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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

System-level Thermoelastic Distortion Analysis for Structural-Thermal-RF Performance Assessment on SWOT

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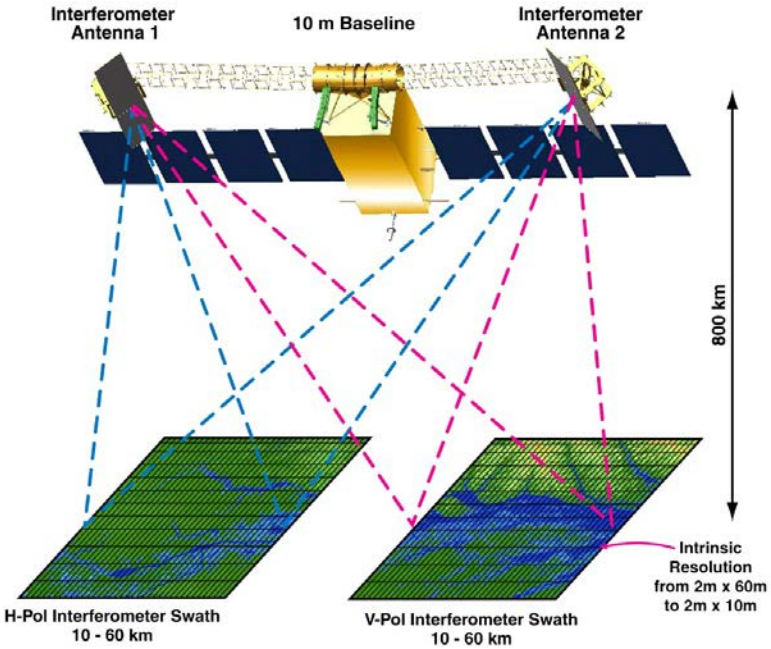
Overview

- SWOT Mission Overview
- STOP Analysis
  - Analysis procedure and basic error descriptions
- Structural FEM
  - Considerations for thermal expansion analysis
- Temperature mapping from Thermal to Structural model
- MATLAB Automation of STOP analysis
- Model Assumptions
- Summary and Challenges

SWOT Mission

- SWOT is Surface Water and Ocean Topography
- Collaboration between NASA and CNES
- Uses Ka-band radar interferometry to measure the depth of surface water across the Earth
- High resolution RF performance demands extremely strict performance requirements.
- RF support structure is designed for thermal stability

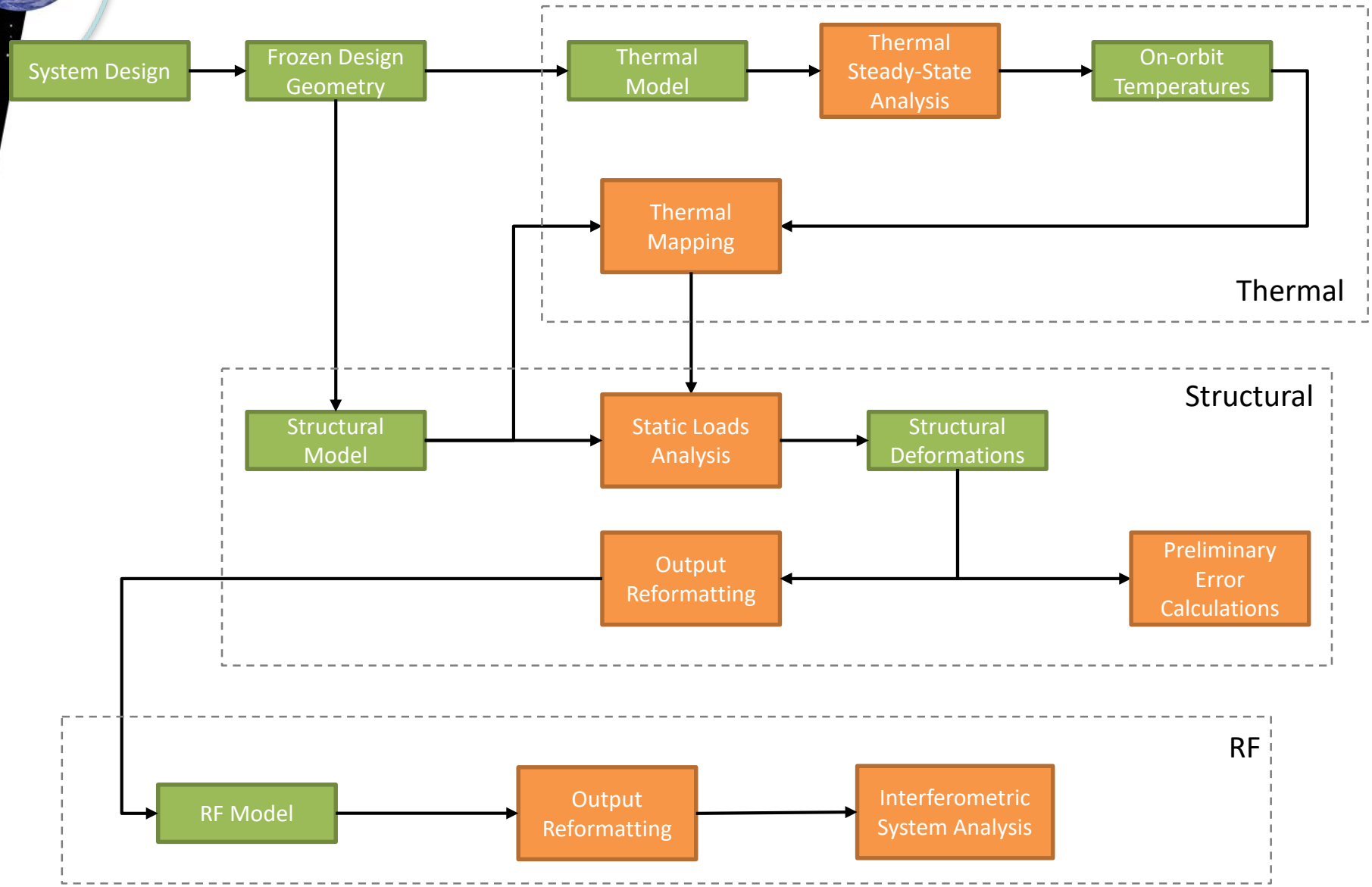


STOP Analysis

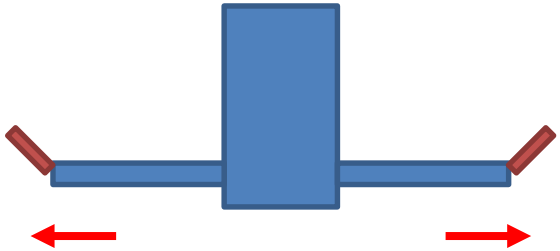
- Structural-Thermal-“Optical” (RF) Performance Analysis is used to assess the effects of thermal distortion on radio-frequency (RF) performance.
- End-to-end analysis that involves thermal, structural, and RF analysis teams.

1. *Thermal simulates Earth orbits at several beta angles and recovers steady-state temperatures across the observatory.*
2. *Structural applies the mapped temperatures to the structural FEM and uses static analysis to recover deformations of antenna panels and feeds.*
3. *RF applies deformations to an RF model and uses a performance metric to predict system performance.*

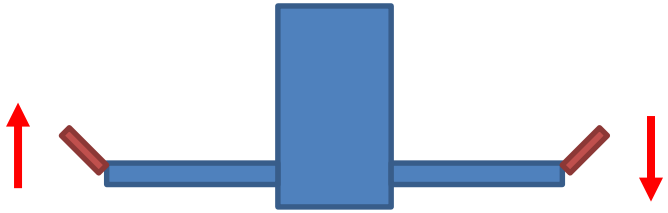
STOP Analysis



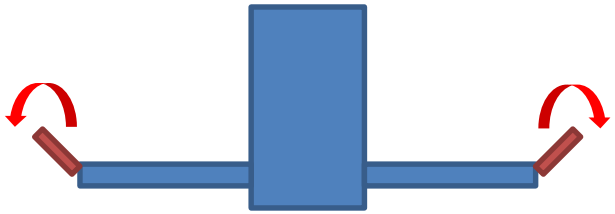
Simplified Antenna Errors



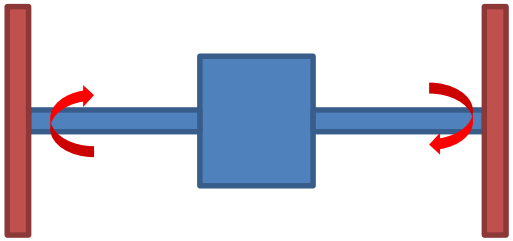
Baseline length error



Roll error



Elevation pointing error

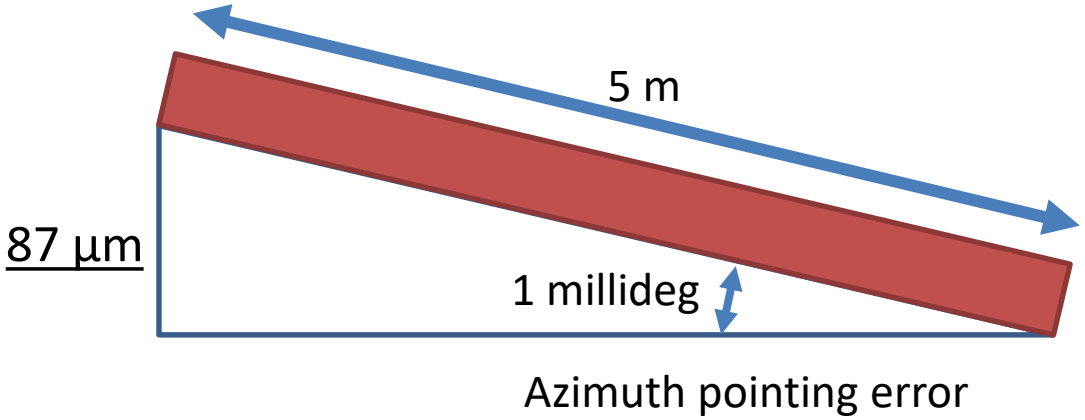


Azimuth pointing error

Also Phase error, Common Pitch error, Relative Azimuth error, Startracker Pointing error, Nadir Instrument pointing/position errors

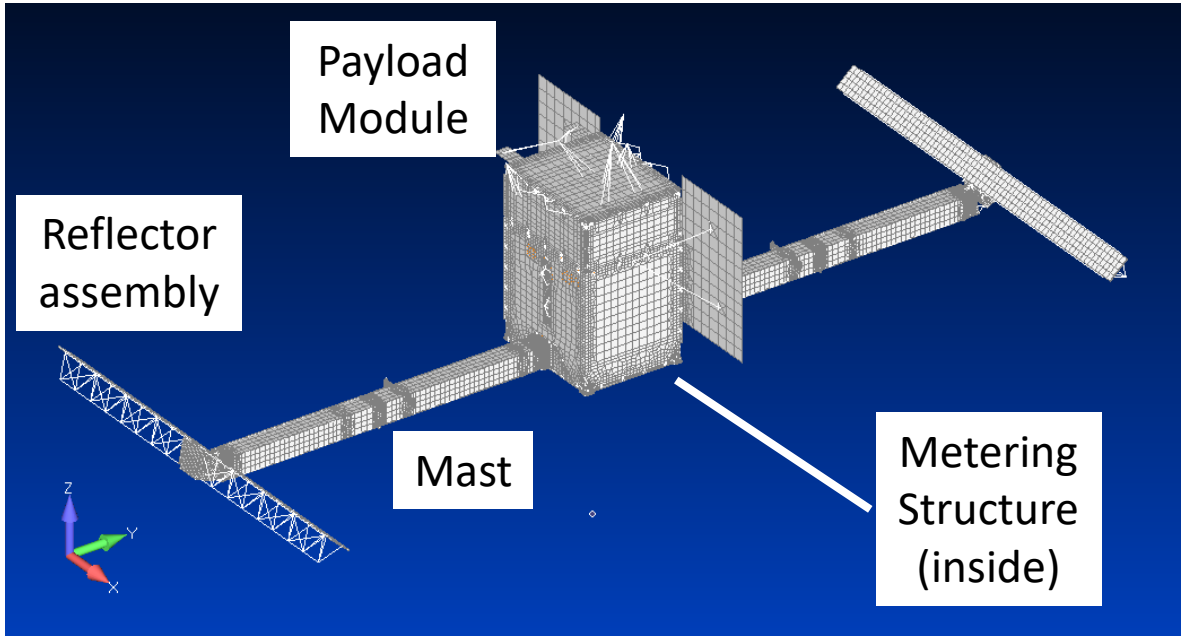
SWOT Error Requirements

- Pointing error requirements are in the range of millidegrees
- What is a millidegree?
  - Reflector array is about 5 meters
  - 5 meters x sin(1 millideg) = <u>87 microns</u>
- SWOT error requirements are very tight!



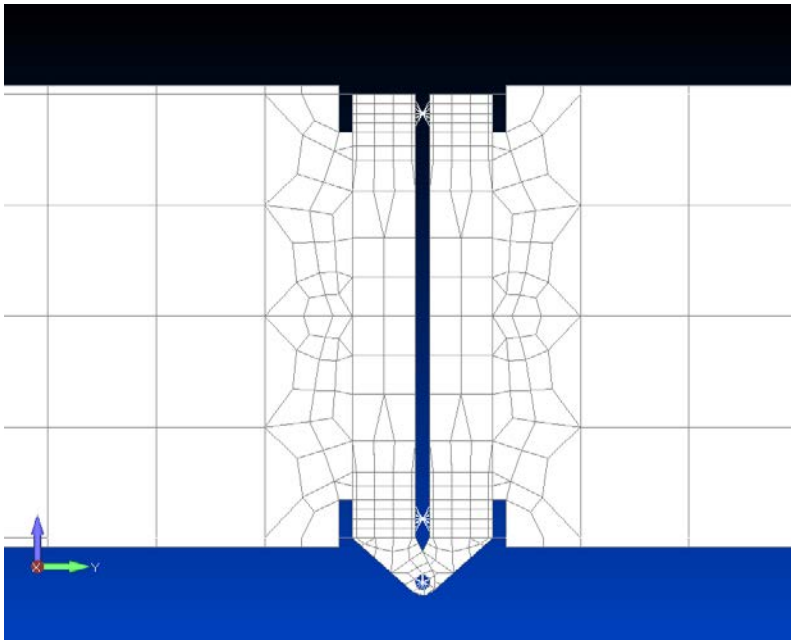
SWOT Structural FEM

- Stiffness model is generally good enough to capture thermal growth
- Model is delivered in pieces by subsystem analysts (payload module, metering structure, mast assembly, reflector assembly) and assembled into deployed configuration
- Model must be scrubbed for representative CTE on all materials and rigid elements
- Use NASTRAN card RIGID = LAGRAN to capture thermal growth of rigid elements (commonly used to represent simplified interfaces and joints)



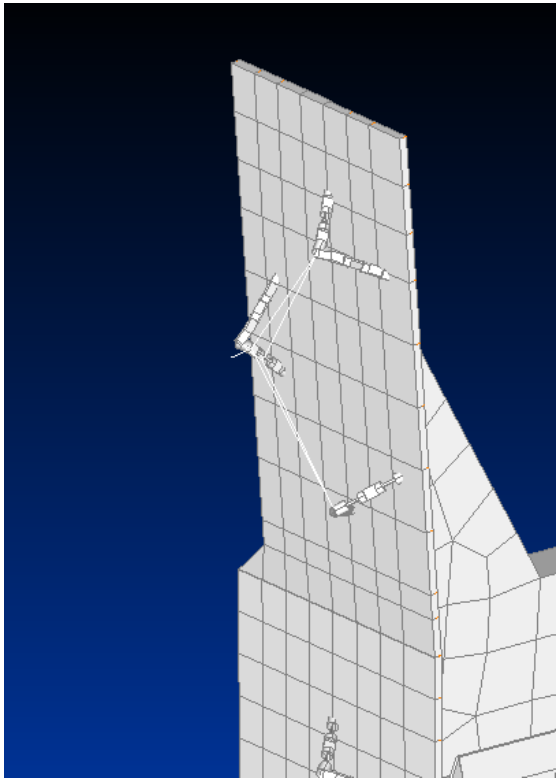
SWOT Structural FEM

- Deployed boundary condition: Fixed at single node with RBE3 element attached to 4 nodes on interior of metering structure (RBE3 is allowed to grow with the structure)
- Interaction with the spacecraft is not considered
- Extra care should be taken to capture CTE and length of simplified joints and fittings



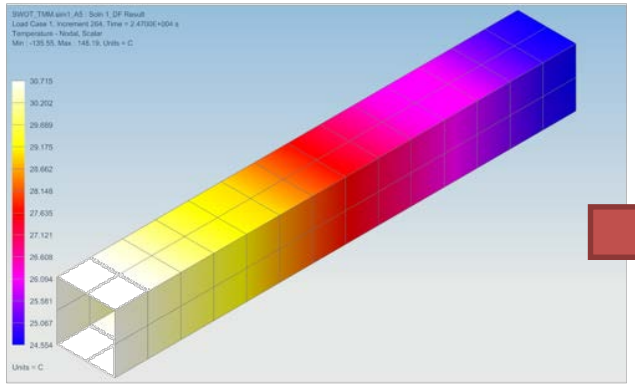
SWOT Structural FEM

- More thermal expansion details should be considered for this analysis
  - 1D elements can be added to get through-thickness expansion of 2D elements
  - Spring elements (no CTE) at interfaces should have coincident nodes to avoid creating rotations
  - Composite materials in boom tube are modeled to produce twist due to fiber layup

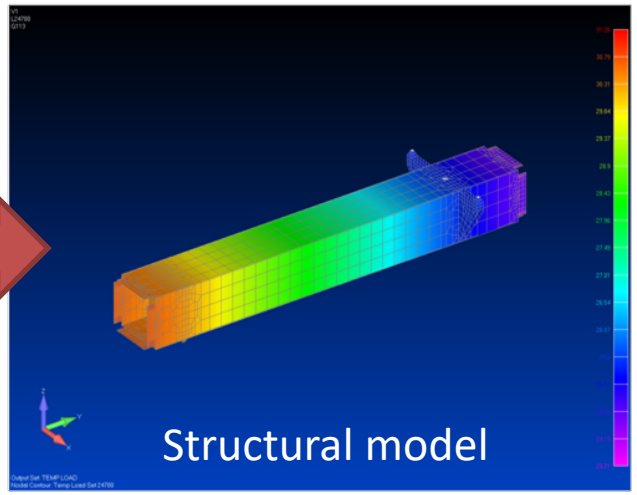


Mapped Nodal Temperatures

- Node/element geometry should match the thermal model so that temperatures can be mapped onto the structural FEM
- Temperatures are only mapped where elements overlap
- Some manual adjustment can be done
- Mapping can be verified by comparing plots of max/min/average temperature vs. time for several subgroups. Contour plots of a single timestep can also be used for comparing temperatures on the thermal and structural models
- Best practice is to “freeze” a geometry model for both Thermal and Structural to work to. Mapping is easiest when the models align.



Thermal model
(one timestep)



Automating the STOP Analysis

- 19 beta angles x 619 timesteps x 800+ output nodes
- Mapped temperatures, NASTRAN input decks, and results files are all text files
- Process can be automated using MATLAB scripting
  1. Reformat mapped nodal temperatures to TEMP cards
  2. Generate a solution deck for each beta angle
  3. Generate a batch file to run all solutions
  4. Post-process deformations to get preliminary error calculations
  5. Reformat node deformations for delivery to RF team

Assumptions

- Materials are linear elastic for small displacements induced by thermal loads
- CTEs are constant over the on-orbit temperature range
- Composite material properties are assumed valid until validated by test
- Temperatures are changing slowly and transient/dynamic effects are not considered
- Simplified interfaces/joints are able to capture thermal growth conservatively
- Thermal mapping successfully captures bulk temperatures and gradients seen in the thermal model

STOP Analysis Cases

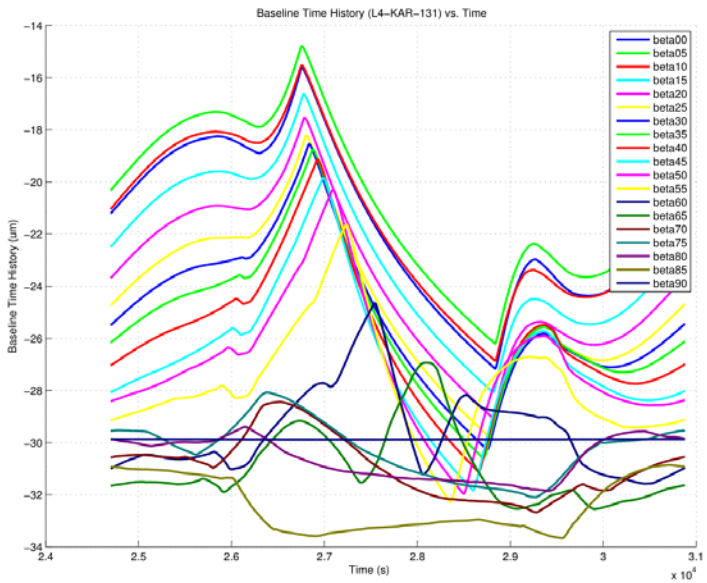
- Subsystem soak check
  - Apply 1°C soak to each subsystem separately
- Hot predictions, 10 second increments
  - Beta = 0, 5, 10, … , 85, 90
- Additional hot predictions for comparison
  - Beta 55 at 5 second increments
  - Beta 55 with yaw steering
- Cold predictions, 10 second increments
  - Beta = 0, 55, 90
- Subsystem comparison
  - Apply temperatures from predicts to each subsystem separately
- AFT predictions, 10 second increments
  - All hot predictions + 15°C
  - All cold predictions - 15°C
- Additional analysis:
  - IRA Athermalized truss study
  - Alignment mechanism thermal stability study

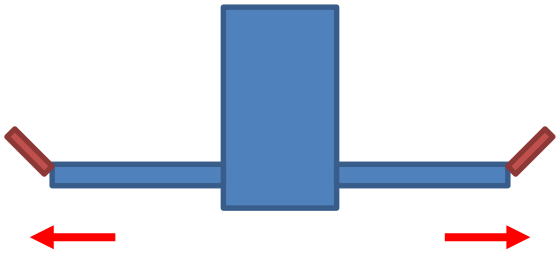
Lots of data:
50+ NASTRAN decks
100 GB mapped thermal data
10 GB deformed results

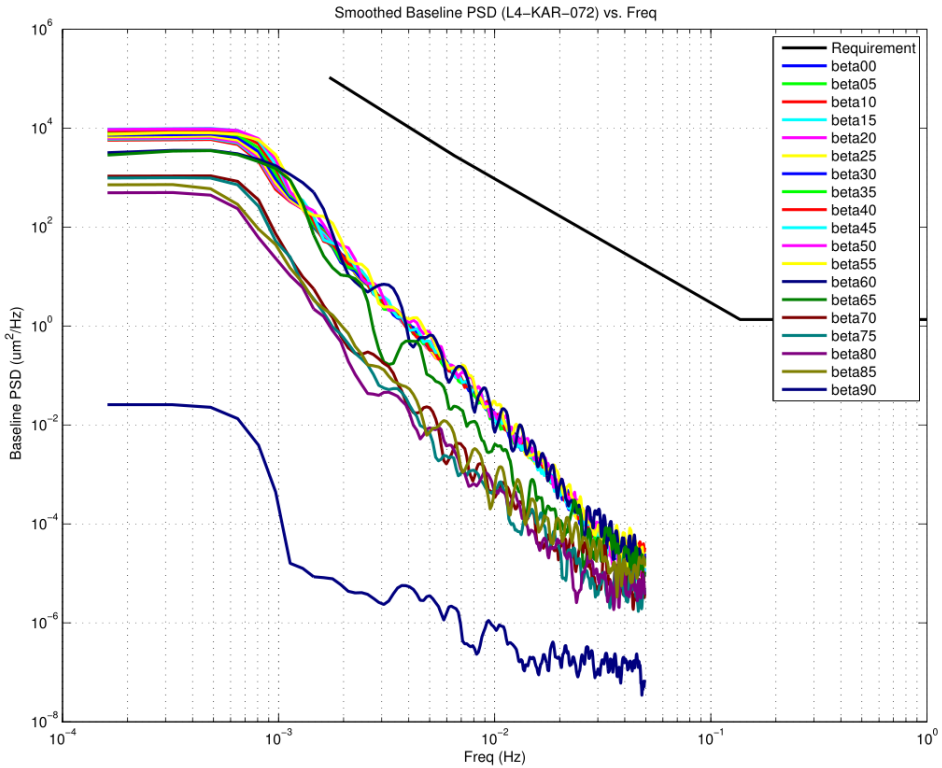
Sample Error Plots

Baseline Length Error
Time History
All orbits

Baseline Length Error
PSD vs requirement
All orbits







Repeat for other error calculations.

Summary and Challenges

SWOT STOP analysis completed in 2013 and 2015, next round scheduled for late 2016/early 2017.
2015 results showed SWOT is still on track to meet system performance requirements.

- Thermal mapping - structural must work closely with thermal to verify the mapping
  - Mismatch in models can map extreme temperatures
- Structural FEM – must make the effort to capture all physics of thermal expansion to reduce uncertainty
  - Capture all sources of thermal expansion, include nonlinear/temperature-dependent material where appropriate, etc.
- Data processing – RF and structural need clear communication regarding coordinate systems and data formatting to fully understand the delivery
- Timeline – frozen geometry is obsolete by the completion of STOP analysis. Errors/delays amplify the effect.
- Uncertainty – each step in STOP analysis adds more uncertainty
- STOP Analysis is a critical tool since there is no test to verify results.