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Using Microwaves for Extracting Water from the Moon

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Edwin Ethridge, PhD, Principal Investigator
Materials & Processes Laboratory
NASA-MSFC-EM40, Huntsville, AL

William Kaukler, PhD
Department of Chemistry
The University of Alabama in Huntsville

Frank Hepburn
Materials & Processes Laboratory
NASA-MSFC-EM20, Huntsville, AL

Water is one of the Most Plentiful Compounds in the Universe

- Earth’s water came from comets early in its history.
- Mars has vast quantities of water not only at the poles but also at lower latitudes (>55^0).
- Significant quantities of water are present on several moons of Jupiter (Europa, Ganymede, and Callisto), Saturn (Enceladus), and Neptune (Titon).

Chronology of “Water on the Moon”

1959, prior to Apollo, scientists **speculated** that there should be some residual **water on the moon from cometary impacts**.

Apollo found “**no water”**.

1994, the SDI-NASA **Clementine spacecraft** mapped the surface. **Microwave radio signals from** South pole **shadowed craters were consistent with the presence of water.**

1998 – Prospector - Neutron Spectrometer – high H concentrations at poles

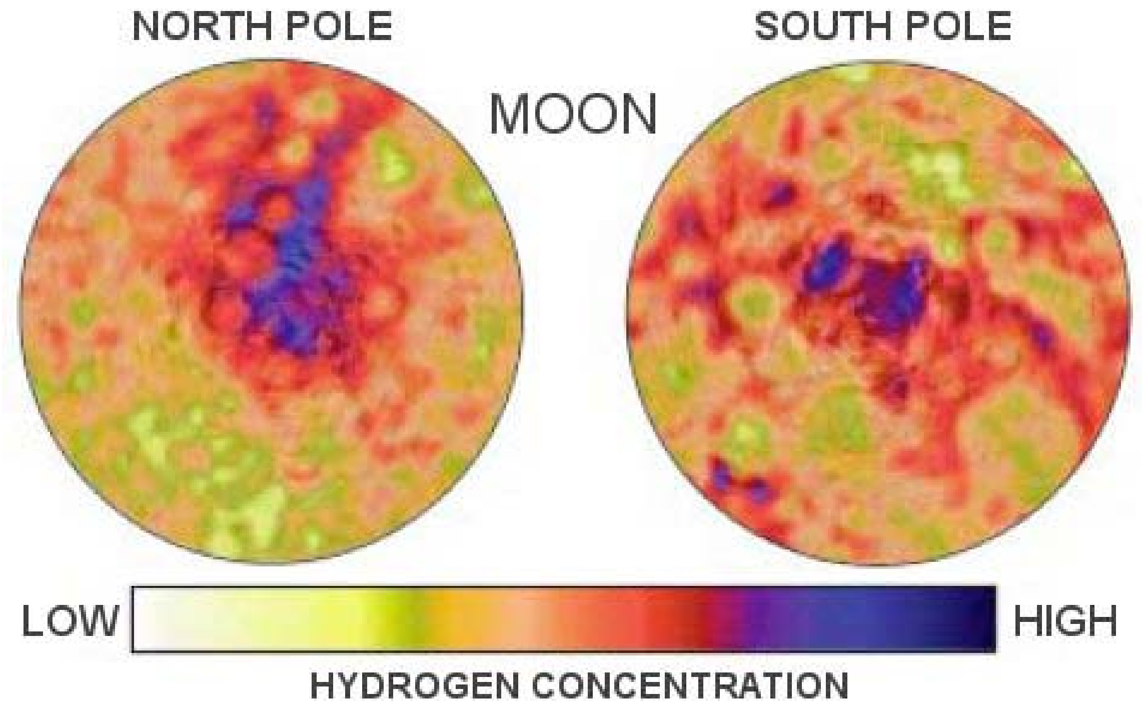
September 2009 – water observed at diverse locations of moon

- **Chandrayaan-1 -** Moon Mineralogy Mapper (M3)
- **Cassini -** Visual and Infrared Mapping Spectrometer (VIMS)
- **EPOXI** spacecraft - High-Resolution Infrared Imaging Spectrometer

October 9, 2009 - Lunar CRater Observation and Sensing Satellite - LCROSS

1998- Lunar Prospector

Hydrogen Maps of the Lunar Poles



1998 Lunar Prospector - Neutron Spectrometer scanned for hydrogen-rich minerals. **Polar craters** yielded **neutron ratios which indicated hydrogen => H_2O**

Average H_2O concentration ~2% → Theoretically approaching Billions of tons

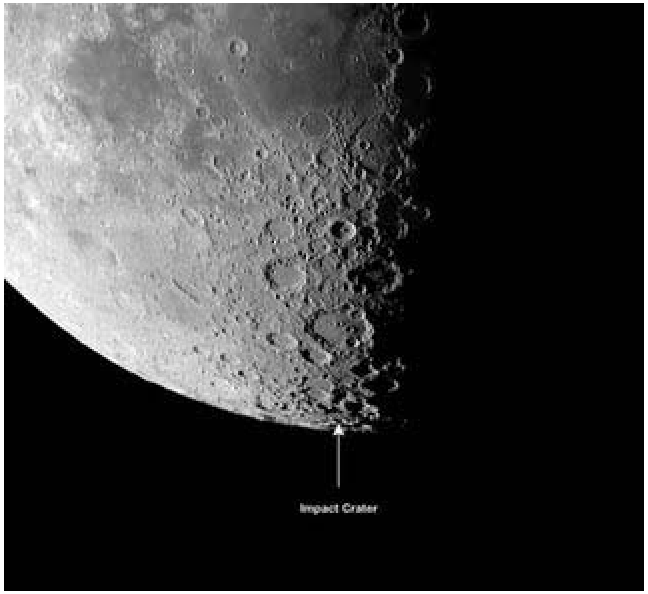
http://www.thespacereview.com/article/740/2

Lunar CRater Observation and Sensing Satellite - LCROSS

- **THIS MORNING 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.**

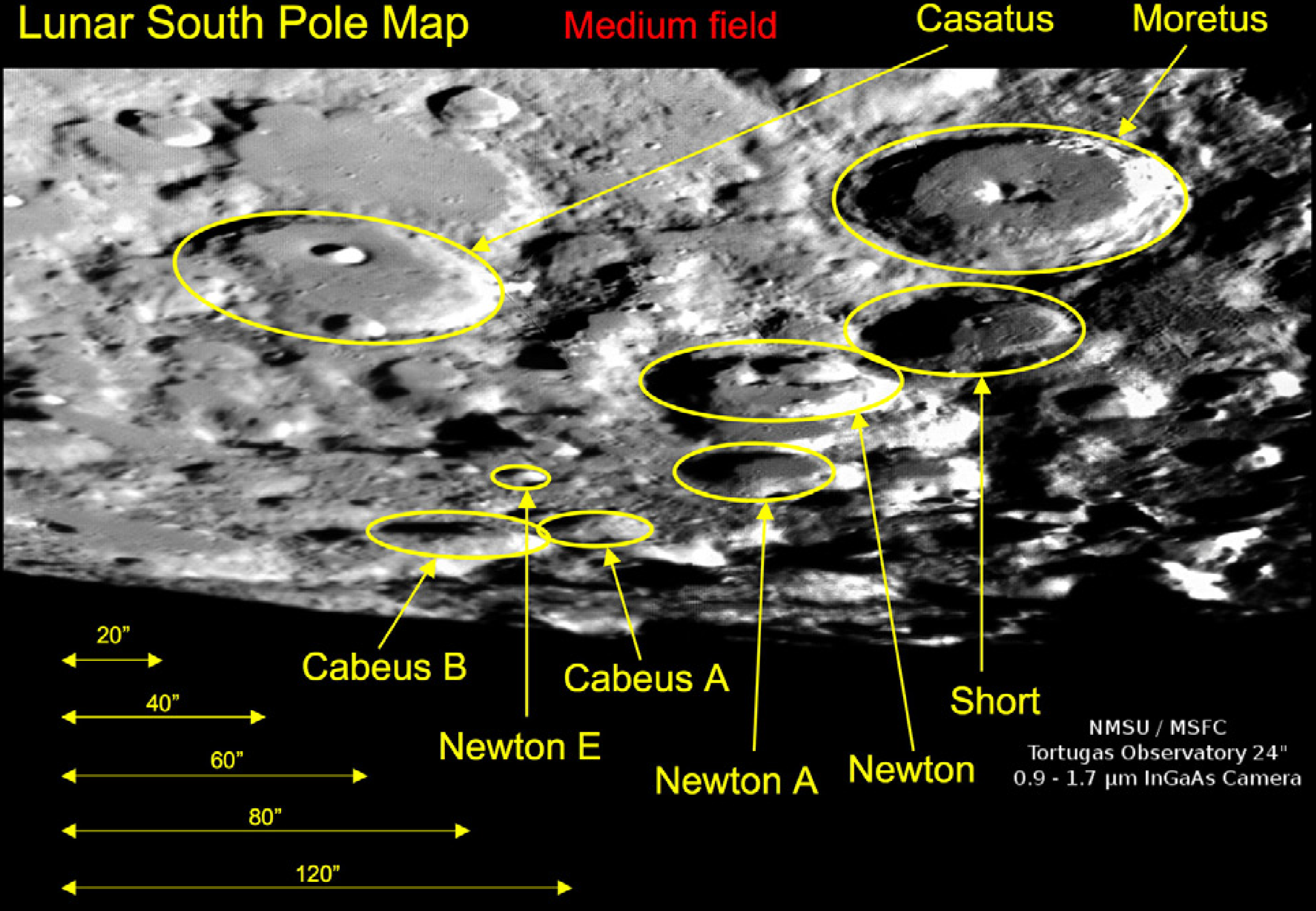
- **Spectral analysis of the resulting impact plume will look for water ice.**



Crater Cabeus A →

Lunar South Pole Map

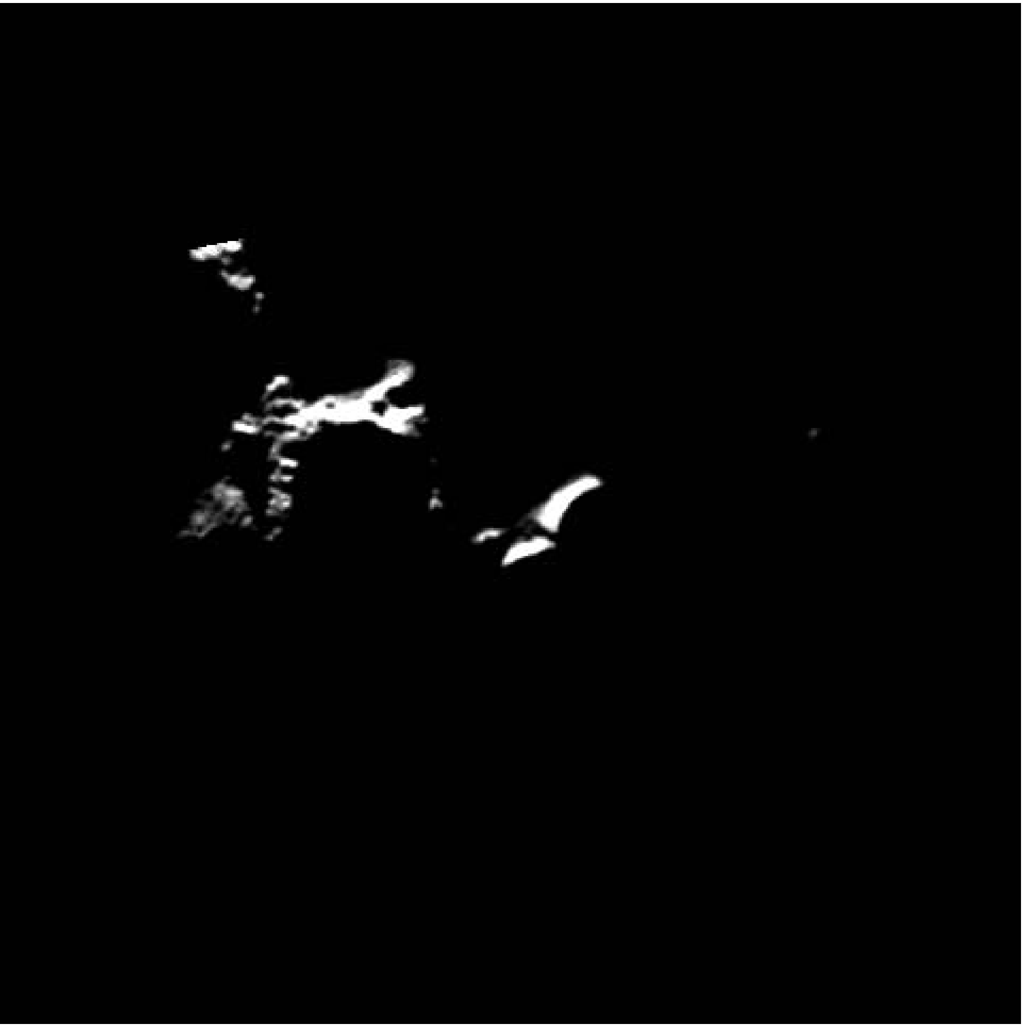
Medium field



NMSU / MSFC
Tortugas Observatory 24"
0.9 - 1.7 µm InGaAs Camera

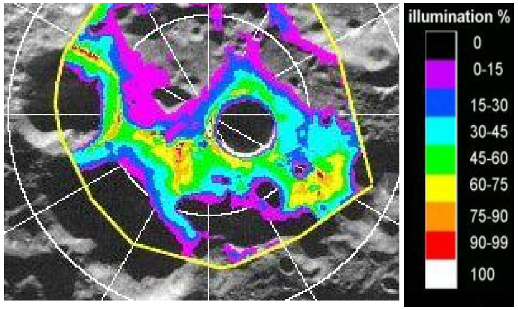
Scale at time of LCROSS impact (1.78 km/arcsec)

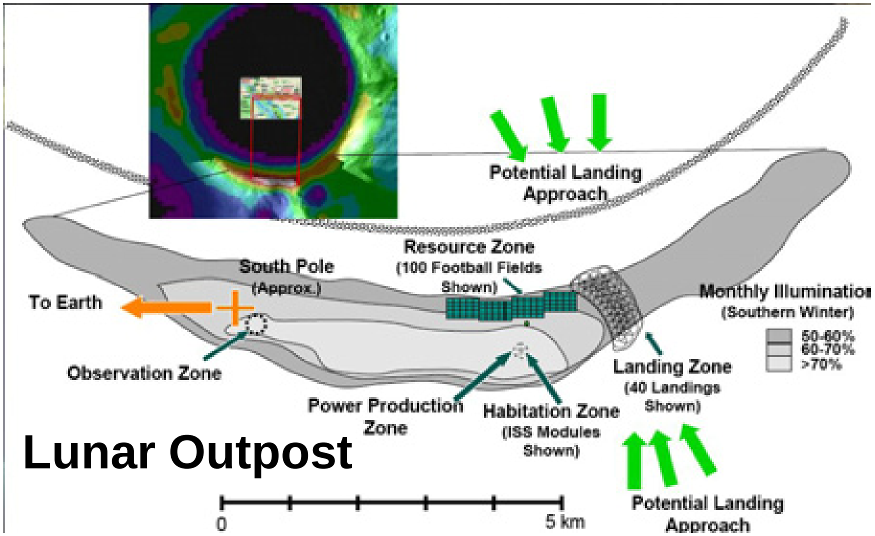
Illumination of the South Polar Region of the Moon over one Lunar Day (28 days)



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

Moon Polar light map





Lunar Outpost

Continuous Sunlight, Continuous Contact with Earth, “Moderate” Temperature, and Resources (water ice?)

Importance of Water

- **Water (and oxygen) for the manned lunar outpost.**
  Resupply requirements:
  1 ton water and 1 ton oxygen per year
  ~$10,000 to $100,000/ pound from Earth to moon
  Increasing to 10 tons per year

- **Eventually (perhaps) - rocket propellant for exploration,**
  Electrolyze water into H and O,
  liquify to LOX and LH
  10’s of tons not launched out of Earth’s
  gravitational well.

Water on the Moon

The water on the moon is in a number of different forms.

Chemically Bound water – Hydroxyl groups -OH
- The hydroxyls can be on the surface of the grains of soil.
- They can also be part of the chemical composition of the rock.
- This could include other hydrated chemical species (at the poles).
- Relatively small weight percent measured in Apollo soils.

Molecular water H2O
- Recently measured water vapor near the lunar surface.
- Water molecules lightly bound to Si+ dipoles on the surface of grains of lunar soil.
- Water ice physically condensed at poles. This physically condensed cryogenically trapped water ice is speculated to be present in relatively high concentrations (on the order of 2 weight percent),

This is the water we have proposed to extract with microwaves.

Use of Microwaves for the Extraction of Lunar Water

- **Lunar Soil (in vacuum) is a Super Thermal Insulator**
  Is like an aerogel, very low heat flow.

- **Microwave energy penetrates the soil heating from the inside out. Penetration depth is dependent on Frequency and dielectric properties.**

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

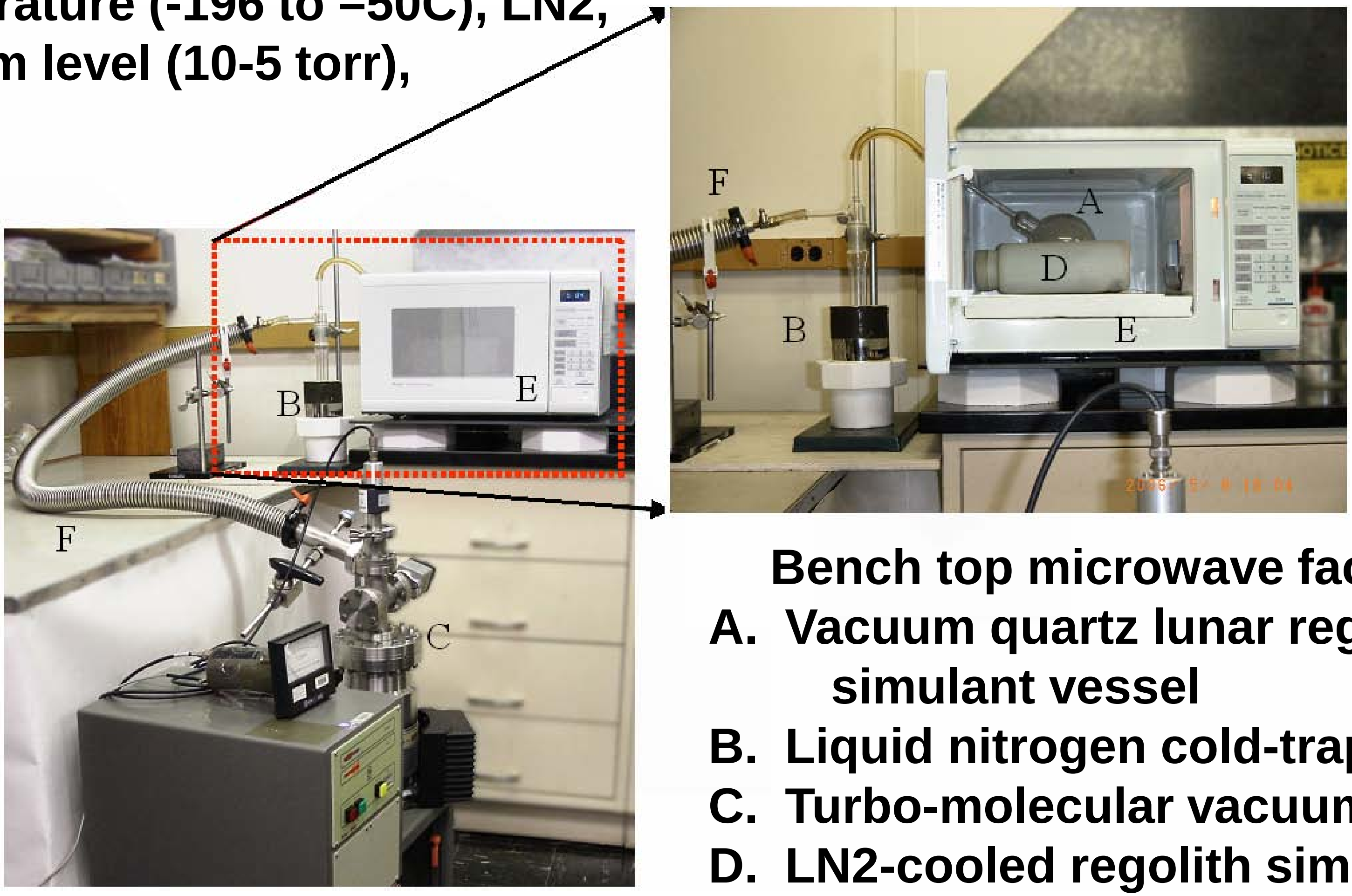
- **Excavation may not be required,**
  - **Cryogenic water ice is as hard as granite**
  - **Saving energy, infrastructure, and equipment**
  - **Little if any disruption of lunar dust (hazard)**

“Moon in a Bottle”
Laboratory Proof of Principle

Fused silica vessel with lunar permafrost simulant.

Experimental Facilities

- Standardized lunar regolith simulant (JSC-1A), particle size distribution and chemistry of (Apollo 14).
- Water ice concentration (2 weight %, 2g)
- Temperature (-196 to –50C), LN2,
- Vacuum level (10-5 torr),



Bench top microwave facility

A. Vacuum quartz lunar regolith simulant vessel
B. Liquid nitrogen cold-trap
C. Turbo-molecular vacuum pump
D. LN2-cooled regolith simulant
E. Microwave oven chamber

Extraction Efficiency

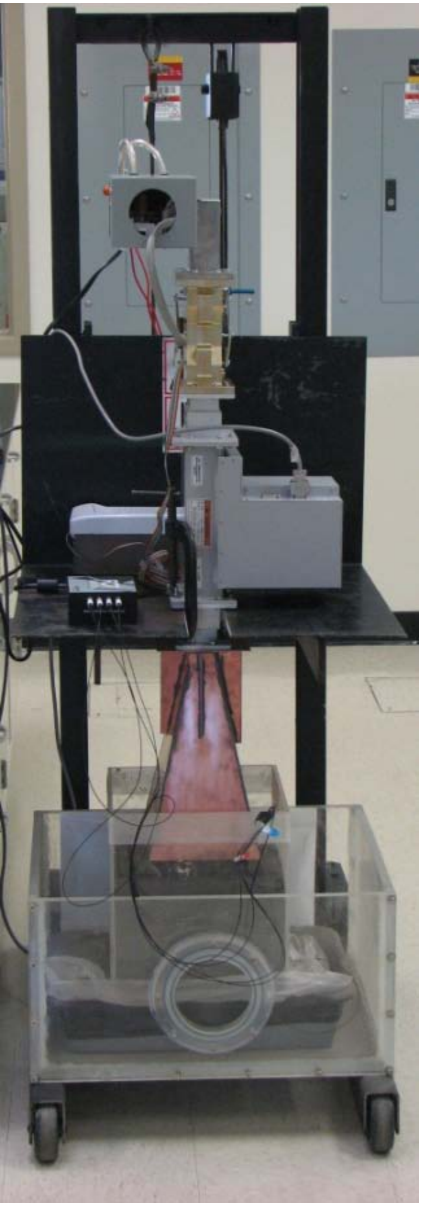
- Microwaves coupled well to soil simulant at LN2 temperature.

- The regolith and the cold trap were weighed before and after the experiment.

- At least 95% of the water added to the regolith simulant was extracted (in 2 minutes) all below 0^{o}C.

- Of the extracted water 99% was captured in the remote cold trap.

Microwave Lunar Water Extraction Prototype



- 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.

- Vacuum chamber evaluation of the microwave penetration and water vapor --> permeability through lunar soil simulant.

Attenuation - Beer-Lambert law

Penetration Depth*

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

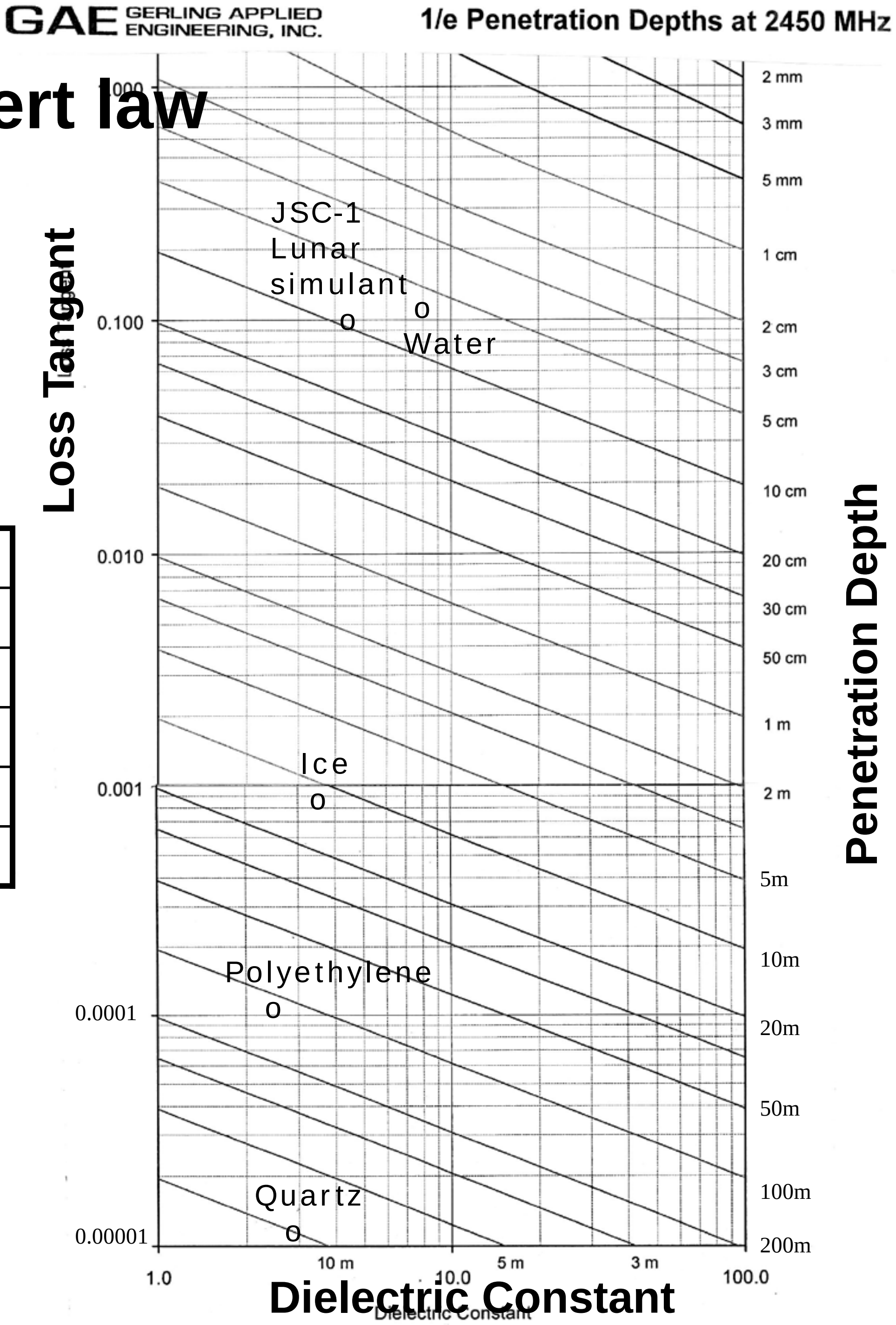
	ε “	ε ‘	Penetration
Water	0.1	8	6cm
Simulant JSC-1	0.1	4	10cm
Ice	0.001	3	1m
Polyethylene	0.0001	2	100m
quartz	0.00001	3	1000m

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

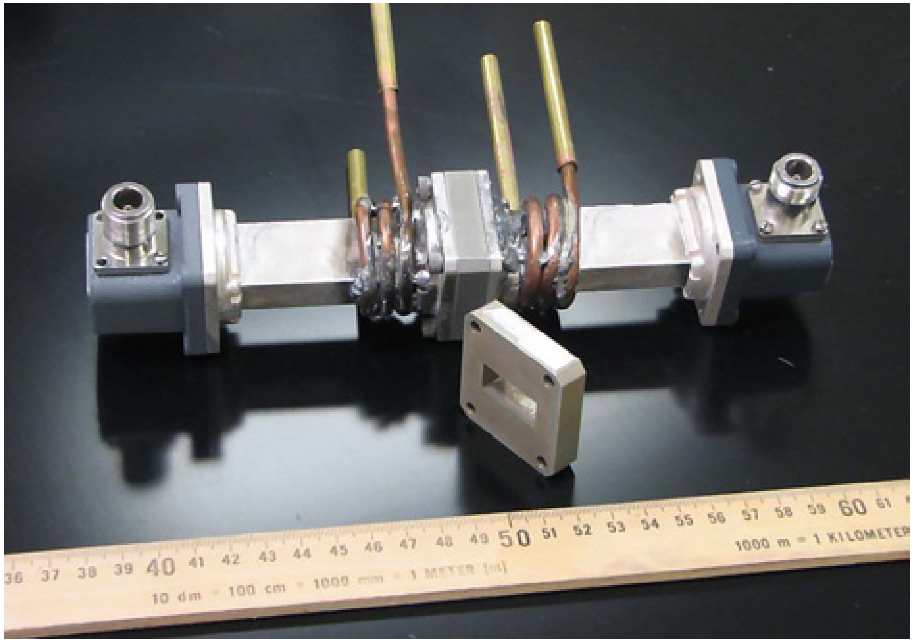
ε' dielectric constant

ε'' loss factor

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



Dielectric Property Measurements
Lunar Soil Simulant – JSC-1A



With Frank Hepburn - EM20

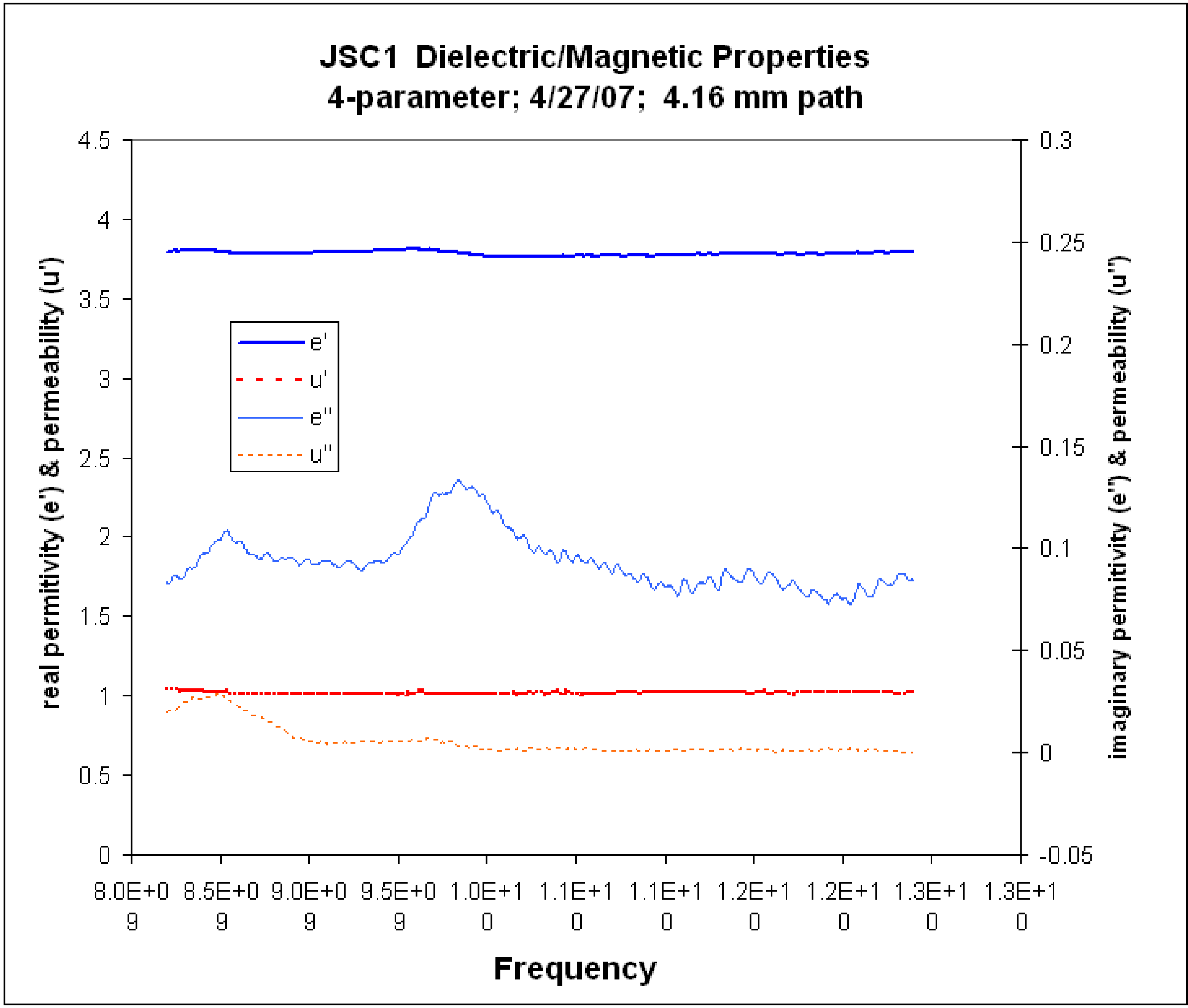
- **Our custom fabricated 10 GHz (range 8 – 12 GHz) X-band waveguide apparatus for dielectric measurements over a range of temperatures, LN_2 to above room temperature.**
- **Heating coils near the coax connectors (not shown) keep the instrument connections at room temperature while the sample residing between the cooling the coil is chilled with free-flowing LN_2.**

Dielectric Properties of JSC-1A Simulant X-band 10 GHz, room temperature

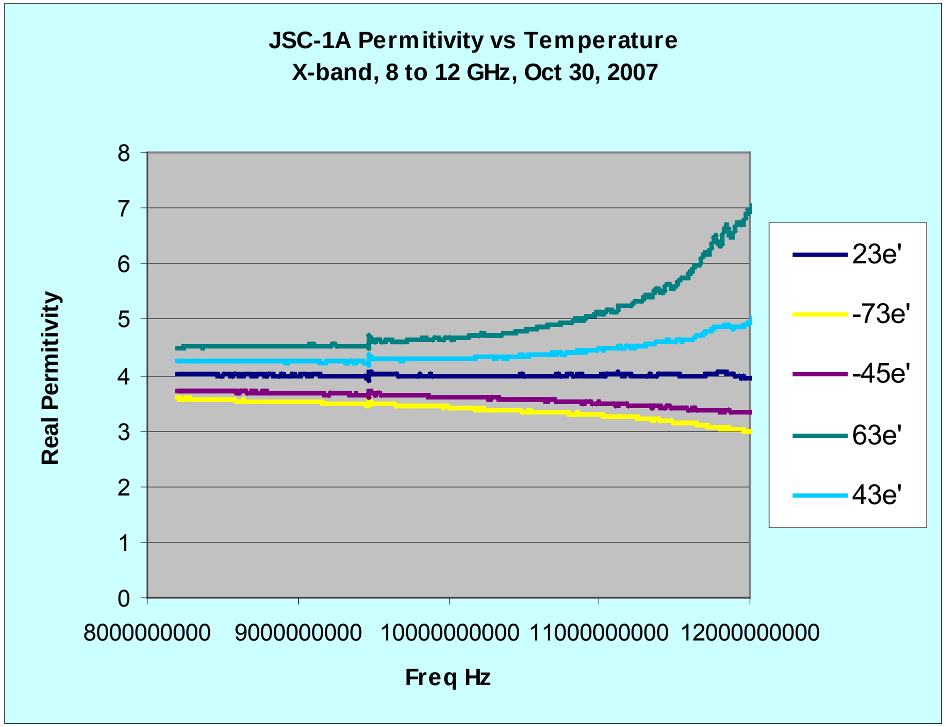
Real and imaginary
1. Electric Permittivity
(dielectric constant & Loss factor) and
2. Magnetic Permeability

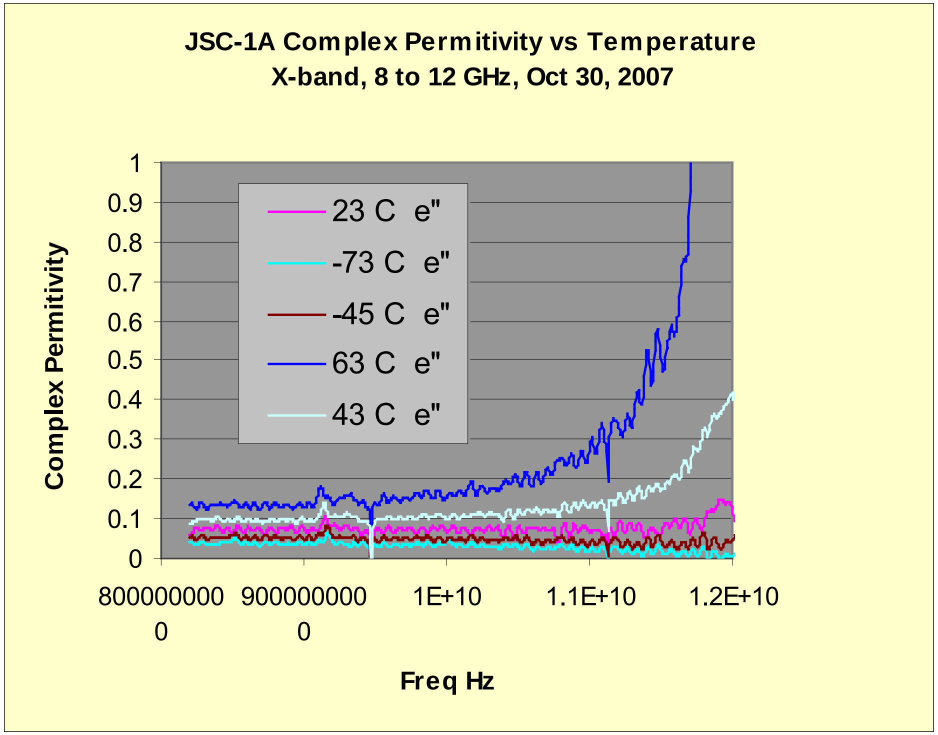
We expect that Nano-phase Fe in lunar soil will significantly affect the permeability.

Proposal pending:
Loan of Apollo Soil sample to measure dielectric properties.



Temperature Dependence (-73C to 63C) of the Dielectric Properties of Lunar Soil Simulant JSC-1A


JSC-1A Permitivity vs Temperature
X-band, 8 to 12 GHz, Oct 30, 2007


JSC-1A Complex Permitivity vs Temperature
X-band, 8 to 12 GHz, Oct 30, 2007

Dielectric constant (real component of permittivity) vs. frequency over the X-band (8 to 12 GHz) for JSC-1A, temperatures

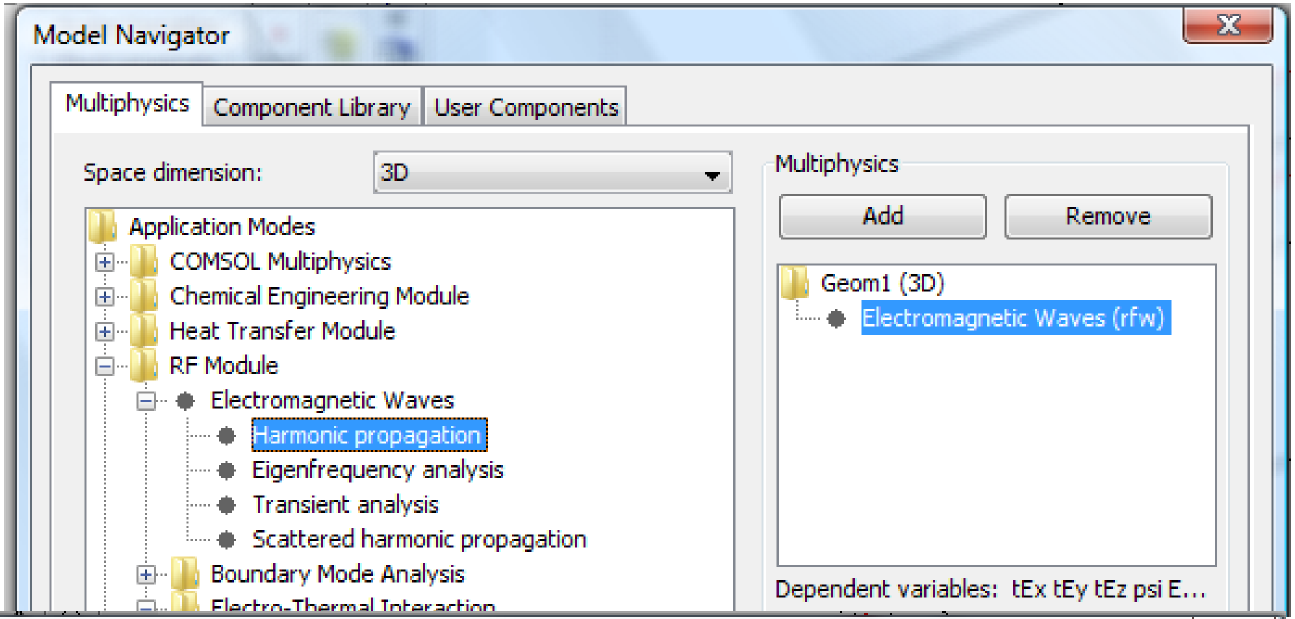
from 63 C to -73 C.

The loss factor (imaginary part of permittivity) vs. frequency 8 to 12 GHz

63 to –73 C.

COMSOL - RF Module – Electromagnetic Waves – Harmonic Propagation

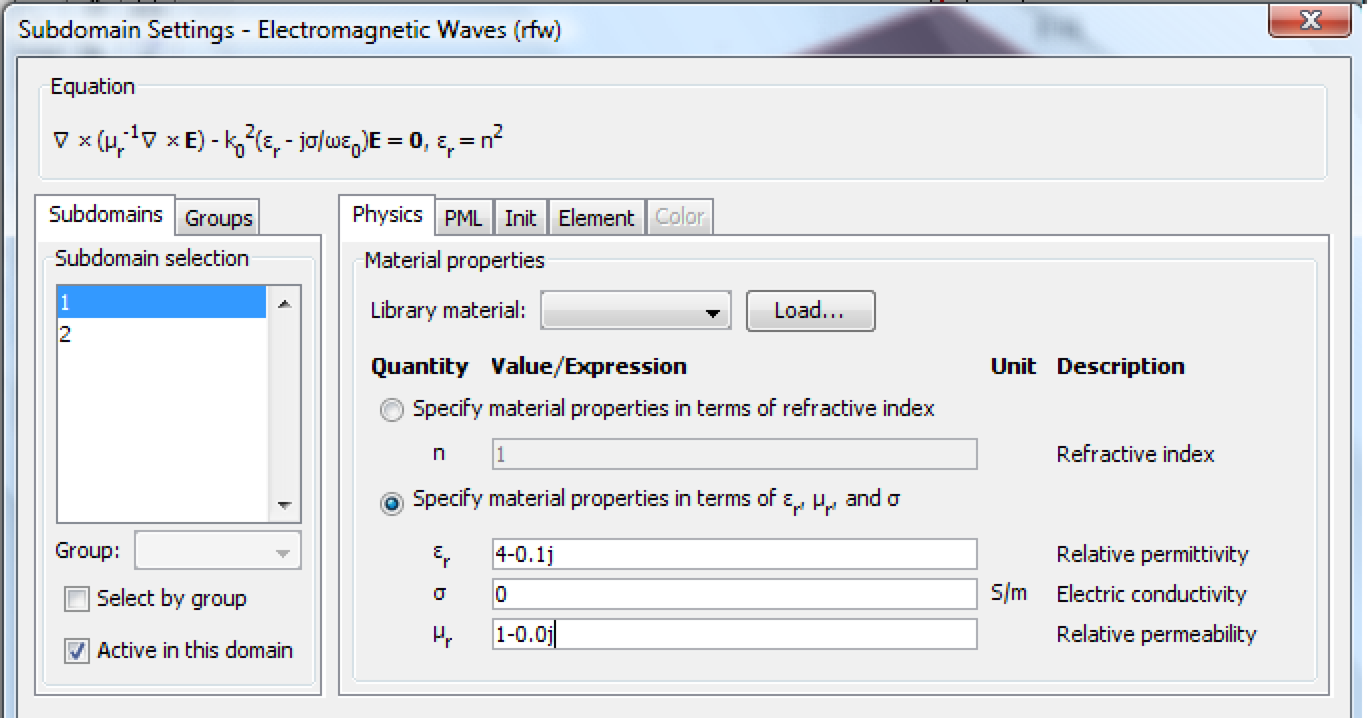
COMSOL 3.5a



Space dimension: 3D

Dependent variables: tEx tEy tEz psi E…

Subdomain Settings



Equation

$\nabla \times (\mu_r^{-1} \nabla \times \mathbf{E}) - k_0^2(\varepsilon_r - j\sigma/\omega\varepsilon_0)\mathbf{E} = \mathbf{0}$, $\varepsilon_r = n^2$

Subdomain selection

1

2

Group:

☐ Select by group

☑ Active in this domain

Material properties

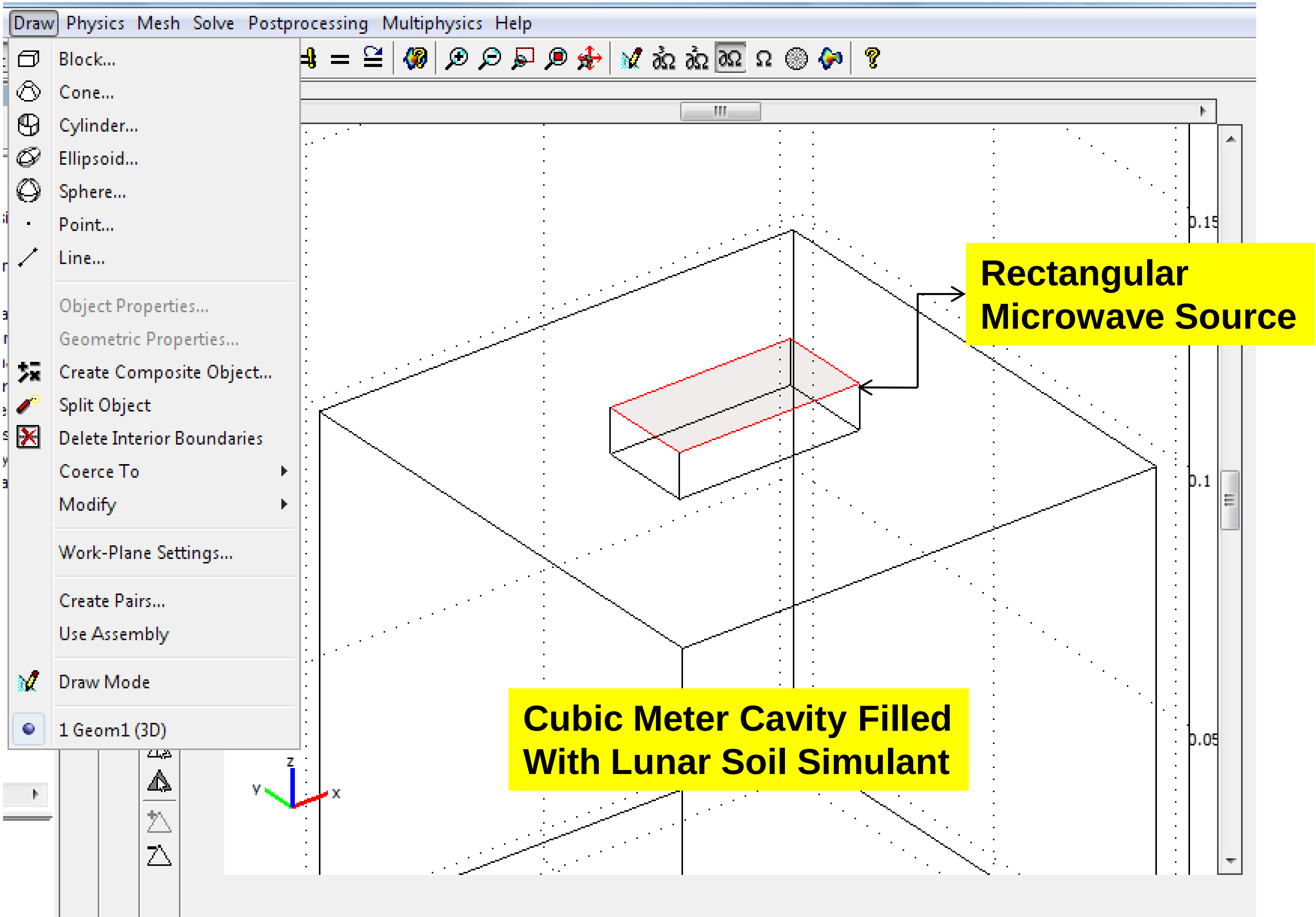
Library material:

Quantity	Value/Expression	Unit	Description
○ Specify material properties in terms of refractive index			
n	1		Refractive index
● Specify material properties in terms of ε_r, μ_r, and σ			
ε_r	4-0.1j		Relative permittivity
σ	0	S/m	Electric conductivity
μ_r	1-0.0j		Relative permeability

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

Lunar Soil Simulant Dielectric Properties

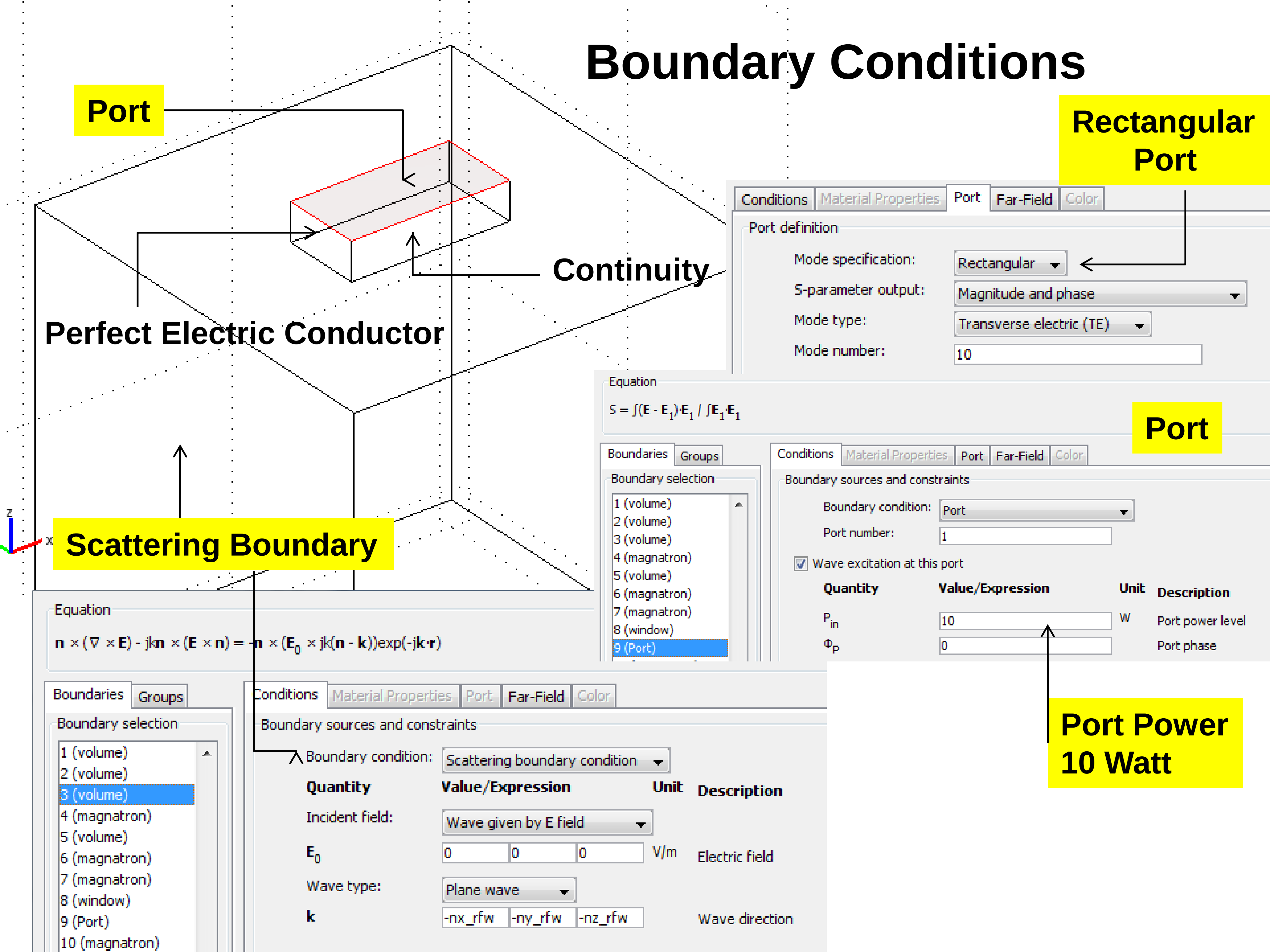
Geometry - Draw



Rectangular Microwave Source

Cubic Meter Cavity Filled With Lunar Soil Simulant

Boundary Conditions



Port

Continuity

Perfect Electric Conductor

Scattering Boundary

Rectangular Port

Port definition

Mode specification: Rectangular

S-parameter output: Magnitude and phase

Mode type: Transverse electric (TE)

Mode number: 10

Equation

$S = \int(\mathbf{E}-\mathbf{E}_1)\cdot\mathbf{E}_1 \,/\, \int\mathbf{E}_1\cdot\mathbf{E}_1$

Port

Boundary selection

1 (volume)
2 (volume)
3 (volume)
4 (magnatron)
5 (volume)
6 (magnatron)
7 (magnatron)
8 (window)
9 (Port)

Boundary sources and constraints

Boundary condition: Port

Port number: 1

☑ Wave excitation at this port

Quantity	Value/Expression	Unit	Description
P_{in}	10	W	Port power level
Φ_p	0		Port phase

Port Power 10 Watt

Equation

$\mathbf{n}\times(\nabla\times\mathbf{E}) - jk\mathbf{n}\times(\mathbf{E}\times\mathbf{n}) = -\mathbf{n}\times(\mathbf{E}_0\times jk(\mathbf{n}-\mathbf{k}))\exp(-j\mathbf{k}\cdot\mathbf{r})$

Boundary selection

1 (volume)
2 (volume)
3 (volume)
4 (magnatron)
5 (volume)
6 (magnatron)
7 (magnatron)
8 (window)
9 (Port)
10 (magnatron)

Boundary sources and constraints

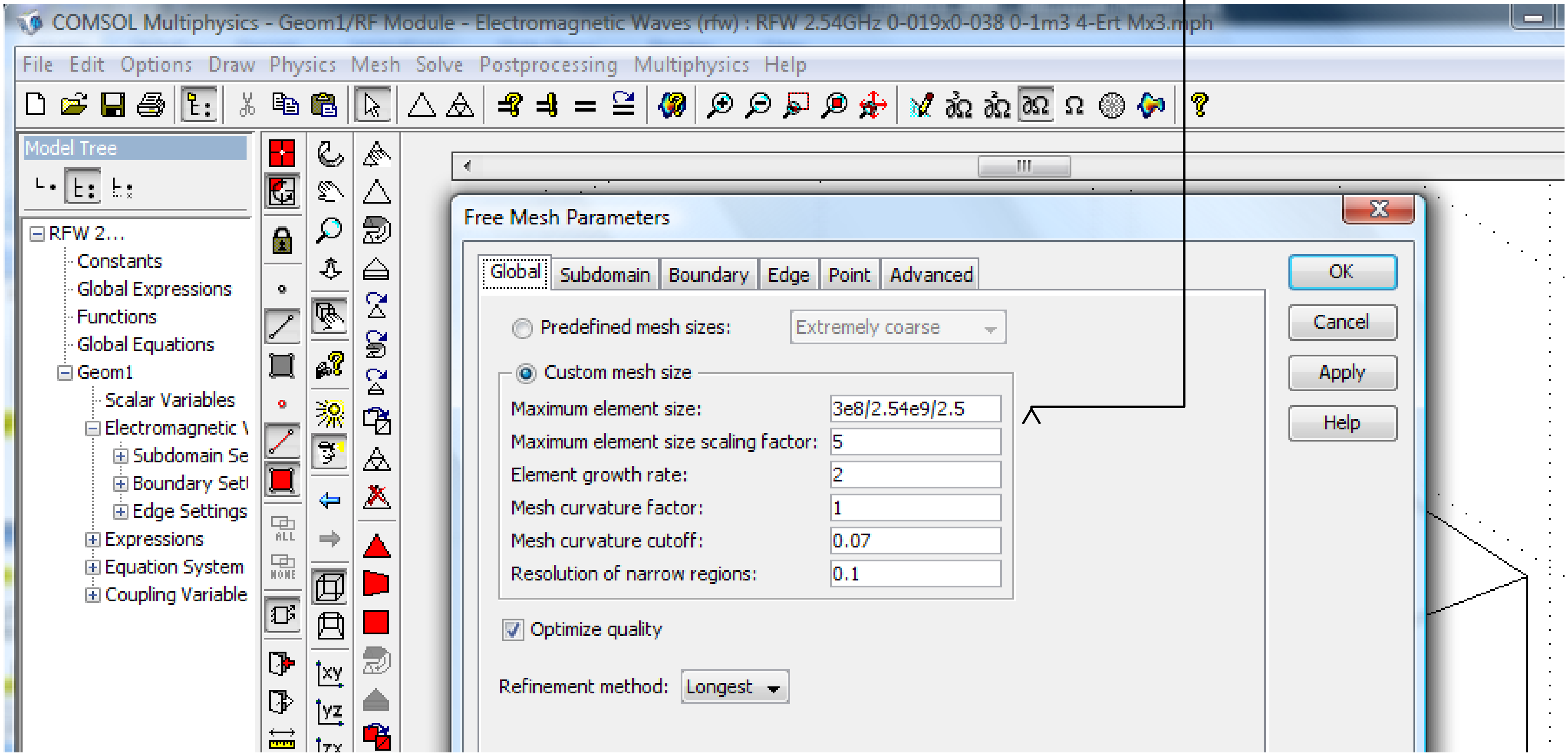
Boundary condition: Scattering boundary condition

Quantity	Value/Expression	Unit	Description
Incident field:	Wave given by E field		
E_0	0 0 0	V/m	Electric field
Wave type:	Plane wave		
k	-nx_rfw -ny_rfw -nz_rfw		Wave direction

Meshing must satisfy the Nyquist criteria

$$\text{Maximum element size} = c \;/\; \lambda \;/\; 2.5$$
$$= 3e8 \;/\; 2.45e9 \;/\; 2.5$$

Free Mesh Parameters



Free Mesh Parameters

Global | Subdomain | Boundary | Edge | Point | Advanced

○ Predefined mesh sizes: Extremely coarse

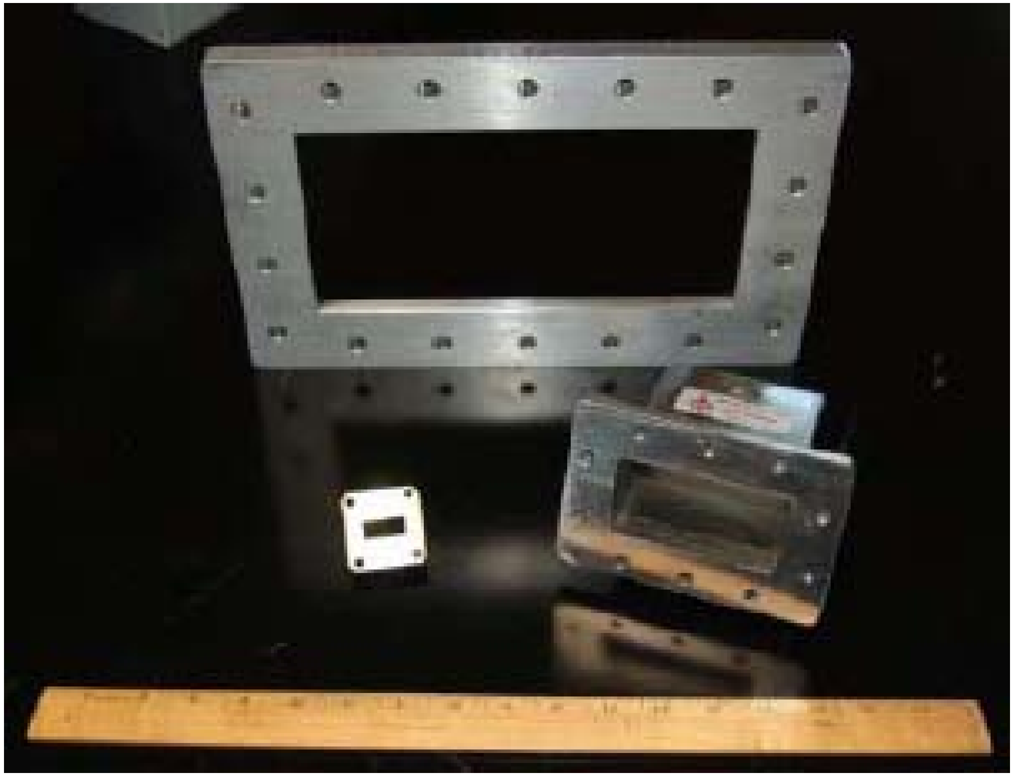
● Custom mesh size

Maximum element size: 3e8/2.54e9/2.5
Maximum element size scaling factor: 5
Element growth rate: 2
Mesh curvature factor: 1
Mesh curvature cutoff: 0.07
Resolution of narrow regions: 0.1

☑ Optimize quality

Refinement method: Longest

Three Microwave Frequencies



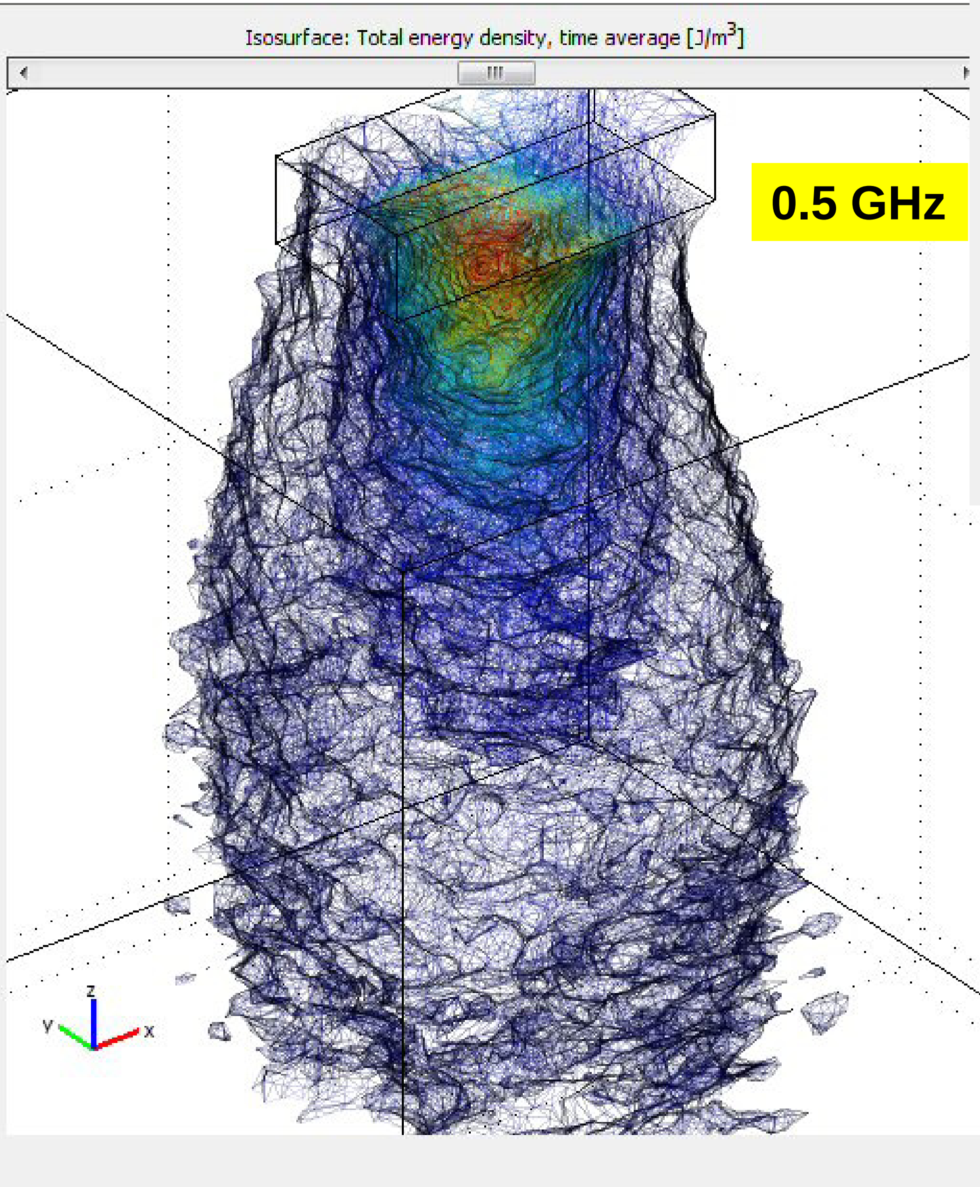
<- 0.9 GHz

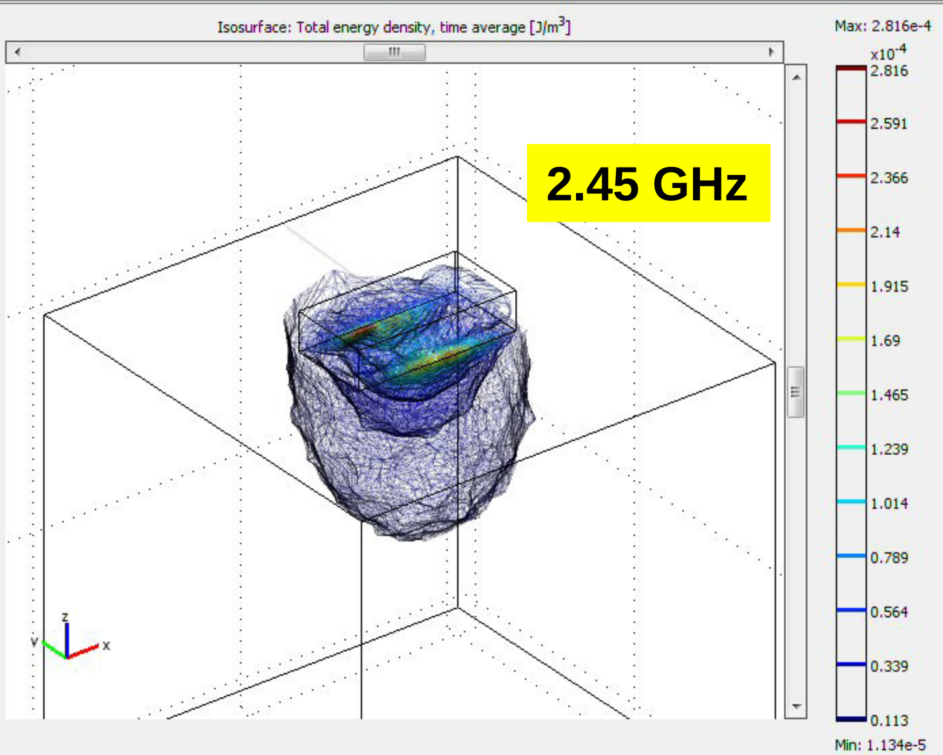
10 GHz ->

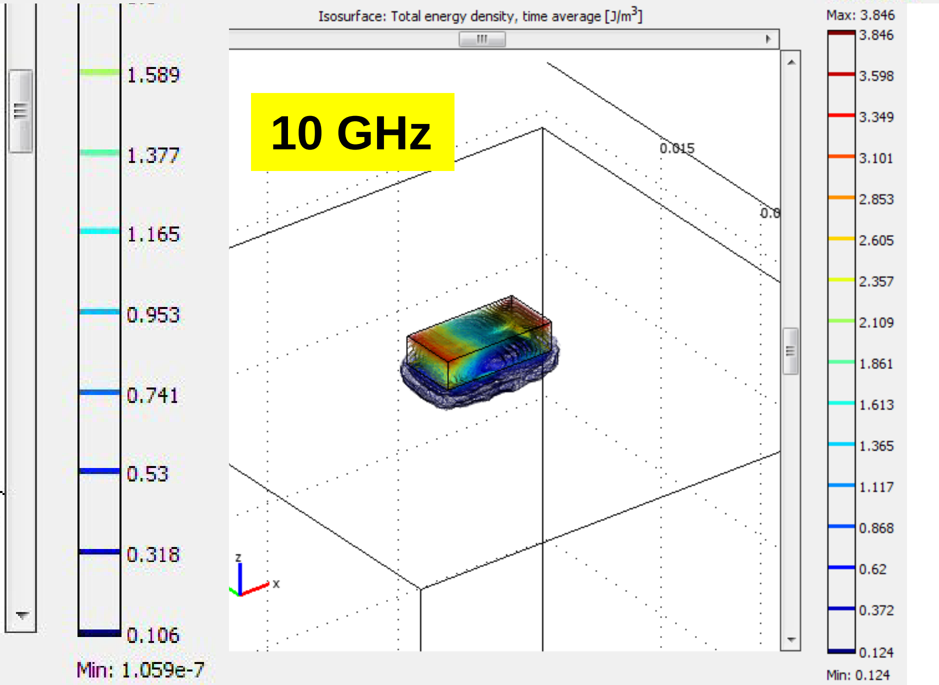
<- 2.45 GHz

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. Each microwave frequency requires different geometry for COMSOL.

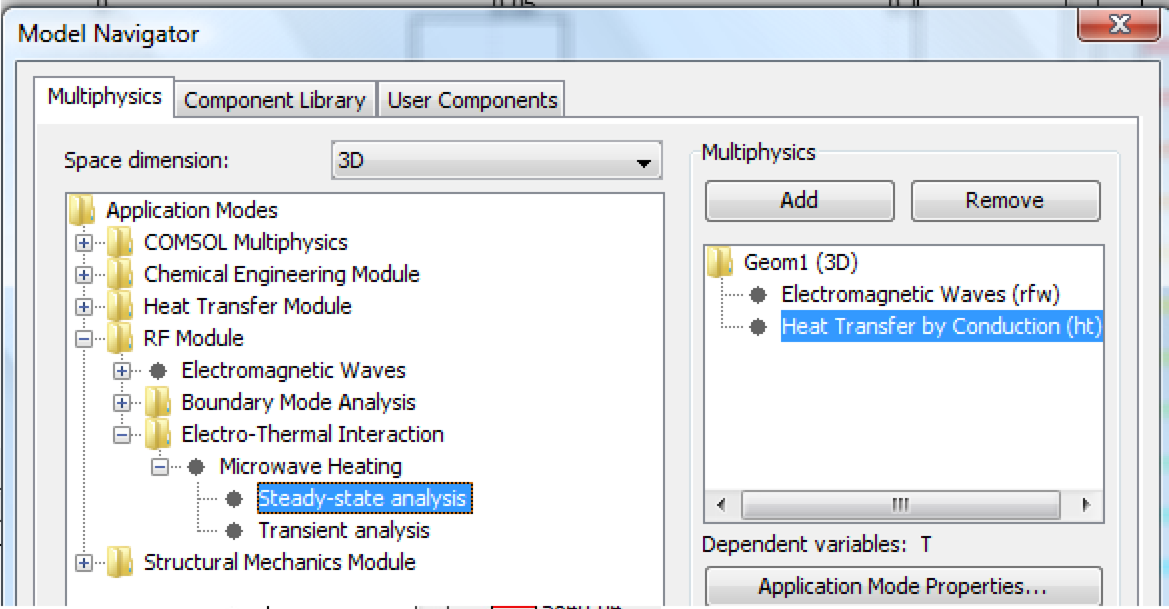
RFW -Total Energy Density
Iso-Surface
Penetration into Simulant







Steady-State Electromagnetism Coupled with Heat Transfer by Conduction


Model Navigator

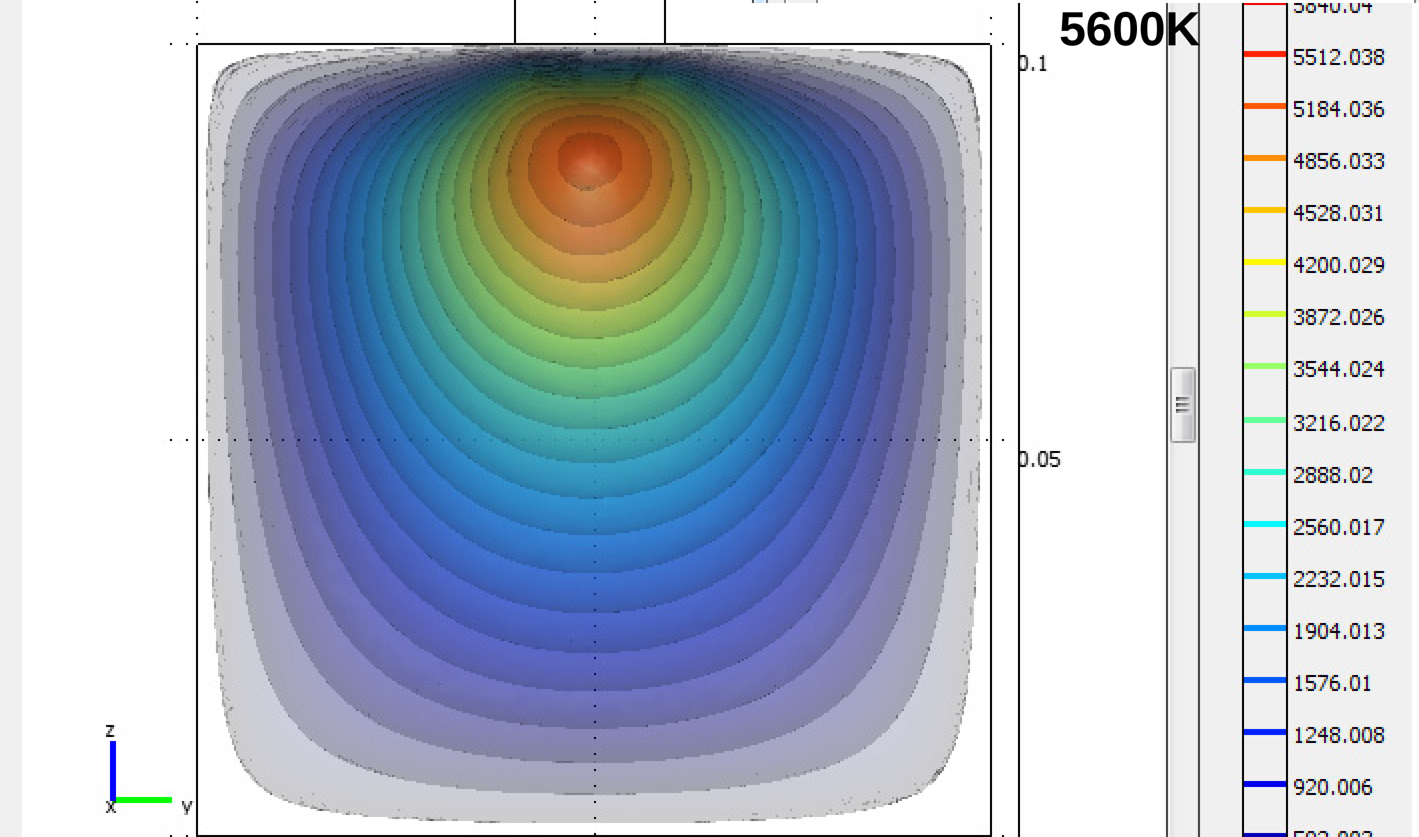
Space dimension: 3D

- Application Modes
  - COMSOL Multiphysics
  - Chemical Engineering Module
  - Heat Transfer Module
  - RF Module
    - Electromagnetic Waves
    - Boundary Mode Analysis
    - Electro-Thermal Interaction
      - Microwave Heating
        - Steady-state analysis
        - Transient analysis
  - Structural Mechanics Module

Multiphysics

- Geom1 (3D)
  - Electromagnetic Waves (rfw)
  - Heat Transfer by Conduction (ht)

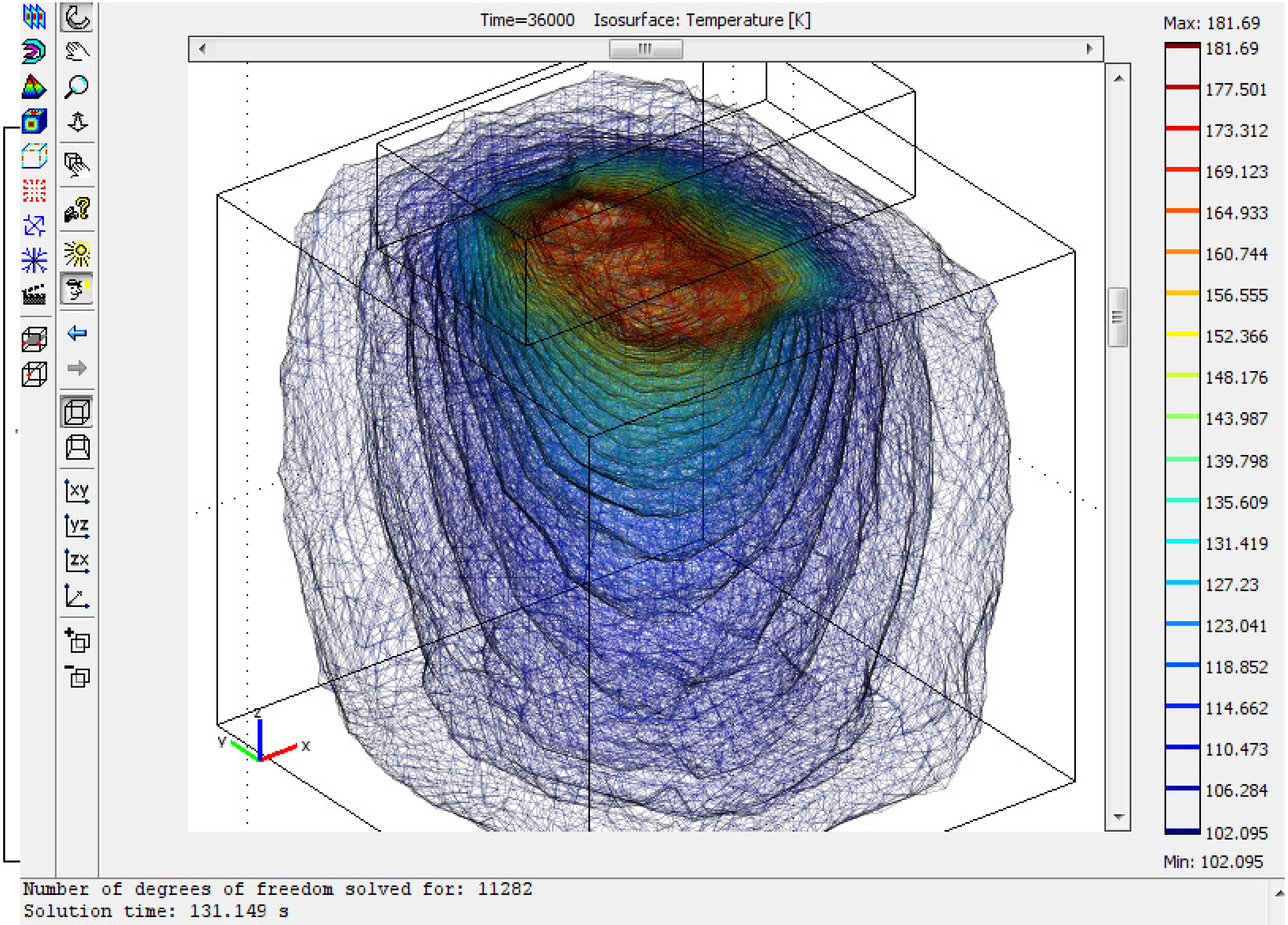
Dependent variables: T



5600K

2.45 GHz
1 KW power
Temperatures to 5000K

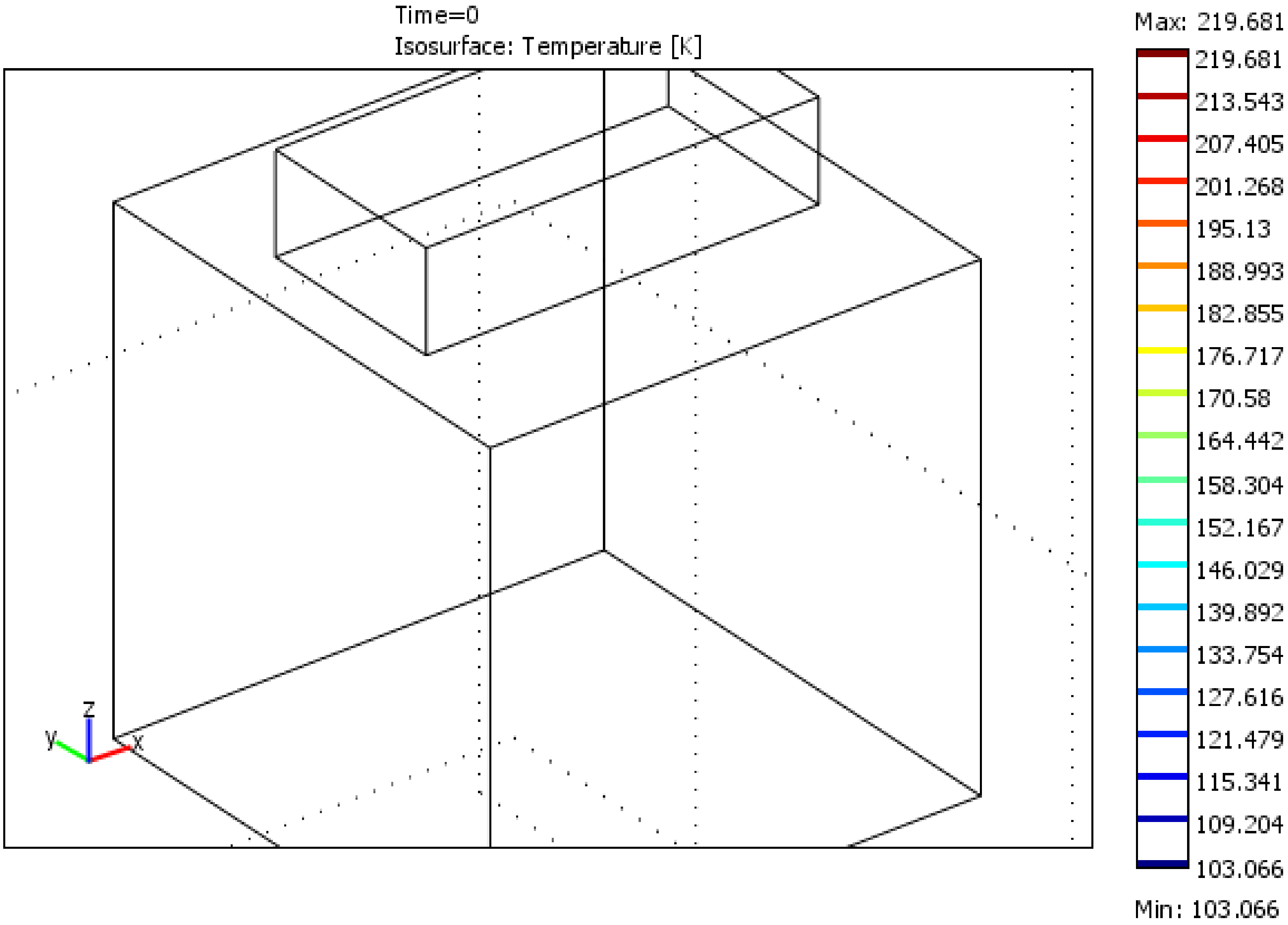
RFW coupled with Heat Conduction - Transient
Temperature Isotherms, 10 hours
Click to start animation



Time=36000 Isosurface: Temperature [K]

```
Number of degrees of freedom solved for: 11282
Solution time: 131.149 s
```

RFW coupled with Heat Conduction - Transient Temperature Isotherms, 10 hours



Application of COMSOL

- Processing parameters and hardware requirements for water extraction is a complex multi-physics 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.

- To Do – Model the Percolation of water vapor through the soil (porous media) characterized by the Darcy constant (currently being measured by Southern Research Institute).

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

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- **Dr. William Kaukler –** University of Alabama-Huntsville
    - Hardware Instrumentation
    - Dielectric Property Test Configurations
- **Frank Hepburn –** Materials & Processes, MSFC-NASA
    - Dielectric Property Measurements - Network Analyzer

COMSOL – Walter Frei -Technical assistance with the models

Contacts:

MSFC Public Affairs – Steve.Roy@msfc.nasa.gov
MSFC Technology Licensing – 256-544-5353
ed.ethridge@nasa.gov

END