50mm (=arctan(2/50)). - Same resolution as R_Z, Resolution = (sensitivity)/6 = 58μm assuming lateral dimension is 50mm.
R_Y	±2°	4′	- Allowed range ~ ΔZ assuming lateral dimension is 50mm (=arctan(2/50)). - Same resolution as R_Z, Resolution = (ϕ width sensitivity)/4 = 58μm assuming lateral dimension is 50mm. - ϕ width (sensitivity = 15′) error is to be adjusted rotating mirror about Y axis and then ϕ shift (sensitivity = 1.3′) is compensated by ΔX.
ΔF	±2 mm	Fixed	-Allowed range from manufacturing limit. - To be compensated by $\Delta Zmir$

Table 5. Error Budgets-Grating Adjuster Requirements

	Range	Resolution	Comments
ΔZ	±2 mm	20μm	- To compensate ΔA, allowed range ~ 2mm - Resolution = sensitivity/ $\sqrt{2}$ /(5 = scaling factor)
ΔX	±1 mm	Fixed	-Allowed range from manufacturing limit. - Sensitivity limit is large so that no adjustment is required. - ΔX error can be compensated by R_Y.
ΔY	±1 mm	Fixed	-Allowed range from manufacturing limit. - Sensitivity limit is large so that no adjustment is required - ΔY error can be compensated by R_X.
R_Z	±0.5°	3′	- Allowed range ~ $\Delta X/2$ assuming lateral dimension is 50mm (=arctan(0.5/50)). - Resolution = (sensitivity)/5 = 44μm assuming lateral dimension is 50mm
R_X	±0.5°	6′	- Allowed range ~ $\Delta Y/2$ assuming lateral dimension is 50mm (=arctan(0.5/50)). - Resolution = (sensitivity)/6 = 88μm assuming lateral dimension is 50mm
R_Y	±0.5°	2.5′	- Allowed range ~ $\Delta X/2$ assuming lateral dimension is 50mm (=arctan(0.5/50)). - Resolution = (sensitivity)/ $\sqrt{2}$ /5 = 35μm assuming lateral dimension is 50mm
ΔA	±1 mm	Fixed	- To be compensated by $\Delta Zgrat$
ΔC	±1 mm	Fixed	- (Sensitivity)/2 is enough