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

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San Diego, August 05, 2009

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Overview

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- Contrast
- Intro to Error Budget
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  - Budget structure
  - Models
  - Control System
- Budget Process
- Budget Tool
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Error Budget Approach

- Create a tool with the capability to generate coronagraph performance error budgets automatically with the ability to:
  - compare different telescope designs and coronagraphs in one tool
  - predict the level and stability of scattered light in the image plane at different radial positions e.g. 3 lambda/D, 4 lambda/D…
- Focus on Dynamics (thermal, jitter)
  - Virtually all engineering requirements are tied to dynamics
    - e.g. stiffness, thermal sensitivities, rigid body pointing….
- Utilize linear models to avoid unnecessary diffraction modeling
  - Linear approach (sensitivity matrices) makes scaling and modification straightforward.

Simplifying Assumptions

- A "set and forget" wave front control approach, the wave front is calibrated at the beginning of an observation, and it is required to stay stable during the observation, this leads to Static Wave Front Budget
- We are in observation mode where the observatory is pointed to a target star, we allow the dynamics to settle, and the system to reach thermal equilibrium, the wavefront is set, and the target is observed
- Near field diffraction effects are ignored because it is assumed DM can correct much of this
- Background speckles look like planets, there is no chromatic differentiation
- Errors are uncorrelated thus error contributions add linearly
- Dynamic models are based on linear models to make scaling and modifying simple
- A set of default PSD parameters defined in the PCEB defined the default classes of optics: the primary, secondary, deformable, flats, off axis parabolas, super flats, and super off axis parabola mirrors
  - Used for beam-walk calculations

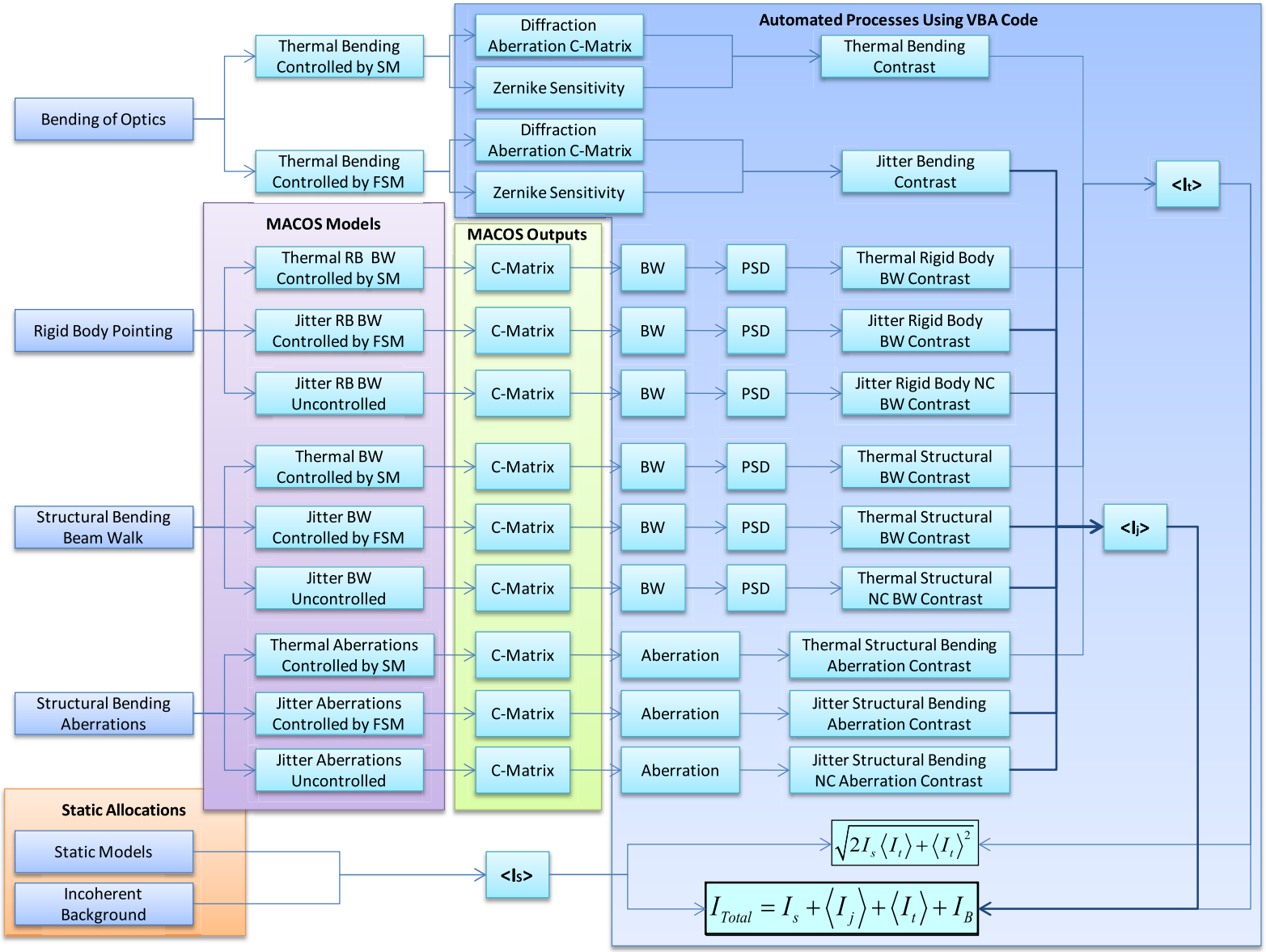
Contrast

- The metric used in the error budget is contrast
- Contrast=Intensity
- Contrast from Dynamics and Static (static is allocated)
  - Errors are uncorrelated so expected value of Total Contrast = sum of individual contrast contributions, the mean contrast is given by $\langle I \rangle = I_s + I_B + \langle I_j \rangle + \langle I_t \rangle$
- The standard deviation of these errors is given by $\sigma_I = \sqrt{2 I_s \langle I_t \rangle + \langle I_t \rangle^2}$

Dynamic Terms

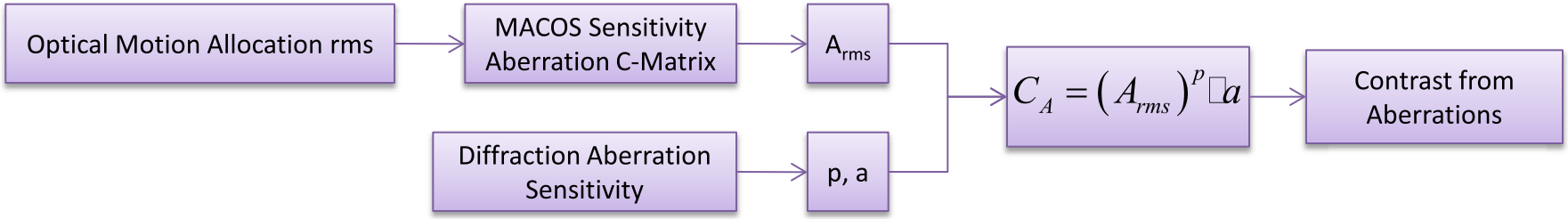
- Thermal, and Jitter:
  - rigid body motions of the elements
    - Beam walk
    - aberrations
  - bending of the surface of the optics
    - aberrations
- Rigid body motion of the instrument
  - Line-of-sight pointing errors

Error Budget Structure

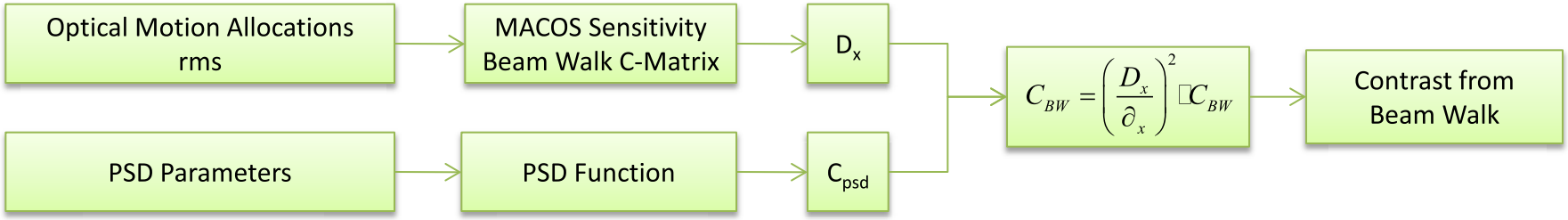


Models and Contrast Formulas

- Aberration Models:
  - A Fraunhofer pupil-to-image plane model known as the "diffraction aberration sensitivity" model, contrast as a function of wavefront components for ideal coronagraph designs
  - A MACOS based aberration sensitivity model known as the "Zernike sensitivity matrix" model, determines Zernike mode amplitudes when an optic moves 6 DOF

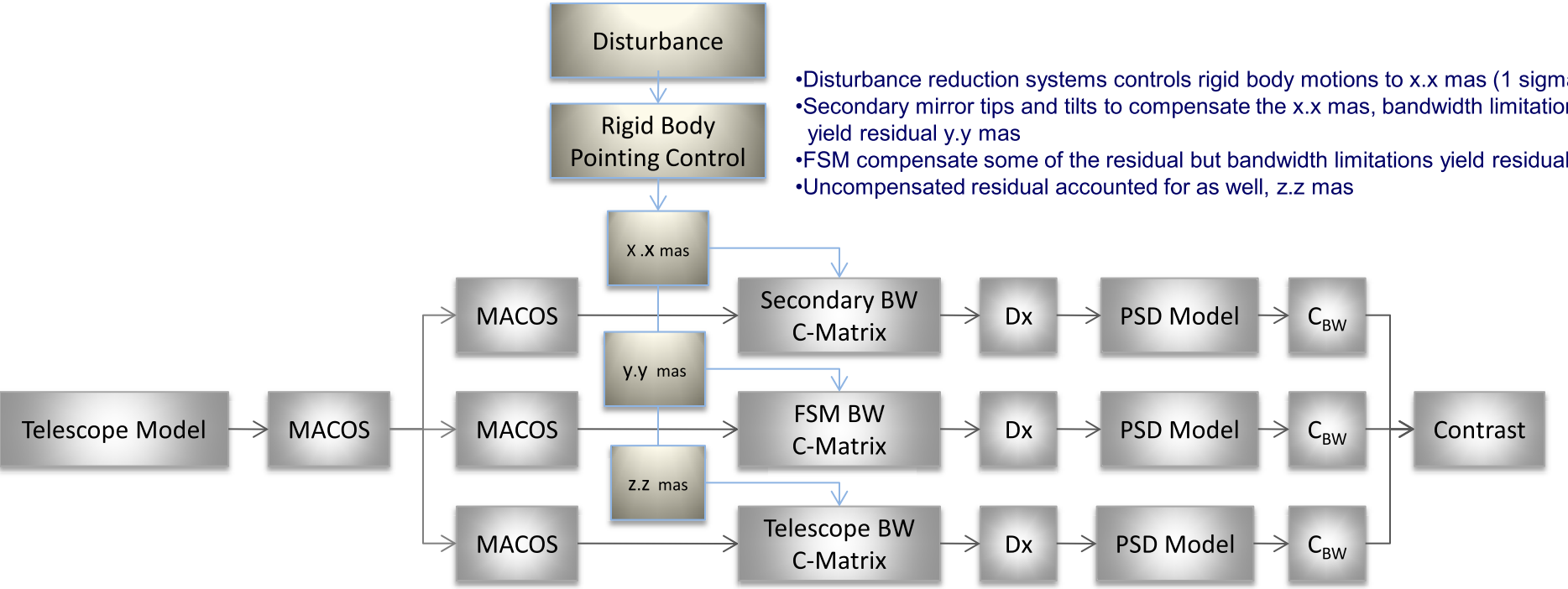


- Beam Walk Models:
  - Beam walk sensitivity matrix model from MACOS, determines δx or beam walk when optics move 6 DOF
  - Contrast coefficient (C_{PSD}) from PSD (beam walk described by Charley Noecker in detail)

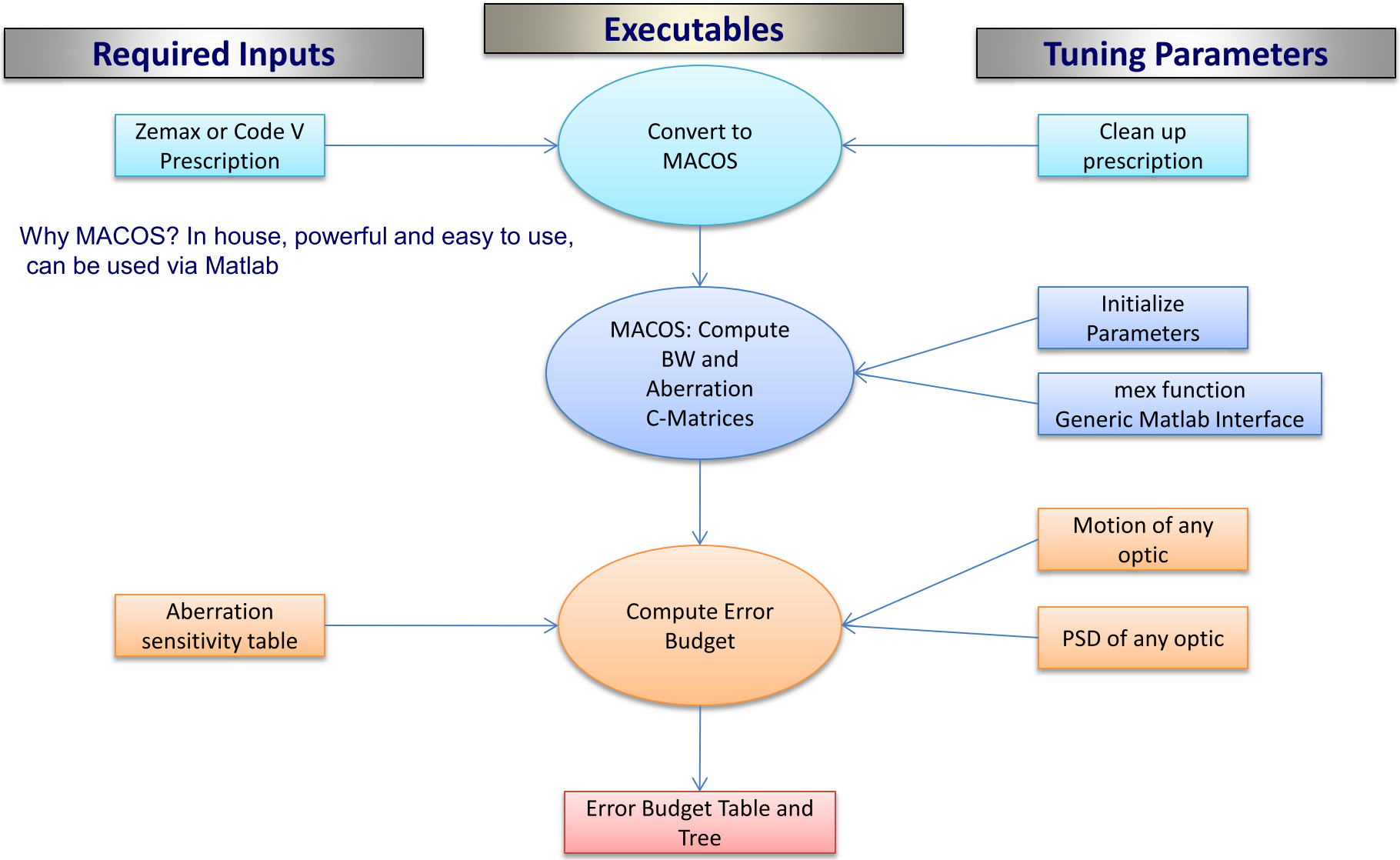


Control System

- A multi-tiered pointing control system
  - The secondary mirror compensates low frequency pointing errors
  - FSM compensates high frequency pointing errors
  - Some high frequency errors which can not be controlled are accounted for in error budget
- the error budget does not make assumptions about bandwidth but assigns pointing residual to sub systems



Process to Create an Error Budget



The Budget Tool

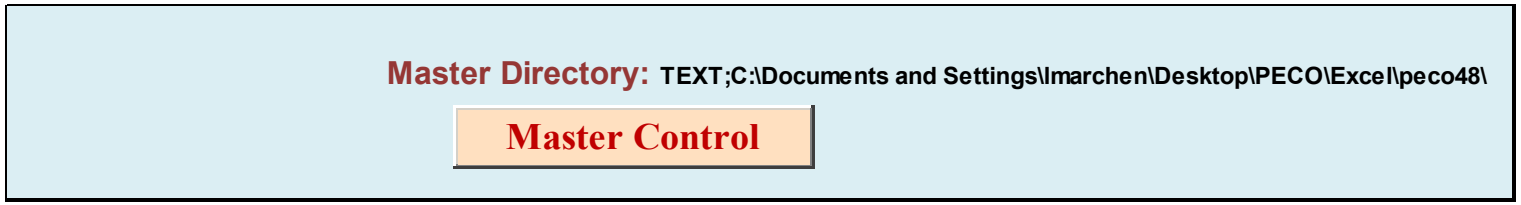
- Error Budget tool was developed on Excel 2007, tool uses:
  - Standard Excel 2007 applications
  - Visual Basic for Applications (VBA) programming code
  - Form and ActiveX controls
- The Budget is comprised of several Excel 2007 worksheets, includes:
  - Optics: contains the default PSD parameters, optical design information, PSD parameters for all optics in prescription, and beam walk contrast coefficient
  - Allocations: contains allowable error for each error term, and contains the master control used to exercise the error budget tool
  - Budget: contains a summary of the error terms, and rolls up individual errors into high level error terms
  - Error tree: contains a graphical representation of the Budget worksheet
  - ZernikeCoeff: contains diffraction aberration sensitivity data
  - Dynamic Worksheets: contains a set of worksheets where the calculations for the dynamic terms are performed

Automation

- programmed scripts or macros with the required Excel applications to generate an entire Error Budget
- Used logical functions that allow programs to make decisions and perform tasks based on optical design information (standard excel applications, and VBA code)
- the most complicated equations were converted to user defined functions using VBA code, easy to enter, and saves time
- Controls were programmed to call macros or to perform an event, this is how the Error Budget tool is exercised

Exercising the Error Budget Tool

- To exercise the error budget tool:
  - C-Matrices, and optical design information are required by the macros when running (data from c-matrix process)
  - User must define directory containing c-matrices and optical data prior to exercising the tool
  - To exercise the tool the user must click on the master control, this starts the sequence of commands, and computes the error budget



Automatic Steps Performed via VBA Code

- When the tool is exercised the following steps are automatically performed in sequence:
  1. Optics worksheet cells are cleared, optical data including beam diameter, conic constant, and element names data are imported from optical data files. PSD parameters table is populated based on the imported optical information, and contrast coefficients for each optic are computed.
  2. Budget worksheet cell ranges for each error term are set then cleared, and new optical information is entered for each error term
  3. Dynamic worksheets are computed one at a time for each error term, general example:
     1. The dynamic worksheet is cleared, including table headers and data
     2. VBA code reads optical data from Optics worksheet, determines the number of columns and rows to be populated by the sensitivity data, set the range to be populated by data
     3. Sensitivity data is imported form data files in master directory, data is post-processed, converted from text to number, and numbers are formatted
     4. Column and row labels are entered and formatted, locations determined by code according to optical information in Optics worksheet
     5. Code identifies the error term, and enters the error allocations found in the Allocations worksheet, computes Dx or Arms
     6. Code inputs the corresponding contrast function in the Budget worksheet, and used 5 as an input to compute the contrast contribution
     7. The individual errors are summed and reported in the Error Tree worksheet graphic

Excel Tool Demonstration

- Goal
  - demonstrate tool in real time for a particular optical design
  - Look at results in budget worksheet
  - Look at allocated errors in the Allocations worksheet
  - Determine some of the main error drivers

Move to Excel Tool to Perform Real Time Demonstration