A Model-Based Systems Engineering Application for Radiometric Measurement Uncertainty

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- Introduction
- RBI Measurement Uncertainty Model
  - The Systems Modeling Language (SysML) Model
  - Potential Benefit – Design Trade Study
- Conclusion and Future Work

Introduction

Radiation Budget Instrument (RBI)

- A NASA funded satellite-based radiometer being developed for flight on the Joint Polar Satellite System (JPSS) -2 Mission for 2021 launch. A follow-on to the Clouds and the Earth's Radiant Energy System (CERES) instrument, to continue long-term data record for understanding of climate change.

- One of the RBI's performance requirement, radiometric uncertainty of the Earth scene measurement, is the focus of this study.

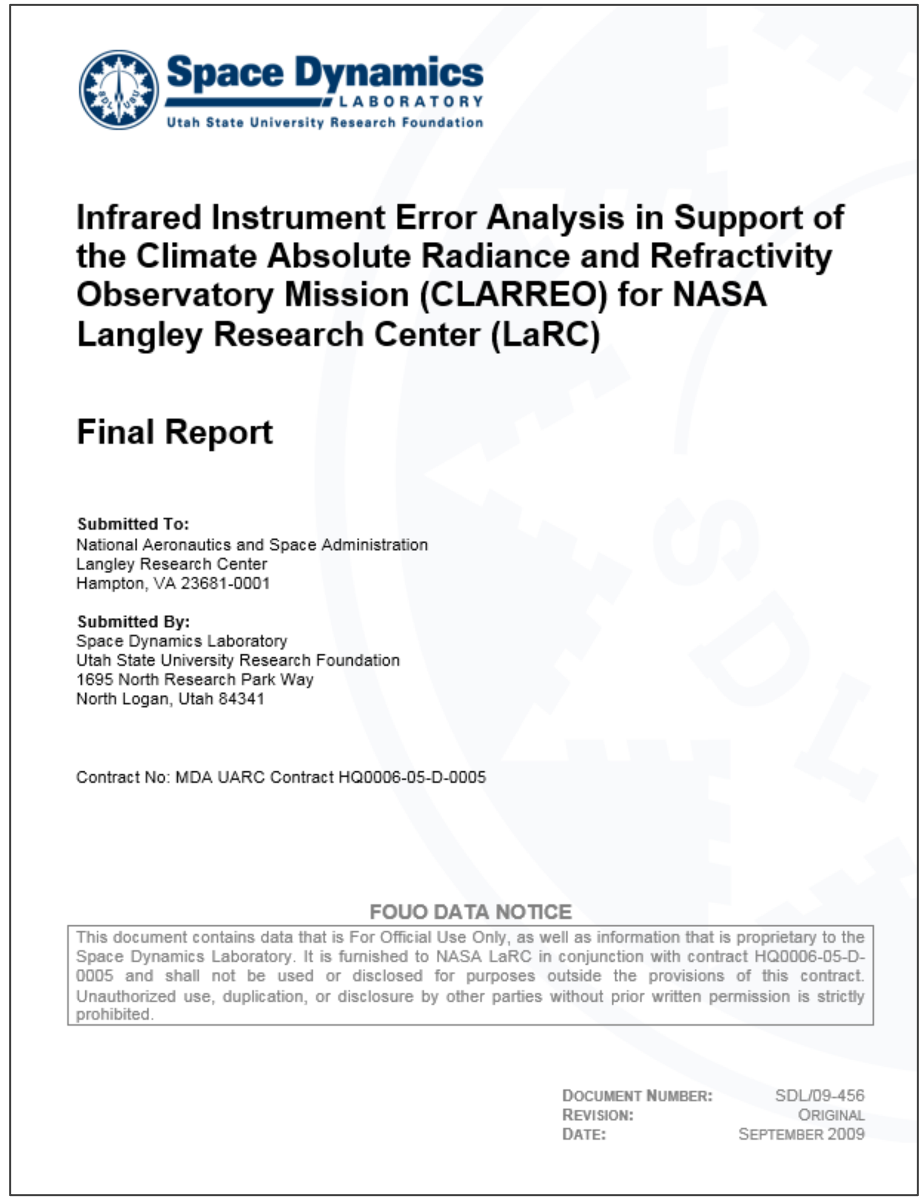
- Radiometric uncertainty model (Eq. 2) is obtained through the Law of Propagation of Uncertainty of a physics-based measurement equation (Eq. 1).

$$L_{ht} = \underbrace{\left(\frac{S_{ht}-S_{lt}}{S_{hc}-S_{lc}}\right)}_{S}(L_{hc} - L_{lc}) + L_{lt} + G \qquad (1)$$

$$U^2_{L_{ht}} = (L_{hc} - L_{lc})^2 U^2_S + S^2 U^2_{L_{hc}} + (-S)^2 U^2_{L_{lc}} + U^2_{L_{lt}} + U^2_G \qquad (2)$$

Example of Typical Uncertainty Analysis (1 of 2)

- SDL provided a physics-based measurement equation.
- The measurement uncertainty was based on the law of propagation of uncertainty.



Space Dynamics LABORATORY
Utah State University Research Foundation

Infrared Instrument Error Analysis in Support of the Climate Absolute Radiance and Refractivity Observatory Mission (CLARREO) for NASA Langley Research Center (LaRC)

Final Report

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Langley Research Center
Hampton, VA 23681-0001

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Utah State University Research Foundation
1695 North Research Park Way
North Logan, Utah 84341

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REVISION:	ORIGINAL
DATE:	SEPTEMBER 2009

Example of Typical Uncertainty Analysis (2 of 2)

- Along with a final report, SDL provided a spreadsheet model to compute the uncertainty.

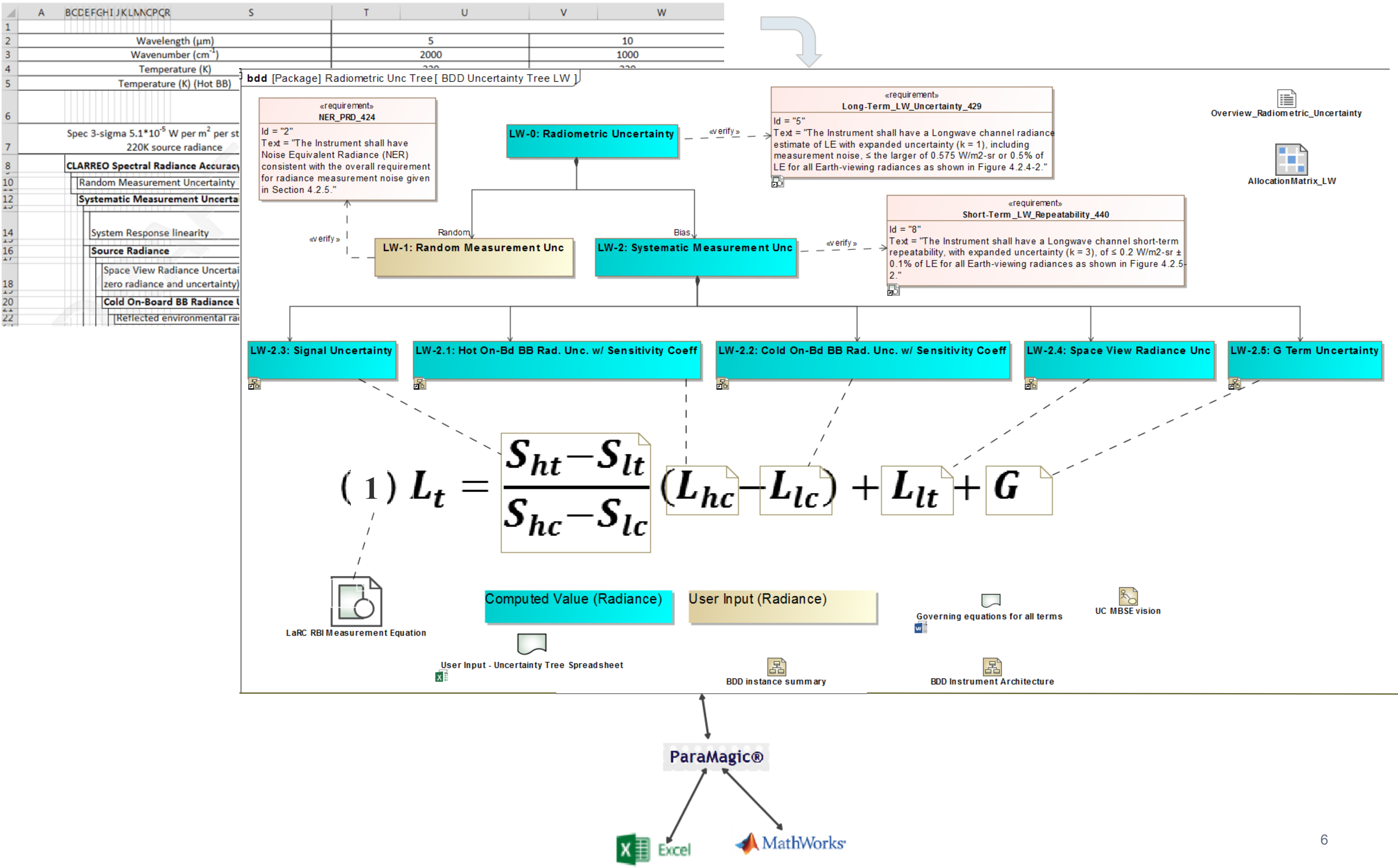
	A	BCDEFGHIJKLMNOPQR / S	T	U	V	W
1						
2		Wavelength (μm)	5		10	
3		Wavenumber (cm^{-1})	2000		1000	
4		Temperature (K)	220		220	
5		Temperature (K) (Hot BB)	300		300	
6			Budget Temp (mK)	Radiance (W per m^2 per str per wn)	Budget Temp (mK)	Radiance (W per m^2 per str per wn)
7		Spec 3-sigma $5.1*10^{-5}$ W per m^2 per str per cm^{-1} 220K source radiance				
8		CLARREO Spectral Radiance Accuracy				
10		Random Measurement Uncertainty				
12		Systematic Measurement Uncertainty				
14		System Response linearity				
16		Source Radiance				
18		Space View Radiance Uncertainty (assumed to be zero radiance and uncertainty)				
20		Cold On-Board BB Radiance Uncertainty				
22		Reflected environmental radiance				

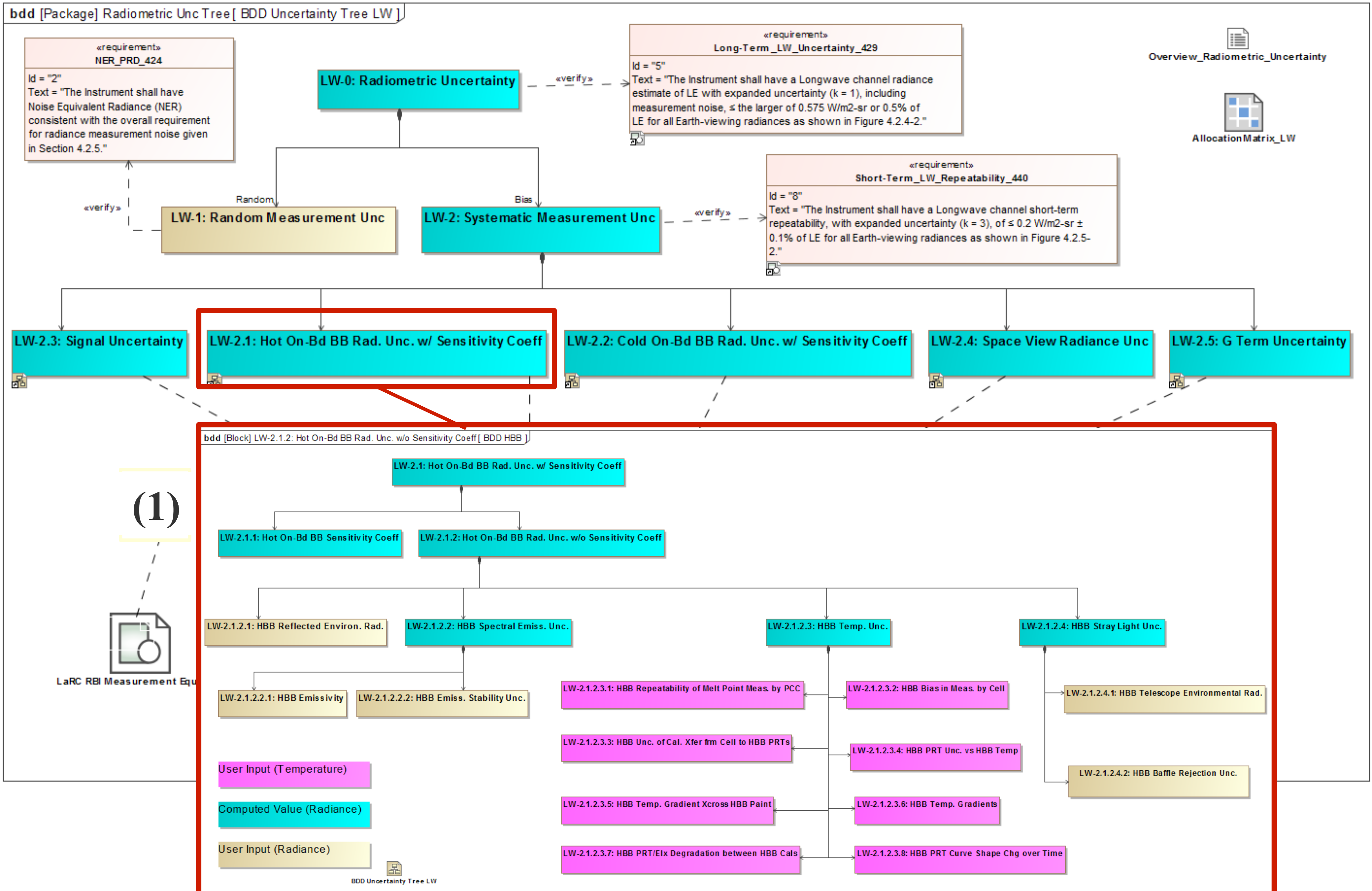
=(U14^2+U16^2+U76^2+U78^2+U84^2+U86^2+U88^2+U96^2+U80^2+U82^2+U90^2+U92^2+U94^2+U102^2+U100^2+U104^2+U106^2+U108^2+U110^2)^0.5

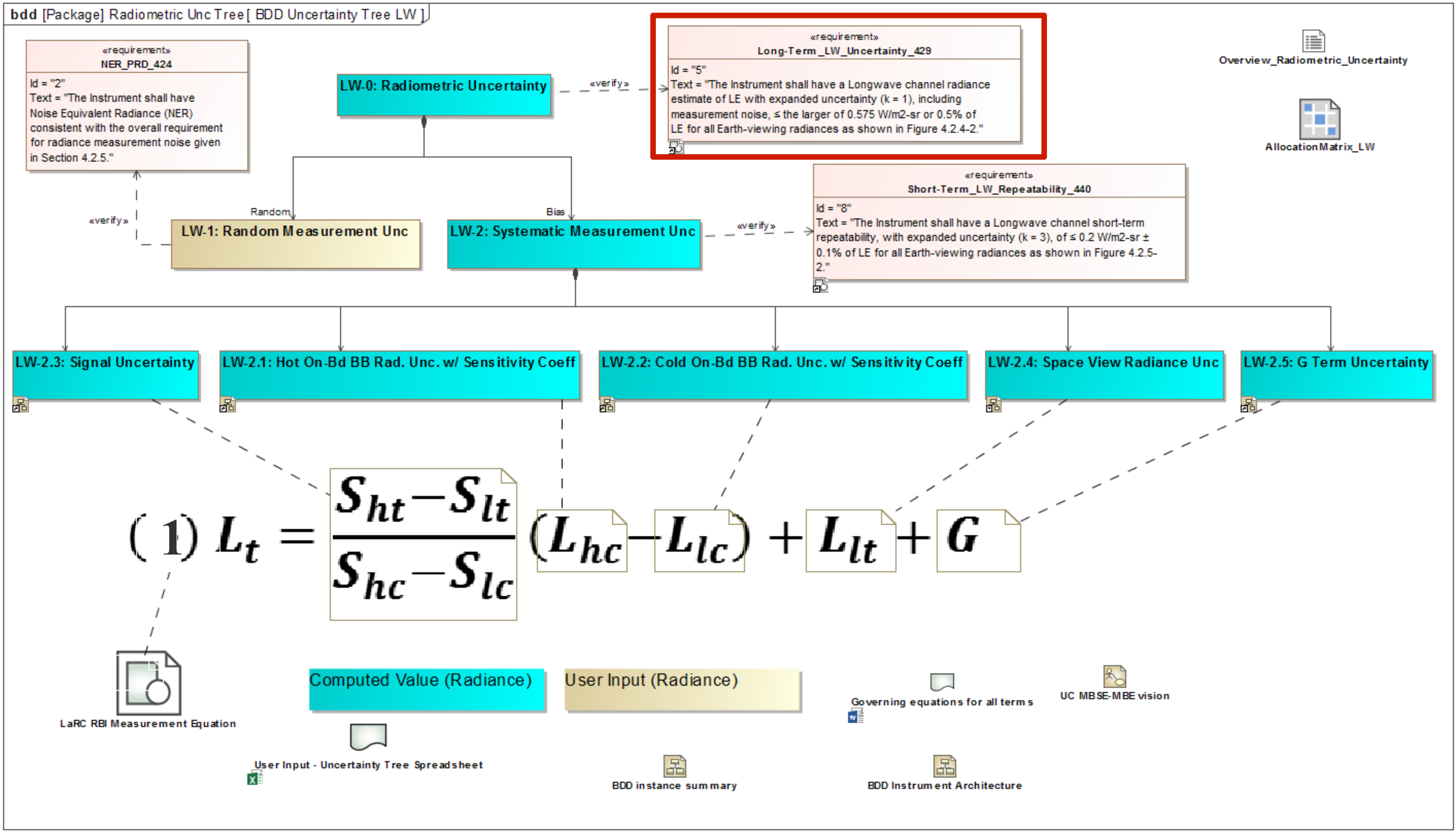
- Difficulty in understanding the **computational structure hierarchy**

National Aeronautics and Space Administration

Uncertainty Model Transformation




bdd [Package] Radiometric Unc Tree [BDD Uncertainty Tree LW]
«requirement» NER_PRD_424
Id = "2"
Text = "The Instrument shall have Noise Equivalent Radiance (NER) consistent with the overall requirement for radiance measurement noise given in Section 4.2.5."
LW-0: Radiometric Uncertainty
«verify»
«requirement» Long-Term_LW_Uncertainty_429
Id = "5"
Text = "The Instrument shall have a Longwave channel radiance estimate of LE with expanded uncertainty (k = 1), including measurement noise, ≤ the larger of 0.575 W/m2-sr or 0.5% of LE for all Earth-viewing radiances as shown in Figure 4.2.4-2."
Overview_Radiometric_Uncertainty
AllocationMatrix_LW
Random
Bias
«verify»
LW-1: Random Measurement Unc
LW-2: Systematic Measurement Unc
«verify»
«requirement» Short-Term_LW_Repeatability_440
Id = "8"
Text = "The Instrument shall have a Longwave channel short-term repeatability, with expanded uncertainty (k = 3), of ≤ 0.2 W/m2-sr ± 0.1% of LE for all Earth-viewing radiances as shown in Figure 4.2.5-2."
LW-2.3: Signal Uncertainty
LW-2.1: Hot On-Bd BB Rad. Unc. w/ Sensitivity Coeff
LW-2.2: Cold On-Bd BB Rad. Unc. w/ Sensitivity Coeff
LW-2.4: Space View Radiance Unc
LW-2.5: G Term Uncertainty
(1)
LaRC RBI Measurement Equ
bdd [Block] LW-2.1.2: Hot On-Bd BB Rad. Unc. w/o Sensitivity Coeff [BDD HBB]
LW-2.1: Hot On-Bd BB Rad. Unc. w/ Sensitivity Coeff
LW-2.1.1: Hot On-Bd BB Sensitivity Coeff
LW-2.1.2: Hot On-Bd BB Rad. Unc. w/o Sensitivity Coeff
LW-2.1.2.1: HBB Reflected Environ. Rad.
LW-2.1.2.2: HBB Spectral Emiss. Unc.
LW-2.1.2.3: HBB Temp. Unc.
LW-2.1.2.4: HBB Stray Light Unc.
LW-2.1.2.2.1: HBB Emissivity
LW-2.1.2.2.2: HBB Emiss. Stability Unc.
LW-2.1.2.3.1: HBB Repeatability of Melt Point Meas. by PCC
LW-2.1.2.3.2: HBB Bias in Meas. by Cell
LW-2.1.2.3.3: HBB Unc. of Cal. Xfer frm Cell to HBB PRTs
LW-2.1.2.3.4: HBB PRT Unc. vs HBB Temp
LW-2.1.2.3.5: HBB Temp. Gradient Xcross HBB Paint
LW-2.1.2.3.6: HBB Temp. Gradients
LW-2.1.2.3.7: HBB PRT/Elx Degradation between HBB Cals
LW-2.1.2.3.8: HBB PRT Curve Shape Chg over Time
LW-2.1.2.4.1: HBB Telescope Environmental Rad.
LW-2.1.2.4.2: HBB Baffle Rejection Unc.
User Input (Temperature)
Computed Value (Radiance)
User Input (Radiance)
BDD Uncertainty Tree LW


bdd [Package] Radiometric Unc Tree [BDD Uncertainty Tree LW]
«requirement»
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Id = "2"
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«requirement»
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Bias
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LW-1: Random Measurement Unc
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LW-2.3: Signal Uncertainty
LW-2.1: Hot On-Bd BB Rad. Unc. w/ Sensitivity Coeff
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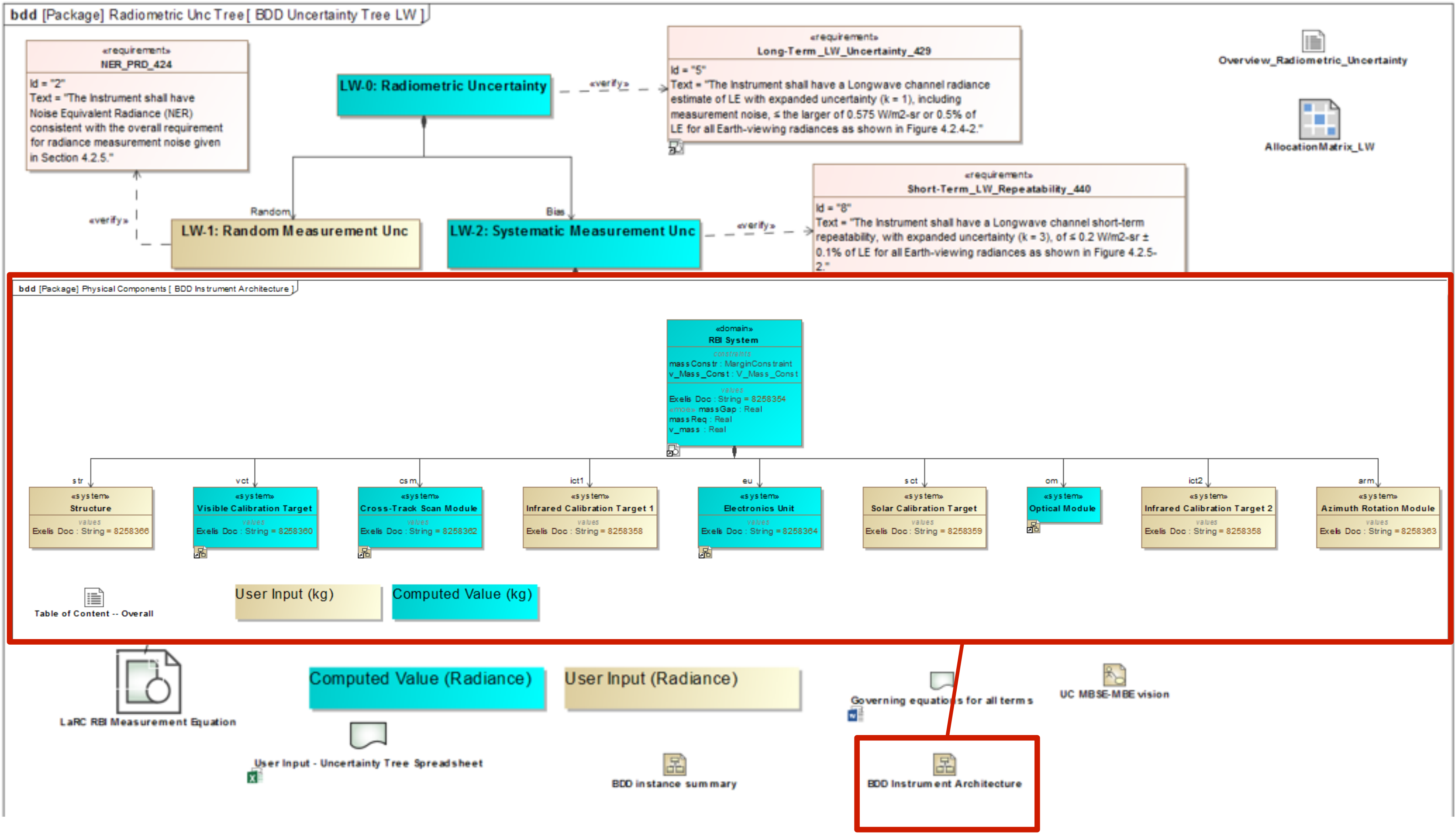
LW-2.5: G Term Uncertainty
(1) $L_t = \frac{S_{ht} - S_{lt}}{S_{hc} - S_{lc}} (L_{hc} - L_{lc}) + L_{lt} + G$
LaRC RBI Measurement Equation
Computed Value (Radiance)
User Input (Radiance)
Governing equations for all terms
UC MBSE-MBE vision
User Input - Uncertainty Tree Spreadsheet
BDD instance summary
BDD Instrument Architecture



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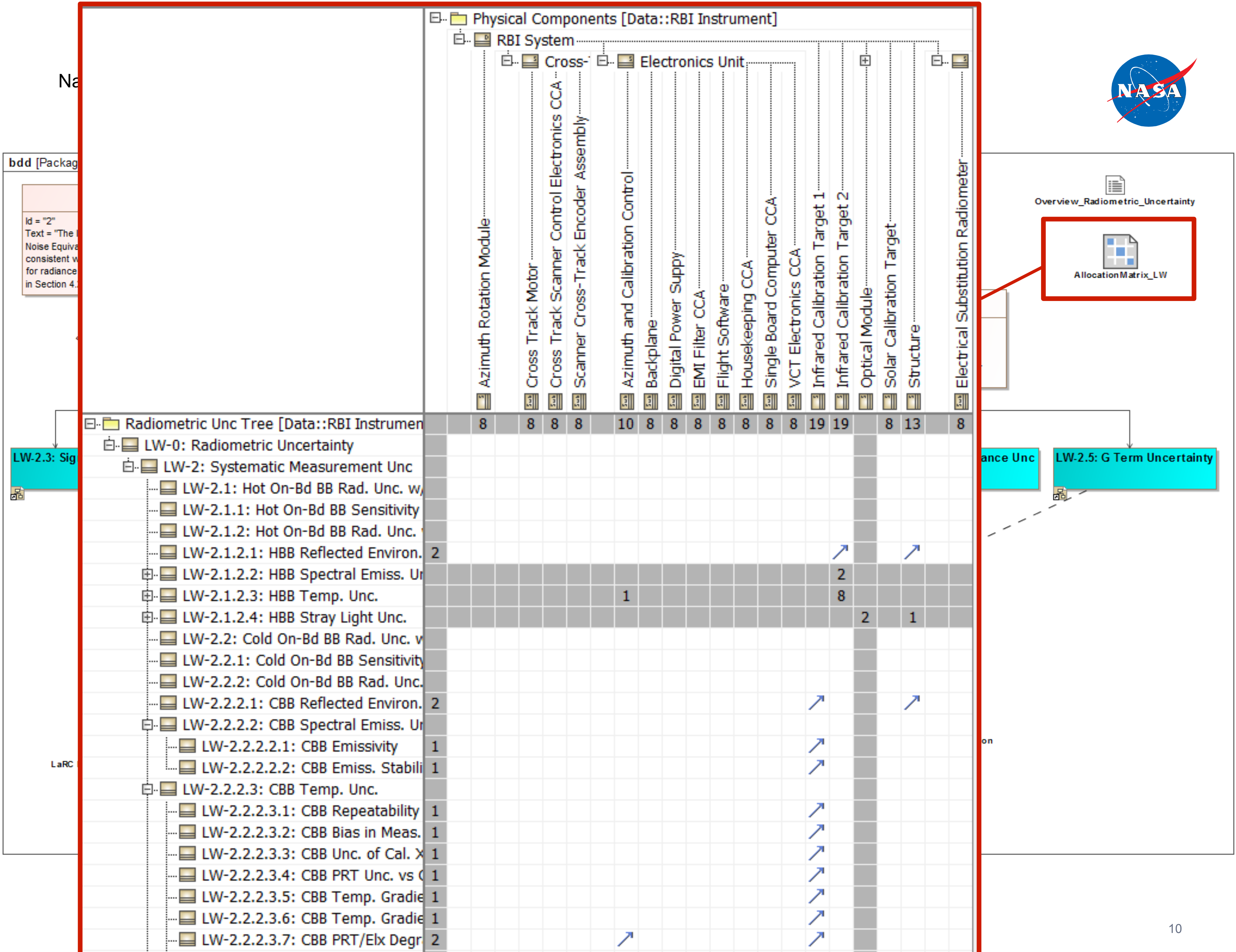
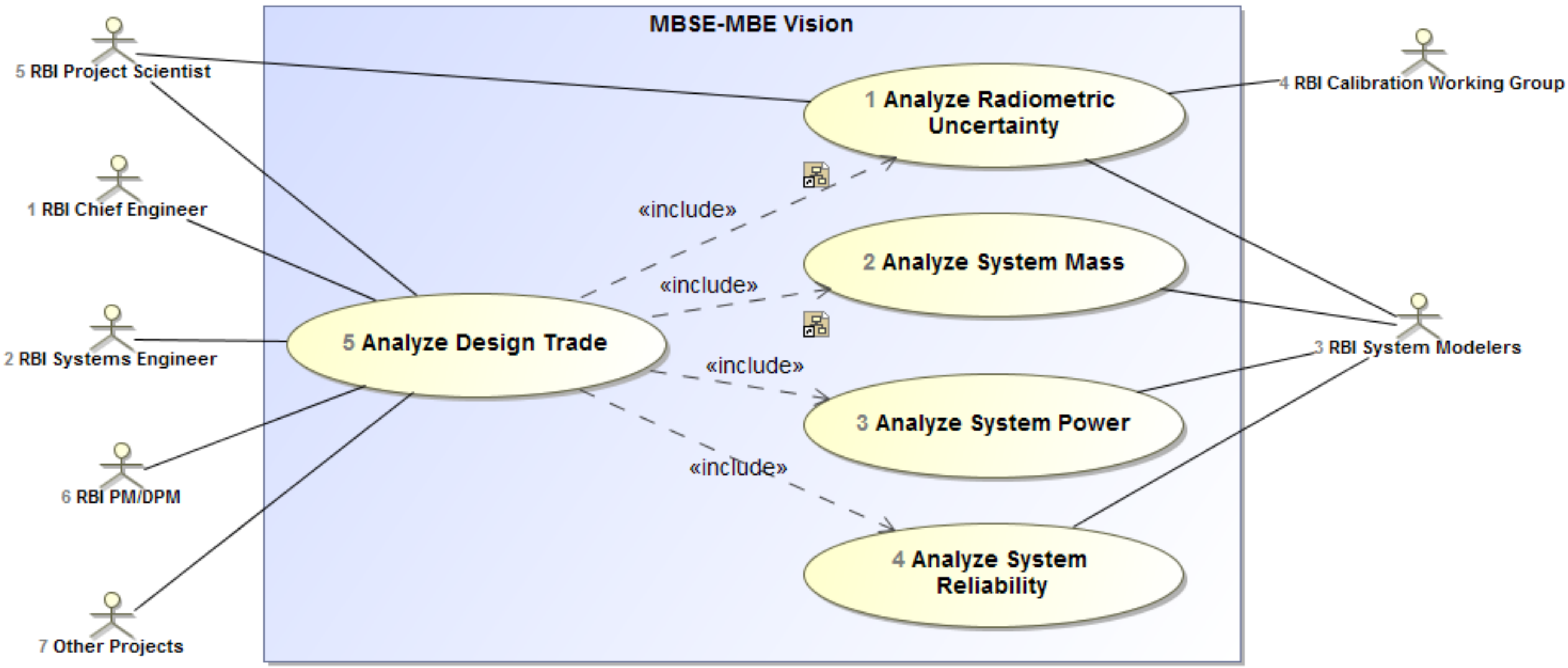
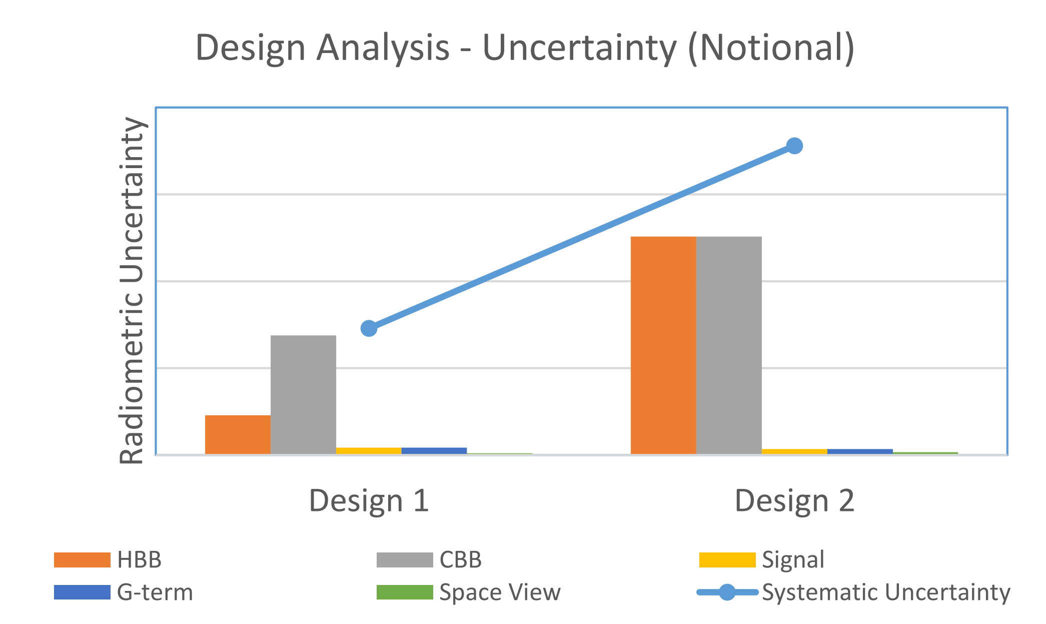
Random
Bias
«verify»
LW-1: Random Measurement Unc
LW-2: Systematic Measurement Unc
«verify»
bdd [Package] Physical Components [BDD Instrument Architecture]
«domain»
RBI System
constraints
massConstr : MarginConstraint
v_Mass_Const : V_Mass_Const
values
Exelis Doc : String = 8258354
«moe» massGap : Real
massReq : Real
v_mass : Real
str
«system»
Structure
values
Exelis Doc : String = 8258366
vct
«system»
Visible Calibration Target
values
Exelis Doc : String = 8258360
csm
«system»
Cross-Track Scan Module
values
Exelis Doc : String = 8258362
ict1
«system»
Infrared Calibration Target 1
values
Exelis Doc : String = 8258358
eu
«system»
Electronics Unit
values
Exelis Doc : String = 8258364
sct
«system»
Solar Calibration Target
values
Exelis Doc : String = 8258359
om
«system»
Optical Module
ict2
«system»
Infrared Calibration Target 2
values
Exelis Doc : String = 8258358
arm
«system»
Azimuth Rotation Module
values
Exelis Doc : String = 8258363
Table of Content -- Overall
User Input (kg)
Computed Value (kg)
LaRC RBI Measurement Equation
Computed Value (Radiance)
User Input (Radiance)
Governing equations for all terms
UC MBSE-MBE vision
User Input - Uncertainty Tree Spreadsheet
BDD instance summary
BDD Instrument Architecture

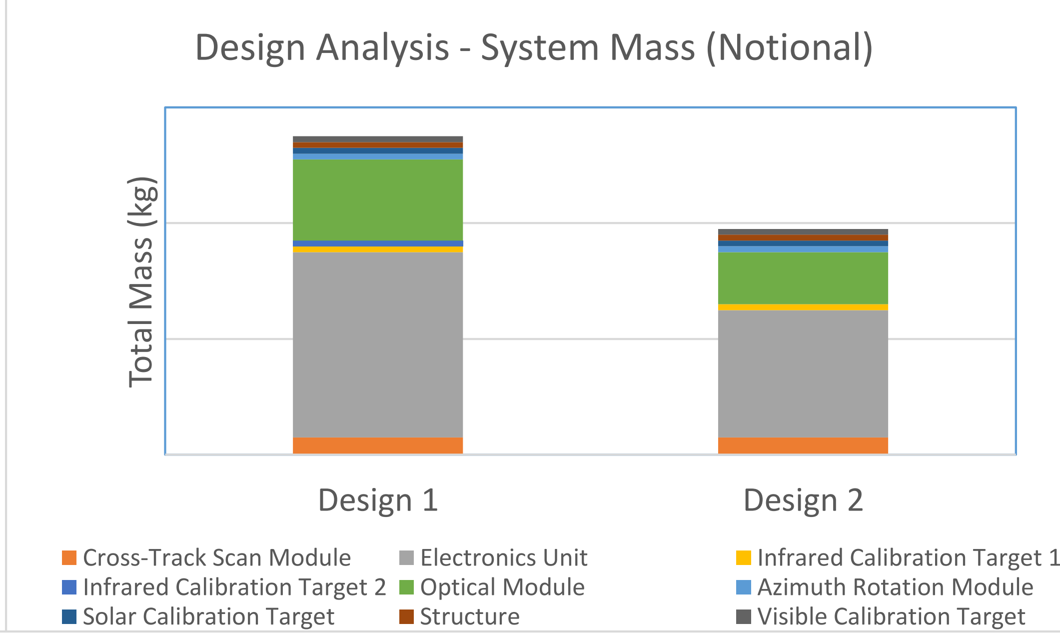

Physical Components [Data::RBI Instrument]
RBI System
Cross-
Electronics Unit
Azimuth Rotation Module
Cross Track Motor
Cross Track Scanner Control Electronics CCA
Scanner Cross-Track Encoder Assembly
Azimuth and Calibration Control
Backplane
Digital Power Suppy
EMI Filter CCA
Flight Software
Housekeeping CCA
Single Board Computer CCA
VCT Electronics CCA
Infrared Calibration Target 1
Infrared Calibration Target 2
Optical Module
Solar Calibration Target
Structure
Electrical Substitution Radiometer
Radiometric Unc Tree [Data::RBI Instrumen
LW-0: Radiometric Uncertainty
LW-2: Systematic Measurement Unc
LW-2.1: Hot On-Bd BB Rad. Unc. w/
LW-2.1.1: Hot On-Bd BB Sensitivity
LW-2.1.2: Hot On-Bd BB Rad. Unc.
LW-2.1.2.1: HBB Reflected Environ.
LW-2.1.2.2: HBB Spectral Emiss. Ur
LW-2.1.2.3: HBB Temp. Unc.
LW-2.1.2.4: HBB Stray Light Unc.
LW-2.2: Cold On-Bd BB Rad. Unc. w
LW-2.2.1: Cold On-Bd BB Sensitivity
LW-2.2.2: Cold On-Bd BB Rad. Unc.
LW-2.2.2.1: CBB Reflected Environ.
LW-2.2.2.2: CBB Spectral Emiss. Ur
LW-2.2.2.2.1: CBB Emissivity
LW-2.2.2.2.2: CBB Emiss. Stabili
LW-2.2.2.3: CBB Temp. Unc.
LW-2.2.2.3.1: CBB Repeatability
LW-2.2.2.3.2: CBB Bias in Meas.
LW-2.2.2.3.3: CBB Unc. of Cal. X
LW-2.2.2.3.4: CBB PRT Unc. vs (
LW-2.2.2.3.5: CBB Temp. Gradie
LW-2.2.2.3.6: CBB Temp. Gradie
LW-2.2.2.3.7: CBB PRT/Elx Degr
bdd [Packag
Id = "2"
Text = "The
Noise Equiva
consistent w
for radiance
in Section 4.
LW-2.3: Sig
ance Unc
LW-2.5: G Term Uncertainty
Overview_Radiometric_Uncertainty
AllocationMatrix_LW
LaRC
NASA

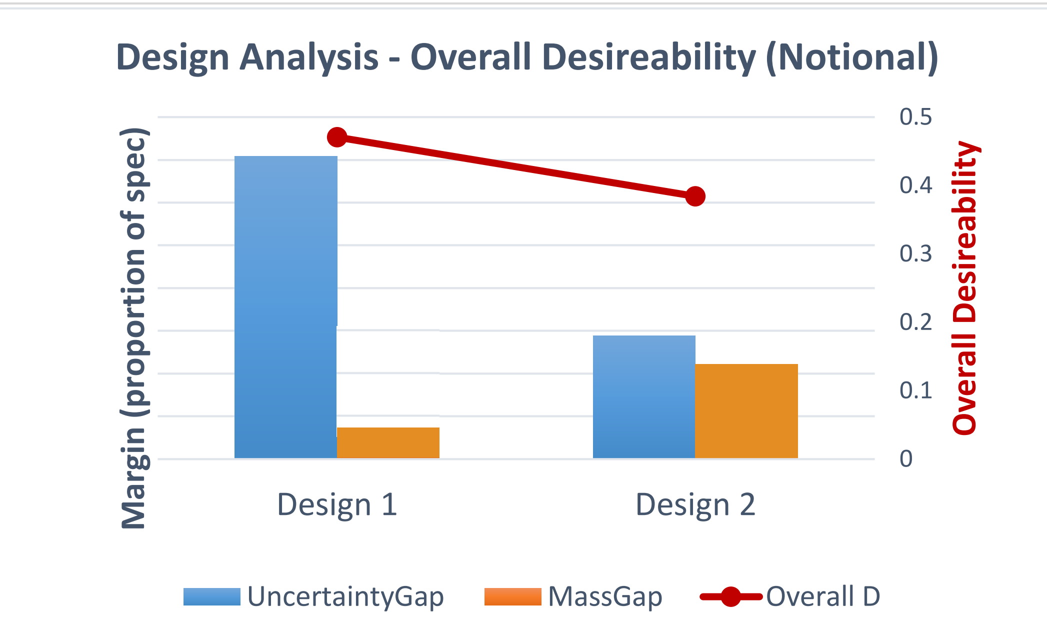
Potential Benefit - Design Trade Study (1 of 2)



Potential Benefit - Design Trade Study (2 of 2)







Another useful approach to optimization of multiple responses is to use the simultaneous optimization technique popularized by Derringer and Suich (1980). Their procedure makes use of **desirability functions**. The general approach is to first convert each response y_i into an individual desirability function d_i that varies over the range

$$0 \leq d_i \leq 1$$

where if the response y_i is at its goal or target, then $d_i = 1$, and if the response is outside an acceptable region, $d_i = 0$. Then the design variables are chosen to maximize the overall desirability

$$D = (d_1 d_2 \cdots d_m)^{1/m}$$

where there are m responses.

Reference: Myers, R. and Montgomery, D. (2002). *Response Surface Methodology, 2nd edition*. John Wiley & Sons, Inc..

Conclusion and Future Work

The typical spreadsheet radiometric uncertainty model was transformed to a SysML model.

The SysML uncertainty model helps:

- To visualize the computational structure hierarchy.
- To trace the uncertainty performance to its requirement.
- With integration to proper software, to compute uncertainty and mass values, and to perform design trade study.

Future work are:

- To include other RBI’s technical performance measures (TPMs) (e.g., system power, system reliability, etc.)
- To include penalty schemes to the TPMs for different stakeholder’s desires for the project
- To verify if the system-level design’s performances meet the project’s requirements.