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"Harnessing the Sun for the Moon: Thermo-Optical Analysis and Orbital Simulation of a Lunar Solar Power Satellite for Future Lunar Exploration"

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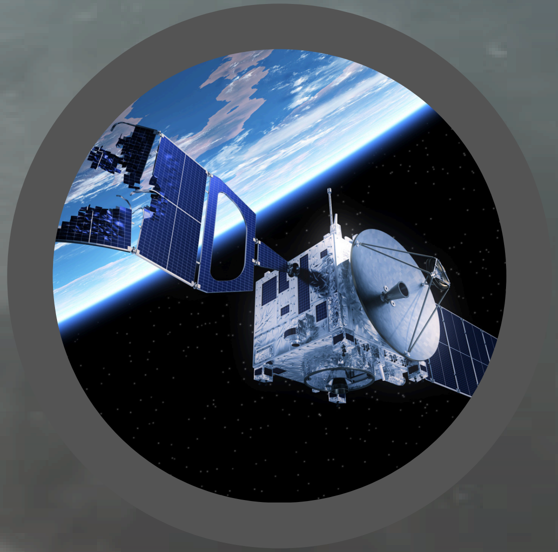
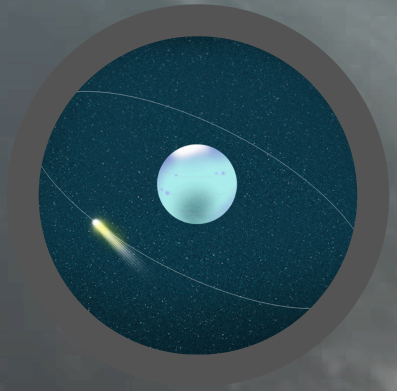
Presentation Outline





State of the Art

Dyson Sphere combined with the most promising SBSP Satellite

Model Design

Development of a 3D model based on the SPS Type 3 satellite.

Simulations

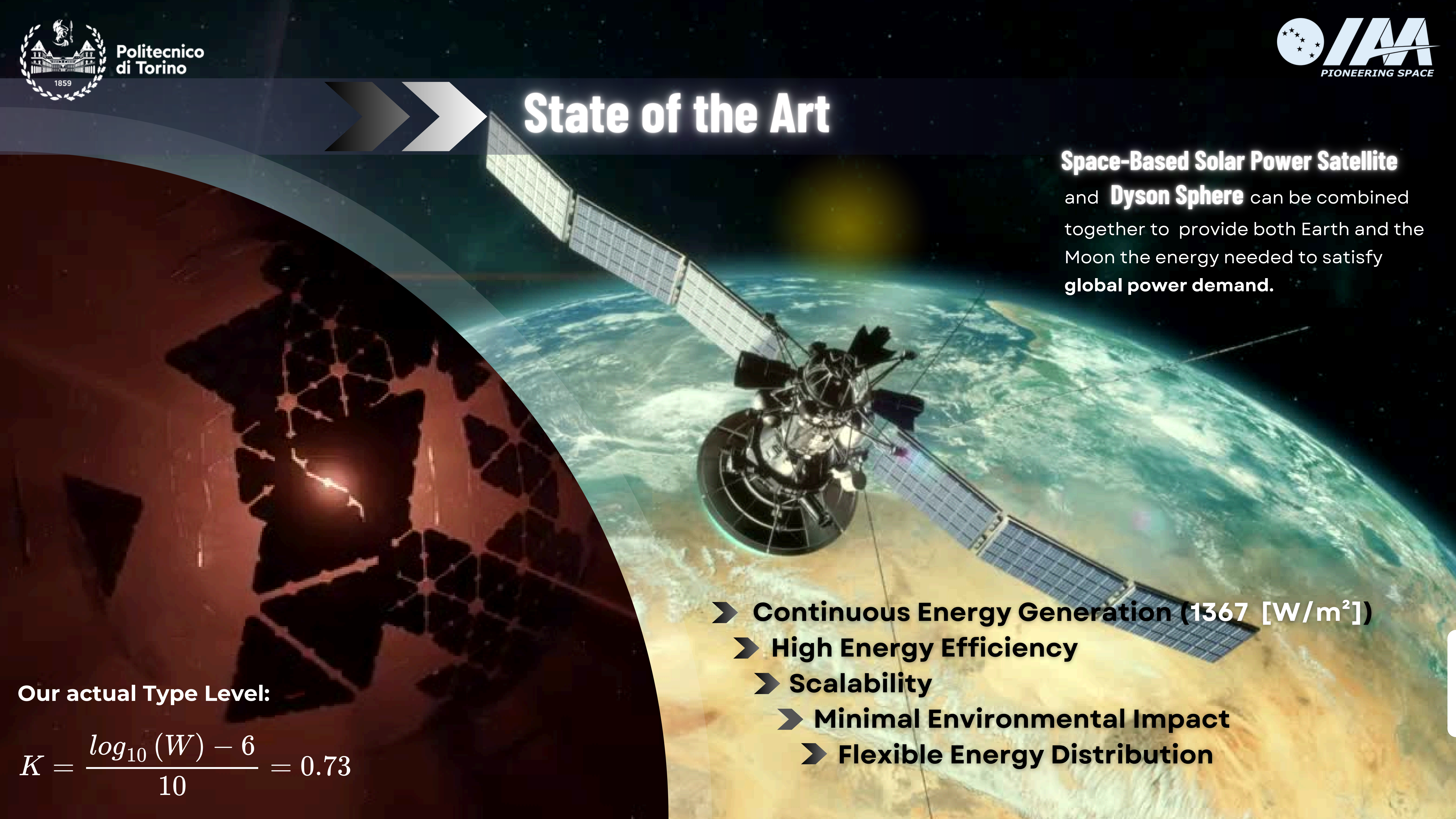
Optical, Thermal and Orbital Simulations with Ansys, Matlab and STK

Results

Outputs of the implemented model and simulations

Conclusion

Comparison with existing terrestrial facilities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State of the Art
Space-Based Solar Power Satellite
and Dyson Sphere can be combined together to provide both Earth and the Moon the energy needed to satisfy global power demand.
Continuous Energy Generation (1367 [W/m²])
High Energy Efficiency
Scalability
Minimal Environmental Impact
Flexible Energy Distribution
Our actual Type Level:
$$K = \frac{log_{10}(W) - 6}{10} = 0.73$$

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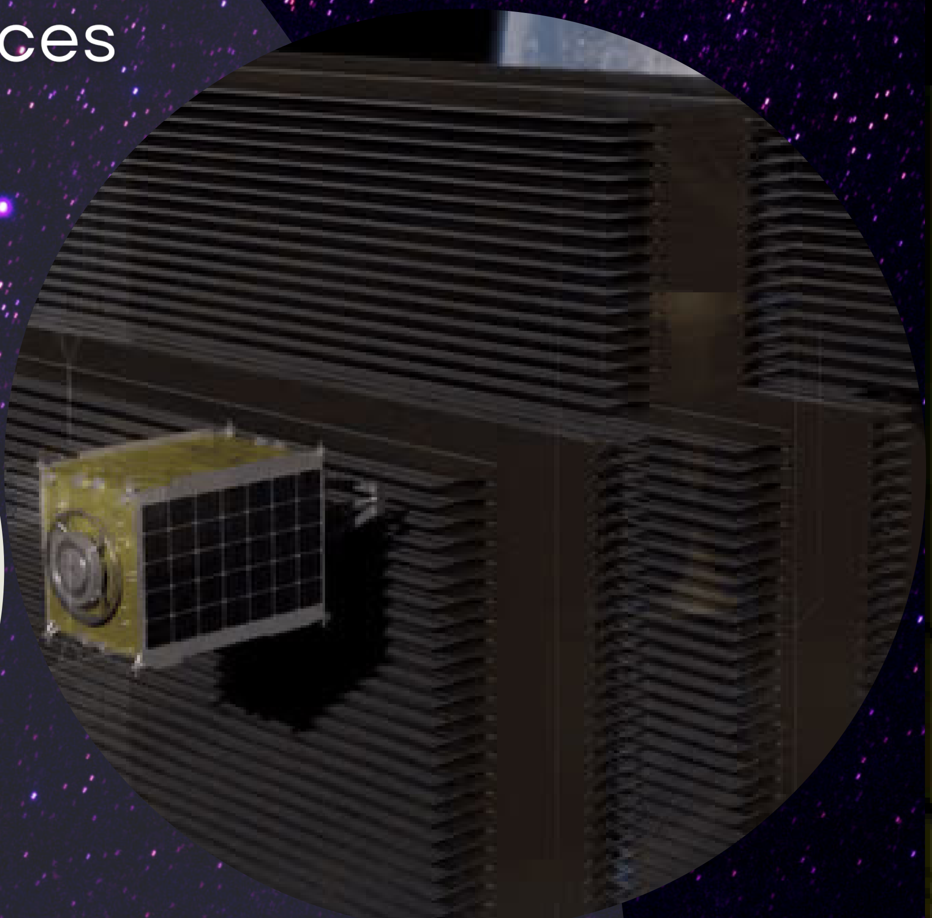
Implemented Design: SPS Type 3

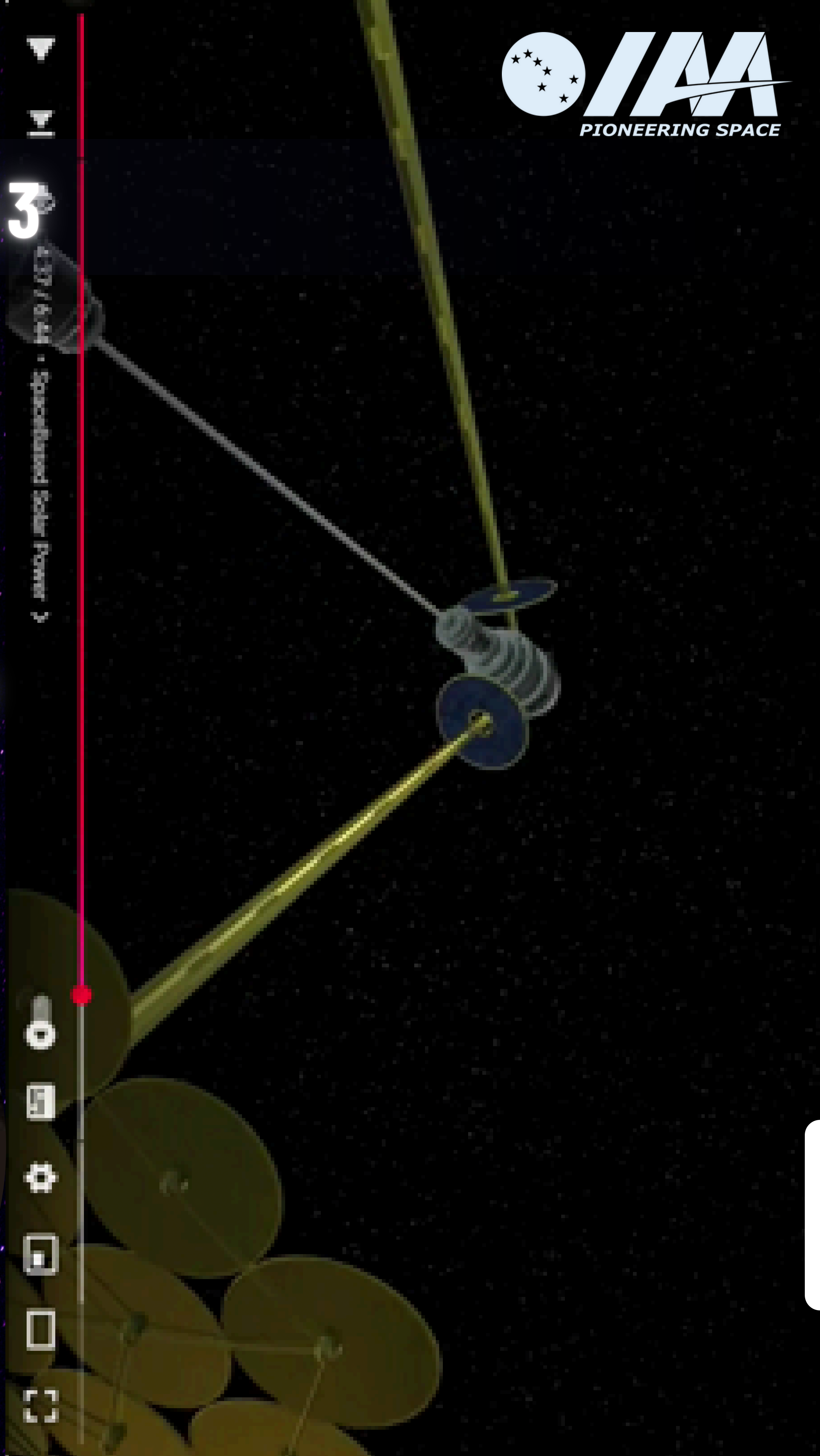
Why this configuration?

- Minimized Launch Costs
- Minimized Solar Panel Surface
- High Modularity & Scalability
- High Energy Collection Capability
- Alignment with Current Technological Advances
- Less complex to Implement and Simulate
- NASA Report available

from **2 GW Satellite**

to **100 MW Satellite**





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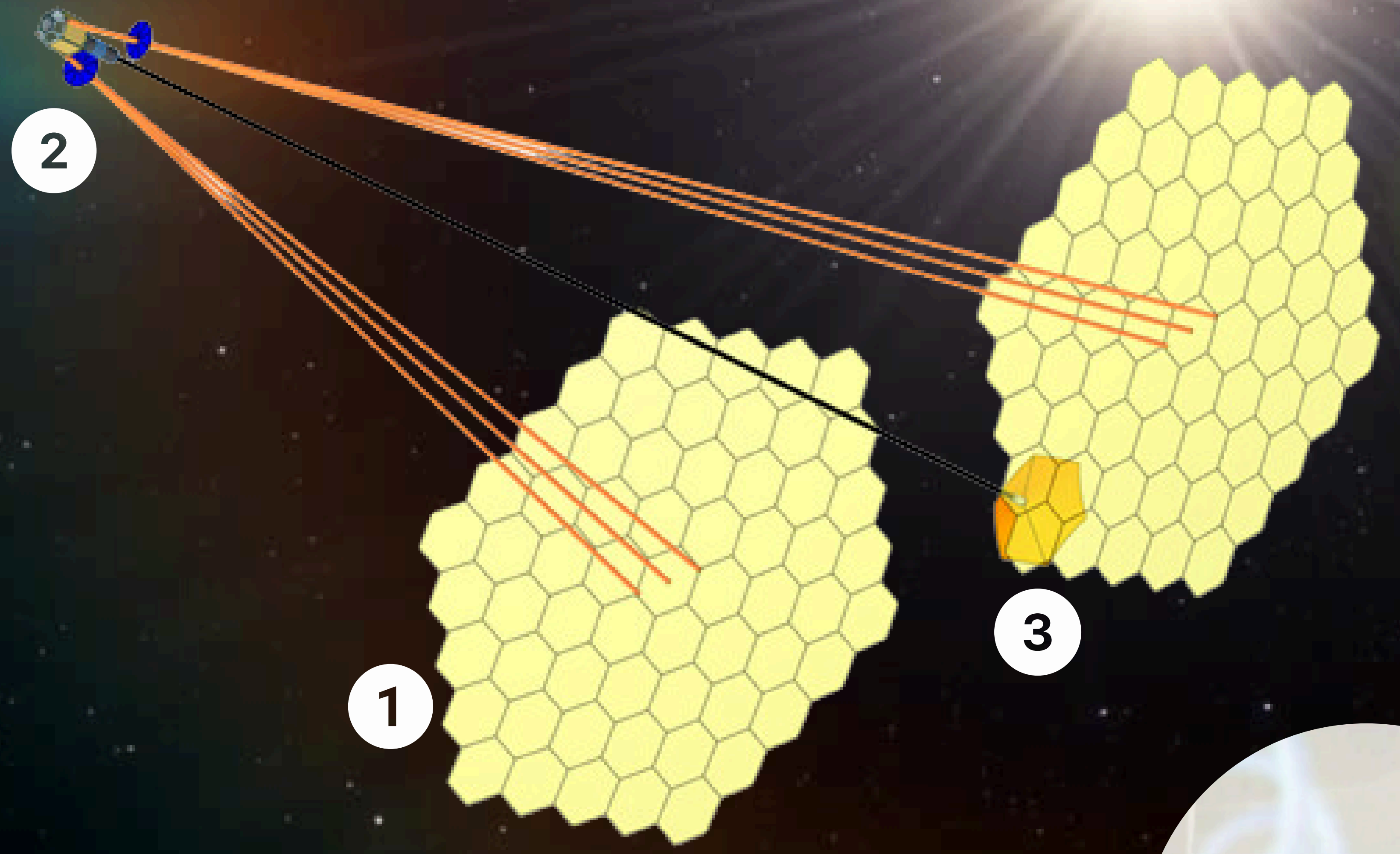
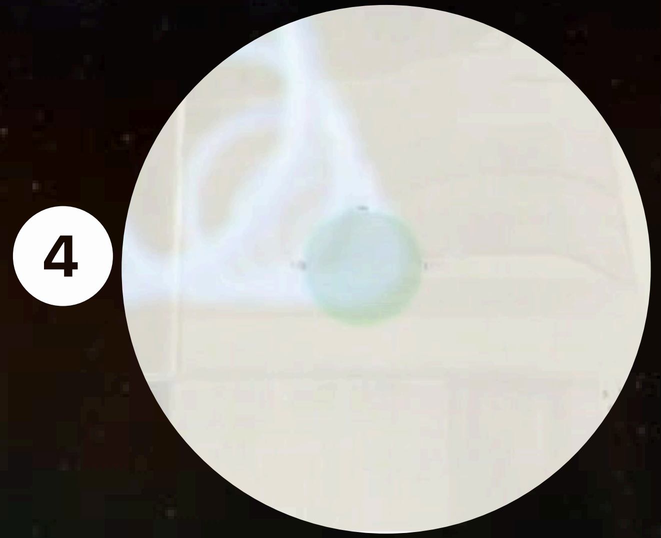
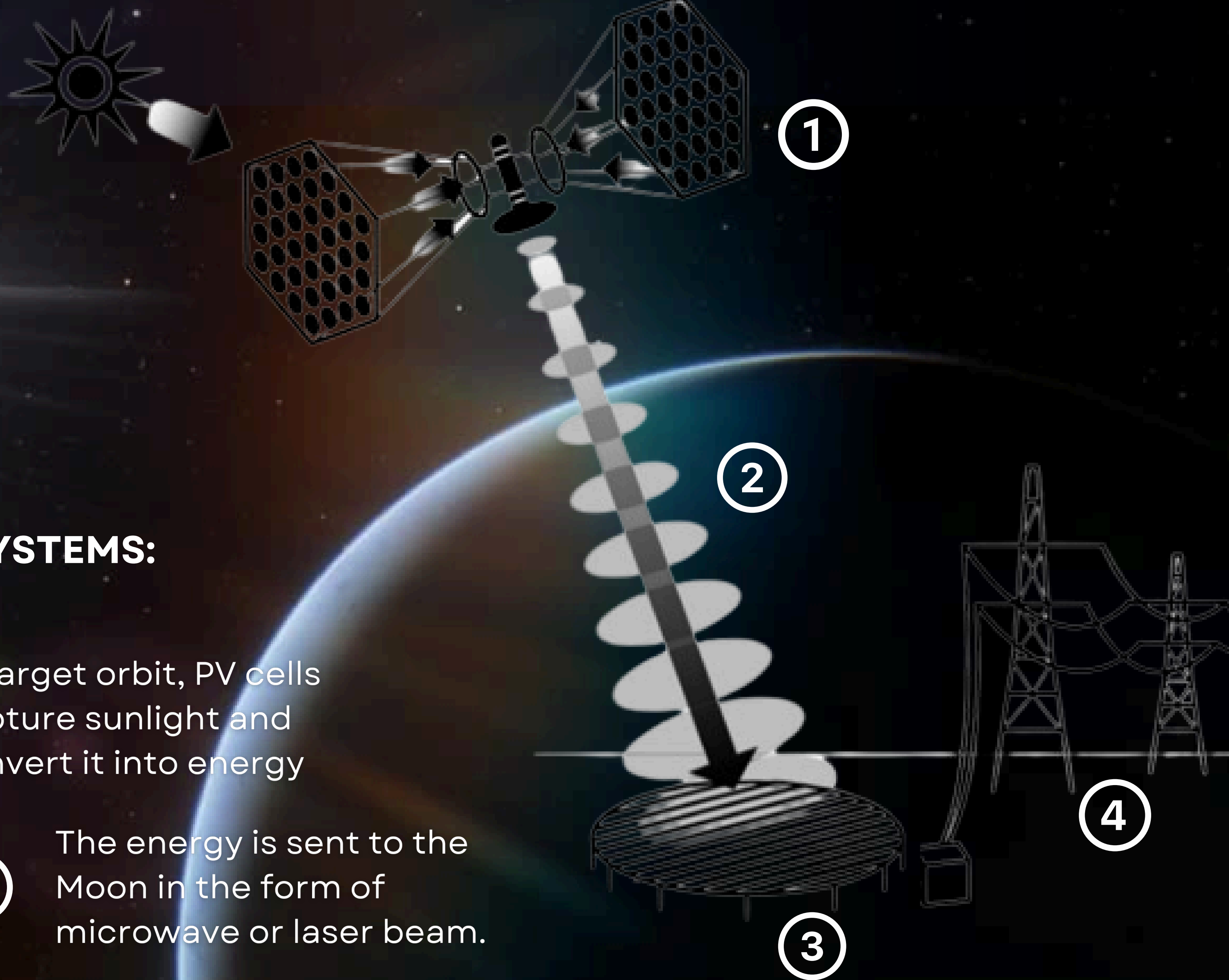
Model Setup

3D CAD Model





1 MIRROR
2 ABSORBER
3 ANTENNA
4 RECTENNA



SUBSYSTEMS:

1. In target orbit, PV cells capture sunlight and convert it into energy
2. The energy is sent to the Moon in the form of microwave or laser beam.
3. A ground receiver captures the beam and converts it into electricity.
4. The electricity is then sent to the power grid.

Matematical Model

Final Delivered Power:

$$P_{final} = n\dot{q}_{sun} S_{mirror} C_{gs} \prod_{i=1}^{m} \eta_i$$

where:

n = number of Satellites → **Scalability**

$$\dot{q}_{sun} = 1367 \frac{W}{m^2}$$

S_{mirror} = Mirror's surface → **Modularity**

C_{gs} = Capacity Factor of the Ground Station

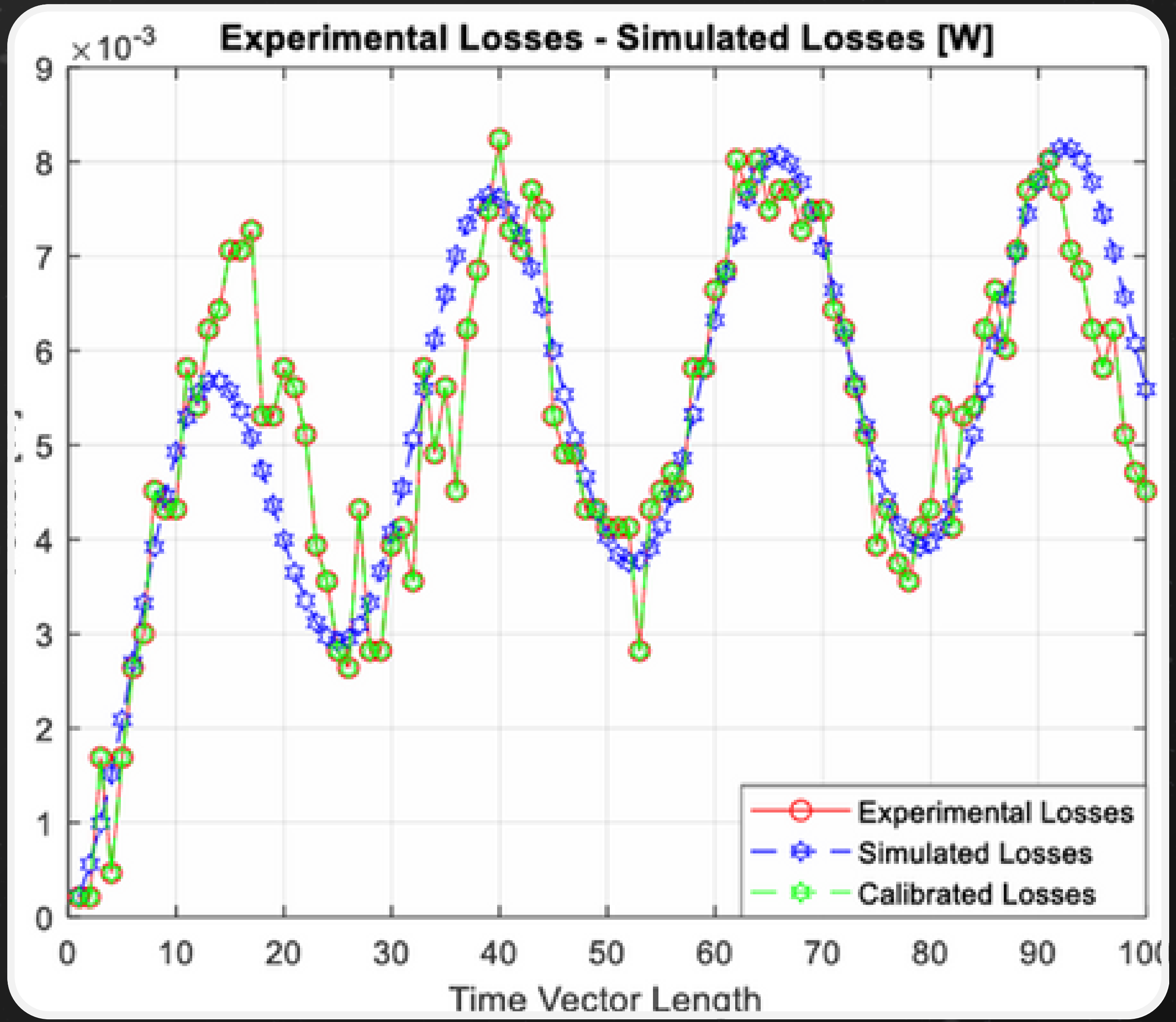
η_i = Efficiency of component i → **Bottleneck**

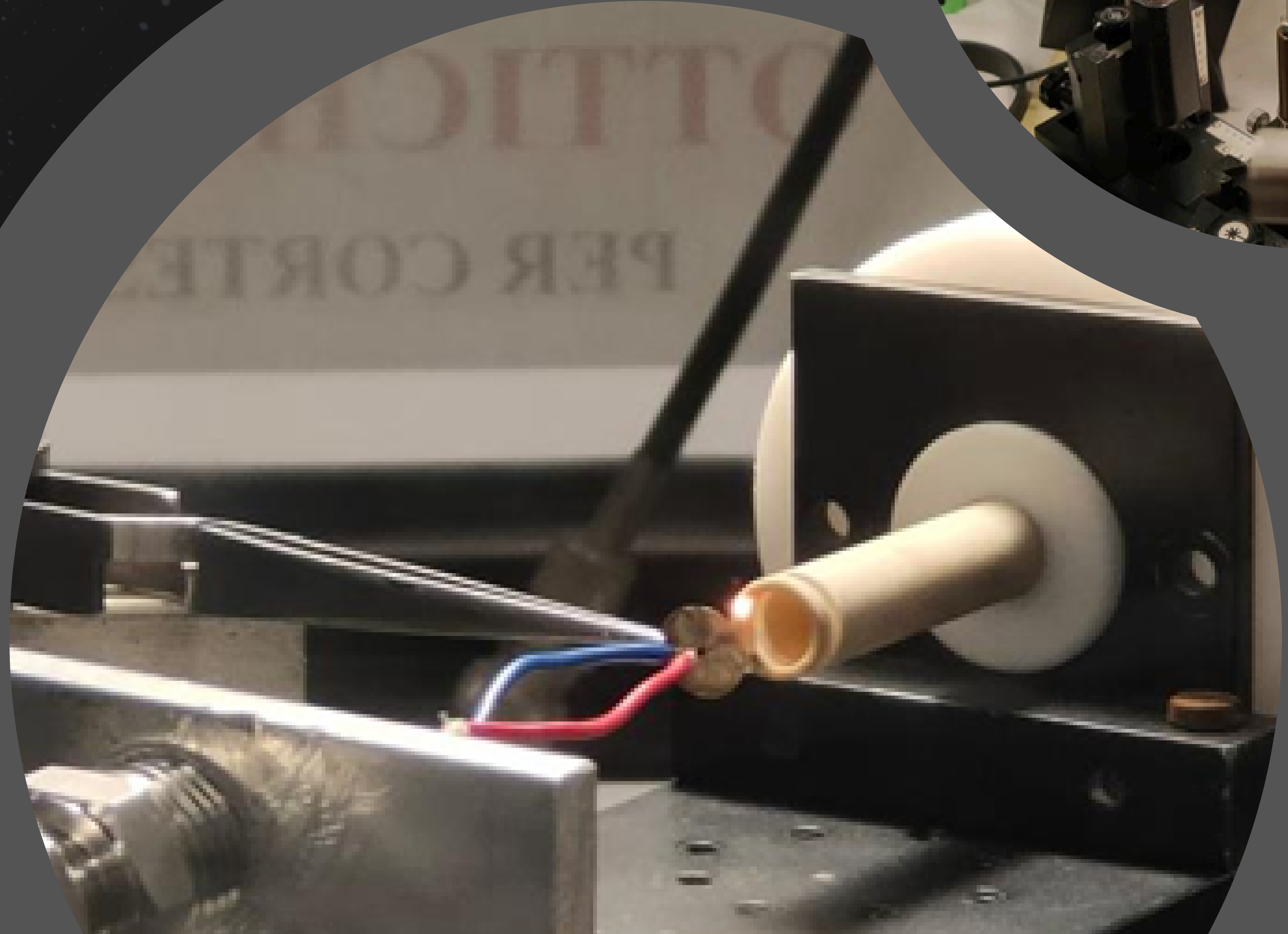
$$\begin{cases}
\dot{q}_{sun} = \dot{q}_{abs,sat} + \dot{q}_{trasm,sat} + \dot{q}_{refl,sat} \\
\dot{q}_{refl,sat} = \dot{q}_{refl,sat_{left}} + \dot{q}_{refl,sat_{right}} + \dot{q}_{refl,sat_{side}} \\
\dot{q}_{refl,sat_{right}} = \rho_{sat,right} \left(\dot{q}_{earth} + \dot{q}_{albedo} \right) \\
\dot{q}_{rad,sat_{left}}(t) = \varepsilon_{sat,left} \sigma_0 \left(T^4_{sat,left}(t) - T^4_{space} \right) \\
\dot{q}_{rad,sat_{right}}(t) = \varepsilon_{sat,right} \sigma_0 \left(T^4_{sat,right}(t) - T^4_{space} \right) \\
\dot{q}_{reflector} = \eta_r \dot{q}_{refl,sat_{left}} \\
\dot{q}_{collector} = \eta_c \dot{q}_{reflector} \\
\dot{q}_{abs,coll} = \dot{q}_{rad,coll_{left}} + \dot{q}_{rad,coll_{right}} + \dot{q}_{rad,coll_{side}} \\
\dot{q}_{PV} = \eta_{PV} \dot{q}_{abs,coll} \\
\dot{q}_{antenna} = \eta_{DC,DC} \eta_{DC,RF} \eta_{a,e} \eta_{b,e} \dot{q}_{PV} \\
\dot{q}_{gs} = C_{gs} \eta_{gs} \eta_{at,e} \eta_{RF,DC} \eta_{DC,DC} \dot{q}_{antenna} \\
\dot{q}_{user} = \eta_{tr} \dot{q}_{gs} \\
\dots
\end{cases}$$

→ **Thermal Dynamics**

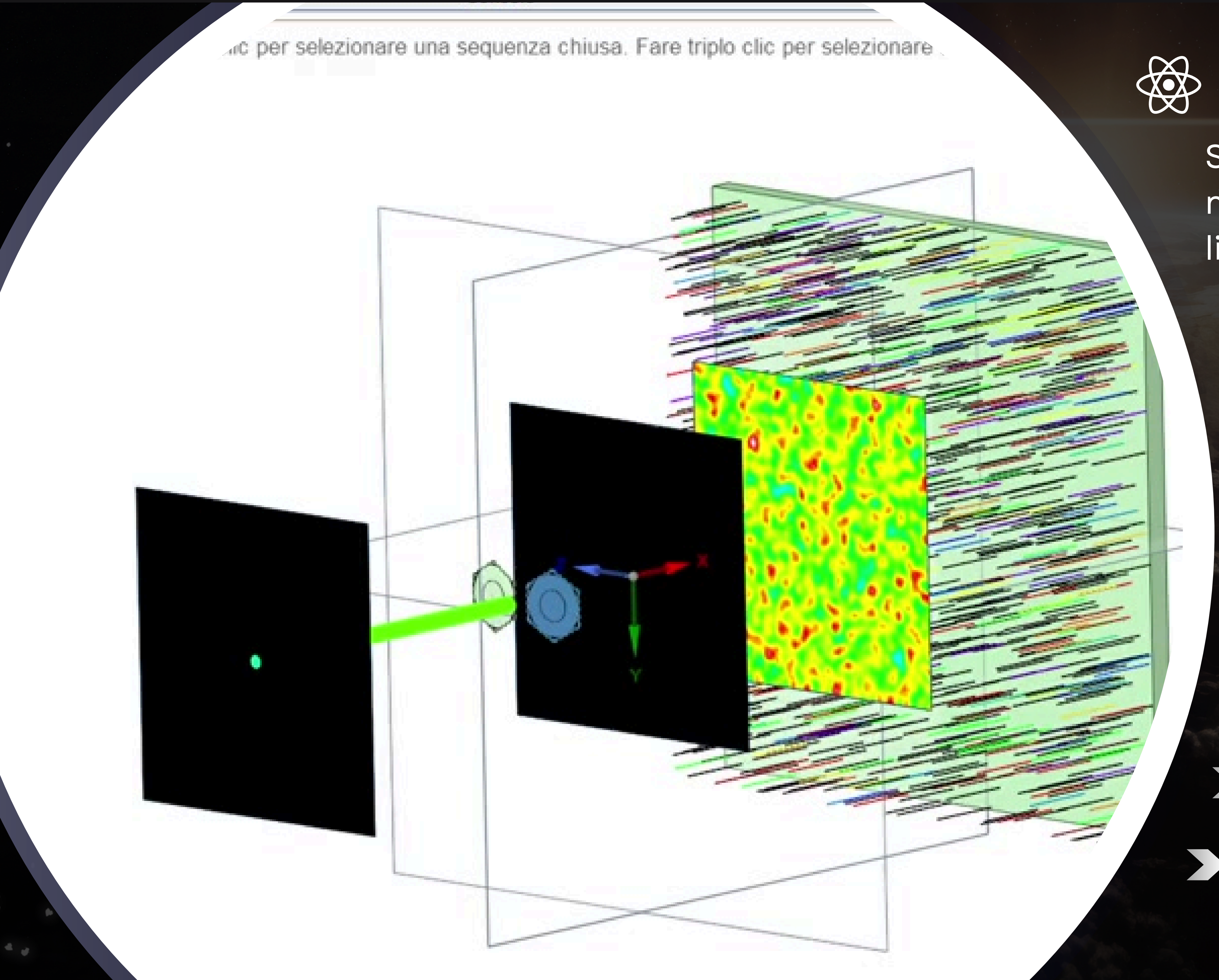
Model Validation

- **Experimental** work performed in **Polimi** Propulsion Lab:
  - **Pulsed CO2 Laser Beam** hitting a sensitive disc (brass)
- The **Mirror** and the **Absorber** surface can be modeled in the same way!





Optical Simulation



ANSYS SPEOS

Since it is not possible to recreate the 1:1 scale model on Ansys due to graphical and computational limitations, the model was scaled down to **1:130000.**

The model used to simulate optically satellite configuration consists of:

- Radiative plate (Sun Radiation)
- 3 Radiative Sensors (Output)
- 2 Parabolic Mirrors (Hexagons)
- 2 PV's Absorbers (Elliptical)
- 1 Transmitting Antenna (Beaming)

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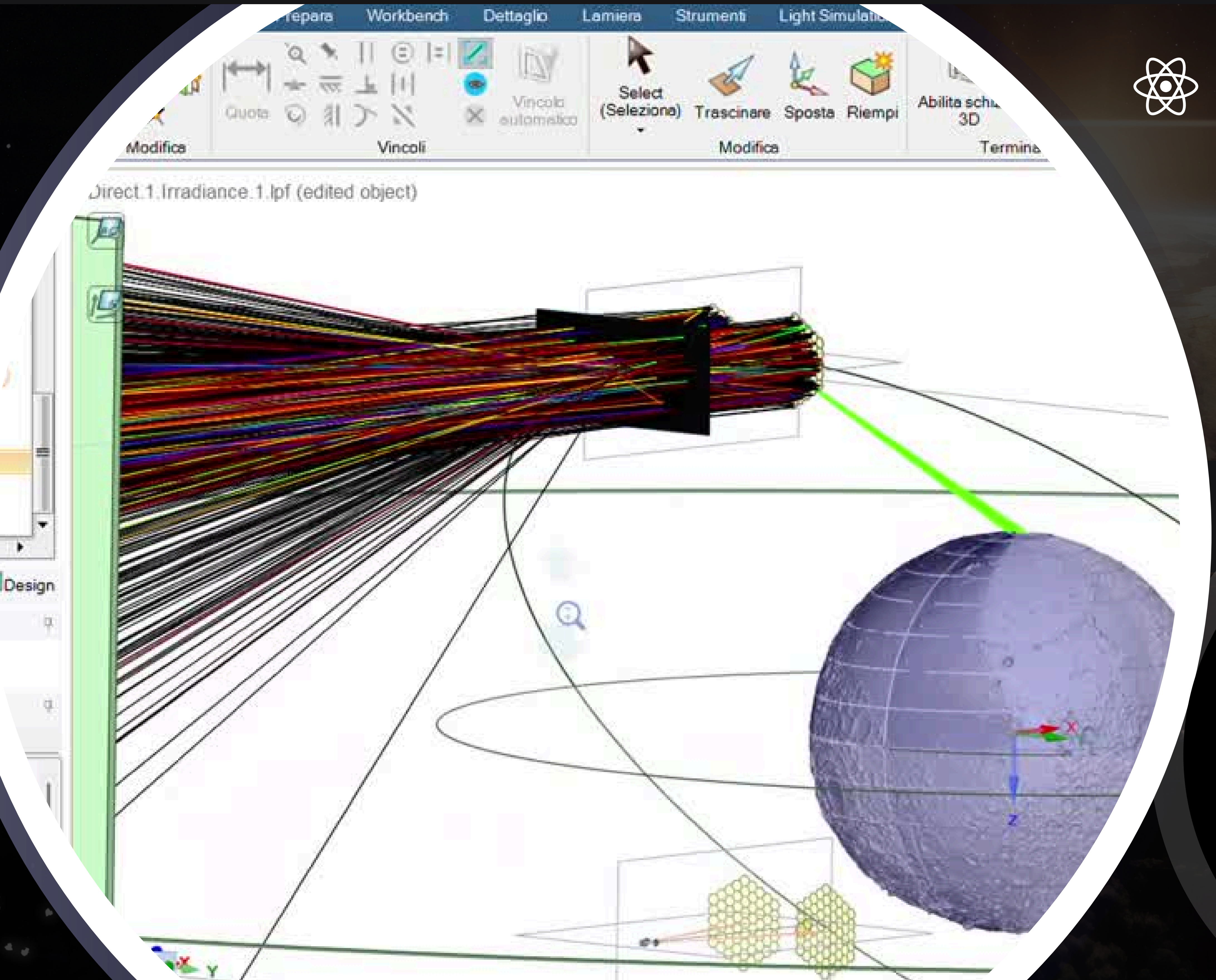
Optical Simulation

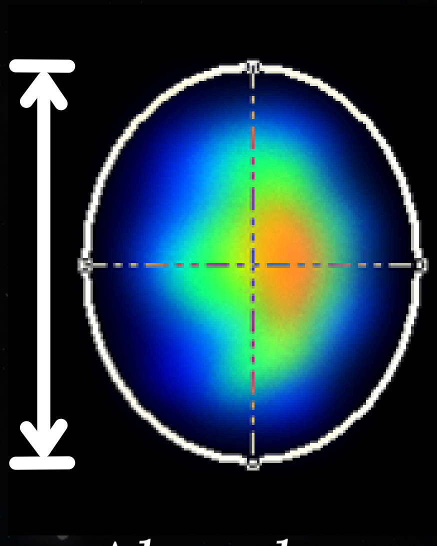


ANSYS SPEOS OUTPUT:

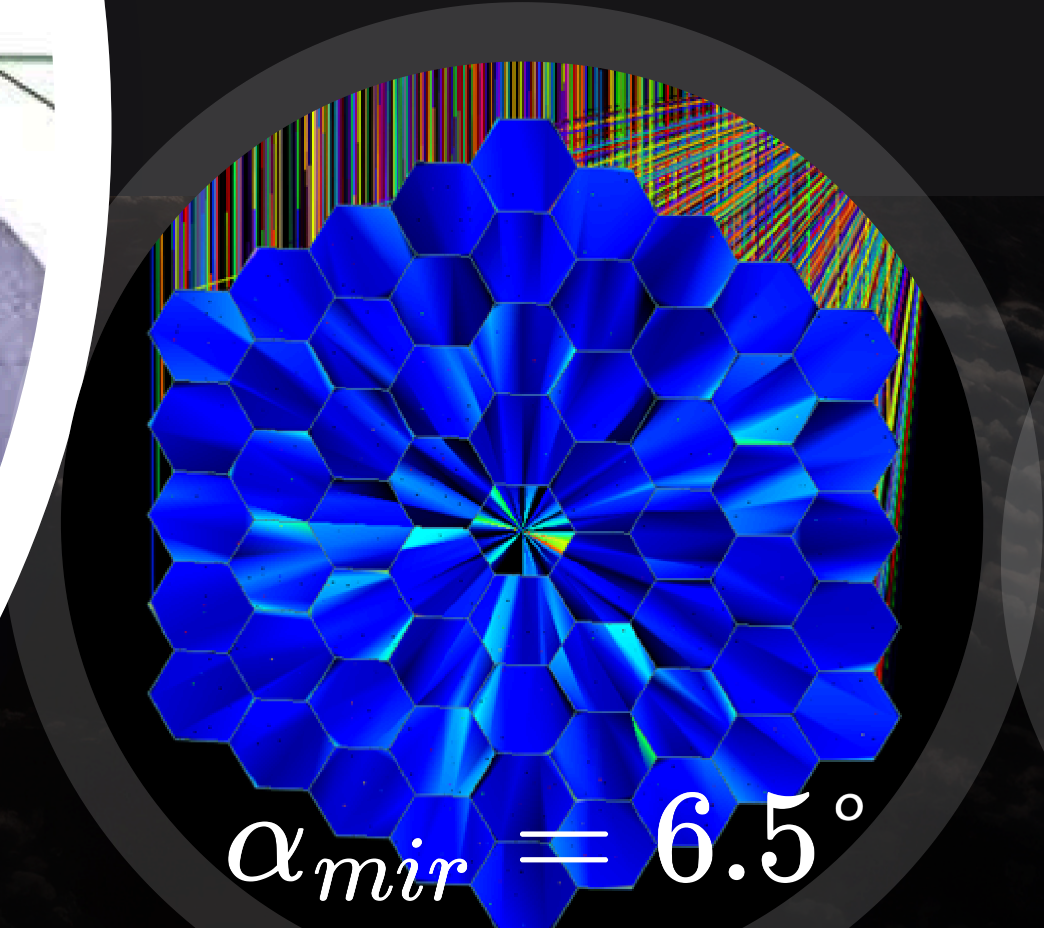
$$\dot{q}_{absorber} = 81 \frac{kW}{m^2}$$

$$P = 50 \text{ MW}$$

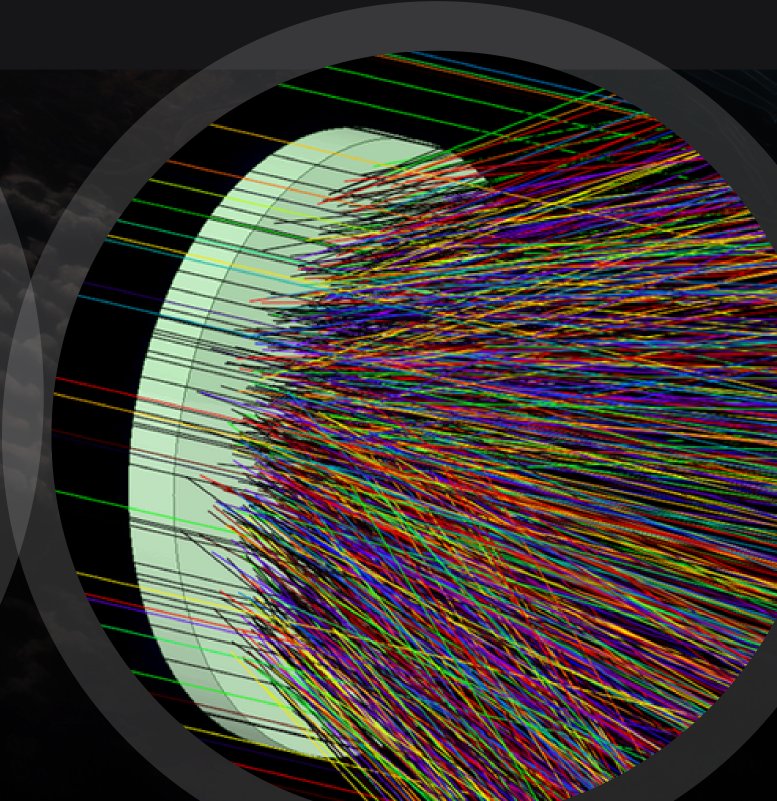
$$\Delta X_{mir,abs} = 200m$$



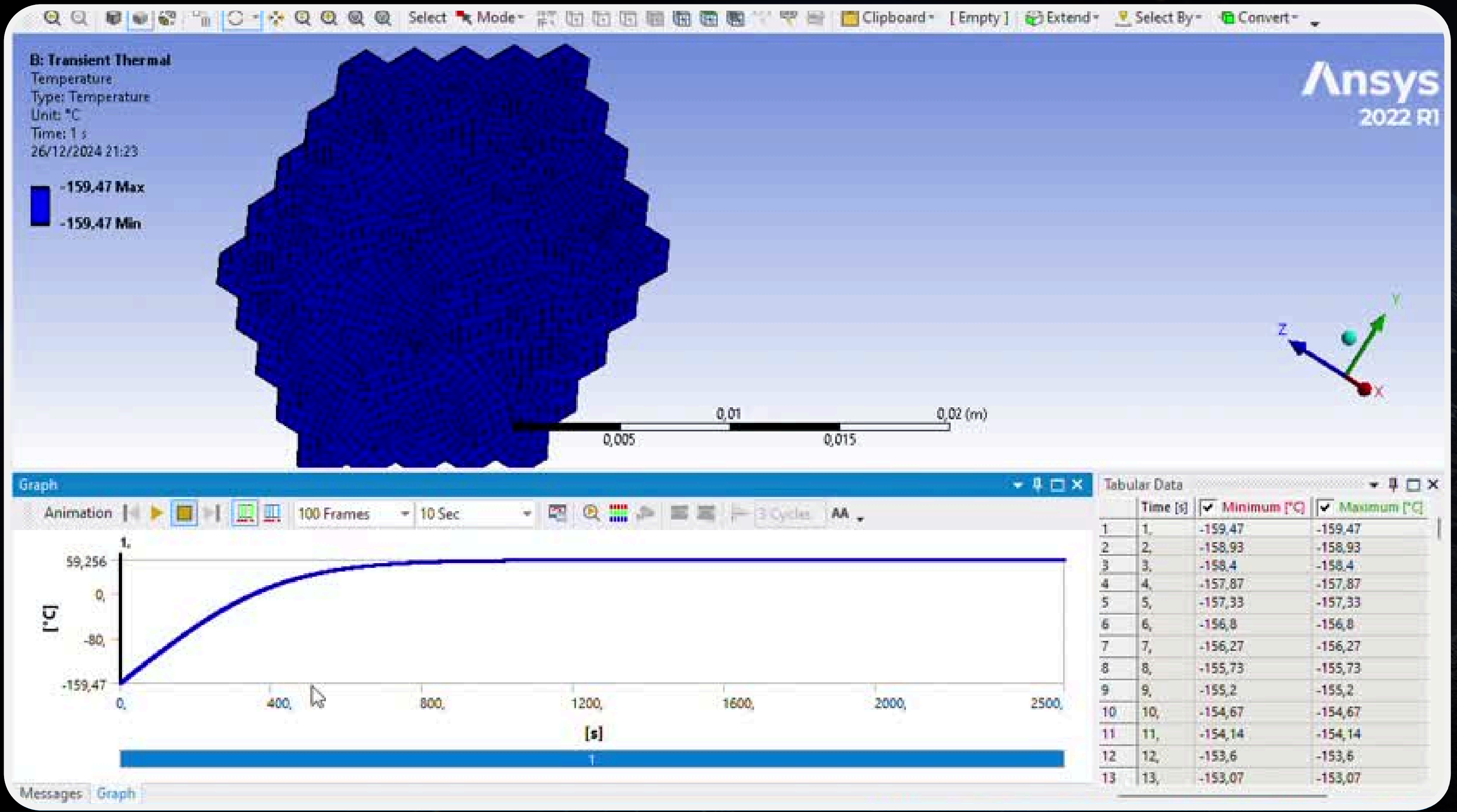
Absorber



$$\alpha_{mir} = 6.5°$$

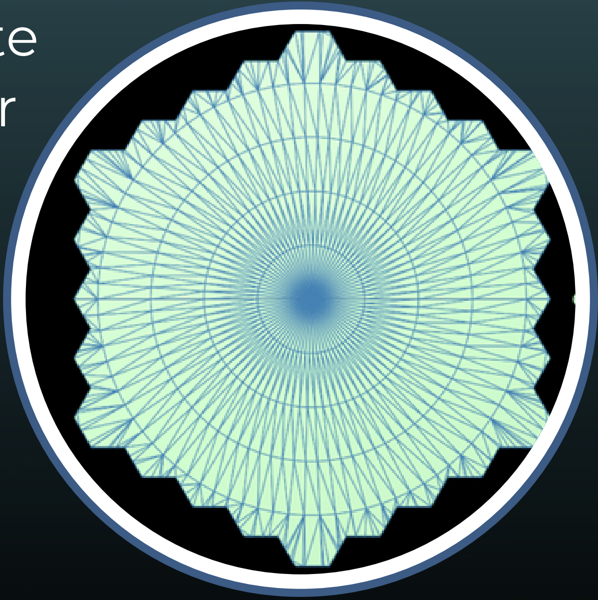


Thermal Simulation



ANSYS THERMAL TRANSIENT: Mirror

- The aim of the Thermal Simulation is to estimate the transient and final T [°C] values of the mirror and absorber, ensuring they remain below the material's creep temperature.
- This limitation guarantees the preservation of mechanical properties during the operational phase, extending mission's duration.



Thickness: 0.75 [micron]

Mass: 115 [kg]

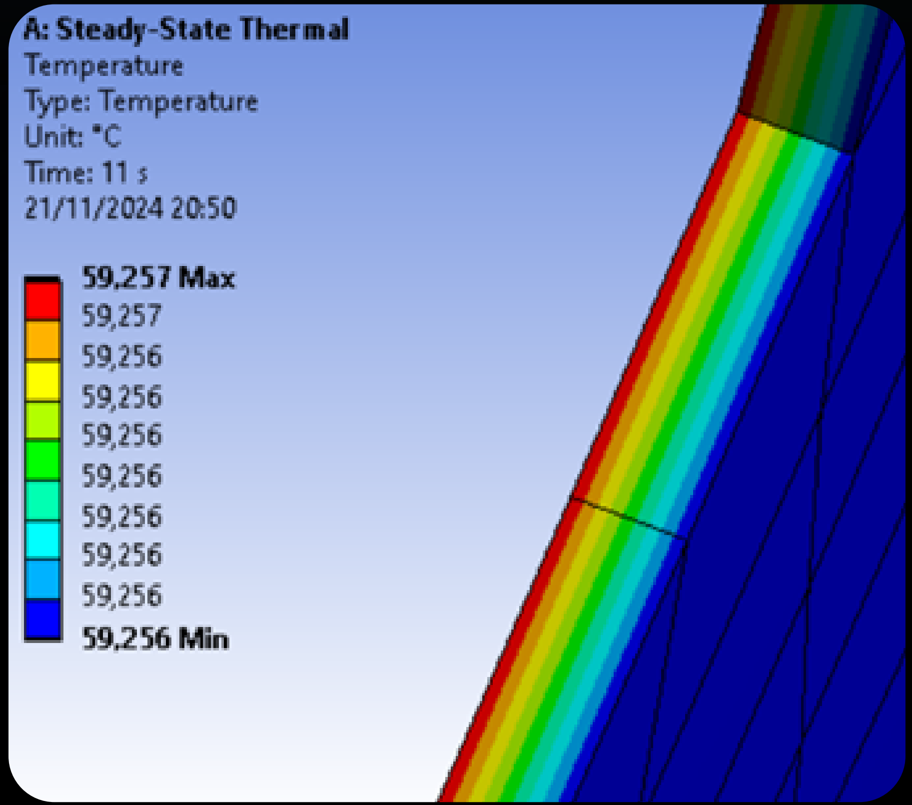
Equilibrium Time: ~2000 [s]

Material: Aluminum

Heat Flux: 1367 [W/m^2]

Final T: 59.3 [°C]

Primary Creep T: ~198 [°C]



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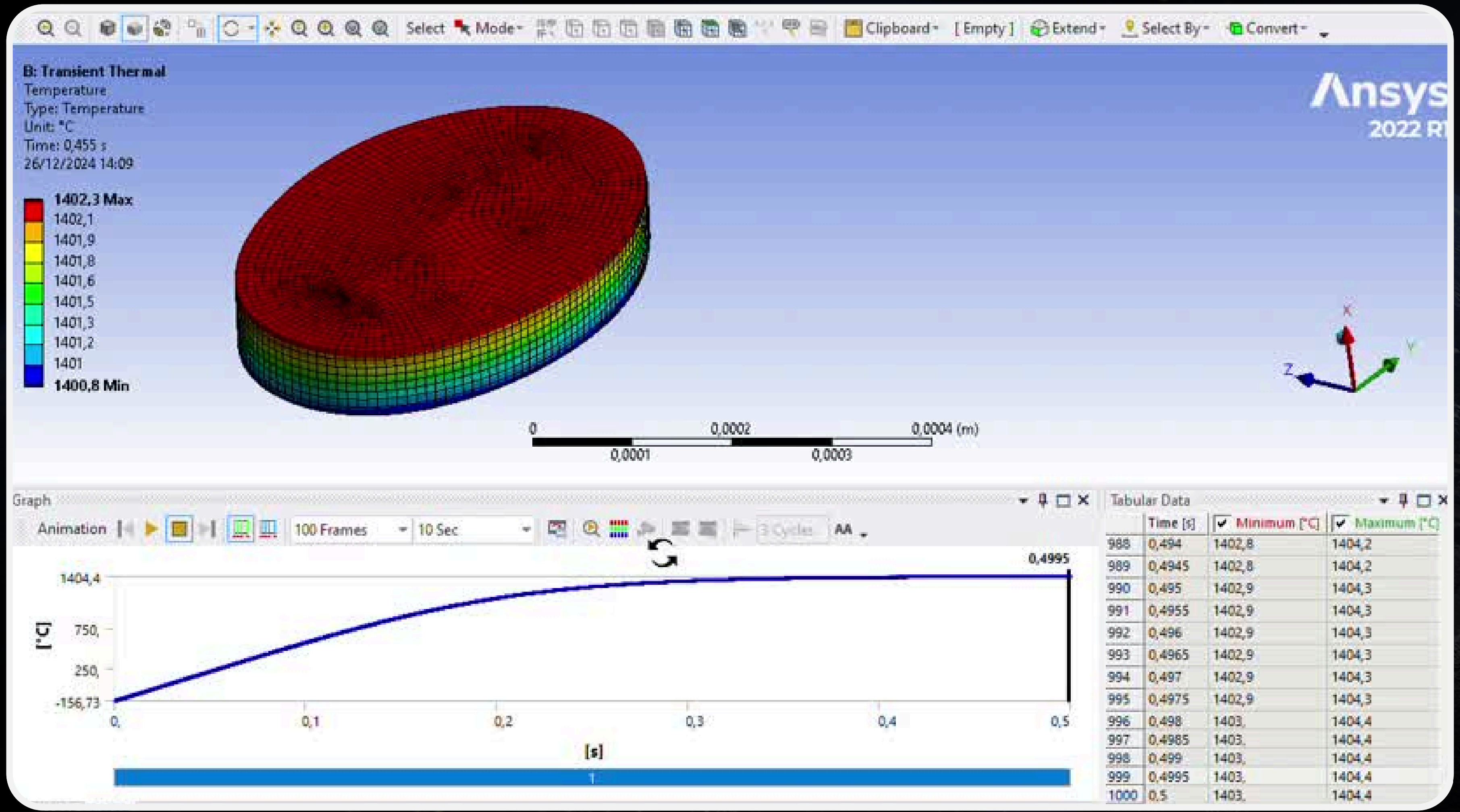
Thermal Simulation



ANSYS THERMAL TRANSIENT: Absorber

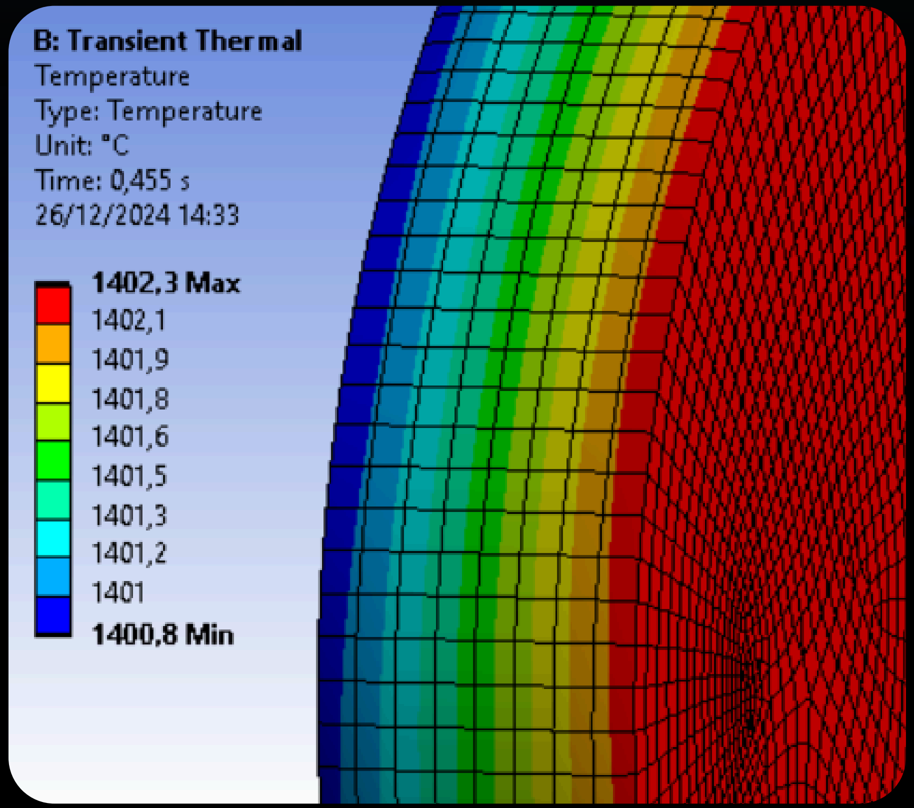
- The aim of the Thermal Simulation is to estimate the transient and final T [°C] values of the mirror and absorber, ensuring they remain below the material's creep temperature.
- The thickness of both the absorber and mirror is set equal to the sensitive disc tested in lab at Polimi.

Material: Graphite

Heat Flux: 900,000 [W/m^2]

Final T: 1402 [°C]

Primary Creep T: ~1440 [°C]



Thickness: 0.75 [mm]

Mass: 40 [kg]

Equilibrium Time: ~0.5 [s]

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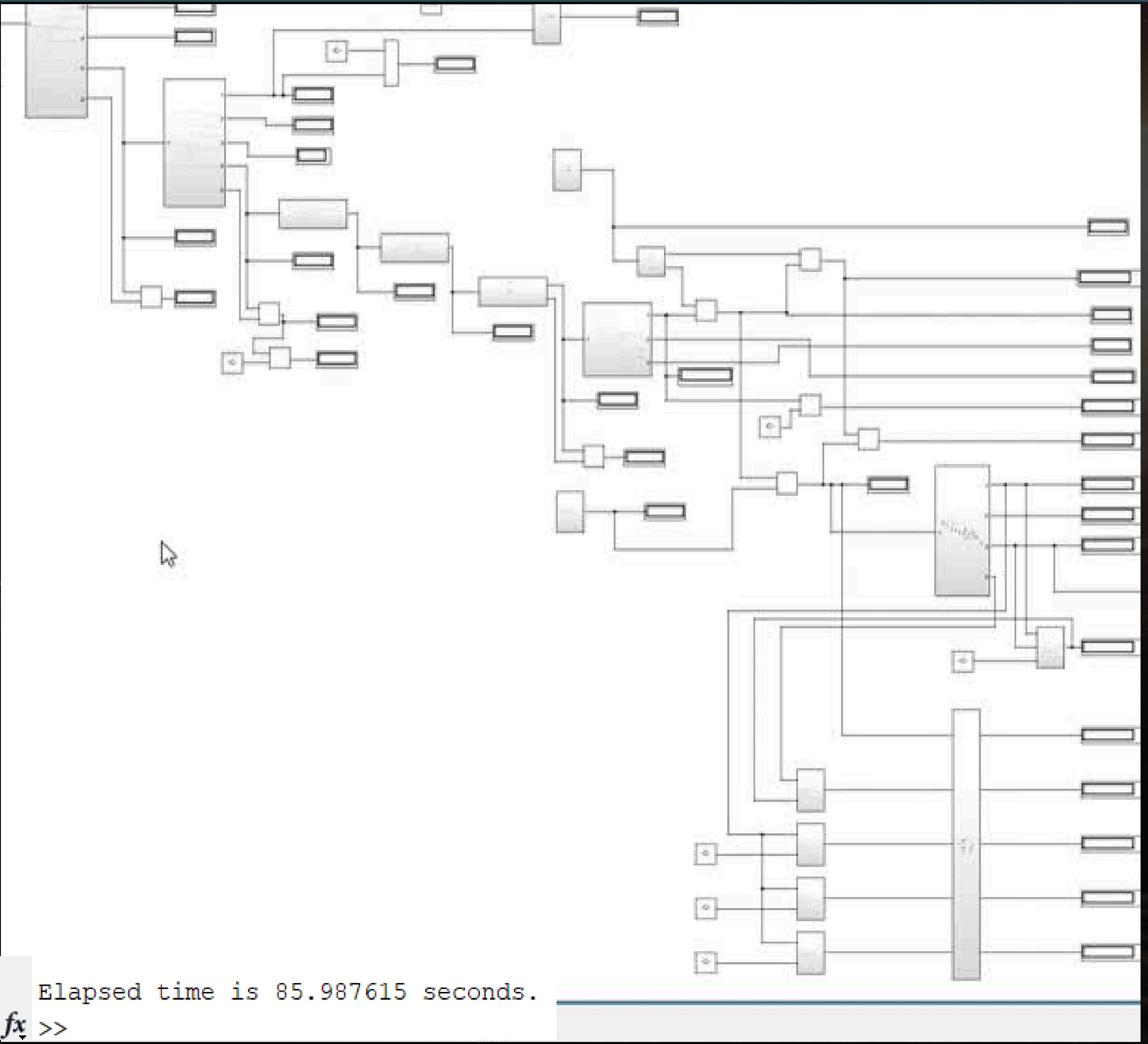
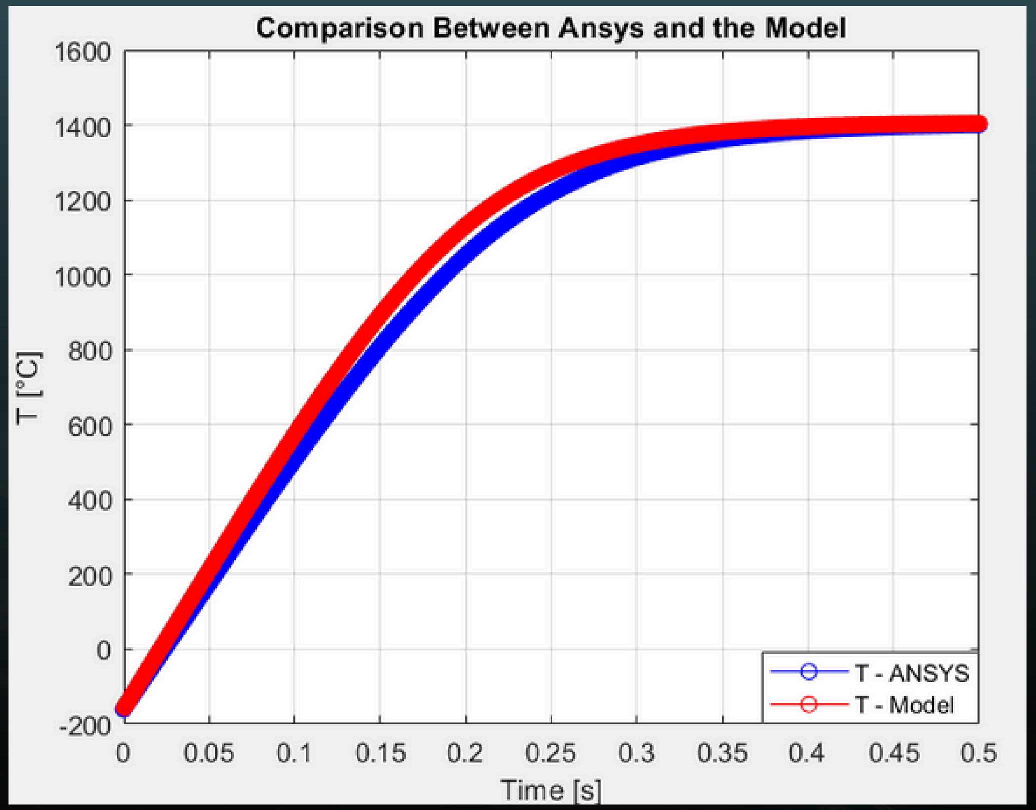
Implemented Model VS Ansys Simulations



MODEL VALIDATION

- The results of the simulations performed with Ansys are used to **cross-check** the implemented model output.
- The proposed model is then **augmented** with the results of the dedicated simulations, leading to more **robust** and **accurate Simulator**.



Absorber Heating Profile

Error between Ansys and Model? 0.093%

Ansys Time: ~2 h → **Just to mesh the Mirror!**

Simulator Time: 86 s → **To size the entire System**

Orbital Simulation

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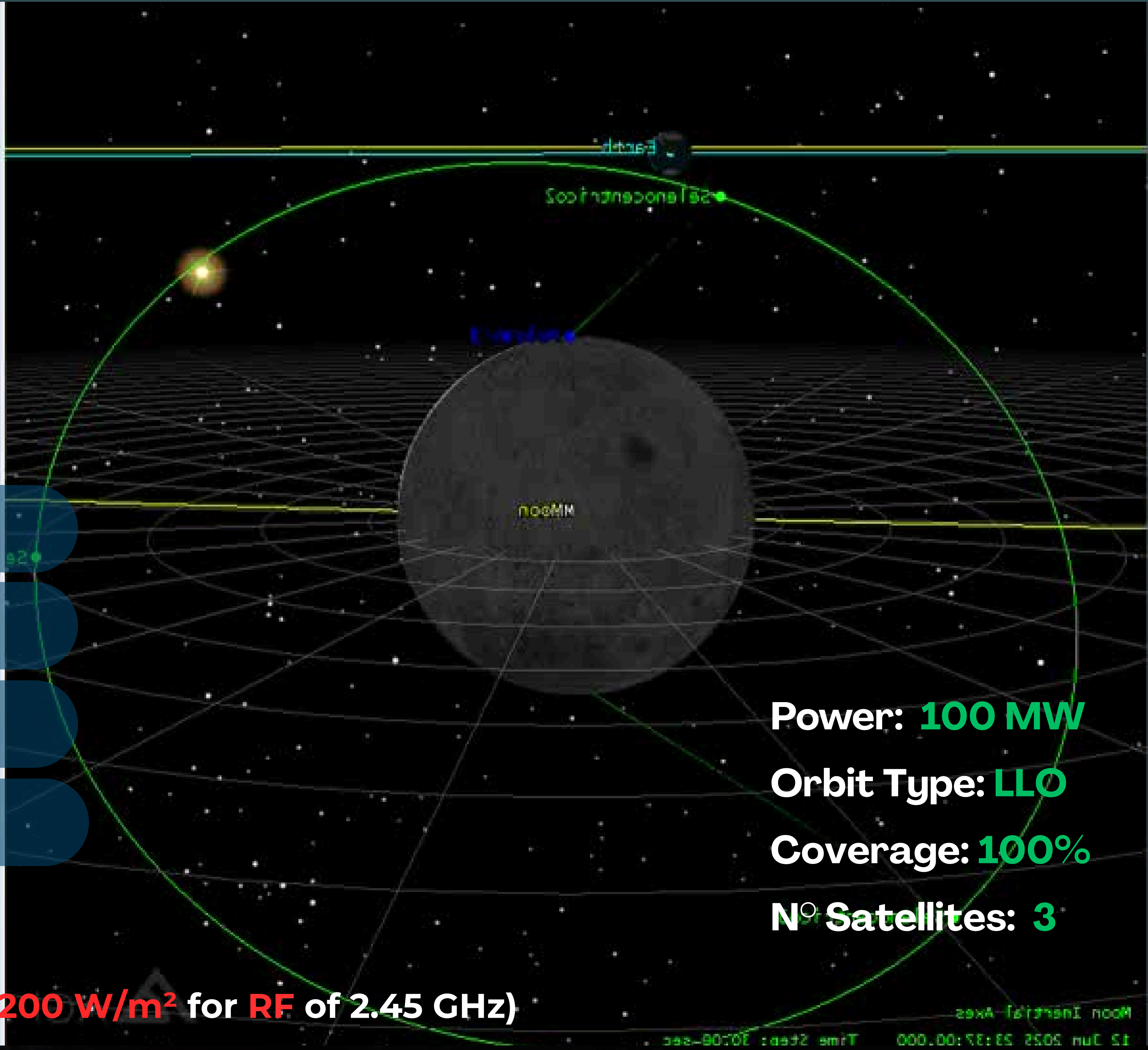
Objective of the orbital simulations? To determine:

- N° of Satellites
- N° of Rectennas
- Orbital and Ground Configuration

INPUT DATA: 2 GW Satellite

	Power Consumption	N° of Satellites
Earth	18.7 [TW]	9360
USA	1.1 [TW]	550
Torino	**550** [MW]	**0.28**
Moon	**???** [MW]	**?**

HOW MANY GROUND STATIONS?



Power: 100 MW

Orbit Type: LLO

Coverage: 100%

N° Satellites: 3

It depends upon the max allowable heat flux on ground (~200 W/m² for RF of 2.45 GHz)

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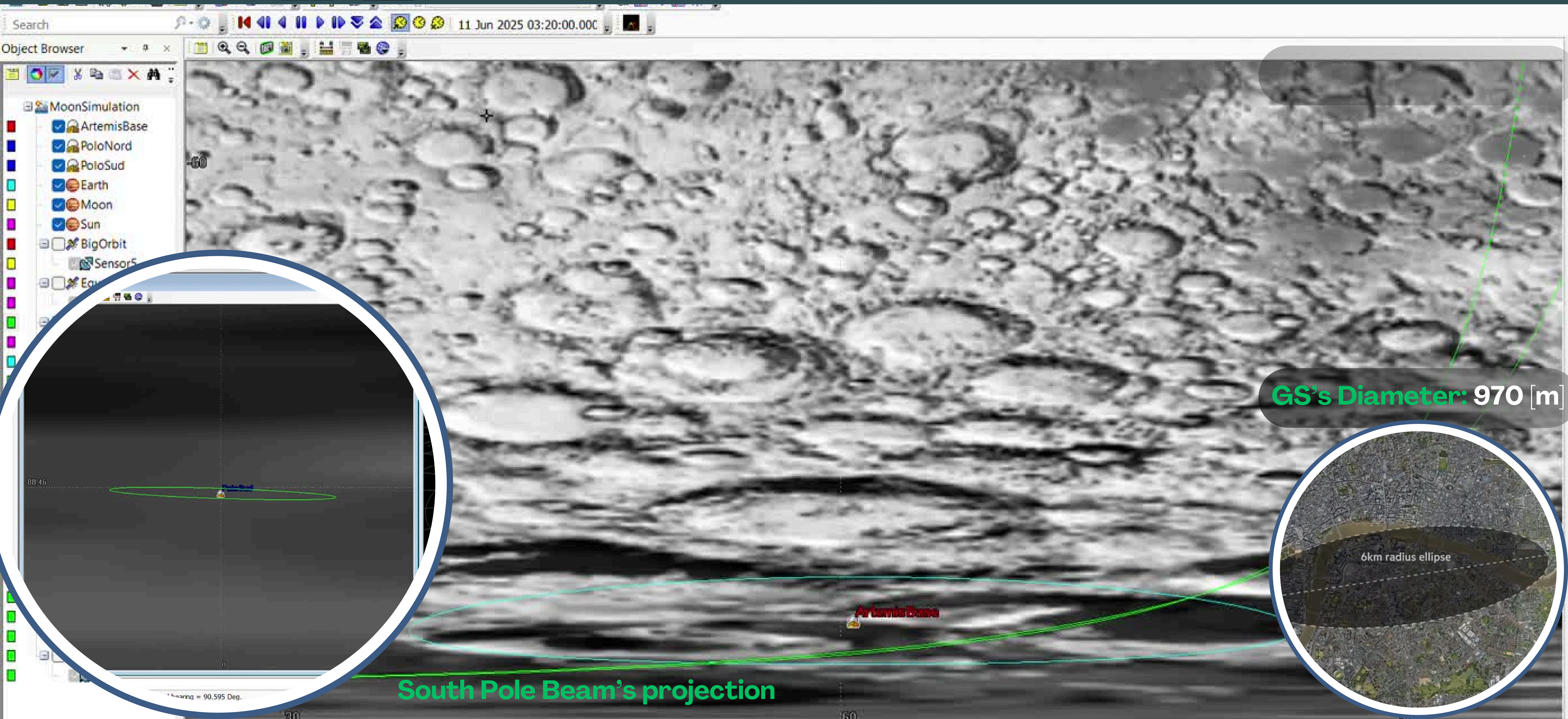
Orbital Simulation (STK) - South Pole



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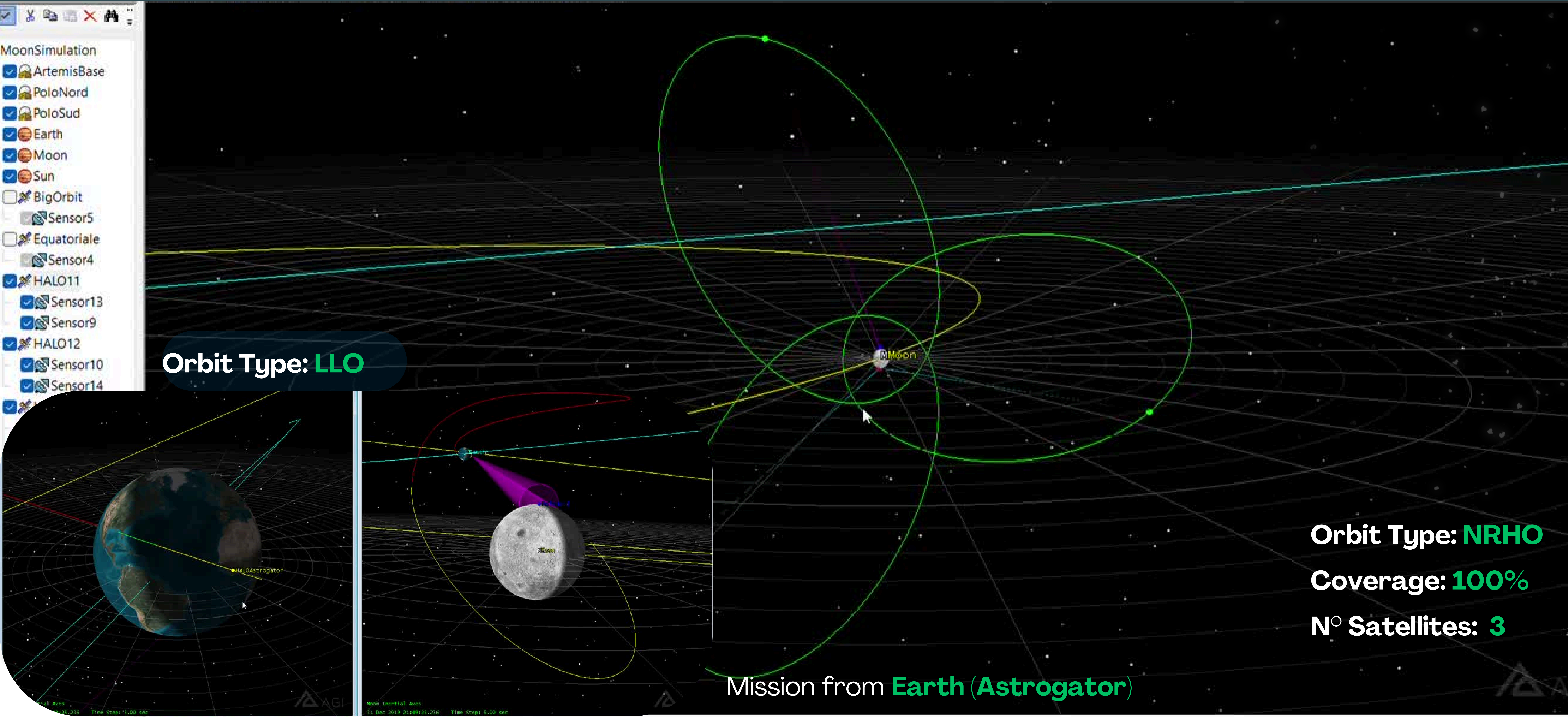
Orbital Simulation (STK)



Orbit Type: **LLO**

Orbit Type: **NRHO**

Coverage: **100%**

N° Satellites: **3**

Mission from **Earth** (**Astrogator**)

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Model Output - Ground Comparison

Noor Solar Park (Abu Dhabi)	1 SPS Type 3 Satellite
Surface: 8 [km^2]	**Rectenna's Surface:** ~ **0.74** [km^2]
Delivered Power: 1.18 [GW]	**Delivered Power:** **1.18** [GW]
Average Heat Flux: 147 [W/m^2]	**Average Heat Flux:** **97** [W/m^2]
Capacity Factor: 20 %	**Capacity Factor:** **99.7** %
Operative Life: 25 years	**Operative Life:** **25** years
Final Power Flux: 29.4 [W/m^2]	**Final Power Flux:** **96.7** [W/m^2]
Cost of Energy: 0.024 ÷ 0.013 [$/kWh]	**Cost of Energy:** ~ **0.011** [$/kWh]


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Thank You
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