Using Microwaves to Heat Lunar Soil

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Water is one of the Most Plentiful Compounds in the Universe

- Earth's water likely came from comets early in its history.
- Large quantities of water are frozen at the lunar poles.
- Mars has vast quantities of water not only at the poles but also at lower latitudes.
- Some speculate that Mars' moon Phobos may have water
- Significant quantities of water are present on several moons of Jupiter (Europa, Ganymede, and Callisto), Saturn (Enceladus), and Neptune (Titon).

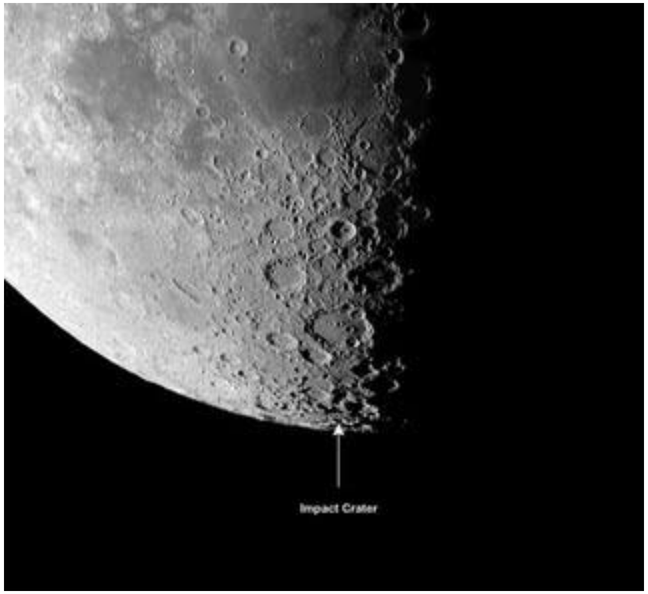
Lunar CRater Observation and Sensing Satellite - LCROSS

- The Centaur upper stage impacted a permanently shadowed crater, Cabeus A near the south pole of the Moon.

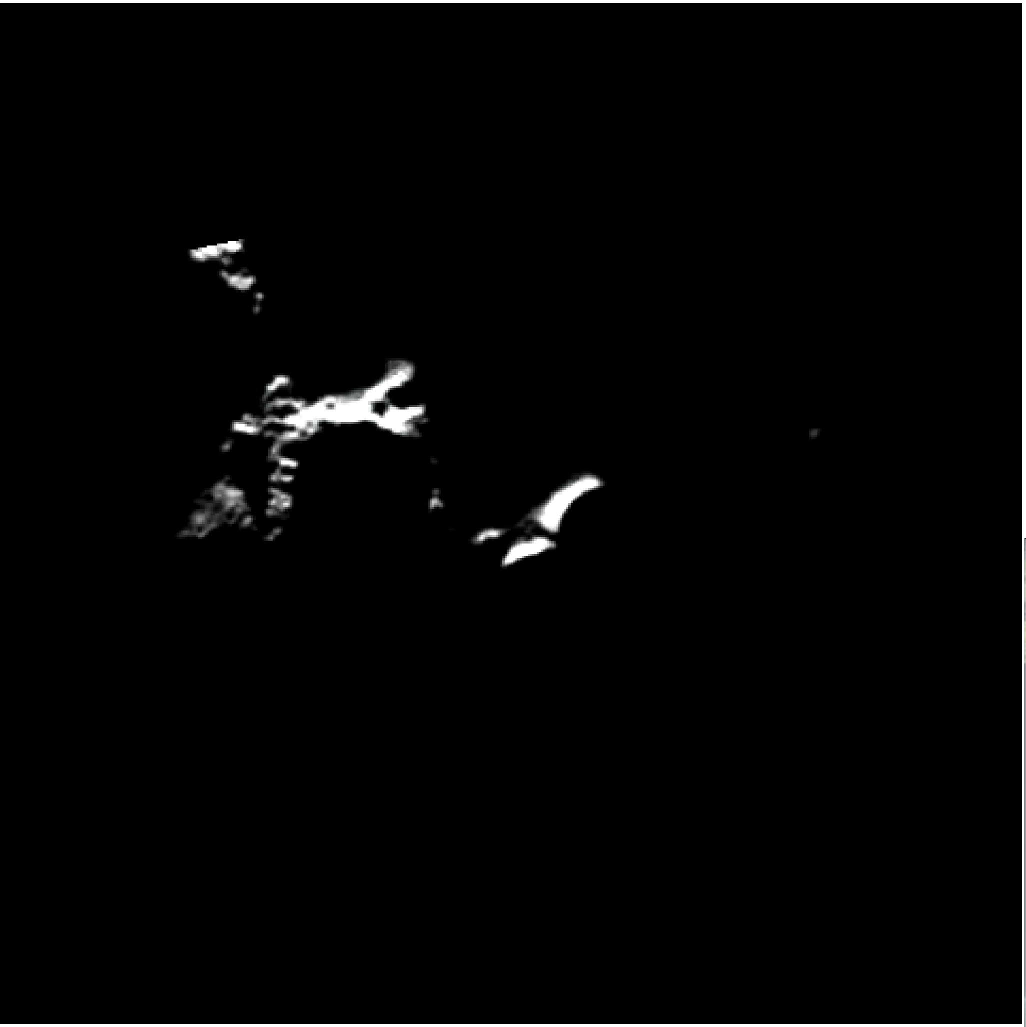
- Mission Objective - confirm the presence of water ice in a permanently shadowed crater at the Moon's South Pole.

- Spectral analysis of the resulting impact Confirmed large quantities of water ice.

Crater Cabeus A →

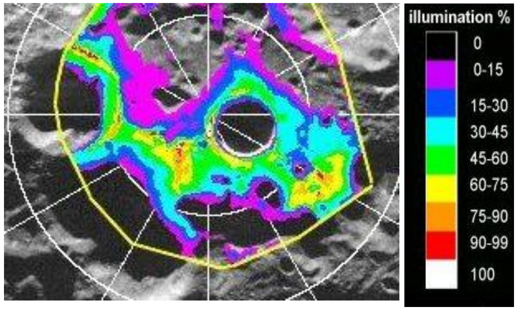


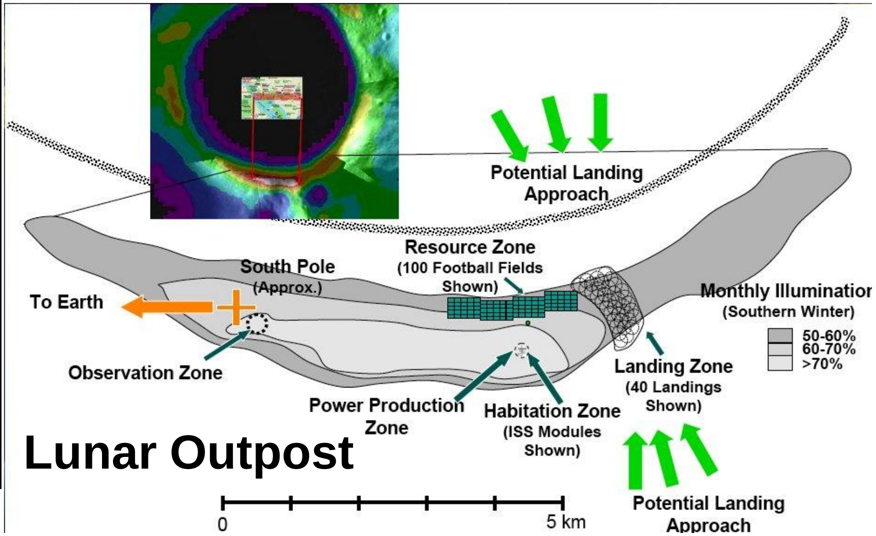
Illumination of the South Polar Region of the Moon over one Lunar Day (28 days)



http://www.lpi.usra.edu/resources/clemen/clemen.html

Moon Polar light map





Continuous Sunlight, Continuous Contact with Earth, Moderate Temperature, and Resources (water)

Importance of Water

- **Water (and oxygen) for the manned lunar outpost.**
  Resupply requirements:
  1 ton water and 1 ton oxygen per year
  (~$100,000 per pound from Earth to lunar surface)

- **Eventually - rocket propellant for exploration,**
  Electrolyze water into H and O, liquify LOX
  10's of tons of mass not launched from Earth
  (~$10,000s per pound to LEO)

- **Water is an excellent radiation shielding material for manned missions.**

Use of Microwaves for the Extraction of Lunar Water

- Lunar Soil is a Super Thermal Insulator – like aerogel
  very low heat flow.

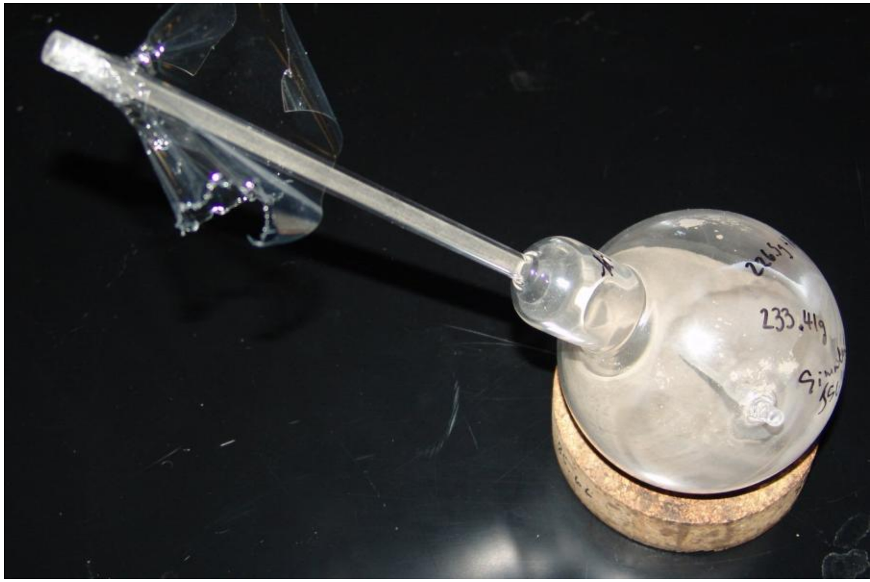
- Microwave energy penetrates the soil heating from within.
  Penetration depth is dependent on Frequency,

- Conversion from electricity through microwaves to heat,
  efficient, heating causes sublimation of water ice.

- Excavation is not required,
  Cryogenic water ice is as hard as granite
  Lower mass, less infrastructure, and equipment
  Little if any disruption of lunar dust (hazard)

Water Extraction Efficiency

- Microwaves coupled to soil simulant at LN2 temperature.
- At least 95% of the water from the regolith permafrost simulant was extracted (2 minutes).
- Of the extracted water 99% was captured in the cold trap.



Fused silica vessel with lunar permafrost simulant.

Microwave Attenuation - Beer-Lambert law

Penetration Depth*

$$\text{Penetration} \sim \frac{\lambda\ (\varepsilon')^{1/2}}{2\pi\varepsilon''}$$

	ε “	ε ‘	Penetration
Water	0.1	8	6cm
Simulant JSC-1	0.1	4	10cm
Ice	0.001	3	1m
Polyethylene	0.0001	2	100m
quartz	0.00001	3	1000m

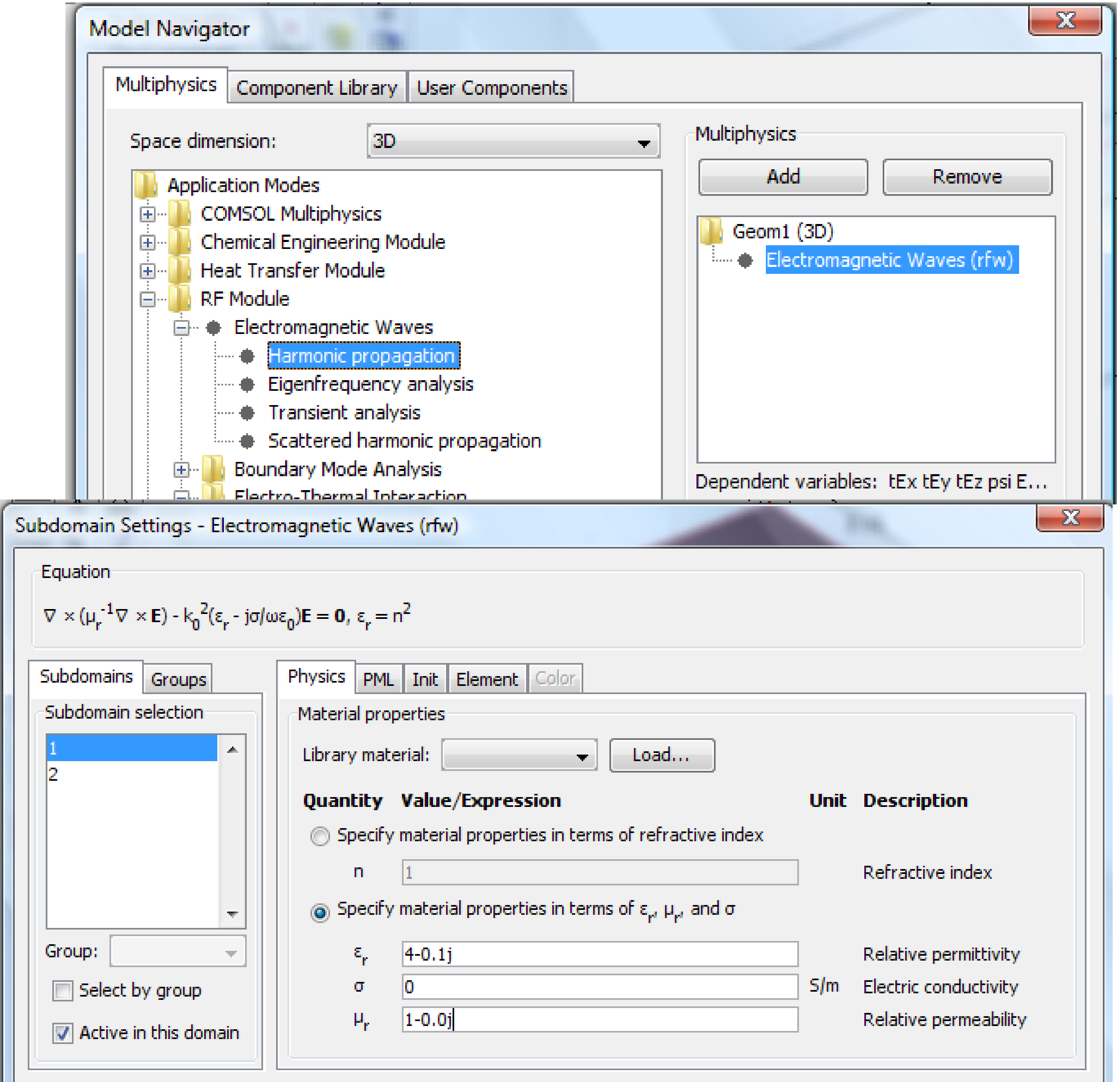
$\varepsilon = \varepsilon' + j\,\varepsilon''$

ε' dielectric constant

ε'' loss factor

*1/e (0.37) of the original value.

COMSOL - RF Module – Electromagnetic Waves – Harmonic Propagation



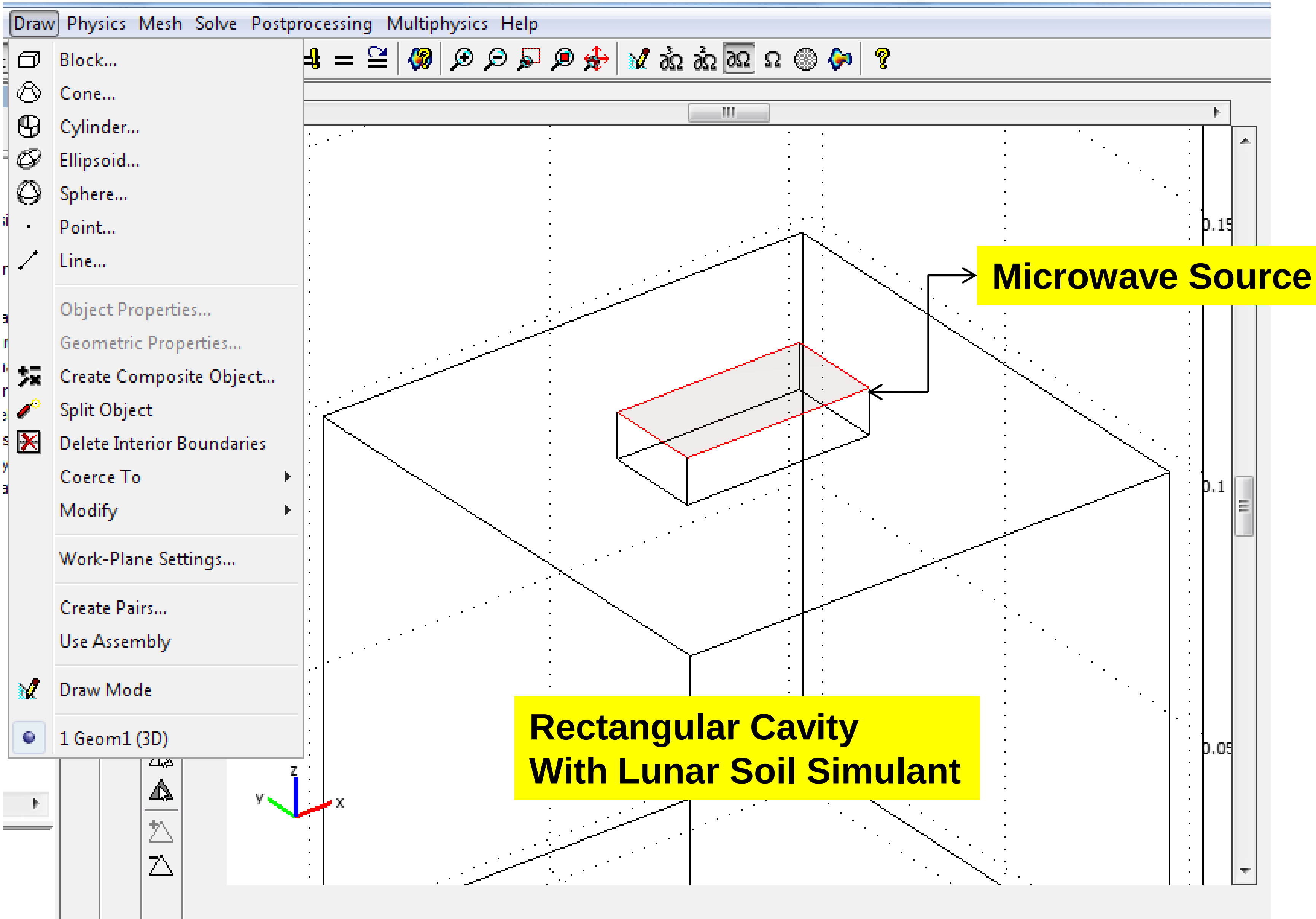
COMSOL 3.5

Subdomain Settings

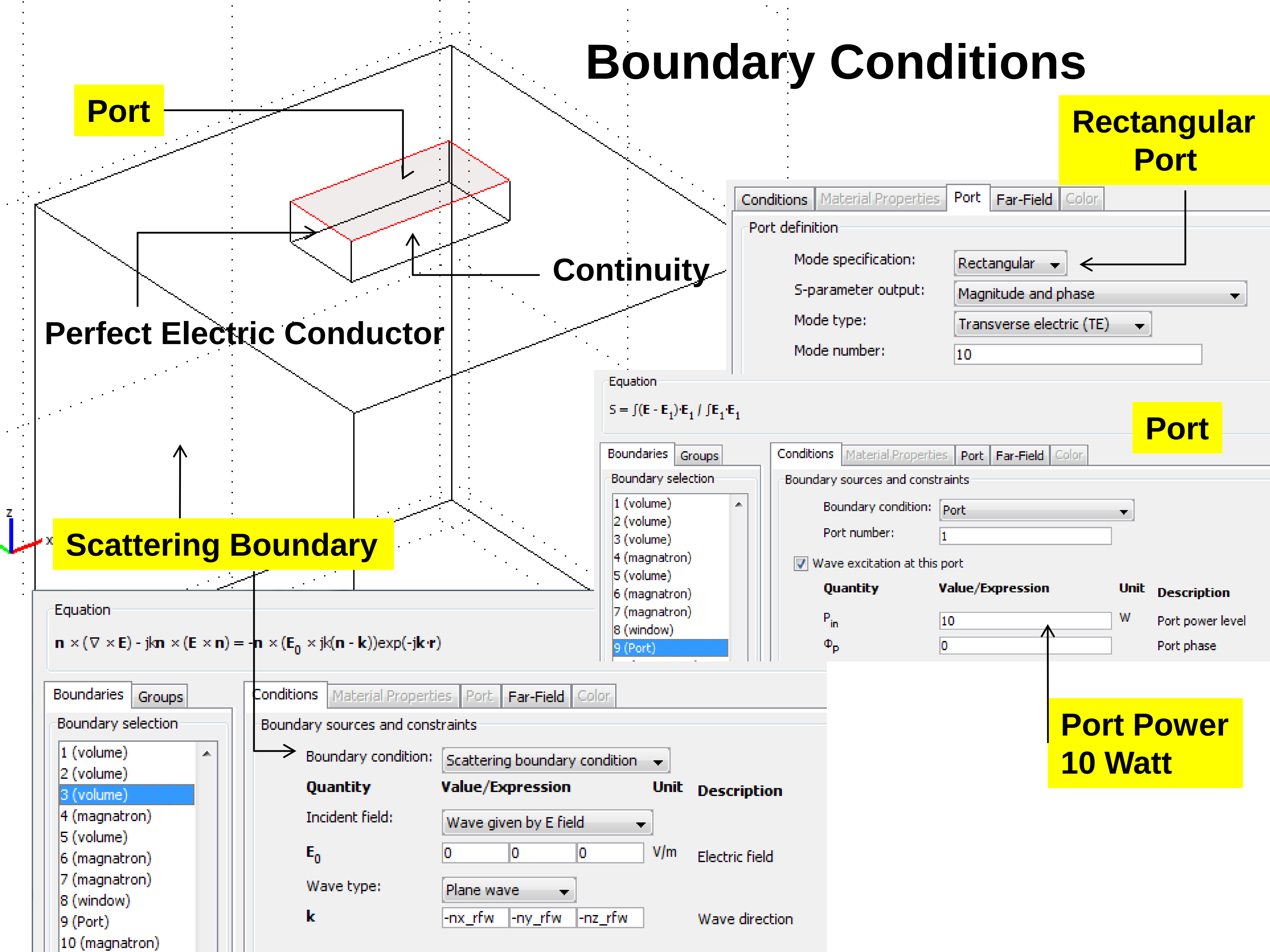
Electric Permittivity
4 - 0.1j
Magnetic Permeability
1 - 0.0j

Lunar Soil Dielectric Properties

Geometry - Draw



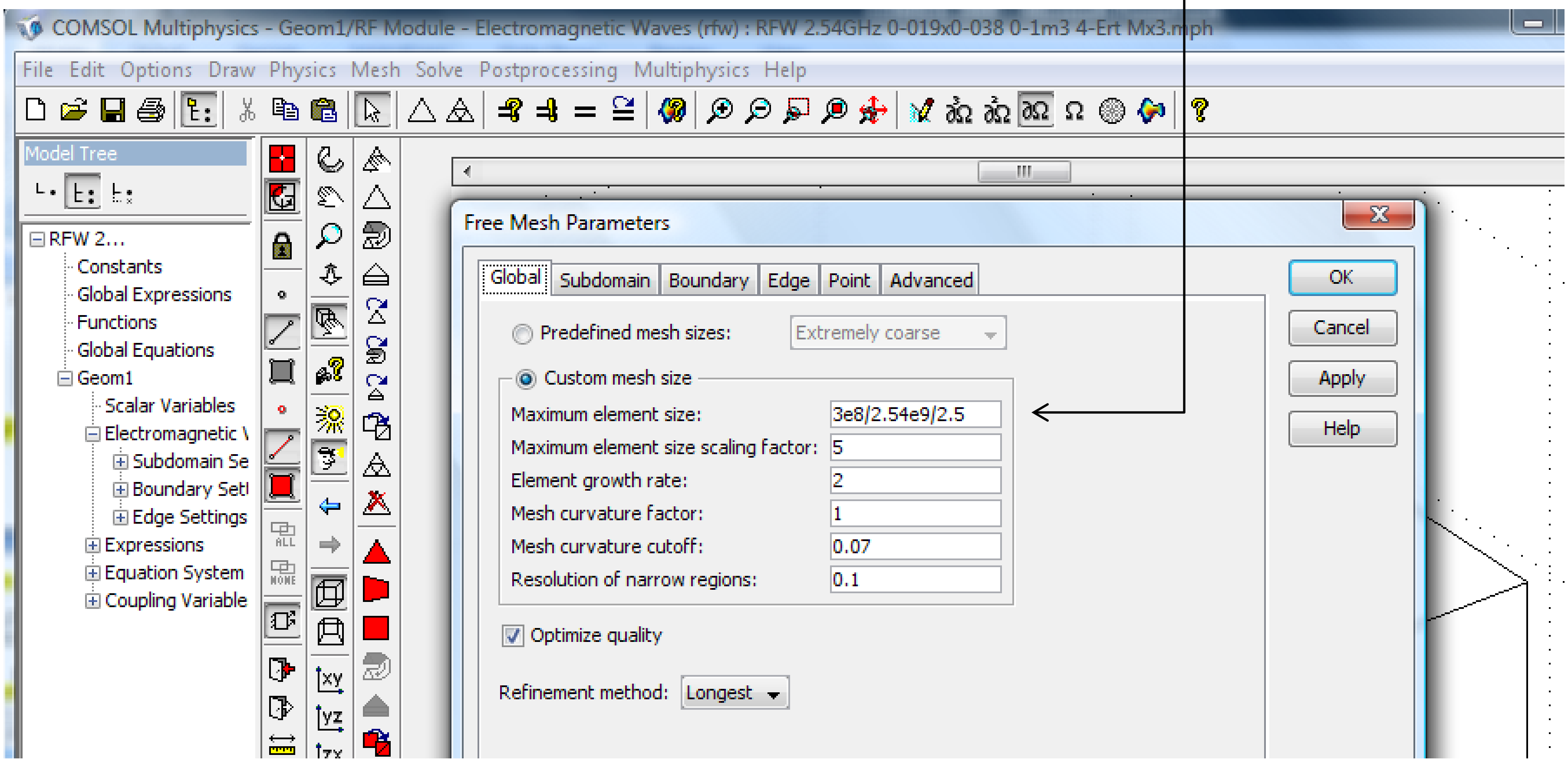
Boundary Conditions



Meshing must satisfy the Nyquist criteria

Maximum element size = c / λ / 2.5
= 3e8 / 2.45e9 / 2.5

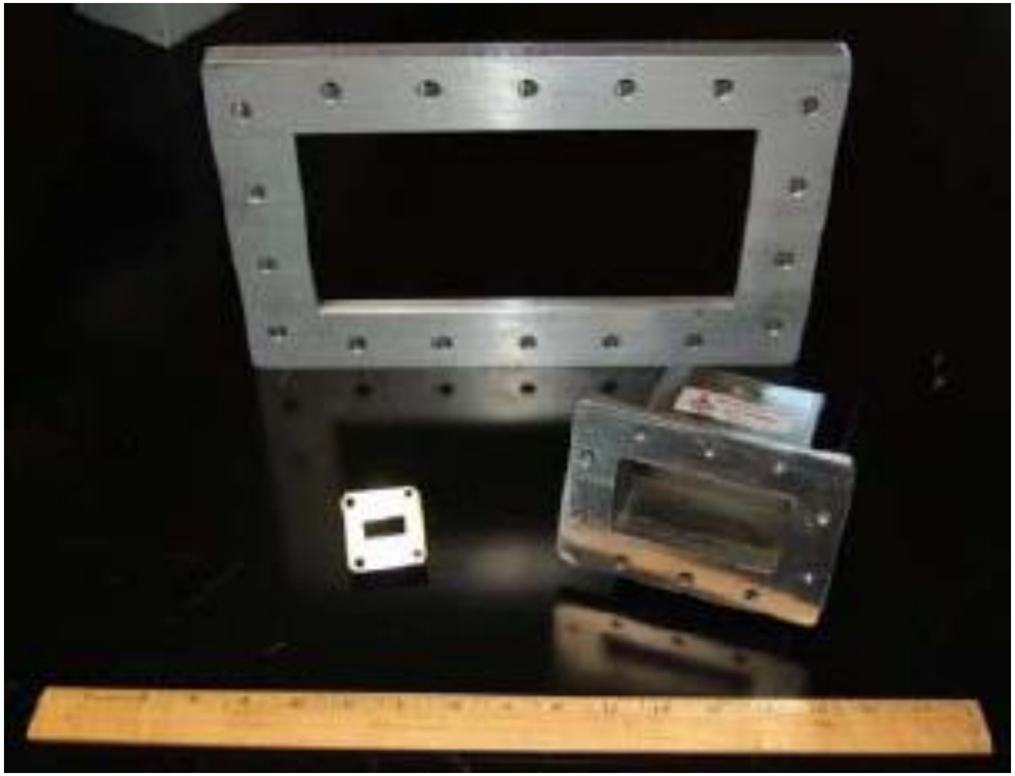
Free Mesh Parameters



Three Microwave Frequencies

<- 0.9 GHz

10 GHz ->



<- 2.45 GHz

Microwave flanges for the three different microwave frequencies (0.9 GHz, 2.45 GHz and 10 GHz) used in this project showing the relative sizes of the experimental and test measurement hardware. Their standard sizes are designated WR975, WR340 and WR90 respectively.

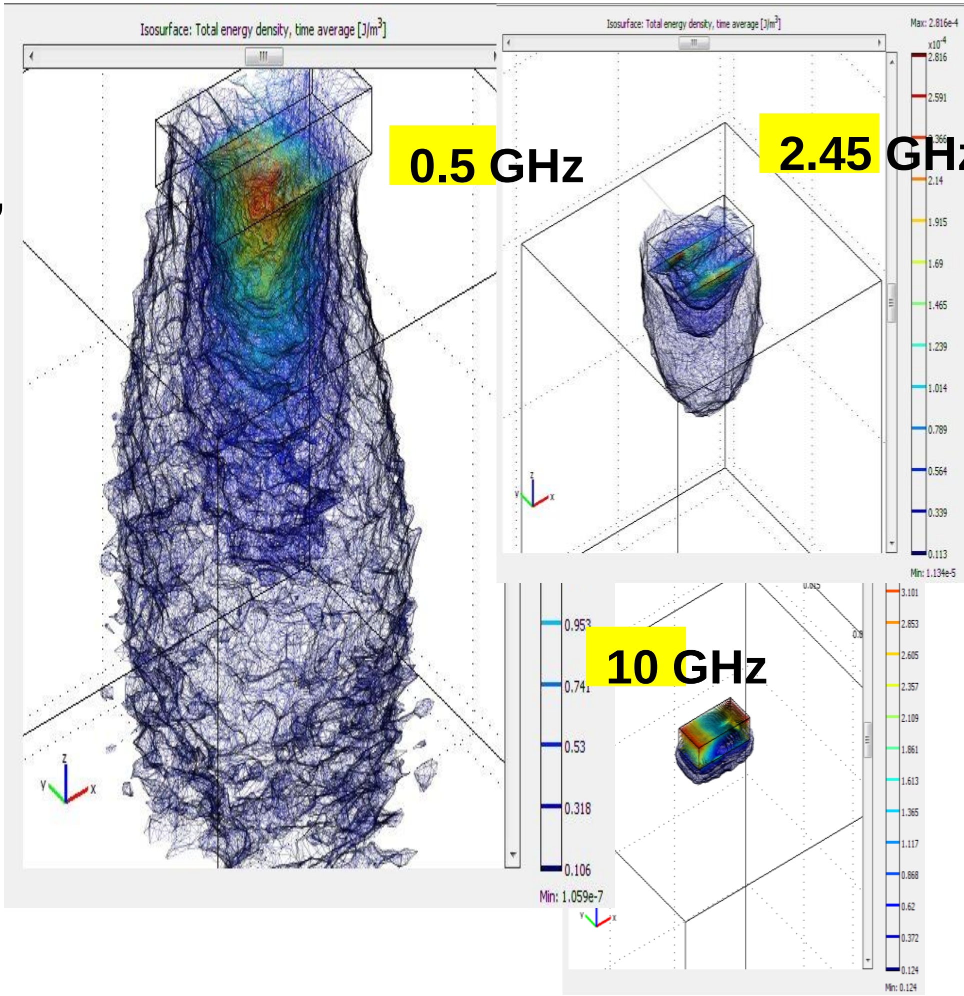
COMSOL Mutliphysics Calculations of Microwave Penetration at 3 Frequencies

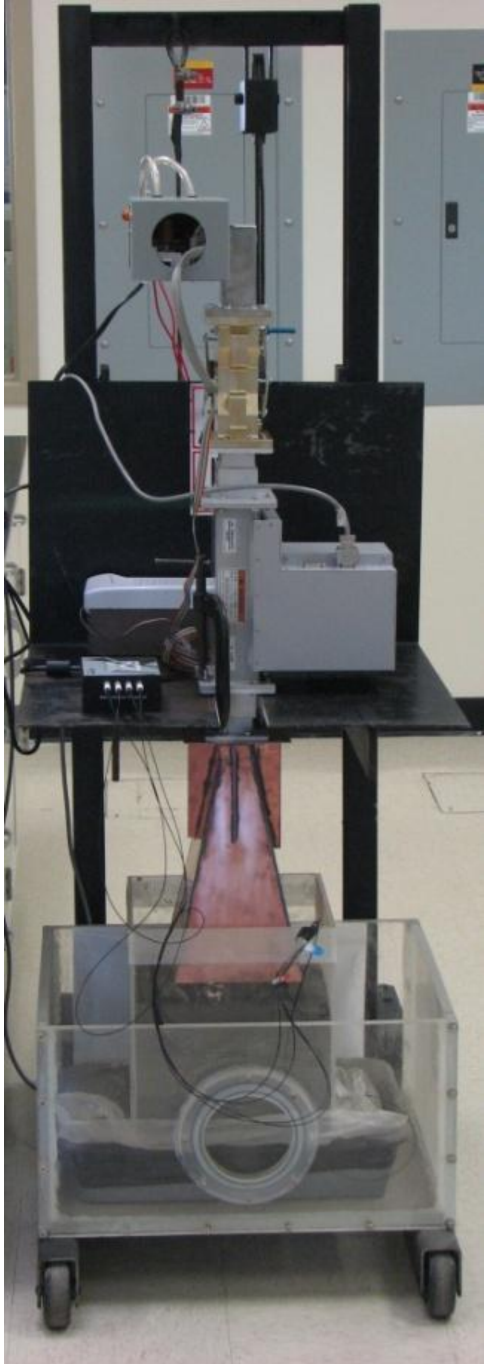
Gained experience with COMSOL Multi-Physics FEA with my International Space Station Experiment "Fluid Merging Viscosity Measurement" to model 2 liquid drop Coalescence.

COMSOL has a Microwave Physics Module, Recognized that it would valuable to use to model microwave heating.

First COMSOL model developed for Calculating microwave absorption at different frequencies.

Illustration shows how penetration is strongly dependent on microwave frequency.

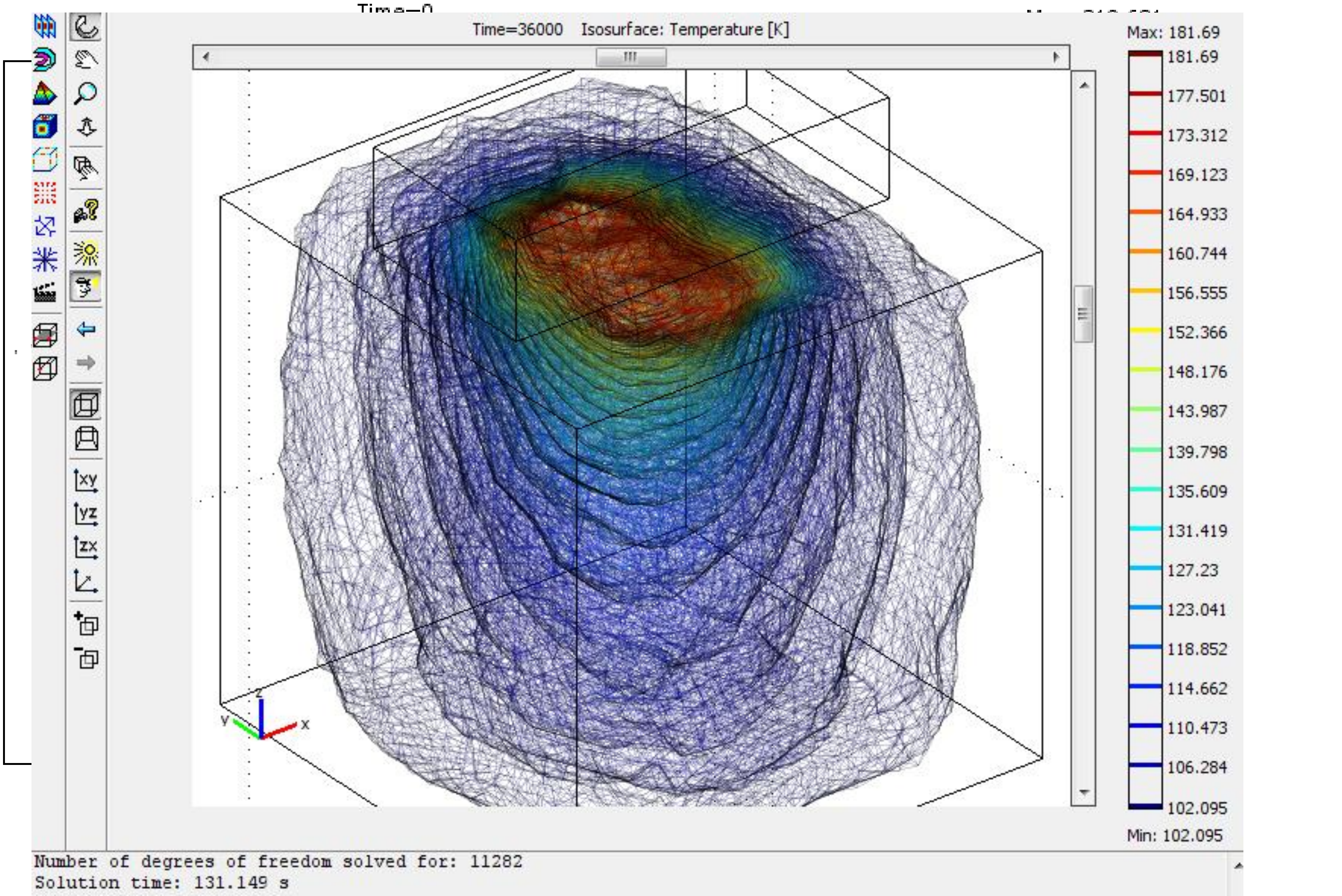




Demonstration Experiments of an Microwave Apparatus on a Rover

- **Magnetron source (2.45 GHz, 1100 W) with isolator, auto-tuner and copper high-gain horn.**
- **Mounting provides mobility over surface and height adjustment of horn.**
- **Temperatures within the bed of simulant (JSC-1A) were made using fiber optic temperature sensor in place during heating.**
- **Beamed microwaves into simulated lunar surface with a homemade high gain horn launcher**
- **Soil heated and absorption according to Beer-Lambert law**
- **This Demonstrated that the microwaves pass into the soil with minimal (1%) back reflection**

Microwaves coupled with Heat Conduction
Temperature Increases with time
Plotted Isotherms at 10 hours



Application of COMSOL

- Processing parameters and hardware requirements for water extraction with microwaves is a complex multiphysics problem.

- Microwave coupling to materials and heating is dependent on frequency and materials properties.

- Materials properties are a function of frequency and temperature.

- Can calculate microwave penetration and heating, with frequency and temperature dependent lunar soil dielectric properties.

- Possible to model the percolation of water vapor through the soil (porous media) characterized by the Darcy constant.

- Parametric modeling will permit the evaluation of processing parameters most suitable for prototype hardware development, trade studies, and testing.