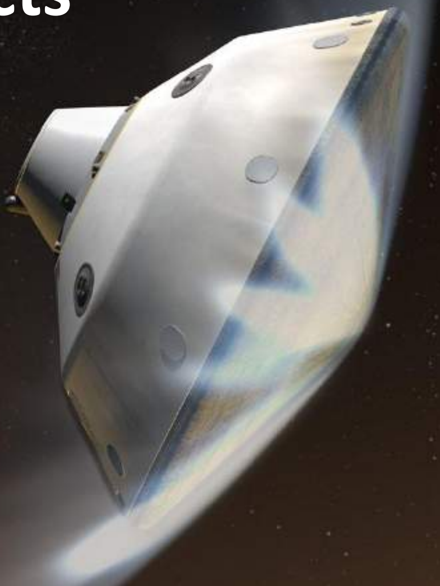
X-ray microtomography applied to NASA missions and projects



Joseph C. Ferguson
STC at NASA Ames Research Center

May 24th, 2018
Mountain View, CA

Ablative Thermal Protection Systems

Carbon preform

+

Resin

=

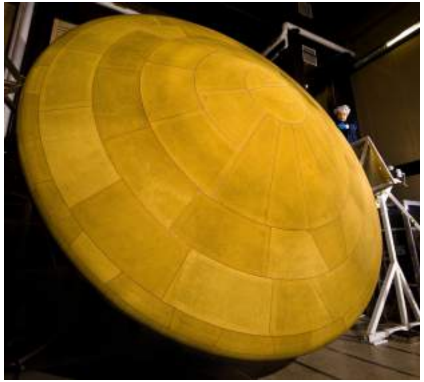
PICA

Stackpoole et al., *AIAA 2008-1202*

Stardust Capsule

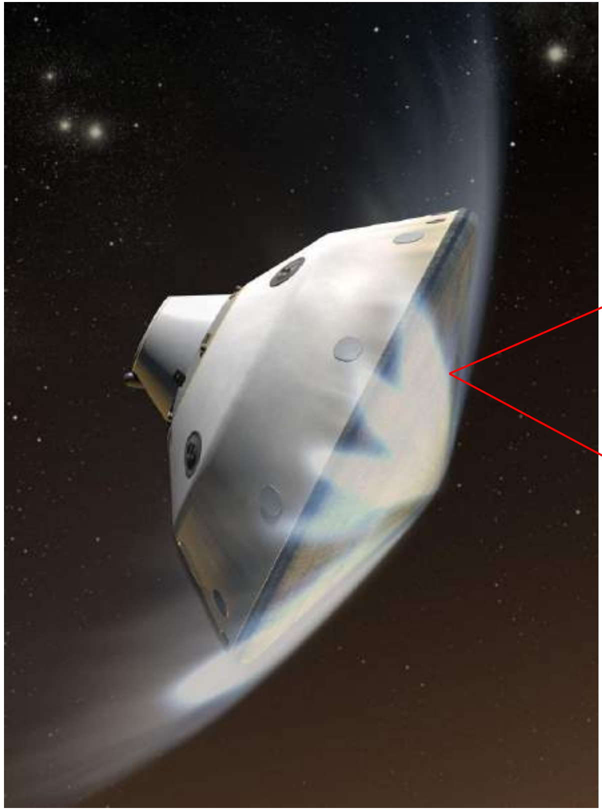
www.spacex.com

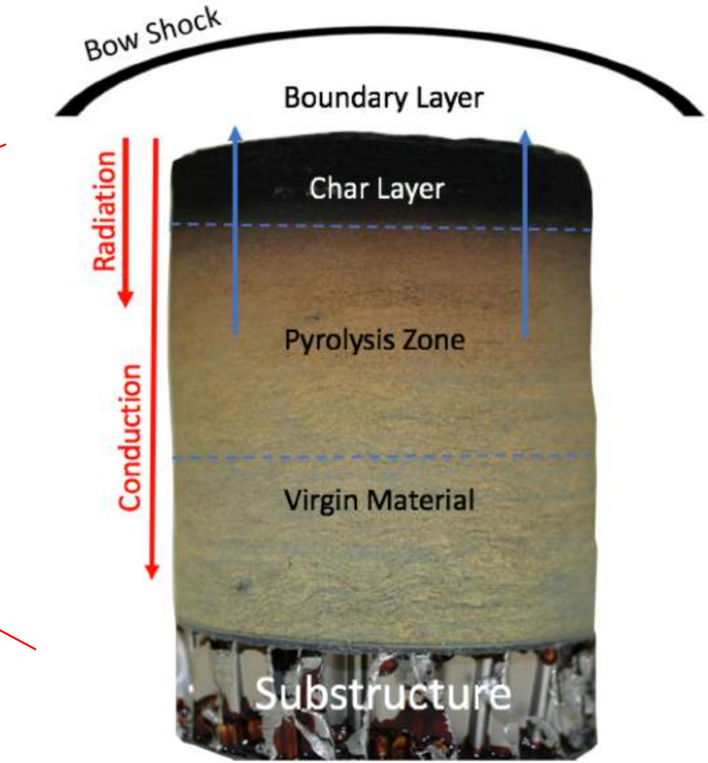
Dragon V1 & V2



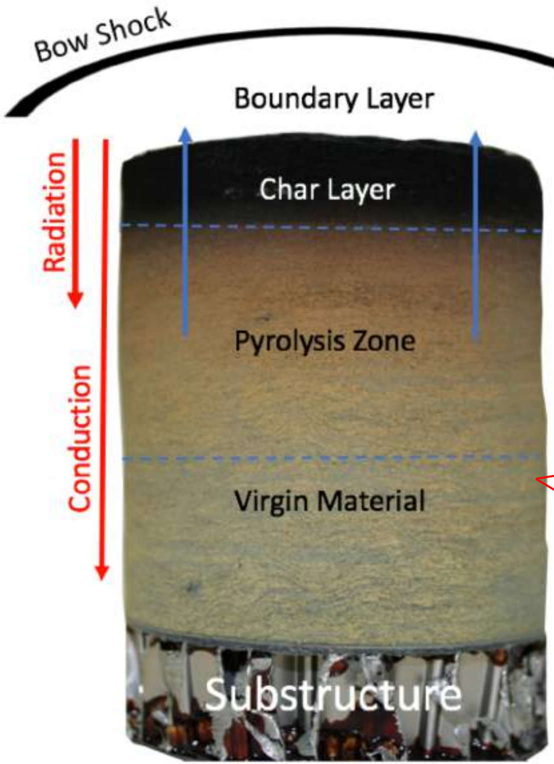
Mars Science Laboratory

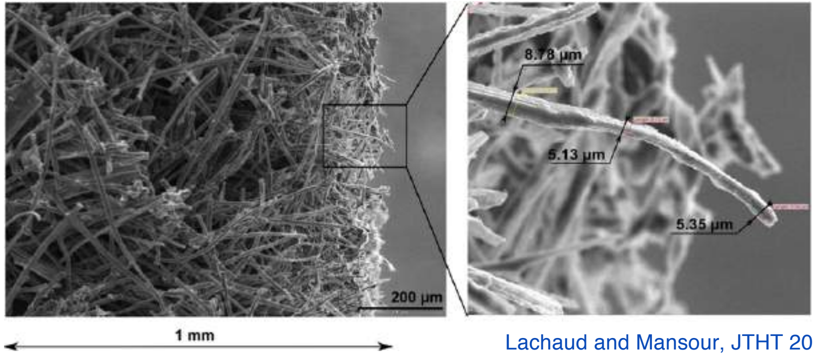
Material Design and Modeling



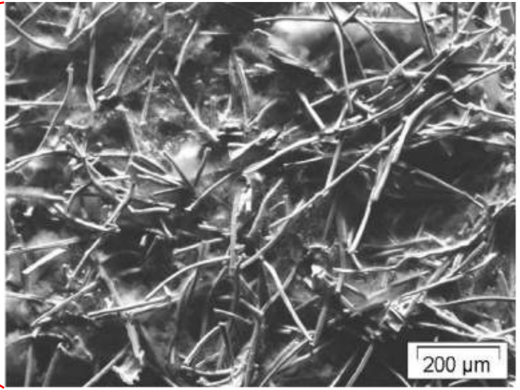


Material Design and Modeling





Lachaud and Mansour, JTHT 2013

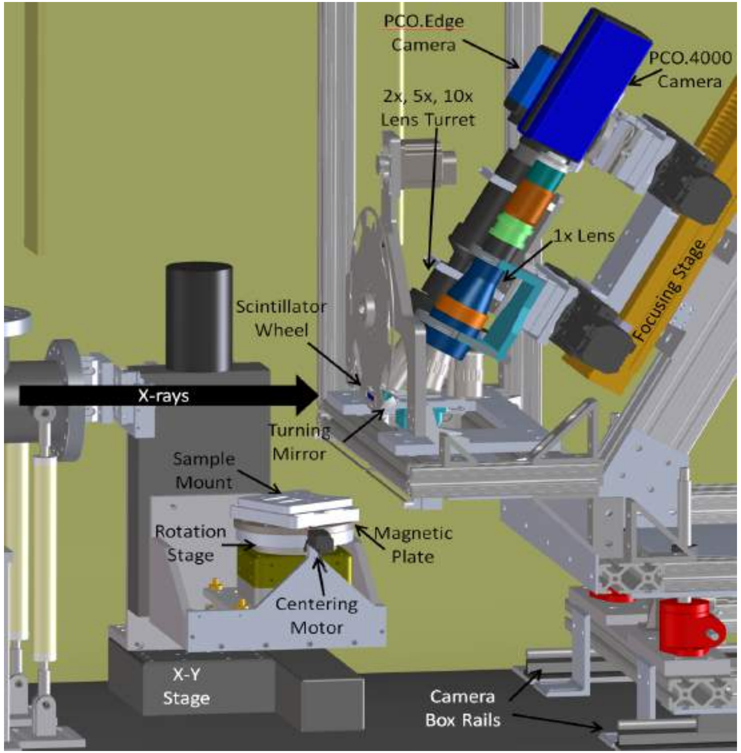


Lawson et. al. 2010

X-ray micro-tomography


Berkeley Labs, Flickr

- Advanced Light Source (ALS) at the Lawrence Berkeley Natl. Laboratory
- Synchrotron electron accelerator used to produce 14Kev X-rays
- Used for many research areas, including optics, chemical reaction dynamics, biological imaging, and **X-ray micro-tomography**.



http://www2.lbl.gov/MicroWorlds/ALSTool

Mansour et. al, A new approach to light-weight ablators analysis: from micro-tomography measurements to statistical analysis and modeling, 44th AIAA Thermophysics. (2013)

X-ray micro-tomography

Collect X-ray images of the sample as you rotate it through 180°

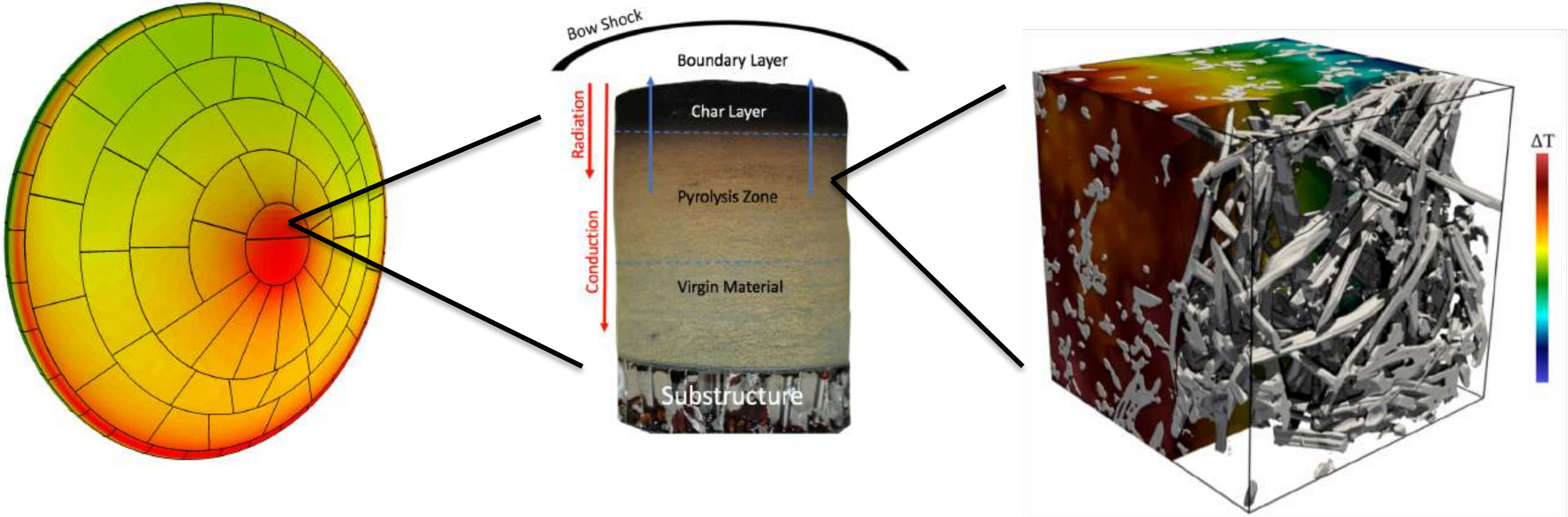
Penetrating power

Multiple angles

Use this series of images to “reconstruct” the 3D object

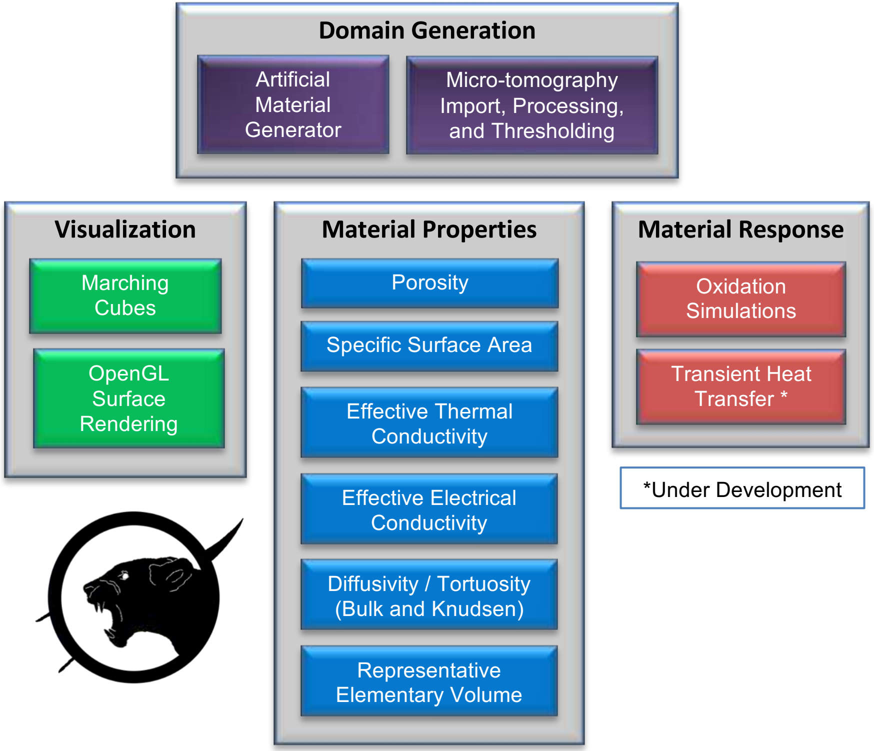
Courtesy of D. Parkinson (ALS)

Micro-scale modeling



1. Material Properties
    1. Phenomenological Properties
    2. Thermal transport
    3. Mass transport
2. Material Decomposition
    1. Oxidation
    2. Sublimation
    3. Spallation

Porous Microstructure Analysis (PuMA)



Domain Generation

Artificial Material Generator

Micro-tomography Import, Processing, and Thresholding

Visualization

Marching Cubes

OpenGL Surface Rendering

Material Properties

Porosity

Specific Surface Area

Effective Thermal Conductivity

Effective Electrical Conductivity

Diffusivity / Tortuosity (Bulk and Knudsen)

Representative Elementary Volume

Material Response

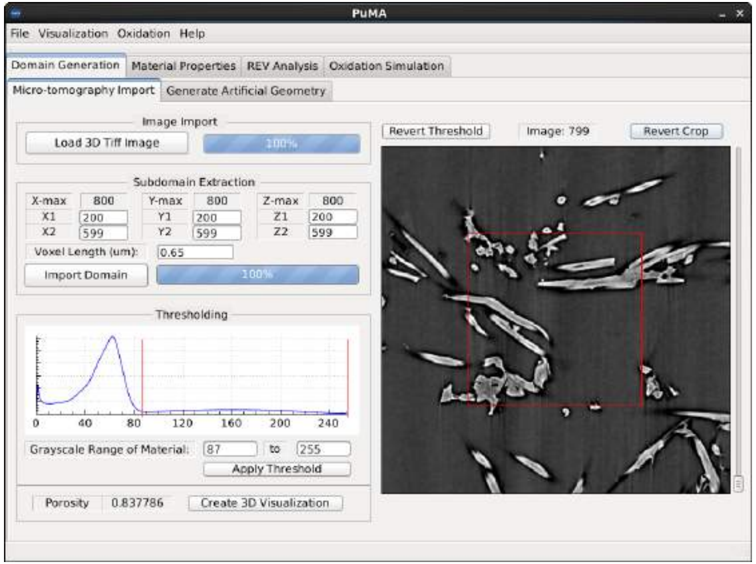
Oxidation Simulations

Transient Heat Transfer *

*Under Development

Technical Specifications

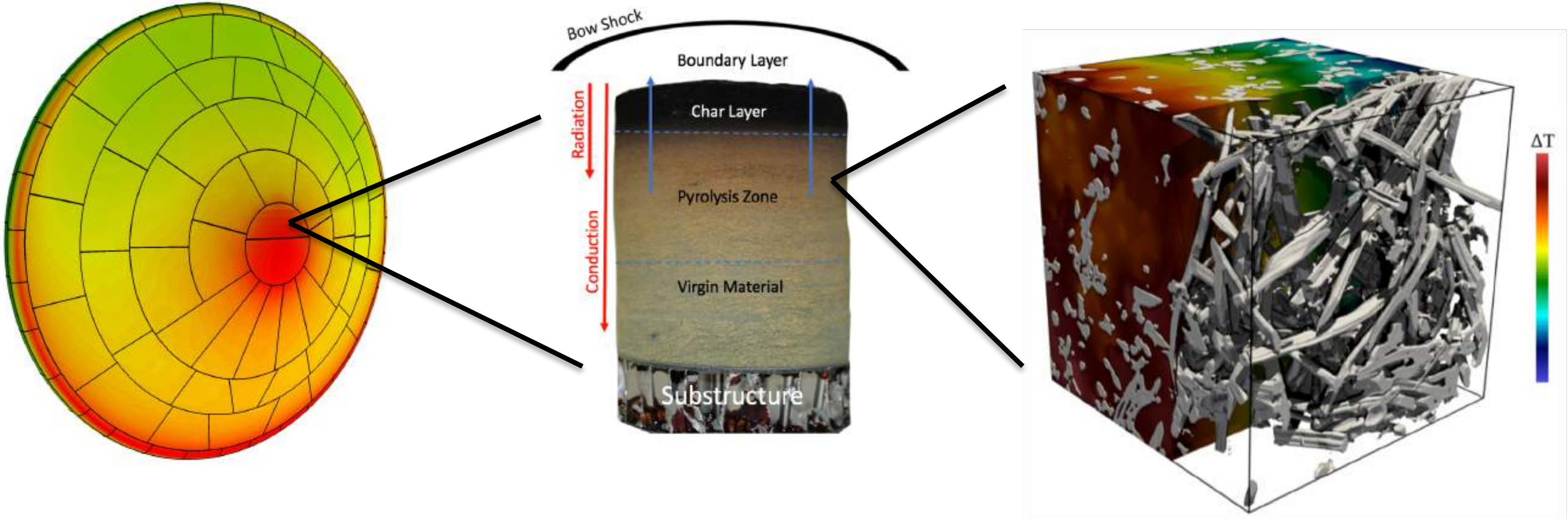
- Written in C++
- GUI built on QT
- Visualization module based on OpenGL
- Parallelized using OpenMP for shared memory systems



X-max 800
X1 200
X2 599
Y-max 800
Y1 200
Y2 599
Z-max 800
Z1 200
Z2 599
Voxel Length (um): 0.65
Grayscale Range of Material: 87 to 255
Porosity 0.837786
Image: 799

Ferguson et. al, PuMA: the Porous Microstructure Analysis software. Submitted to SoftwareX (2017)

Micro-scale modeling



1. Material Properties
   1. Phenomenological Properties
   2. Thermal transport
   3. Mass transport
2. Material Decomposition
   1. Oxidation
   2. Sublimation
   3. Spallation

Effective Material Properties

Porosity

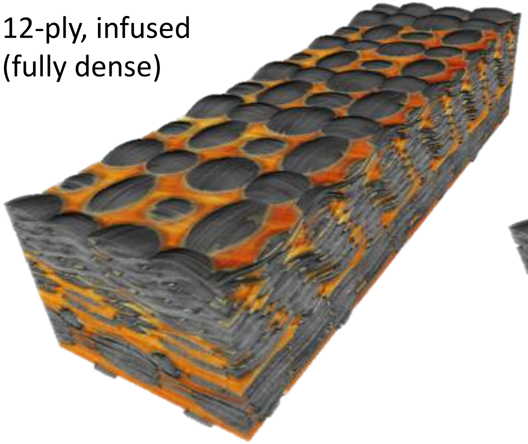
- Based on the grayscale threshold
- Sum of all void voxels over the total volume

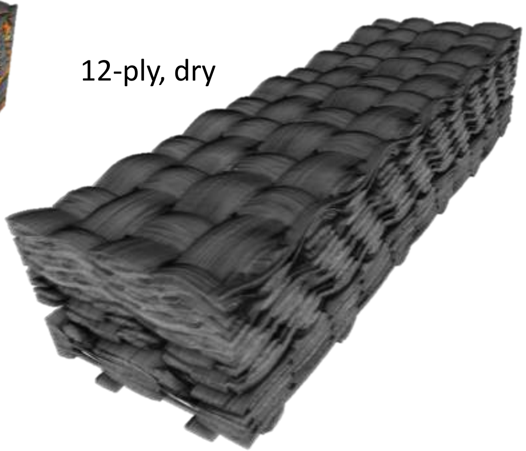
Specific Surface Area

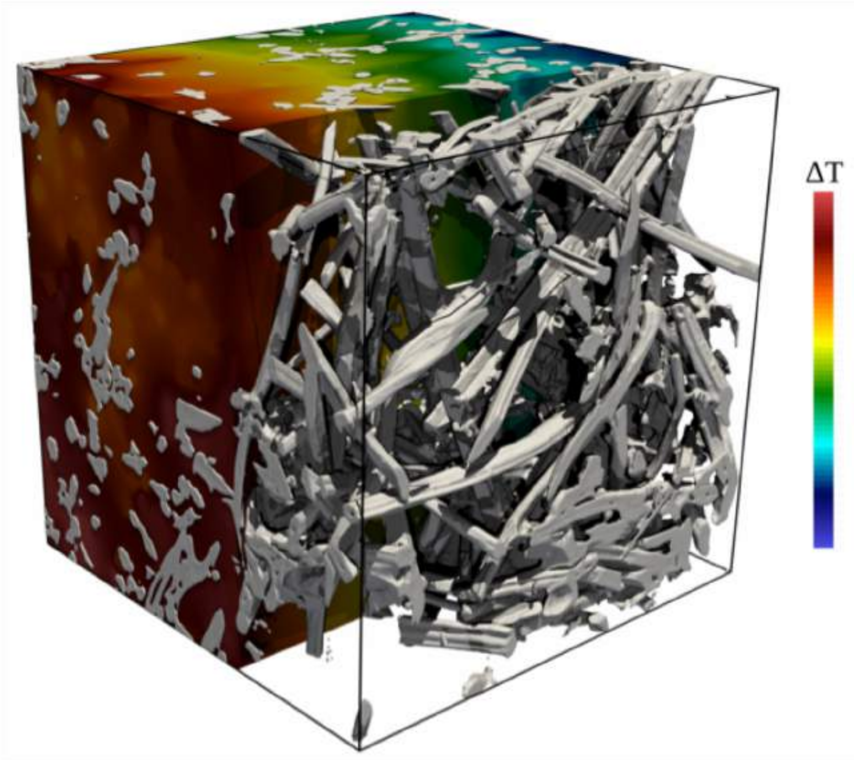
- Based on the Marching Cubes algorithm
- Overall surface area computed as a sum of individual triangle areas

Effective Thermal Conductivity

- Computes effective thermal conductivity using a finite difference method [Weigmann, 2006]
- BicGStab iterative method and FFTW used to solve linear system of equations [Sleijpen, 1993]
- Parallelized based on OpenMP
- Verified against complex analytical solutions

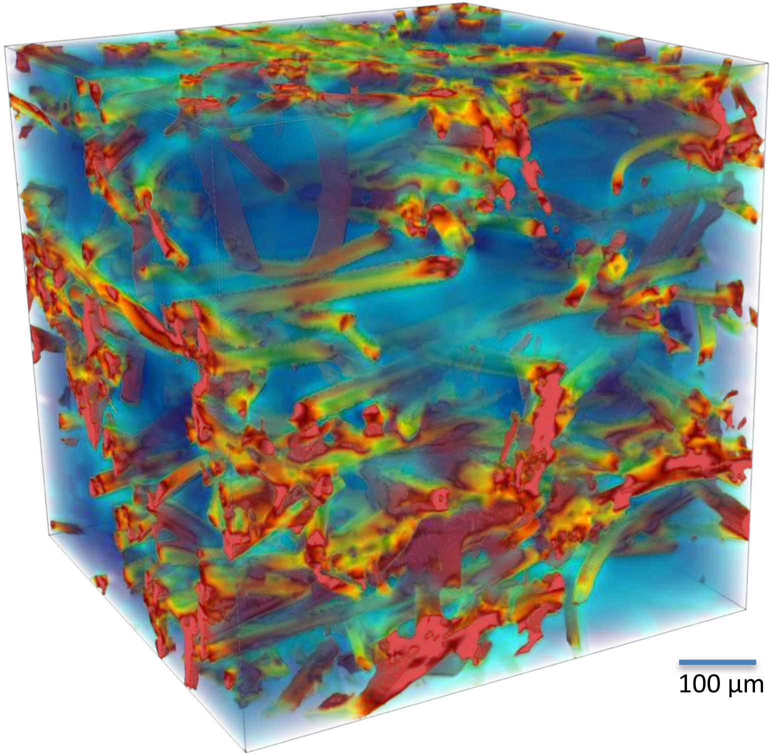

12-ply, infused
(fully dense)


12-ply, dry



Effective Electrical Conductivity

- Computes effective electrical conductivity using a finite difference method [Weigmann, 2006]
- 1V voltage differential applied; solved with periodic boundary conditions
- BicGStab iterative method and FFTW used to solve linear system of equations [Sleijpen, 1993]
- Parallelized based on OpenMP
- Verified against complex analytical solutions
- Steady state current flow through a material can be determed

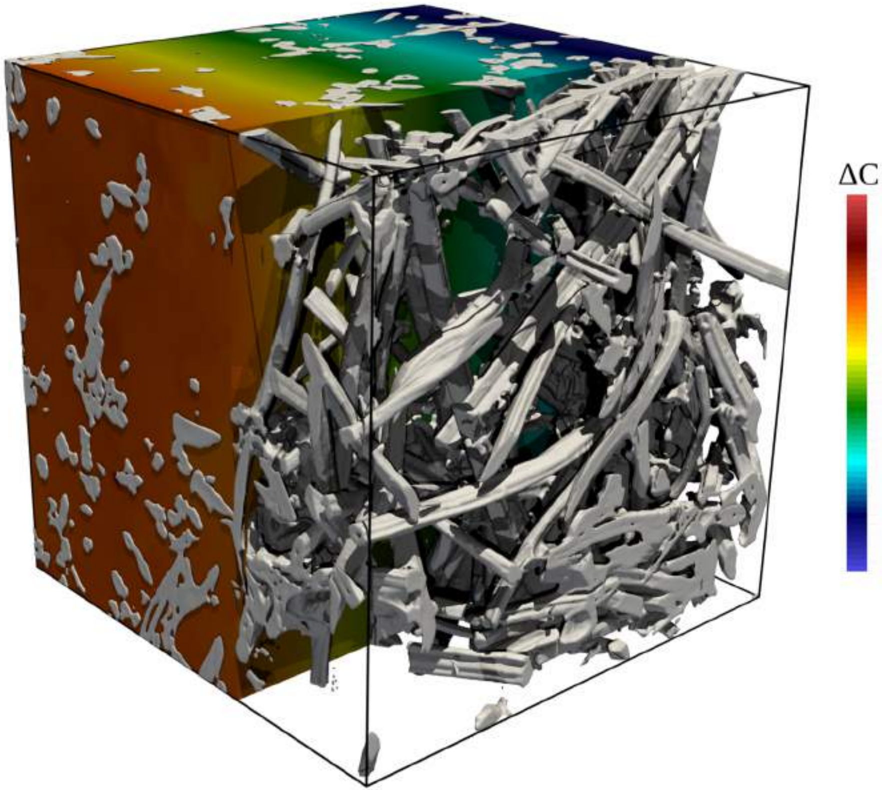


Steady state current flow through a carbon fiber material with an imposed voltage differential

Diffusivity / Tortuosity

Continuum

- Quantifies a materials resistance to a diffusive flux
- Solves for effective diffusivity using a finite difference method
- Valid for Kn << 1
- Solves diffusion equation using periodic boundary conditions



Ferguson et. al, Particle methods for tortuosity factors in porous media, *9th Ablation Workshop, Bozeman MT. (2017).*

Diffusivity / Tortuosity – Random Walk

Transitional/Rarified

- Random walk method to simulate diffusion
- Mean square displacement method used to solve effective diffusion
- Valid for all Knudsen numbers.
- Knudsen number is varied by changing the molecular mean free path

$$Kn = \frac{\bar{\lambda}}{\bar{d}} = \frac{mean\ free\ path}{characteristic\ length}$$

- Surface collisions based on marching cubes triangles with diffuse reflections used

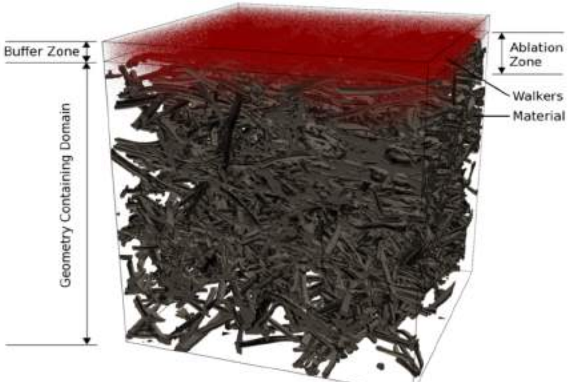
High Knudsen

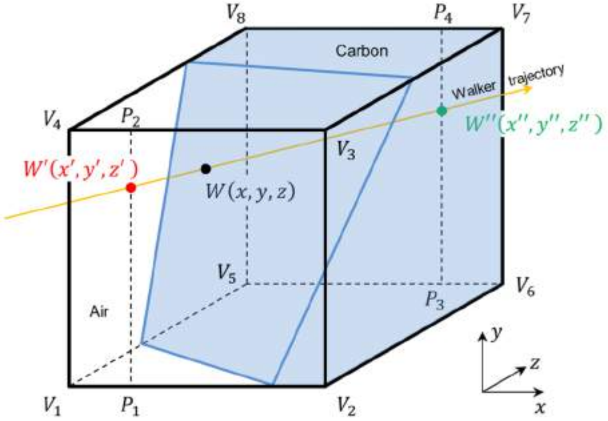
Low Knudsen

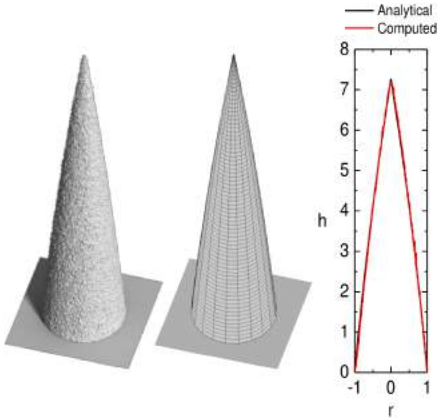
Ferguson et. al, Particle methods for tortuosity factors in porous media, *9th Ablation Workshop, Bozeman MT. (2017).*

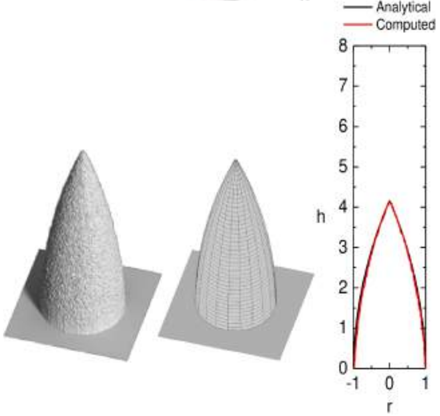
Micro-Scale Oxidation Simulations

- Particle-based oxidation method
- Diffusion simulated through random walks
- Collision detection with linear interpolation method
- Sticking probability method for material recession
- Verified against analytical solutions for single fiber





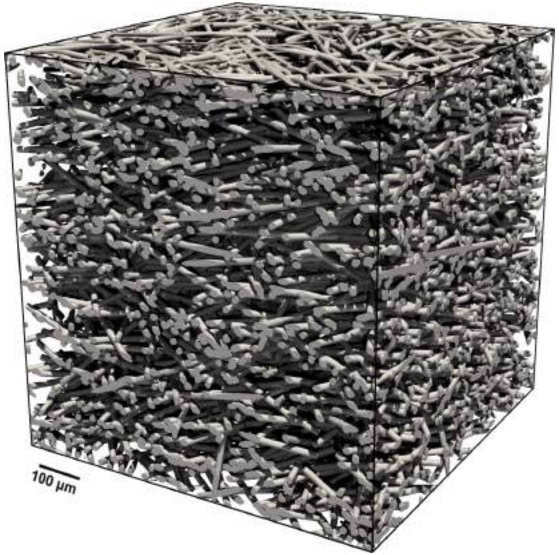




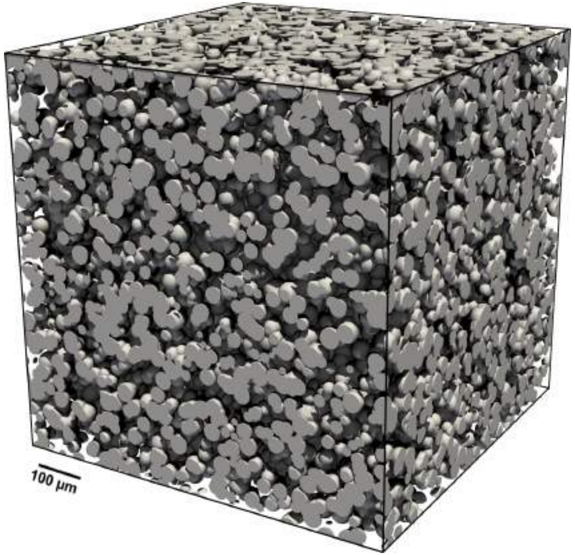
Ferguson et. al, Modeling the oxidation of low-density carbon fiber materials based on micro-tomography, *Carbon. (2016).*

Material Generation

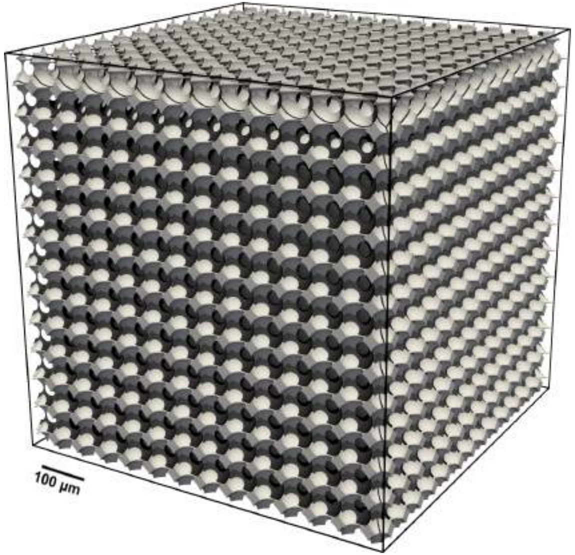
Random Fiber Structures



Packed Sphere Beds

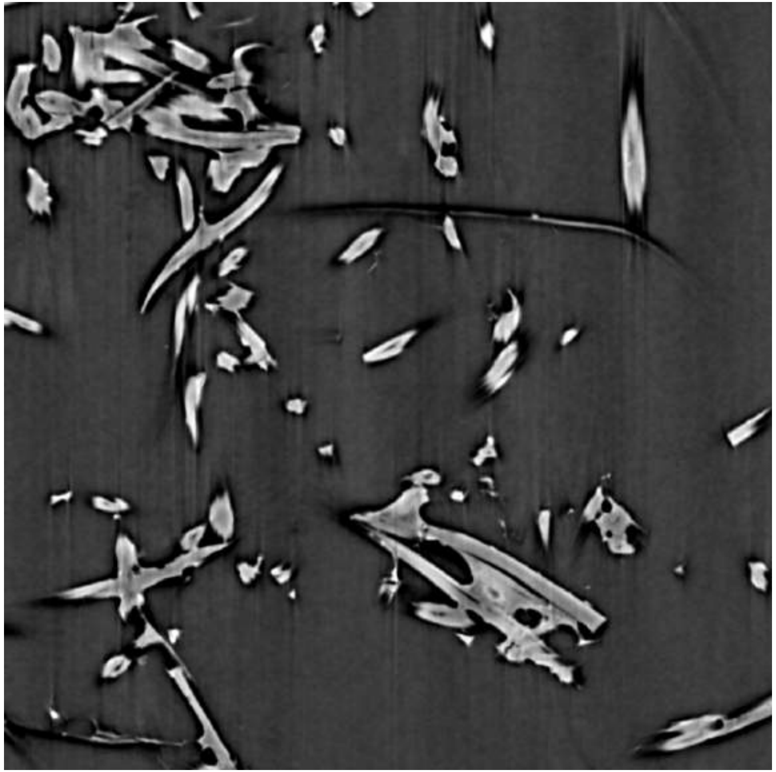


Periodic Foams

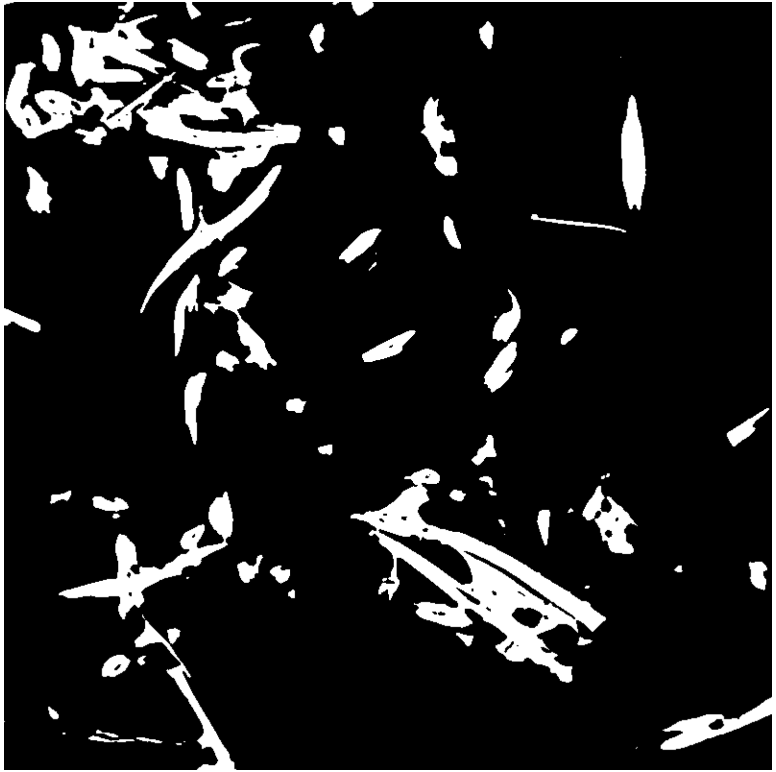


Challenges: Segmentation

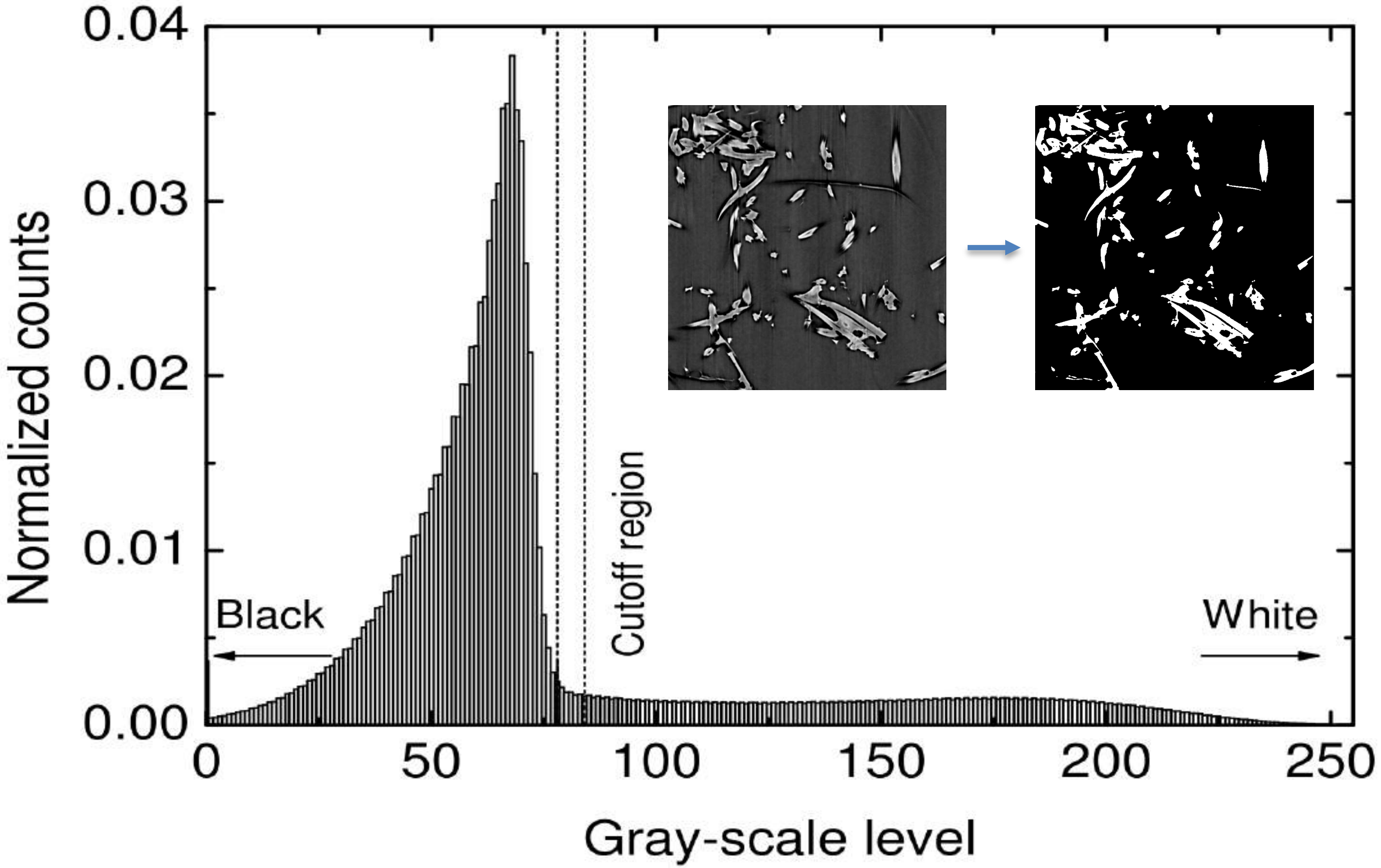
Raw Grayscale Data



Segmented Data

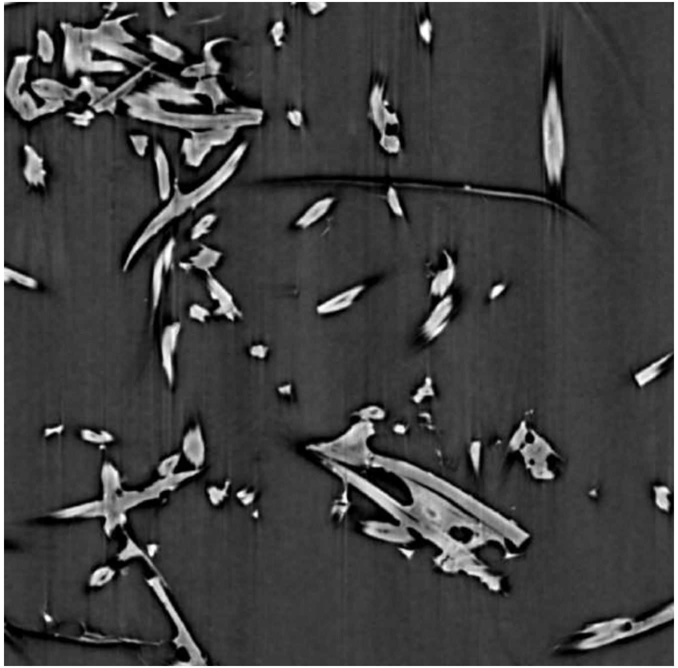


Thresholding Approach



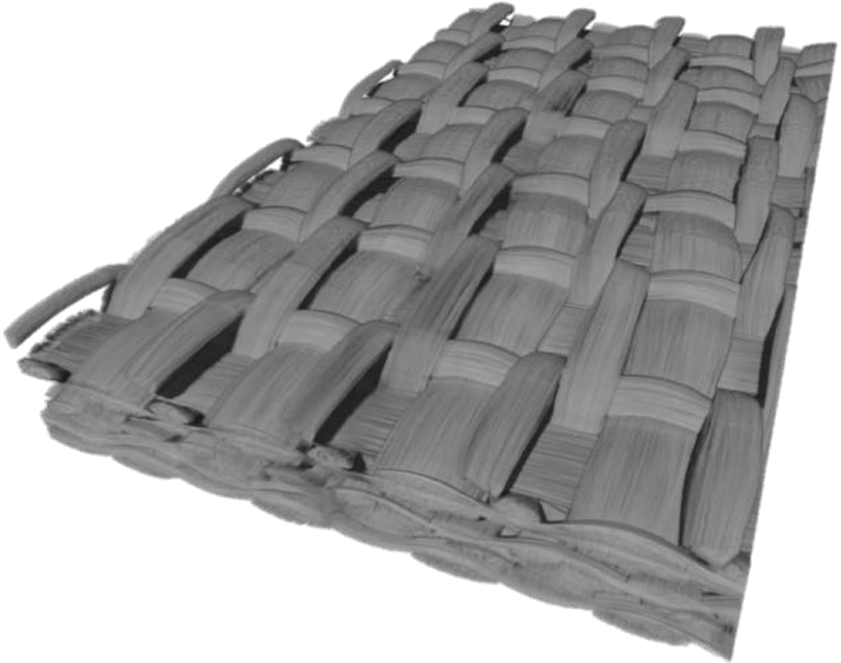
When Thresholding Works Well

1. **Two phase materials**
2. **Direction is irrelevant**
3. **High contrast between phases**



When Thresholding Fails

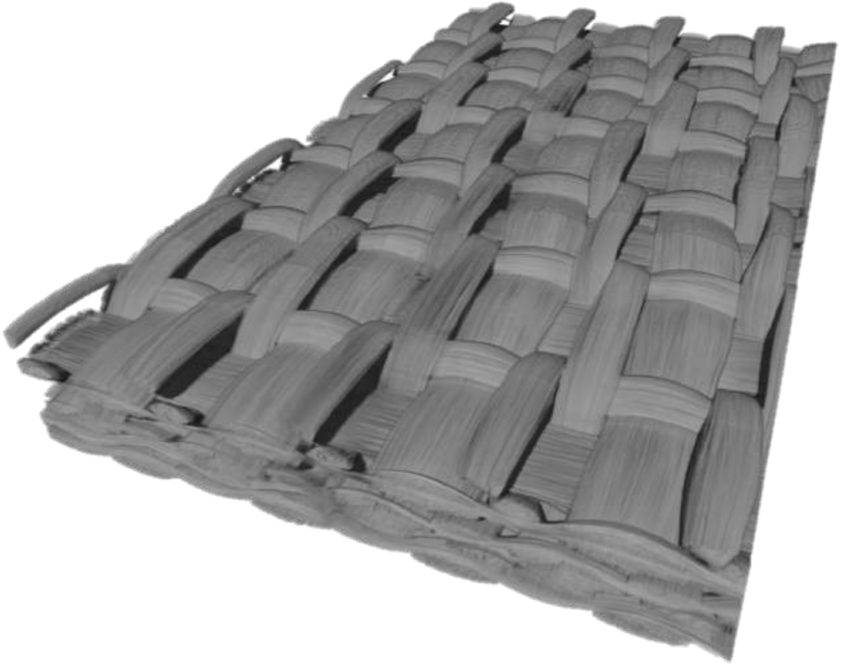
1. **Multi phase materials**
2. **Direction is important**
3. **Low contrast between phases**



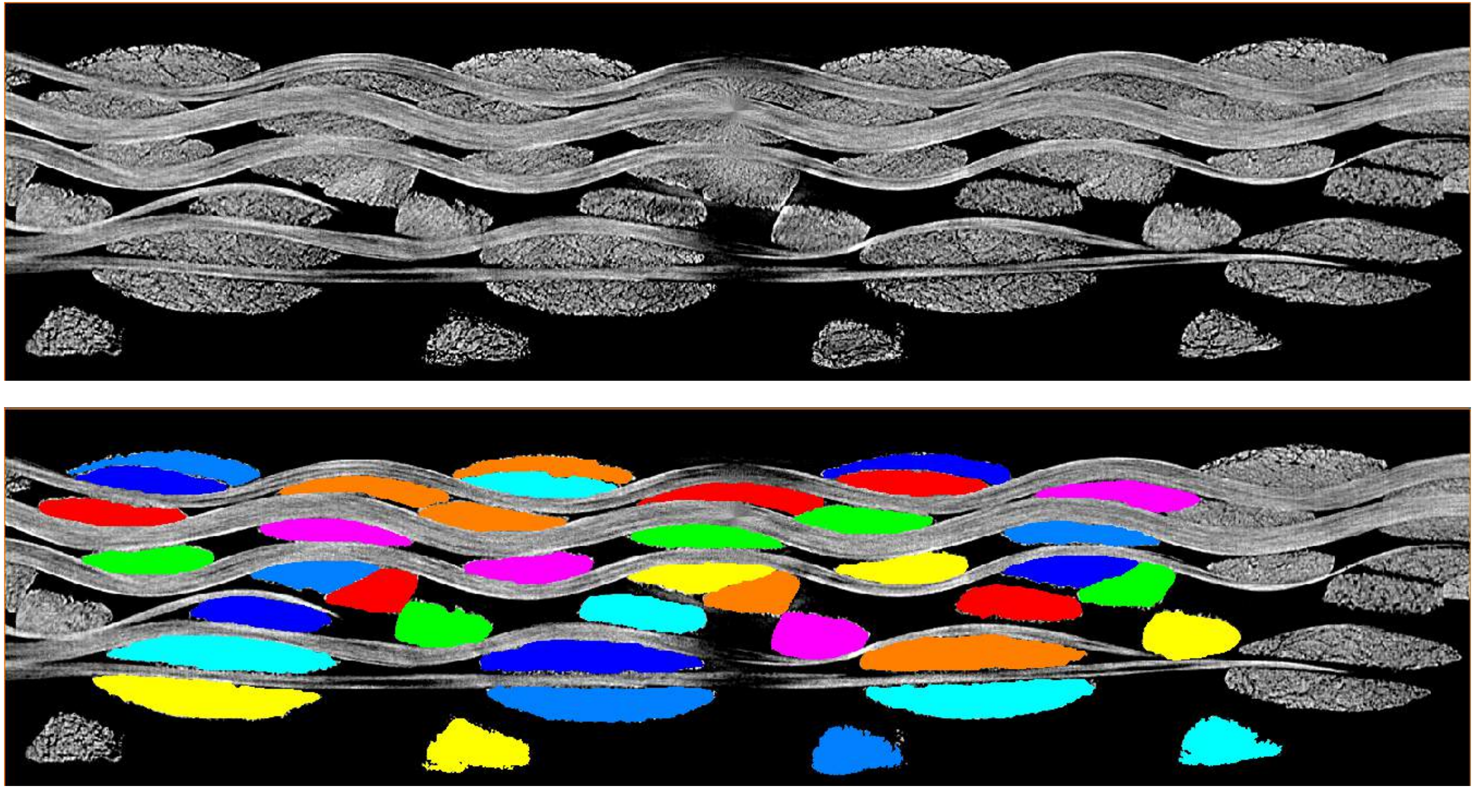
Example 1: Woven Materials

Why thresholding fails

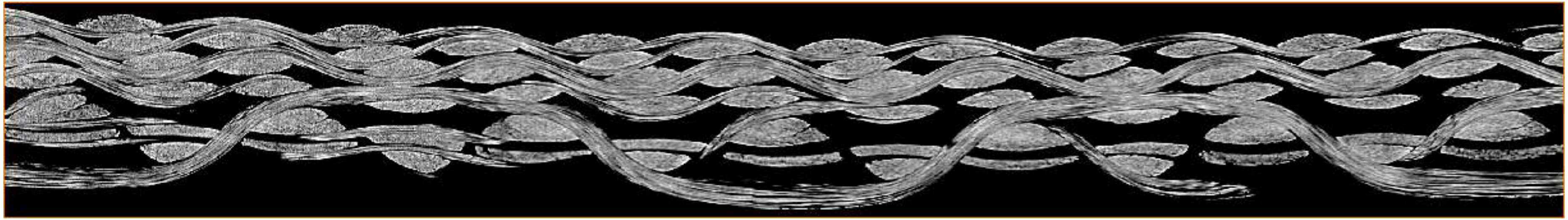
Need to separate the weave directions from one another for modeling purposes

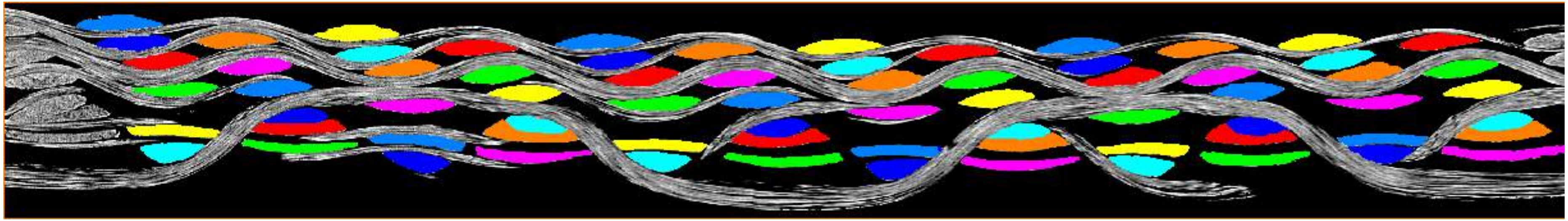


Example 1: Woven Materials



Example 1: Woven Materials



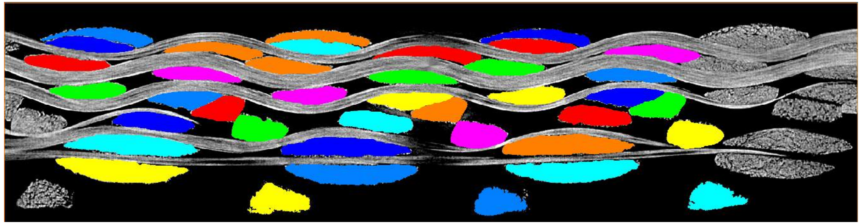


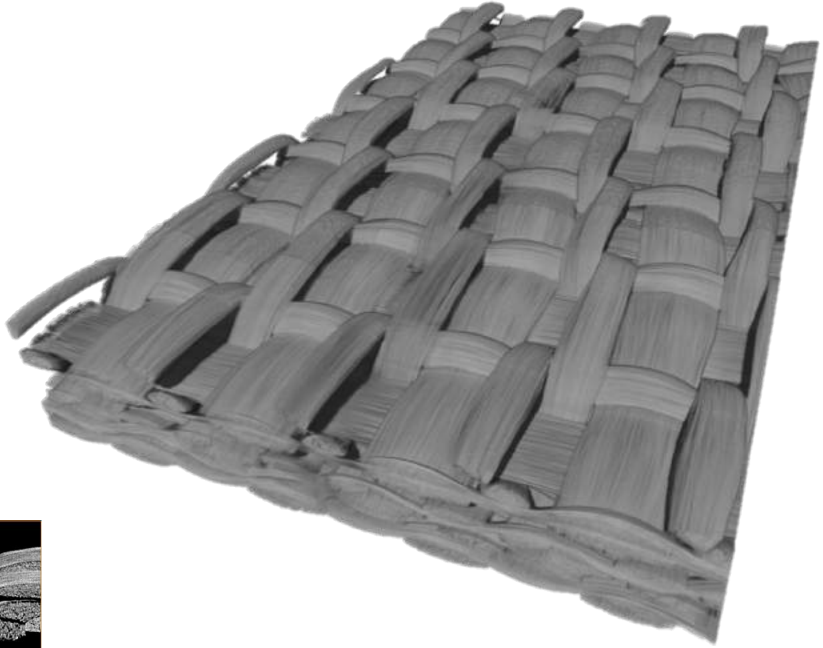
Example 1: Woven Materials

Training Data Available

1. 6-ply weave
2. 4-ply weave
3. 12-ply weave

Manually Segmented

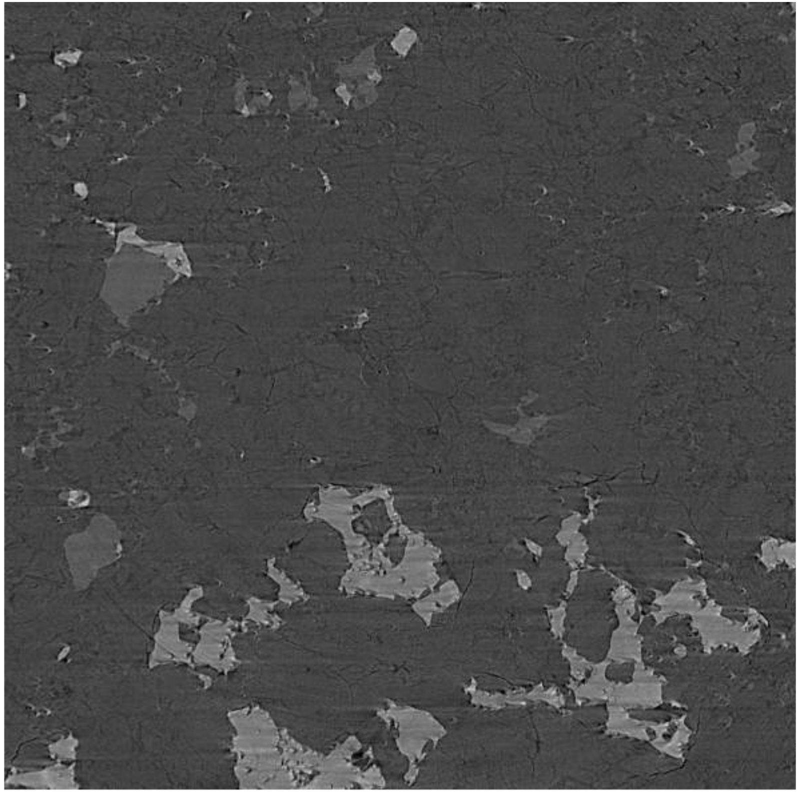




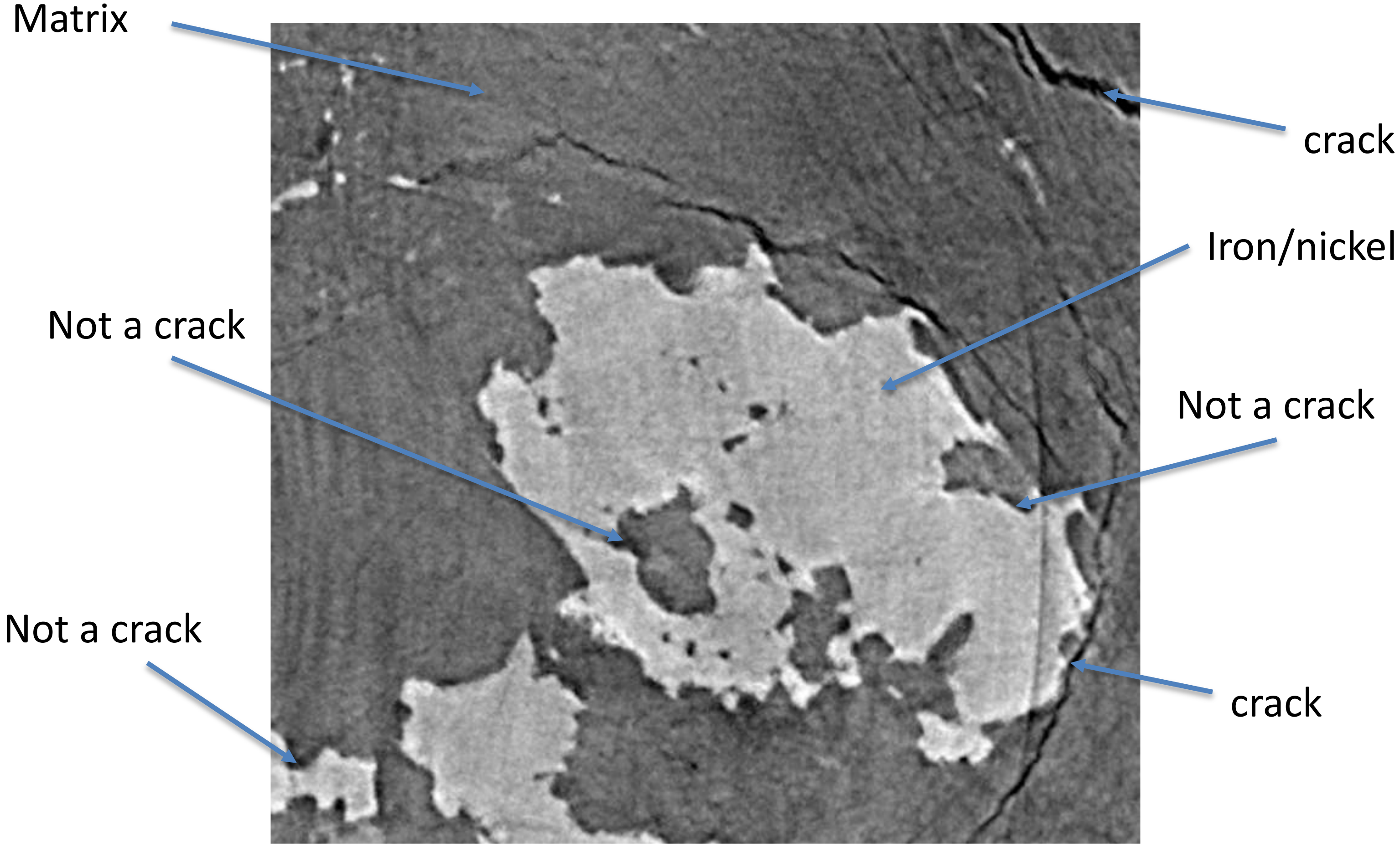
Example 2: Asteroid Samples

Why thresholding fails

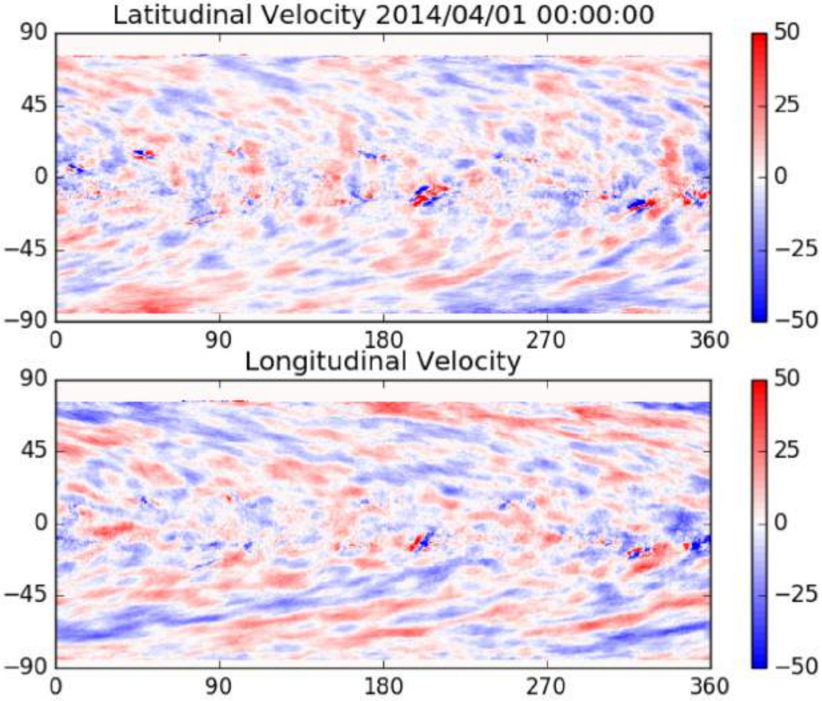
Multiple phases with overlap in grayscale value. Can't distinguish between phases through thresholding methods

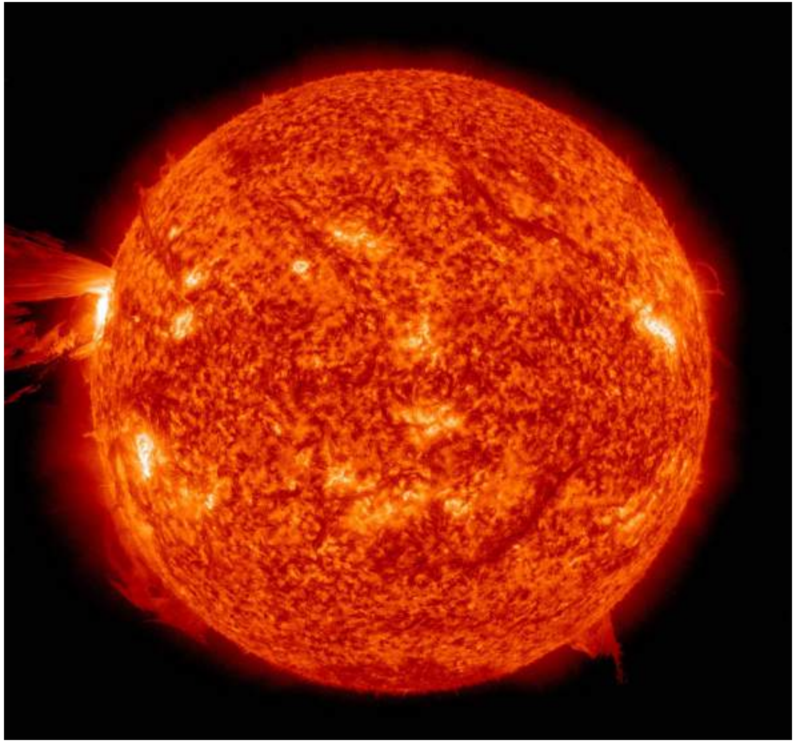


Example 2: Asteroid Samples

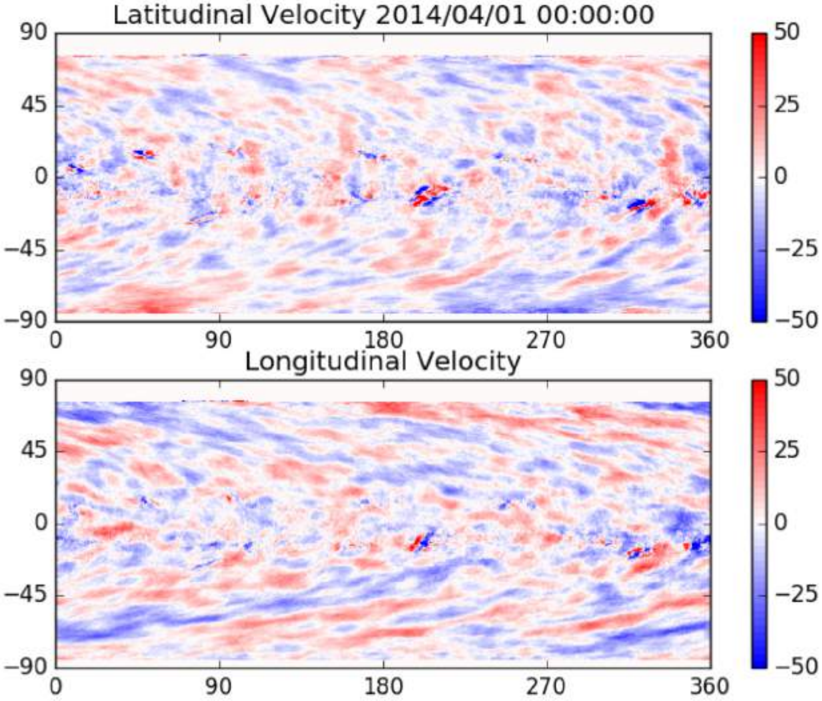


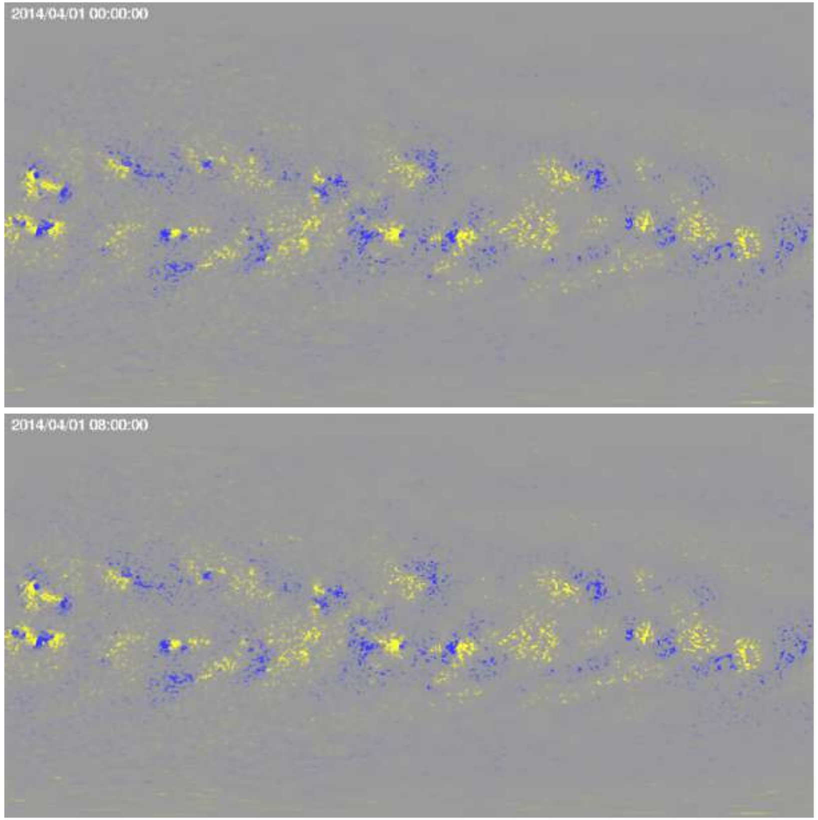
Prediction of sun spots





Prediction of sun spots

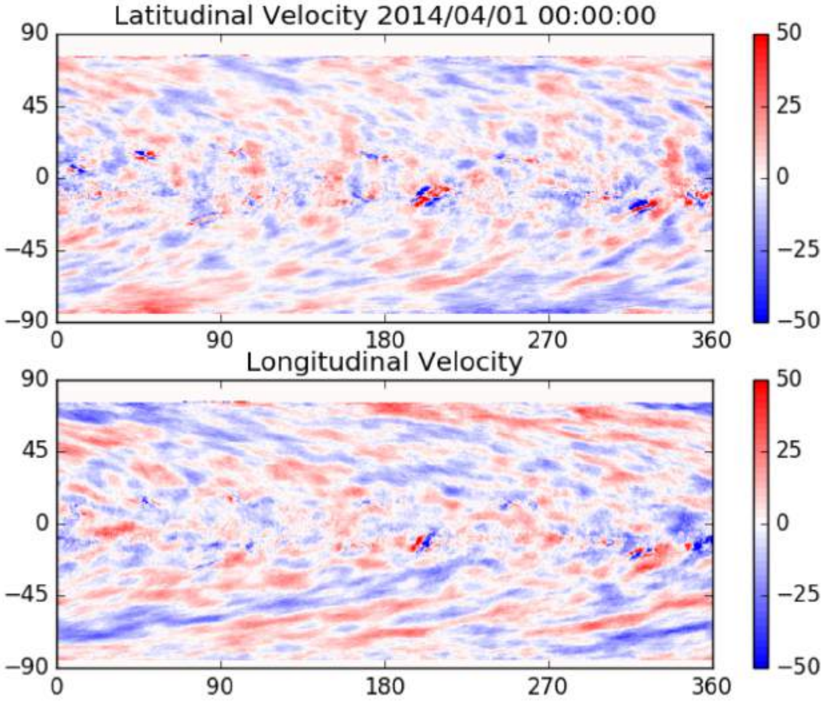




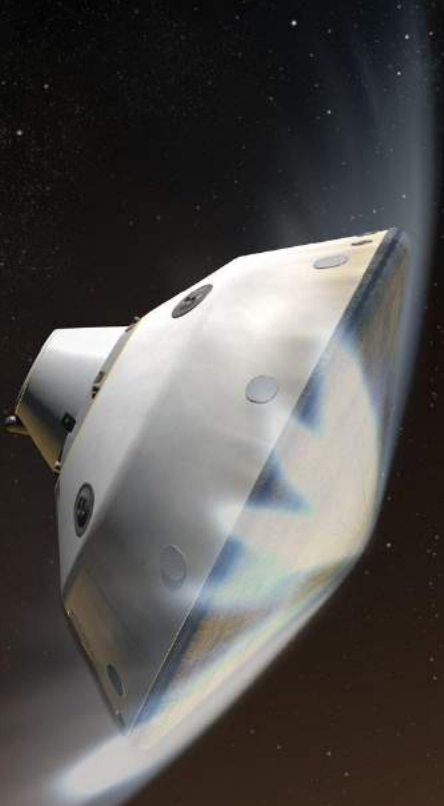
Prediction of sun spots

Unknowns

1. How to apply ML/AI techniques to time-series data
2. Would processing velocity data give more information: gradients, curl, etc.



Questions?



Point of Contact: Joseph C. Ferguson
Joseph.c.ferguson@nasa.gov

May 24th, 2018
Mountain View, CA