System Architecting: Defining Optical and Mechanical Tolerances from an Error Budget

Julia Zugby
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Overview

This tutorial provides a general overview of system architecting, providing insight into the top down approach of optical and mechanical tolerance allocations. Optical systems can be quite complex and having insight into the methodology of the development of allocations to the mechanical and optical systems will enhance an engineer's understanding of their impact across a large team. Top level system sensitivities drive the need for system performance to which designers are driven to meet. This tutorial will prove invaluable as a general guideline for understanding tolerance development as part of system and will summarize system architecting to provide the reader the necessary insight of system development and requirements flowdown for opto-mechanical tolerancing.

Purpose:

The purpose of this tutorial is to provide a general overview and methodology associated with requirements derivation for a spaced based optical system case study and the methodology associated with flowing requirements to opto-mechanical designers. The paper will follow a simple case study to illustrate the system concept, to system architecture, followed by requirements flowdown. The reader will gain a general sense of the approach and development that goes into architecting a full system and the over arching concerns facing optical systems. While the purpose is to provide the reader with a general sense of requirement derivation and how those requirements are levied to the mechanical design of an optical system, it's important for engineers to understand that designs are typically highly iterative and require cross-disciplinary communication to negotiate tolerances and requirement allocations. In general, readers should be familiar with optical tolerancing and sensitivity budgets, which will touched upon briefly for this tutorial. Excellent resources include Paul Yoder "Opto-mechanical System Design" and "Optical System Design" by Robert E Fischer.

1 Customer's Request:

As an engineer, our job is to translate a customer's idea and develop a viable solution that will meet their needs and satisfy expectations. A customer has many constraints when seeking a solution to a technical request. Typically these constraints involve: performance, cost and time. Typically, only two of the three requests can be met. For purposes of this tutorial, the following case study will be evaluated: a customer requests a space based telescope to look at Jupiter's red spot. The telescope must be able to continuously resolve the "Great Red Spot" (GRS) in the visible (400-900 nm), be ready to launch in 12 months and cost $10,000. Experience will tell you that a telescope can indeed be built to resolve the Great Red Spot on Jupiter, the 12 month lead time is tight but can be done, and the $10,000 dollar budget is unrealistic. For purposes of this case study, your team has been given the green light to build a telescope that must be delivered in 12 months and funding will be provided as needed.

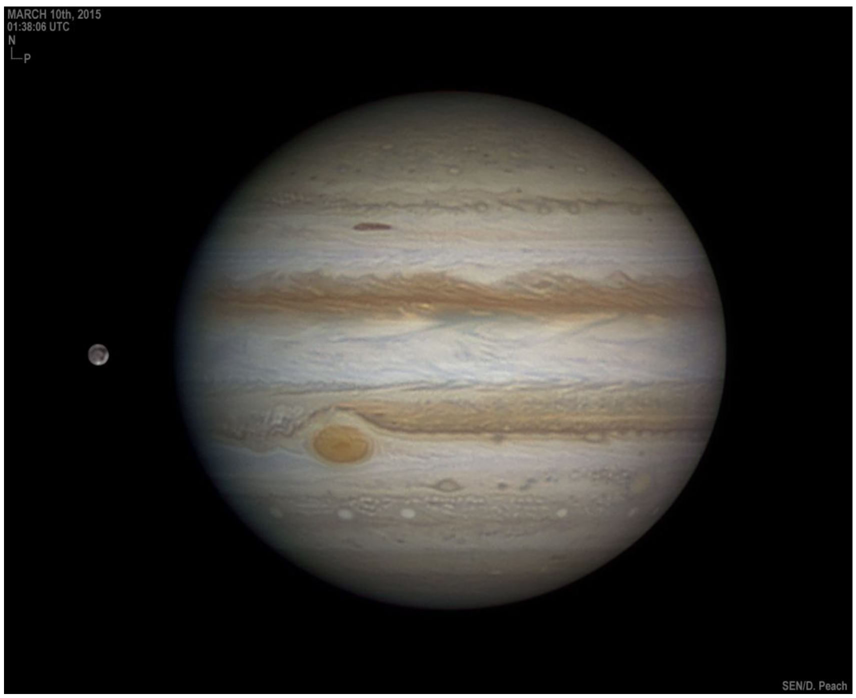

Image 1: Picture of Jupiter with the Great Red Spot. Image Courtesy of NASA.

Upon receiving this request, you identify four main objectives, three of which are critical for this particular customer (cost has been removed): 1) Must continuously resolve Jupiter's Red Spot, 2) Image from 400-900 nm, and 3) Launch in 12 months. It must be reiterated the importance of defining your requirements clearly and early. Often times this step is pushed back until there's more definition of the initial customer space. However, having clearly stated objectives early in the project will avoid costly and stressful situations down the road. To emphasize the importance of this step see Image 2.

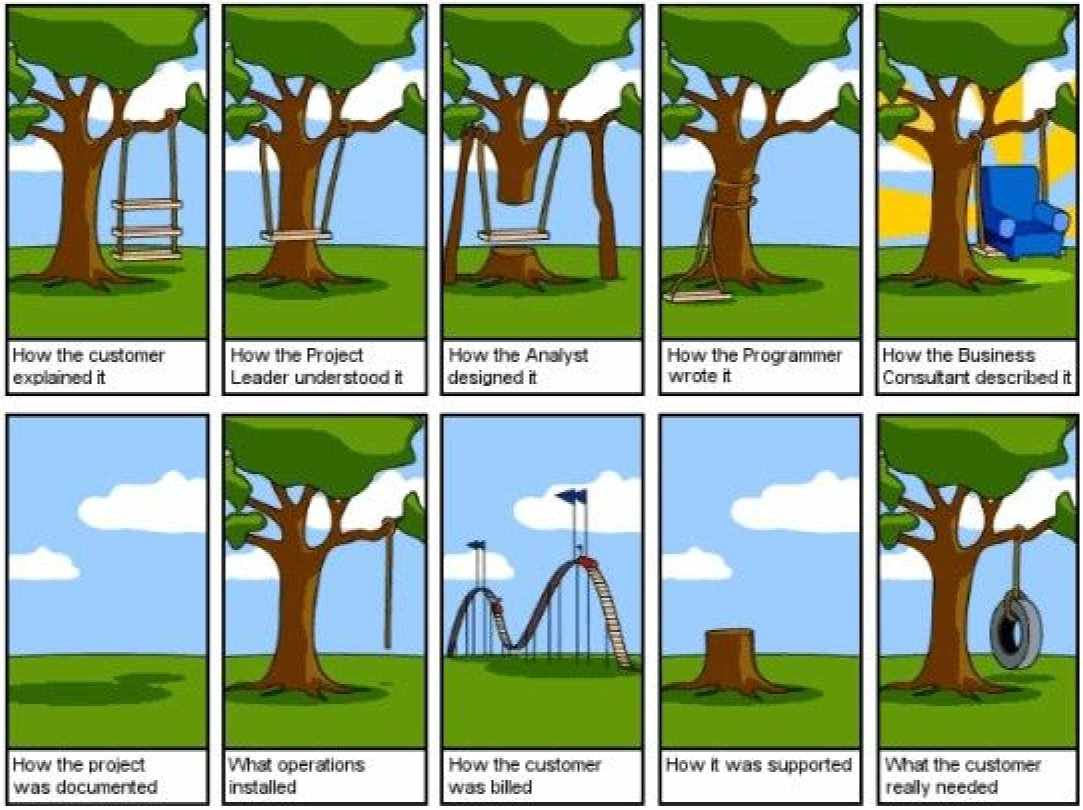

Image 2: Poor requirements definition. Image Courtesy of ProjectCartoon.Com

2 Defining Performance Metrics:

Your team is now waiting to receive direction on what to design. Your first step is to determine the performance metric that the team should work towards and flow down requirements in terms of the specified metric. Typical performance metrics are the following:

- RMS WFE: Root Mean Square Wavefront Error
- MTF: Modulation Transfer Equation (typically at specific frequencies)
- Distortion
- Fractional Encircled Energy
- Beam Divergence
- Geometric RMS Image Size
- Dimensional Limits
- Boresight
- Throughput

Based on the customer's request of having a stable image while resolving the GRS you decide the appropriate metric to flow through to your team is RMS WFE. Resolving the GRS typically means a strehl ratio > 0.8. So we convert the strehl ratio to RMS WFE:

$$SR \approx e^{-(2\pi W_{RMS}/\lambda)^2} \approx 1 - (2\pi W_{RMS}/\lambda)^{2}$$

You choose to use 500 nm (or 0.5 um) as your evaluation wavelength, so your top level allocation for the system performance becomes:

$$W_{RMS} = \frac{\lambda\sqrt{1-SR}}{2\pi} = 35\ nm$$

3 Concept Design:

Typically, several concepts will be drafted and traded at the beginning of a project to weigh the pros and cons of each approach. To maintain the 12 month schedule, you decide that a typical on-axis Cassegrain Telescope is the design your team will pursue.

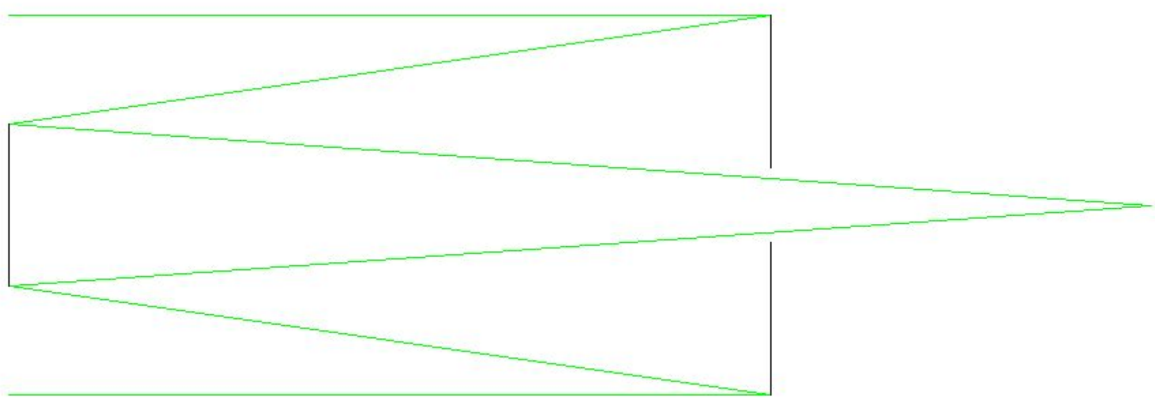

Image 3: Simple layout of Cassegrain system. Zemax.

The customer requested continuous viewing of the GRS (and likely also meant resolving at Strehl of ~0.8. This is a good example of further clarification. As an engineer, do not be afraid to clarify!), so this also requires a trade for maintaining the image in focus during thermal instability, dryout conditions, and 1-g offload when going from Earth to space. There are several ways to maintain focus: athermalize the whole design, include a focusing mechanism, have active thermal control over the entire telescope, actuated optics, and more! You decide that your team can afford to have a focusing mechanism on the secondary to adjust focus. The decisions you're making are all in an effort to maintain the launch schedule of months

4 Error Budget Development:

Top level performance of 35 nm is defined and now must be allocated to the different areas that will affect performance. The sample budget is not a comprehensive list of terms involved in error budgeting, but provides an overview of the terms that go into error budgeting when architecting a system. For example, Table 2 does not include the focusing mechanism that your team is planning to use, nor does it include the closed loop control system that will be used to control the mechanism on the secondary. These terms will likely help the error budget in Table 2, but for simplicity, these terms are left out. Error budgeting and design is a highly iterative process. Preliminary modeling of the system should be fed into the error budget, with initial allocations provided.

Level	1	2	3	4	Description
Total Performance	27				Requirement = 35 nm
Nominal Design Residual		15			Design residual inherent to design, assume on-axis
Static Image Quality		21			Image quality under static conditions
1g offload			4		Result of aligning on Earth and releasing in space
dryout			4		Result of materials shrinking as they outgas & lose moisture
Static Thermal offset			7		Result of aligning in lab at 22C and having +5 degrees
Manufacturing			18		Ability/Allocation for how well the optics must be made
Primary				10	How well the Primary Mirror is made and mounted
Secondary				15	How well the Secondary Mirror is made and mounted
Alignment			4		How well the System can be aligned
Primary to Secondary				4	How well the Primary and secondary can be initially aligned
Telescope to sensor				2	How well the Telescope can be aligned to the sensor
Non-Static Image Quality		10			Changes faster than your thermal control
Thermal Gradients			10		Gradients across optics and system that impact performance

Table 1: Top Level Error Budget for a simple optical space-based telescope

Each of the terms of the top level error budget will be refined as the project develops and the design progresses. At this point, you've developed a sensitivity table of the system to the degrees of freedom of each optic, similar to the sensitivity Table previously executed for Hmwk#4 "Mounting Requirements for Focusing Doublet", see Appendix A.

5 Optical and Mechanical Tolerances:

Initial allocations have been provided to the opto-mechanical team. You see that part the initial allocation to work towards the is "Manufacturing" line item. Your team has been flown a requirement of 10 nm for the primary and 15 nm for the secondary which is supposed to encompass both the initial manufacturing quality of the optic and the mounting of the optic. You begin to build your opto-mechanical design, and evaluate the design using Finite Element Analysis (FEM). This provides you insight to your design. Using the same FEM, you begin to apply the different environmental load conditions. The environmental load conditions that you initially evaluate are the static thermal offset (which has and allocation of 7 nm) and the 1 g offset. Using the evaluated results from the FEM under the different load conditions, you begin to see the sensitivity of the system to different environments. For each allocation, you find that the system performs better than expected and have margin to relax tolerances that don't have a big impact.

For example: The primary mirror was allocated 10 nm for manufacturing and mounting error. After speaking with vendors, they can manufacture the radius of curvature to 1% of the total radii, with a surface figure error (SFE)of 4 nm. The contribution from mounting is only 2 nm. The FEM modeling is also showing positive margin for your design under all your environmental conditions, so, to save time on mounting machining complexity and cost you decide to relax the mount design and tolerances, which would now contributes 5 nm of surface figure error. Between the SFE and mount, (rss these terms for 6.5 nm) you still have margin 3.5 nm that may need to be used elsewhere in the design.

This process is continued until each of the terms have been satisfied and the design is considered manufacturable.

Summary:

When designing an optical system it is important to consider the conditions under which the system will be used. Not all systems require complex error budgeting and requirement allocations, but going through the exercise of allocating to the different conditions the design may encounter will ensure a robust design. It's also important to have insight into the system trade-offs one has as an engineer. This is vital to designing manufacturable, timely, and cost effective designs that meet customer expectations.

References:

P. Lightsey, "Optical Performance for the James Webb Space Telescope", Proc. of SPIE Vol. 5487, 0277-786X, (2004)

Paul Yoder, "Opto-mechanical System Design"

Robert E Fischer, "Optical System Design"

J. Burge, Introduction to Opto-Mechanical Design Course Notes, 2016

APPENDIX A:

Mounting Requirements for Focusing Doublet

Julia Zugby

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Introduction

This report analyzes a focusing doublet using collimated HeNe laser light coming to a focus on a Position Sensing Detector (PSD). The analysis of the optical system looks at the Assembly Tolerances required to meet 0.04λ RMS, which takes into account lens position errors with the PSD being used as a compensator with +/- 5 um adjustment capability. This report does not cover the tolerances of the lenses themselves or the operational conditions under which this lens system is to be used. The entrance pupil diameter of the doublet is 20 mm in diameter with a nominal effective focal length of 100 mm. As mentioned, the analysis is under HeNe laser light at 632.8 nm with a diffraction limited operation Strehl Ratio of greater than 80%. The net effect of all motions will be reported as the root sum square (RSS) of the individual components under compensation with the PSD. A detailed analysis of the tolerances of each component shows an RSS performance of 0.036 RMS delta wavefront from nominal.

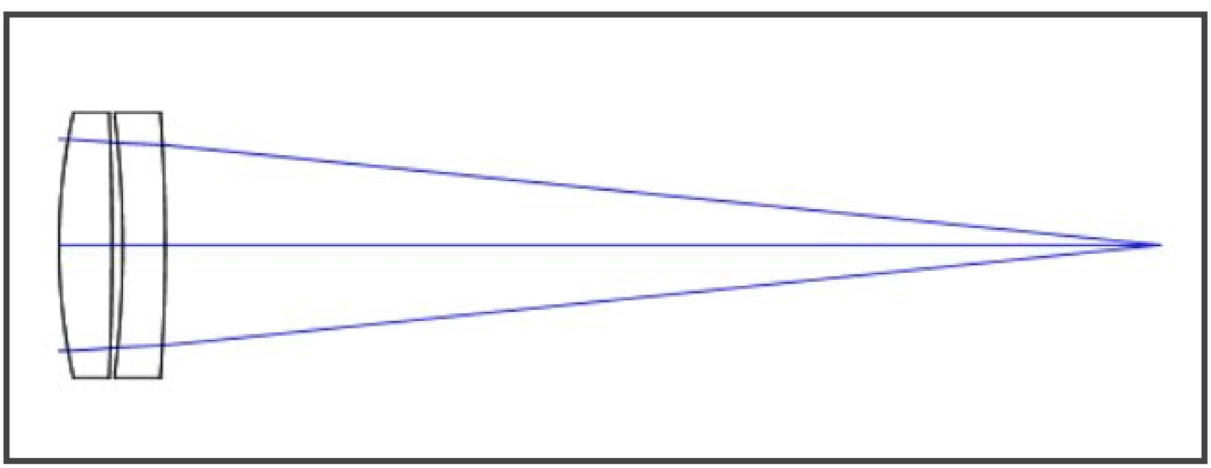
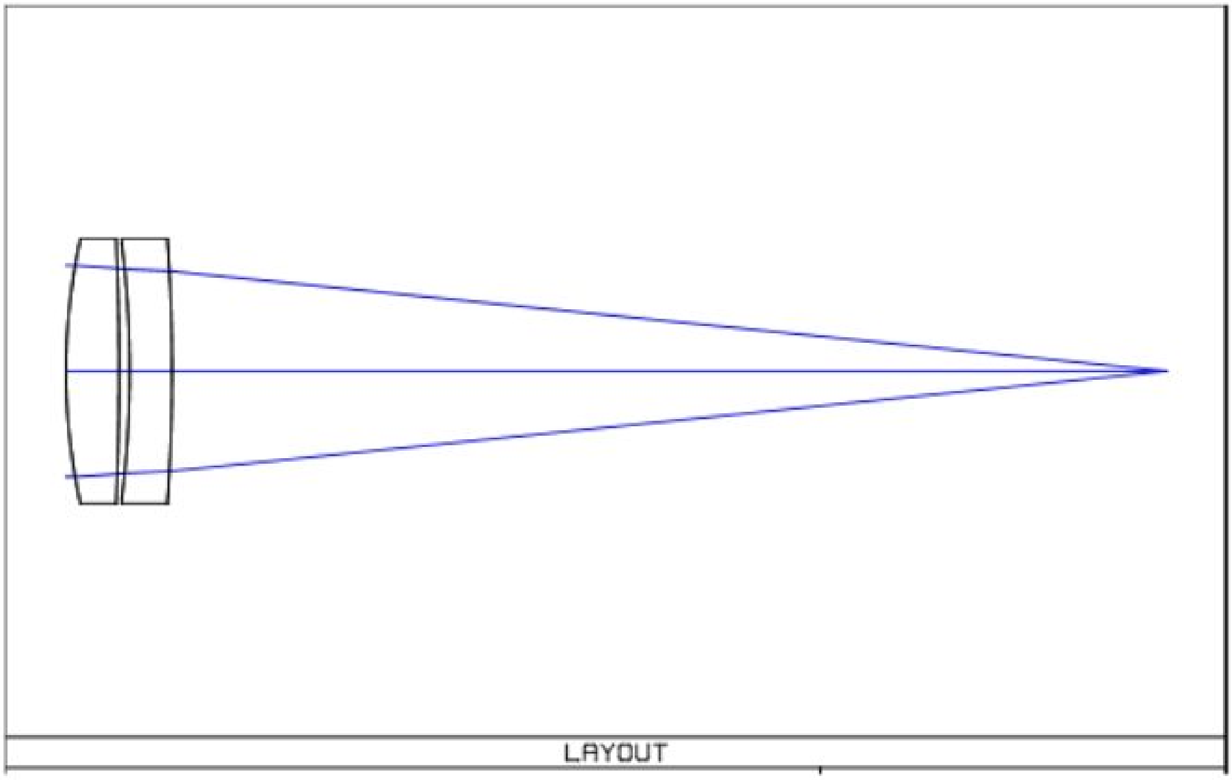


Image 1: Doublet lens system layout

Optical Design

The optical design is a typical doublet lens pair. It is assumed that when referring to "system" that the detector is included with the system. The system parameters are provided in the image below.



SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Diameter
OBJ	STANDARD	Infinity	Infinity		0
STO	STANDARD	Infinity	0		20
2	STANDARD	58.6	5.0	N-SK15	25
3	STANDARD	-277.0	1.0		25
4	STANDARD	-97.0	4.0	N-SK15	24
5	STANDARD	-174.0	93.824		25
IMA	STANDARD	Infinity			

INDEX OF REFRACTION DATA:
Index data is relative to air at the system temperature and pressure.
Index of refraction at 632.8 nm
N-SK15 1.620702

Tolerance Analysis
The system was perturbed given the parameters listed in Table 2. Motions of each lens and the lens system were captured for the RMS wavefront error as a result of perturbing the lens and finding the best focus. The sensitivity of the change in RMS wavefront error from the nominal design is provided in the final "sensitivity" column using the equation:

$$Sensitivity = \frac{RMS\ wavefront\ for\ Compensated\ Perturbation - Design\ Nominal}{Perturbation}$$

		Nominal		0.002	RMS Wavefront		
Lens 1		perturbation		RMS (includes nominal)	Comp Z		Sensitivity
	Tip	0.001	radians	0.0066	-0.0001	mm	4.6
	Tilt	0.001	radians	0.0066	-0.0001	mm	4.6
	Decenter X	25	um	0.0051	-0.000018	mm	0.000124
	Decenter Y	25	um	0.0051	-0.000018	mm	0.000124
	Lens 1-2 thickness	100	um	0.0027	-0.165672	mm	0.000007
Lens 2							
	Tip	0.001	radians	0.0117	0.000027	mm	9.7
	Tilt	0.001	radians	0.0117	0.000027	mm	9.7
	Decenter X	25	um	0.0052	0.000007	mm	0.000128
	Decenter Y	25	um	0.0052	0.000007	mm	0.000128
Lens System							
	Tip	0.001	radians	0.0046	-0.000079	mm	2.6
	Tilt	0.001	radians	0.0046	-0.000079	mm	2.6
	Decenter X	10	um	0.002	0	mm	0
	Decenter Y	10	um	0.002	0	mm	0
	Focus Compensation Error	5	um	0.011697			

Table 1: System perturbations with associated Image sensitivities to RMS change in wavefront

The sensitivities for each perturbation were then used to reassign tolerance values for a new RMS wavefront error. Each wavefront error was then RSS'd together to meet the 0.04 RMS wavefront allocation for the assembly tolerances of the doublet, as shown in Table 2 below. RMS wavefront in Table 2 is calculated by:

$$RMS\ Wavefront\ Error = Perturbation\ * Sensitivity$$

Lens 1		perturbation		Sensitivity	RMS Wavefront	
	Tip	0.001	radians	4.6	0.0046	
	Tilt	0.001	radians	4.6	0.0046	
	Decenter X	100	um	0.000124	0.0124	
	Decenter Y	100	um	0.000124	0.0124	
	Lens 1-2 thickness	100	um	0.000007	0.0007	
Lens 2						
	Tip	0.001	radians	9.7	0.0097	
	Tilt	0.001	radians	9.7	0.0097	
	Decenter X	100	um	0.000128	0.0128	
	Decenter Y	100	um	0.000128	0.0128	
Lens System						
	Tip	0.005	radians	2.6	0.013	
	Tilt	0.005	radians	2.6	0.013	
	Decenter X	10	um	0	0	
	Decenter Y	10	um	0	0	
	Focus Compensation Error	5	um		0.011697	
				RSS	0.037	RMS wavefront

Table 2: Tolerance values to for assembly of doublet to meet allocation of 0.04 waves RMS.