U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

Digital Twin and Industry 4.0 in Support of Heliostat Technology Advancement

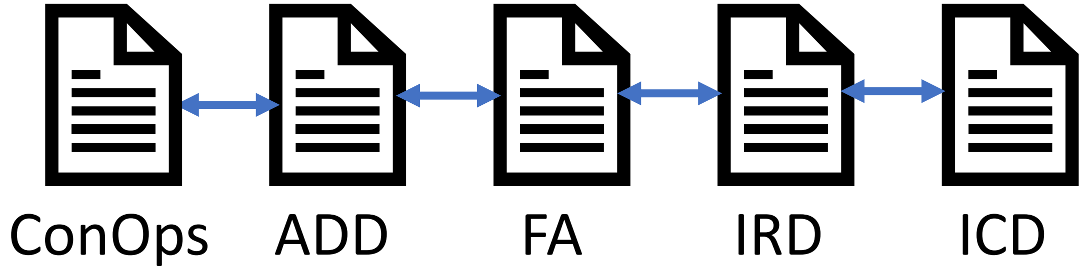
conceptional design • components • integration • mass production • heliostat field

Major Goals and Objectives

- The project aims to apply multiple technologies from the Industry 4.0 to the heliostat design, manufacturing, deployment and operations in order to realize the cost reduction seen by other industries which have adopted these technologies.
- Industry 4.0 technologies: digitization of manufacturing, construction, product development and operation
  - ***Model Based System Engineering (MBSE):***
    - *"the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."*
  - ***Digital Twins:***
    - Digital twins are virtual replicas of systems, processes, production lines, …. pulling data from IoT sensors, devices, and other objects connected to the internet.
  - *Industrial Internet of Things (IIoT):*
    - Sensors with IP address allows the systems to connect with other web-enabled devices. This connectivity make it possible for large amounts of data to be collected, analyzed and exchanged.
  - *Machine Learning:*
    - AI and machine learning allow companies to take full advantage of the volume of information generated
  - ***Virtual** and Augmented Reality*
    - Virtual Reality, (and extended reality) represent new opportunities for the training of professionals, the control of machines, and the design of industrial products.

Why Use Model Based Systems Engineering ?

- Traditional document-based systems engineering is too difficult to manage



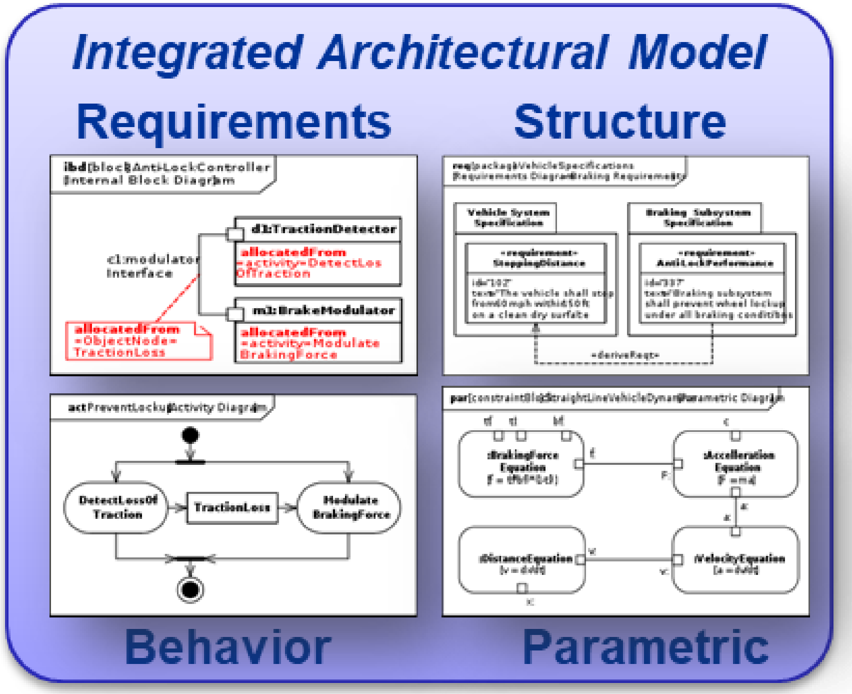
Challenges

- **Updating**
- **Managing**
- **Coordinating**
- **Keeping Current**
- **Costly**
- **Time-consuming**

- MBSE:
  - Facilitates communication among all the stakeholders (using a common language)
  - Avoids duplication of effort by creating models of the same systems with different processes, tools and representations
  - Captures system knowledge in a computer process-able and human understand-able format
  - Naturally enforces agreement early in the design process (e.g., ontology, schema, attributes)

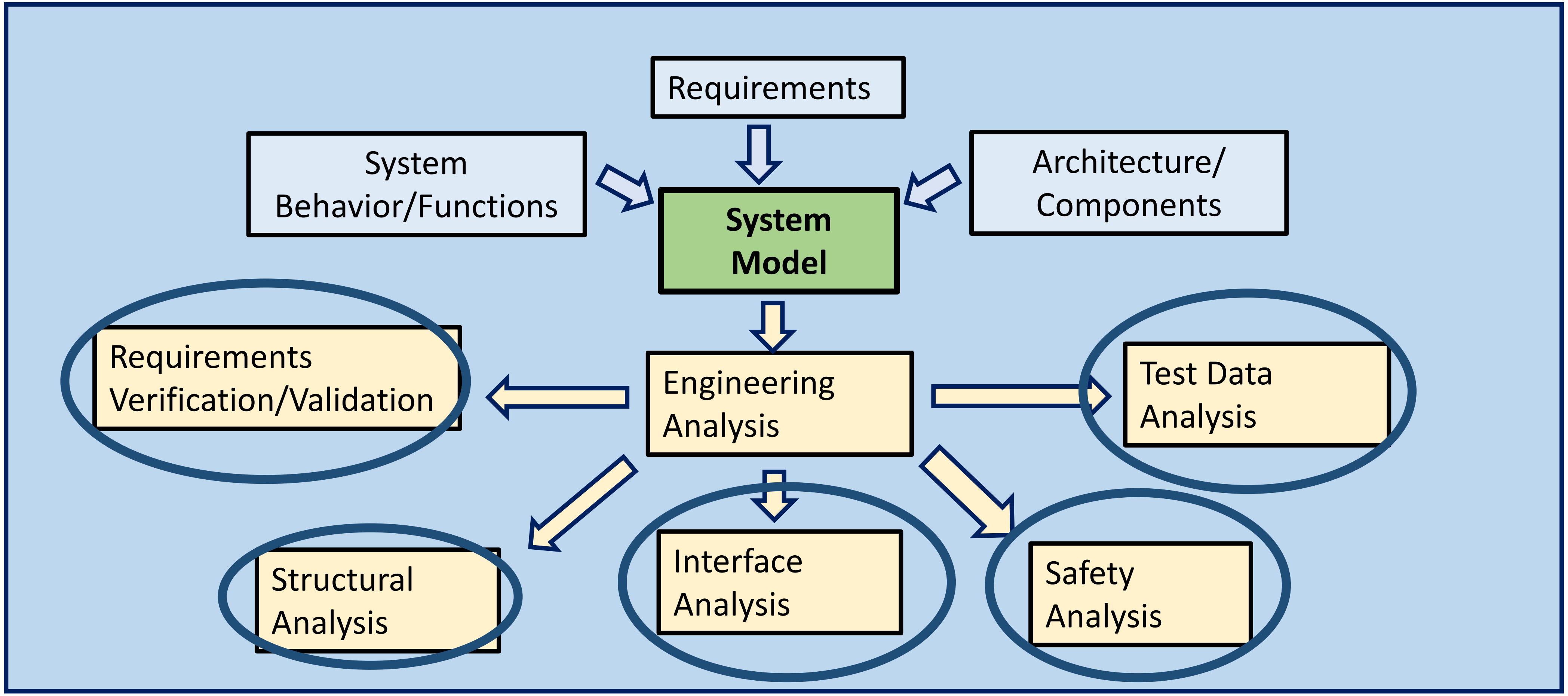
MBSE concepts

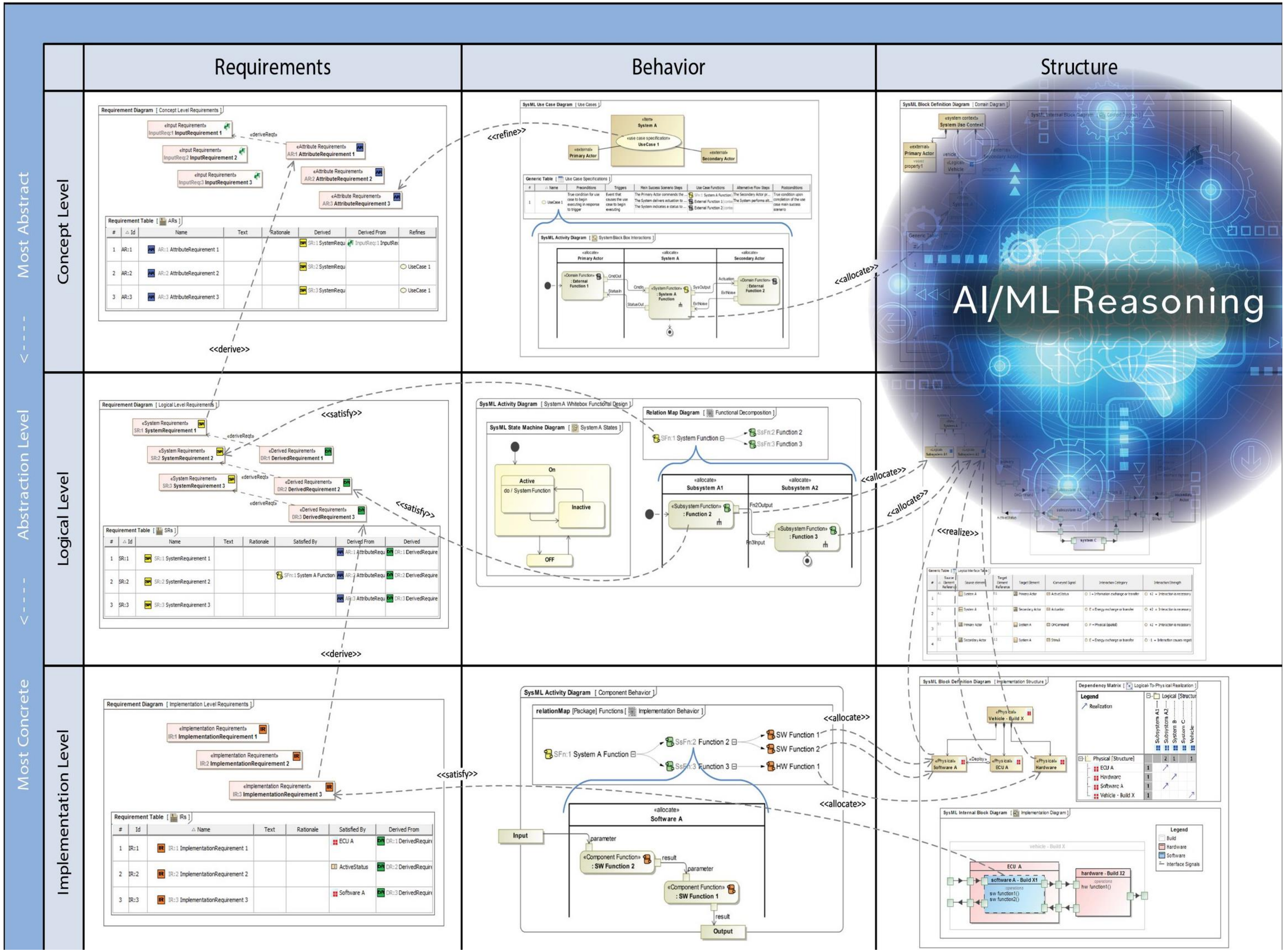
- Models use common data sets
  - Provides a consistent view of the architecture
  - Can lead directly to system specifications & test plans
  - Reduces systems integration and testing risks
  - Promotes traceability
  - Makes it possible to identify gaps and overlaps
  - Facilitates model reuse and integration
- Uses a standards-based modeling language
  - Allows to create a simulation for the system behavior, trade analysis, or verification and integration test
  - Models can be used with many standard compliant automation tools
- Automation tools are used to generate artifacts
  - Less labor intensive to generate & update



Modeling Goals

The goal for SysML model is to use it for engineering analysis.
Use it for Requirements Verification, Test Data Analysis, Interface Analysis, and Safety Analysis.





From INCOSE
Vision 35

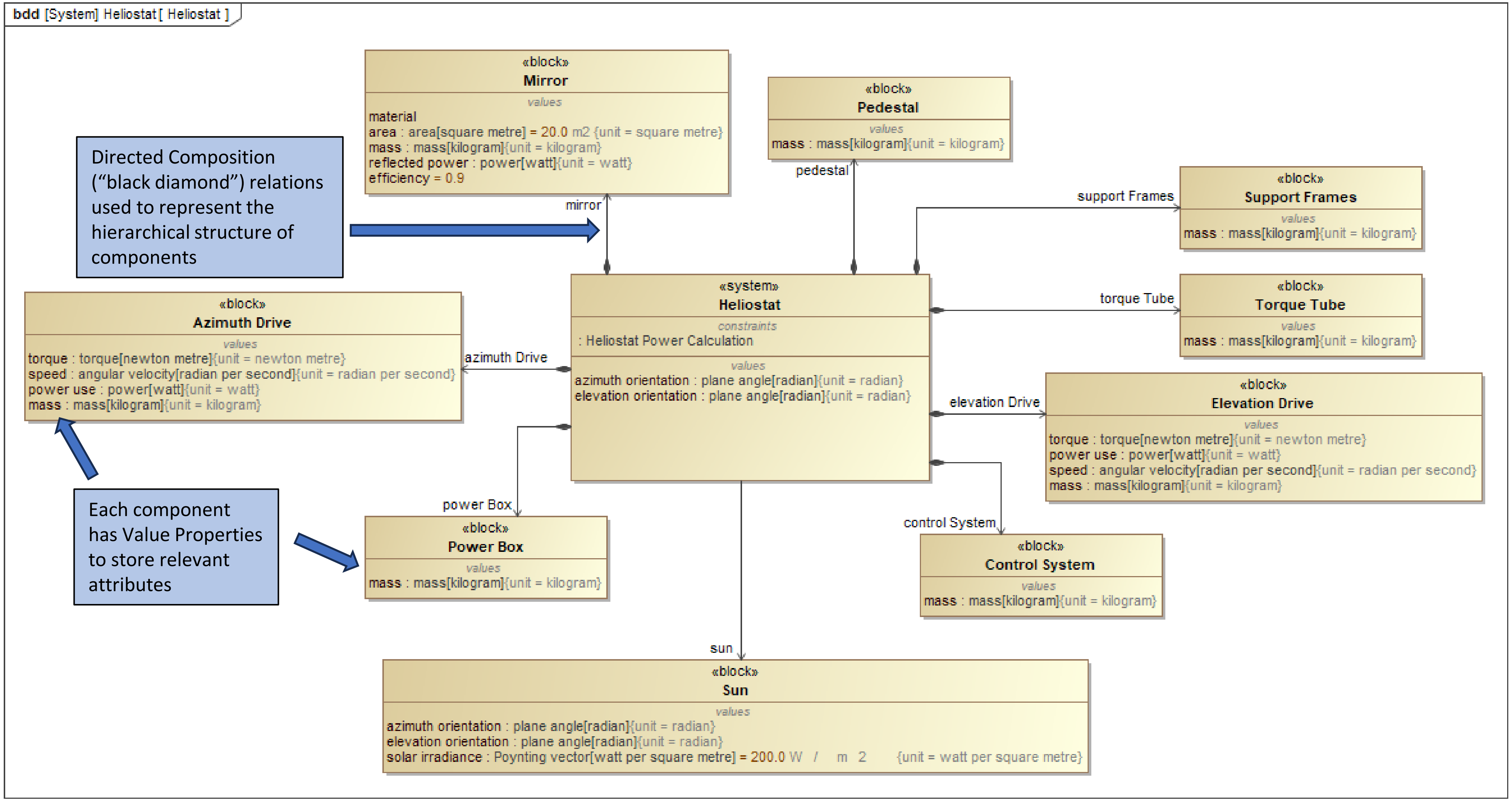
Tietronix RFP 38488-006

MBSE usage in other industries

- Which Industries have adopted MBSE: aerospace, defense, nuclear power plants, rail, automotive, manufacturing
- Companies that use MBSE: Lockheed Martin, Northrop Grumman, Ford, Daimler AG (Mercedes-Benz), Joby Aviation, shipbuilder Thyssenkrupp Marine Systems
- Entities we support(ed): NASA (all centers), ESA, General Dynamic, Ford, Safran
- Other: Rolls Royce, SAIC, Thales, Airbus, John Deere, General Motors, IBM

General Heliostat Structural Model

- Model of a generic heliostat

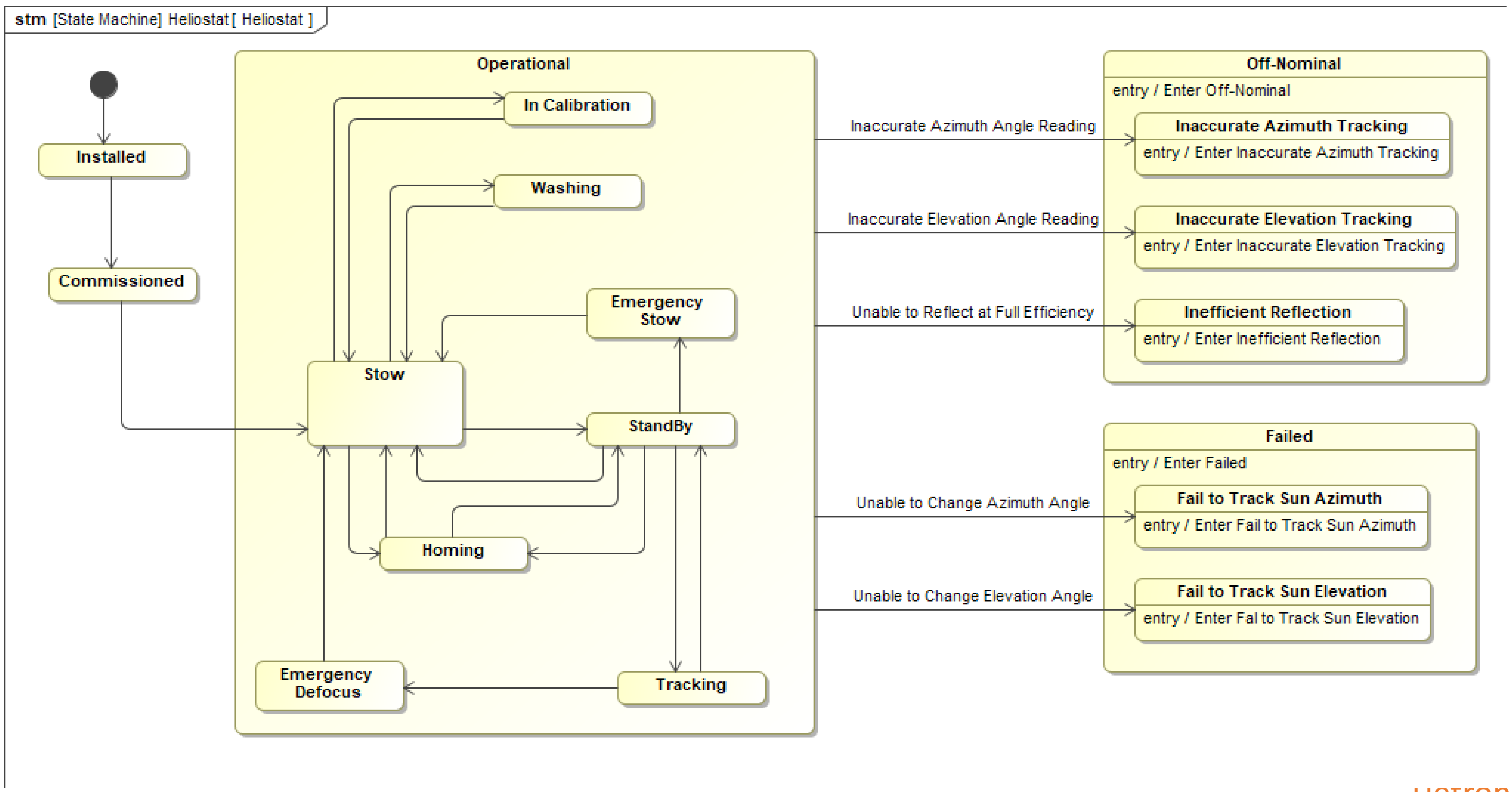


Source of Information

- *SolaPACES Technical Report No. III – 1/00c*

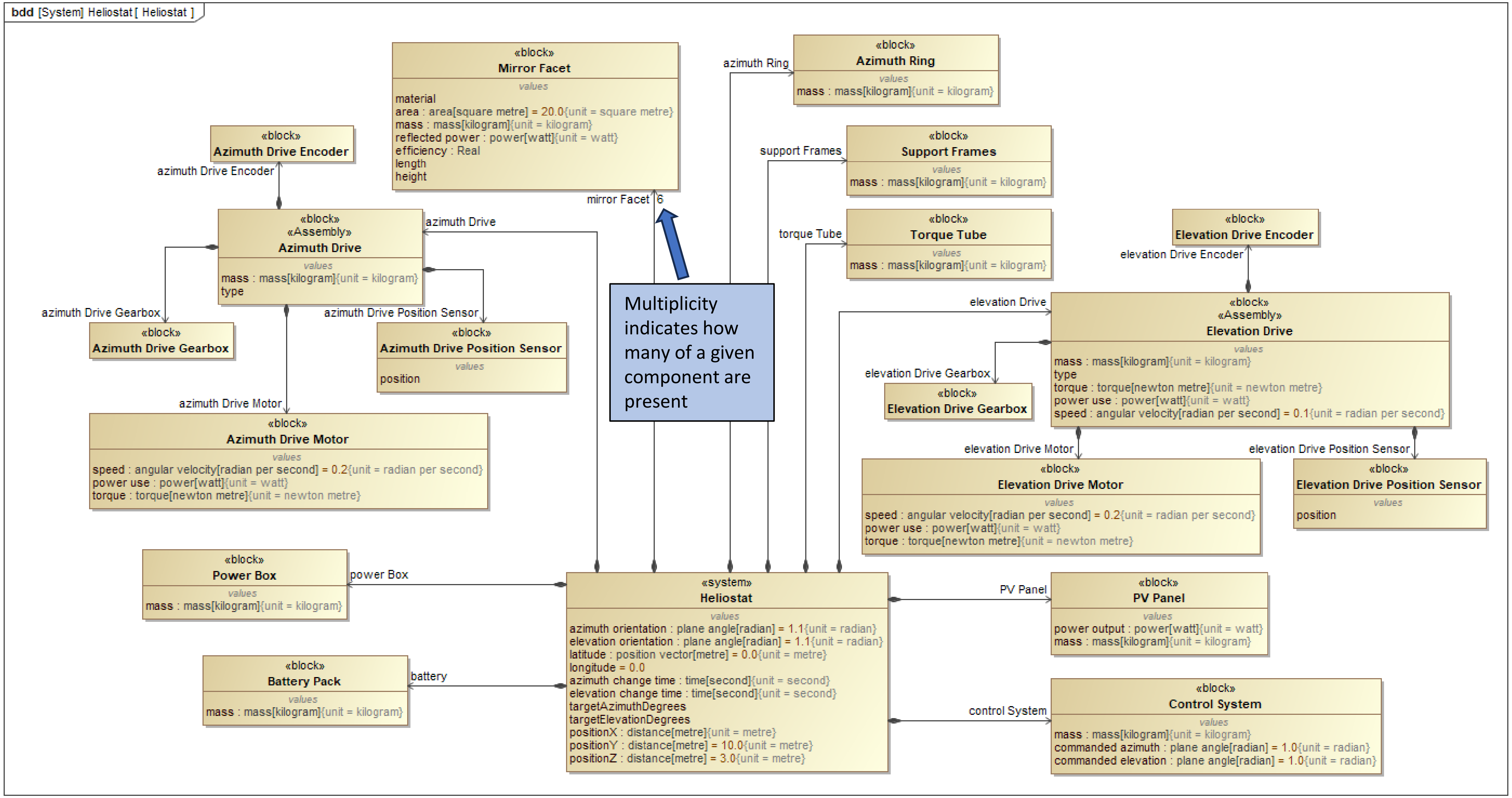
Behavior Model – Generic Heliostat

State Machine Diagram – Behavior model captures the different states of the Heliostat



SunRing Architecture

- Generic heliostat model was modified with SunRing-specific features to represent actual SunRing architecture



Source of Information
- *NREL Technical Report NREL/TP-7A40-80482*

Models Capture

- Requirements
- Functional decomposition
- Components
- Environment
- Functions to Components mapping
- Requirements to Components mapping
- Requirements to Tests mapping
- Components specifications
- Behavior Model using State Machines
- Failures using State Machines and activity diagrams
- Parametrics capturing equations relevant to the system behavior

Requirement Table

Name: Lists the requirements pertaining to the SunRing components

Text: Contains details that the requirements must fulfill

Satisfied By: Contains the SunRing component which the requirement is met by

Refined By: Requirements are refined by the function of the component it is satisfied by

Verified By: Contains the Sequence Diagram Test Case that verifies whether it meets the requirement or not

Verify Method: Specifies the specific verification method used for the verify relation

Roller Pinion Test | **Requirements** × | Roller Pinion Test | Roller Pinion Test | Roller Pinion Test

Add New | Add Nested | Add Existing... | Delete | Remove From Table | Unnest | Nest | Columns | Export | Report

Criteria

Scope (optional): Requirements ... Filter:

#	Id	Name	Text	Satisfied By	Refined By	Verified By	Verify Method
11		Specifications					
12	7	7 Dynamic Loading Slewing Operation	Shall have an average torque of 41 lbf-ft Shall have an average speed of 10 RPM Shall have an acceleration of 0.042 rad/s² Duty cycle shall be at 100% for 12 minutes	Azimuth Drive	Produce Torque Enabling Azimuth Change		
13	8	8 Additional Parameters	Shall be a type DC - brush or brushlesh Shall have a gearbox ratio selected by vendor Shall have a max backlash of 24.0 mrad Shall require a quadrature type encoder Shall have a minimum encoder resolution of 419 pulses/revolution Shall have a lifetime of 30 years Shall have a lifetime - total output shaft rotations of 1,357,814 Shall have an operating voltage of 24V prefferred or 12V alternative if presented Shall have a preffered thermal overload protection based on cost Shall have a IP Rating of 65 Power and encoder wiring shall be a quick connector or pre-wired with un-terminated wire Shall have a output shaft connection type that is a tapered shaft with a threaded end Lifetime maintenance shall have none preferred, otherwise vendor shall specify procedure and interval Shall have a minimum self-locking capacity of 77 lbf-ft	Azimuth Drive	Relay Azimuth Angle to Control System(c Provide Reduction Gearing for Elevation D	Failure Roller Pinion Testing Normal Roller Pinion Testing Azimuth Gear Track Test Position Error Test	Test
14	9	9 Dynamic Loading Tracking Operation	Shall have a torque of 49 lbf-ft Shall have a speed of 0.5 RPM Shall have an acceleration of 0.042 rad/s² Duty cycle shall be at 20%	Azimuth Drive	Produce Torque Enabling Azimuth Change		

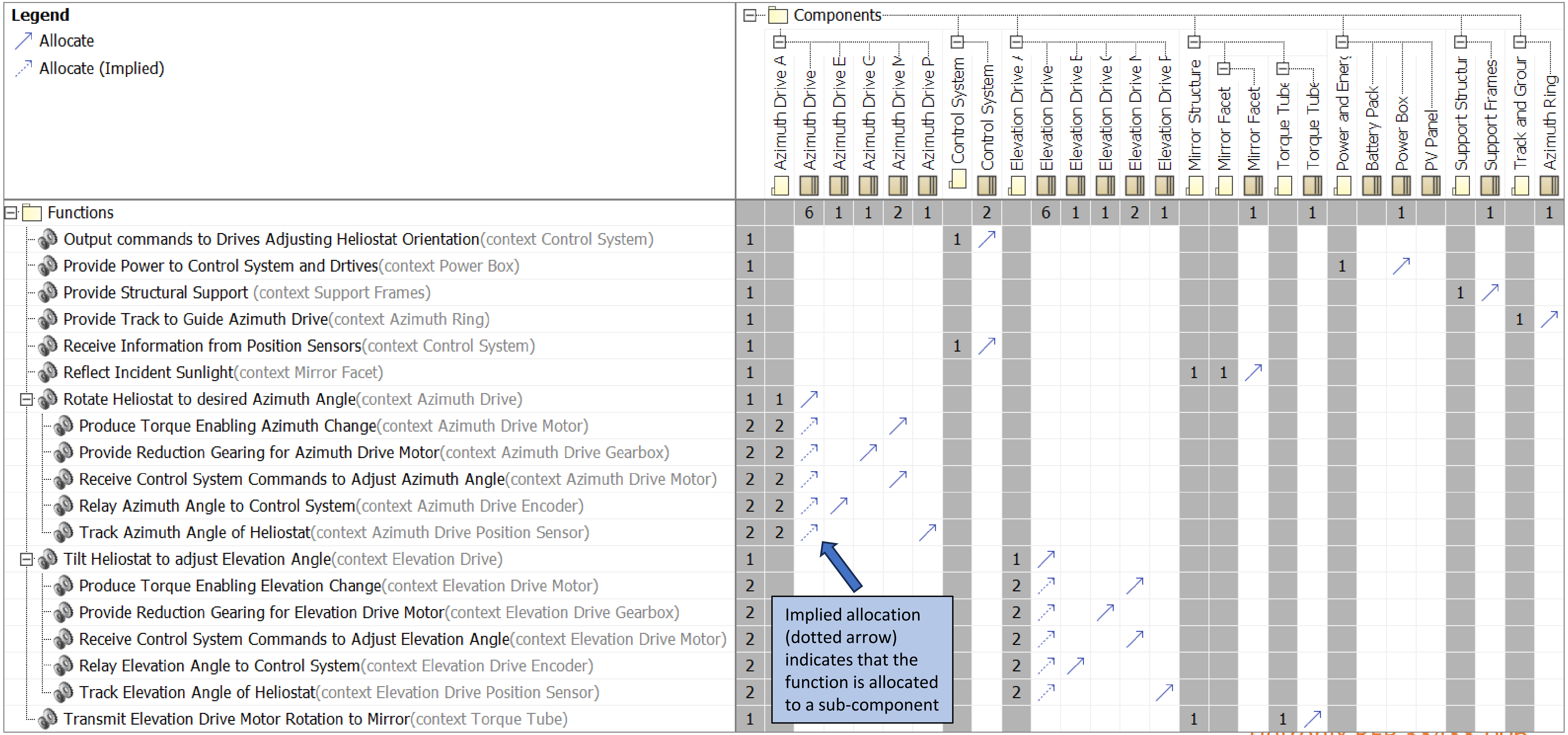
Source(s) of Information

DE-EE0008024_CTRL_Heliostat Local Controller Specification_0006_RevC.pdf
DE-EE0008024_CTRL_Heliostat Wireless Communications System Specification_0010_Rev-.pdf
DE-EE0008024_ELEC_Heliostat PV and Battery Specification_0007_RevB.pdf

DE-EE0008024_SF_Azimuth Actuator Specification_0012_RevE.pdf
DE-EE0008024_SF_Elevation Actuator Specification_0013_RevF_HB.pdf
DE-EE0008024_SF_Heliostat Overall Specification_0004_Rev-.pdf

Functional Allocation

- Allocation matrix was created to allocate heliostat functions to components

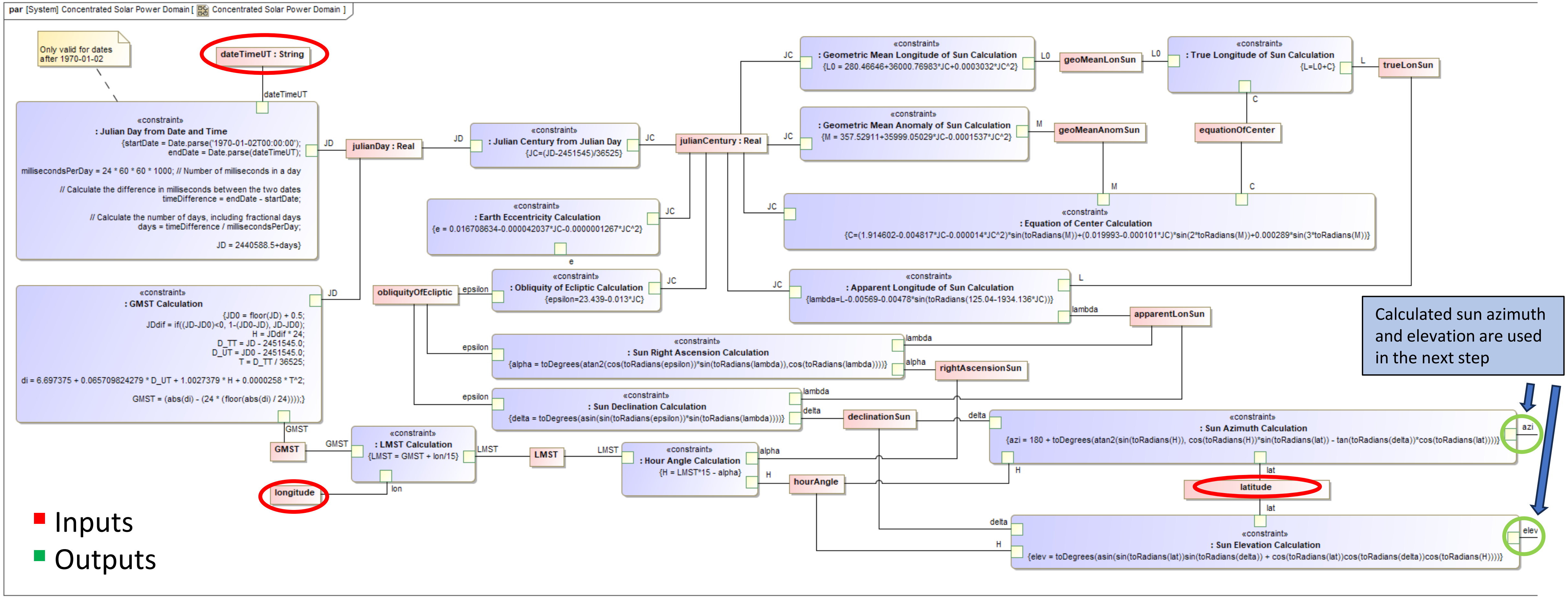


Heliotronix RFP 38488-006

Source of Information
- NREL Technical Report NREL/TP-7A40-80482

Solar Calculations and Simulations (1/3)

- Using a set of equations, sun azimuth and elevation at a given location were calculated with latitude, longitude, and universal time and date as inputs

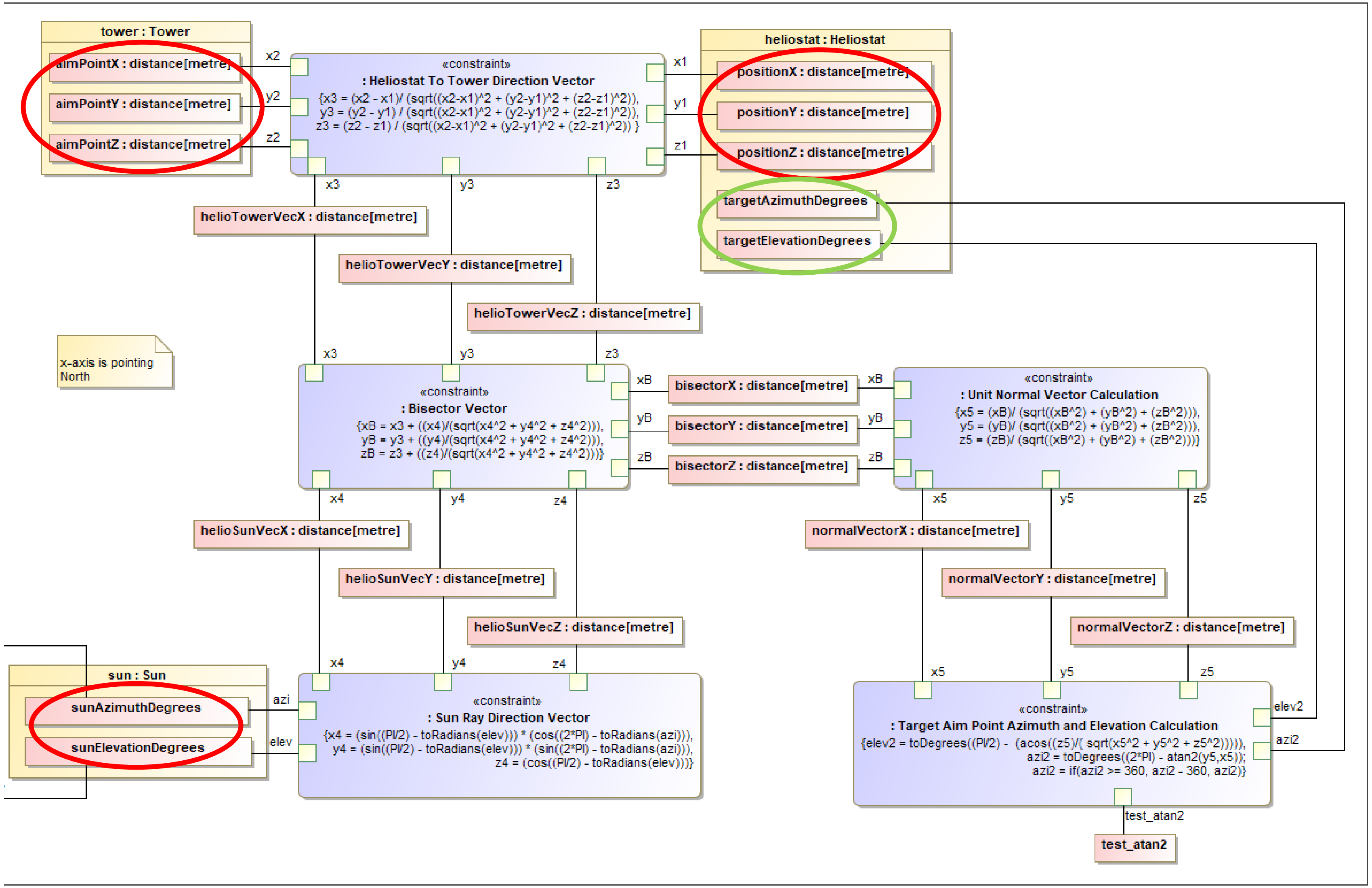


Source of Information

- *NOAA Solar Position Calculator*
- *US Navy Astronomical Applications Department, "Computing Approximate Sidereal Time"*

Solar Calculations and Simulations (2/3)

- Using Sun azimuth and elevation angles calculated in the previous step and heliostat and tower position in a local Cartesian coordinate system, target azimuth and elevation settings for the heliostat were calculated such that the sun's rays are reflected onto a target aim point on the tower



- Inputs
- Outputs

Tietronix RFP 38488-006

Solar Calculations and Simulations (3/3)

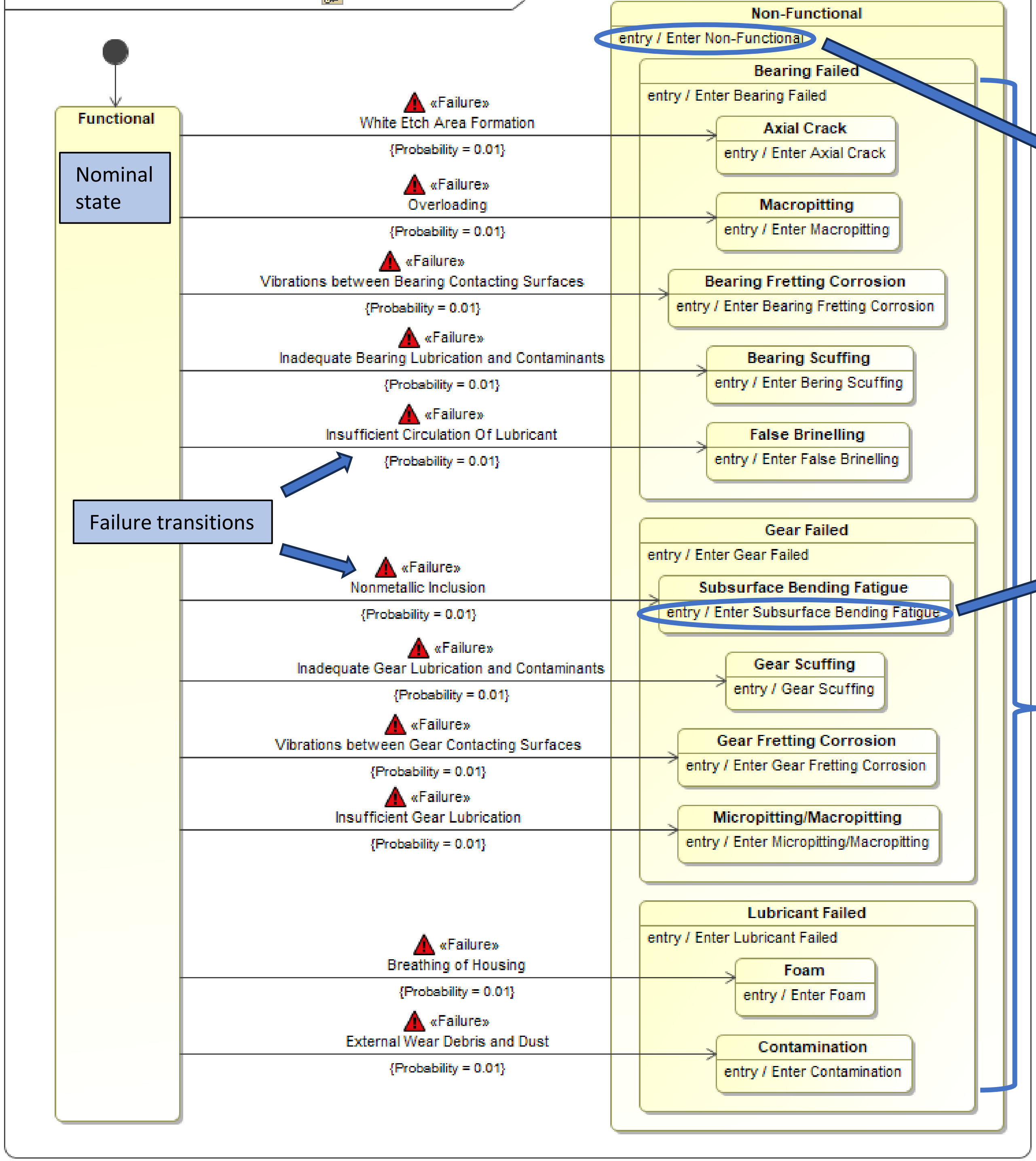
- Using various time inputs, sun azimuth and elevation values throughout the day were obtained, along with the corresponding heliostat azimuth and elevation settings for reflecting onto the tower aim point

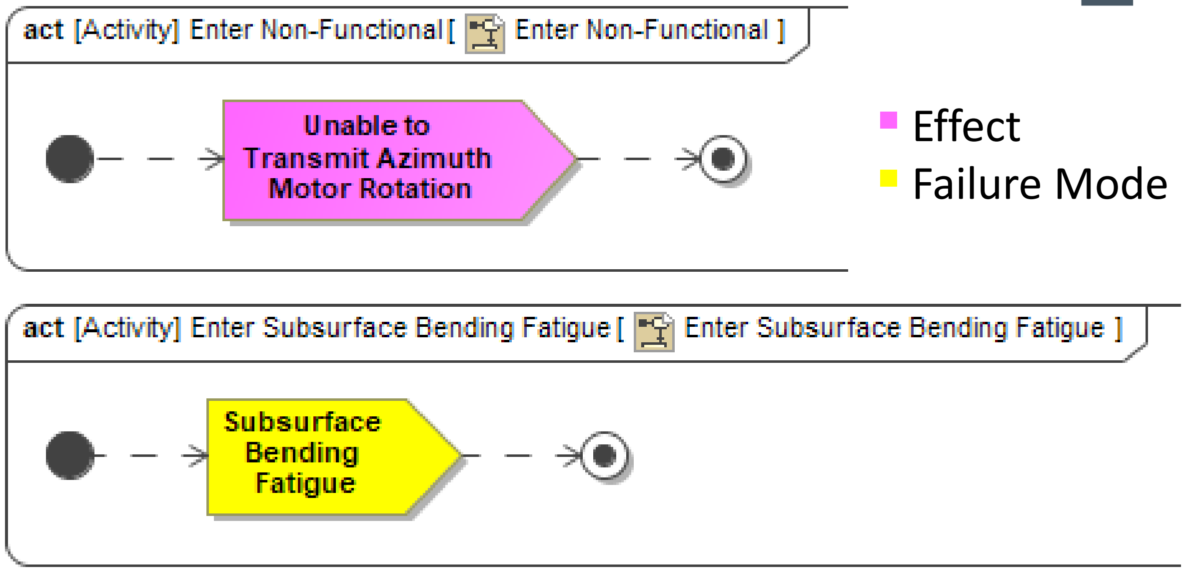
#	Name	dateTimeUT : String	latitu	lon	sun.sunAzi	sun.sunElev	heliostat.targetAzi	heliostat.targetElev	heliostat.po : distance[	heliostat.po: : distance[	heliostat.po : distance[	tower.aimPointX : distance[metre]	tower.aimPointY : distance[metre]	tower.aimPointZ : distance[metre]
1	concentr	2023-05-17T 11:00:00	29.5593	-95.09	63.6824	-6.1157	65.3159	40.1724	0	10	3	0	0	150
2	concentr	2023-05-17T 11:30:00	29.5593	-95.09	67.5304	-0.1718	68.9287	43.098	0	10	3	0	0	150
3	concentr	2023-05-17T 12:00:00	29.5593	-95.09	71.57	6.7462	72.7324	46.5154	0	10	3	0	0	150
4	concentr	2023-05-17T 12:30:00	29.5593	-95.09	74.9423	12.995	75.9137	49.6109	0	10	3	0	0	150
5	concentr	2023-05-17T 13:00:00	29.5593	-95.09	78.2022	19.3417	78.9893	52.7616	0	10	3	0	0	150
6	concentr	2023-05-17T 13:30:00	29.5593	-95.09	81.4218	25.7637	82.0211	55.9554	0	10	3	0	0	150
7	concentr	2023-05-17T 14:00:00	29.5593	-95.09	84.6828	32.2404	85.0774	59.1818	0	10	3	0	0	150
8	concentr	2023-05-17T 14:30:00	29.5593	-95.09	88.0878	38.7519	88.2409	62.4311	0	10	3	0	0	150
9	concentr	2023-05-17T 15:00:00	29.5593	-95.09	91.779	45.2763	91.6225	65.6931	0	10	3	0	0	150
10	concentr	2023-05-17T 15:30:00	29.5593	-95.09	95.976	51.7858	95.3859	68.9564	0	10	3	0	0	150
11	concentr	2023-05-17T 16:00:00	29.5593	-95.09	101.0539	58.2391	99.7967	72.2051	0	10	3	0	0	150
12	concentr	2023-05-17T 16:30:00	29.5593	-95.09	107.7256	64.5616	105.3313	75.4137	0	10	3	0	0	150
13	concentr	2023-05-17T 17:00:00	29.5593	-95.09	117.5076	70.5945	112.9408	78.5334	0	10	3	0	0	150
14	concentr	2023-05-17T 17:30:00	29.5593	-95.09	133.8953	75.9289	124.7415	81.4508	0	10	3	0	0	150
15	concentr	2023-05-17T 18:00:00	29.5593	-95.09	163.3135	79.4211	145.5617	83.8556	0	10	3	0	0	150
16	concentr	2023-05-17T 18:30:00	29.5593	-95.09	201.9658	79.1107	180.9132	84.942	0	10	3	0	0	150
17	concentr	2023-05-17T 19:00:00	29.5593	-95.09	229.1734	75.2367	216.8711	83.9494	0	10	3	0	0	150

Time, latitude, longitude inputs

Sun azimuth, elevation, heliostat azimuth, elevation

State Machines and Failure Modes (1/2)





- Effect
- Failure Mode

Failed states and sub-states

- Failure modes for each heliostat component were modeled with state machines and signals using the Tietronix MBFME methodology

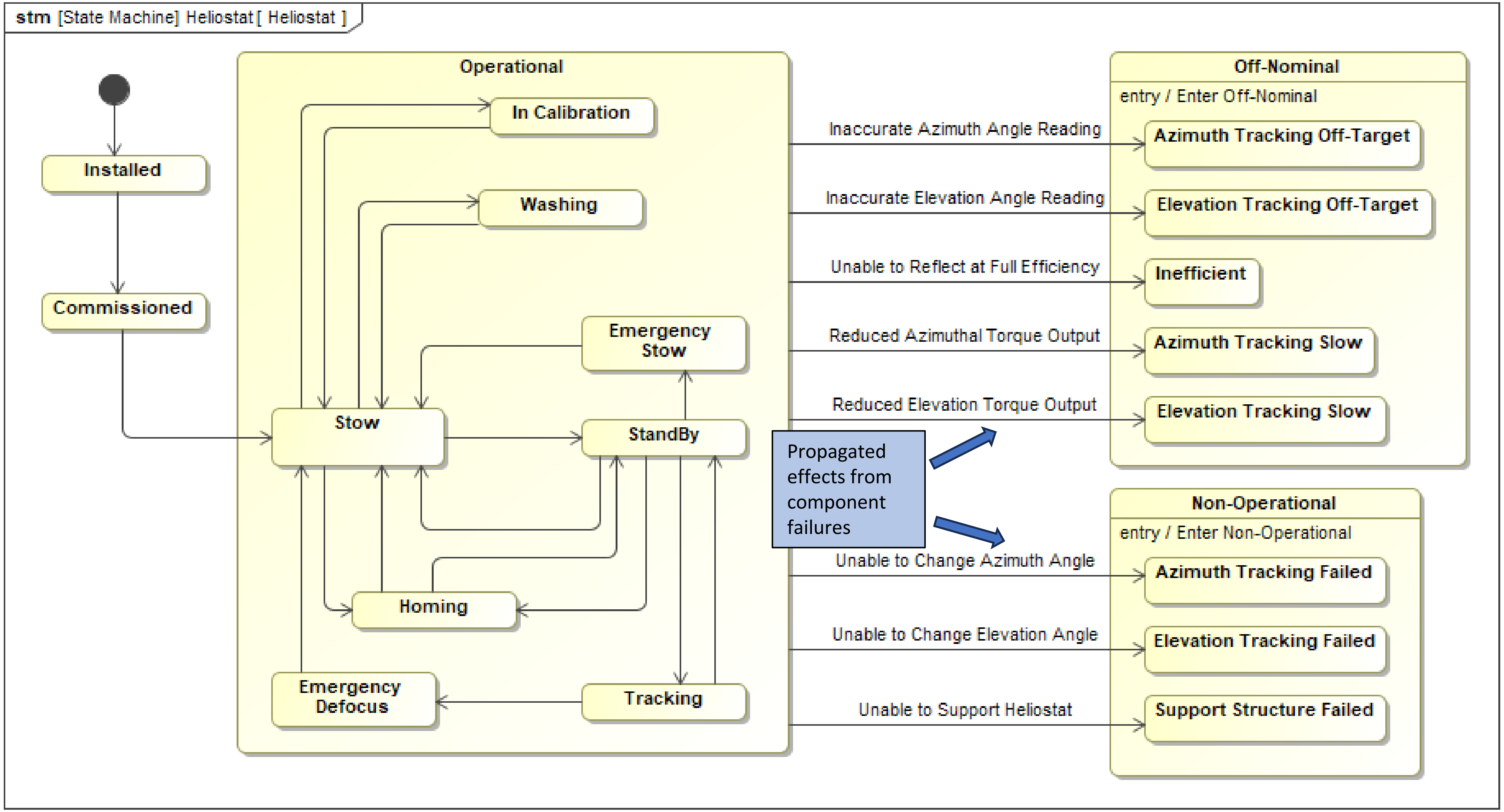
Source of Information

- *NREL, "Gearbox Typical Failure Modes, Detection and Mitigation Methods"*
- *Criticality Analysis and Maintenance of Solar Tower Power Plants by Integrating the Artificial Intelligence Approach*

ration • mass production • heliostat feld

State Machines and Failure Modes (2/2)

- A state machine diagram was used to model the main operational states of the heliostat, as well as off-nominal/non-operational states caused by failures in certain components



Source of Information

- *NREL, "Gearbox Typical Failure Modes, Detection and Mitigation Methods"*
- *Criticality Analysis and Maintenance of Solar Tower Power Plants by Integrating the Artificial Intelligence Approach*

Failure Modes, Effects, and Criticality Analysis (FMECA)

- A FMECA table was generated using the Tietronix FMECA plugin to review the modeled failures, their effects, and possible propagation paths

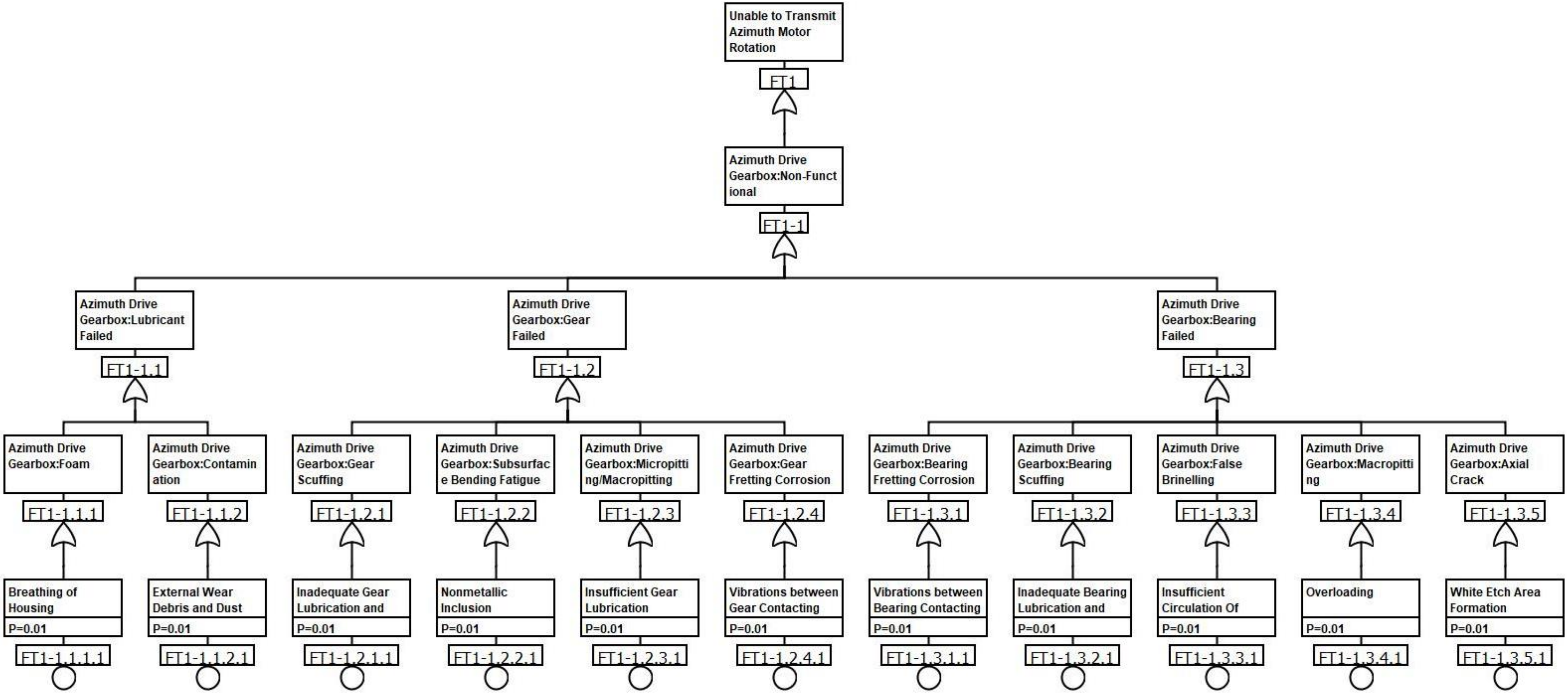
All | Summary

Hierarchy: ALL Row Count: 104

Module	LRU/Assembly	Item	Potential Failure Mode	End Effect	Potential Cause(s)	FPPath	Likelihh...
Heliostat	Elevation Drive	Elevation Drive Gearbox	Foam	EFFECT: Heliostat N...	EVENT: Elevation Drive Gearbox Breathing of Housing	FAILURE: Elevation Drive...	0.01
Heliostat	Azimuth Drive	Azimuth Drive Gearbox	Gear Failed	EFFECT: Heliostat N...		FAILURE: Azimuth Drive ...	
Heliostat	Elevation Drive	Elevation Drive Gearbox	Contamination	EFFECT: Heliostat N...	EVENT: Elevation Drive Gearbox External Wear Debri...	FAILURE: Elevation Drive...	0.01
Heliostat	Azimuth Drive	Azimuth Drive Encoder	Alignment Shift	EFFECT: Heliostat Re...	EVENT: Azimuth Drive Encoder Vibrational Resonance	FAILURE: Azimuth Drive ...	0.04
Heliostat		Power Box	Short Circuit	EFFECT: Heliostat N...	EVENT: Power Box Water Leakage	FAILURE: Power Box Sho...	0.02
Heliostat		Power Box	Short Circuit	EFFECT: Heliostat N...	EVENT: Power Box Water Leakage	FAILURE: Power Box Sho...	0.02
Heliostat		Power Box	Short Circuit	EFFECT: Heliostat N...	EVENT: Power Box Water Leakage	FAILURE: Power Box Sho...	0.02
Heliostat		Power Box	Short Circuit	EFFECT: Heliostat N...	EVENT: Power Box Water Leakage	FAILURE: Power Box Sho...	0.02
Heliostat		Control System	Electronics Failed	EFFECT: Heliostat N...	EVENT: Control System Faulty Wiring Connection	FAILURE: Control Syste...	0.02
Heliostat		Control System	Electronics Failed	EFFECT: Heliostat N...	EVENT: Control System Faulty Wiring Connection	FAILURE: Control Syste...	0.02
Heliostat		Control System	Electronics Failed	EFFECT: Heliostat N...	EVENT: Control System High/Low Temperatures	FAILURE: Control Syste...	0.04
Heliostat		Control System	Electronics Failed	EFFECT: Heliostat N...	EVENT: Control System High/Low Temperatures	FAILURE: Control Syste...	0.04
Heliostat		Control System	Electronics Failed	EFFECT: Heliostat N...	EVENT: Control System Lightning	FAILURE: Control Syste...	0.02
Heliostat		Control System	Electronics Failed	EFFECT: Heliostat N...	EVENT: Control System Lightning	FAILURE: Control Syste...	0.02
Heliostat		Control System	Electronics Failed	EFFECT: Heliostat N...	EVENT: Control System Electrical Transient	FAILURE: Control Syste...	0.02
Heliostat		Control System	Electronics Failed	EFFECT: Heliostat N...	EVENT: Control System Electrical Transient	FAILURE: Control Syste...	0.02
Heliostat		Control System	Electronics Failed	EFFECT: Heliostat N...	EVENT: Control System Water Leakage	FAILURE: Control Syste...	0.02
Heliostat		Control System	Electronics Failed	EFFECT: Heliostat N...	EVENT: Control System Water Leakage	FAILURE: Control Syste...	0.02
Heliostat	Azimuth Drive	Azimuth Drive Gearbox	False Brinelling	EFFECT: Heliostat N...	EVENT: Azimuth Drive Gearbox Insufficient Circulati...	FAILURE: Azimuth Drive ...	0.01
Heliostat		Torque Tube	Corroded	EFFECT: Heliostat N...	EVENT: Torque Tube Moisture	FAILURE: Torque Tube C...	0.05
Heliostat	Azimuth Drive	Azimuth Drive Encoder	Thermal Distortion	EFFECT: Heliostat Re...	EVENT: Azimuth Drive Encoder High/Low Temperat...	FAILURE: Azimuth Drive ...	0.04
Heliostat	Azimuth Drive	Azimuth Drive Gearbox	Mircropitting/Macropitting	EFFECT: Heliostat N...	EVENT: Azimuth Drive Gearbox Insufficient Gear Lu...	FAILURE: Azimuth Drive ...	0.01
Heliostat	Azimuth Drive	Azimuth Drive Gearbox	Bearing Failed	EFFECT: Heliostat N...		FAILURE: Azimuth Drive ...	
Heliostat	Azimuth Drive	Azimuth Drive Encoder	No Signal Output	EFFECT: Heliostat N...	EVENT: Azimuth Drive Encoder Electronics Failure	FAILURE: Azimuth Drive ...	0.02
Heliostat	Azimuth Drive	Azimuth Drive Gearbox	Macropitting	EFFECT: Heliostat N...	EVENT: Azimuth Drive Gearbox Overloading	FAILURE: Azimuth Drive ...	0.01
Heliostat	Azimuth Drive	Azimuth Drive Gearbox	Foam	EFFECT: Heliostat N...	EVENT: Azimuth Drive Gearbox Breathing of Housing	FAILURE: Azimuth Drive ...	0.01
Heliostat		PV Panel	Diode Failed	EFFECT: Heliostat N...	EVENT: PV Panel Diode Failure	FAILURE: PV Panel Diod...	0.01
Heliostat		PV Panel	Diode Failed	EFFECT: Heliostat N...	EVENT: PV Panel Diode Failure	FAILURE: PV Panel Diod...	0.01
Heliostat		PV Panel	Diode Failed	EFFECT: Heliostat N...	EVENT: PV Panel Diode Failure	FAILURE: PV Panel Diod...	0.01
Heliostat		PV Panel	Diode Failed	EFFECT: Heliostat N...	EVENT: PV Panel Diode Failure	FAILURE: PV Panel Diod...	0.01
Heliostat	Azimuth Drive	Azimuth Drive Gearbox	Subsurface Bending Fatigue	EFFECT: Heliostat N...	EVENT: Azimuth Drive Gearbox Nonmetallic Inclusion	FAILURE: Azimuth Drive ...	0.01
Heliostat	Elevation Drive	Elevation Drive Gearbox	Bearing Scuffing	EFFECT: Heliostat N...	EVENT: Elevation Drive Gearbox Inadequate Bearing...	FAILURE: Elevation Drive...	0.01
Heliostat	Azimuth Drive	Azimuth Drive Gearbox	Bearing Scuffing	EFFECT: Heliostat N...	EVENT: Azimuth Drive Gearbox Inadequate Bearing ...	FAILURE: Azimuth Drive ...	0.01
Heliostat	Elevation Drive	Elevation Drive Gearbox	Subsurface Bending Fatigue	EFFECT: Heliostat N...	EVENT: Elevation Drive Gearbox Nonmetallic Inclusion	FAILURE: Elevation Drive...	0.01
Heliostat	Elevation Drive	Elevation Drive Gearbox	Gear Fretting Corrosion	EFFECT: Heliostat N...	EVENT: Elevation Drive Gearbox Vibrations between ...	FAILURE: Elevation Drive...	0.01
Heliostat	Azimuth Drive	Azimuth Drive Gearbox	Gear Scuffing	EFFECT: Heliostat N...	EVENT: Azimuth Drive Gearbox Inadequate Gear Lu...	FAILURE: Azimuth Drive ...	0.01
Heliostat		Mirror Facet	Surface Cracked	EFFECT: Heliostat Re...	EVENT: Mirror Facet High Wind Load	FAILURE: Mirror Facet Su...	0.05
Heliostat		Mirror Facet	Surface Cracked	EFFECT: Heliostat Re...	EVENT: Mirror Facet Material Fatigue	FAILURE: Mirror Facet Su...	0.05
Heliostat	Elevation Drive	Elevation Drive Gearbox	Gear Scuffing	EFFECT: Heliostat N...	EVENT: Elevation Drive Gearbox Inadequate Gear Lu...	FAILURE: Elevation Drive...	0.01

Fault Tree Analysis

- Fault Trees were generated for each component using the Tietronix Fault Tree plugin to perform a top-down analysis of the possible causes of each undesirable effect



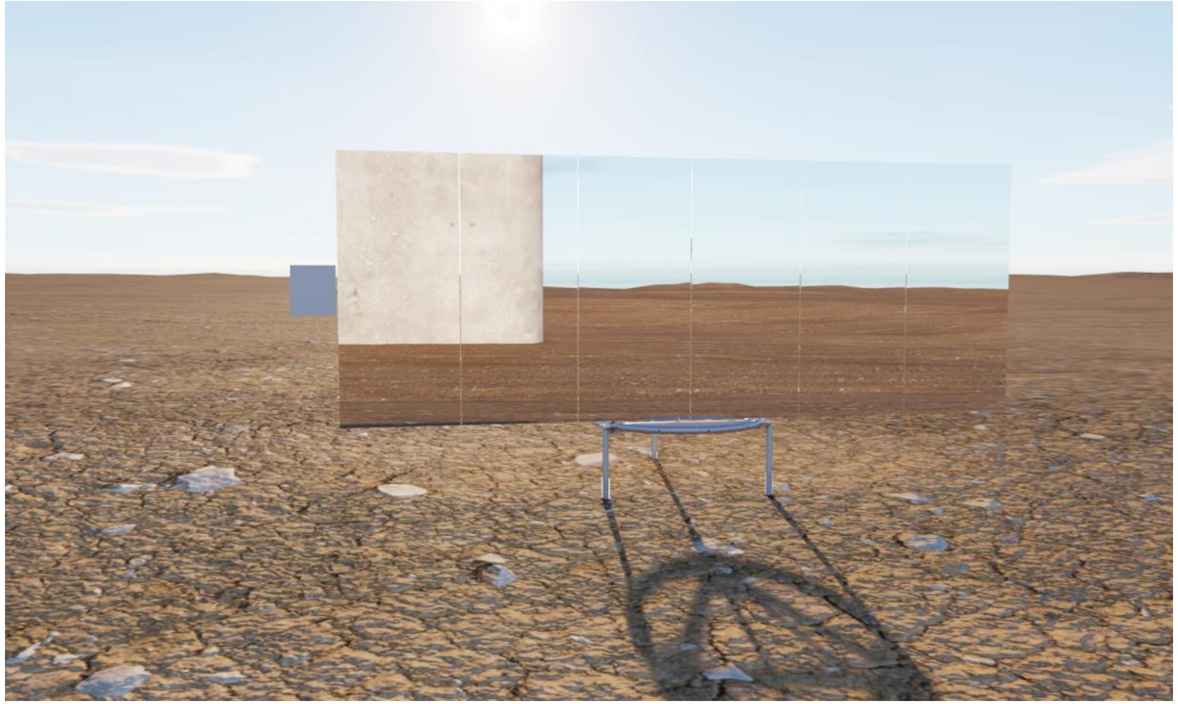
What is a Digital Twin?

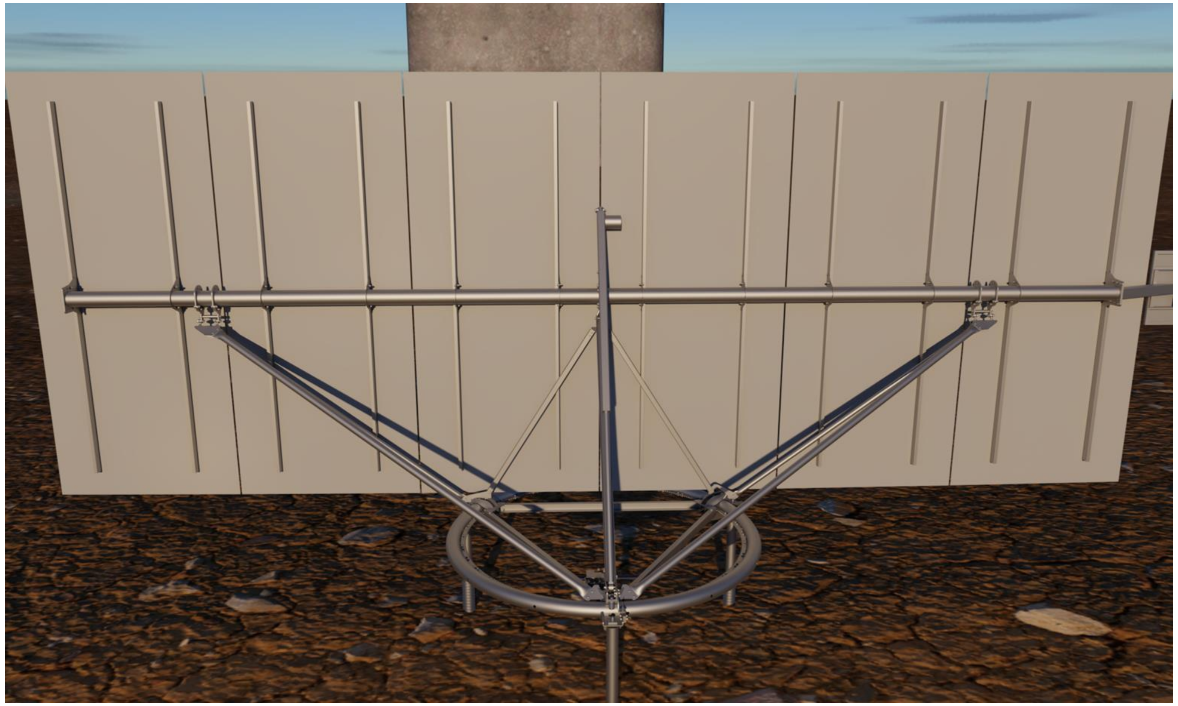
DT is a virtual model, designed to accurately reflect a physical system that enables better **understanding**, **prediction** and **collaboration** throughout all the lifecycle phases

- **Characteristics of a DT:**
  - Provide a collaborative and immersive 3D multimodal environment that enables stakeholders from different locations to share and collaborate effectively.
  - Contain/Access to the MBSE models to support design trade studies, analysis and real-time operational decision making.
  - Integrate with real-time data and IoT technologies to
    - Monitor and control real-time operations and
    - Drive simulation to perform system design, what-if analysis and optimization.
  - Enable data mining and machine learning techniques to continually update and train the virtual model with operational data, with the objective of maintaining synchronization between the digital and physical twins
  - Use the digital Twin to support VR/AR Training and operational procedures development and verification

Initial Digital Twin prototype

Initial Digital Twin prototype

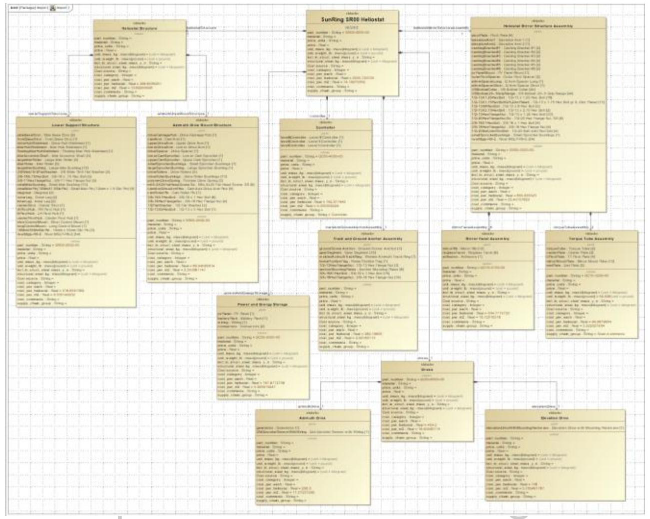


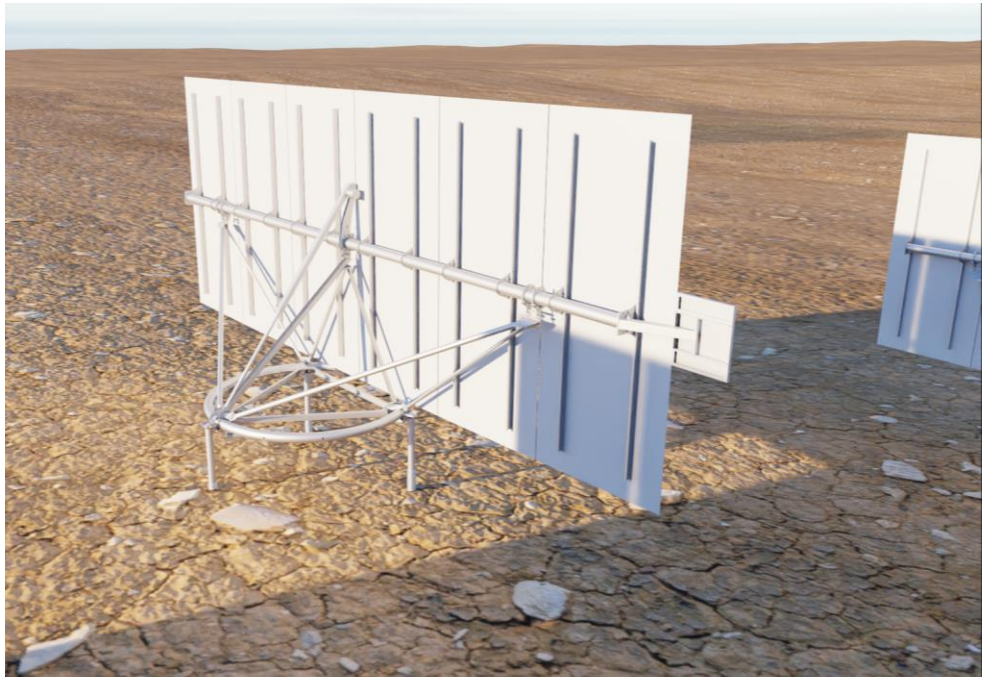


Initial Digital Twin prototype

Lev	Qty	Description	Part Number
0	1	SunRing SR00 Heliostat	SR00-9000-00
1	1	Track and Ground Anchor Assembly	
2	3	Ground screw anchors	DC10-6000-00
2	18	Gear segments	SR00-
2	1	Welded azimuth track ring	SR00-1002-00
2	1	Home position flag	DC10-1000-05
2	3	1/2-13 hex flange nut	96282A104
2	6	Anchor mounting plates	SR00-9000-01
2	78	3/8-16 x 1 hex bolt	92620A624
2	78	3/8-16 flanged hex nut	96282A103
1	1	Heliostat Structure	
2	1	Lower Support Structure	SR00-2002-00
3	2	SIDE BASE STRUT	SR00-2002-01
3	1	FRONT BASE STRUT	SR00-2002-02
3	1	DRIVE HUB WELDMENT	SR00-2112-00
3	1	IDLER HUB WELDMENT	SR00-2212-00
3	1	FLOATING IDLER HUB WELDMENT	SR00-2312-00
3	5	Idler Eccentric Shaft	SR00-2802-01
3	5	Large Idler Roller	SR00-2802-02
3	5	Idler Roller	SR00-2602-01
3	10	Large Idler Bushing	BB2012DP4
3	5	3/8 Wide 18-8 flat washer	92217A529
3	5	3/8-16 x .75 Hex Bolt	92620A622
3	5	5/8-11 Hex Flange Nut	96282A105
3	10	Small idler bushing	BB1212DP4
3	5	Small idler pin (12mm x 1.5 slic pin)	
3	2	Diagonal	SR00-4002-01
3	2	Outer Leg	SR00-4002-02
3	2	Inner Leg	DC10-4002-07
3	1	Center Strut	SR00-4002-04
3	1	RH Pivot Hub	SR00-4002-03
3	1	LH Pivot Hub	SR00-4002-06
3	1	Center Pivot Hub	SR00-4002-05
3	1	Short Control Mount	SR00-Control_Lower_Mount
3	1	Long Control Mount	SR00-Control_Mount
3	3	18mm x 55mm slic pin	
3	54	Rivet MGLP-R8-E	
2	1	Azimuth Drive Mount Structure	SR00-2502-00
3	1	Drive carriage hub	SR00-2532-00
3	1	Cam arm	SR00-2522-01
3	1	Upper drive arm	SR00-2512-04
3	1	Lower drive arm	SR00-2512-03
3	1	Drive spacer	SR00-2512-05
3	1	LOWER CAM SPROCKET	SR00-2512-01
3	1	UPPER CAM SPROCKET	SR00-2512-02
3	1	SMALL SPROCKET BUSHINGS	BB1412DP4
3	1	LARGE SPROCKET BUSHING	BB2522DP4
3	5	Drive Rollers	SR00-2702-01

Mappings between 3D model, SysML models, BOM



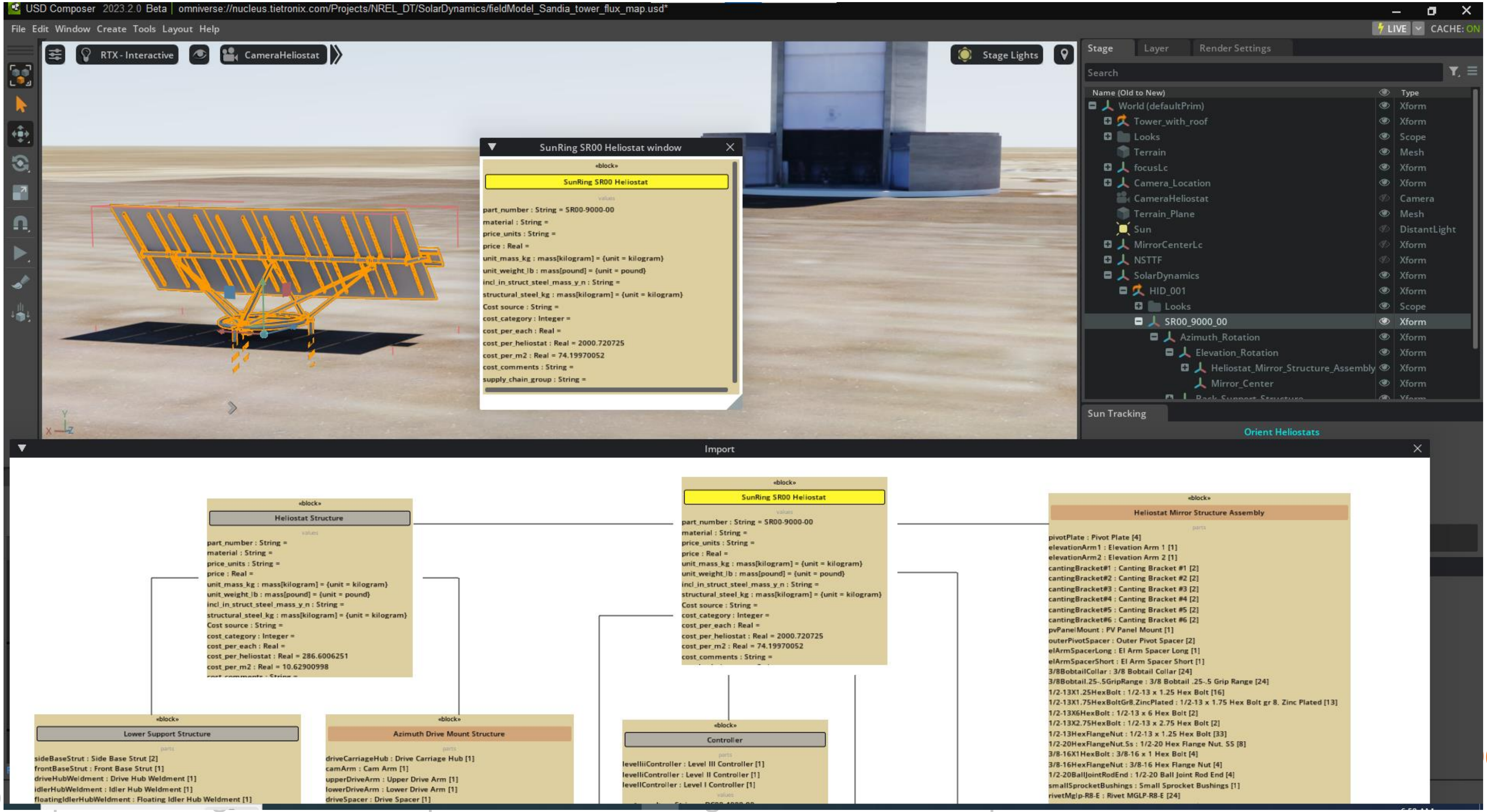


Tietronix RFP 38488-006

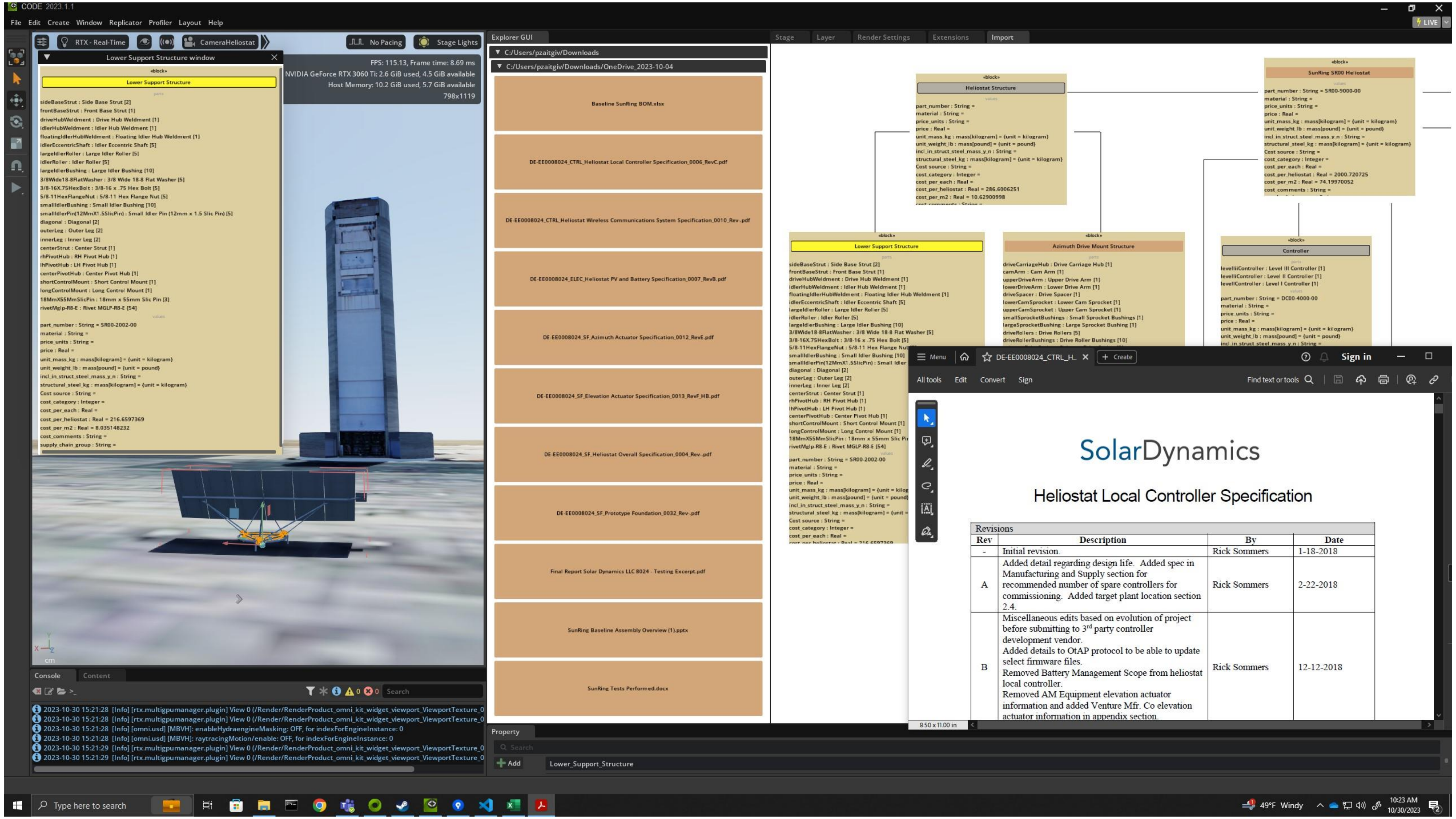
Accomplishments

- Digital Twin:
  - Pre-Processed and Imported 3D model of heliostats into Omniverse platform
  - Integrated SysML Models with 3D models
  - Integrated documents into Omniverse platform
    - Select document from DT UI
  - Computation of heliostat orientation over a day/year
    - Internally in Omniverse
  - Fluxmap Generation using Omniverse Ray Tracing
    - Tried to use internal Ray Tracing to generate reflected flux on the receiver. Ongoing assessment.
  - Integrated TieSOL ray tracing software with Omniverse:
    - TieSOL computes the heliostat(s) fluxmap based on DT data inputs and send back the result to be graphically displayed
  - Playback of test data
  - VR output:
    - Omniverse scene to Quest Pro device
    - Assess output to NREL CAVE
  - Ongoing/future computations integration:
    - Computation of Wind Load on heliostat at any point in time given orientation, wind direction, wind speed, characteristics of heliostat (geometry, structure,…)
    - Computation of heliostats motors power usage
    - Real Time integration of heliostat testing telemetry

Integration SysML models with 3D models



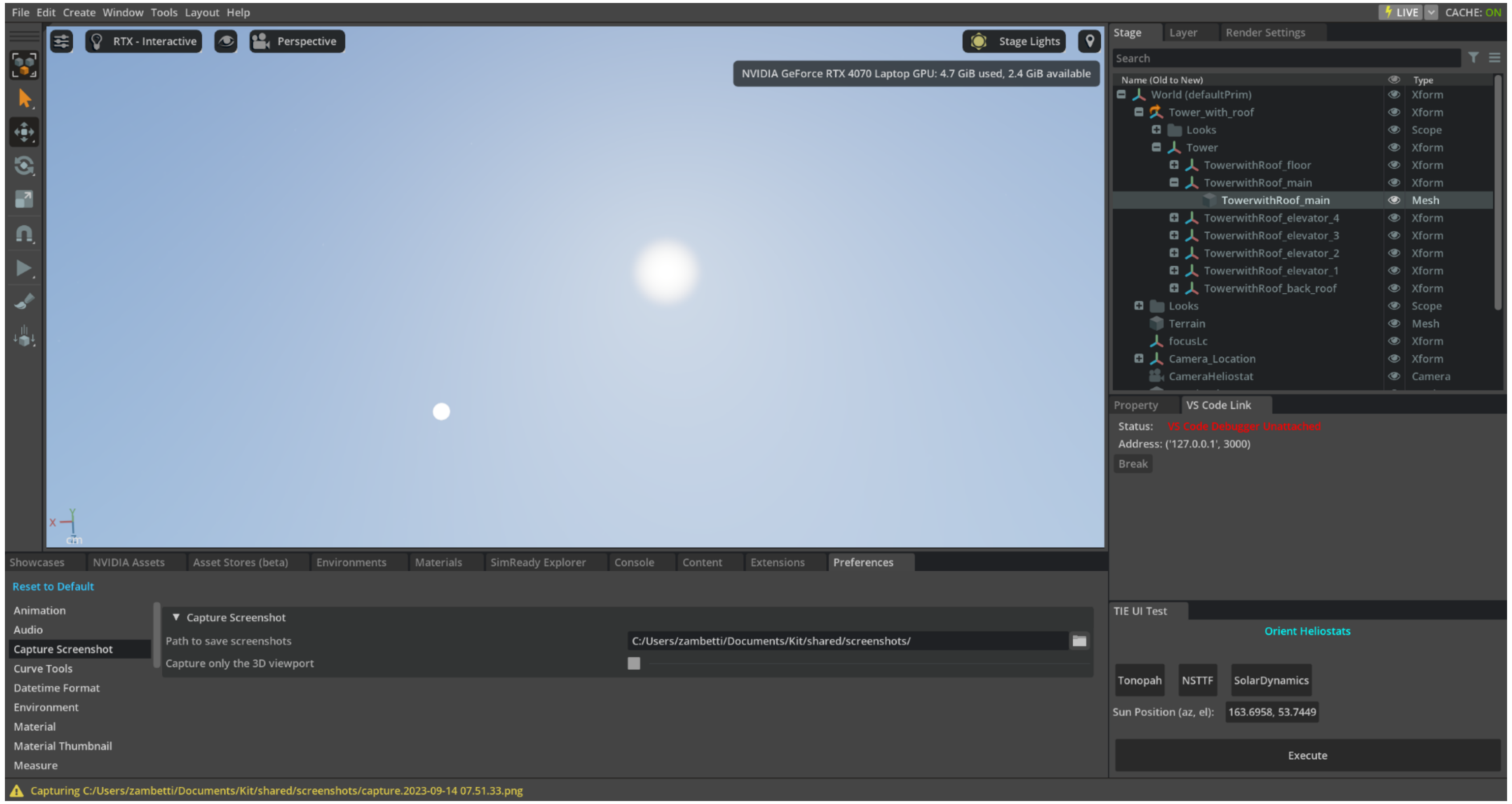
Integration of Documents within DT



Computation of heliostat orientation
Omniverse Sun Position

- We used two separate methods to compute the sun azimuth and elevation for testing purpose
- Both methods gave the same results withing 2 decimal points
- When comparing a distant light source oriented as per the appropriate azimuth and elevation, we found that our plotted sun did not match the one plotted in the Omniverse environment.
- Inquired and obtained the Omniverse Sun code from Nvidia
  - Very low accuracy model
  - Modified the code to use our (high accuracy) sun position algorithm

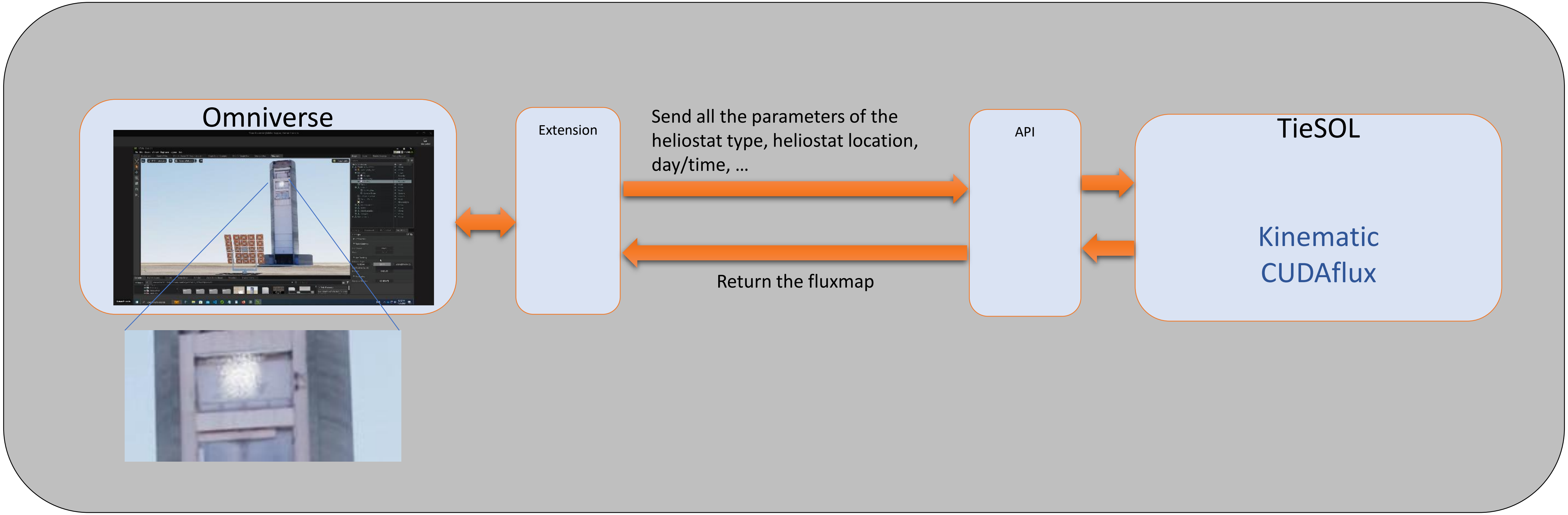
✓ Fixed the issue



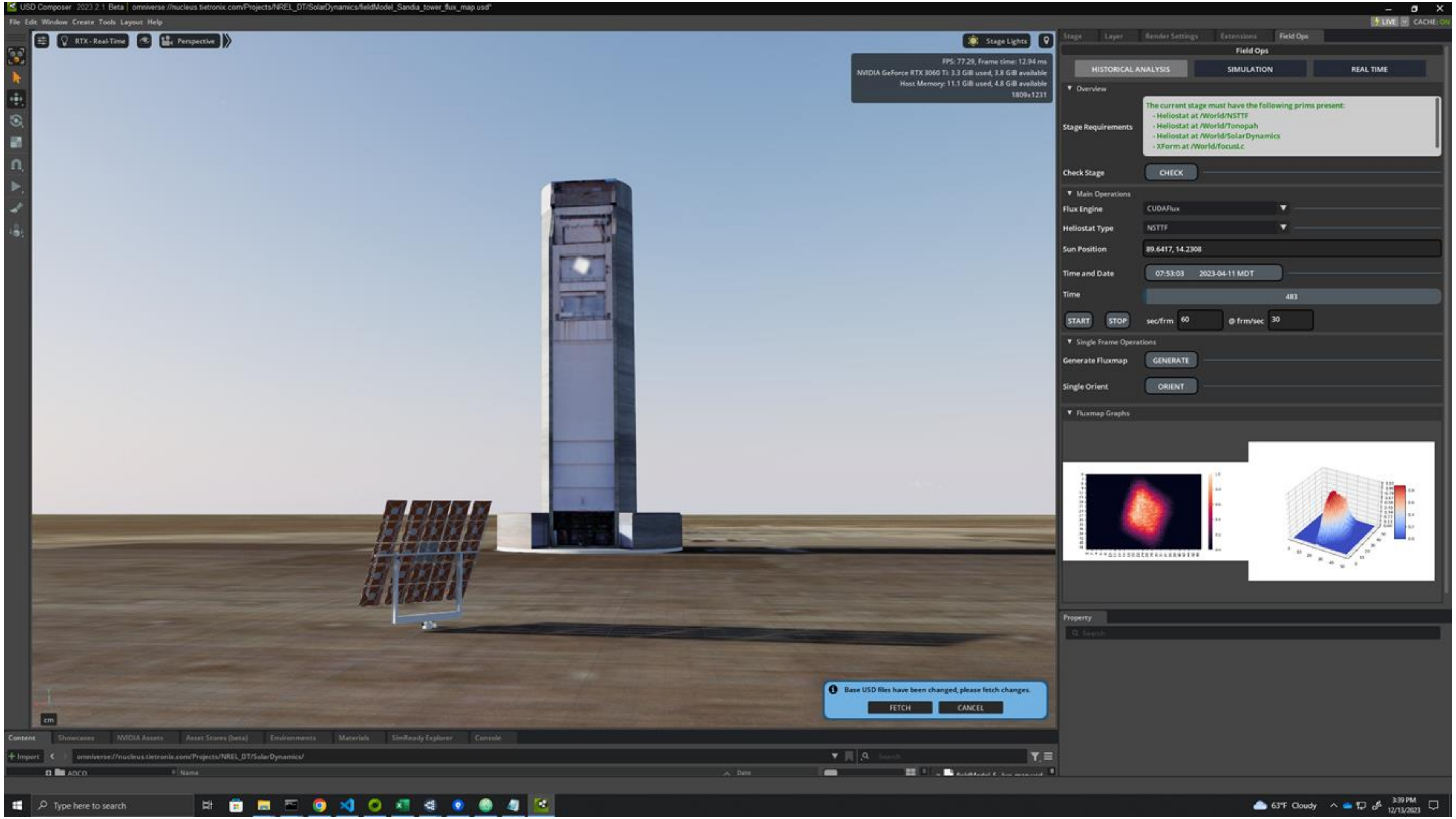
Fluxmap Generation

- Generation of the reflected flux on the receiver within the Digital Twin can be achieved through:
  - Integration with external Ray Tracing software
    - Integrated with TieSOL
  - Internal Omniverse Ray Tracing capability
    - Ray Tracing is targeted toward visual accuracy (not physics accuracy)
    - Multiple Ray Tracing modes: Accurate, Path Tracing, Real Time

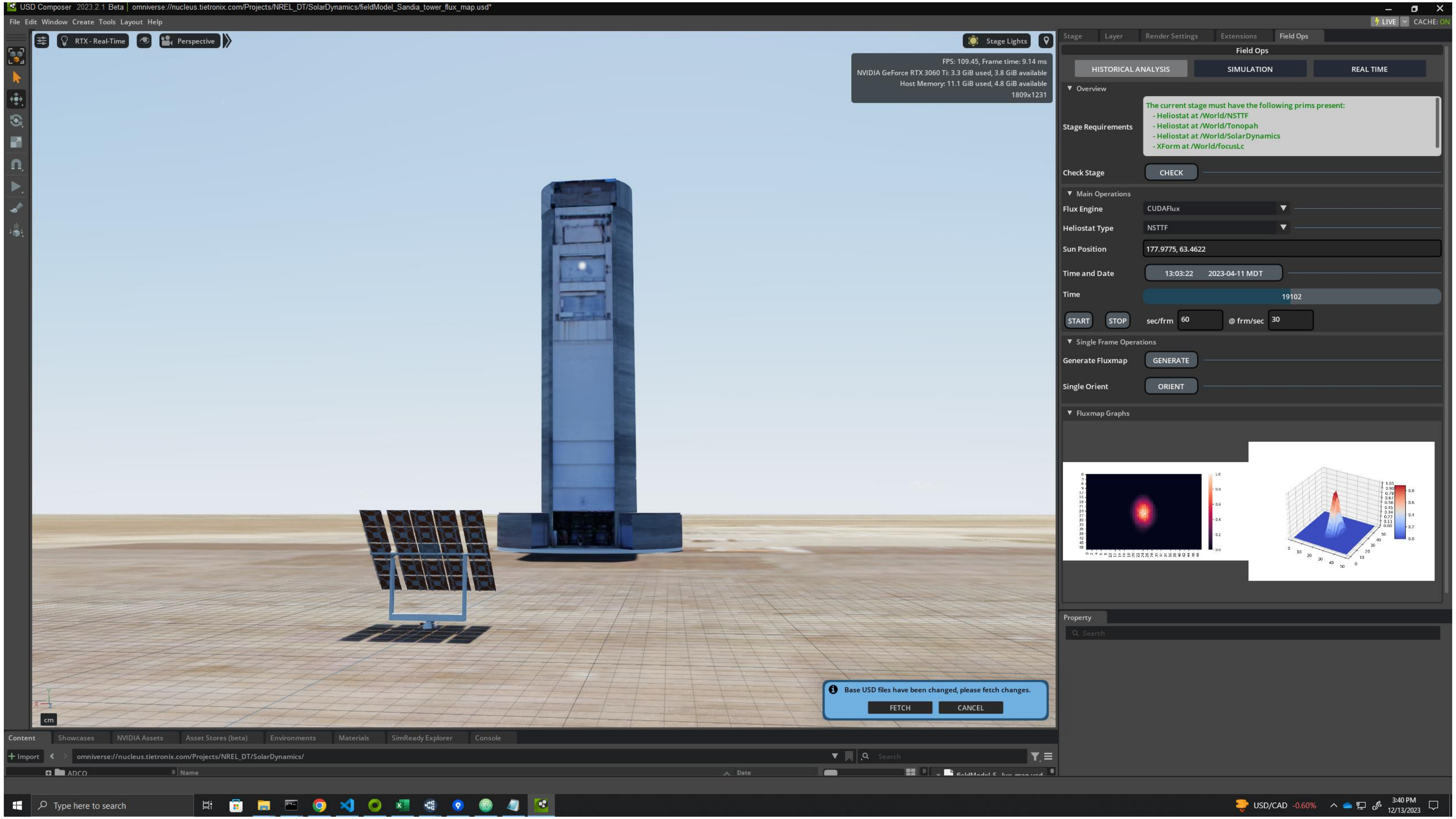
Integration with TieSOL



Fluxmap Generation using TieSOL



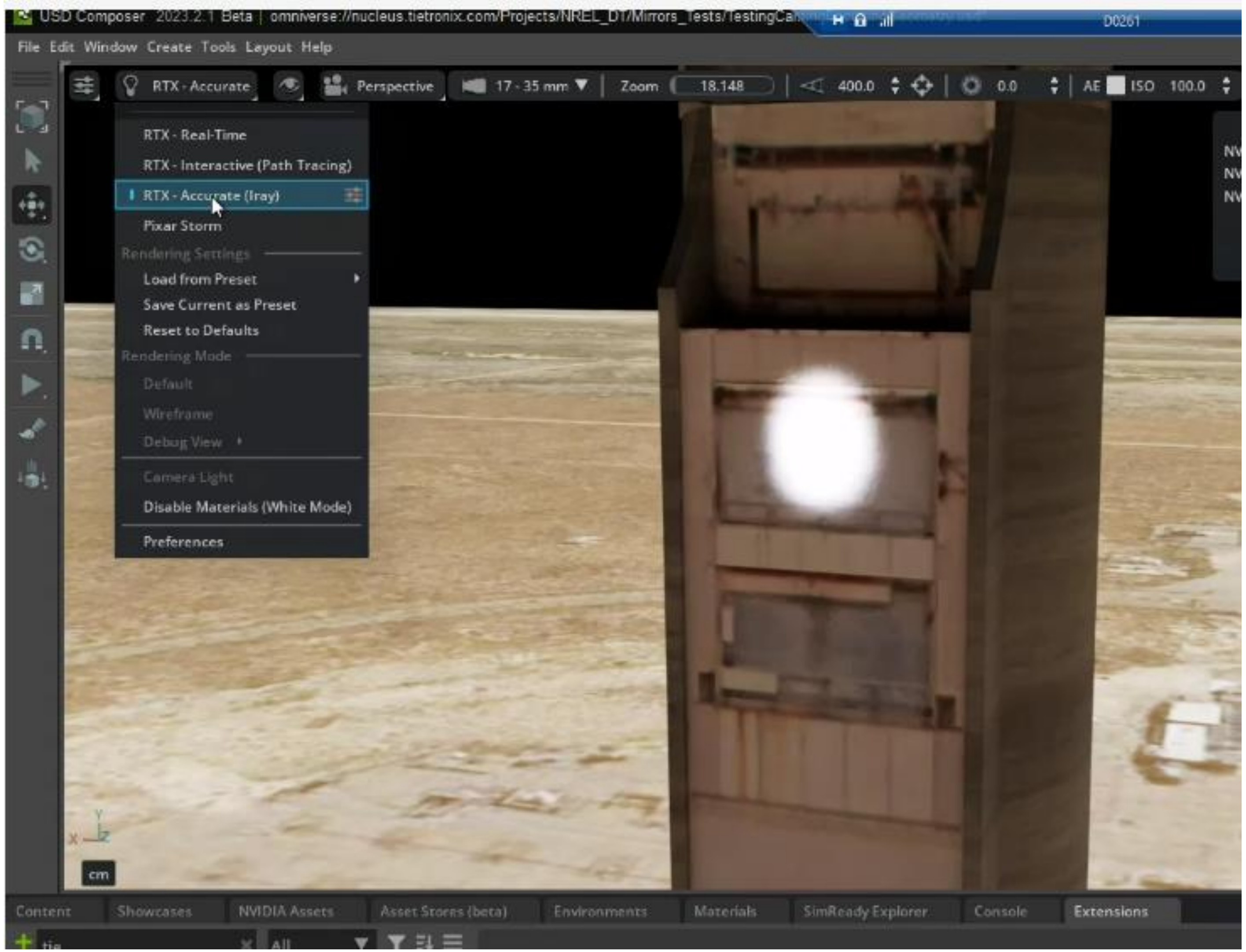
Fluxmap Generation using TieSOL



Tietronix RFP 38488-006

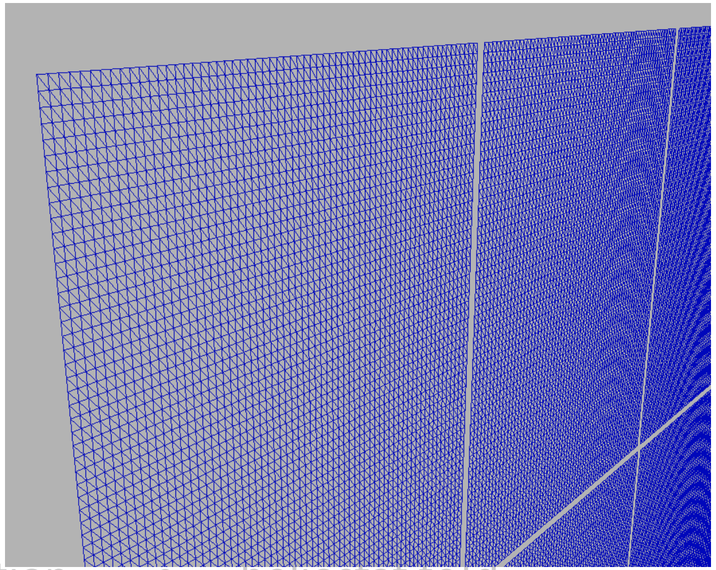
Ray Tracing in Omniverse

- Omniverse has multiple rendering modes
  - Real Time (no ray tracing)
  - Path Tracing (RTX Path Tracing)
  - Accurate (RTX Full Ray Tracing)
- Assess if full ray tracing mode can be used
  - Can it provide an accurate fluxmap on receiver
- Ongoing work to understand all parameters used in Omniverse
  - Sun Model, sun shape, …
  - Intensity mapping to actual DNI
- In Discussion with NVIDIA to clarify capability and potentially influence their development effort.
  - Need Physics based accurate Ray Tracing, not only accurate Visual Rendering



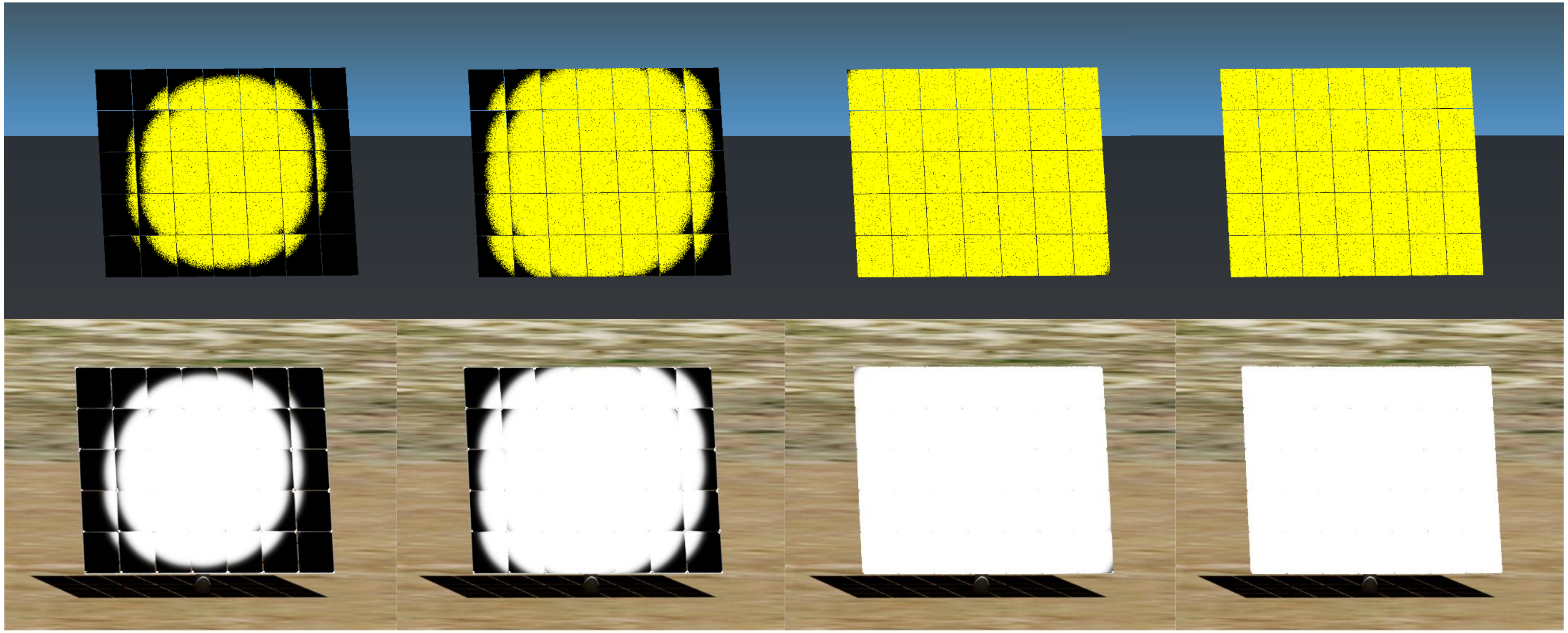
Fluxmap Generation in Omniverse

- Omniverse has an internal Ray Tracing engine
- Tried to use it for fluxmap generation
  - As the 3D models did not have the detailed geometry for facets Canting and Focusing, used Normal maps on top of the heliostat 3D model.
    - Problem: Omniverse supports 16 bits normal maps – needs 32 bits
      - Insufficient accuracy for the slight normal deviation due to canting and focusing
      - Trying to get some help from Nvidia
- Increased geometry detail in 3D model
  - Procedurally subdivide each mirror facet by a specified number of segments (in our tests 64x64)
  - Displace the vertices of each grid element by the computed canting and focusing values
- The next two slides show a comparison of the sun seen from a focal point at 524 m, generated in TieSOL (above) and Omniverse (below)



Ray Tracing in Omniverse

- Comparison of reflected Sun in Crescent Dunes Heliostats between TieSOL and Omniverse
  - *Generated the reflected Sun in four heliostats placed at 524 m slant range from the receiver (corresponding to the four Canting/Focusing bands at Tonopah) viewed from the Receiver*



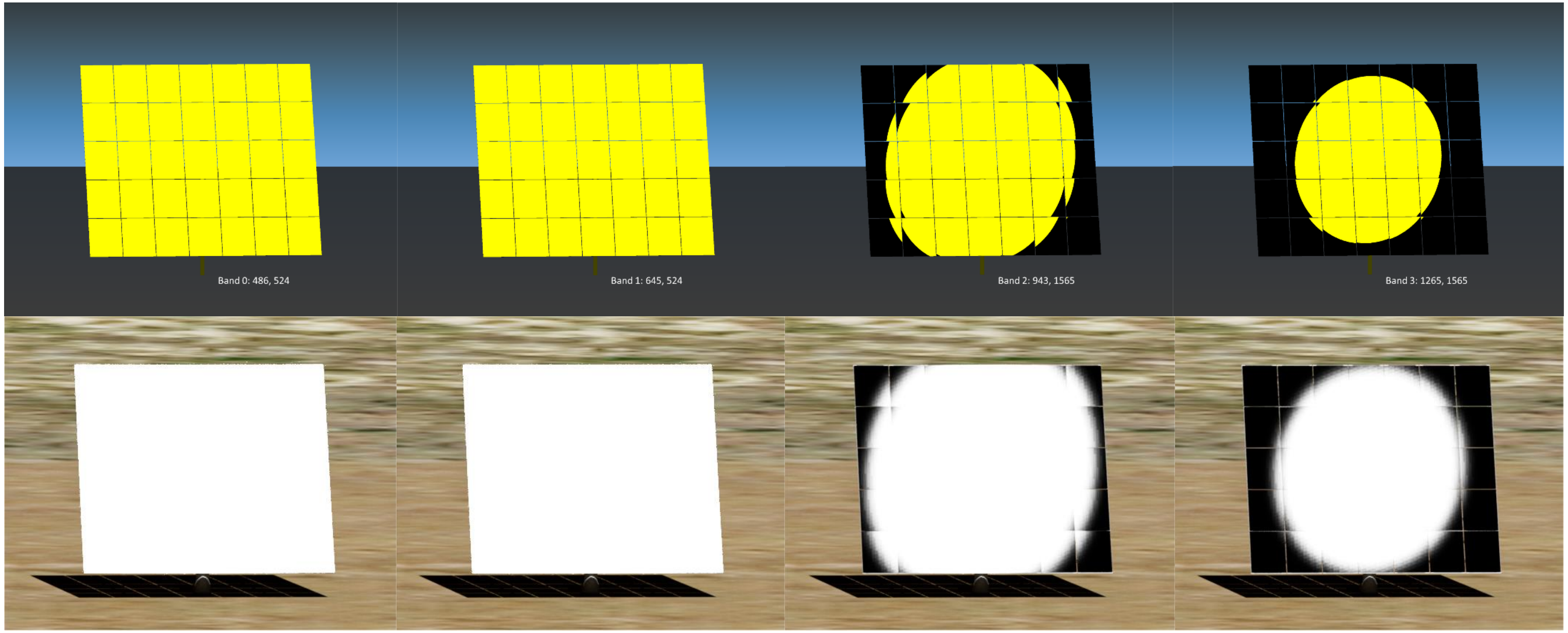
TieSOL: Pillbox
Sun size: 0.5312 deg

Omniverse
Sun size: 0.5336 deg

- Canting Only: using 4 settings for canting. From right to left
  - `Canting: 486m; 645m; 943m; 1265m`

Tietronix RFP 38488-006

Ray Tracing in Omniverse



- Using 4 settings for canting and focusing. From left to right (canting, focusing)
  - Band 1: Canting = 486m; Focusing = 524m
  - Band 2: Canting = 645m; Focusing = 524m
  - Band 3: Canting = 943m; Focusing = 1565m
  - Band 4: Canting = 1265m; Focusing = 1565m

Playback Test Data Integration

- Playback existing telemetry log files from test run
  - Test log file from Solar Dynamics

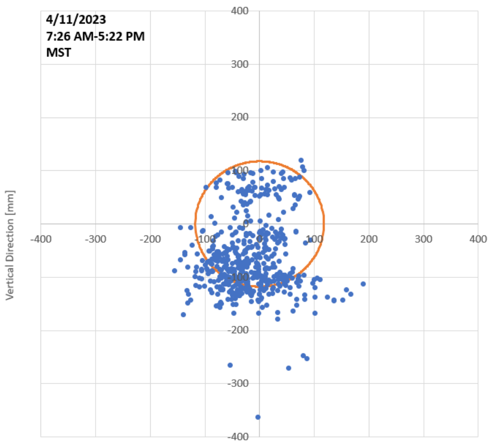
plot limit (max/min) 400

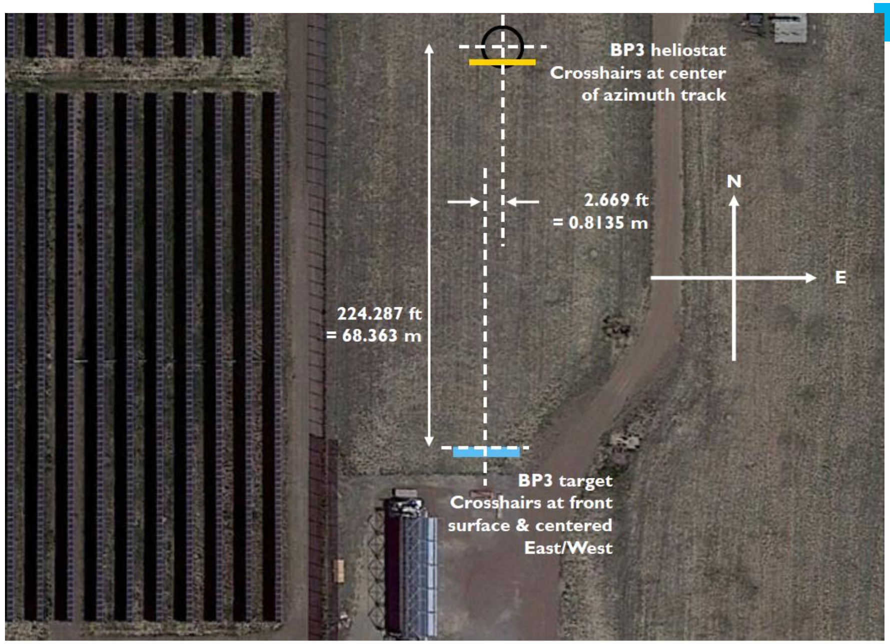
start time 7:26 AM
end time 5:22 PM

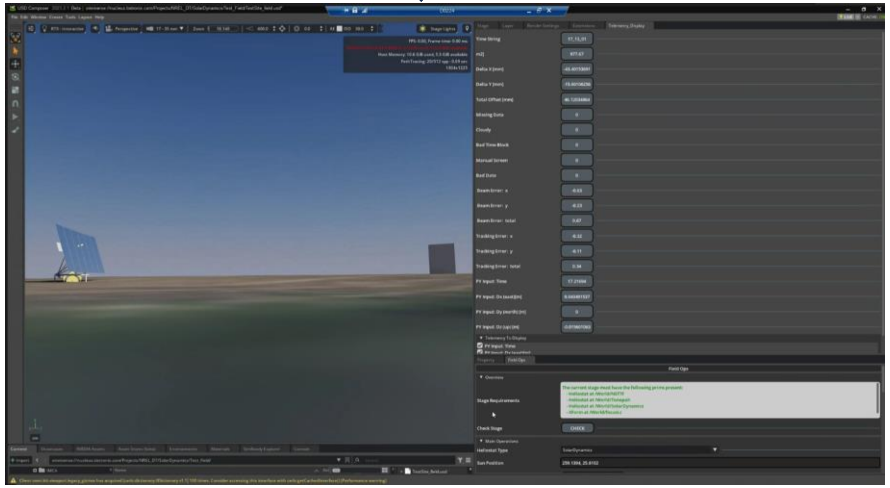
	Delta X	Delta Y
Max	189.1416	119.8990
Min	-156.2253	-390.2582

555 # good datapoints
0 0 8 0 8 # bad datpoints

Data Timestamp to Standard Mountain Time						DNI	Centroid [mm]									
Min	Sec	HR	MST	MST Rounded to Nearest Min	MST: Python Alg. Format	DNI [W/m2]	Delta X [mm]	Delta Y [mm]	Total Offset [mm]	Missing Data	Cloudy	Bad Tin	Manual Screen	Bad Data	Beam Error: x	B
26	54	7.448333	7:26:54 AM	7:27:00 AM	7.448333333	856.59	123.7991341	-137.922008	185.3340387	0	0	0	0	0	1.81	
27	58	7.466111	7:27:58 AM	7:28:00 AM	7.466111111	858.91	-30.86505219	-101.5031459	106.0921301	0	0	0	0	0	-0.45	
29	02	7.483889	7:29:02 AM	7:29:00 AM	7.483888889	861.55	41.81461501	-104.1743836	112.2531257	0	0	0	0	0	0.61	
30	04	7.501111	7:30:04 AM	7:30:00 AM	7.501111111	862.76	4.161014368	-138.3499187								
31	06	7.518333	7:31:06 AM	7:31:00 AM	7.518333333	863.26	-23.54525902	-114.4291863								
32	09	7.535833	7:32:09 AM	7:32:00 AM	7.535833333	864.50	-34.31565146	-123.8364515								
33	11	7.553056	7:33:11 AM	7:33:00 AM	7.553055556	867.69	-26.51096201	-105.0776732								
34	13	7.570278	7:34:13 AM	7:34:00 AM	7.570277778	869.41	82.56978563	-142.1167647								
35	16	7.587778	7:35:16 AM	7:35:00 AM	7.587777778	868.75	151.6606689	-142.2767335								
36	18	7.605	7:36:18 AM	7:36:00 AM	7.605	869.90	136.0632199	-142.976488								
37	21	7.6225	7:37:21 AM	7:37:00 AM	7.6225	870.96	-0.211621463	-132.4143646								
38	23	7.639722	7:38:23 AM	7:38:00 AM	7.639722222	872.14	3.014143766	-106.7625861								
39	25	7.656944	7:39:25 AM	7:39:00 AM	7.656944444	875.10	-46.1146962	-95.18948995								
40	28	7.674444	7:40:28 AM	7:40:00 AM	7.674444444	877.28	67.44113755	-109.5191498								
41	31	7.691944	7:41:31 AM	7:42:00 AM	7.691944444	878.60	3.352683022	-98.21661343								
42	35	7.709722	7:42:35 AM	7:43:00 AM	7.709722222	881.46	44.65989298	-112.3666067								
43	37	7.726944	7:43:37 AM	7:44:00 AM	7.726944444	883.74	49.26909318	-101.8524121								
44	40	7.744444	7:44:40 AM	7:45:00 AM	7.744444444	884.21	167.4084405	-131.4714014								
45	42	7.761667	7:45:42 AM	7:46:00 AM	7.761666667	883.17	97.1560668	-111.4877111								
46	46	7.779444	7:46:46 AM	7:47:00 AM	7.779444444	883.75	-1.601756276	-112.110561								
47	49	7.796944	7:47:49 AM	7:48:00 AM	7.796944444	886.78	-26.49090633	-107.2695373								
48	52	7.814444	7:48:52 AM	7:49:00 AM	7.814444444	889.06	-39.10006589	-107.1773541								
49	54	7.831667	7:49:54 AM	7:50:00 AM	7.831666667	890.13	-23.1207443	-96.91681421								
50	58	7.849444	7:50:58 AM	7:51:00 AM	7.849444444	890.77	-40.41543096	-111.3233997								
52	01	7.866944	7:52:01 AM	7:52:00 AM	7.866944444	891.89	10.93750871	-93.14335999								
53	03	7.884167	7:53:03 AM	7:53:00 AM	7.884166667	892.88	158.9094159	-124.0710376								
54	06	7.901667	7:54:06 AM	7:54:00 AM	7.901666667	894.79	189.1415875	-112.0726404								
55	08	7.918889	7:55:08 AM	7:55:00 AM	7.918888889	895.94	100.8955724	-119.4129893								
56	11	7.936389	7:56:11 AM	7:56:00 AM	7.936388889	896.89	-20.50603025	-118.1872405								
57	13	7.953611	7:57:13 AM	7:57:00 AM	7.953611111	899.19	-83.26490654	-107.9295335								
58	15	7.970833	7:58:15 AM	7:58:00 AM	7.970833333	901.04	-52.05393817	-107.5421068								
59	17	7.988056	7:59:17 AM	7:59:00 AM	7.988055556	902.04	-23.33032756	-111.6851849								
00	20	8.005556	8:00:20 AM	8:00:00 AM	8.005555556	903.46	9.725660166	-99.56835544								
01	22	8.022778	8:01:22 AM	8:01:00 AM	8.022777778	905.92	59.9181172	-101.7659644								
02	24	8.04	8:02:24 AM	8:02:00 AM	8.04	906.61	32.64313613	-125.4419286								

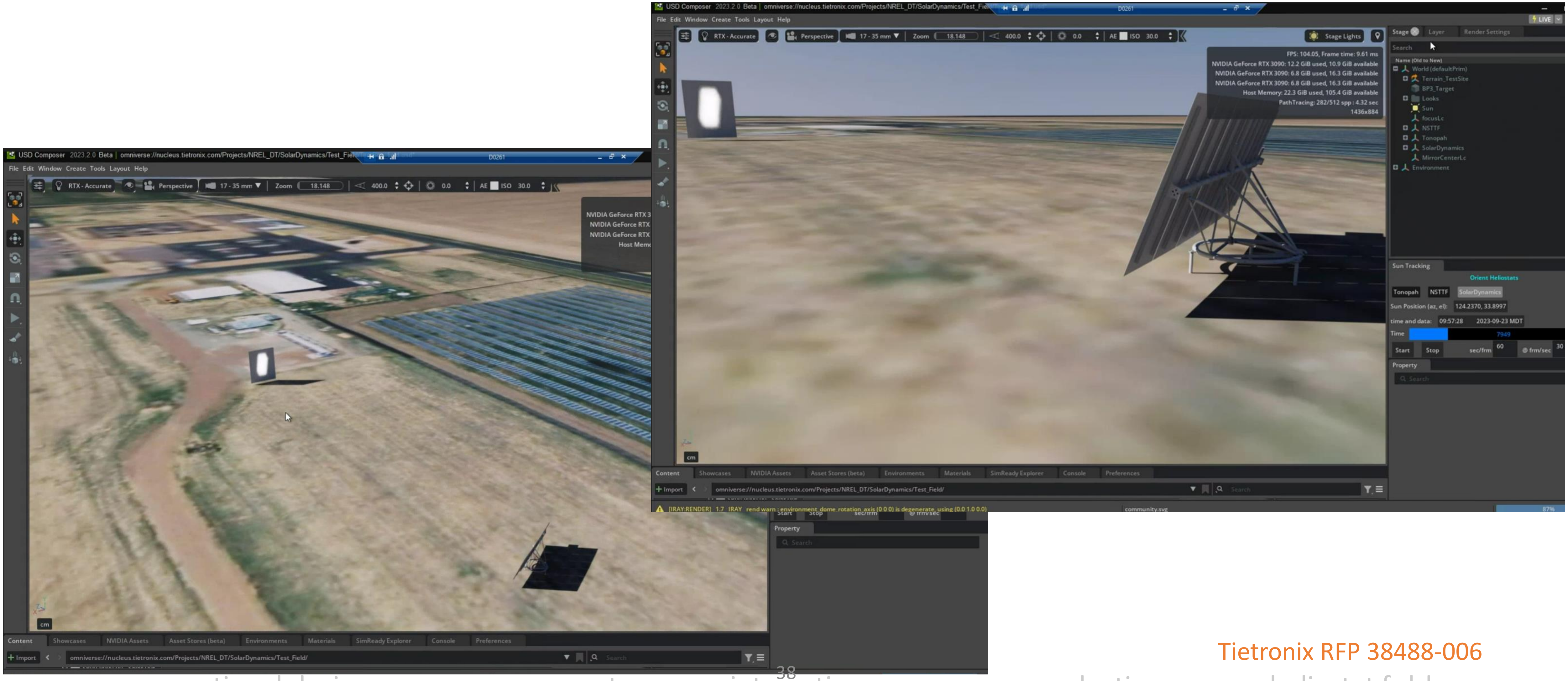




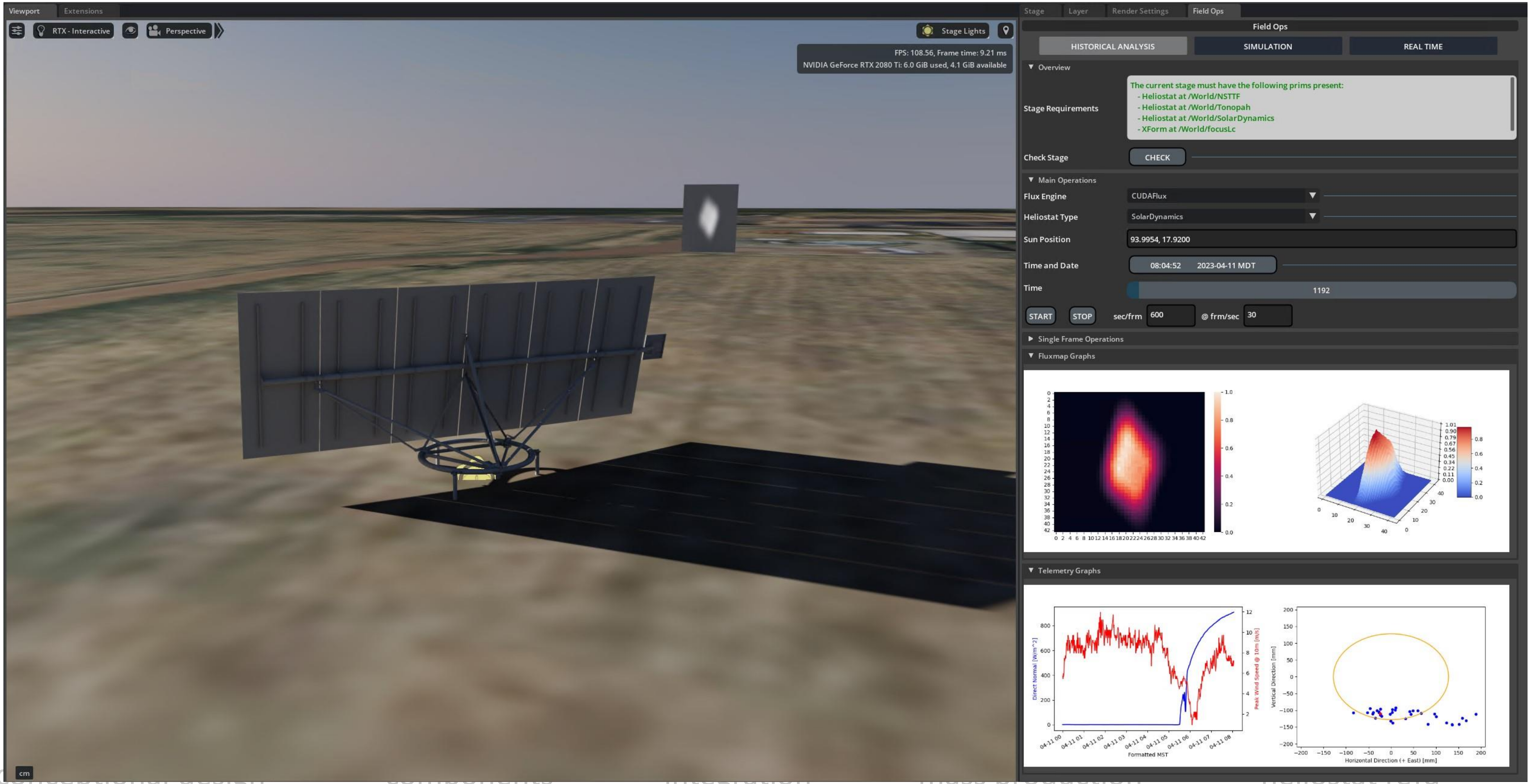


Tietronix RFP 38488-006

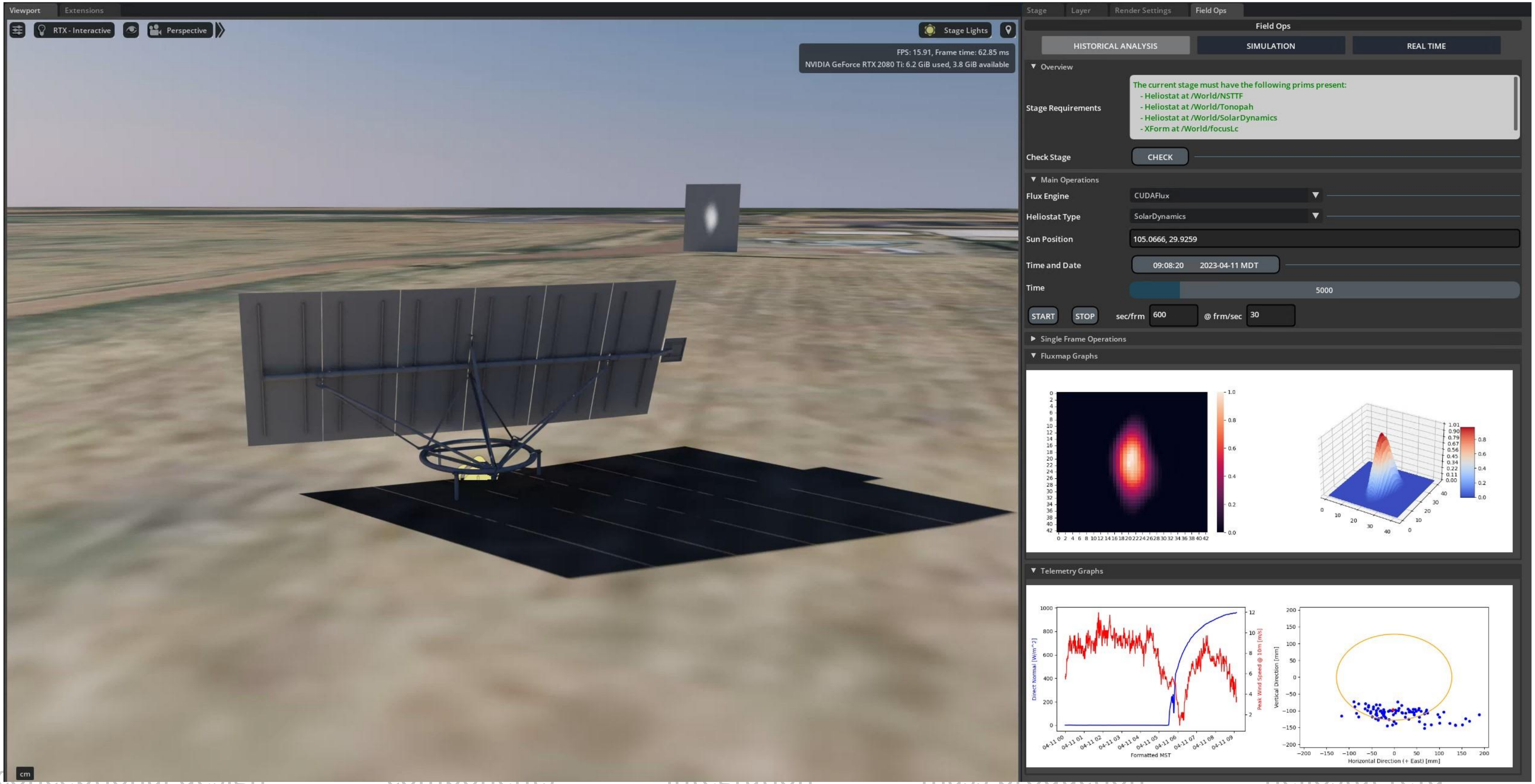
Solar Dynamics Test Site



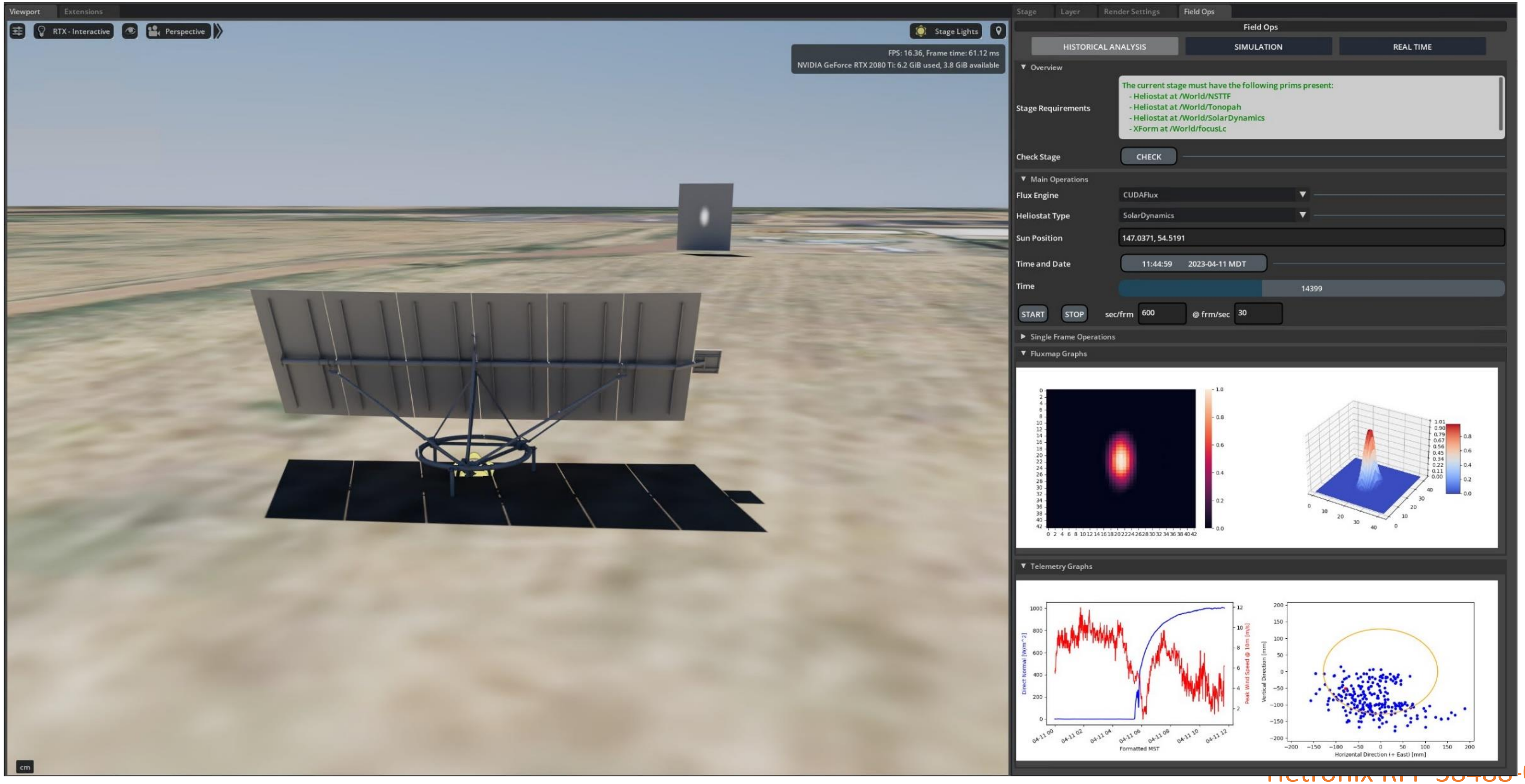
Playback using TieSOL Ray Tracing



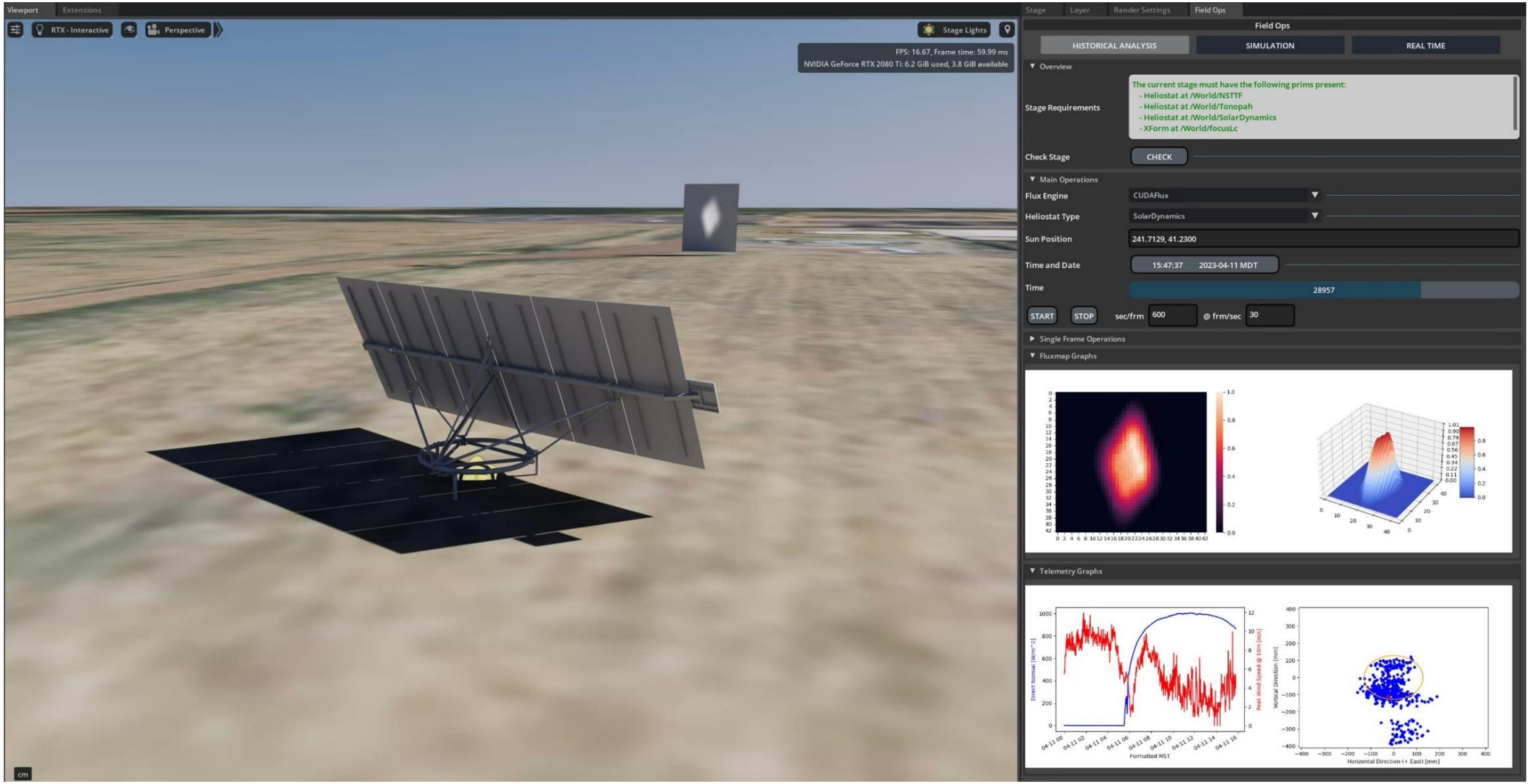
Playback using TieSOL Ray Tracing



Playback using TieSOL Ray Tracing

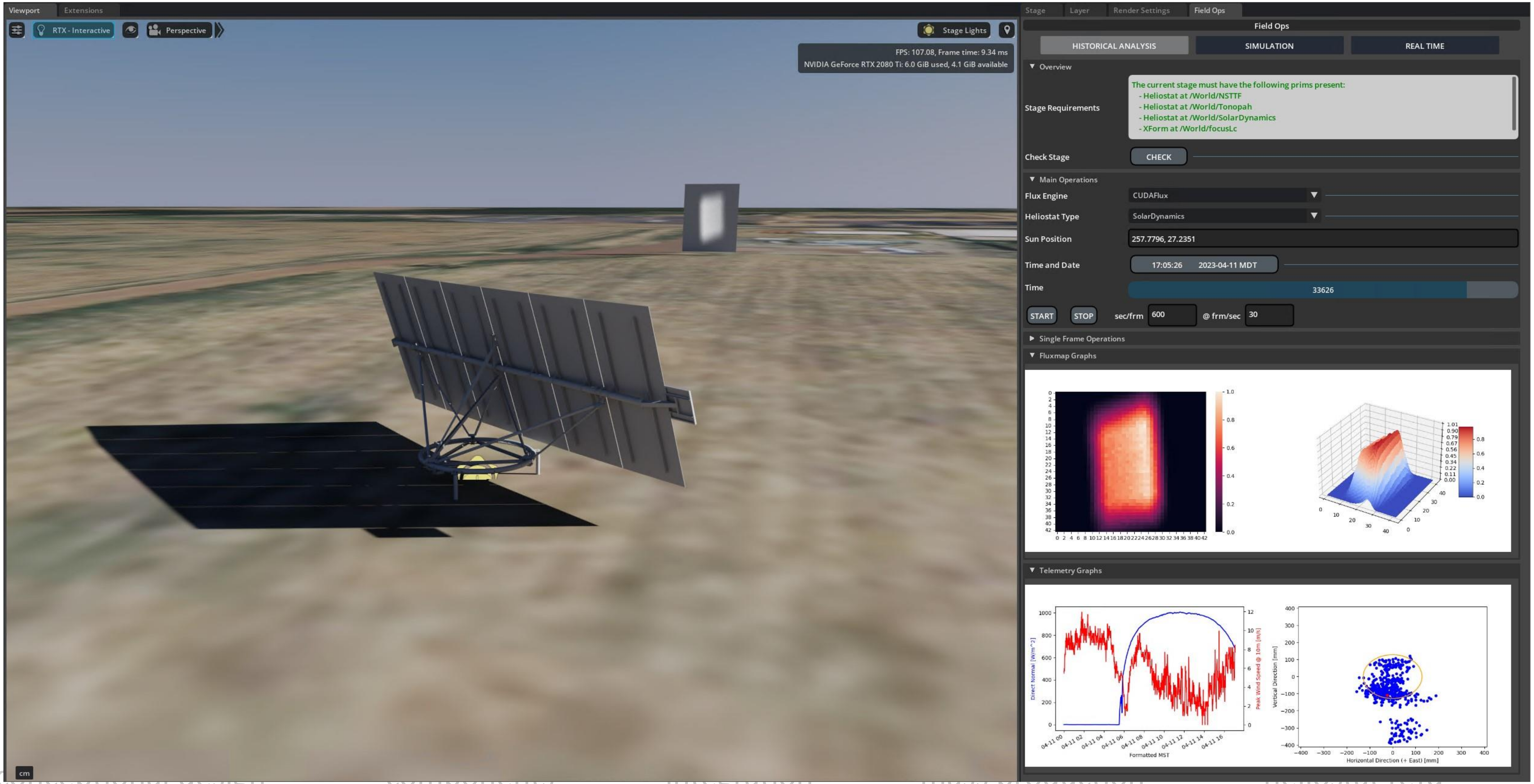


Playback using TieSOL Ray Tracing

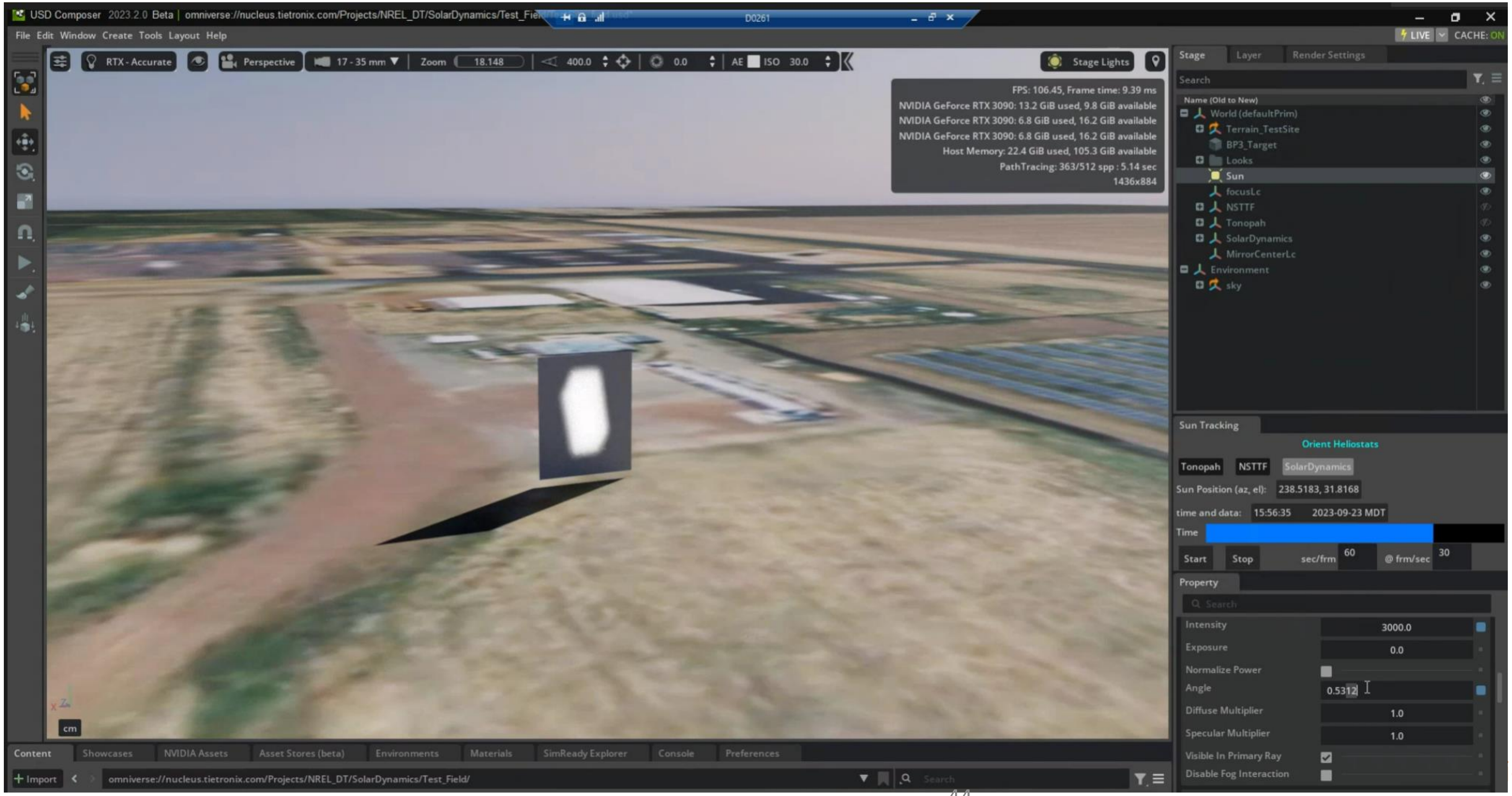


Tietronix RFP 38488-006

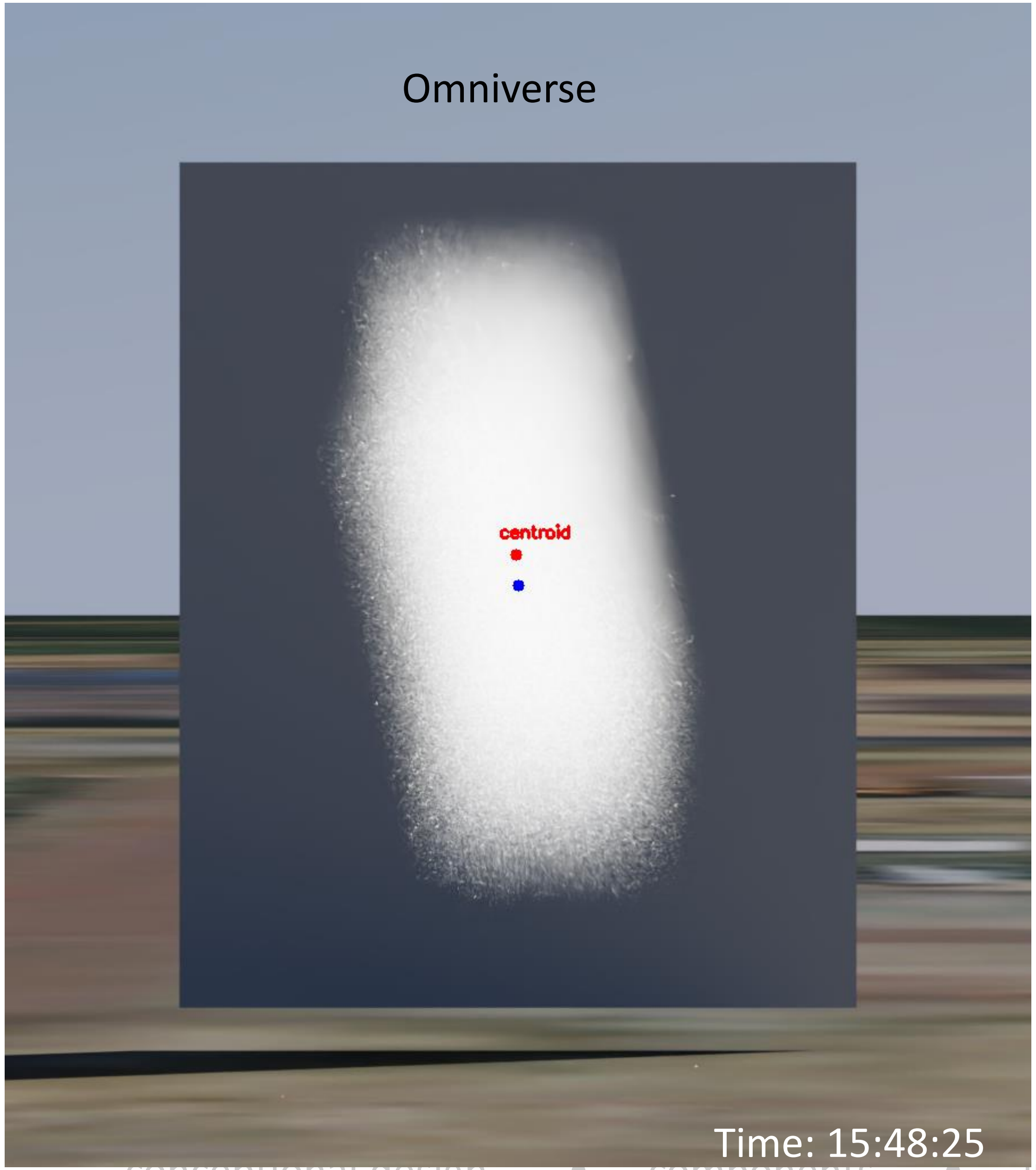
Playback using TieSOL Ray Tracing

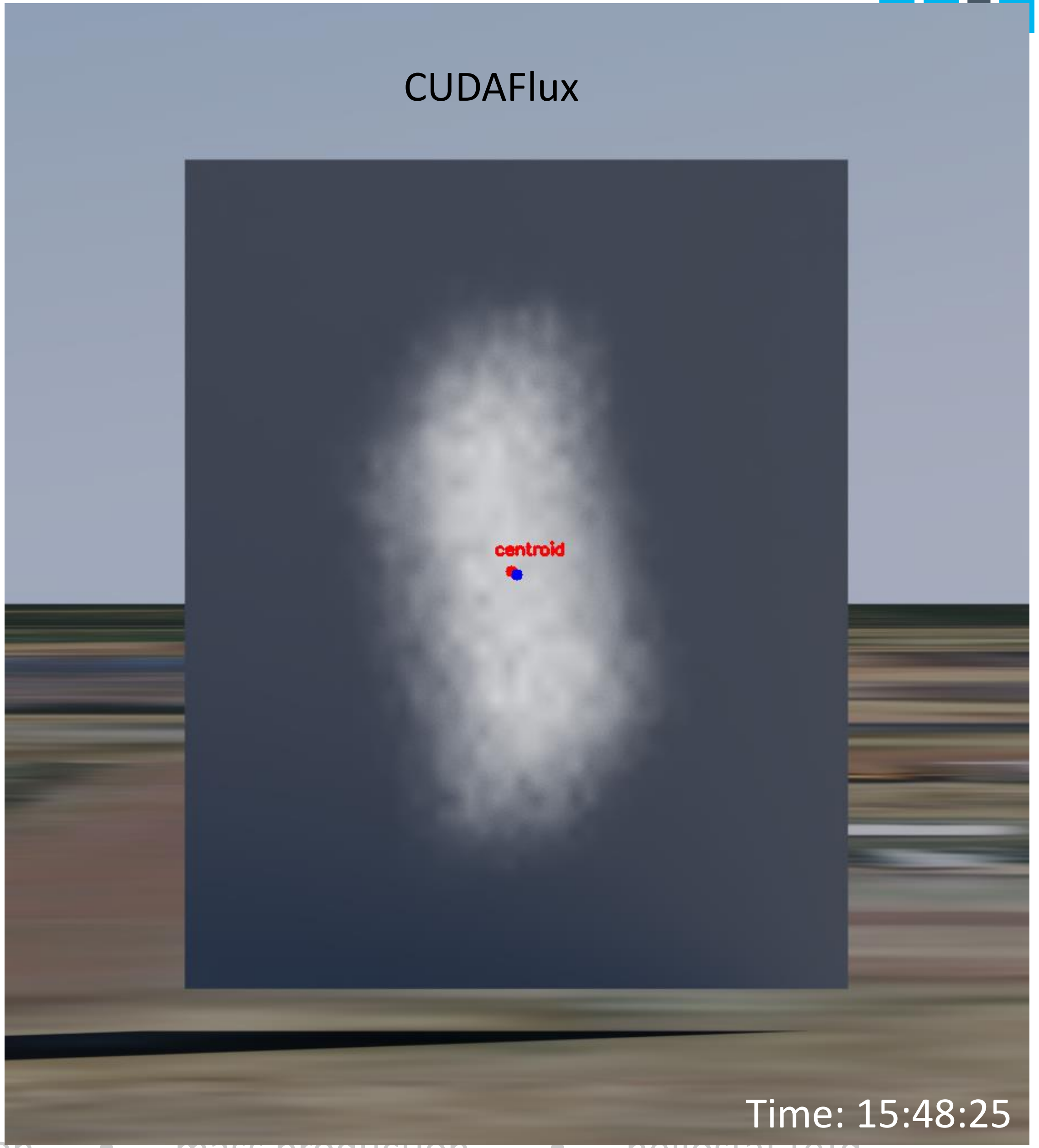


Test Data with Omniverse Ray Tracing



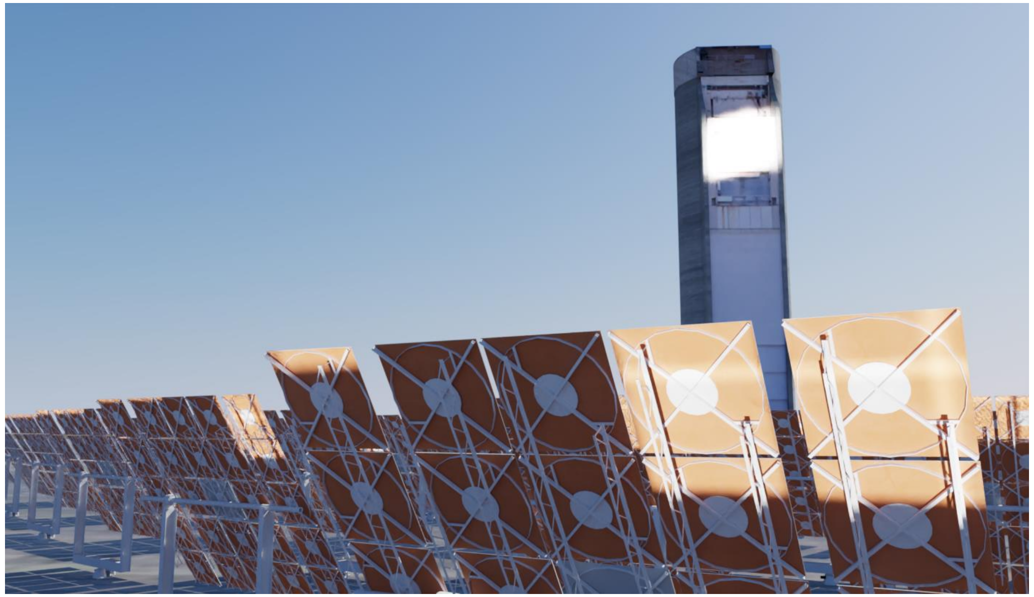
Centroid Computation

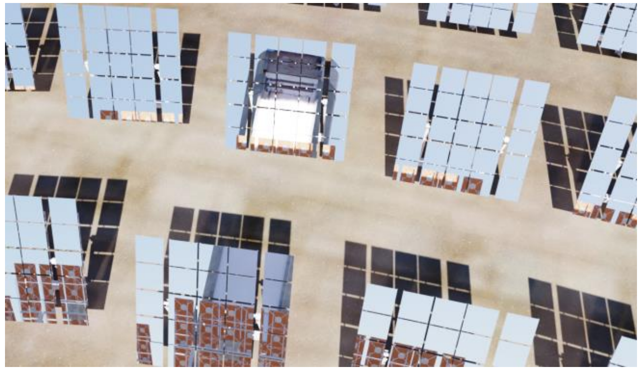




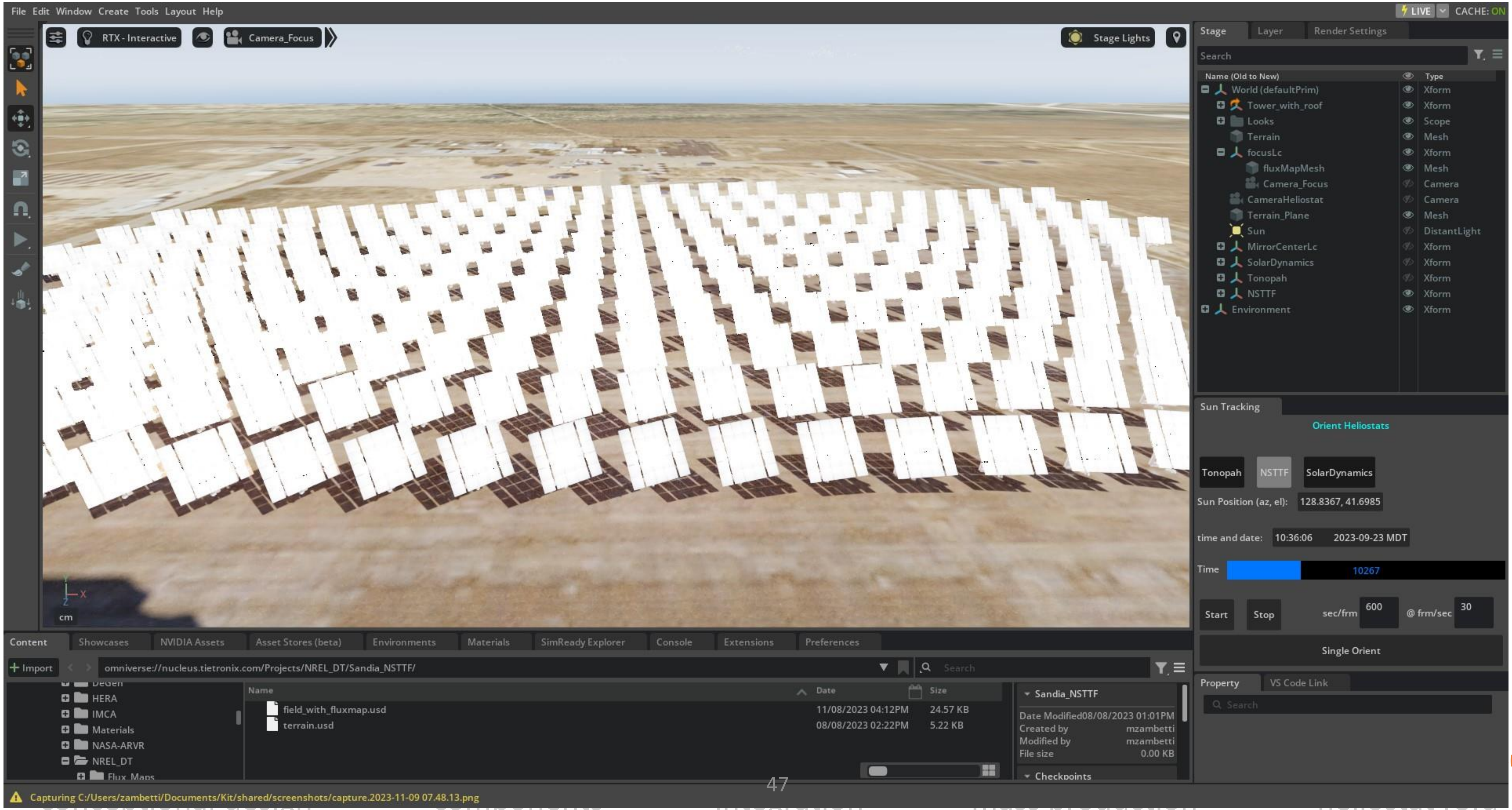
Scaling Up

- Can Omniverse support the development of a full solar field Digital Twin?
  - Developed initial DT for NSTTF



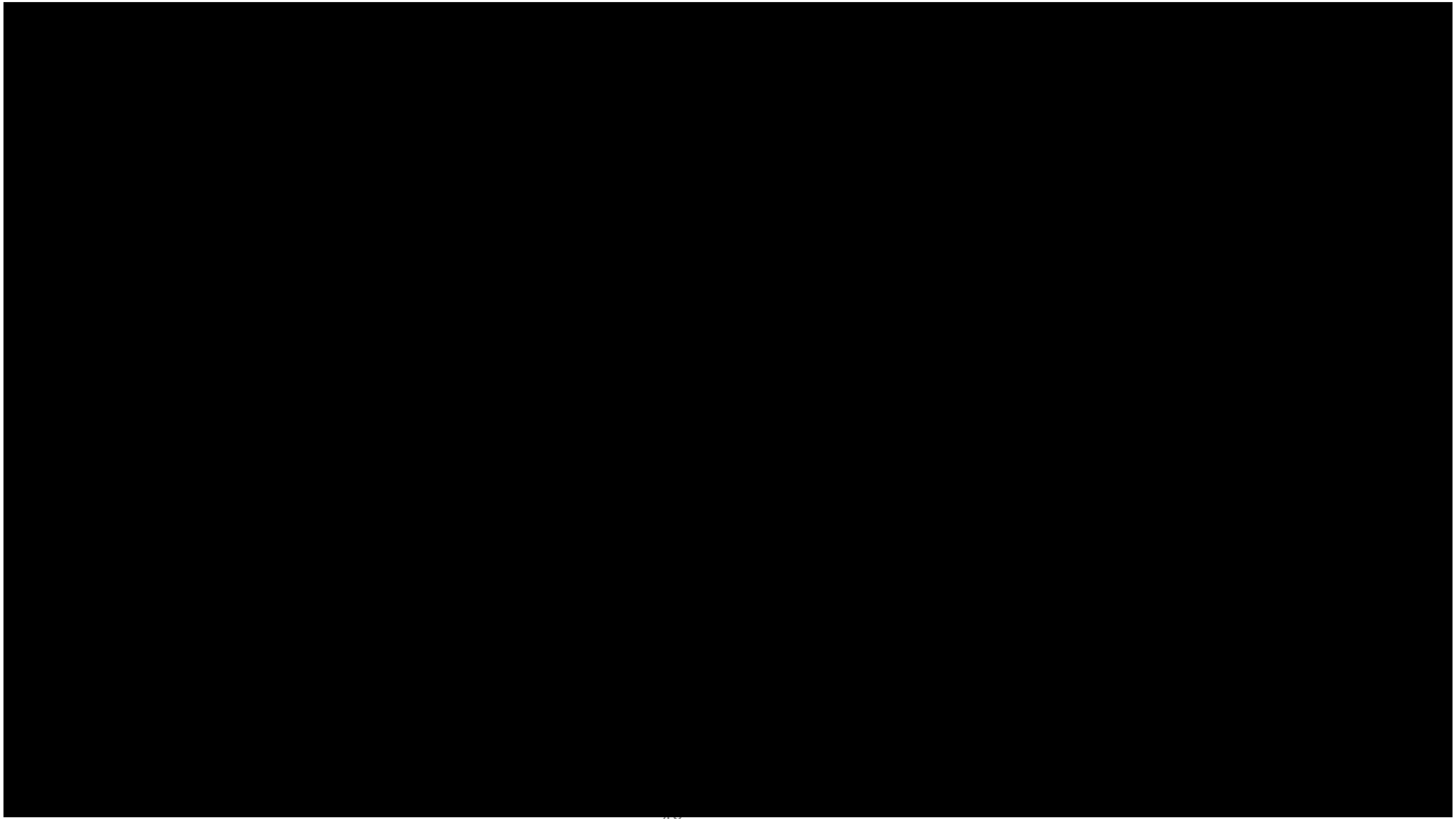


Full NSTTF solar Field



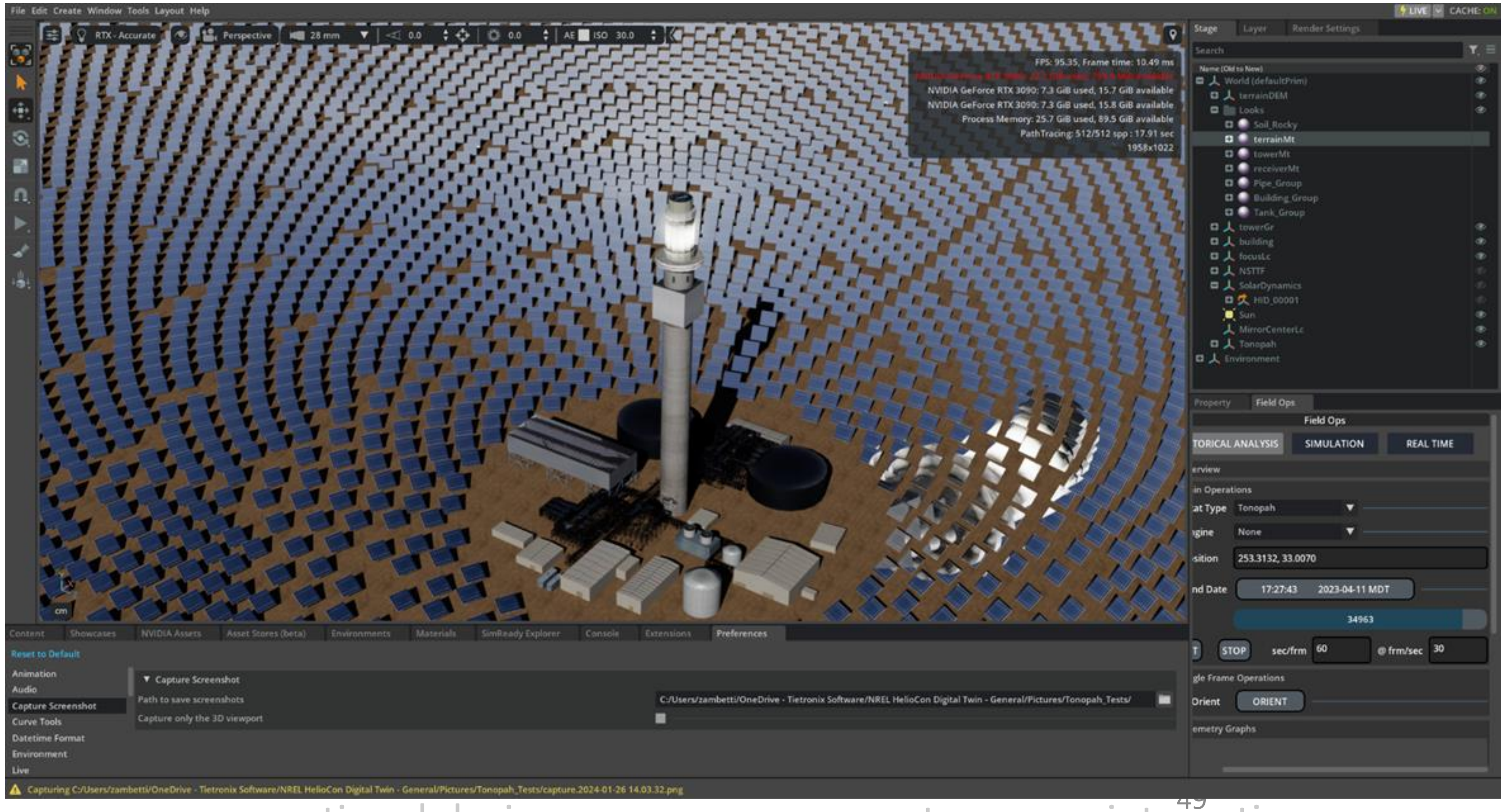
006

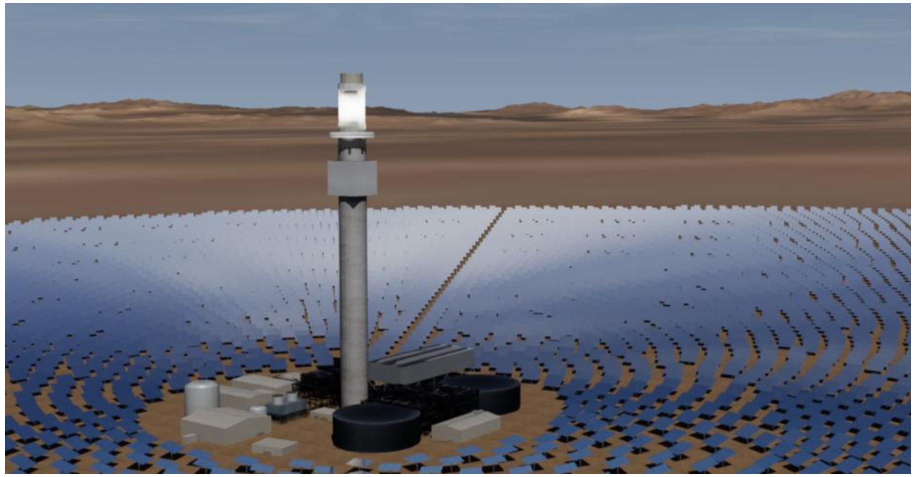
NSTTF



Full Field DT

- Digital Twin:
  - Full Crescent Dunes Field in Omniverse:
    - Motion of Heliostats very slow
    - Fluxmap from Ray Tracing
    - Four heliostats Canting/Focusing characteristics



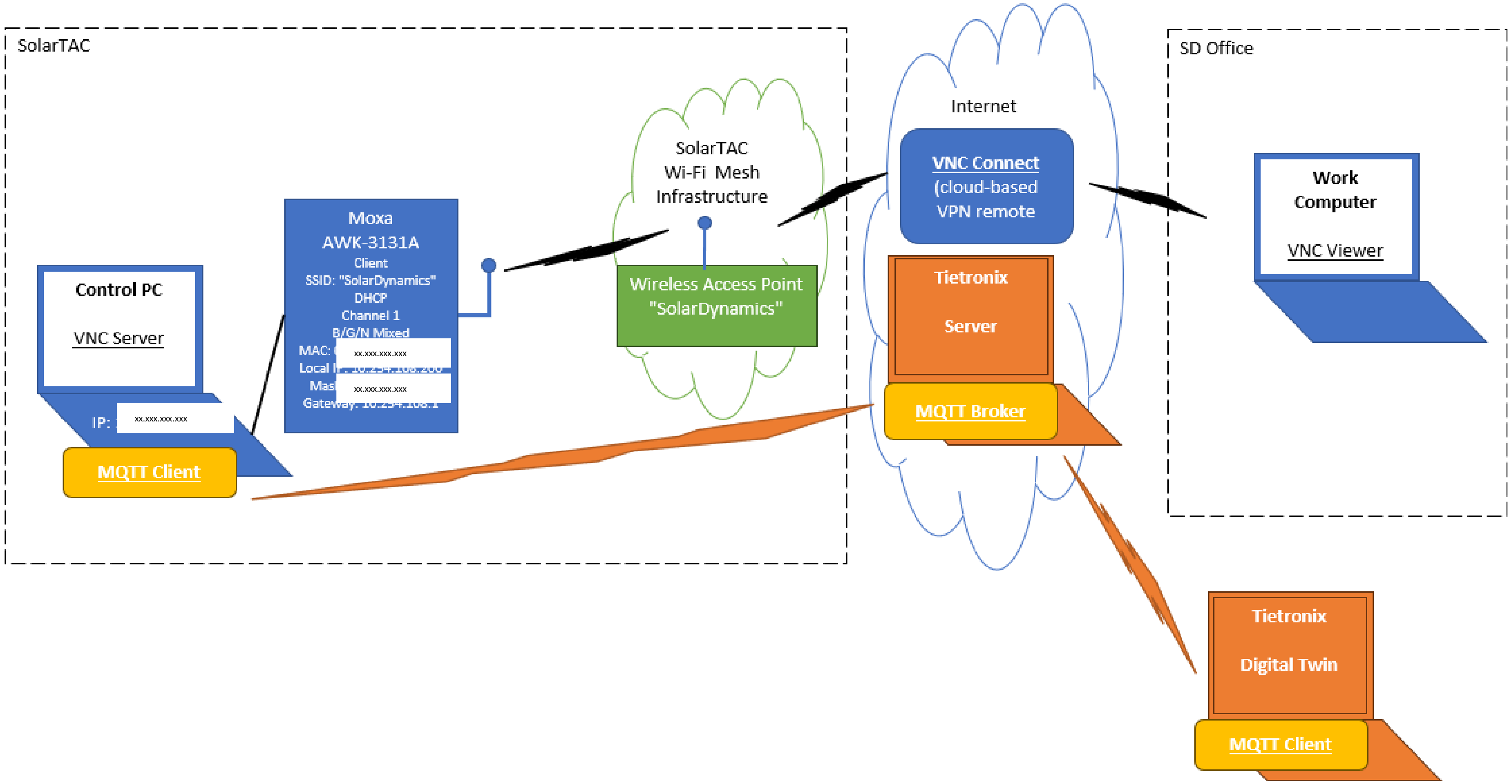


Tietronix RFP 38488-006

Real Time Streaming Telemetry to DT

- Working with SolarDyn on connection architecture
  - *Goal: stream telemetry data from SunRing test to Digital Twin*

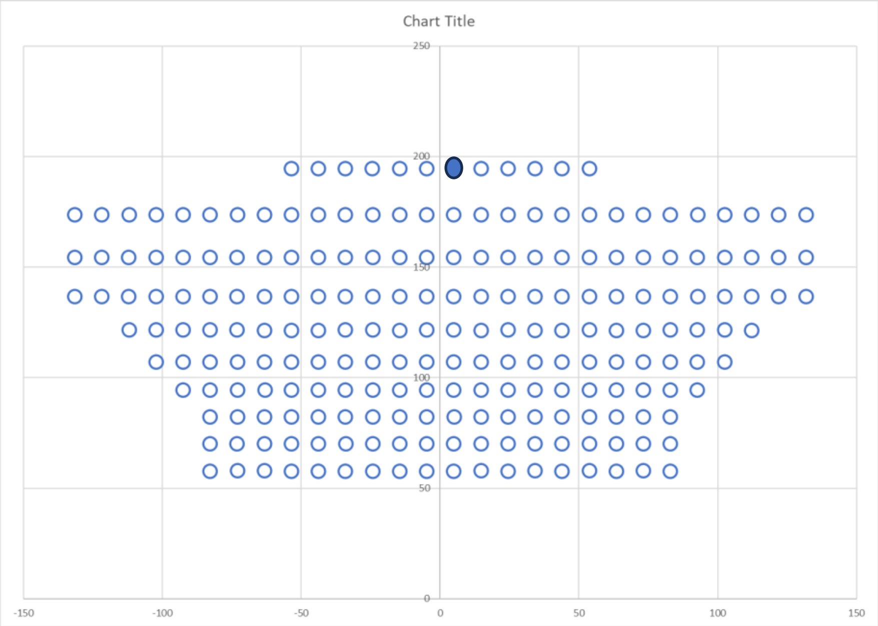
- Timestamp (month, day, year, hour, minute, second)
- Sun azimuth position in degrees
- Sun elevation position in degrees (horizon = 0, zenith = 90)
- heliostat mode
- heliostat status code
- Azimuth status code
- Elevation status code
- Azimuth mode
- Azimuth Setpoint Error
- Azimuth Drive Setpoint Position from Home (or zero reference) in degrees.
- Azimuth Driver Feedback Position from Home in degrees.
- Elevation Mode
- Elevation Setpoint Error in motor encoder counts.
- Elevation Setpoint position in degrees.
- Elevation Feedback in degrees.



NSTTF Test Data to DT

- Captured log file at the NSTTF
  - One heliostat motion
  - Working on setting up the playback from the log file

Main T	Time	Helio	Mode	Sleep	Track	X Targ	Y Targ	Z Targ	az offset	el offset	reserved	Az Targ	El Targ	Az	Elev
20:01	12:20:00 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:02	12:20:02 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:03	12:20:02 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:04	12:20:03 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:06	12:20:06 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:07	12:20:06 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:08	12:20:08 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:09	12:20:09 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:10	12:20:09 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:13	12:20:12 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:14	12:20:12 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:15	12:20:14 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:16	12:20:15 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:17	12:20:17 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:19	12:20:18 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:20	12:20:20 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:21	12:20:20 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:22	12:20:21 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:23	12:20:23 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:25	12:20:24 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:26	12:20:26 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:28	12:20:27 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:29	12:20:27 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:30	12:20:29 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:33	12:20:30 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:34	12:20:33 PM	_14E01	_fs_	A	0	0	0	0	0	0	0	180	0	179.99	-83.82
20:35	12:20:35 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:36	12:20:35 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:38	12:20:35 PM	_14E01	CUSP	A	0	0	0	0	0	0	0	180	-84.01	179.99	-83.82
20:40	12:20:39 PM	_14E01	_FS_	A	0	0	0	0	0	0	0	180	0	179.99	-83.51
20:41	12:20:41 PM	_14E01	_FS_	A	0	0	0	0	0	0	0	180	0	179.99	-83.09
20:42	12:20:42 PM	_14E01	_FS_	A	0	0	0	0	0	0	0	180	0	179.99	-82.48
20:44	12:20:42 PM	_14E01	_FS_	A	0	0	0	0	0	0	0	180	0	179.99	-82.48
20:45	12:20:44 PM	_14E01	_FS_	A	0	0	0	0	0	0	0	180	0	179.99	-81.86



Wind Loads Moments

- Status:
  - Obtained from SolarDyn:
    - Wind Coefficients Table

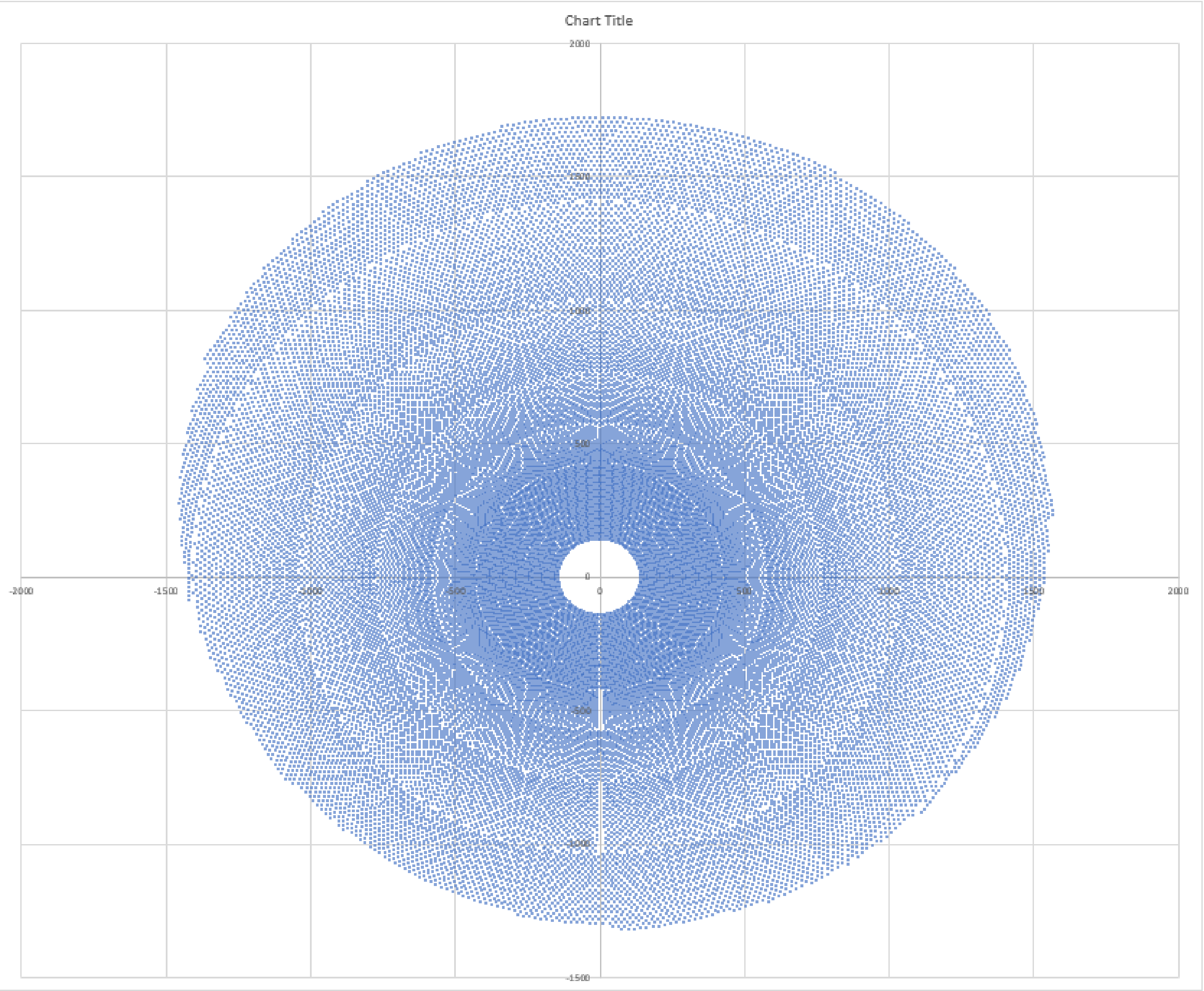
Mz Coeffficient Database

Config	Interior or Exterior	Tilt (°)	Azimuth (°)	Wind Direction (°)	Beta (°)	Mz Load Coeff Summary			
						Gusts Loads		Mean Loads	
						Max Peak GCMz	Min Peak GCMz	Max Mean GCMz	Min Mean GCMz
B01	Exterior	30	0	180	0	0.099	-0.102	0.010	-0.002
B11	Exterior	30	45	135	0	0.163	-0.090	0.066	-0.006
B21	Exterior	30	90	90	0	0.064	-0.038	0.013	0.012
C01	Exterior	60	0	180	0	0.183	-0.183	0.007	-0.003
C11	Exterior	60	45	135	0	0.343	-0.157	0.133	-0.016
C21	Exterior	60	90	90	0	0.172	-0.169	0.006	-0.014
D01	Exterior	75	0	180	0	0.182	-0.183	0.005	-0.003
D11	Exterior	75	45	135	0	0.164	-0.389	0.011	-0.135
D21	Exterior	75	90	90	0	0.181	-0.214	0.007	-0.020
E01	Exterior	90	0	180	0	0.189	-0.178	0.006	-0.004
E11	Exterior	90	45	135	0	0.367	-0.196	0.121	-0.021
E21	Exterior	90	90	90	0	0.189	-0.218	0.013	-0.022

    - Moments computation formula

$Moment = q_z * GC_M * A_{ref} * L * Width\_ratio$

    - Field Layout 40,000 heliostats in AZ
    - NSO Wind Data
  - Implemented the computation in TieSOL

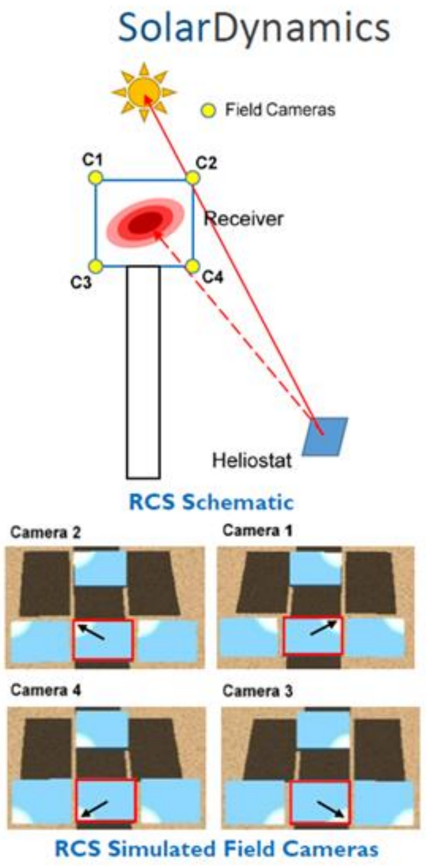


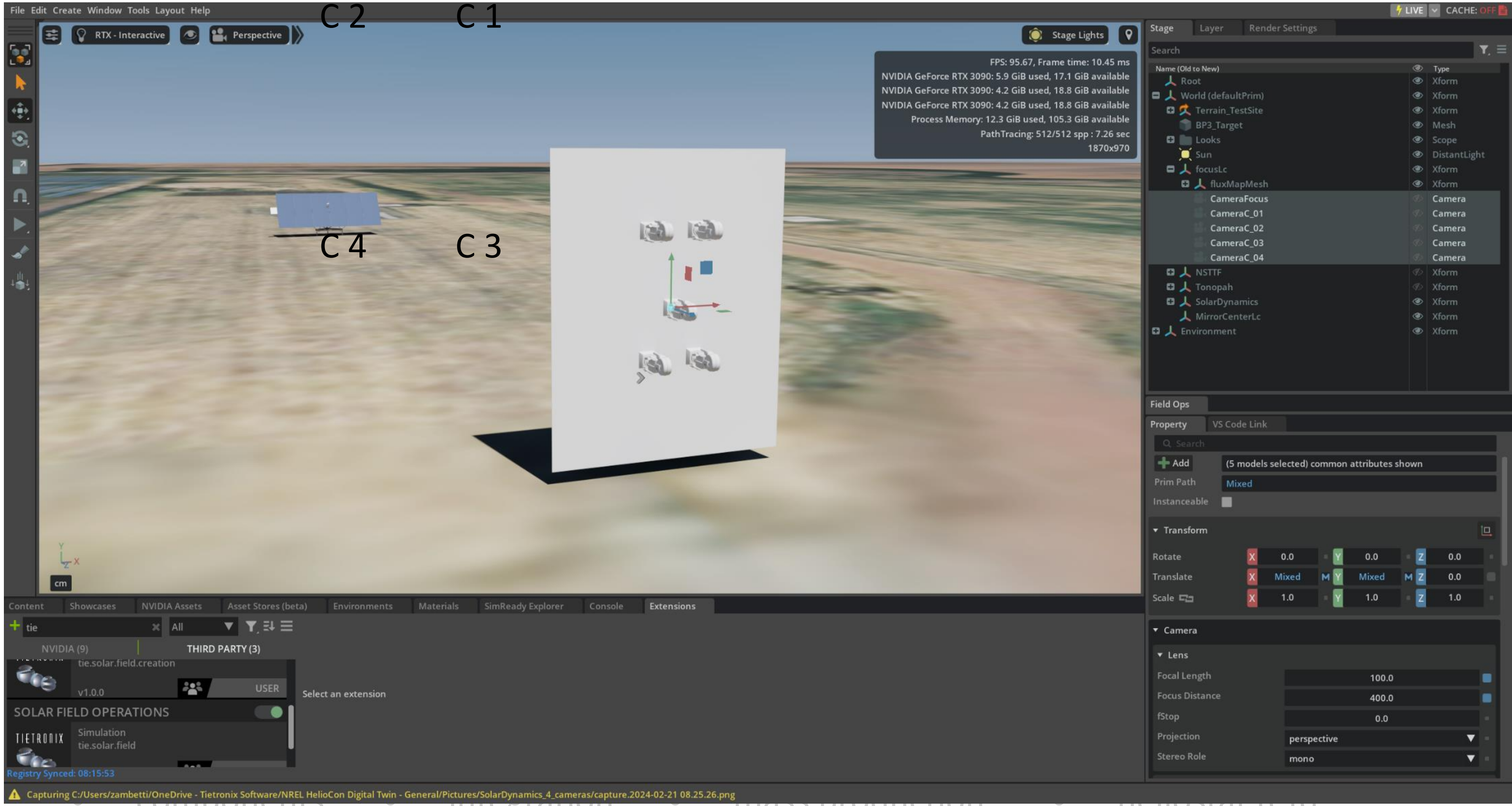
Wind Loads Computation

- Wind Effect Computation Overview
  - Determine the wind row and classify heliostat as “interior” or “exterior”
    - heliostats within the outermost 3 rows in the direction of the wind are considered exterior
  - Compute tilt and beta angles
    - tilt = zenith angle of the heliostat normal
    - beta = 180 – wind direction – azimuth
      - wind direction is measured CW from North
      - azimuth is measured CCW from South
      - beta is measured positive CCW from the heliostat normal to the wind direction
  - Perform table look up of the Mz load coefficients
    - perform bilinear interpolation in tilt and beta dimensions
    - tilt values are 30, 60, 75, 90
    - beta exists in 3 ranges
      - 180, 150, 115, 90, 65, 30, 0
      - 135, 115, 90, 65, 45, 30, 0, -180, -210
      - 90, 65, 30, 0, -180, -210, -245
  - Compute the mean and peak moments in lbf-ft
    - NSO wind data provides 15-meter wind speed and 7-meter wind direction
    - wind direction used to determine wind row (exterior vs interior) in step 1
    - wind speed converted from m/s to mph, reduced from 15-meter to 10-meter height, scaled from 1-minute mean to 3-second gust, then used in the computation of gust min/max peak moments
    - the 3-second gust is then scaled to 1-hour mean, and used in the computation of the mean min/max mean moments
  - Apply flexibility matrix to convert moments into rotations/deflections
    - thetax is the vertical beam displacement (delta elevation); thetay is the horizontal beam displacement (delta azimuth)

$$\begin{bmatrix} \Theta x \\ \Theta y \end{bmatrix} = \begin{bmatrix} f41 & f42 & f43 & f44 & f45 & f46 \\ f51 & f52 & f53 & f54 & f55 & f56 \end{bmatrix} \begin{bmatrix} Fx \\ Fy \\ Fz \\ Mx \\ My \\ Mz \end{bmatrix}$$

Rapid Calibration System

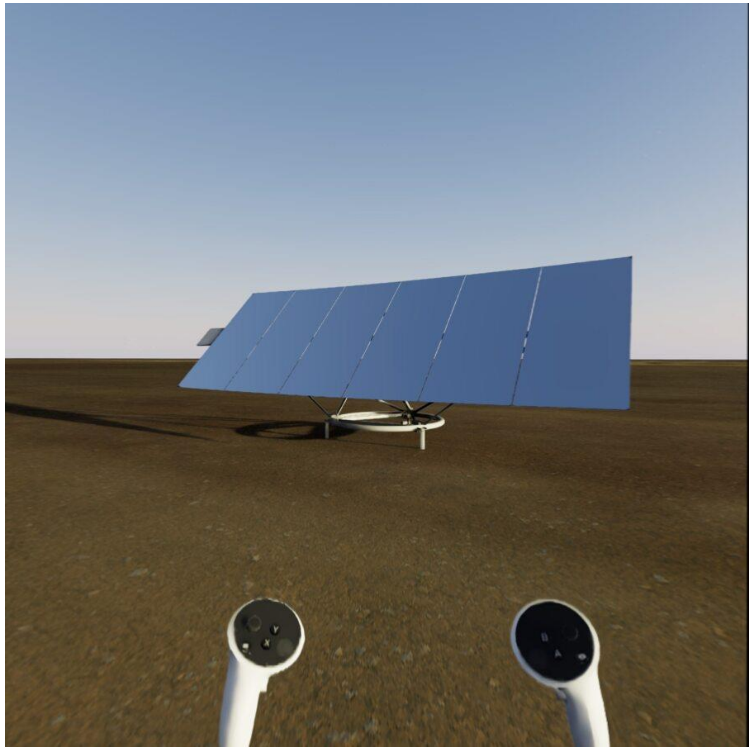


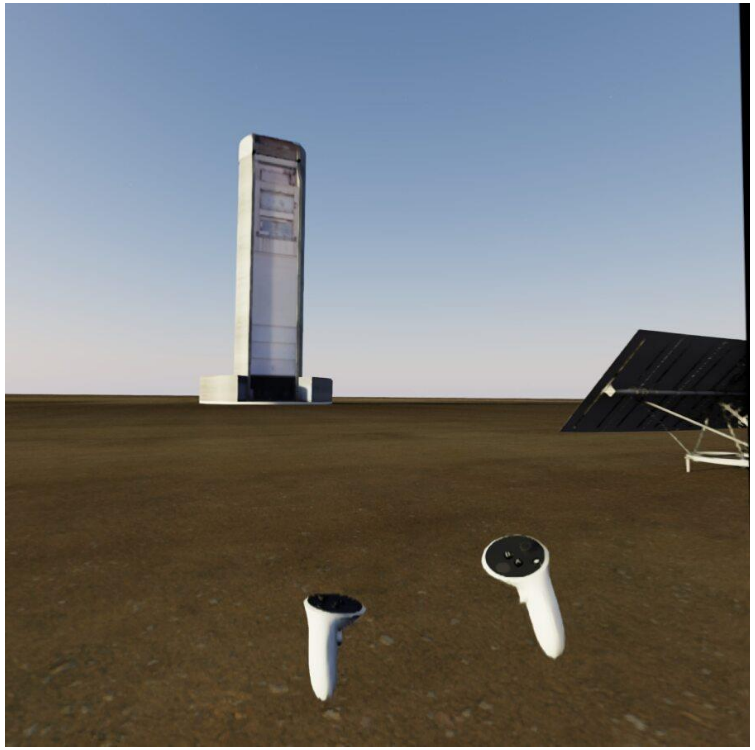


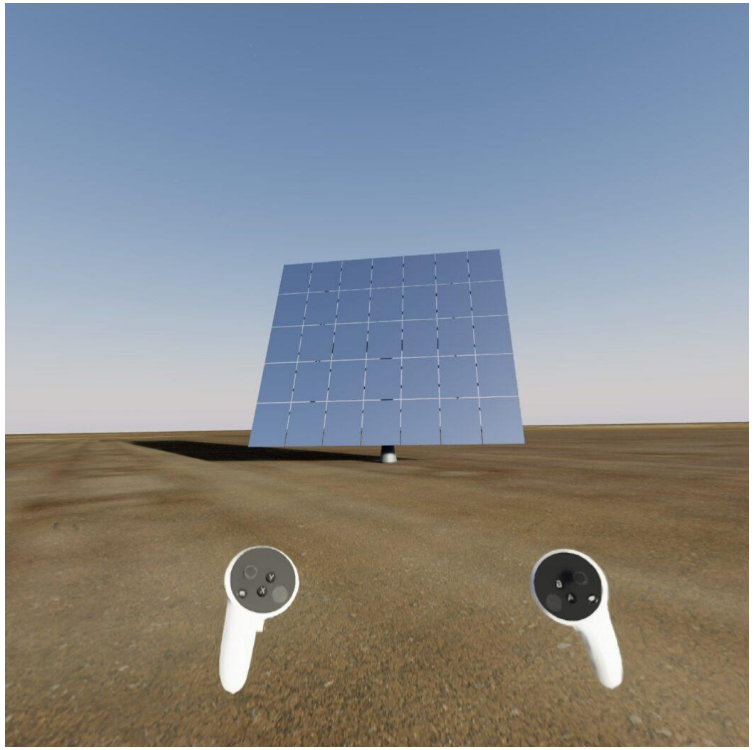
Rapid Calibration System

DT to Virtual Reality deployment

- Omniverse provides the capability to render a scene in a Virtual Reality device



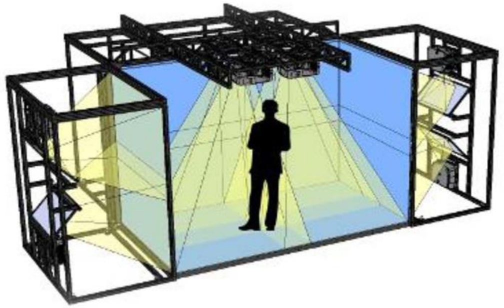




Virtual Reality

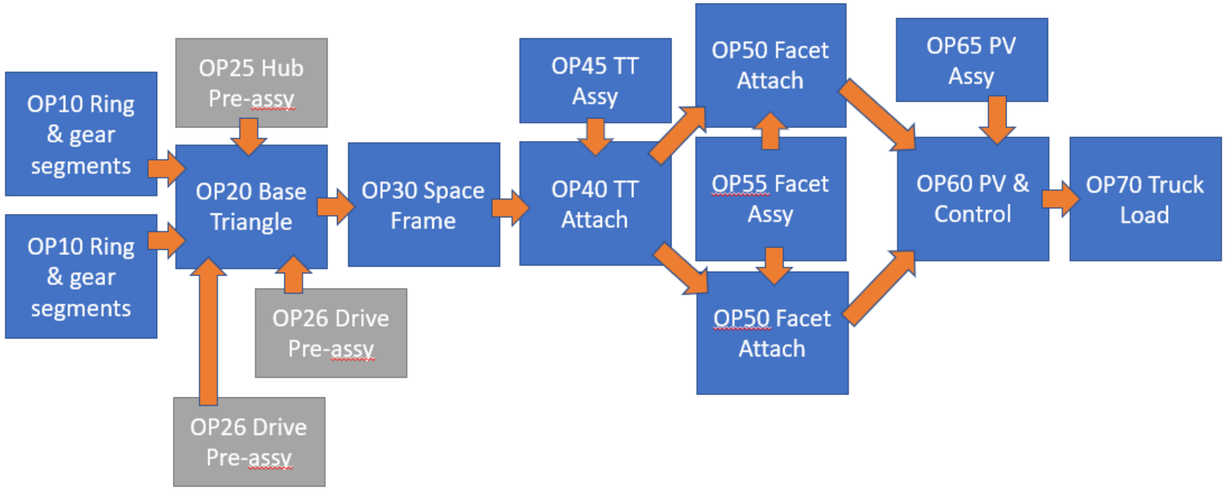
	**Varjo XR-1**
	Meta Quest 2
	Meta Quest Pro
	HTC VIVE Pro 2
	HTC VIVE Elite XR

- Assess the capability to display in NREL CAVE
  - CAVE is a two-surface (floor and wall) environment illuminated with six Christie 304K projectors in 4k mode. Four projectors are blended on the wall. Two projectors are blended on the floor. We send a 4K right-eye and 4K left-eye signal to each projector; the projectors interleave these into active stereo images.
  - The system is driven by a single server with six NVIDIA A6000 GPUs with two NVIDIA Quadro Sync II cards. We currently run the system as 12 separate X-screens and fine tune the blend between them in software.
- Omniverse does not support CAVE rendering
  - Newest version of Omniverse remove a capability that we could have used for prototyping

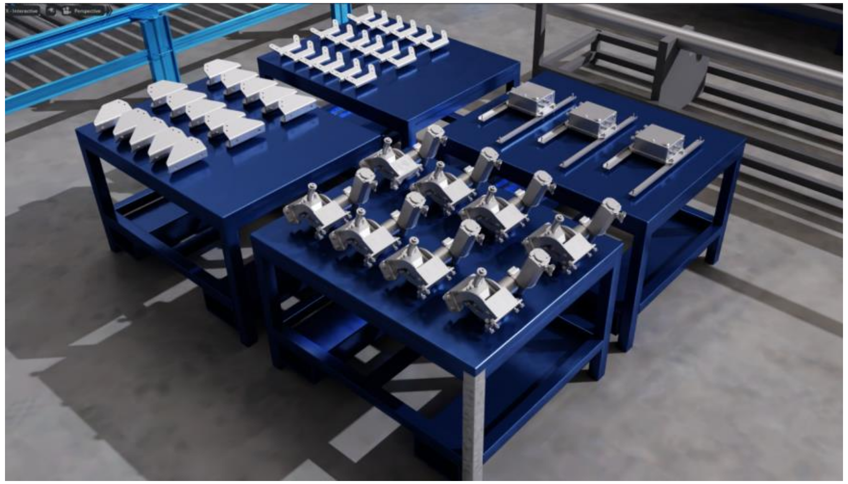


DT for Manufacturing Assembly Line

- Develop Digital Twin of heliostats manufacturing process
  - OP10 – Track Ring Unload & Gear Segment Installation
  - OP20 – Base Triangle & Az Drive Assembly
    - OP25 – Hub Pre-assembly
    - OP26 – Drive Pre-assembly
  - OP30 – Space Frame Structure Assembly
  - OP40 – Torque Tube and El Drive Installation
    - OP45 – Torque Tube Assembly
  - OP50 – Mirror Installation
    - OP55 – Mirror Assembly & Alignment
  - OP60 – Control Box & PV Panel Installation & Wiring

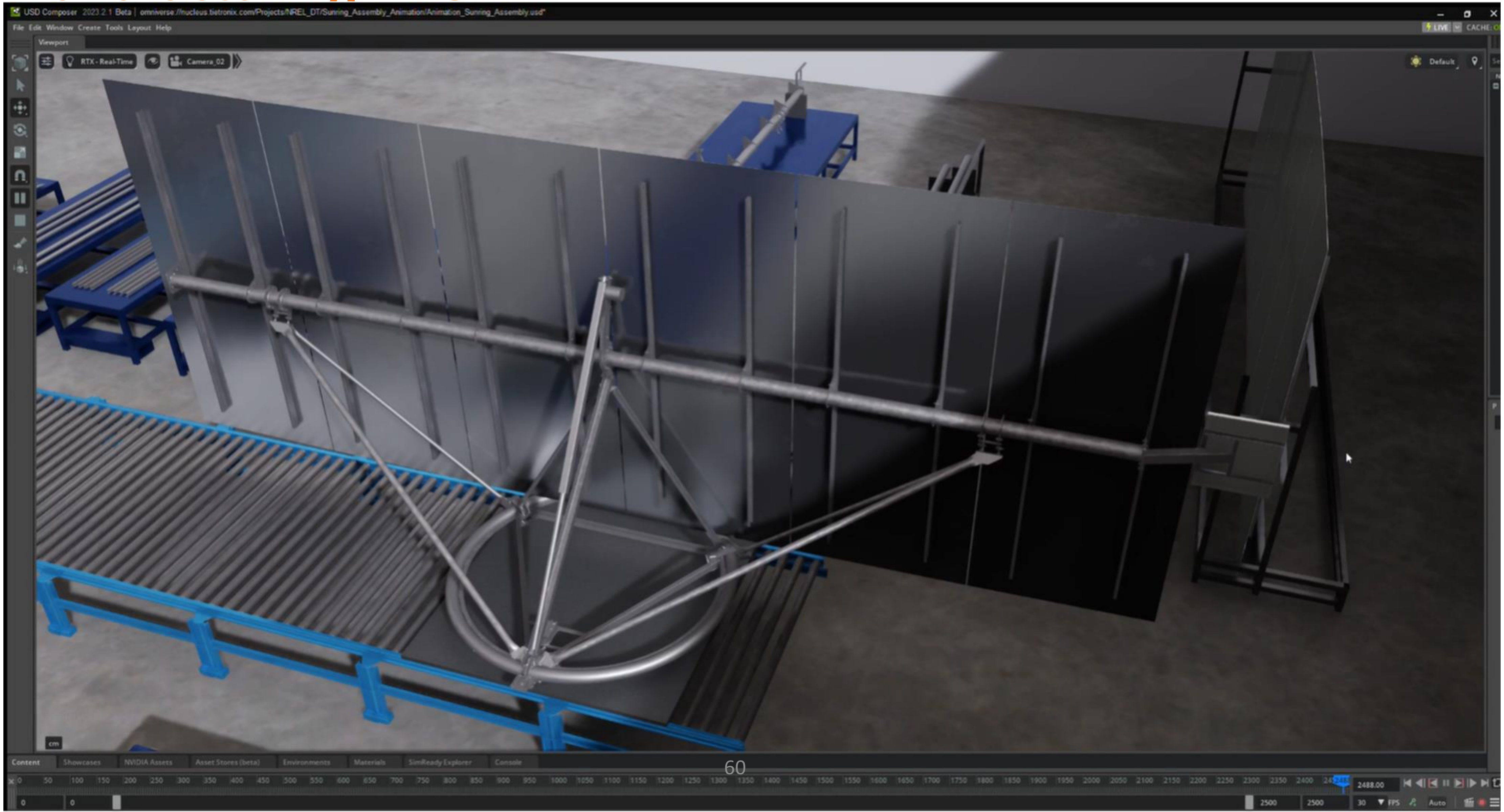


Manufacturing Line DT

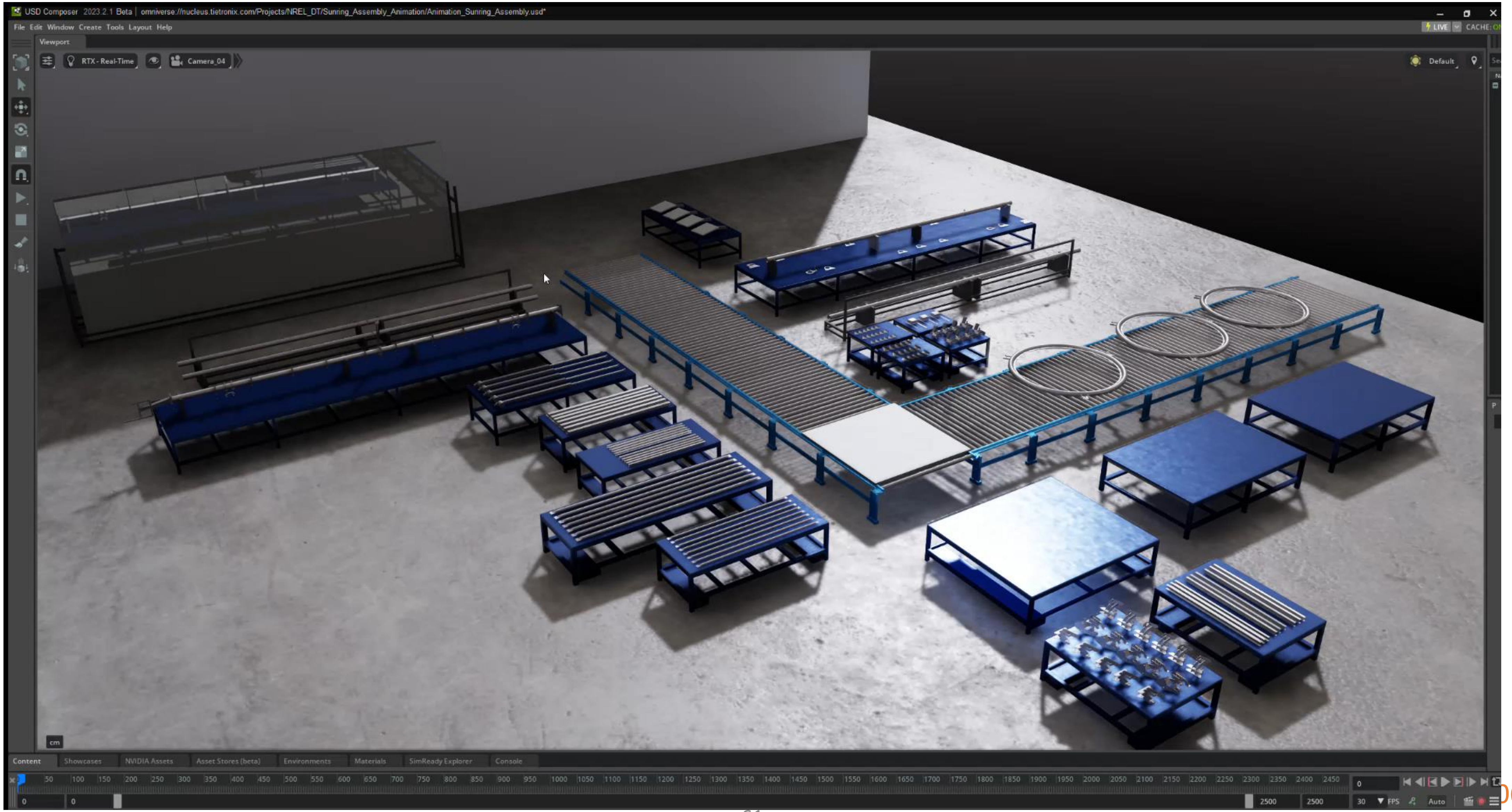





Manufacturing Line



Manufacturing Assembly



06