A General Tool for Evaluating High-contrast Coronagraphic Telescope Performance Error Budgets

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ABSTRACT

This paper describes a general purpose Coronagraph Performance Error Budget (CPEB) tool that we have developed under the NASA Exoplanet Exploration Program. The CPEB automates many of the key steps required to evaluate the scattered starlight contrast in the dark hole of a space-based coronagraph. It operates in 3 steps: first, a CodeV or Zemax prescription is converted into a MACOS optical prescription. Second, a Matlab program calls ray-trace code that generates linear beam-walk and aberration sensitivity matrices for motions of the optical elements and line-of-sight pointing, with and without controlled coarse and fine-steering mirrors. Third, the sensitivity matrices are imported by macros into Excel 2007 where the error budget is created. Once created, the user specifies the quality of each optic from a predefined set of PSDs. The spreadsheet creates a nominal set of thermal and jitter motions and combines them with the sensitivity matrices to generate an error budget for the system. The user can easily modify the motion allocations to perform trade studies.

Keywords: Visual Basic for Applications, coronagraph, error budget, high-contrast imaging, Terrestrial Planet Finder.

1. Introduction

The past decade has witnessed the development of several variants of optical telescopes designed to observe faint exoplanets by blocking the light of their parent stars (see e.g. Coronagraph Workshop 2006). There have also been encouraging technological advances in the demonstrated ability to reduce scattered light to levels consistent with detection of terrestrial exoplanets (e.g. Moody and Trauger, 2008). As with most trail-blazing technical developments, the experiment cart has led the error budget horse down unchartered paths. However, the link between the science requirements, the concept developers, the experimentalists, and the engineers who will perform detailed design work is ultimately the performance error budget. The error budget ties the science requirements to the instrument performance requirements and is crucial to identifying the most challenging aspects of the instrument design.

The instrument performance requirements for high-contrast imaging systems come in two flavors: static and dynamic. Static requirements, e.g. the smoothness and shape of the mirrors (Shaklan and Green, 2006), the image-plane mask requirements (Lay et al., 2005) and the allowable contamination level (Balasubramanian et al., 2009), are tied to the ability of the wavefront control system to compensate for phase and amplitude imperfections. Comprehensive error budgets for the static errors have not been published in the literature, but a treatment of surface and amplitude requirements per surface has been given by Shaklan and Green (2006). Dynamic errors, both thermal and jitter, have been addressed by Shaklan et al. (2005). In that work, as here, the system was assumed to be ‘set and forget.’ That is, after initially controlling the wavefront to compensate for static errors, dynamic effects perturbed the system and increased the scattered light level. This scenario is consistent with the long integration times required to detect extremely faint exoplanets and to sense high-contrast aberration-induced instrument speckles.

2. Model Description

The CPEB is a tool developed in the Excel 2007 environment. The CPEB predicts the level and stability of scattered light in the image plane within a region of spatial frequencies, known as the “dark hole”, where a deformable mirror (DM) controls residual scattered light levels to below the planet’s signal level. The instrument’s level of scattered light is measured in terms of contrast, approximately given by the mean scattered starlight level relative to the peak incident starlight level when the coronagraph mask is removed. See Green and Shaklan (2003) for a detailed description. All contrast calculations are performed in the spatial frequency domain between 2λ/D and 8λ/D, where λ is the wavelength and D is the telescope diameter. Other values can be chosen if desired.

The CPEB is a flexible tool that allows the user to perform simple trade studies pertaining to dynamic (thermal and jitter) sensitivities. The tool generates a CPEB in three highly automated steps: 1) create the optical prescription in JPL’s MACOS ray-tracing tool; 2) Create sensitivity matrices for beam walk and aberrations; 3) Create an error budget using the sensitivity matrices and user-input optical element motion and bending allocations. The budget does not address the static requirements. Instead, the user supplies the static (beginning of observation) contrast and this is then combined with individual dynamic terms yielding a final mean contrast and contrast stability value.

As in our previous work (Shaklan et al, 2005), the PCEB is based on the following assumptions:

1) A wave front control “set and forget” approach where the wave front is calibrated at the beginning of an observation, and there is no recalibration or remeasurement during the time of the observation;
2) Observations begin in thermal equilibrium.
3) Background speckles look identical to planets, that is there is no chromatic differentiation;
4) Near field diffraction effects are ignored because it is assumed that the DM can correct much of these effects;
5) Errors are uncorrelated thus the contrast contributions add linearly;
6) A set of predefined optical elements which are described by a set of default PSD parameters defined in the PCEB are the primary, secondary, deformable, flats, off axis parabolas, super flats, and super off axis parabola mirrors;
7) The dynamic models are based on linear models to make scaling and modifying simple.

Dynamic Terms

The dynamic errors included in the error budget are tied to pointing, structural bending (relative motion of the optics) and optical element bending. These errors result in aberrations and beam walk, the two fundamental effects tracked by the CPEB. Beam Walk is the motion of the optical beam across the surface of imperfect optics. Rigid body pointing errors and structural deformation cause the beam to deviate from its nominal state at the start of an observation.

Combining Terms

In the ‘set and forget’ scenario, the wavefront control system has a large influence over the initial wavefront setting. The implication is that the ‘static’ system requirements are closely tied to the performance limitations of the wavefront control system. The dynamic terms, on the other hand, are not mitigated by the wavefront control system except as related to the pointing control system, described below. It is thus straightforward to specify (allocate) element motion and bending requirements within the CPEB that can then be related to thermal (e.g. temperature, gradient) and structural (e.g. isolation, stiffness) requirements. However, we do allocate a portion of the budget to static terms represented by a single value I_s that is the start-of-observation leakage of starlight. By ‘coherent’ we mean that this light can interfere with the starlight leakage arising from dynamic terms. The error budget contrast stability in the presence of dynamic and static terms is given by the following equation

$$\sigma = \sqrt{2I_s\langle I_t\rangle + \langle I_t\rangle^2} \tag{1}$$

where $\langle I_t \rangle \equiv \langle |E_t|^2 \rangle$ is the instrument contrast due to thermal effects, and E_t is the time-variable complex field (Shaklan et al 2005). We assume that the thermal timescale is of the order of the observation time T. We are concerned with how contrast changes from one observation to the next; therefore, jitter effects become irrelevant when computing the temporal variability of the background, since we assume that the dynamic terms due to jitter occur at a short time scale compared to T. The instrument or mean contrast is given by

$$\langle I\rangle = I_s + I_B + I_t + I_j \tag{2}$$

Where I_s is the static contrast, I_B is the contrast due to background, and I_j is the contrast due to jitter.

Models and Contrast Calculations

The error budget is built upon two main types of models, the Aberration and Beam Walk models. Aberration models consist of the Coronagraph Aberration Contrast Sensitivity (CACS), and the Aberration per DOF (APDoF) models. The CACS model computes image plane contrast for ideal coronagraph designs as a function of wavefront components decomposed into low-order Zernike polynomials. The APDoF model relates the 6-degree of freedom motion of the optical elements to Zernike amplitudes. The two models are combined to compute contrast from aberrations as shown in Figure 1.

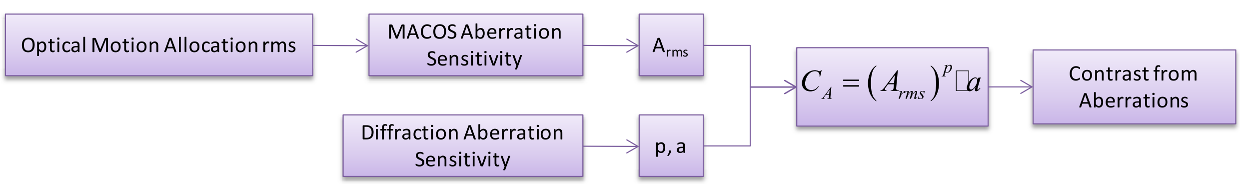

Figure 1. Aberration Contrast Calculation. Optical motions allocation rms are combined with the MACOS aberration sensitivity matrix to compute the Zernike mode rms amplitudes, and is subsequently used as an input for the aberration contrast equation along with the power and coefficients from the aberration sensitivity data to calculate contrast due to aberrations.

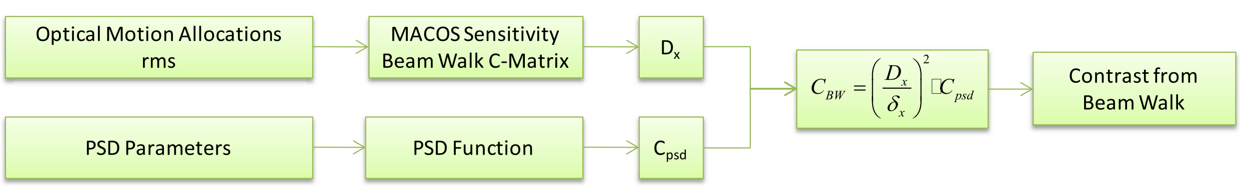

Figure 2. Beam walk calculation. Dx is the beam walk computed from the sensitivity matrix given 6 degrees of freedom motion of the optics. CBW is the contrast coefficient for a unit of beam walk δx at a single image plane position.

The Beam Walk models consist of the Beam Walk Contrast Sensitivity (BWCS), and the Beam Walk per DOF (BWPDoF) models. The BWCS model computes contrast at a single location in the image plane per unit of beam walk. This model is based on Noecker's beam walk analysis (Noecker 2005) relating the optical PSD and the lateral motion of the beam across the optic to the change in the shape of the wavefront. The BWPDoF model computes beam walk per six DOF of the optics, the MACOS beam walk sensitivity. These two models combine to compute contrast from beam walk for each optic as shown in Figure 2.

Control System

We employ a nested pointing control system (Fig. 3) where we assume that a disturbance reduction system controls pointing to a few mas residual. The secondary mirror tips and tilts to compensate this residual but due to bandwidth limitations there will be some uncompensated residual. Likewise a Fine Guiding Mirror compensates part of the residual, and also due to bandwidth limitation there will be a residual which cannot be compensated, but it is accounted for in the error budget (Shaklan et al, 2005). The error budget does not assume a particular time constant for these control systems. Instead, each is allocated an r.m.s. residual motion. These motions can be tied to the control system bandwidth and disturbance spectrum but these are not relevant to the CPEB per se.

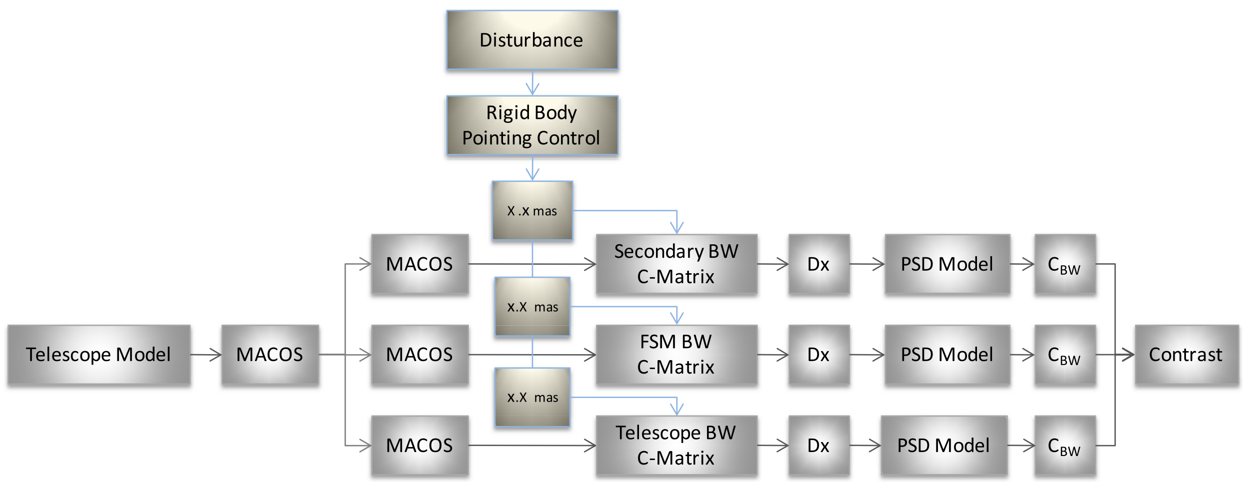

Figure 3. Pointing Control. The Error Budget assumes a multi-tiered system. The FGM compensates high frequency disturbances, the secondary mirror compensates low frequency disturbances, and there is a residual which is not compensated.

3. Error Budget Methodology

There are three stages to computing an error budget for a Coronagraphic stellar telescope according the approach used for the Terrestrial Planet Finder Coronagraph (TPF-C) Error Budget. The first stage, conversion stage, consists of converting the optical prescription from Code V or Zemax to MACOS format. The second stage, C-matrix stage, consists of generating the optical sensitivity matrices using a generic Matlab-MACOS interface, a mex function which allows for optical sensitivity computations to be set up in Matlab with access to full MACOS functionality. The final stage, the Error Budget stage, consists of importing the sensitivity matrices and the optical design information into an Excel document, and computing an error budget. Performing this process using the TPF-C approach presents a major problem as a result of lack of automation. The three stages of the process are tedious and time consuming due to the fact that some of the critical steps for each stage are to be performed manually by entering one command at a time, creating new scripts for each different optical design, or by modifying existing scripts to accommodate new designs. The entire process takes approximately two to three weeks.

Improved Method

We have followed the same general methodology, see Figure 4, as the TPF-C error budget but have improved some of the most important processes for each stage. We have improved both the conversion and c-matrix stages by developing two packages of Matlab user defined functions. The conversion stage utilizes a Zemax to MACOS converted, an executable, developed by John Lou, or a Code V to MACOS converter based on the Macro-Plus language in Code V written by Hiroshi Kadowagua at the Jet Propulsion Laboratory. A MACOS converted prescription requires considerable editing. For this we use one of the Matlab packages containing user defined functions based on the class constructor method, and cell arrays of structures. This package contains functions that allow the user to change or delete optical parameters, insert new optical element, delete existing optical elements, and change parameter formats. This computes the MACOS prescription required as an input by the c-matrix stage.

The c-matrix stage computes the MACOS aberration and beam walk sensitivities, and the optical information data files. The c-matrix stage uses the second package which was developed as a general tool for generating sensitivity matrices, and optical information files. The C-Matrix stage is almost fully automated requiring the user to only set the initial parameters and instructions. This is done in a parameter initialization Matlab script where the user defines the type of C-Matrix to be computed by selecting the pointing control element, system stop, elements involved in sensitivity matrices, and flags to perform certain calculations. When the parameter initialization file has been updated the user can simply run a script calling the user the initialization file and the user defined functions to generate both the sensitivity matrix data sets as well as the optical information data files which are used as inputs for the next stage of the error budget computing process.

For the third stage we developed an excel tool based on Excel 2007, Visual Basic for Applications (VBA) code, and Form and ActiveX controls. Excel VBA is a programming application that allows the user access to the Excel application through the programming Visual Basic code (Green et al 2007). Some of the VBA code benefits we took advantage of in this stage are the automation of repetitive steps by programming the required excel functionality to macros, programming macros to execute certain procedures based on given criteria by using logical functions and operators which make the process even faster by shortening the number of steps required to perform a task. We developed user defined functions using VBA code for the most complex equations in the budget thus the user does not need to input very complex equations multiple times. We created control groups using VBA code, Form and ActiveX controls to allow the user interaction with the error budget in a variety of ways; for example, the user may use default error allocations for the error terms, or the user may choose to enter different error allocations via controls or by manually entering the values directly in the excel spreadsheet cells. The entire process using the new approach takes a day or less; the Error Budget stage itself takes less than 30 seconds to compute a CPEB as opposed to 2 to 5 days with the old approach.

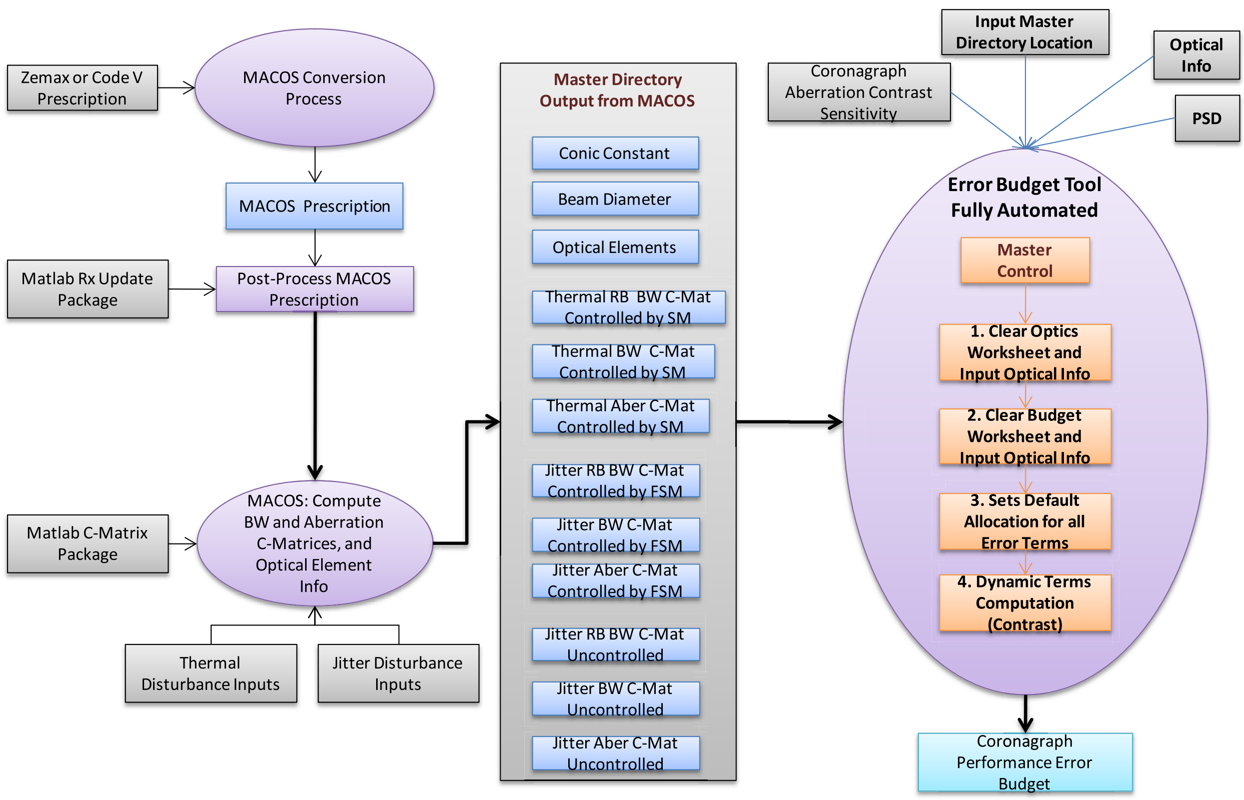

Figure 4. Error Budget Methodology. Includes conversion, C-Matrix, and Error Budget stages. The conversion stage requires a Zemax or Code V optical prescription input to generate a MACOS prescription with help of Matlab Rx Update package. The C-Matrix process uses the Matlab C-Matrix package, and the MACOS prescription as an input to compute and save the sensitivity matrices, and the optical design information to text files. The Error Budget stage consists of four main steps executed in sequence, and initiated by the Master Control: 1) updates Optics worksheet with new data; 2) updates Budget worksheet with new data; 3) generates default allocation tables for all error terms in the Allocations worksheet; 4) computes and reports contrast for each error term in the Budget and Error Tree worksheets.

Error Budget Automatic Steps

The user exercises the CPEB tool via a single control from the ActiveX Control group, labeled Master Control (MC), and embedded in the Allocations worksheet. The MC requires a master directory that contains the c-matrices and the optical data files for an optical design. The MC is of the type Command Button which can be programmed to control an event or to call a macro to execute a sequence of commands. We programmed the MC to perform four important tasks (fig. 4): 1) import the optical design information and c-matrices into the Optics worksheet in the optical parameter category; 2) clear and update the Budget worksheet with new design information; 3) initially set default allocation in the Allocations worksheet for all error terms; 4) import c-matrices and compute contrast. The CPEB computation is initiated by user in two steps where the user first defines the location of the master directory in the Allocations worksheet, and then clicks on the MC to start the computation.

The first task involves a series of automatic procedures which were programmed into macros. In this task the macros are programmed to check for existing optical parameters in the Optics worksheet cells, if the data exists it is deleted; otherwise, it continues executing the next step in the sequence. The next step is to import the optical data including the optics name list, optics conic constant, and the beam size for each optic into ranges defined in the code. When the data is imported a set of logical functions embedded in the Element Type column look at the Element List and

Conic Constant columns to determine the element type definition to be embedded there; these can be any of the seven element classes define in table 1. Furthermore, logical functions embedded in the PSD table columns look at the Element Type column to check the element type, and the PSD parameter values for the corresponding element type are referenced from table 1 to populate the PSD table. The RMS WFE column has been embedded with a user defined function to calculate the RMS WFE in nanometers for each optic based on the PSD values in the PSD table. The Contrast Coefficient table cells also contain an embedded user defined function which calculates what we call Beam Walk Contrast Coefficient, C_{BW}, based on the PSD parameter for each optic and a range of spatial frequencies given by Noecker (2005):

$$C_{psd} = \left(\frac{2\pi}{\lambda} \sqrt{ \iint 16\pi^2 (\delta_x k_x)^2 \cdot \left[\frac{A}{1 + \left(\frac{\sqrt{{k_x}^2 + {k_y}^2}}{k_0} \right)^2} \right] dk_x dk_y } \right)^2 \quad (3)$$

where A, ${k_x}^2$, ${k_y}^2$, k_0, and δ_x are the PSD parameters specified for seven types of optics as in Table 1. The optics worksheet at this point in the process serves as a reference for the rest of the steps in the sequence.

Table 1. Standard PSD Parameters. Default element classes included in the error budget includes primary, secondary, flats, off-axis parabolas, super flats, super off-axis parabolas, and deformable mirror. Parameters are referenced to populate PSD Parameter table for defining the optics in the optical prescription.

Standard PSD Parameters					
Element Type	***k0***	***A***	***N***	***deltax***	***lamda***
PM	4	1.73E-17	2.5	1.00E-05	650
SM	10	1.38E-18	3	1.00E-05	650
Flat	10	1.25E-20	3	1.00E-05	650
OAP	10	1.25E-20	3	1.00E-05	650
SF	100	1.00E-22	3	1.00E-05	650
SOAP	100	1.00E-22	3	1.00E-05	650
DM	240	8.52E-22	3	1.00E-05	650

For the second task we programmed a macro to update the error summary tables in the Budget worksheet with new design information. The update is primarily a formatting and labeling exercise; no contrast calculation occurs at this stage of the process. The update is done by defining the ranges to be updated, clearing them, populating them with the new design information from the Optics worksheet, and applying the appropriate formatting to the cells in them.

The third task is to allocate default values to the allowable optical element motions or the Zernike RMS Amplitudes for all error terms. The default values for all error terms are programmed in the code itself; these values were defined based on experience from working with similar coronagraph optical designs. We later describe the different ways the user is able to allocate errors in the budget.

The last task consists of importing the C-Matrices for the dynamic models. For this particular task there is a group of macros which have been programmed to clear the worksheets containing dynamic error calculations first, look at the optical information in the Optics worksheet and enter the appropriate labels in the columns and table headers, import the data for each worksheet, post process the data, and calculate the parameters A_{rms} the Zernike RMS amplitude, and D_x the beam walk given the allocated motions of the optics in the Allocations worksheet. Then the code inputs the equations for contrast from aberrations and beam walk into the Budget worksheet, and references these parameters to calculate contrast for each error term in the error budget.

Allocation Process

The allocation process begins with the CPEB tool allocating default values for each error term for which engineering judgment and experience is used to distribute the error throughout the subsystems. Individual allocations can be changed by the user manually by entering the values in the Allocations worksheet cells directly. For example, if we want to know what the effect of a 10 nrad x-rotation of the secondary mirror for the error term Thermal Beam Walk Controlled by Secondary Mirror is, we go to the Allocations worksheet and enter this value into the cell for Secondary column and Rx under the appropriate error term. Another way a user may change the allocations for any error terms is via a control box which contains a group of controls that allow the user to choose default values for the allocations or to increment the values for secondary mirror or all the other optics where translations and rotations are incremented separately. For example, the user may choose to switch from default values to increment values, and increase or decrease the rotations or translations of the secondary mirror or the rest of the elements as shown by Figure 5.

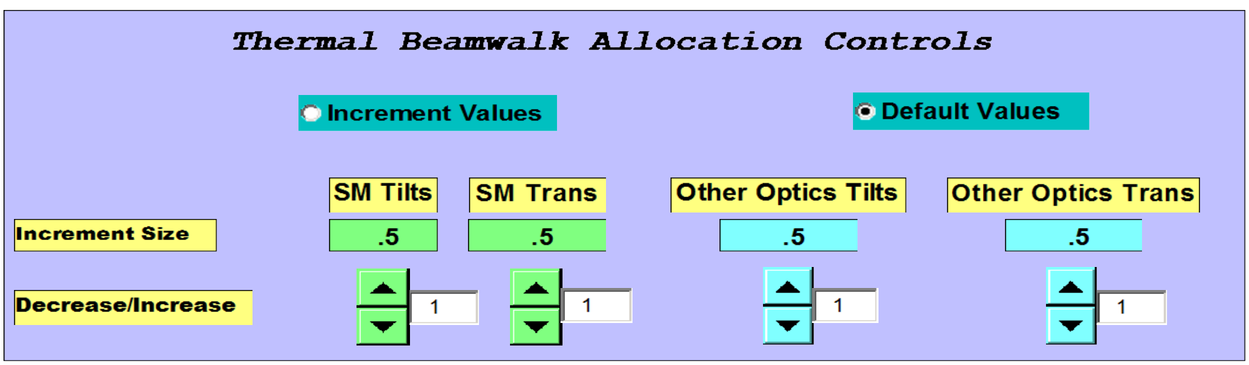

Figure 5. Control box for Thermal Beam Walk Allocation Controls Term. User chooses to use default values or increment the values for secondary mirror or all other optics. Translations and rotations are separated so they can be changed separately.

4. Example and Results

Now we present an example of the error budget tool for a telescope and coronagraph design based on the PECO mission concept study (Guyon, 2009). For this design a Code V prescription was converted to a MACOS prescription using the conversion stage process, and a set of sensitivity matrices and optical information files were computed using the c-matrix stage process as discussed earlier. We placed those file into a directory, specified the location of the directory in the Allocations worksheet, and automatically generated a performance error budget by clicking on the Master Control program in the CPEB Excel workbook. The error budget partitions budget among the dynamic and the static contrast. The static contrast has been allocated a default value of 1e-10 contrast while we require that the standard deviation of contrast remains stable within 2e-11 to achieve a SNR of 5 on a planet 1e-10 times fainter than the parent star. Table 2 show a summary of the error terms in the error budget. The most important error terms are the thermal terms highlighted in red. These are combined with the static allocation to give the contrast stability highlighted in red (Table 3).

Table 2. PECO Error Summary Table. The table shows a summary of the error terms in the error budget including beam walk, aberrations, pointing, and static.

Error Summary Table			
	2 λ/D	4 λ/D	8 λ/D
Jitter Structural Deformation Beamwalk Medium	6.39E-13	9.04E-13	1.10E-12
Jitter Structural Deformation Beamwalk Fast	2.01E-13	2.30E-13	2.32E-13
Jitter Bending of Optic	1.10E-11	4.54E-13	2.60E-13
Jitter Structural Deformation Aberrations Medium	1.61E-15	4.59E-17	8.68E-17
Jitter Structural Deformation Aberrations Fast	1.61E-15	4.57E-17	8.60E-17
Thermal Structural Deformation Beamwalk Slow	4.33E-13	6.86E-13	9.05E-13
Thermal Bending of Optic	3.89E-13	1.22E-14	1.11E-14
Thermal Structural Deformation Aberrations Slow	2.77E-15	7.99E-17	1.88E-16
Thermal Rigidbody Pointing Slow	1.27E-13	3.86E-13	6.57E-13
Jitter Rigidbody Pointing Medium	3.71E-12	3.68E-12	3.07E-12
Jitter Rigidbody Pointing Fast	9.26E-13	9.21E-13	7.69E-13
Static	1.00E-10	1.00E-10	1.00E-10
Background Error	1.50E-11	1.50E-11	1.50E-11

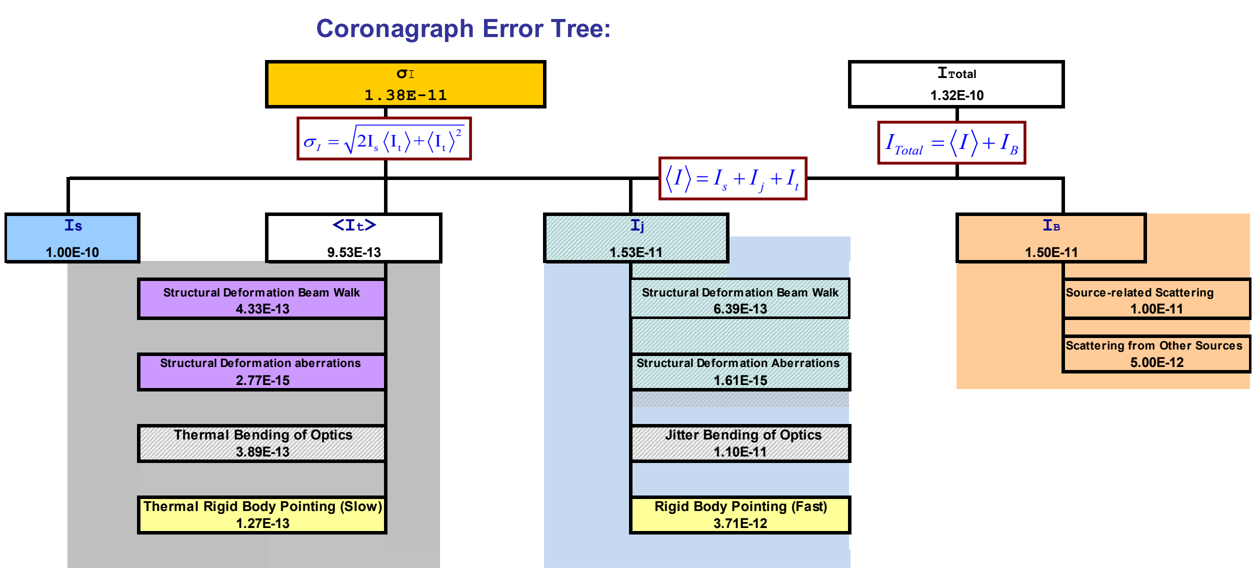

Figure 6. Graphical Error Budget Representation, Error Tree, for PECO 2. Shows high level error terms, and the rolled up dynamic error components.

Table 3. Top level errors table. The table shows the mean contrast, standard deviation of contrast (static and thermal), thermal contrast, jitter contrast, and static contrast. Highlighted is the standard deviation of contrast with is the most important term in the error budget.

Top Level Errors								
						2 λ/D	4 λ/D	8 λ/D
Final Contrast =		WFE +Background				1.32E-10	1.22E-10	1.22E-10
$\sigma_I = \sqrt{2I_s\langle I_t\rangle + \langle I_t\rangle^2}$						1.38E-11	1.48E-11	1.78E-11
$\langle I_t \rangle$						9.53E-13	1.08E-12	1.57E-12
I_j						1.53E-11	1.74E-12	2.02E-12
I_s						1.00E-10	1.00E-10	1.00E-10

Particular Study Example

We can look at the Thermal Structural Deformation Beam Walk Compensated by Secondary mirror as an example to determine which error allocations, and which elements contribute the most to this term. To do this we must look at the individual error terms under Thermal Structural Deformation Beam Walk Compensated by Secondary Mirror, see Table 4. This determines that the total beam walk on primary and secondary mirrors contribute the most to this error term. Now to determine the source of this error we can go to the Allocations worksheet under Thermal Structural Deformation Beam Walk, change the allocations for each optic and observe how it affects the beam walk on both primary and secondary mirrors. By doing this we determined that the wide dichroic, pupil relay, power optic, and hyperboloid optics contribute to much of this error, and that we are less sensitive to the motions of the primary and secondary mirrors for this particular term; however, secondary mirror motions do contribute to the Thermal Aberrations term. Similar studies are performed to defined requirements for all subsystems.

Table 4. Leakage due to Thermal Structural Deformation Beam Walk compensated by secondary mirror. The Dx column is the total beam walk that occurs on the surface of the optic when elements move. The other columns show the contrast contribution by each element.

	Dx	Contrast (2λ/D)	Contrast (4λ/D)	Contrast (8λ/D)
Primary	7.73E-07	1.38E-13	4.16E-13	7.10E-13
Secondary	7.73E-08	2.44E-13	1.88E-13	1.04E-13
OAP1	7.05E-08	1.88E-15	1.44E-15	7.96E-16
OAP2	2.19E-08	7.67E-16	4.92E-16	2.63E-16
Widedichroic	3.20E-08	1.16E-15	7.48E-16	4.01E-16
PupilRelay(OAPA)	4.30E-08	2.96E-15	1.90E-15	1.02E-15
OAHyperboloid1	2.03E-08	1.48E-14	1.08E-14	5.92E-15
OAHyperboloid2	1.02E-08	3.80E-15	2.77E-15	1.51E-15
PupilRelay(OAPB)	9.41E-09	1.42E-16	9.12E-17	4.88E-17
DM1	5.66E-09	1.40E-14	3.44E-14	4.39E-14
DM2/FSM	5.20E-09	1.18E-14	2.90E-14	3.70E-14
PIAAM1	5.71E-09	5.19E-17	3.33E-17	1.78E-17
PIAAM2	2.83E-09	1.80E-17	1.15E-17	6.15E-18
Apodizer	2.14E-09	1.04E-17	6.65E-18	3.56E-18
OAP5	2.73E-09	1.67E-17	1.07E-17	5.72E-18

7. CONCLUDING REMARKS

We have utilized this tool with several different coronagraph optical prescriptions. The end-to-end time to compute a CPEB is approximately one day or less; this depends mostly on the optical prescription conversion issues mostly originating from Zemax or Code V nuances. The tool makes it straightforward to perform trade studies such as investigating the effect of optical PSD's, motion allocations, or different coronagraph masks.

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