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Tolerance Analysis of the Far Ultraviolet Spectroscopic Explorer (FUSE) : A Statistical Approach

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ABSTRACT

We present a new statistical technique for evaluating the error budget of an optical system. Each parameter evaluated in the error budget is assigned a standard deviation. Randomly generated, gaussian distributed offsets are then generated for each parameter. The optical system is raytraced a large number of times using the offsets to simulate alignment errors. In this way it is straightforward to simultaneously evaluate the degradation in the optical performance introduced by random misalignments and fabrication errors. The error budget for a system is then be defined in terms of the standard deviations assigned to each parameter under consideration.

Keywords: analysis, optical systems, tolerancing

1. INTRODUCTION

The Far Ultraviolet Spectroscopic Explorer (FUSE) is a NASA mission designed to make high resolution ($\lambda/\Delta\lambda$ = 30,000) spectroscopic observations in the Far Ultraviolet (FUV; 912-1200Å) with unprecedented sensitivity[1]. To accomplish the mission goals, the FUSE prime instrument utilizes four coaligned Rowland type spectrographs. The channels are paired such that each pair of spectrographs share a common imaging, microchannel plate detector. Thus, there are four spectrographs and only two detectors. Each spectrograph uses a first generation, holographically ruled grating to maximize the spectral resolution and minimize the astigmatism[2,3].

As part of the FUSE Phase B effort we are developing the error budget for the prime science instruments. The goal of any error budgeting process is to distribute the total allowable error in an optical system (e.g. an rms blur of the image at the focal plane) amongst the potential errors for each optical component. The basic question in developing an error budget is selecting the methodology for allocating the error. One approach to developing an error budget is to evaluate algebraically the defocus blurs associated with path length variations induced by fabrication and alignment errors[4]. However, this technique does not account for the aberrations in the optical path other than defocus. In systems with dispersive optics the aberrations induced by misalignments can be substantial. Another algorithm commonly employed is to scan each optic along a given axis in rotation or translation while monitoring the behavior of the image at the focal plane of the system. This method provides a good estimate of the relative sensitivities of the image to rotational and positional offsets, but considers only single axis motions. In reality there are simultaneous alignment and fabrication errors associated with each optical element. The errors are also not necessarily independent; displacement along one axis can be equivalent to rotation and translation along different axes. Therefore, simply adding predicted rms blurs in quadrature in not necessarily appropriate. It is clear that, while the techniques mentioned above are good approximations, they may not be sufficiently accurate for optical systems whose performance depends upon aberration control.

The holographic gratings baselined for the FUSE instrument correct for the stigmatism inherent to a standard Rowland circle spectrograph. Furthermore, the performance of the spectrograph varies depending upon the environment the instrument is operating in, such as in the laboratory or on orbit. Separate error budgets are required which address the specific operating conditions in order to understand how the instrument will perform during integration, calibration, and flight. Therefore, we felt it necessary to develop a more accurate method for determining the error budget which accounts for the actual instrument performance.

2. TOLERANCE MODELING

In our approach the error analysis is based on a raytrace of the spectrograph to provide the most accurate model for evaluating the effects of misalignment and fabrication errors. The raytrace includes imperfect optics. By introducing errors into the optical path and tracking the spectrograph performance it is straightforward to derive an error budget. The distribution used to generate the random errors can be chosen to best represent the system under study. For FUSE we have chosen to distribute the random errors using a gaussian. The tolerance for any given parameter is characterized by the standard deviation of the related gaussian distribution. Gaussian distributions were chosen due to a lack of mature data relating to the mechanical systems, such as the optical bench and mounts. As more data becomes available the model will be updated to better reflect the actual system performance.

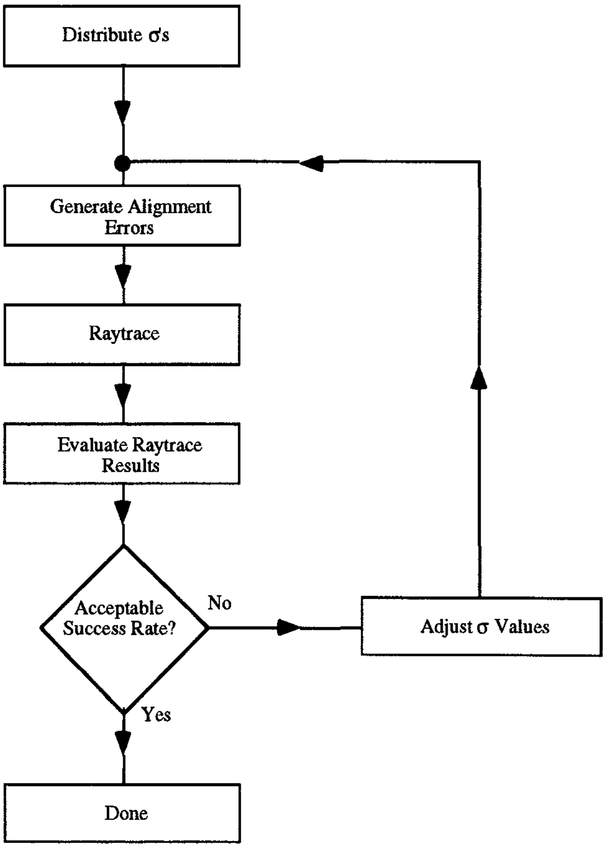

Figure 1 : Flow chart depicting the tolerancing algorithm adopted for the FUSE instruments.

Our methodology is shown in Figure 1 in the form of a flow chart. The first step is to assign standard deviations to the parameters included in the error budget based on single axis tolerance scans. The raytrace is then run many times, each time using a different set of randomly generated offsets. For each raytrace the image at the focal plane is analyzed to determine whether or not it satisfies the performance criteria. The success rate, the percentage of raytraces which meet the performance criteria, is then recorded. After each tolerance run the operator reviews the success rate, adjusts the individual standard deviations and/or the distribution, and initiates another tolerance run. The process is repeated until the desired success rate is achieved.

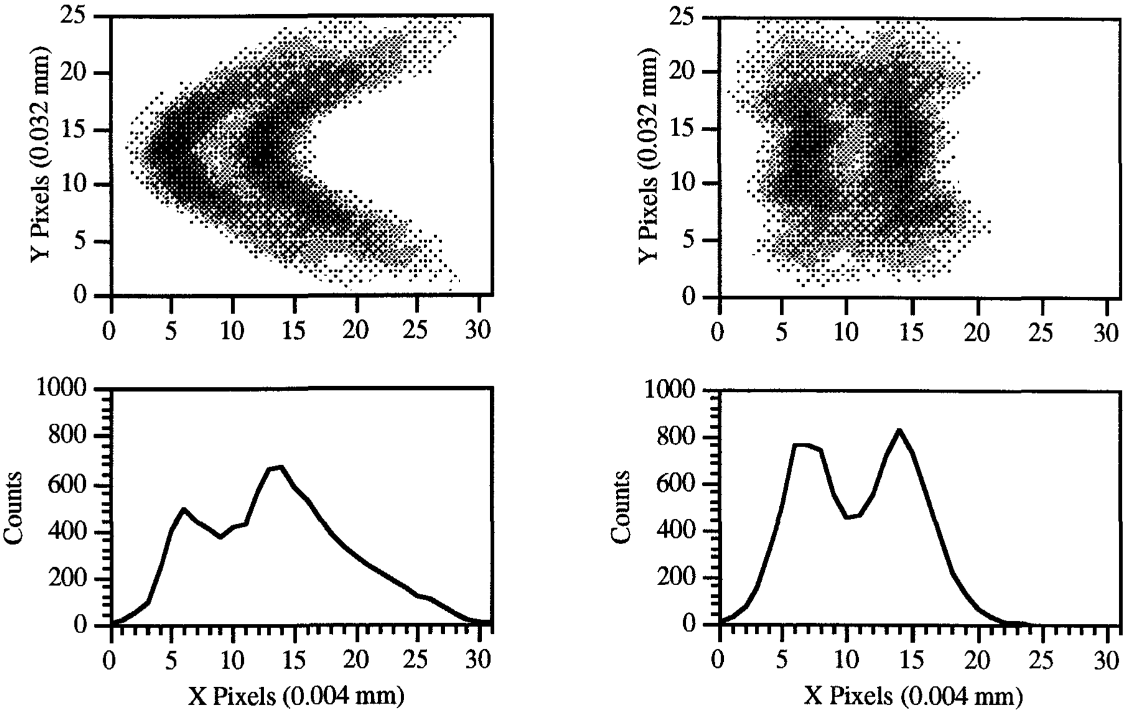

Figure 2 : (a) Upper panel : Gray scale contour map of raytrace model data showing two lines separated by 1 part in 30,000 at 912Å. Lower panel : Histogram of the data summed along the y-axis which demonstrates how the resolution is degraded by the line curvature. (b) Upper panel : The same line pair shown in (a) with the line curvature removed. Lower panel : Histogram of the corrected data which shows how the resolution has been increased. Straightening of the lines increases the resolution of the system and thus the resolution margin. By taking this into account the tolerances can be relaxed.

The error budgeting process for FUSE follows the algorithm outlined above. For the purposes of the FUSE program the success rate goal is 67% and two lines are considered resolved if there is a 20% modulation between two lines separated by 1 part in 30,000. A powerful feature of this technique is that it can be modified to better represent how the actual system will operate and be used. For example, a thermal model of the instrument and spacecraft demonstrates that a uniform distribution over a limited range is more appropriate to use for short time scales as opposed to a gaussian distribution. This is accounted for in the in-flight tolerances. As another example, Figure 2a shows a contour map of a pair of diffracted lines separated by 1 part in 30,000 at 912Å. The lines exhibit significant curvature, which can degrade the resolution of the spectrograph. The in-flight data will be corrected for this curvature to maximize resolution and the sensitivity to weak emission or absorption features, after the data is telemetered to the ground. Straightening of the lines increases the resolution margin of the system, thus loosening the tolerances required to meet the resolution requirement of 30,000. Figure 2b shows the 912Å line pair straightened. This straightening is included in the error budgeting software to provide a higher level of fidelity in the error budget.

Finally, the whole error budgeting process can be automated through software scripts. The operator need only check the success rate, alter the standard deviations, and start the process again periodically. Depending upon the particulars of the optical system under study, the computer, and the error budgeting software it can take anywhere from 10 minutes to 10 hours for one tolerance run.

3. CONCLUSIONS

In simple optical systems where the aberrations induced by misalignments are simple, standard error budgeting techniques are generally adequate. However, in aberration corrected systems the performance dependence on misalignment errors is not necessarily simple. To account for this we have developed a statistical methodology for deriving the error budget of an optical system. Our technique assigns standard deviations to the parameters being evaluated. The optical path is then raytraced numerous times. For each raytrace randomly generated, gaussian distributed offsets, based on the standard deviations, are added to the raytrace to simulate misalignment errors. This technique is superior to the standard methods of error budgeting because it account all errors simultaneously and incorporates a raytrace model to provide the most accurate information regarding system performance.

4. REFERENCES

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