Integrated Modeling: Past, Present, and Future

Gary Mosier, Code 592, JWST Integrated Modeling Lead
Kuo-Chia (Alice) Liu, Code 592, RST Integrated Modeling

April 28, 2021

Acknowledgement

- **Presenters would like to acknowledge the RST IM team for their contribution to this presentation package**
  - Carl Blaurock, RST IM Analysis Lead
  - Michael Akkerman, RST IM STOP Analyst
  - James Govern, RST IM Systems Engineer
  - Joe Howard, RST Optical Modeling Lead
  - Parker Lin, RST IM Jitter Analyst
  - Carson McDonald, RST IM STOP Thermal Analyst

What is Integrated Modeling?

Given all the times I've been asked that over the past 25 years, it would've been nice to have had this graphic on a laminated card in my wallet… <u>but there's more to it than this</u>.

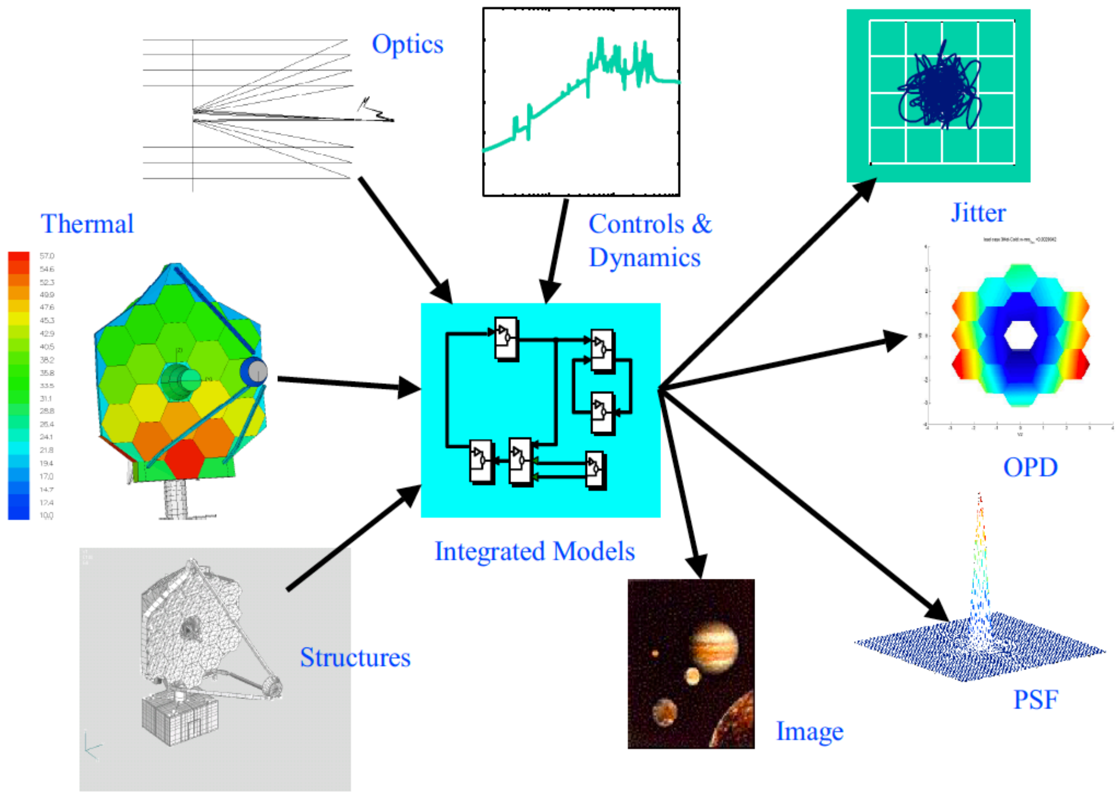


Figure 2: Integrated Modeling for JWST

Integrated Modeling (IM) Overview

- **IM is a multi-disciplinary analysis process critical to the success of many GSFC missions, including large space telescopes such as James Webb Space Telescope (JWST) and Roman Space Telescope (RST)**
  - Responsible for verifying performance requirements that cannot be practically verified by test or can only be partially verified by test
  - Provide system-level performance predictions to guide hardware design and trades for meeting driving optical stability requirements

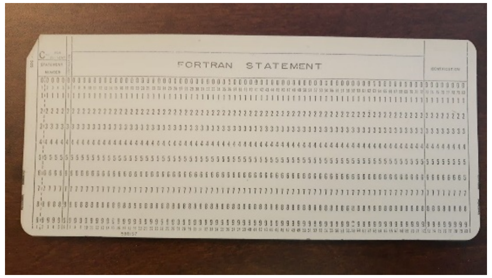
- **IM involves the rigorous application of many Systems Engineering processes to <u>the development and operation (use) of models</u> (i.e. think of the model as "the system")**
  - Defining analysis assumptions, configurations, and scenarios for requirement verification by analysis
  - Managing model verification, uncertainty, and validation activities to support requirement verification by analysis
    - Documenting model guidelines to support verification
    - Determining model uncertainty factor through Monte Carlo analysis and test validation
    - Establishing model validation plans

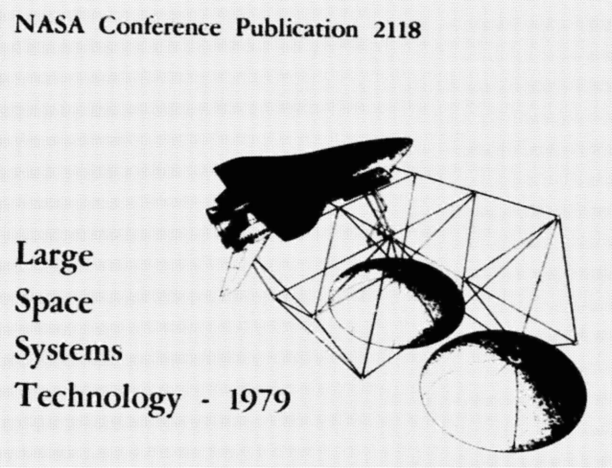
Integrated Modeling

PAST

1979 - Large Space Systems Technology Program Tech Review

NASA was just crawling out of the punch card era





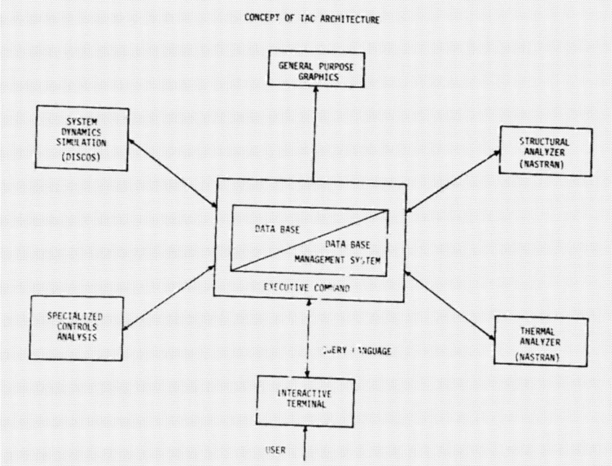
INTERACTIVE ANALYSIS PROGRAM ACTIVITY

J. P. Young, H. P. Frisch, and G. K. Jones
NASA Goddard Space Flight Center

W. J. Walker
Boeing Aerospace Company

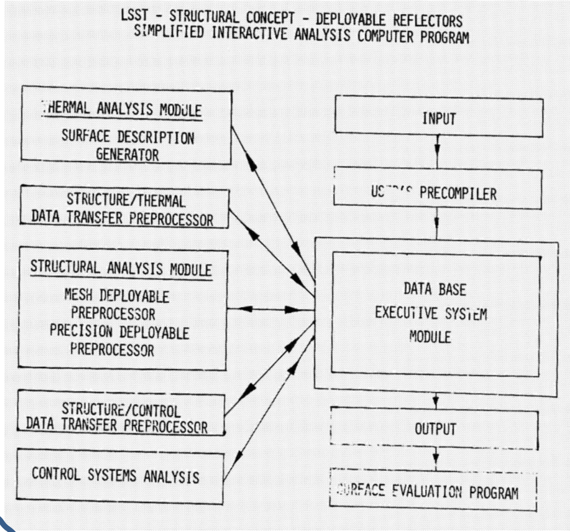
IAC–Capable of Performing

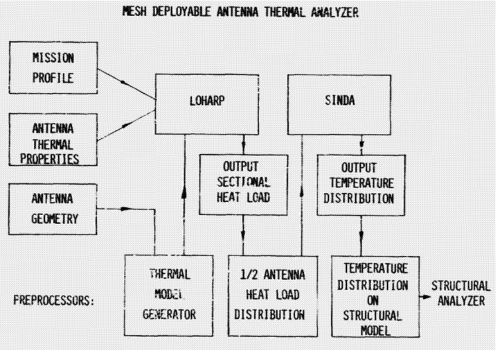
- Thermal/structural analysis in a standalone mode
- Thermal/structural coupled analysis in a sequential mode
- Structural/control system coupled analysis
- Quasi-static thermal/structural/control system coupled analysis
- Fully coupled thermal/structural/control system analysis

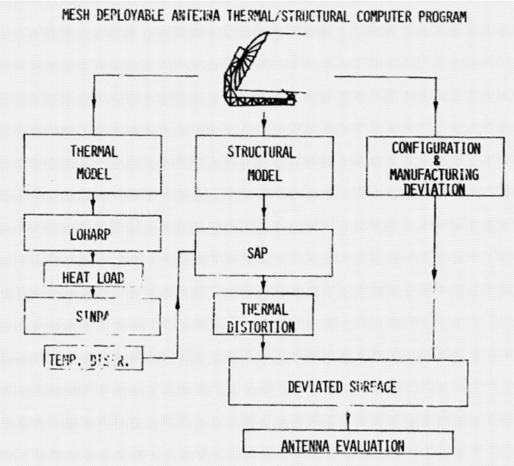


JPL ANALYTICAL PERFORMANCE PREDICTION CAPABILITY

R. Chen
Jet Propulsion Laboratory







Late 90's – SIM, NGST, JPL's "IMOS"

On Multidisciplinary Modeling Of The Space Interferometry Mission

Robert L. Grogan
Robert.L.Grogan@jpl.nasa.gov
Robert A. Laskin
Robert.Laskin@jpl.nasa.gov
Jet Propulsion Laboratory

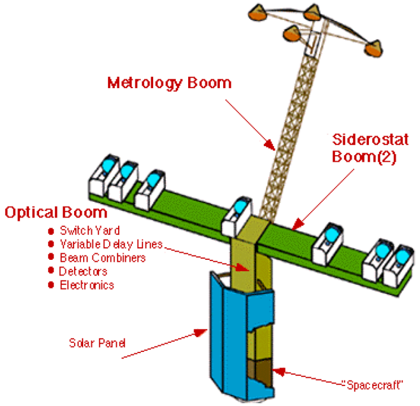


Figure 1.1: SIM Spacecraft Configuration

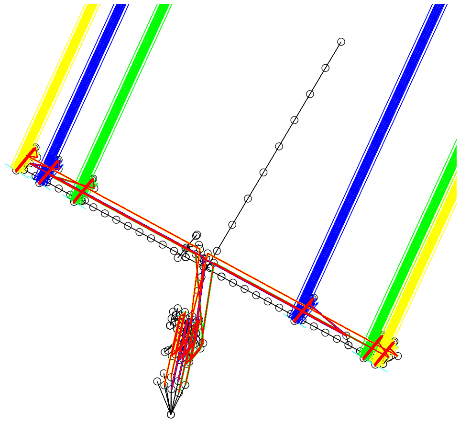


Figure 2.2: SIM Finite Element Model With Optical Ray Trace

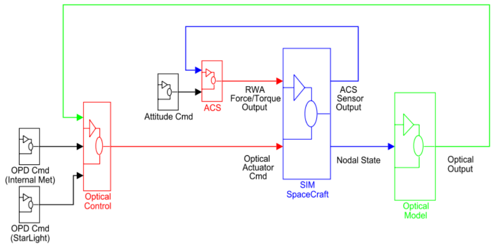


Figure 2.3: Block Diagram

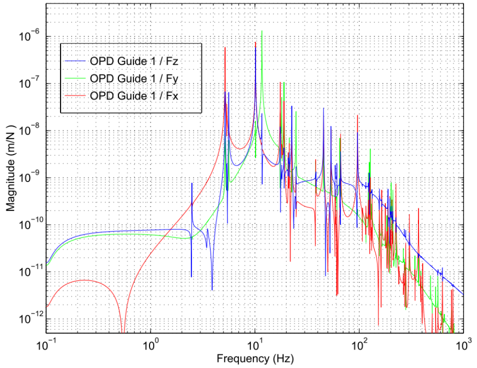


Figure 3.2: RWA Disturbance to OPD Frequency Response (10 Hz Isolation)

NGST Monograph No. 6 Performance Analysis Using Integrated Modeling

By

Gary Mosier, Keith Parrish, Michael Femiano
NASA Goddard Space Flight Center

David Redding, Andrew Kissil, Miltiadis Papalexandris
Jet Propulsion Laboratory

Larry Craig, Tim Page, Richard Shunk
NASA Marshall Space Flight Center

August 2000

NEXT GENERATION NGST SPACE TELESCOPE

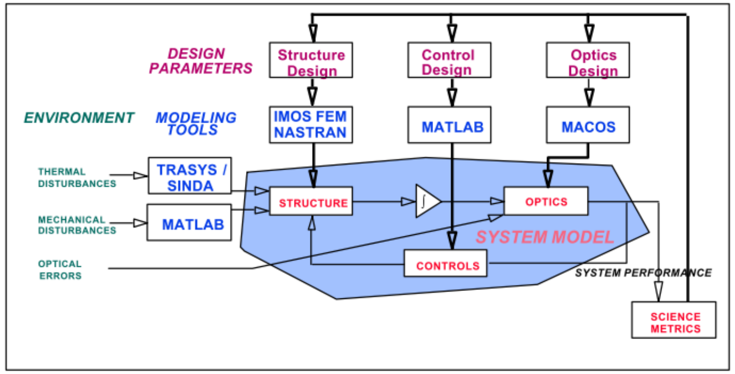


Figure 1-2 NGST integrated modeling environment

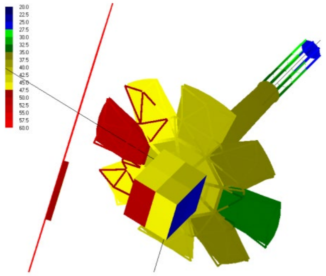


Figure 4-4 OTA steady state thermal model results

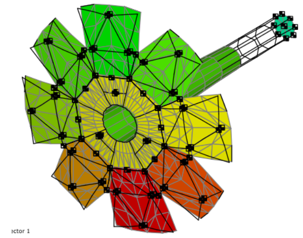


Figure 6-1 OTA steady-state temperatures

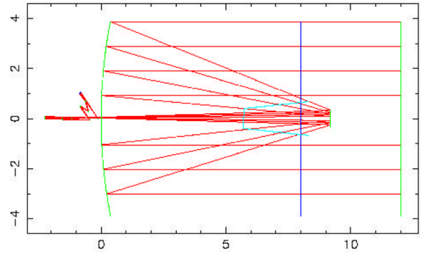


Figure 3-1 MACOS optical layout

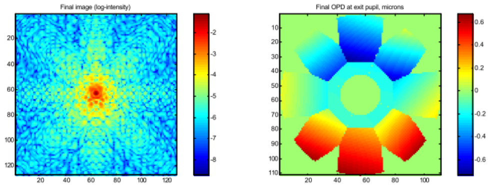


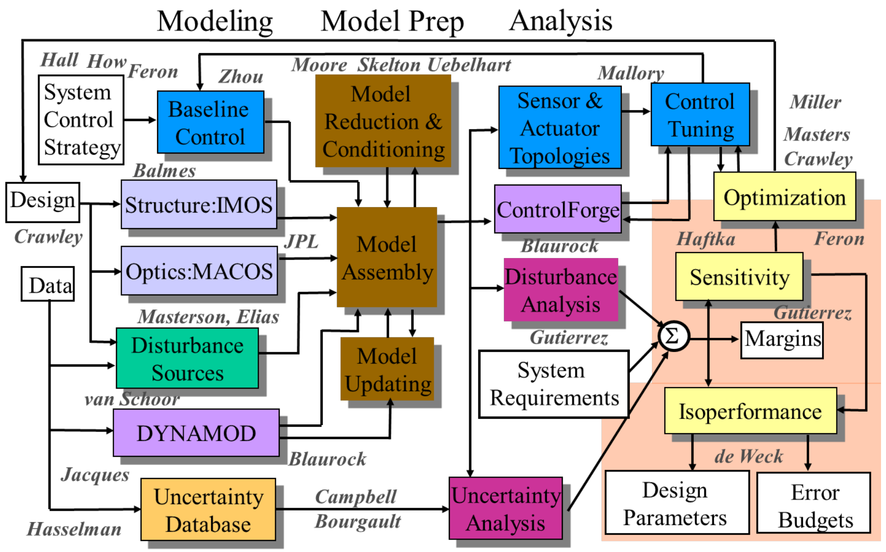
Figure 6-5 Final image (log-intensity) and OPD

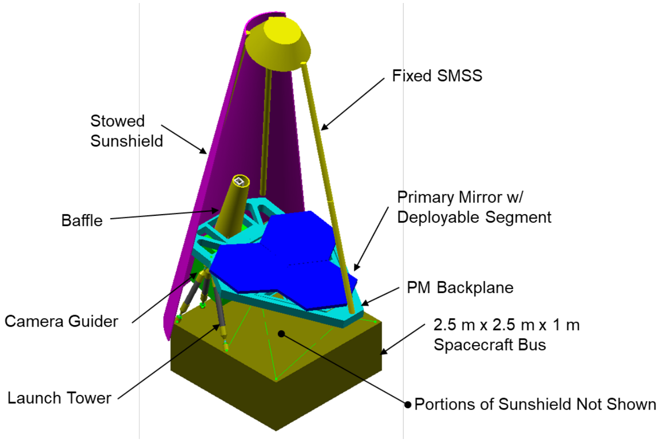
Figure 7-6 Jitter results from linear model

Integrated Modeling

Late 90's/Early 00's – MIT's "DOCS", Nexus, TPF

MIT SSL – DOCS IM Framework





Dynamics Analysis of the Nexus Spacecraft

Scott A. Uebelhart[†]
Gregory J.W. Mallory[‡]
David W. Miller[*]

MIT Space Systems Laboratory

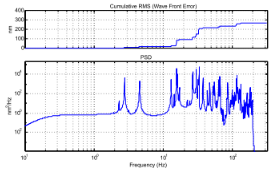


Figure 4: WFE results

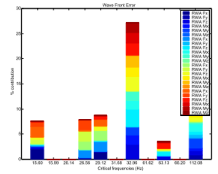


Figure 6: Disturbance contributions to critical frequencies

INTEGRATED MODELING APPROACH FOR THE TERRESTRIAL PLANET FINDER MISSION

Marie Levine[1a], Gregory Moore[a], Scott A. Basinger[a], Andrew Kissil[a], Eric Bloemhof[a], Steve Gunter[a]
[a]California Institute of Technology, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA, USA, 91109;

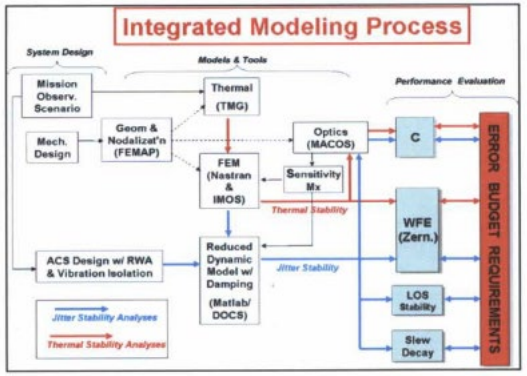


Figure 2 Integrated Modeling Process Diagram

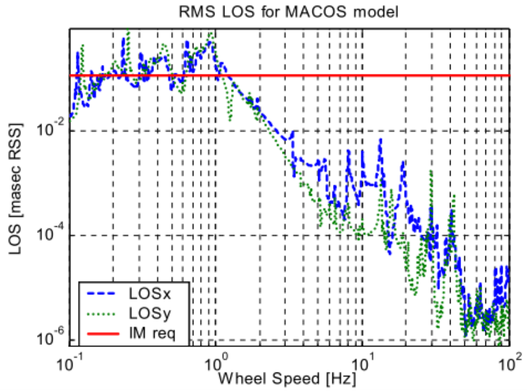


Figure 4-1 LOS Jitter X (solid) and Y (dashed) versus wheel speed for 2-stage passive isolation design, versus image motion requirements

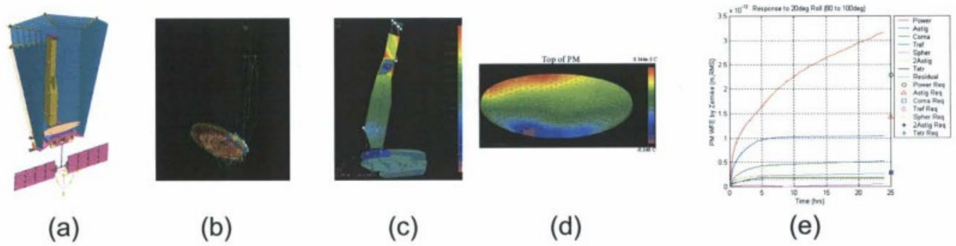
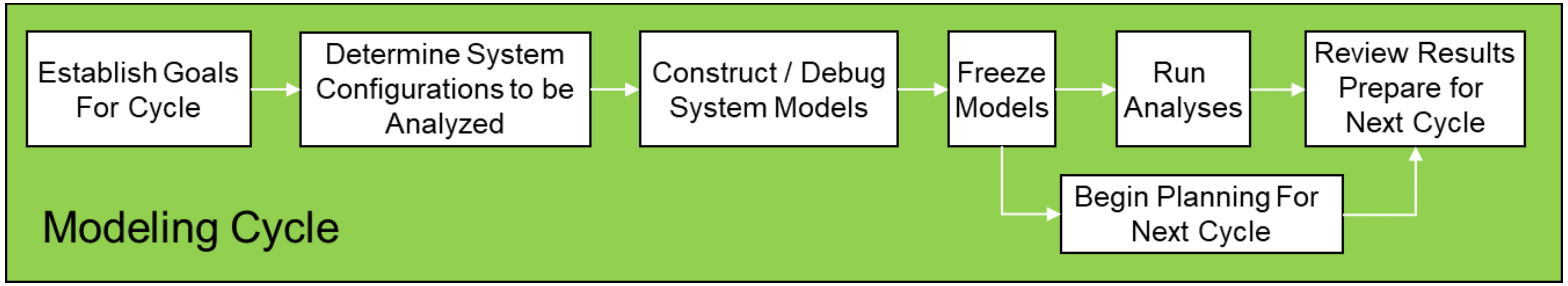


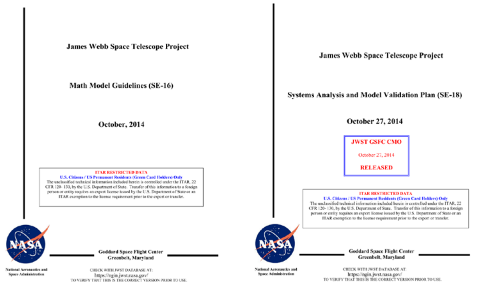
Figure 3 Summary results of the TPF Minimum Mission Coronagraph analysis using integrated modeling process.

2002 – JWST

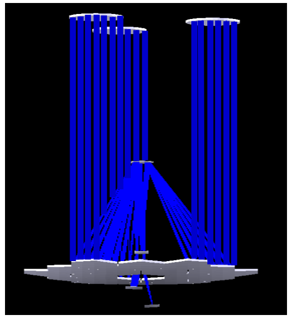
- **TRW is selected as prime contractor for NGST, NGST becomes JWST, TRW becomes NGST (now NGAS)**
- **Big changes for IM leadership role… Management >> Technical**
  - Coordination of “Vertical Integration” of discipline models, up the supply chain (analogous to H/W I&T)
  - Coordination of “Horizontal Integration” of multidisciplinary models
  - Scheduling – managing a series of modeling cycles (~6 months duration per cycle, ~24 cycles from 2002-2020)

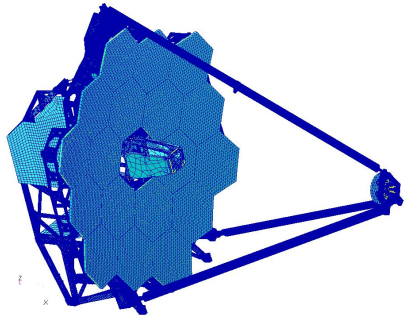


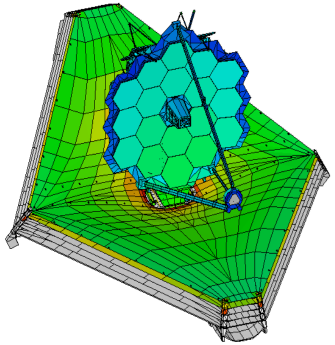
  - Establishing and maintaining standards and requirements for development and use of models
    - Math Models Guidelines Document, System Analysis & Model Validation Plan
    - Model construction and assembly, including interfaces
    - Model verification – Was the model correctly built? Was it correctly used?
    - Model validation – Does the model agree with test data, to within some tolerance?
    - Configuration management – models, data, documentation



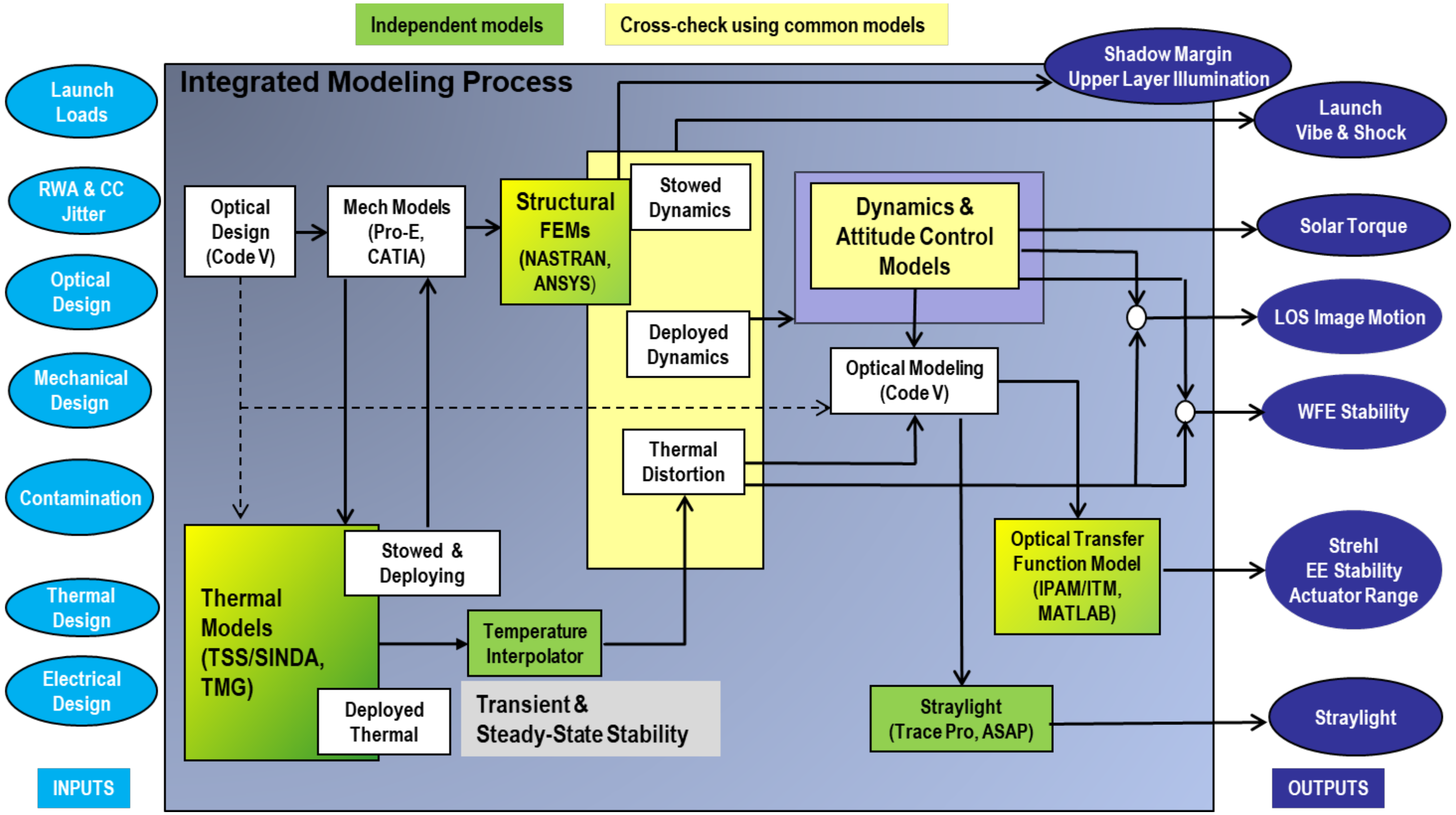
2002-2020 – JWST

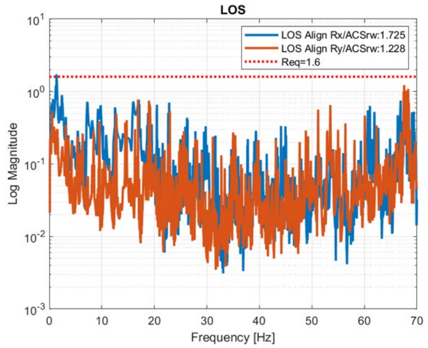


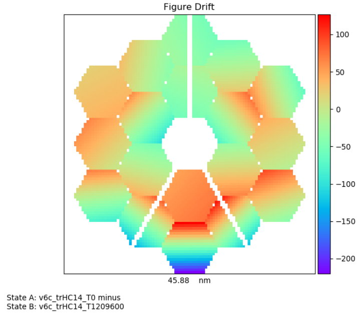


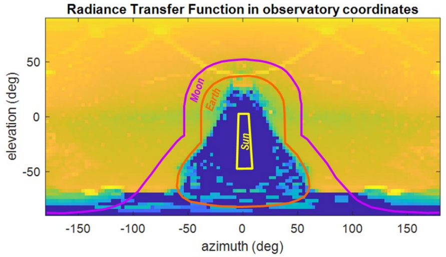


And so, for nearly 20 years, this was my life…









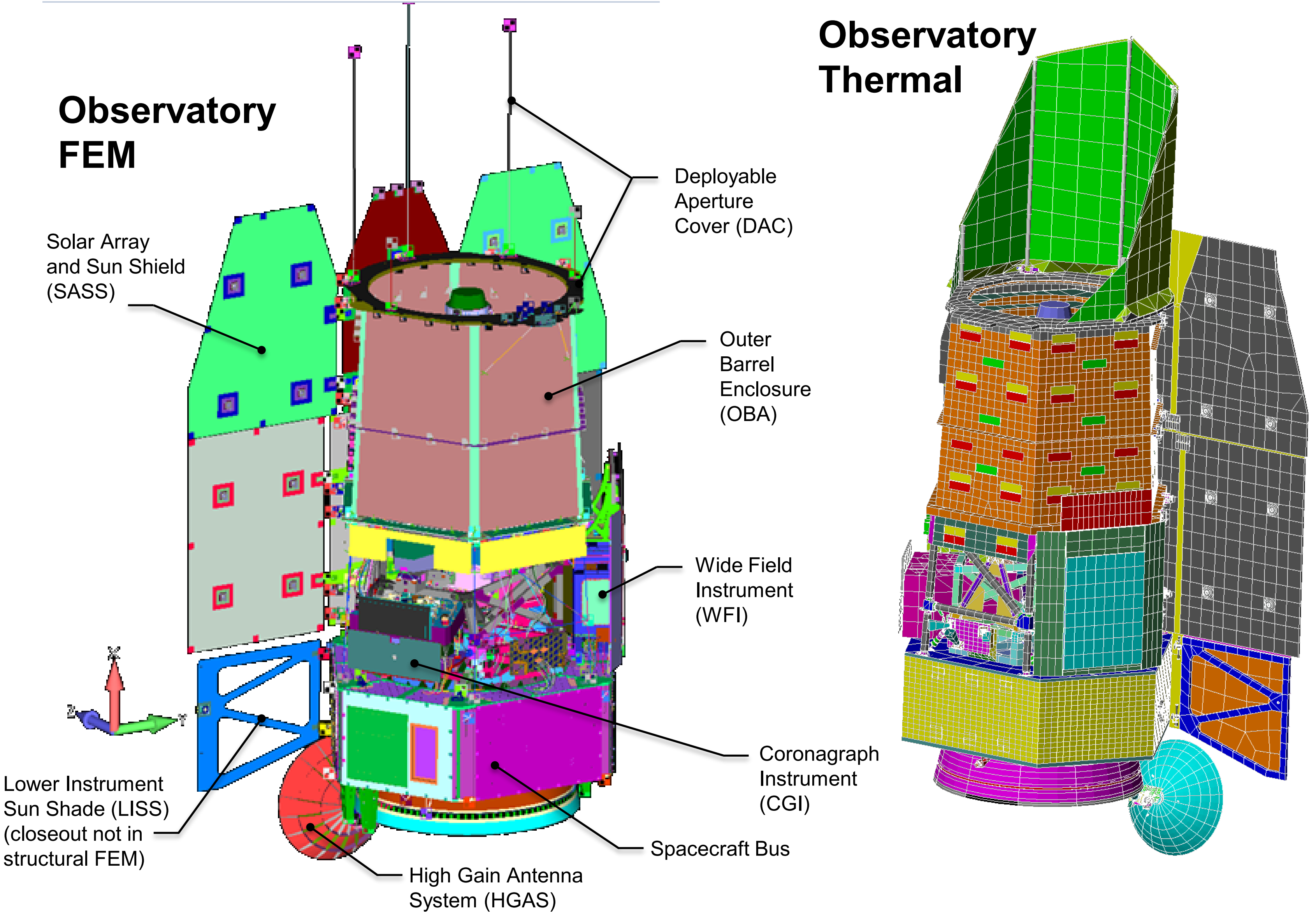
Integrated Modeling

PRESENT – THE RST STORY

Integrated Modeling

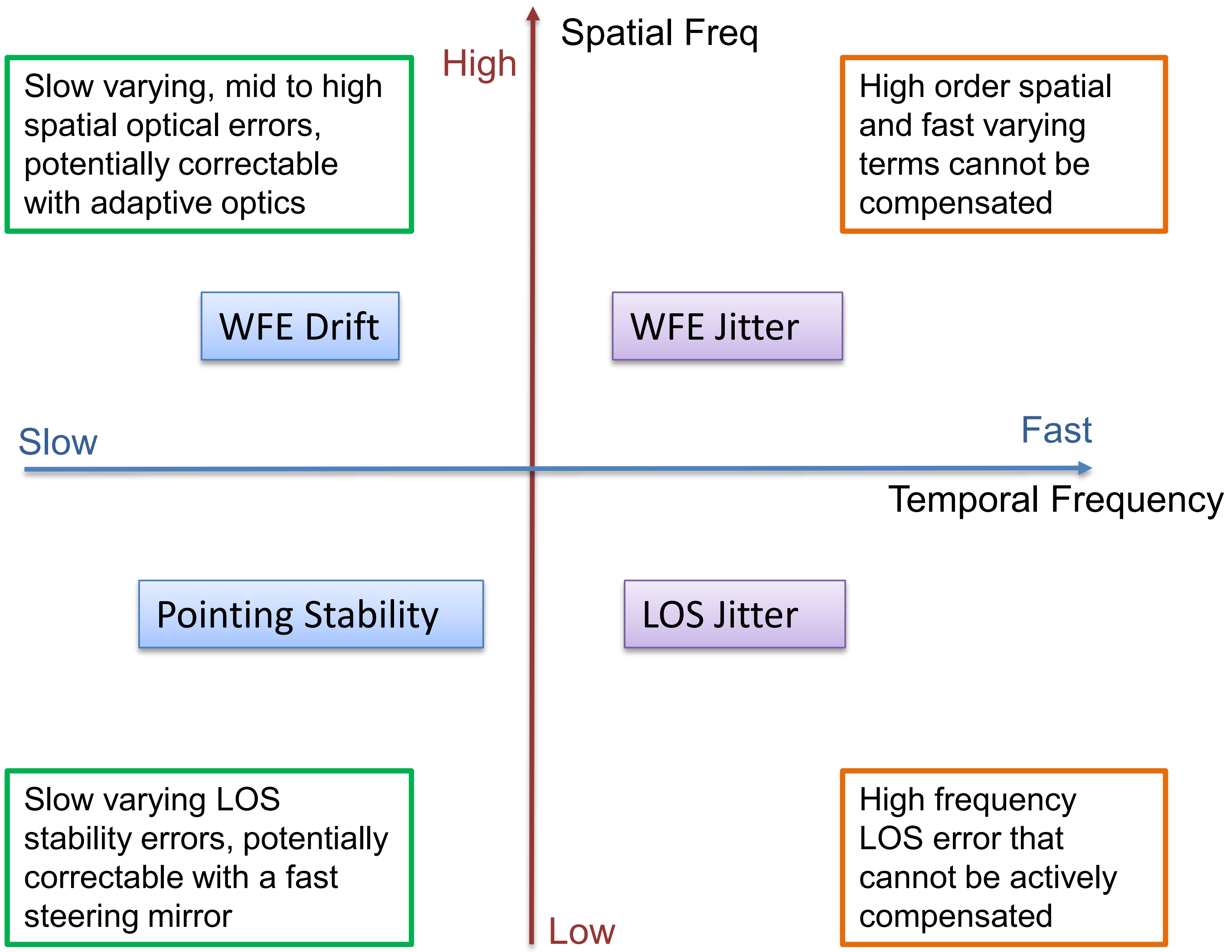
Nancy Grace Roman Space Telescope (RST) Integrated Modeling

- **Leveraged JWST modeling approach, material property database, and IM processes**
  - Improved upon JWST heritage where appropriate
- **Held IM reviews early in Phase A with a JWST review board to incorporate important JWST lessons learned into RST IM workflow**
- **RST project IM team has a different scope than JWST**
  - RST is an in-house mission which requires GSFC IM to be both the “prime” and oversight IM organization
  - RST system design and models are less complex than JWST

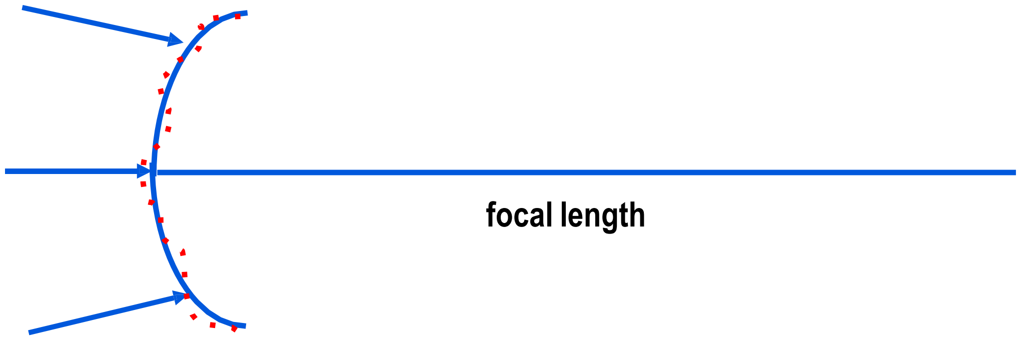


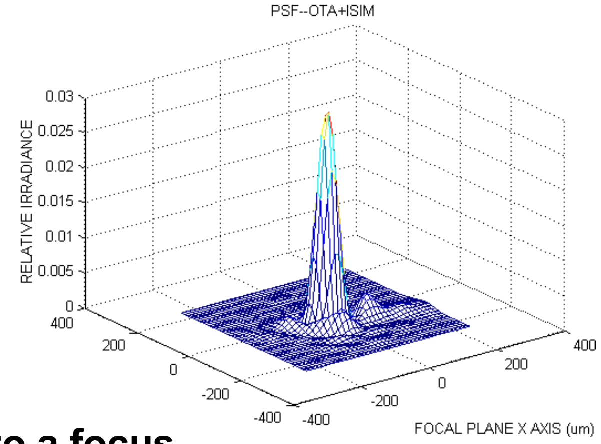
Optical Stability Terminology

- **Pointing Stability**
  - Rigid-body control error from ACS that only affects pointing (or line-of-sight motion)
- **Line-of-Sight (LOS) Jitter**
  - Mechanical vibration induced errors that affect LOS at high frequencies
- **Wavefront Error (WFE) Drift**
  - Thermoelastic effects (or thermal distortion) due to temperature variations
- **WFE Jitter**
  - Mechanical vibration induced errors that affect mirror bending motion

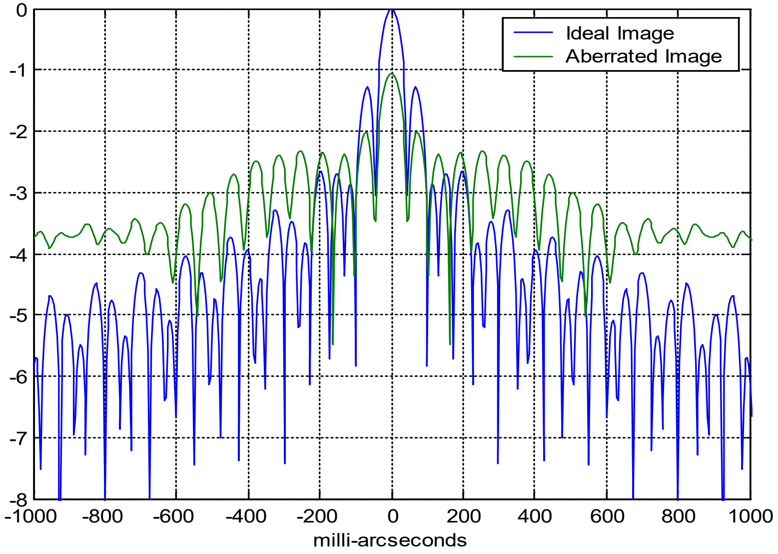


Optics of Imaging Systems





- **In a perfect system, all rays appear to converge from a "reference sphere" to a focus**
  - Radius of curvature of the sphere is the system focal length (~19m for RST Wide Field)
- **The effect of the finite aperture (limiting diameter of primary mirror) is <u>diffraction</u>, and the resulting point spread function (PSF) is an Airy distribution**
- **Physical aberrations in real systems cause the individual rays to arrive at focus out of phase (measured by optical pathlength difference, or OPD, also called <u>wavefront error</u>), resulting in distortions to the PSF**
- **Line-of-sight (LOS) error results in <u>blurring</u> of the PSF (moving the centroid of the PSF)**
- **Standard metrics used to characterize performance of imaging systems <u>include</u>:**
  - Strehl ratio – ratio of the peak amplitude of the real PSF to that of the ideal PSF
  - Encircled energy – the integral under the curve of a slice through the PSF core



Jitter (or Micro-vibration) Definition

- **Jitter is motion of the optical beam caused by motion of the optics due to**
  - Mechanism disturbances (reaction wheels, stepper actuators, cryocoolers, etc.)
  - Control system imperfections (actuator and sensor noise) associated with active optics
- **Jitter is a system-level problem and can be managed more effectively by a multi-disciplinary team**
  - "Understand and managing spacecraft jitter is a highly multi-disciplinary task" – Gary Hendersen (Aerospace Corporation)
- **Combinations of design tools are used to develop the most cost-effective strategies to mitigate jitter concerns**

Mechanism	Control Systems	Structural Dynamics	Optics	On-orbit Operation
Lower disturbance inputs	Compensate low-frequency errors	Reduce dynamic responses	Active optics	Avoid operating mechanisms during observation

Jitter Requirements and Design Architecture

LOS Jitter [asec]	Frequency [Hz]: <0.01	0.01-0.1	0.1-1	10-100	>100	Design Considerations	
100++	Low Fidelity STOP	ACS		Low Fidelity Jitter	Low Fidelity Jitter	Not challenging	Typical GSFC Missions
10-100	Mid Fidelity STOP	ACS		Mid Fidelity Jitter	Mid Fidelity Jitter	Not challenging	
0.1-10	High Fidelity STOP	ACS	LOS Control* /Post-Proc	High Fidelity Jitter + VIS*	High Fidelity Jitter + VIS*	Requires careful modeling and analysis with review from an experienced team	
0.01-0.1	High Fidelity STOP + Ctrl for Stability	ACS	LOS Control /Post-Proc	High Fidelity Jitter + VIS	High Fidelity Jitter + VIS	Design driver; requires system planning on architecture development, mitigation strategies, and testing	Large Space Telescopes & Laser Comm
1e-3-0.01	High Fidelity STOP + Ctrl for Stability	ACS	LOS Control /Post-Proc	High Fidelity Jitter + VIS	High Fidelity Jitter + VIS	Design driver; requires system planning on architecture development, mitigation strategies, and testing	
1e-4-1e-3	High Fidelity STOP + Ctrl for Stability	ACS	LOS Control / Post-Proc	High Fidelity Jitter + VIS	High Fidelity Jitter + VIS	Beyond state of the art; requires significant technology development in addition to system planning	Future Flagship Missions

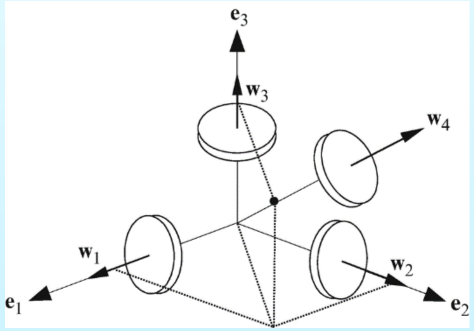
ACS = attitude control system, STOP = structural-thermal-optical-performance, VIS = vibration isolation system
VIS* = VIS may not be necessary, pending analysis assessments

Jitter Requirement Flowdown Considerations

- **Developing error budgets to aid requirement flowdown**
  - Pointing and Optical Error Budgets
- **Building early models to support analysis assessments and budgeting work**
  - For missions with a LOS jitter requirement less than ~1 arcsec, a structural model should be developed in phase B in support of jitter analysis and design
- **Interface requirements**
  - Specifying or flowing jitter requirements to subsystem at the interfaces is often problematic
    - Interface dynamic responses do not correlate well with optical responses which often lead to overly conservative interface requirements
    - Observatory-level, coupled dynamic behavior cannot be easily broken out correctly at the interfaces
    - We are often driven to this approach because “it was done before” or for programmatic reasons
- **ACS stability and IM jitter division**
  - Provide a frequency separation
    - Below/above ACS bandwidth or Nyquist of ACS sampling frequency
    - First flexible-body mode
  - Divide by disturbance sources instead of frequency to avoid double-booking
    - ACS incorporates sensor and actuator control torque related errors, while jitter covers high frequency disturbances (wheel imbalance and bearing noise)
- **Using IM and flight-proven analysis tools to provide jitter assessments ASAP**
  - Use analysis as a design tool to determine jitter mitigation approaches
  - Identify sensitive components and provide stiffness requirements as appropriate
- **Flowing sub-system requirements at a level that can be verified by the sub-system team**
  - Wheel imbalance, stepper detent and micro-stepping level, isolation system transmissibility

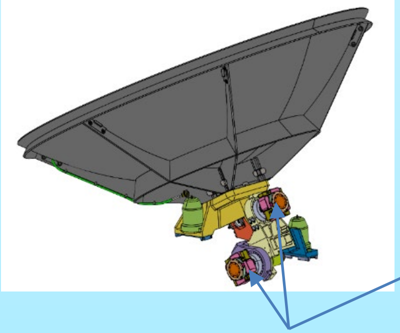
Typical Dynamic Disturbances: Mechanisms

Spacecraft



Reaction Wheels

- Three or more reaction wheels for attitude control
- Continuous disturbance source due to static and dynamic imbalance, as well as bearing noise



High Gain Antenna System (HGAS) or Solar Array Drive (SAD)

- 1 or 2-axis gimbal actuator
- 3 phase, stepper motor with a harmonic drive
- Generate disturbance during stepping only

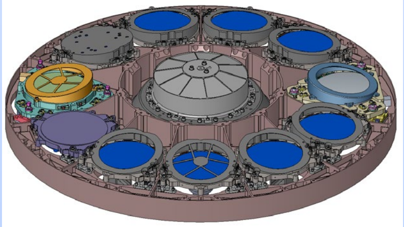
Payload

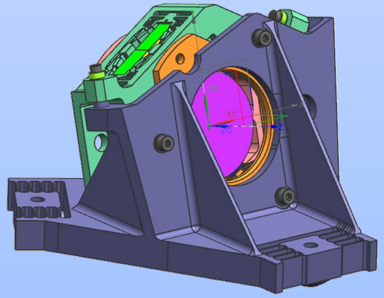
Cryocooler

- Cooling sensors and/or detectors to low temperatures
- Disturbance at integer harmonics of fundamental drive frequency

Optical Element Selection Assembly (RST Element Wheel Assembly)

- 3-phase stepper motor
- Not operating during observing time



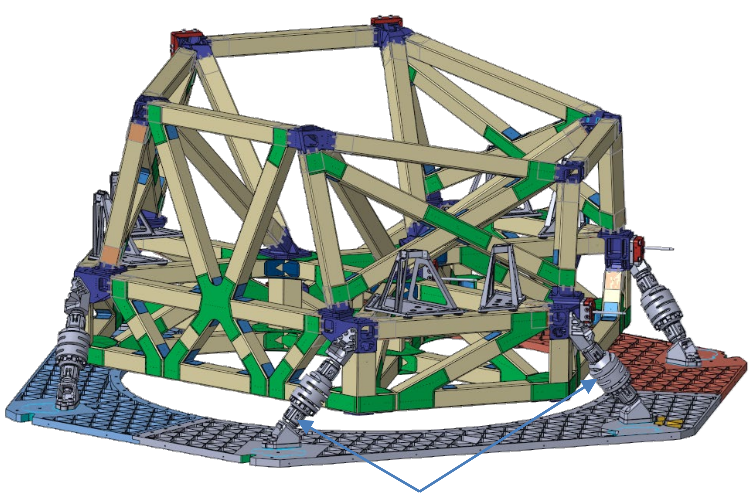


Fast steering mirror for LOS control (RST Coronagraph Instrument FSM)

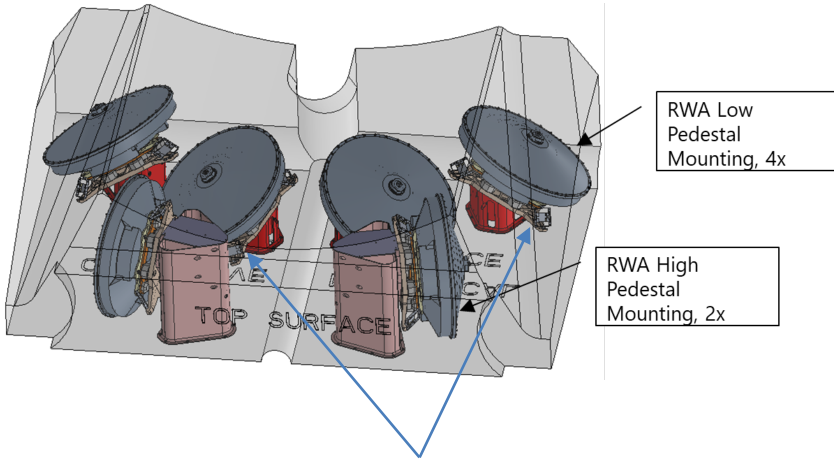
- PZT stacks with counterbalanced reaction mass

Passive Jitter Disturbance Mitigations Options

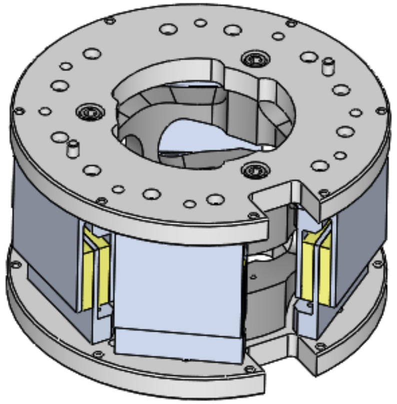
- **Consider simple passive system for jitter mitigation first**
- **Vibration isolation system**
  - between Spacecraft and Payload to mitigate all Spacecraft disturbances
  - between flight reaction wheels and bus panel
- **Damper system**
  - Reduces jitter settling time caused by HGAS and/or SAD stepper actuators
  - Add dampers at location with high strain energy such as the HGAS boom or SAD root
  - Incorporate tuned mass dampers (TMDs) at location with high kinetic energy



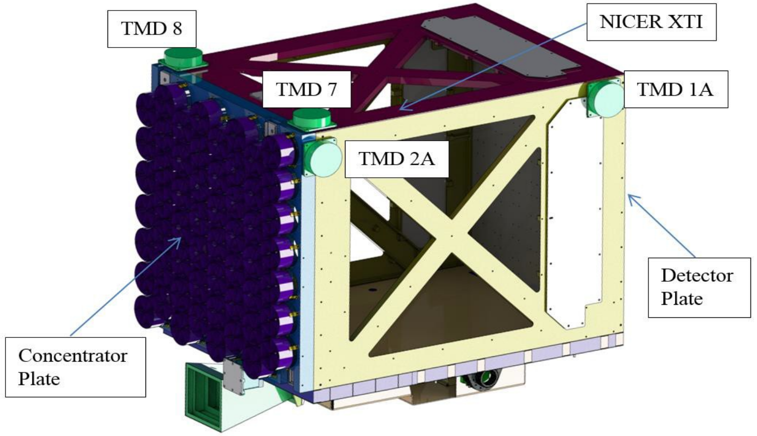
RST Launch Loads and Vibration Isolation System



RST Reaction Wheel Vibration Isolation System



RST HGAS Damper

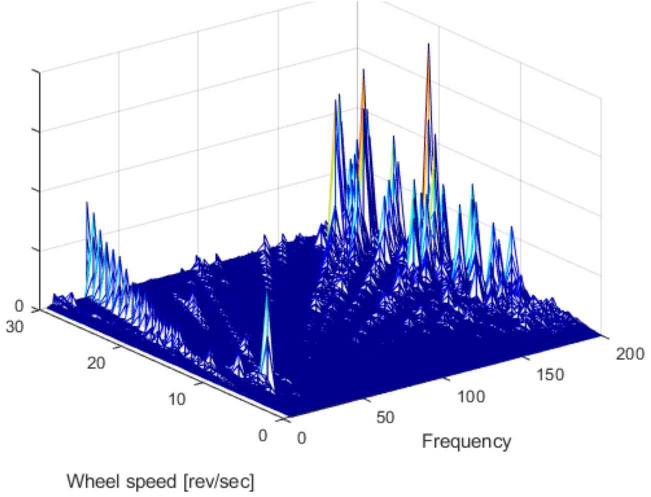


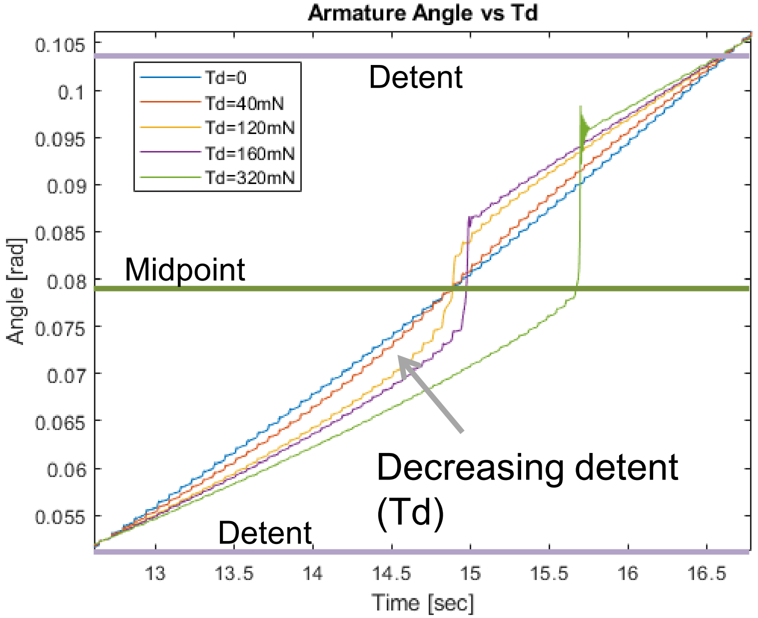
NICER TMDs

Other Jitter Mitigation Options

- **Reaction Wheel Assembly (RWA)**
  - Procure redundant wheels to keep wheel speed low during observation
  - Implement RWA speed separation and "drive-through" algorithm
    - ACS to implement minimum separation (~1 rev/sec) between wheel speeds
    - ACS to drive through problematic wheel speeds quickly
- **Stepper Actuator**
  - Implement low detent stepper motor with microstepping
  - Coordination with thermal early to accommodate power dissipation
- **Cryocooler**
  - Allow tunability in drive frequency
  - Active cancelling system
- **Coordinate science observation with actuator commands**
  - Incorporate no-step (or actuator movement) flag during science exposures
    - Step may be required, image will be lost or degraded
  - Avoid mechanism movement as much as possible during observation

Wheel disturbance amplitude varies with speed squared

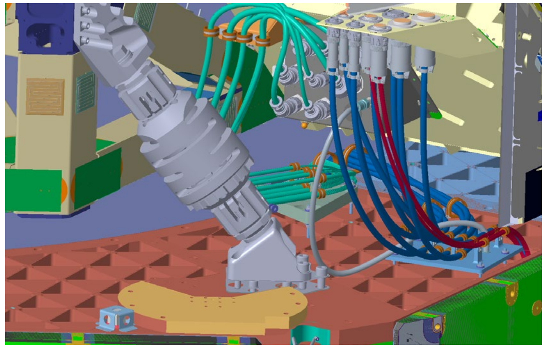


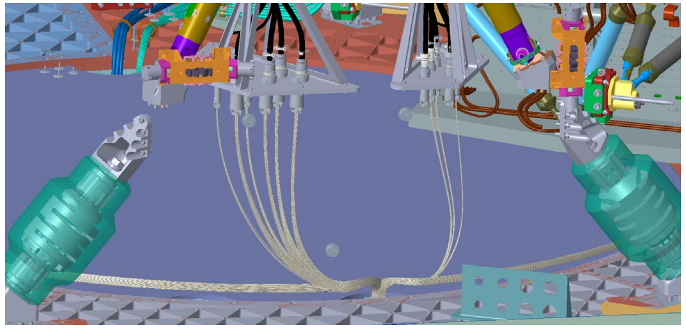


Jitter Mitigation Challenges: Shunt Path and Thermal Impacts

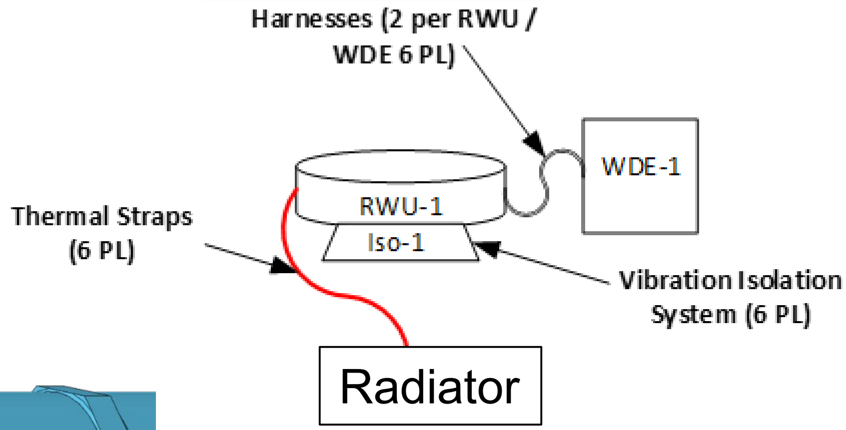
- **Harnesses, thermal straps, waveguide, and purge lines across VIS/damper mechanically shorts VIS and damper system**
  - Use soft harness construction and thermal strap design to alleviate shunt path concerns
  - Provide guidelines on harness routing to provide service loops and separate out harness bundles as much as possible
- **Test shunt path with and without passive isolation/damper system to determine shunt path impacts to system performance**

Examples of harnesses crossing VIS interface

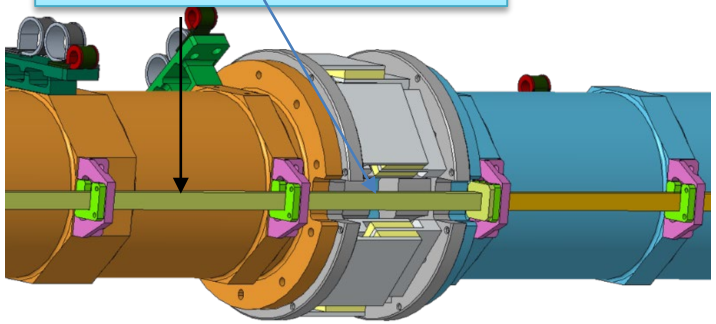




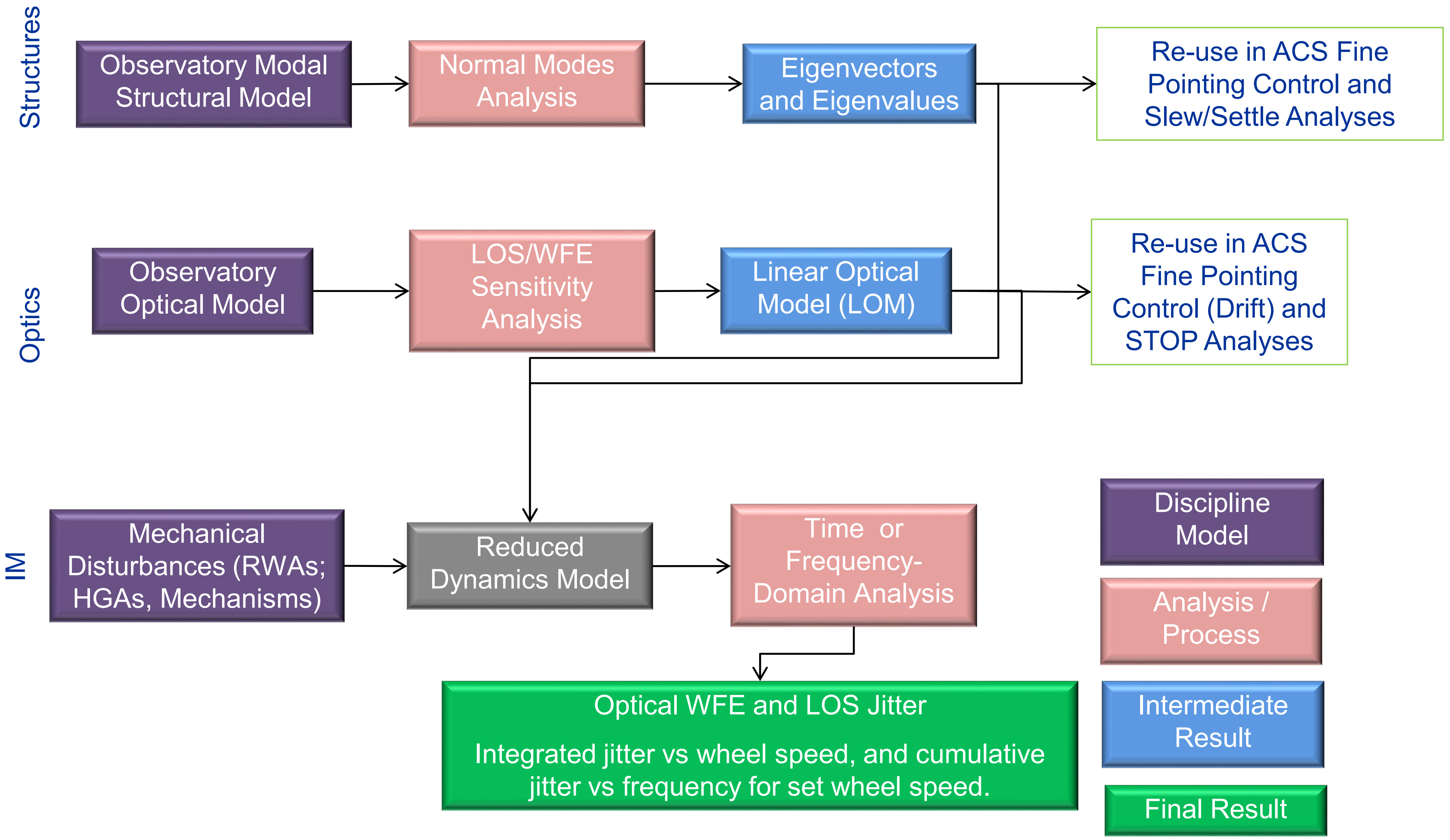
RWA shunt path



Waveguide pass-through



Dynamic Analysis Flow



Integrated Modeling

Dynamics Model Uncertainty

- **Frequency Uncertainty**
  - Typically assume 10% uncertainty in modal frequency
  - Incorporate frequency uncertainty in jitter analysis by varying either input disturbance frequency or model modes
- **Damping Uncertainty**
  - Use conservative damping assumptions
    - Bill Haile compiled results from various spacecraft and recommended 0.3%
    - SDO did FRF measurements of the Strength Verification Unit bus and determined 0.3% as a 95th percentile number
    - RST uses 0.25% for room temperature metal and 0.1% for composites
- **Modal Gain Uncertainty**
  - Apply model uncertainty factor (MUF) to analytical predictions
  - Typical GSFC mission uses a MUF of 2 or requires a factor of 2 margin
  - "MUFology" table (below) was first developed by Bob O'Donnell (Aerospace Corporation) and adopted/modified by GSFC on JWST, SDO, and RST
  - RST recently used Monte Carlo analysis to validate MUF and updated dynamics MUF based on the Monte Carlo results

Example of RW Jitter MUF Table

WIM

RW Jitter MUFology	Below 20 Hz									Above 40 Hz					
	Net		Contributor MUFs in dB							Net		Contributor MUFs in dB			
	Gain	dB	Analysis Only		Component Test		Sub-system		System Test	Gain	dB	Analysis Only	Compt Test	Sub-system	System Test
RWA Disturbance	1.15	1.2	5		1.2	1	0.6		0.3	1.58	4	10	4	2	1
RWVIS	1.26	2	2	1	1.2		0.6		0.3	1.58	4	4	4	2	1
S/C Bus	1.41	3	3	1	1.2		0.6		0.3	2.00	6	6	4	2	1
PVIS	1.26	2	2	1	1.2		0.6		0.3	1.58	4	4	4	2	1
IC	1.26	2	2	1	1.2		0.6		0.3	1.58	4	4	4	2	1
Instrument	1.26	2	2	1	1.2		0.6		0.3	1.58	4	4	4	2	1
AOM	1.41	3	3	1	1.2		0.6		0.3	2.00	6	6	4	2	1
FOA	1.07	0.6	4		1.2		0.6	1	0.3	1.26	2	8	4	2	1
Optical Performance	1.26	2	2	1	1.2		0.6		0.3	1.26	2	2	1.2	0.6	0.3
RSS of dB's	2.07	6.31								4.29	12.65				

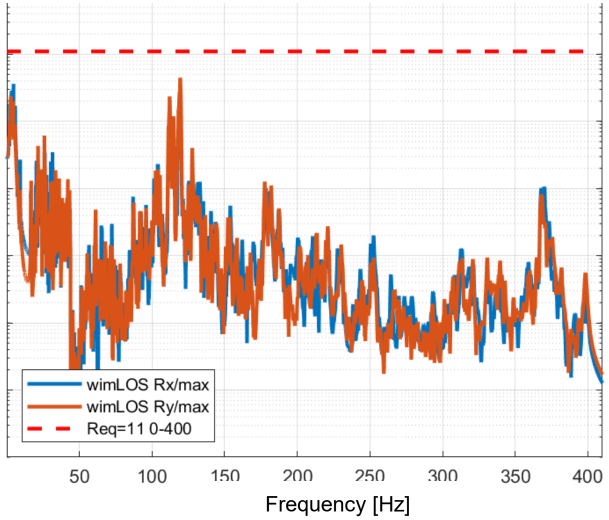
Was	2.04	4.13
Phase A (RWA dist, FOA component testec	2.07	4.29
All component test	1.51	3.71
All sub-system test	1.23	1.92
All system test	1.11	1.39
PVIS+IC Test	1.95	4.06
IOA+IC Modal	1.76	3.24
WFI Modal	1.67	2.96
RW VIS Transmissibility	1.59	2.69
RW+RWVIS IV	1.56	2.42
Bus+IC ETU Modal	1.33	1.82
Observatory Modal	1.28	1.49

Jitter Analysis Tools

- **Disturbance-Optics-Controls-Structures (DOCS)**
  - Software tool developed for end-to-end analysis of the dynamic performance of controlled opto-mechanical systems under SBIR funding
  - Used on several missions and proposal studies: TPF-C, JWST, SDO, LRO, GPM, Landsat-8/TIRS-2, and NICER
- **EllipTool developed by Elliptical Engineering**
  - New jitter and STOP analysis tool developed in 2017 with the goal to simplify user interface and allow more engineers to perform highly specialized IM analyses
  - Missions supported to date: RST, PACE, and Landsat-9
- **Honeywell Reaction Wheel Jitter Analysis Tool**
  - Can be provided as part of Honeywell reaction wheel procurement
  - Used by some of our out-of-house prime: Northrop Grumman and Ball
- **MSC Adams**
  - Multi-body dynamics and motion analysis software
  - Used on GOES-R

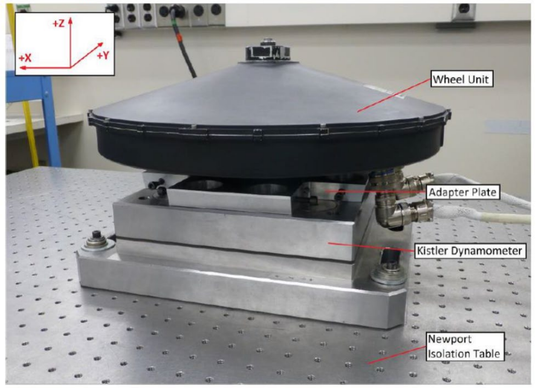
Jitter vs. Wheel Speed (for each wheel)

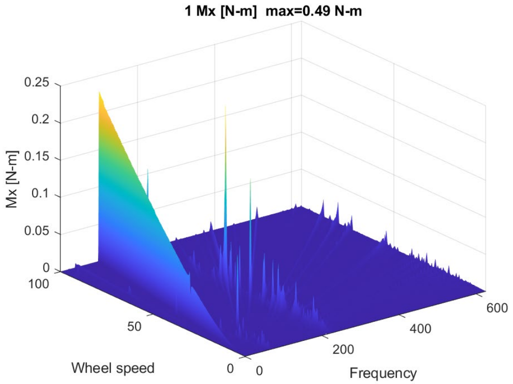
Jitter vs. Frequency (enveloped over all wheels)

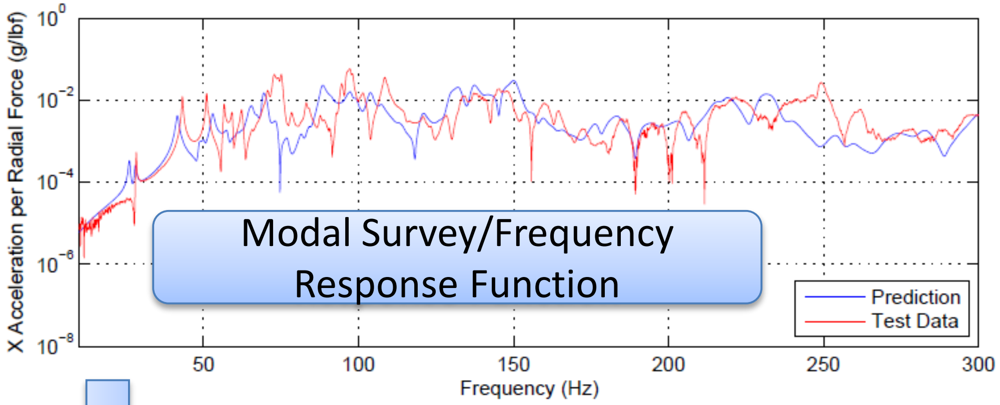


Integrated Modeling

Dynamics Model Validation Approach







Modal Survey/Frequency Response Function

Induced Vibration Test

Dynamometer/ Kistler Table

Validated Mechanism Model

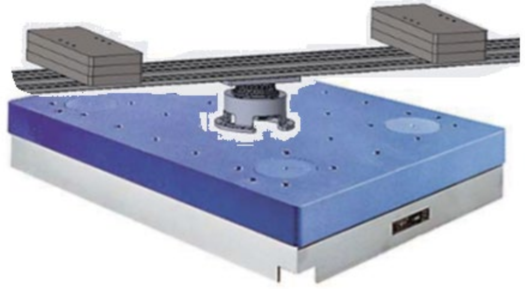
Drive flight analysis

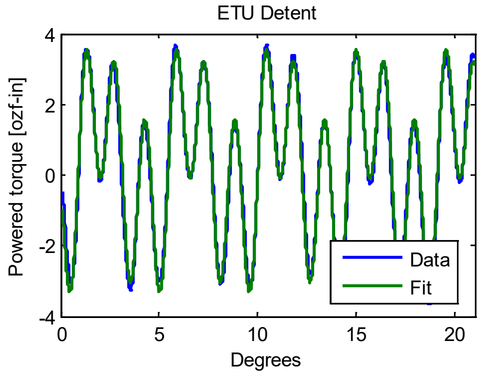
Validated Structural Model

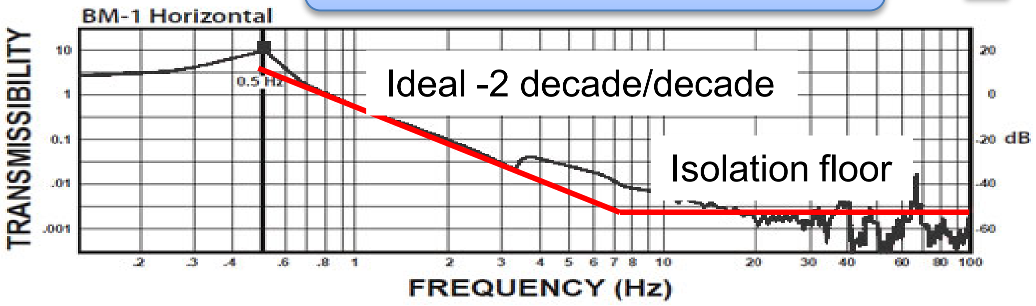
Flight Prediction

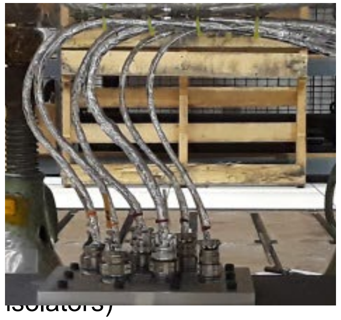
Isolation and Damping System

Shunt Path









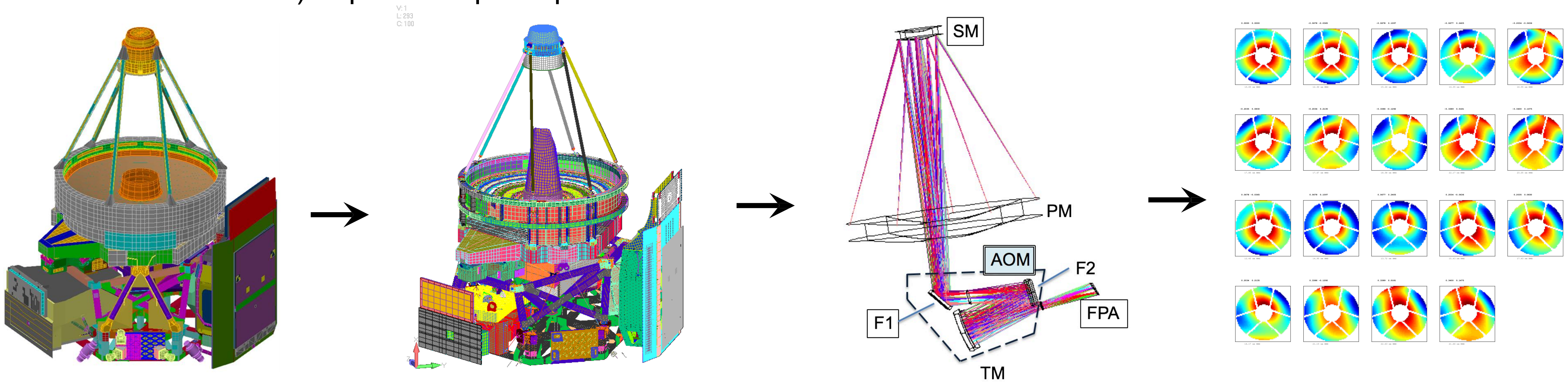
Transmissibility curve from Minus-K (isolator vendor that supplied the JWST OTIS isolators)

IM Jitter Summary

- **Jitter analysis tool and disturbance models have been validated with flight data**
- **Typical GSFC missions are covered by heritage analysis tools, reasonable MUF, and conservative damping**
- **Jitter requirement flowdown to elements or sub-systems require careful consideration**
  - While end-to-end LOS jitter requirement is the most accurate and least conservative approach, it requires the project to have an IM capability in Phase B (prior to Mission PDR)
  - Interface dynamics requirements may avoid programmatic issues early, but a system-level IM jitter prediction will still be required by Mission CDR
- **For large space telescope missions, managing jitter effectively requires system-level planning that includes minimizing disturbance source inputs, augmenting design with passive isolation and/or damper systems, implementing active optics control system, addressing shunt path concerns, and planning appropriate tests for dynamics model correlation**

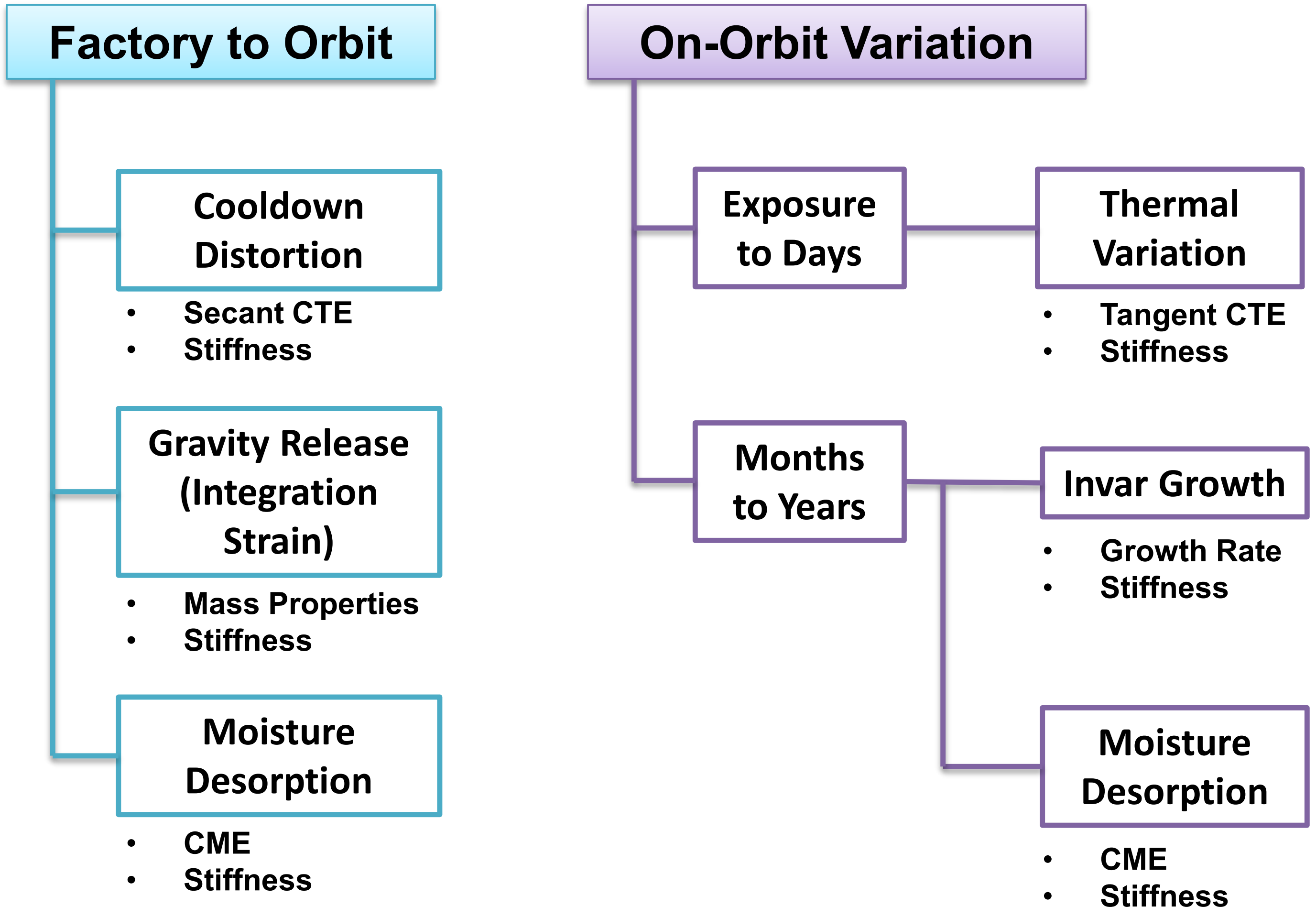
STOP Analysis Introduction

- **STOP = Structural Thermal Optical Performance**
  - Thermal model captures temperature changes due to cooldown (factory-to-orbit) and on-orbit operation (slews)
  - Temperature changes applied to structural FEA model generate quasi-static loads, resulting in displacements and rotations of mirrors and other critical structural components
  - Structural model outputs (displacements/rotations) are superimposed upon nominal positions/orientations of mirrors in the optical ray-trace model
  - Optical analysis is performed either by using a linear optical model (LOM) or full ray-trace model (Code V or Zemax) to provide optical performance metrics



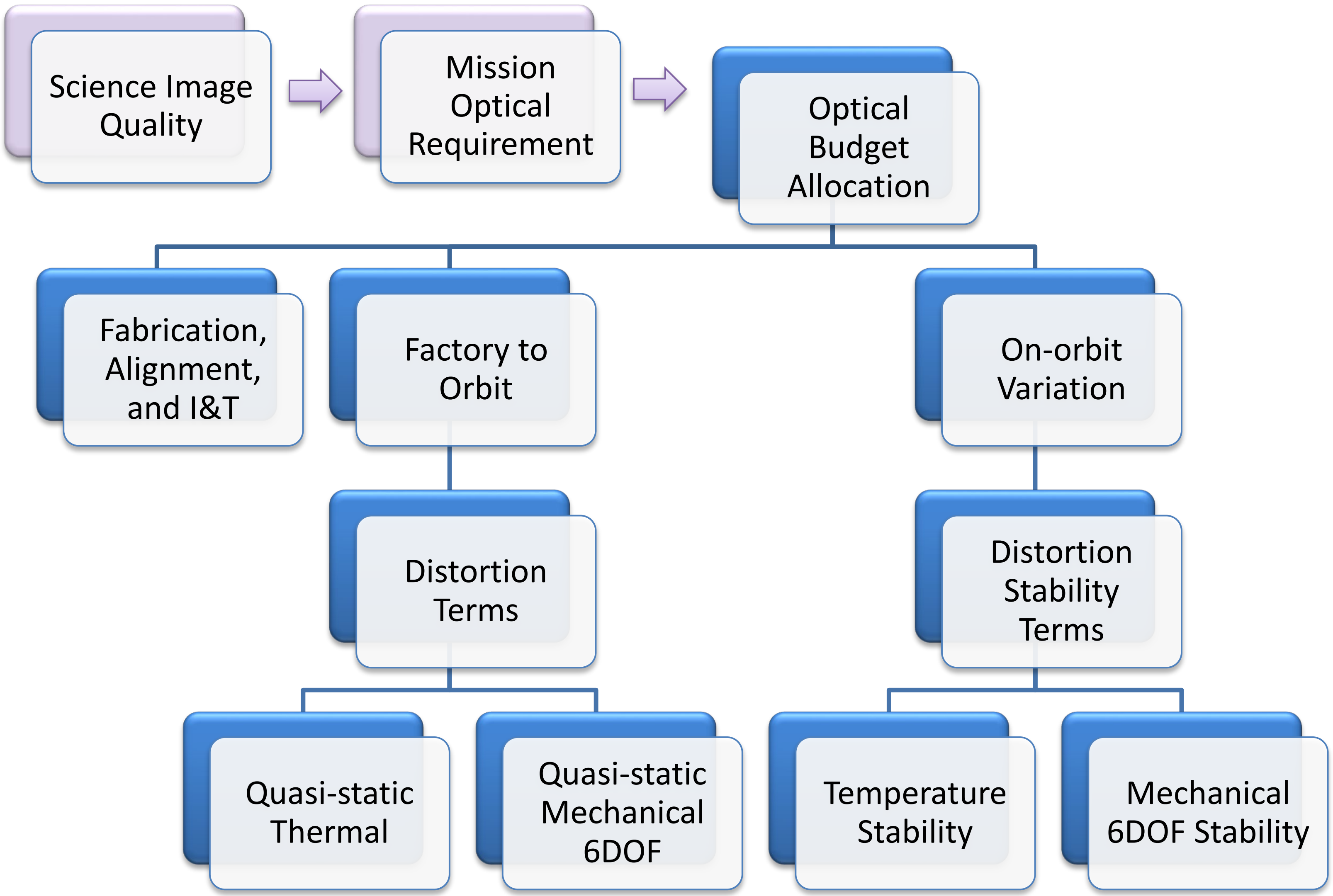
Typical STOP and STOP-Like Effects

- **IM STOP analysis includes thermal distortion and "thermal distortion like" effects**
- **Thermal distortion analysis evaluates cooldown and on-orbit thermal variation effects**
  - Secant and tangent Coefficient of Thermal Expansion (CTE) assumptions are critical to this analysis
- **Moisture desorption**
  - Swap Coefficient of Moisture Expansion (CME) for CTE and moisture fraction for temperatures
- **Gravity release**
  - Apply 1G loads to thermal distortion model
- **Invar growth**
  - Change CTE to invar growth rate



STOP Requirement Flowdown

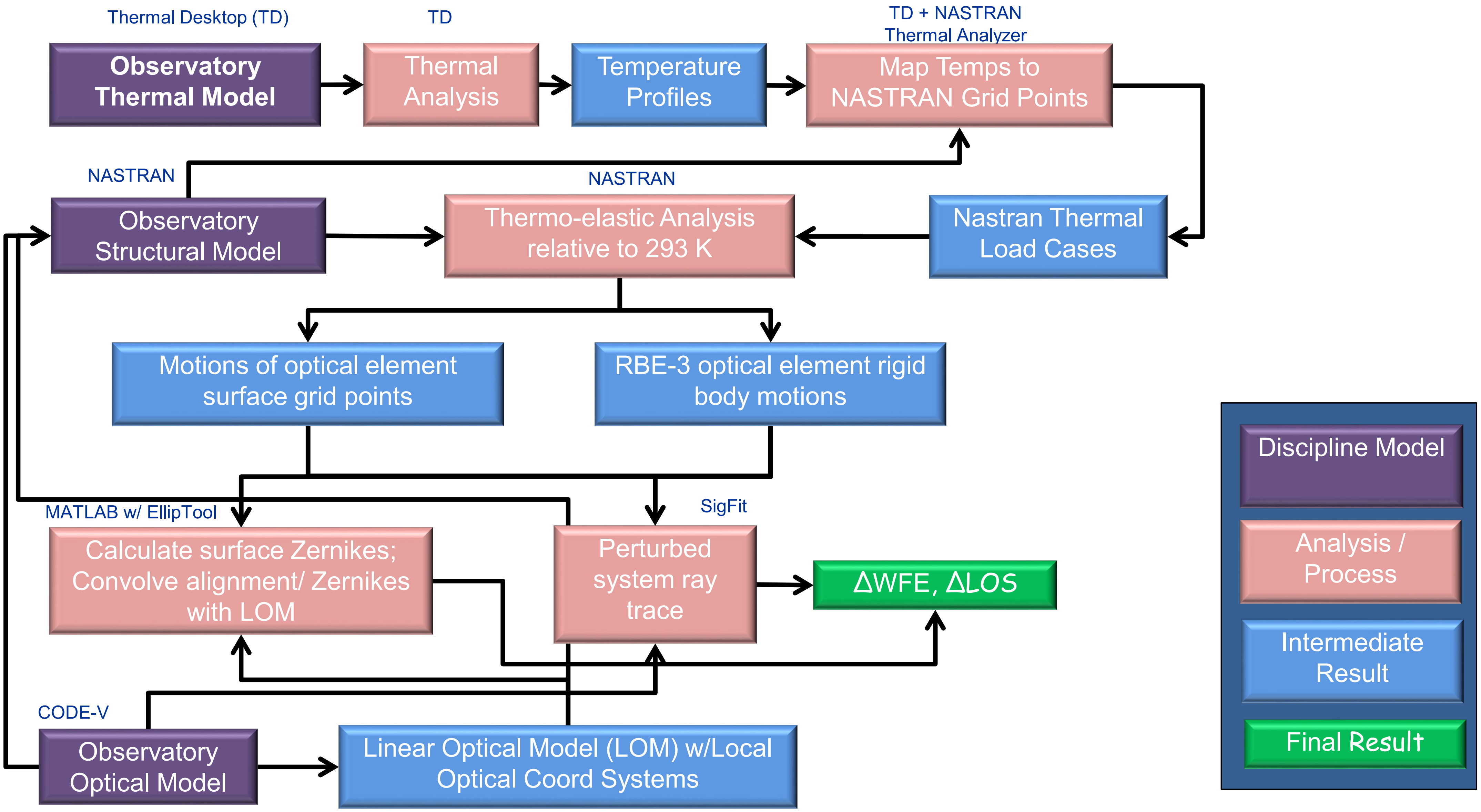
- **Image quality or wavefront error (WFE) requirements can be sub-allocated to different components via an optical error budget**
  - Optical error budget is typically an "RSS" budget
  - This approach is conservative since the end-to-end system has internal cancellation, not captured by RSS budgeting
- **IM provides optical predictions due to various distortion effects to validate error budget**
- **IM also generates optical sensitivities to 6DOF mechanical motion and temperature variation which can be used to flow mechanical alignment and temperature requirements**



Quasi-static Perturbations and Mitigation Options

- **Ground-to-Orbit Effects**
  - Cooldown and gravity release cause alignment and figure errors
  - Mostly mitigated by ground optical verification tests (e.g. cold figure and/or cold alignment, alignment bias for gravity)
  - Active thermal control systems to achieve desired temperature ranges
  - Use flight alignment compensators to correct for any test and model prediction errors during commissioning
- **Thermal Variations**
  - Change in attitude within field of regard, BOL to EOL property changes, power modes/transients
  - Active thermal control systems to minimize temperature changes
  - Concept of operation can be utilized to minimize change in Sun direction during observation if necessary
- **Moisture Desorption and Long-term Material Stability**
  - Change in optical alignment due to dryout and invar growth
  - Use flight alignment mechanisms for alignment error compensation *as necessary*
  - Work with ConOp to schedule focus and alignment adjustments
- **Active optics to control LOS, focus, and potentially higher order Zernikes to correct for slow varying perturbations continuously**

STOP Process

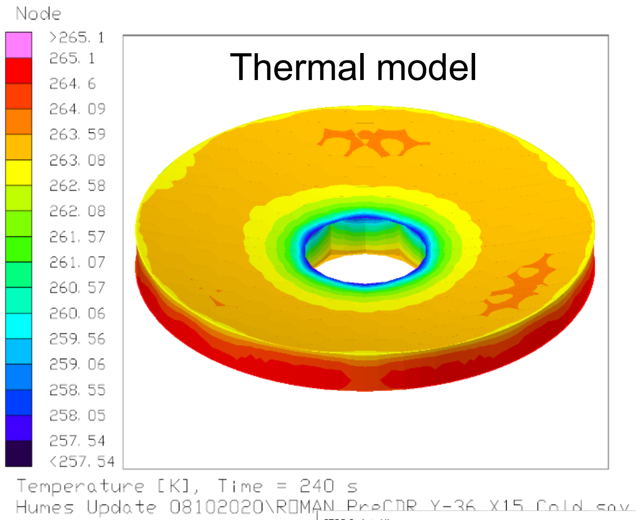


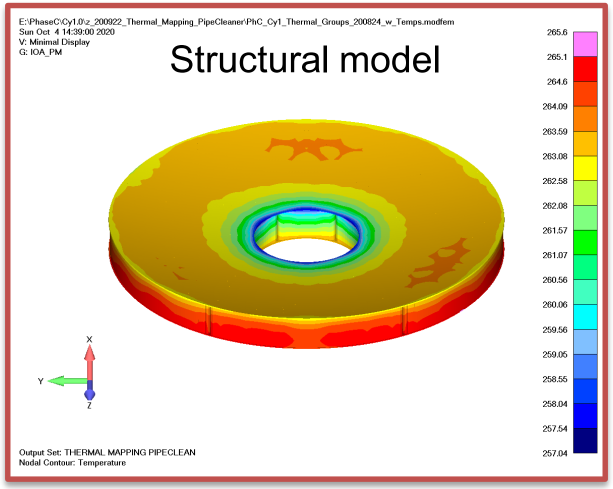
STOP Model Uncertainty

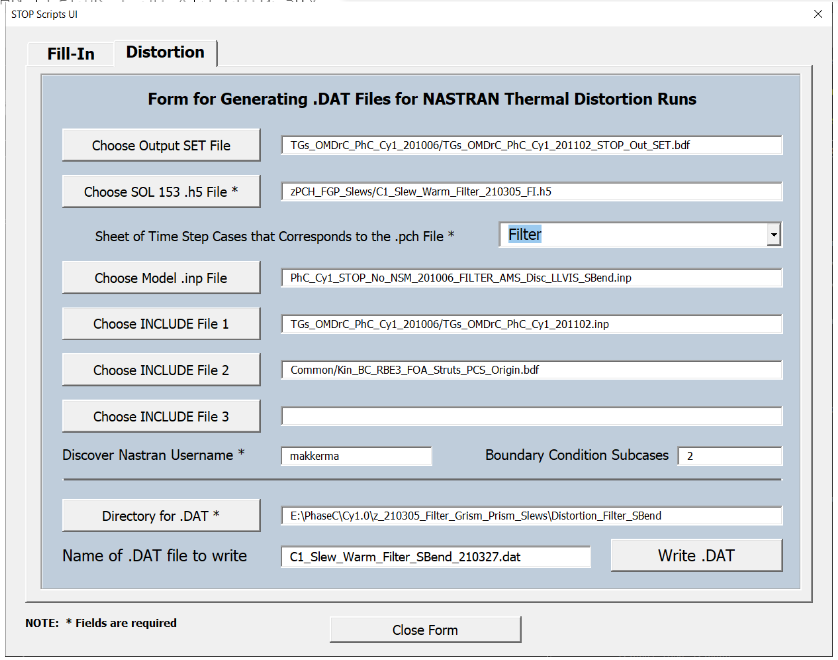
- **Model Uncertainty Factors are discipline level descriptions of historical model accuracy**
  - As a function of degree of test correlation
  - Does not play the same role as margin because they reflect the fact that we know the models are wrong
- **Material property**
  - Rely on coupon testing with measurement variability included in Monte Carlo analysis
- **Thermal**
  - Temperature setpoint and gradient errors
  - Derive an appropriate temperature MUF or use bounding assumptions to cover temperature prediction errors
- **Thermal distortion**
  - 542-PG-8700.1.1, "Structural/Thermal/Optical (STOP) Analysis Structural Model Uncertainty Factors"
  - Monte Carlo analysis to ensure that parametric error contributions are bounded
  - Breakout modeling to ensure that non-parametric error contributions are bounded
- **Gravity release**
  - JWST inherited factor of 1.16 on distortion data
  - RST uses 1.1 on distortion data based on Optical Telescope Assembly experience
- **Moisture desorption and Invar growth**
  - Monte Carlo analysis to capture variations in key modeling parameters and set MUF based on Monte Carlo results

STOP Analysis Tools

- **Heritage STOP modeling and analysis software**
  - Thermal: Thermal DeskTop
  - Structural: MSC Nastran
  - Optical: Code V and Zemax
- **RST STOP "glue-ware"**
  - Thermal-to-Structural Mapping
    - Automated generation of matching temperature contours by group in Thermal Desktop and Femap
  - Structural-to-Optical
    - EllipTool (Elliptical Engineering) uses Linear Optical Model (LOM)
    - SigFit (Sigmadyne) links structural distortion results to both LOM and full ray-trace optical model
- **Highlights on RST developed tools and processes**
  - STOP Monte Carlo
    - Using SigFit/Zemax LOM and NASTRAN SOL 200 (sensitivity/optimization engine)
  - Prediction of element-level performance using boundary condition subcases
  - Substantial reduction in Nastran run time from structuring the model so as to be able to remove non-structural mass from the bulk data in analyses where mass does not matter
  - Double precision temperatures from Nastran SOL 153 using HDF5 file format and a Python conversion script
  - Checking of temperature variation with time for each thermal group







Thermal Model Validation Approach

- **Perform early risk reduction thermal testing to measure key conductances (heat strap interfaces, conductive path to radiator) and material conductivities at cryogenic temperatures**
- **Perform sensitivity analysis to inform optical sensitivity to thermal parameters**
  - Determine component uncertainty and evaluate prediction against requirement margin
  - Determine additional testing (if any) required to validate transient model
- **Thermal vacuum and balance tests**
  - Steady State Thermal Balance testing performed for thermal model correlation and verification of the thermal design
    - Validated element level models delivered and integrated into Observatory model
  - Use hot-to-cold transition data for transient model correlation
    - Levels, ramp rates and durations used will bound worst-case flight expectations
    - Transient tests are being considered for model correlation and to directly validate the adequacy of the thermal design for stability
  - Dedicated setpoint step change thermal test for transient correlation
  - Demonstrate heater control capabilities to meet required temperature stability and adjustment (i.e. tuning) if necessary
  - Demonstrate temperature stability

Integrated Modeling

Structural Model Validation Approach: Thermal Distortion

- **Material characterization at component levels for all composite laminate components**
  - Coefficient of thermal expansion (CTE), coefficient of moisture expansion (CME), Young's modulus (E), Poisson's ratio (ν), and strength measurements
- **Distortion measurements can be achieved through either direct structural displacement measurements (e.g. photogrammetry, laser radar/target, distance measuring interferometry, etc.) or indirect optical measurements through flight optical system**
- **Leverage optical verification and alignment tests to validate models used to predict cooldown, gravity, and long-term stability**
  - Optical tests at operational temperature and bounding environments
  - Gravity loading and flip test
  - Vary stability sensitive components at specified frequencies and use interferometer to measure WFE changes
- **Changes due to moisture desorption and invar growth are too slow to be detected during ground testing**
  - Rely on material testing or heritage database to bound CME and invar growth rate
  - Perform Monte Carlo analysis to validate MUF

IM STOP Summary

- **STOP modeling and analysis software are well established**
- **Typical GSFC missions are covered by heritage analysis tools and 542 established guideline on MUF**
- **IM supports optical requirement flowdown by determining performance sensitivities to mechanical motion and temperature changes**
  - Use IM early as an integral part of error budget development
- **Similar to jitter, managing STOP for large space telescope missions requires a multi-disciplinary team to develop thermal control architecture, specify interface conductance/isolation, design flight actuator to correct for long-term variations, and utilize ConOp to minimize environmental changes**

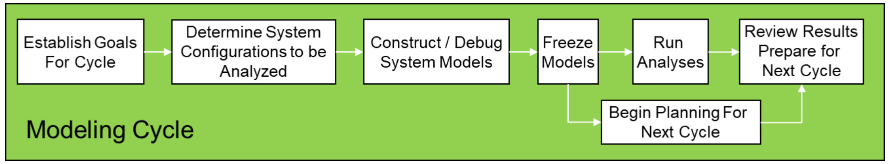
Integrated Modeling

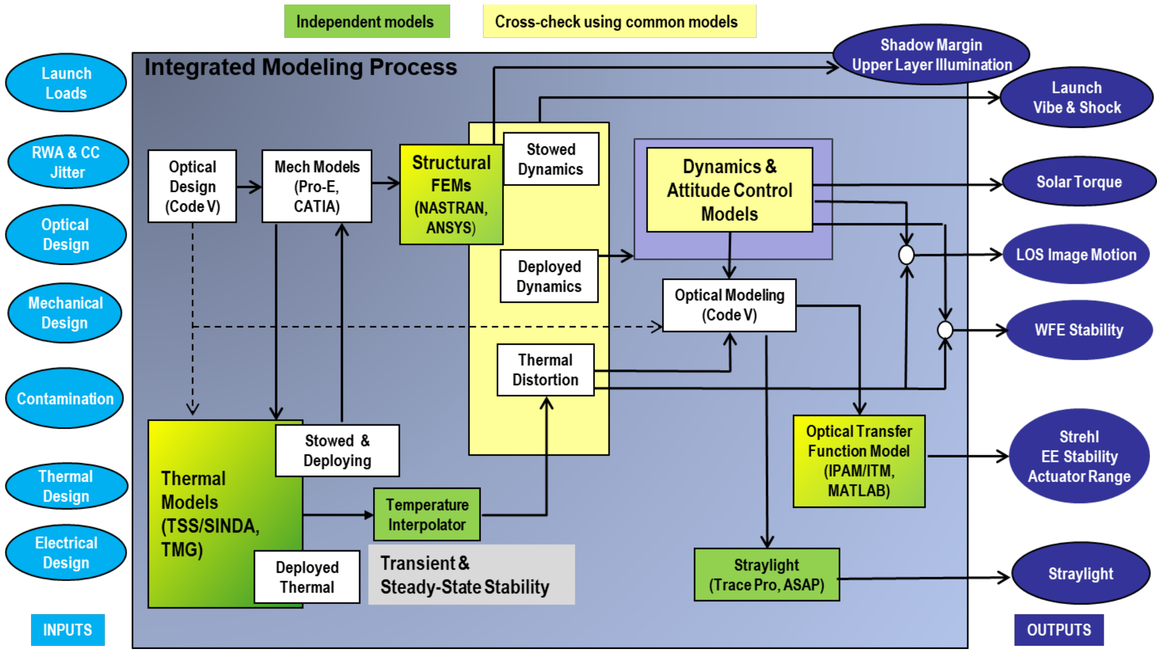
FUTURE

IM – Case for Change

Based on 20+ years of doing IM on JWST:

- **We accomplished a lot, and we learned a lot**
- **We have some good ideas about how to do it better the next time**
- **RST is already doing some of those things, and then some**



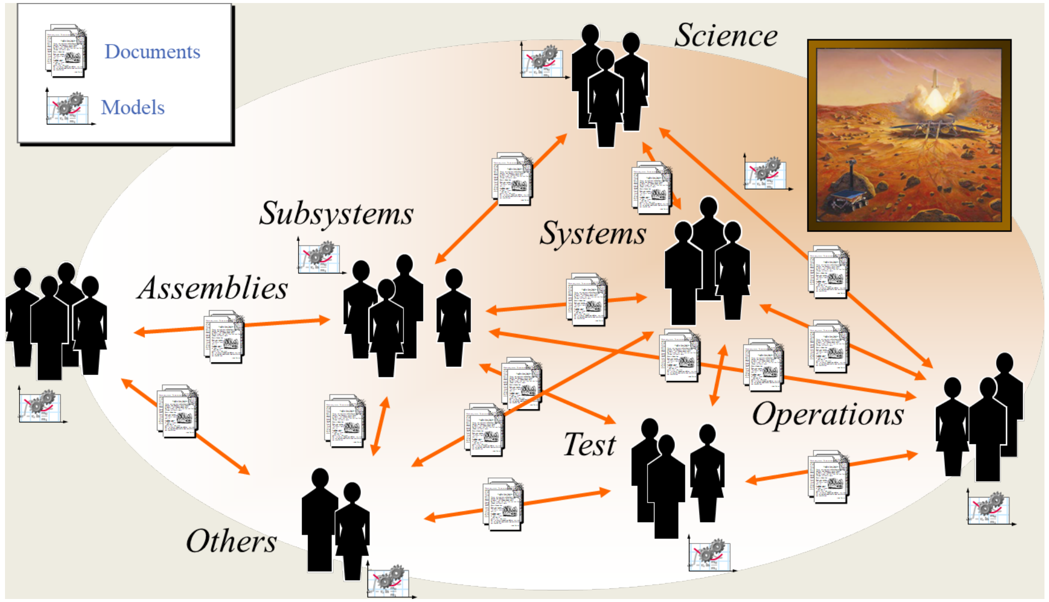


- **Process leverages best-in-class CAE tools, however, driven by required predictive accuracies, hi-fidelity models are huge, negatively impacting time required for:**
  - Model development, V&V (of models)
  - Computation, analysis, review, documentation
- **Significant management effort required to coordinate and execute end-to-end multidisciplinary analyses**
- **Heavy reliance on fragile and mission (model) specific "glue-ware" at tool interfaces**
- **Many inputs still pulled from documents, not linked tools/data**
- **Large data sets manually pushed through pipeline via servers**
- **Summary:**
  - Not exactly robust
  - Not exactly efficient
  - Long modeling cycle times
  - Often, little time available to effectively use models to explore trades or to truly identify and understand system-level complexity
- **Non-technical issues:**
  - Some (many?) problems are coupled with project acquisition (contracts, work packages)
  - During pre-formulation for large, complex projects, put as much effort into scoping the IM effort as the I&T effort, for the sake of reliable cost and schedule estimates

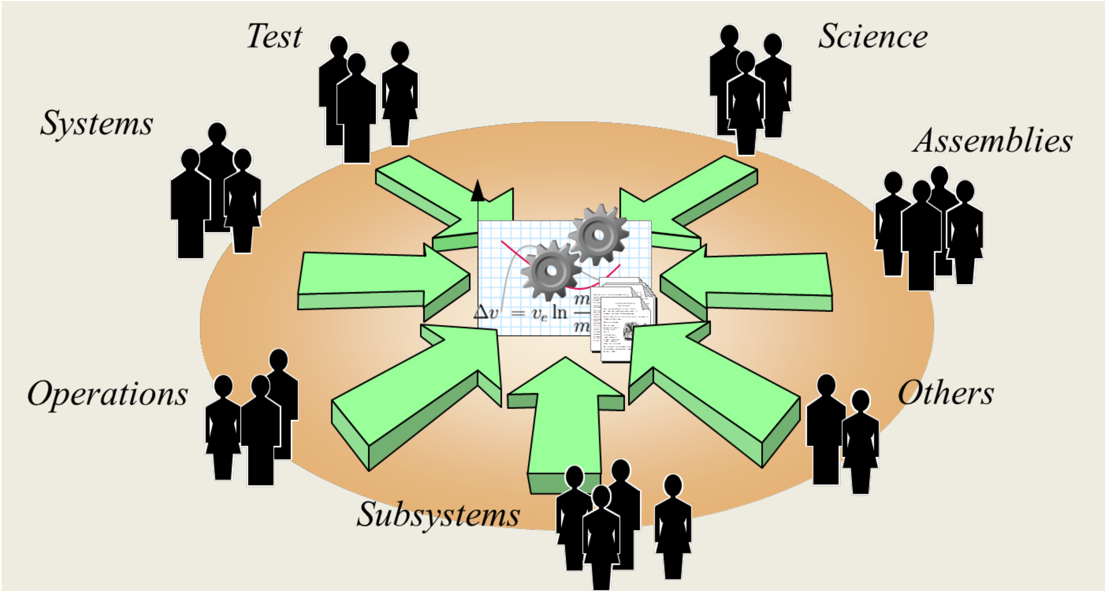
Improved IM in the Context of "Digital Transformation"

The Systems Engineering (SE) leadership role remains unchanged, however, the ever-increasing complexity of missions, both in terms of technology and partnership approach, requires us to evolve our technical management capability with commensurate tools…

Away from this (document- based)



Towards this (model-based)



GSFC IRAD: Strategic Investment Goals for Evolution of IM

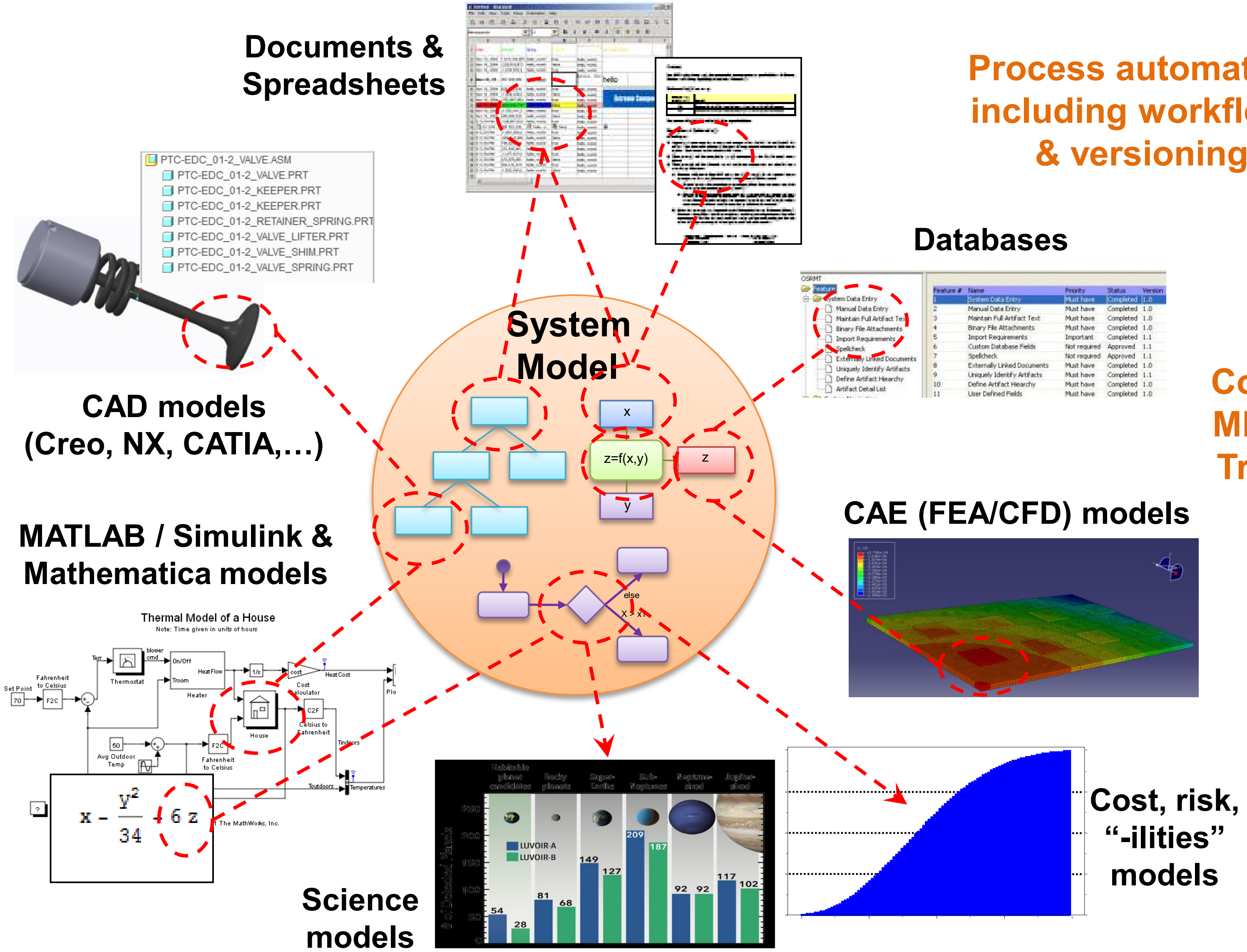
Expand beyond the current opto-mechanical toolset

Interface & data standards

Can't avoid "glue-ware" <u>entirely</u> but we can "do glue-ware right"

Less manual effort

Exploit advanced analytical methods



Process automation, including workflows & versioning

Coordinate with MBSE & Digital Transformation

(Trial) Solution: ModelCenter – Phoenix Integration, Inc.

- ModelCenter Integrate
  - **Automate**
  - **Integrate**
  - To Create a Workflow

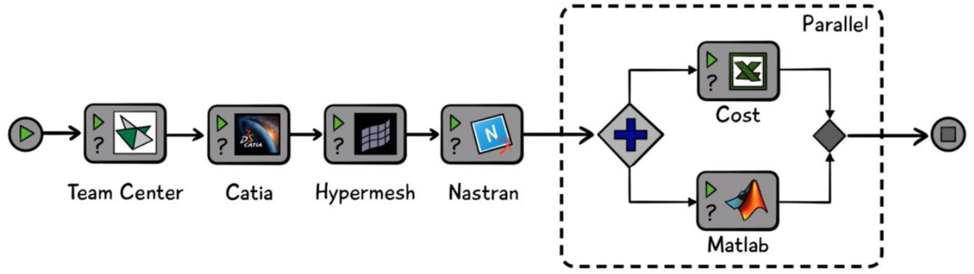
- ModelCenter Explore
  - **Iterate** The Workflow
  - Design Studies
  - Optimizations
  - Risk/Reliability

- ModelCenter MBSE
  - Integrate **Systems Engineering** Models with **Analytical** Models.

Integrated Modeling

ModelCenter Integrate

Connect models
Link inputs and outputs
Automate workflow execution



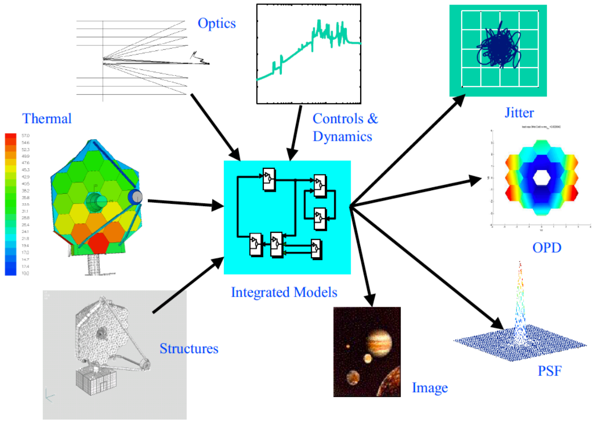
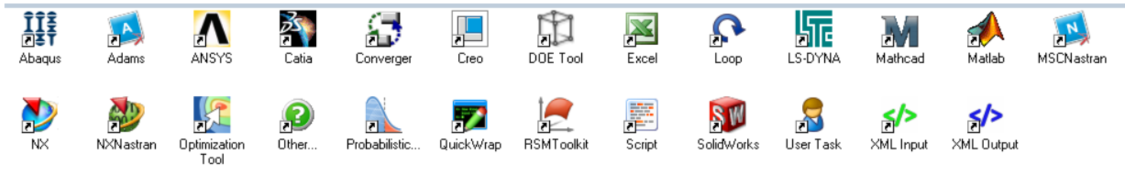
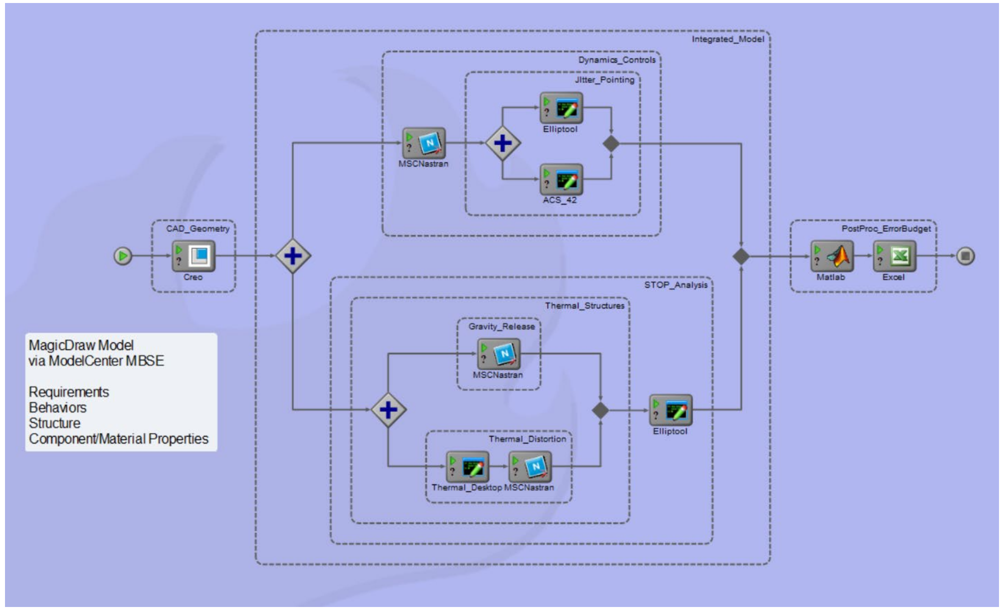


Figure 2: Integrated Modeling for JWST

Out-of-the-box plug-ins for many common CAD/CAE tools, general-purpose tools (Matlab, Excel)





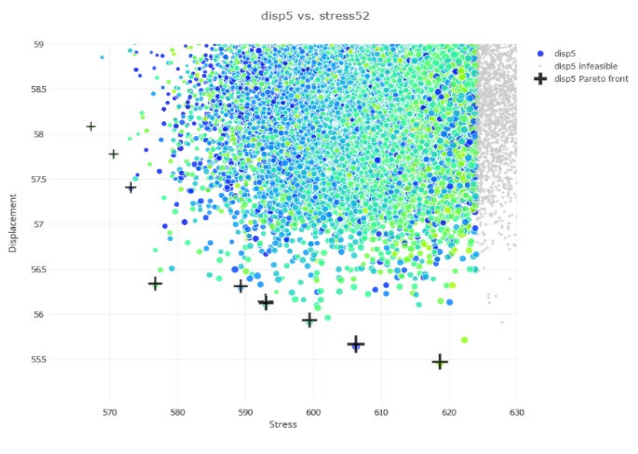
One of the IRAD tasks involves creating a plug-in for Thermal Desktop, and we plan to look at one or more plug-ins for optical tools (Code V, Zemax, etc.)

Integrated Modeling

ModelCenter Explore

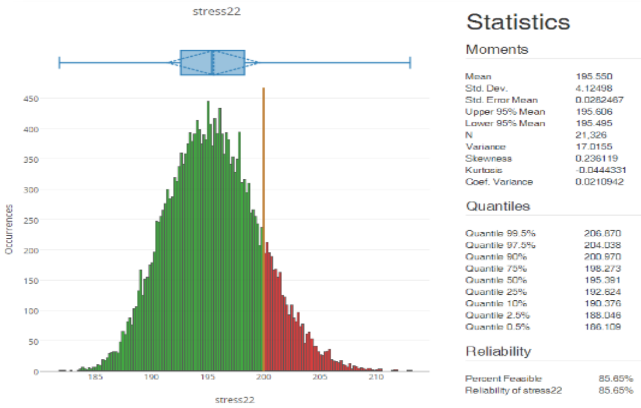
Rapid execution and visualiztion of complex, multivariate analyses via GUI (no coding required)

Sensitivity Analysis



Trade Space Visualization

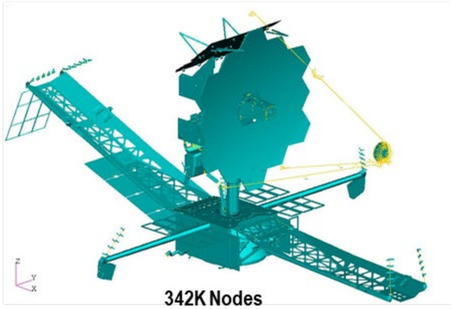
Optimization

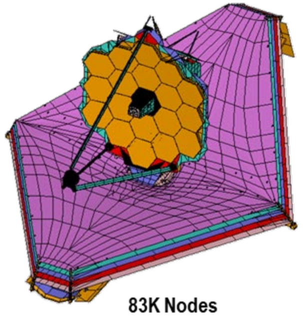


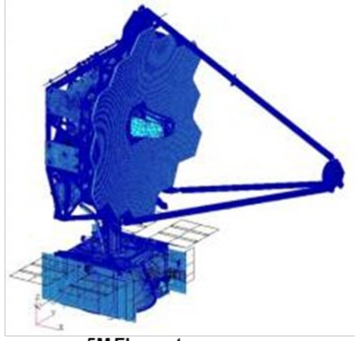
Probabilistic Analysis

Key to ModelCenter Explore: Surrogate Modeling

- **Synonyms: Response Surface Methods, Multi-fidelity Modeling**
- **Importance to Integrated Modeling:**
  - combination of large models and some codes (e.g. Sinda) that don't lend themselves to parallelization → long run times → limited parametric studies, sensitivity analyses, optimizations, UQ, etc.



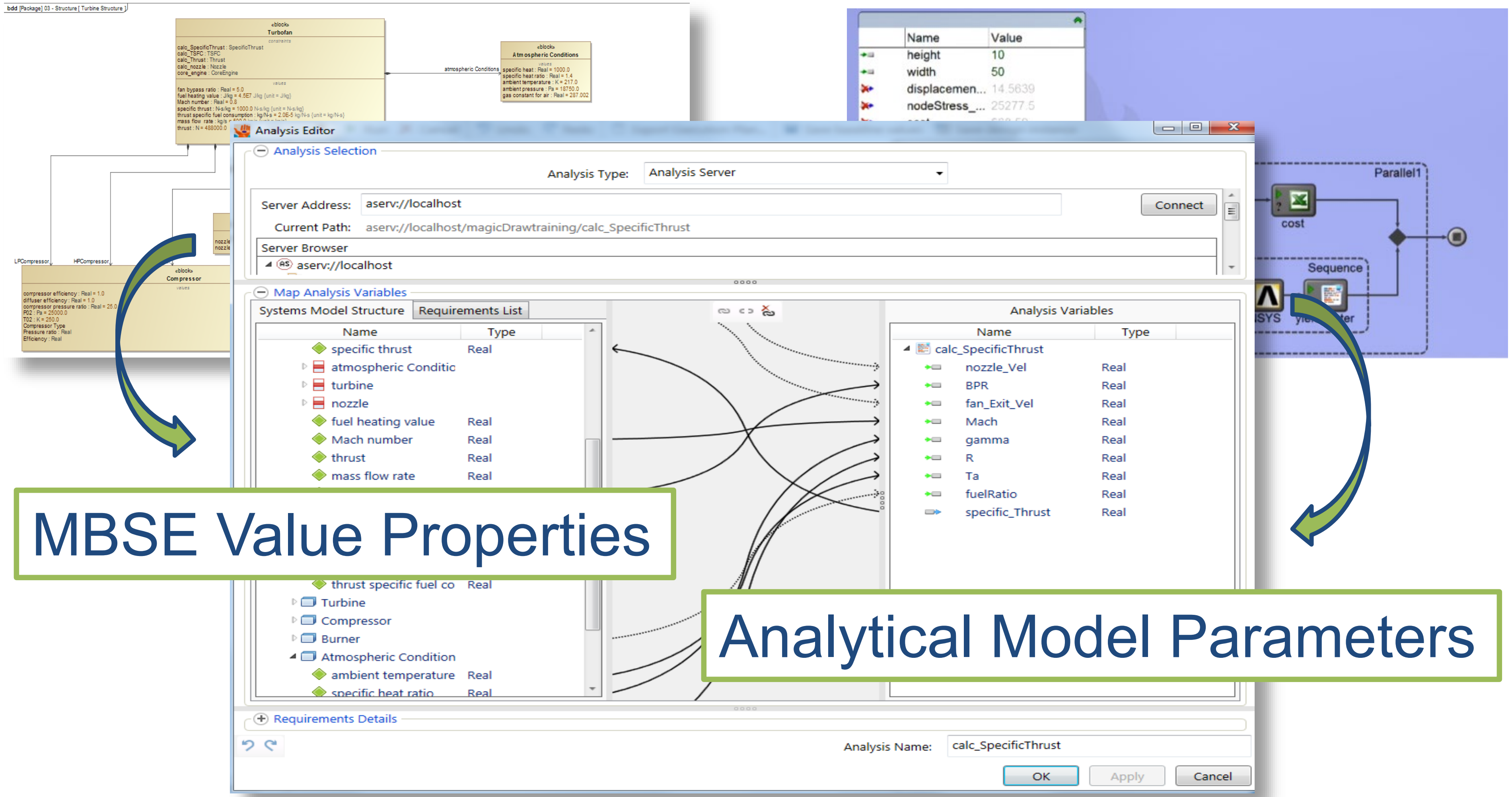




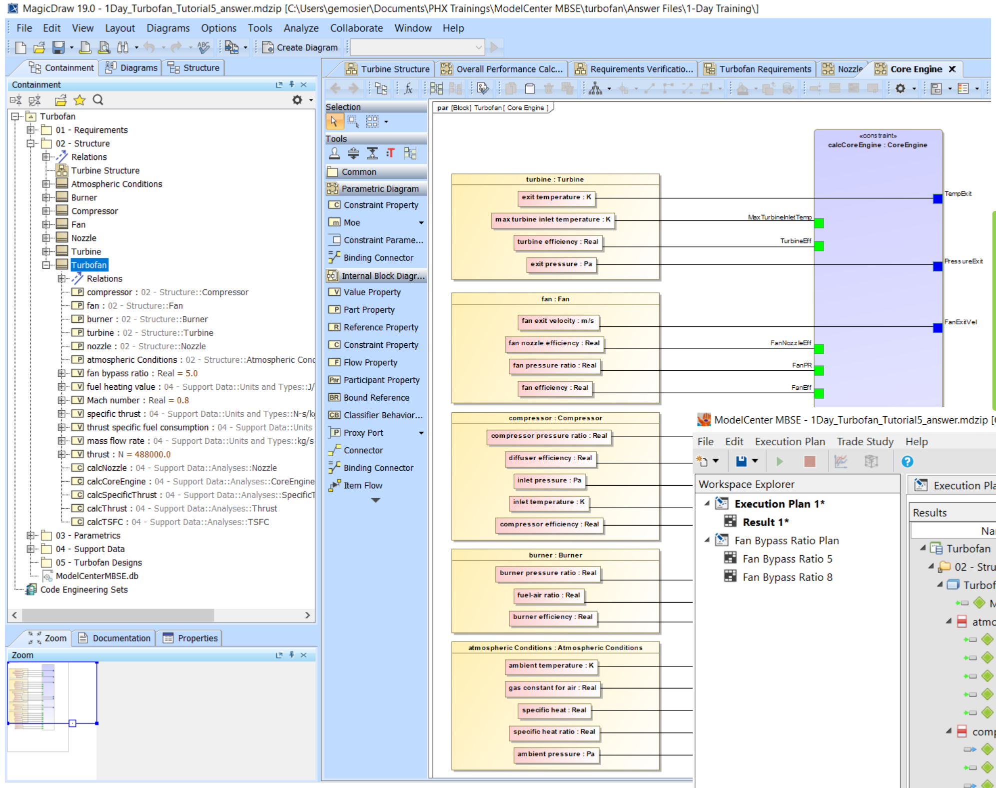
- **Basic Principle:**
  - Run the hi-fidelity, CPU-intensive simulation code a limited number of times, optimally spanning the domains of the independent variables, to develop a "training set"
  - Find one or more lo-fidelity approximations (think "multidimensional curve fits") to the hi-fidelity models
  - Use the lo-fidelity approximations for analyses that require 100's/1000's of runs (Optimization, Uncertainty Quantification, Test-Model Correlation)
  - Methods allow for trade-offs between efficiency (run-time), accuracy (hi-fi/lo-fi correlation), and range of validity

ModelCenter MBSE

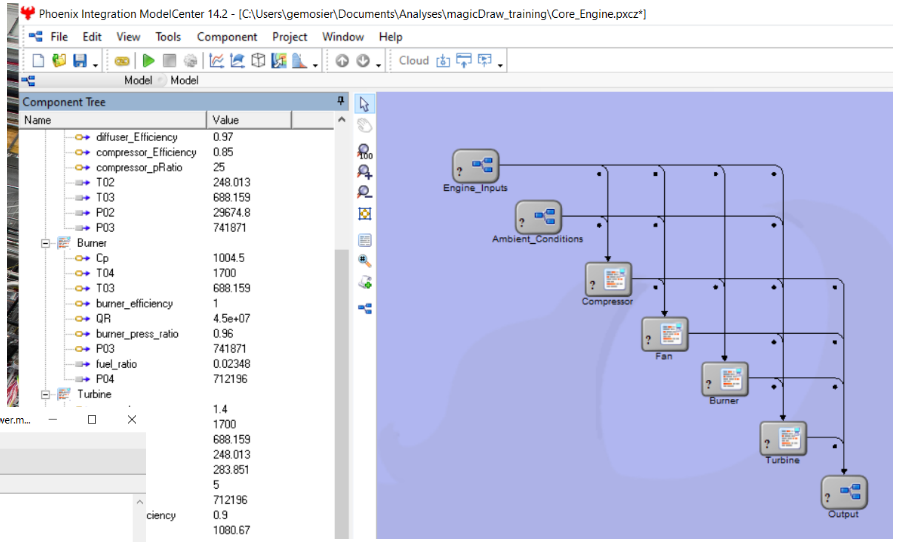
Linking SysML with Analysis



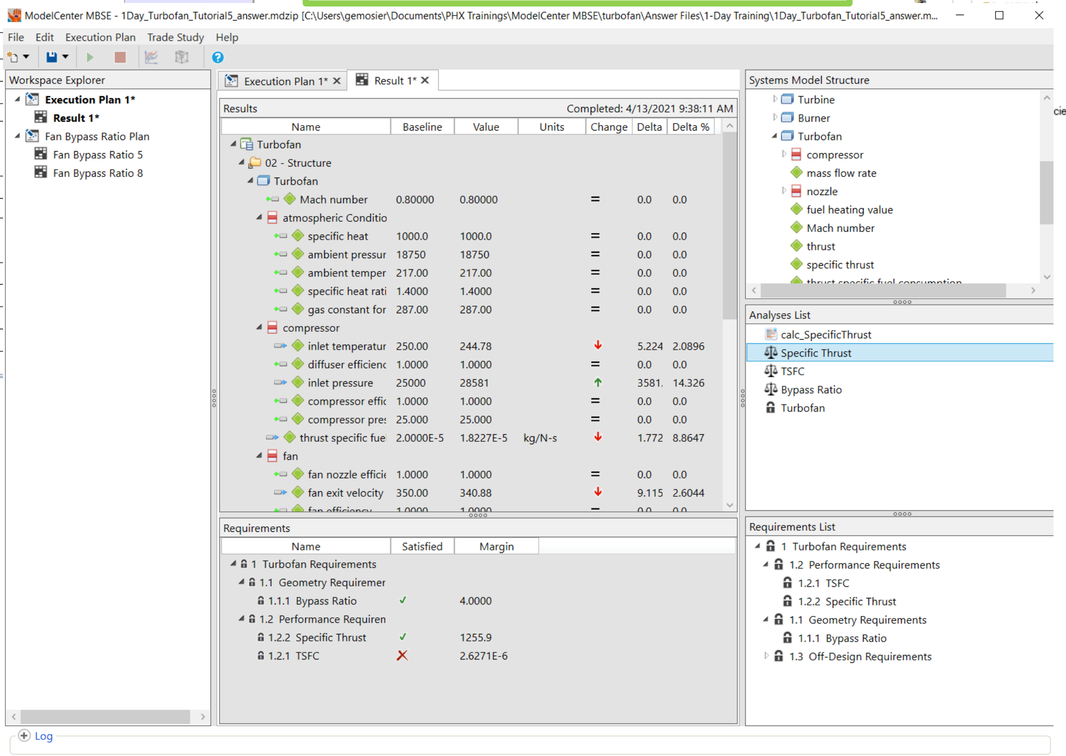
Use Case: Requirements Verification



MagicDraw Model w/ Parametric Diagram



ModelCenter Data Workflow for Integrated Performance Model



ModelCenter MBSE links requirements, parameters, analyses

Integrated Modeling

Why ModelCenter?

- **Alternatives considered included the following, but we felt there would be way too much software development effort required to be up-and-running quickly, particularly for the desired two-way connectivity between the MBSE domain and the physics domain:**
  - DAKOTA (Sandia National Labs)
  - OpenMDAO (Python-based, NASA/GRC, OpenMDAO.org)
  - UQTools (Matlab-based, NASA/LaRC)
- **ModelCenter advantages:**
  - Two-way connectivity to MBSE tools (MagicDraw, Rhapsody, Gensys, Windchill Modeler)
    - Development partially funded by NASA SBIR: S5.04-9920 (2012-P1)
  - Functionality of desktop client is moving to the cloud, including connectivity to OpenMBEE (JPL)
    - Development partially funded by NASA SBIR: S5.04-3336 (2019-P1,2020-P2), H6.04-5764 (2020-P1)
  - Pre-built, out-of-the-box plug-ins for many of NASA's CAD/CAE tools, plus a set of standard methods for rapid integration of new tools ("glue-ware done right")
    - Also includes a generic plug-in ("QuickWrap") allowing the integration of any engineering tool that has an API or can be run in command line mode with input/output files and arguments
    - Doing some programming to create a new software-specific plug-in is the most powerful and robust solution for "production tools" (e.g. what we're trying to do with Thermal Desktop)
  - GUI significantly speeds up development of integrated models, analysis set-up, results visualization

Integrated Modeling

SUMMARY

Integrated Modeling Summary

- In a sense, the phrase “nothing new under the sun” comes to mind when looking back at what had been done in the late 70’s, and that’s true fundamentally, but a lot has changed
- NASA has accomplished a lot over the past 25 years in this area
- The systems that NASA seeks to develop and operate are increasingly complex, with ever more-demanding functional and performance requirements that, in turn, are driving requirements for model accuracy
- Demands on model accuracy drive requirements for model fidelity, size and complexity, and also place significant emphasis rigorous on model verification and validation
  - Aside: One significant regret in that flight projects aren’t doing enough to validate models after launch (not enough useful it-situ measurements are available, don’t want to distract from mission goals)
- Computers and tools are much more capable, and will continue to improve, but…
- … without some process breakthroughs this all adds up increased work – both technical and process/management-oriented – in an often resource-limited environment
- We can sustain and improve our IM capabilities – and this includes a cadre of knowledgeable people in addition to tools and all the rest – but this will require continued investment and process improvement