INTEGRATED MODEL-BASED SYSTEMS ENGINEERING (MBSE) APPLIED TO THE SIMULATION OF THE OSIRIS-REx MISSION

PHOENIX INTEGRATION
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Annapolis, Maryland

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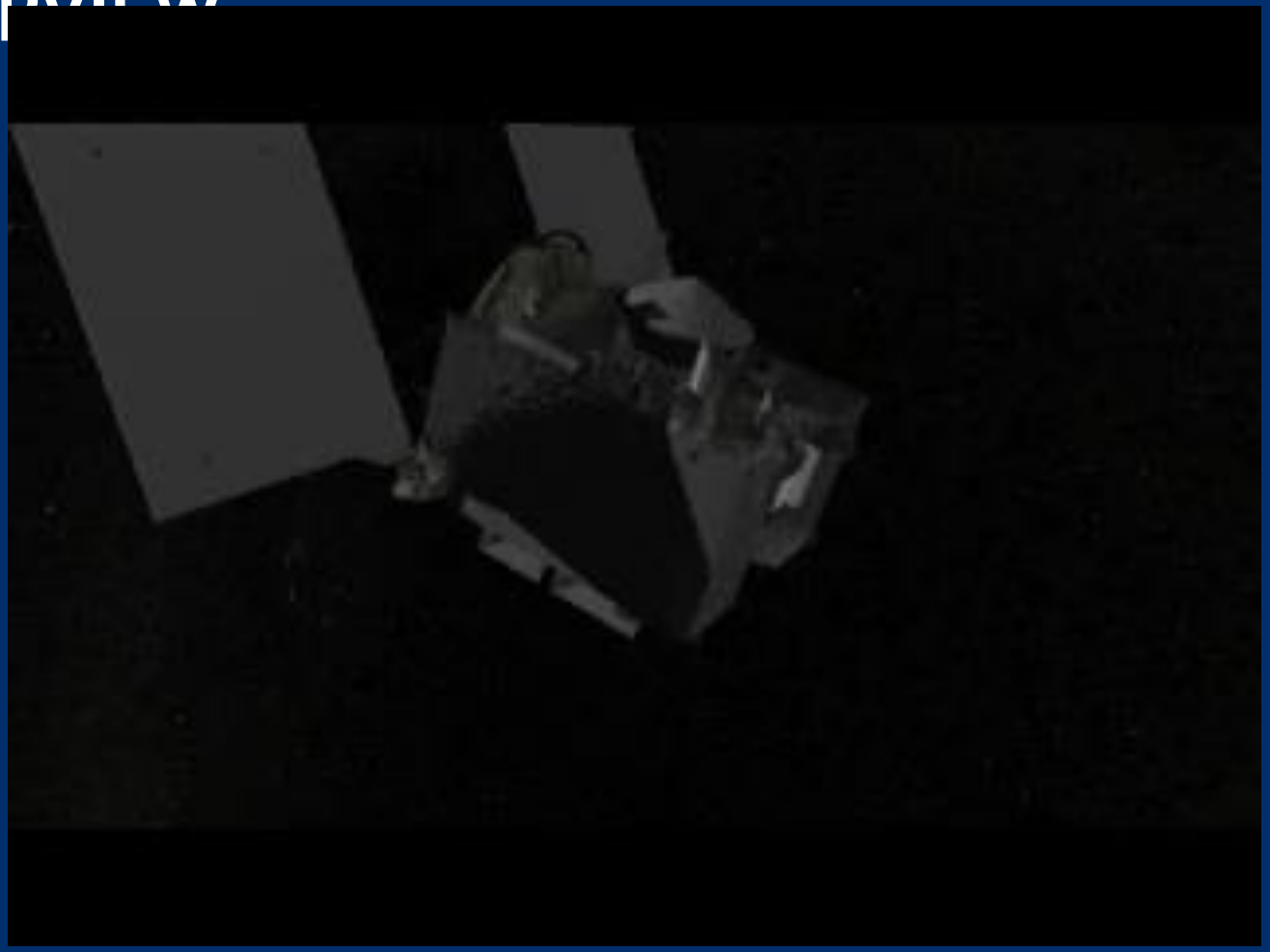
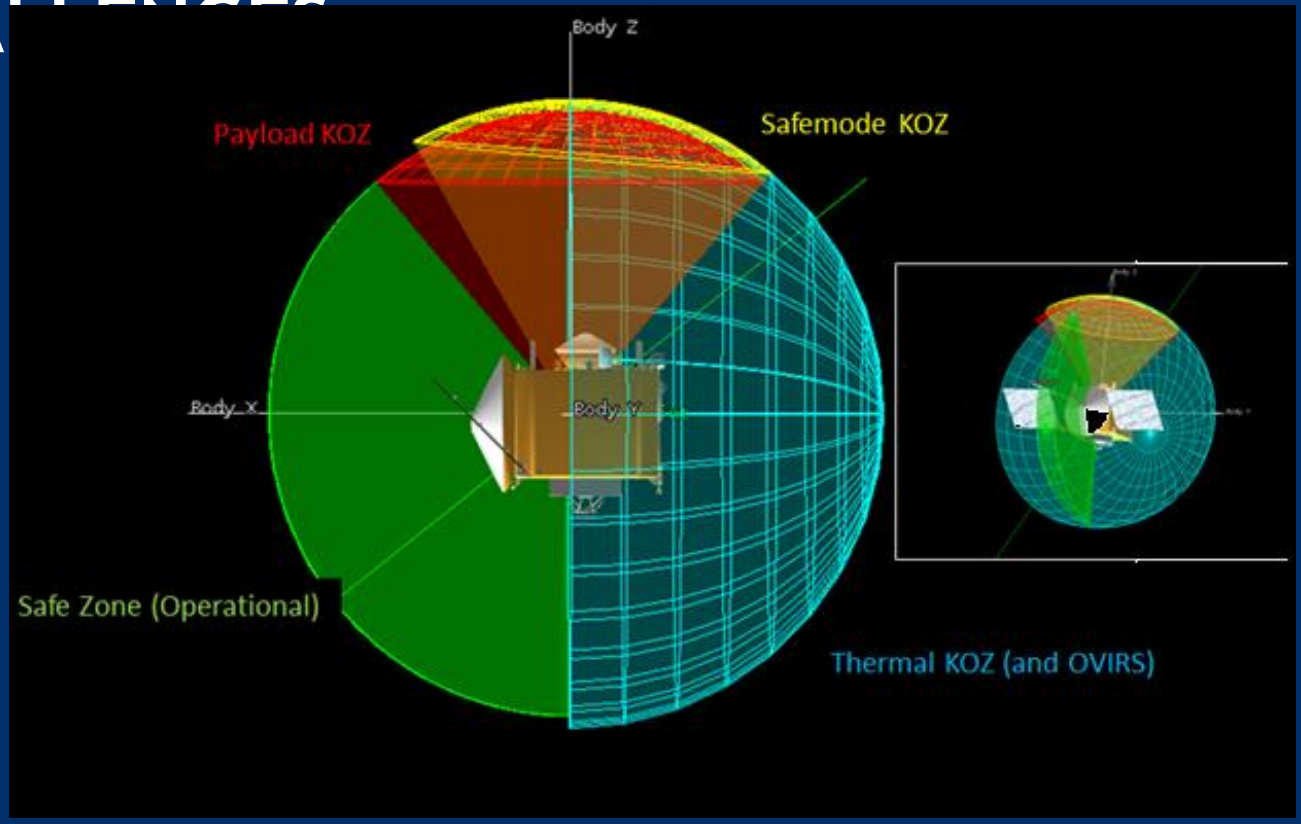
LOCKHEED MARTIN

OSIRIS-REx MISSION OVERVIEW



Video Credit: NASA/Goddard Space Flight Center

OSIRIS-REx MISSION OPERATIONS CHA



- Need to avoid sun in the Thermal KOZ and in the +Z area of the spacecraft.
- Thermal constraints assert sun cannot be in Thermal KOZ past a certain duration threshold.

OBJECTIVES

Previous Operations Process

- Use of GNC prediction software that provides review of constraint violations.
- Run through SoftSim testbed.
- Cannot easily identify spacecraft constraint violations until mid-development.

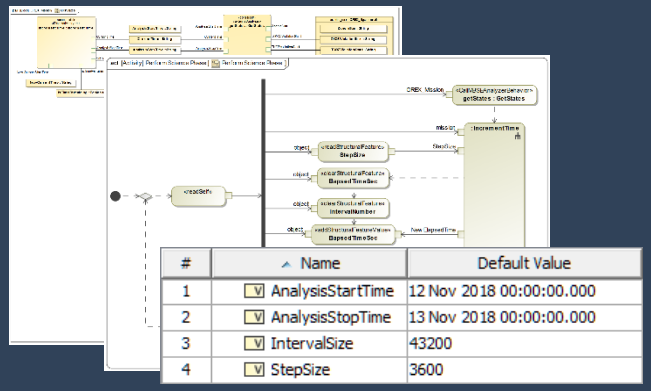
New Operations Process Objectives

- Rapidly evaluate various trajectories for thermal constraint violations to identify preferred mission trajectory.
- Provide quicker, more flexible approach for assessing geometry constraints during early stages of mission planning.
- Efficiently track variables during proposed OSIRIS-REx trajectories.

APPROACH

- Overview
- Challenges
- Objectives
- Approach
- Modeling
- Simulating
- Results
- Reflections
- Future Work

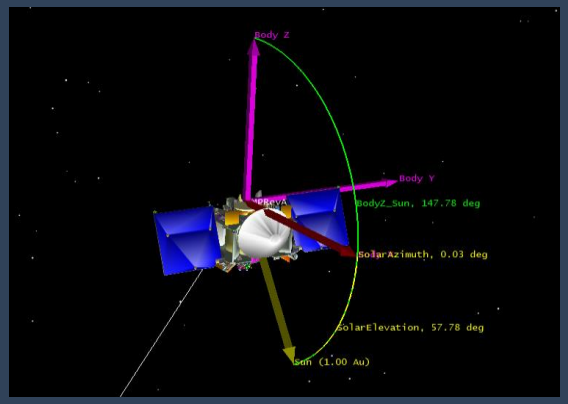
SysML Model + MBSE Analyzer



#	Name	Default Value
1	AnalysisStartTime	12 Nov 2018 00:00:00.000
2	AnalysisStopTime	13 Nov 2018 00:00:00.000
3	IntervalSize	43200
4	StepSize	3600

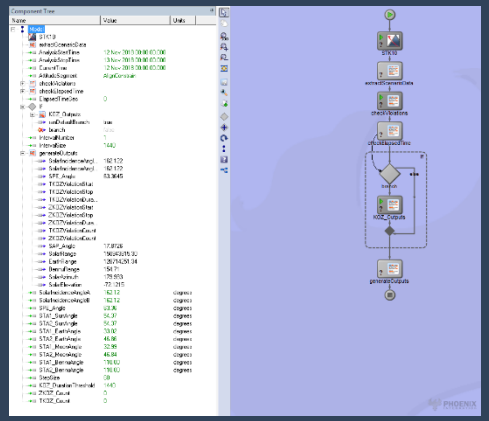
Simulation Settings & Constraints →

Systems Tool Kit (STK)



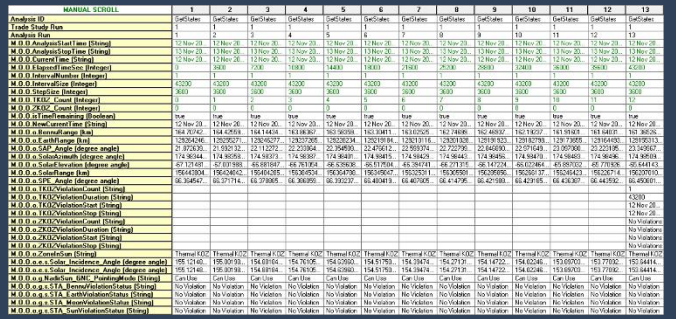
← STK Simulation Results

ModelCenter



STK & MC Simulation Results →

Data Explorer

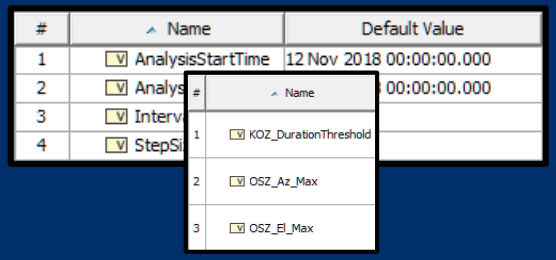


MANUAL SCROLL	1	2	3	4	5	6	7	8	9	10	11	12	13
Analysis ID	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates
Trade Study Run	1	1	1	1	1	1	1	1	1	1	1	1	1
Analysis Run	1	2	3	4	5	6	7	8	9	10	11	12	13
M.D.O.AnalysisStartTime [String]	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...
M.D.O.AnalysisStopTime [String]	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...
M.D.O.CurrentTime [String]	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...
M.D.O.ElapsedTimeSec [Integer]	0	900	7200	10800	14400	18000	21600	25200	28800	32400	36000	39600	43200
M.D.O.IntervalNumber [Integer]	1	1	1	1	1	1	1	1	1	1	1	1	1
M.D.O.IntervalSize [Integer]	43200	43200	43200	43200	43200	43200	43200	43200	43200	43200	43200	43200	43200
M.D.O.StepSize [Integer]	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600
M.D.O.TKOC_Count [Integer]	0	1	2	3	4	5	6	7	8	9	10	11	12
M.D.O.ZKOC_Count [Integer]	0	0	0	0	0	0	0	0	0	0	0	0	0
M.D.O.isTimeRemaining [Boolean]	true	true	true	true	true	true	true	true	true	true	true	true	true
M.D.O.MmeLaunchTime [String]	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...
M.D.O.o.BennuRange [km]	164.40742...	164.42558...	164.44434...	163.98367...	163.96098...	163.30411...	163.02925...	162.74808...	162.46937...	162.19207...	161.91587...	163.64031...	161.36526...
M.D.O.o.EarthRange [km]	129282496...	129295271...	129245277...	129237305...	129228234...	129219184...	129213116...	129201328...	129193233...	129182788...	129173855...	129164450...	129160133...
M.D.O.o.GAP_Angle [degree angle]	21.970635...	21.930732...	22.112972...	22.203964...	22.354959...	22.475812...	22.593976...	22.722795...	22.846890...	22.970149...	23.097306...	23.222195...	23.343607...
M.D.O.o.SolarAzimuth [degree angle]	174.98344...	174.98958...	174.98373...	174.98387...	174.98401...	174.98415...	174.98429...	174.98443...	174.98456...	174.98470...	174.98483...	174.98496...	174.98508...
M.D.O.o.SolarElevation [degree angle]	67.131491...	67.037388...	66.881847...	66.781958...	66.639838...	66.511958...	66.384740...	66.273175...	66.147224...	66.037464...	65.897032...	65.777826...	65.644143...
M.D.O.o.SolarRange [km]	150443804...	150426452...	150404265...	150369534...	150364736...	150345047...	150325511...	150305898...	150285896...	150269137...	150246423...	150226714...	150207010...
M.D.O.o.SPE_Angle [degree angle]	96.394547...	96.371714...	96.378065...	96.366395...	96.350237...	96.480419...	96.467605...	96.4147...	96.421580...	96.423165...	96.43636...	96.443592...	96.458001...
M.D.O.TKOCViolationCount [String]													1
M.D.O.TKOCViolationDuration [String]													43200
M.D.O.TKOCViolationStart [String]													12 Nov 20...
M.D.O.TKOCViolationStop [String]													12 Nov 20...
M.D.O.ZKOCViolationCount [String]													No Violations
M.D.O.o.ZKOCViolationDuration [String]													No Violations
M.D.O.o.ZKOCViolationStart [String]													No Violations
M.D.O.o.ZKOCViolationStop [String]													No Violations
M.D.O.o.ZondeSun [String]	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ
M.D.O.o.e.c.Solar_Incidence_Angle [degree angle]	155.12145...	155.10193...	154.91854...	154.76109...	154.62980...	154.51793...	154.39474...	154.2719...	154.14722...	154.02496...	153.89703...	153.77592...	153.64414...
M.D.O.o.e.s.Solar_Incidence_Angle [degree angle]	155.12145...	155.10193...	154.91854...	154.76109...	154.62980...	154.51793...	154.39474...	154.2712...	154.14722...	154.02496...	153.89703...	153.77592...	153.64414...
M.D.O.o.g.NadirSun_GNC_PointingMode [String]	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use
M.D.O.o.g.s.STA_BennuViolationStatus [String]	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation
M.D.O.o.g.s.STA_EarthViolationStatus [String]	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation
M.D.O.o.g.s.STA_MoonViolationStatus [String]	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation
M.D.O.o.g.s.STA_SunViolationStatus [String]	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation

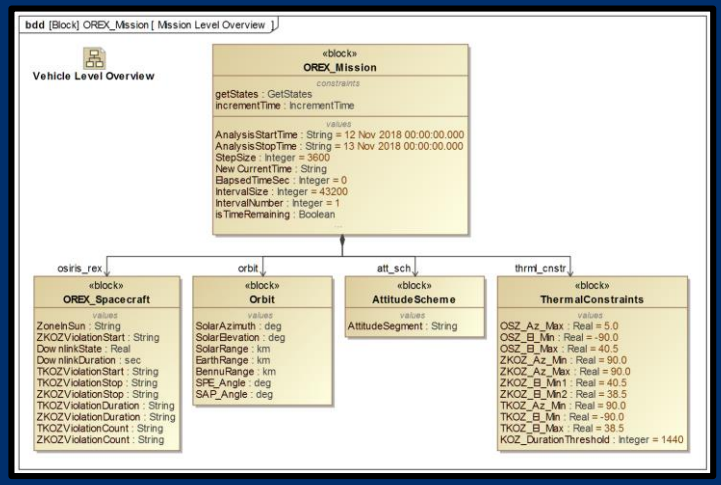
OSIRIS-REx SYSTEM ARCHITECTURE MODEL

The system architecture model captures:

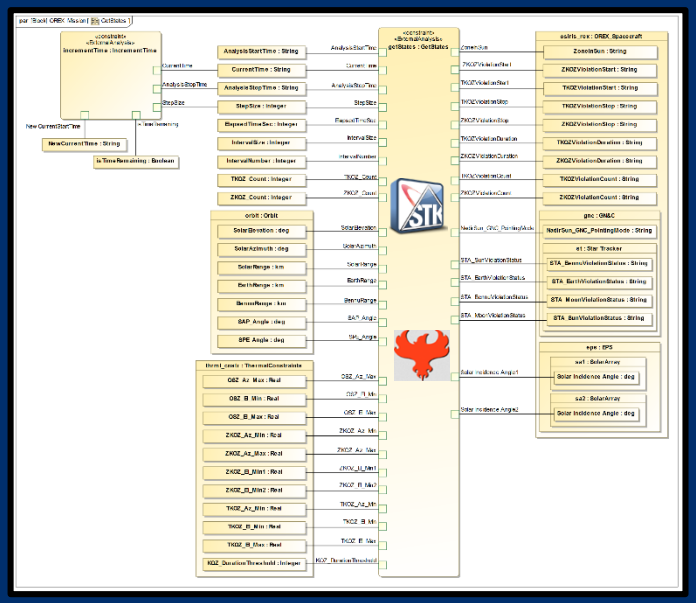
- Overview
- Challenges
- Objectives
- Approach
- Modeling
- Simulating
- Results
- Reflections
- Future Work



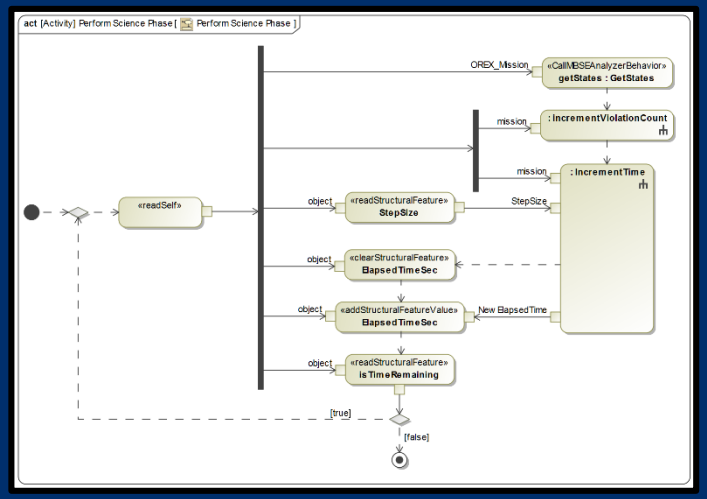
Simulation Settings & Constraints



Structure



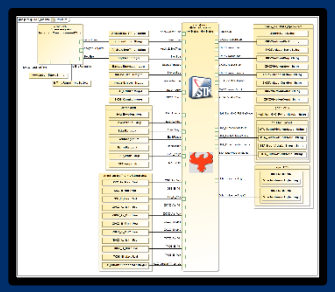
Parametrics

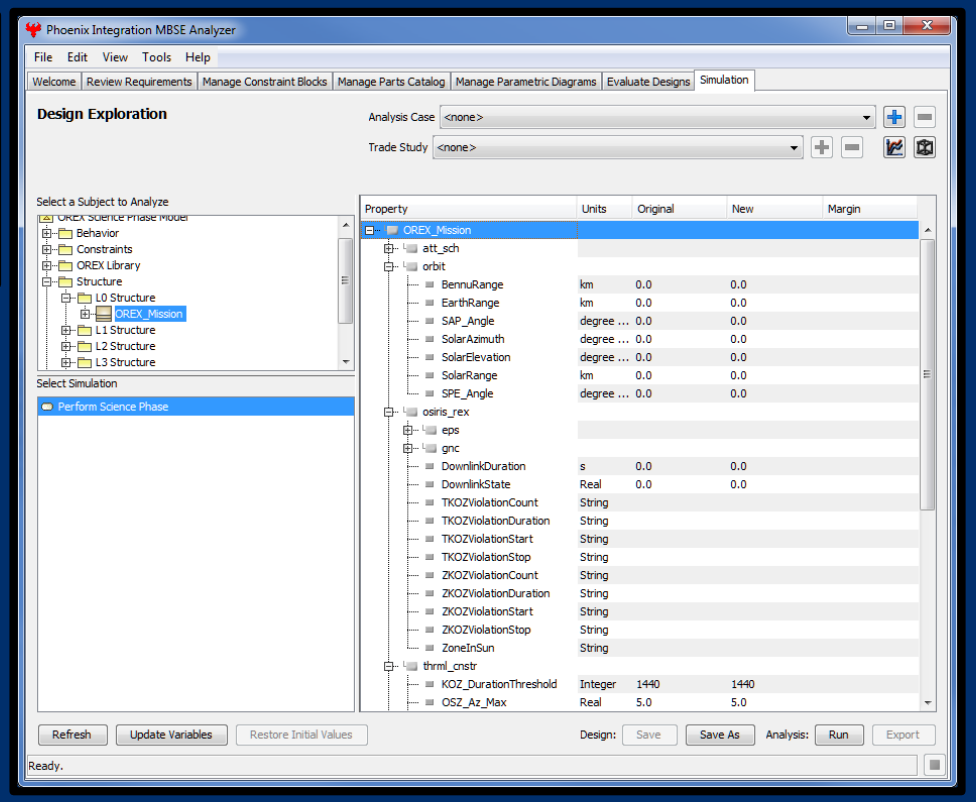


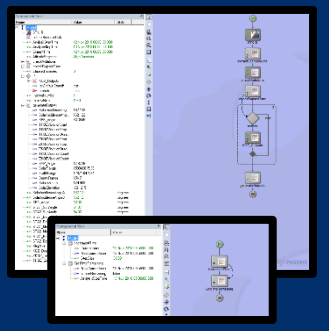
Simulation Sequence

LOCKHEED MARTIN

MBSEPAK (MBSE ANALYZER)



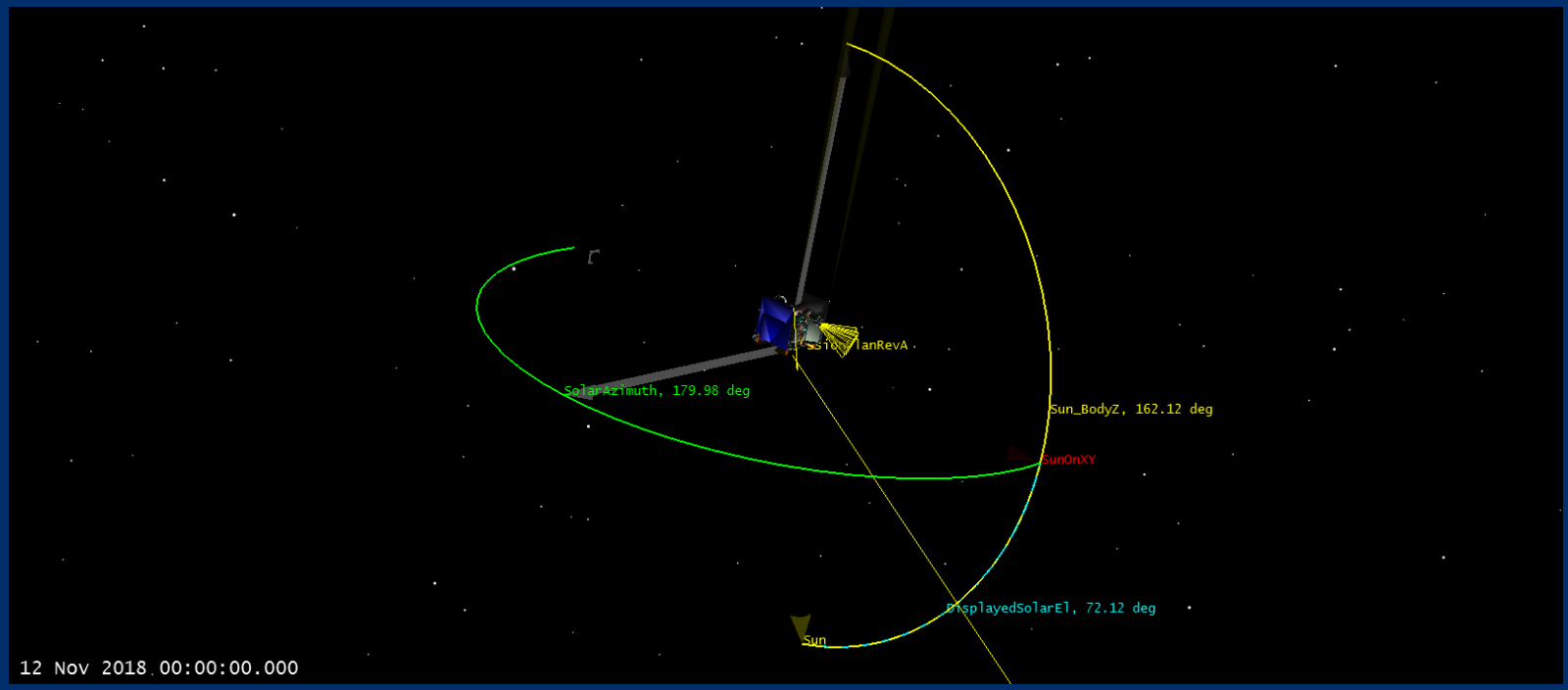




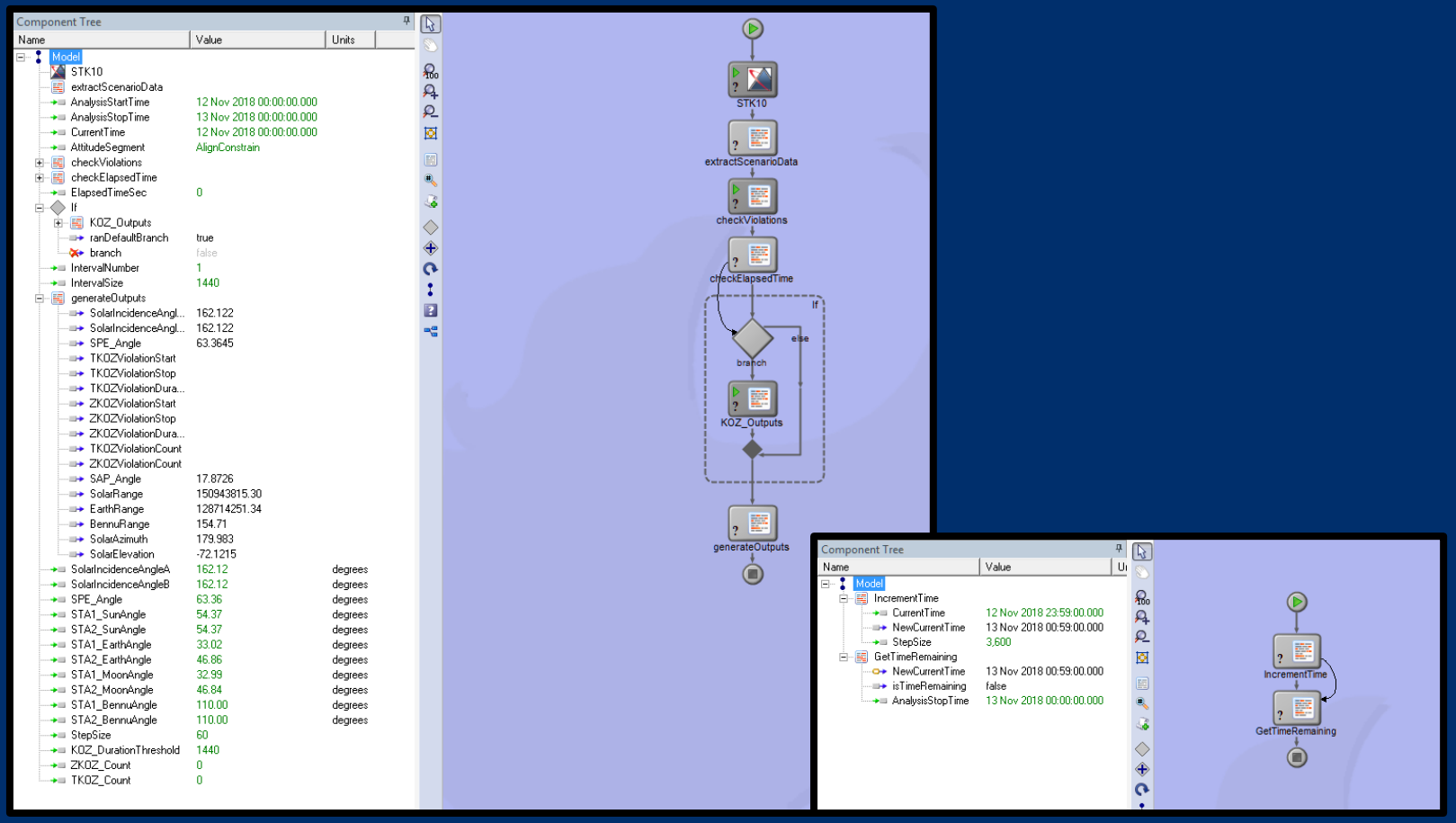
- The constraint block in the architecture model points to ModelCenter workflows using MBSE Analyzer.
- MBSE Analyzer within MBSE Pak solves the parametric diagram by linking it to the model in ModelCenter that consists of scripts and the STK component.

SYSTEMS TOOL KIT (STK)

- To express the Sun vector's azimuth and elevation in reference to the Body Axes, the vector is projected onto the Body XY plane, creating the red "SunOnXY" vector.
- The angle between SunOnXY and Body X is the "SolarAzimuth". The angle between SunOnXY and Body Z is the "SolarElevation".



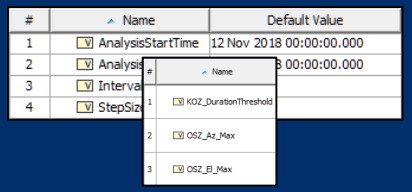
MODELCENTER WORKFLOWS



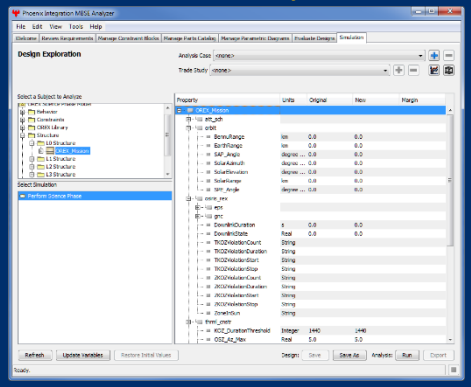
- The scenario results are linked to scripts defined in ModelCenter for determining any constraint violations.

SIMULATION PROCESS OVERVIEW

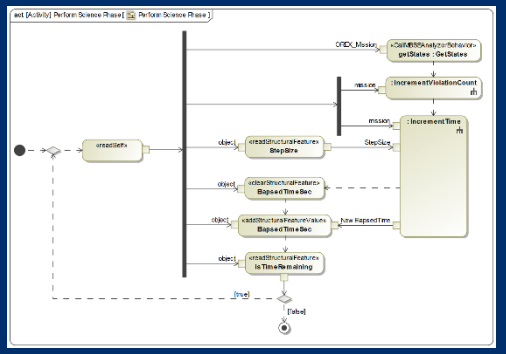
1. Enter simulation settings and constraints.



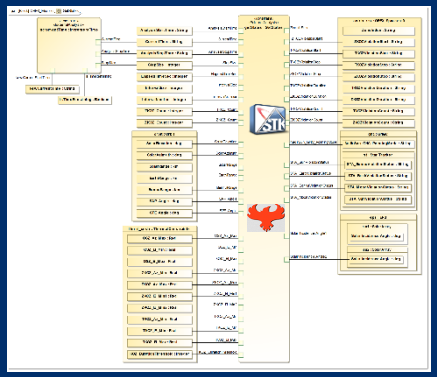
2. Initiate simulation from MBSE Analyzer.



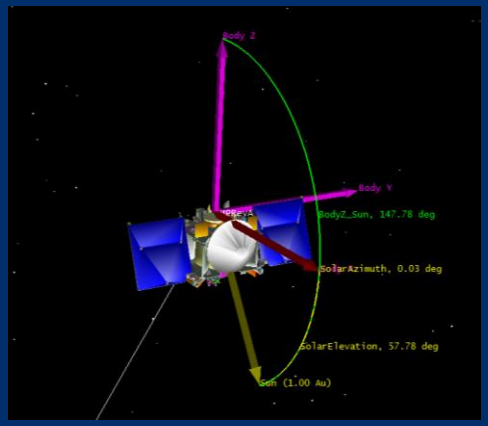
3. Step through the mission simulation.



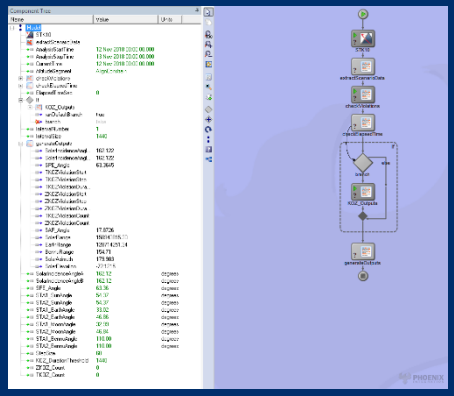
4. Point to external analysis tools.



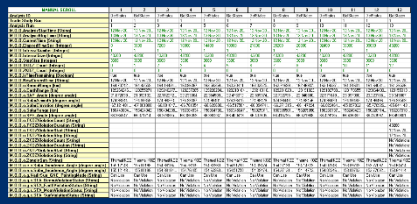
5. Retrieve parameter values from STK.



6. Evaluate STK parameters; return results to MBSE Analyzer.



7. Display simulation results for each time step.



SIMULATION RESULTS & REQUIREMENTS

MANUAL SCROLL	1	2	3	4	5	6	7	8	9	10	11	12	13
Analysis ID	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates	GetStates
Trade Study Run	1	1	1	1	1	1	1	1	1	1	1	1	1
Analysis Run	1	2	3	4	5	6	7	8	9	10	11	12	13
M.0.0.AnalysisStartTime (String)	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...
M.0.0.AnalysisStopTime (String)	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...	13 Nov 20...
M.0.0.CurrentTime (String)	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...
M.0.0.ElapsedTimeSec (Integer)	0	3600	7200	10800	14400	18000	21600	25200	28800	32400	36000	39600	43200
M.0.0.IntervalNumber (Integer)	1	1	1	1	1	1	1	1	1	1	1	1	1
M.0.0.IntervalSize (Integer)	43200	43200	43200	43200	43200	43200	43200	43200	43200	43200	43200	43200	43200
M.0.0.StepSize (Integer)	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600
M.0.0.TKOZ_Count (Integer)	0	1	2	3	4	5	6	7	8	9	10	11	12
M.0.0.ZKOZ_Count (Integer)	0	0	0	0	0	0	0	0	0	0	0	0	0
M.0.0.isTimeRemaining (Boolean)	true	true	true	true	true	true	true	true	true	true	true	true	true
M.0.0.NewCurrentTime (String)	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...	12 Nov 20...
M.0.0.o.BennuRange (km)	164.70742...	164.42559...	164.14434...	163.86367...	163.58359...	163.30411...	163.02525...	162.74699...	162.46937...	162.19237...	161.91601...	161.64031...	161.36526...
M.0.0.o.EarthRange (km)	129264246...	129255271...	129246277...	129237265...	129228234...	129219184...	129210116...	129201028...	129191923...	129182798...	129173655...	129164493...	129155313...
M.0.0.o.SAP_Angle (degree angle)	21.872639...	21.992132...	22.112272...	22.233064...	22.354509...	22.476612...	22.599374...	22.722799...	22.846890...	22.971649...	23.097080...	23.223185...	23.349967...
M.0.0.o.SolarAzimuth (degree angle)	174.98344...	174.98358...	174.98373...	174.98387...	174.98401...	174.98415...	174.98429...	174.98443...	174.98456...	174.98470...	174.98483...	174.98496...	174.98509...
M.0.0.o.SolarElevation (degree angle)	-67.121481...	-67.001988...	-66.881847...	-66.761054...	-66.639608...	-66.517504...	-66.394741...	-66.271315...	-66.147224...	-66.022464...	-65.897032...	-65.770926...	-65.644143...
M.0.0.o.SolarRange (km)	156443804...	156424042...	156404285...	156384534...	156364788...	156345047...	156325311...	156305581...	156285856...	156266137...	156246423...	156226714...	156207010...
M.0.0.o.SPE_Angle (degree angle)	66.364547...	66.371714...	66.378885...	66.386059...	66.393237...	66.400419...	66.407605...	66.414795...	66.421988...	66.429185...	66.436387...	66.443592...	66.450801...
M.0.0.o.TKOZViolationCount (String)													1
M.0.0.o.TKOZViolationDuration (String)													43200
M.0.0.o.TKOZViolationStart (String)													12 Nov 20...
M.0.0.o.TKOZViolationStop (String)													12 Nov 20...
M.0.0.o.ZKOZViolationCount (String)													No Violations
M.0.0.o.ZKOZViolationDuration (String)													No Violations
M.0.0.o.ZKOZViolationStart (String)													No Violations
M.0.0.o.ZKOZViolationStop (String)													No Violations
M.0.0.o.ZoneInSun (String)	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ	Thermal KOZ
M.0.0.o.e.s.Solar_Incidence_Angle (degree angle)	155.12148...	155.00198...	154.88184...	154.76105...	154.63960...	154.51750...	154.39474...	154.27131...	154.14722...	154.02246...	153.89703...	153.77092...	153.64414...
M.0.0.o.e.s.Solar_Incidence_Angle (degree angle)	155.12148...	155.00198...	154.88184...	154.76105...	154.63960...	154.51750...	154.39474...	154.27131...	154.14722...	154.02246...	153.89703...	153.77092...	153.64414...
M.0.0.o.g.NadirSun_GNC_PointingMode (String)	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use	Can Use
M.0.0.o.g.s.STA_BennuViolationStatus (String)	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation
M.0.0.o.g.s.STA_EarthViolationStatus (String)	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation
M.0.0.o.g.s.STA_MoonViolationStatus (String)	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation
M.0.0.o.g.s.STA_SunViolationStatus (String)	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation	No Violation

- System-level and subsystem-level states captured in value properties.
- Requirements verification captured in value properties.
- Values stored at each time step and displayed in Data Explorer.

REFLECTIONS

MBSE Advantages

- Formal, accurate system-level model capture.
- Early identification of requirements issues.
- Early, and on-going requirements and design verification.
- Improved impact analysis of requirements changes.
- Interconnectivity and reuse of existing models to support system design.
- Rapid re-evaluation when design changes occur.

Challenges Encountered

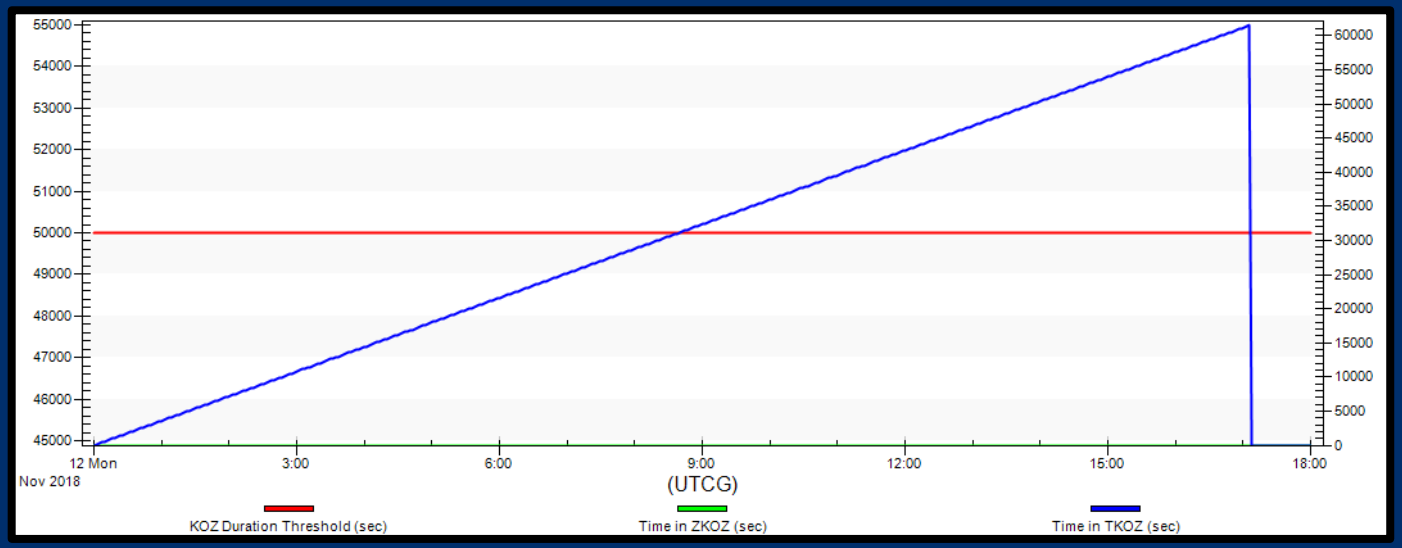
- Could not express time in UTCG without STK Object Model. (resolved in STK11)
- No requirements verification at each time step.
- Dot notation not allowed on parametric diagrams.

Lessons Learned

- The STK Programming Interface allows for great flexibility.
- Collaborating with vendor tech support is imperative.

FUTURE WORK

- Extend the system-level model
  - Include downlink duration and momentum buildup
- Extend and refine the behavioral and analysis models
  - Improve approach for plot generation

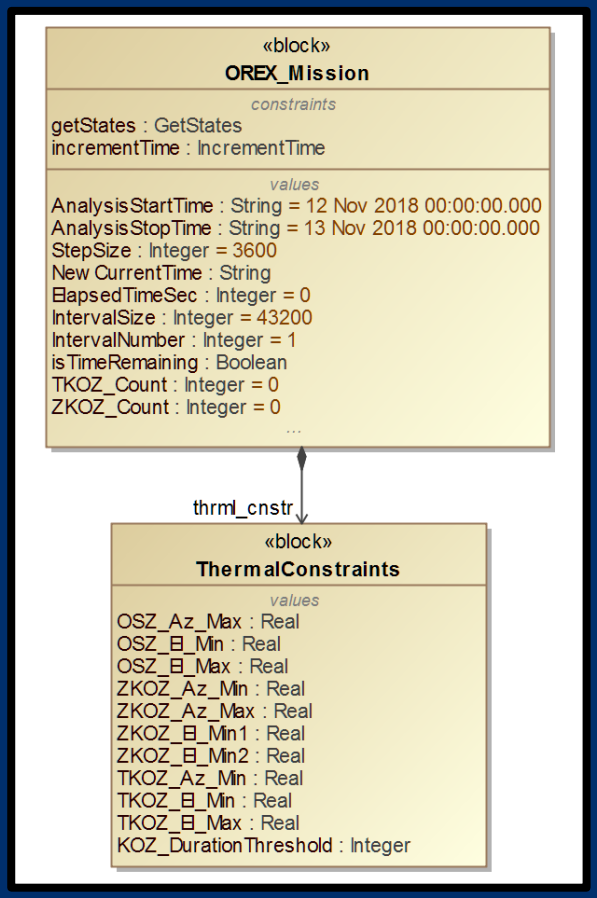


- Enable sensitivity analysis and design optimization
- Implement analysis integration for NASA's *Lucy* mission


LOCKHEED MARTIN

SIMULATION SETTINGS & THERMAL CONSTRAINTS

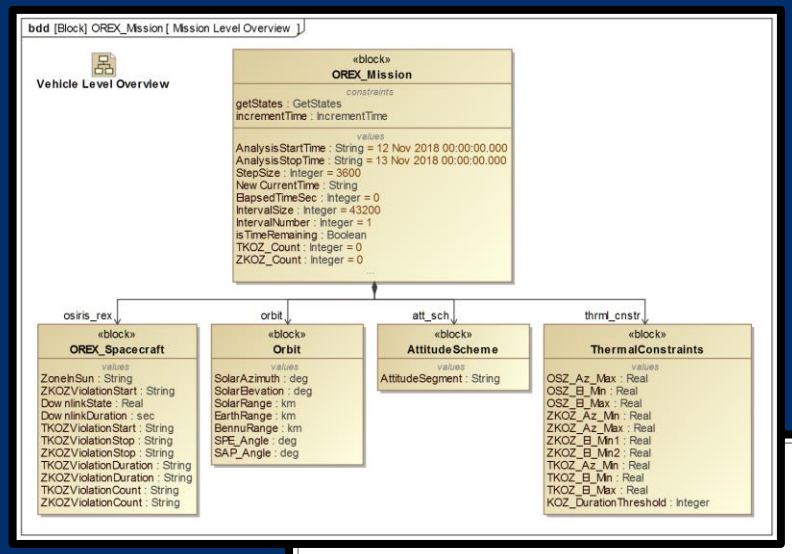
- Simulation time settings and system thermal constraints are captured in the system model.
- This facilitates requirement and constraint changes for efficient impact analysis.



#	Name	Default Value
1	AnalysisStartTime	12 Nov 2018 00:00:00.000
2	AnalysisStopTime	13 Nov 2018 00:00:00.000
3	IntervalSize	43200
4	StepSize	3600

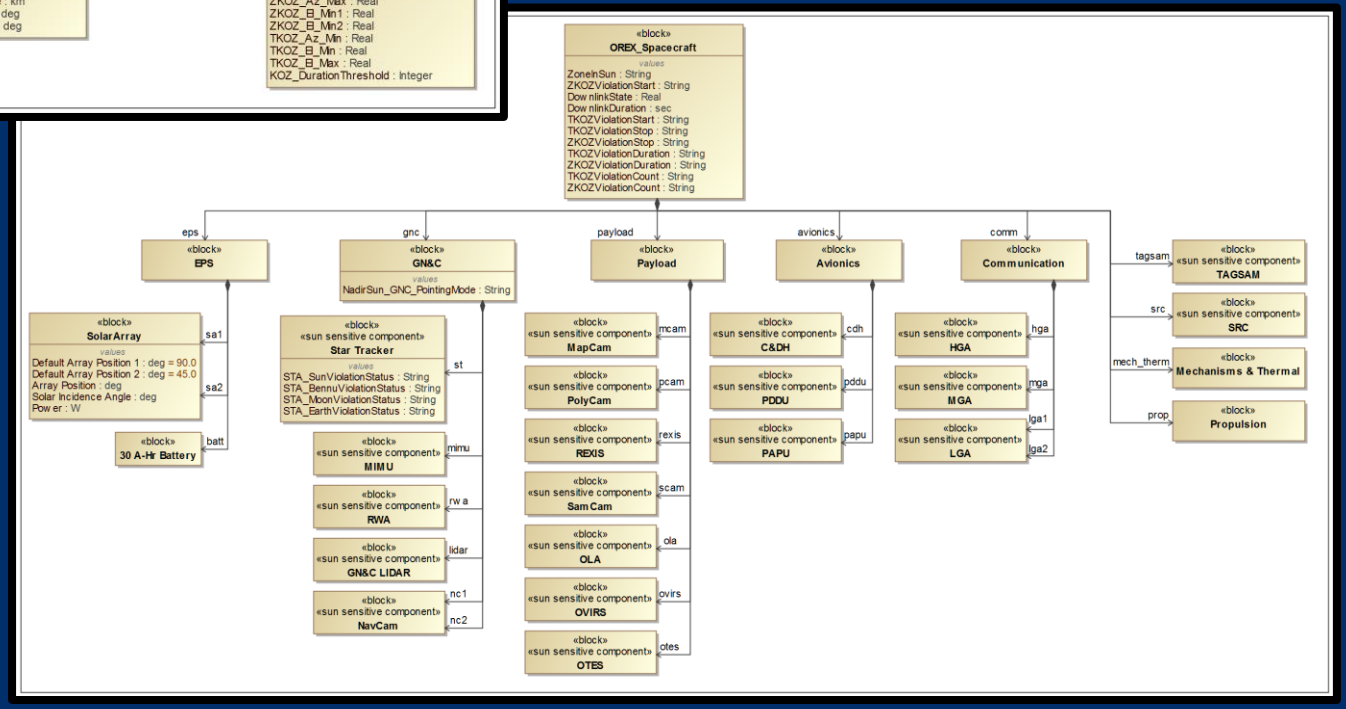
#	Name
1	KOZ_DurationThreshold
2	OSZ_Az_Max
3	OSZ_El_Max
4	OSZ_El_Min
5	TKOZ_Az_Min
6	TKOZ_El_Max
7	TKOZ_El_Min
8	ZKOZ_Az_Max
9	ZKOZ_Az_Min
10	ZKOZ_El_Min1
11	ZKOZ_El_Min2

STRUCTURAL DIAGRAMS



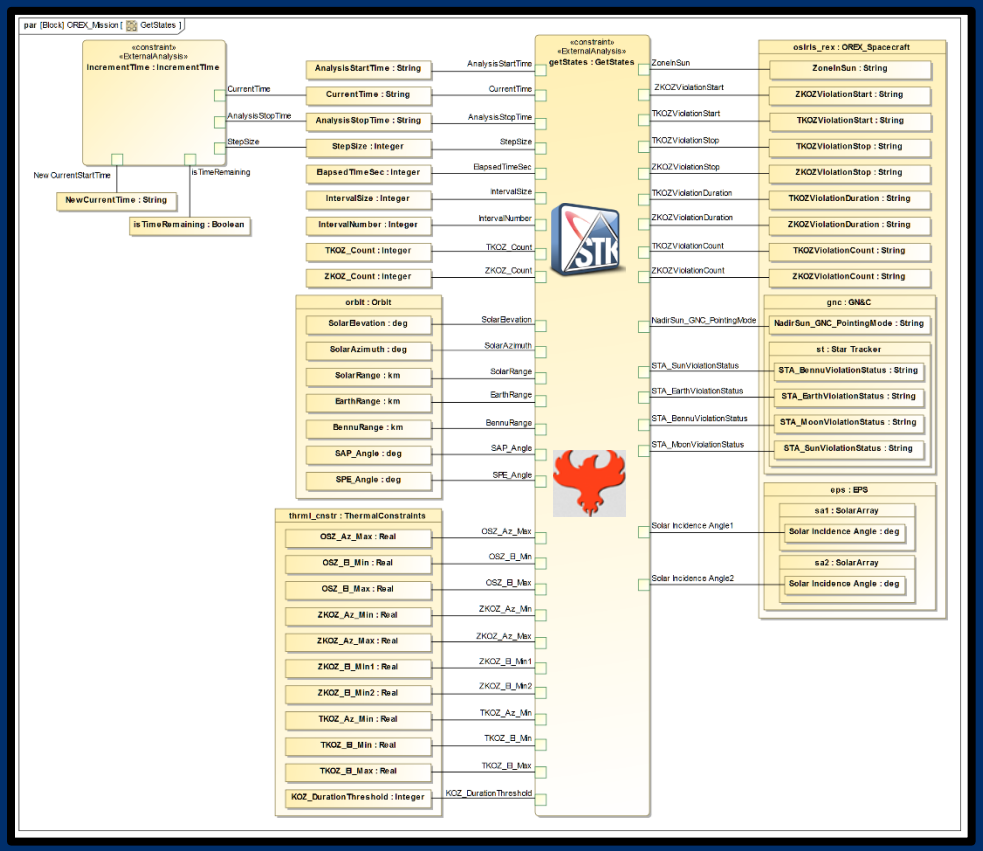
Mission Level

Vehicle Level



PARAMETRIC DIAGRAM

- Using MBSE Pak, value properties are bound to a constraint block that links to a model in ModelCenter that contains scripts and a STK component.
- Inputs to STK:
  - Analysis Start Time
  - Analysis Stop Time
  - Time Step Size
- Outputs from STK
  - Solar Elevation
  - Solar Azimuth
  - Solar Range
  - Earth Range
  - Bennu Range
  - SAP Angle
  - SPE Angle
- Outputs from ModelCenter
  - KOZ in Sun
  - Duration of thermal violations



MAIN SIMULATION LOOP