Enhanced-Resolution Soil Moisture Using Image Reconstruction
Part One: TB Resolution Enhancement

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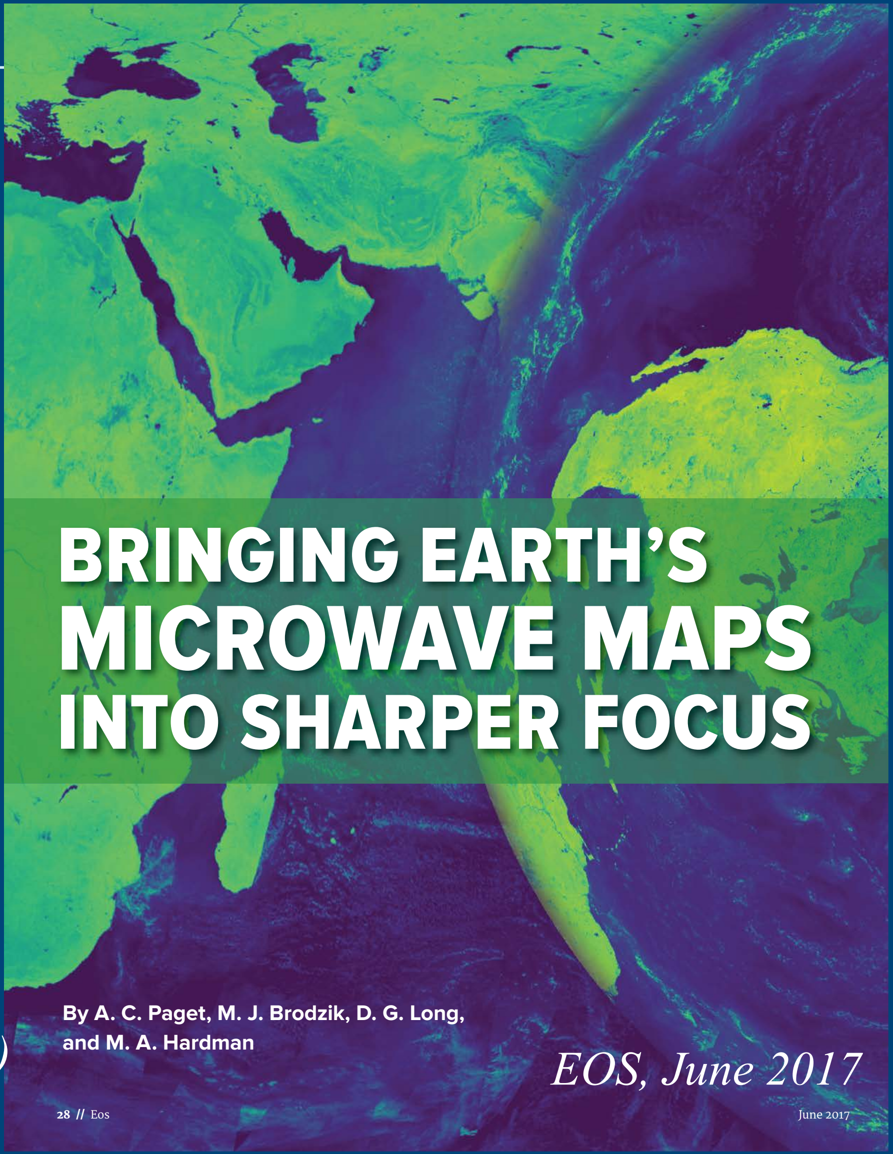
Project Goals

1) Leverage our NASA MEaSUREs image reconstruction system to produce enhanced-resolution SMAP radiometer temperatures (how much enhancement can be achieved?)

2) Investigate potential improvement this yields in soil moisture retrievals



EOS, June 2017

CETB (Calibrated, Enhanced-Resolution T_Bs)
http://nsidc.org/data/nsidc-0630:
SMMR, 6 SSM/Is, 4 SSMISs, AMSR-E, at up to 3.125 km

Image Reconstruction

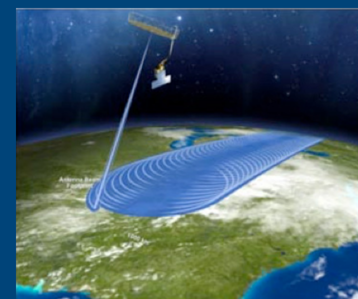
Backus Gilbert (BG) and the radiometer version of Scatterometer Image Reconstruction (rSIR) trade off enhanced spatial resolution and noise

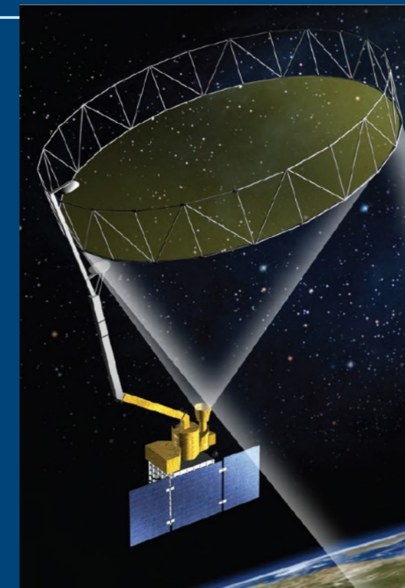
Both techniques require a reasonable (not necessarily exact) knowledge of the instrument antenna pattern, which determines the Measurement Response Function (MRF), to weight the contribution of overlapping measurements for a given gridded pixel TB

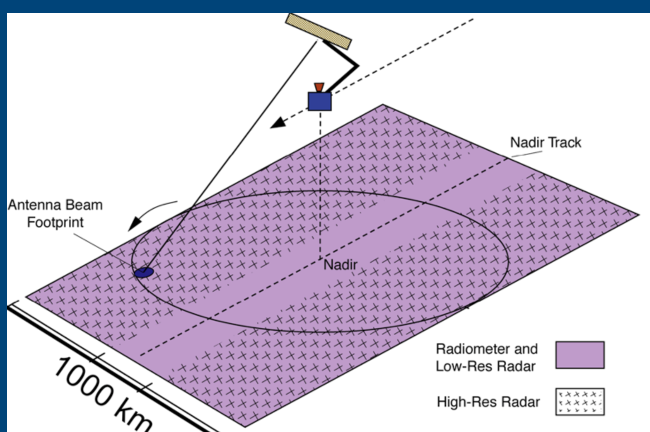
	BG	rSIR
Technique	Matrix Inversion (slow) for each pixel	Iterative (at least 10x faster)
Regularization Tuning Parameter	"gamma" (dimensionless)	number of iterations

Image Reconstruction for SMAP

- 4 channels at ~51 deg incidence angle
- 685 km, 8-day repeat orbit
- H, V, 3rd & 4th Stokes @ 1.41 GHz
- ~40 ms integration interval w/80 MHz bandwidth
- Nominal 39 km x 47 km footprint
  - ~30 km resolution
- 1000 km swath width, 14.6 rpm







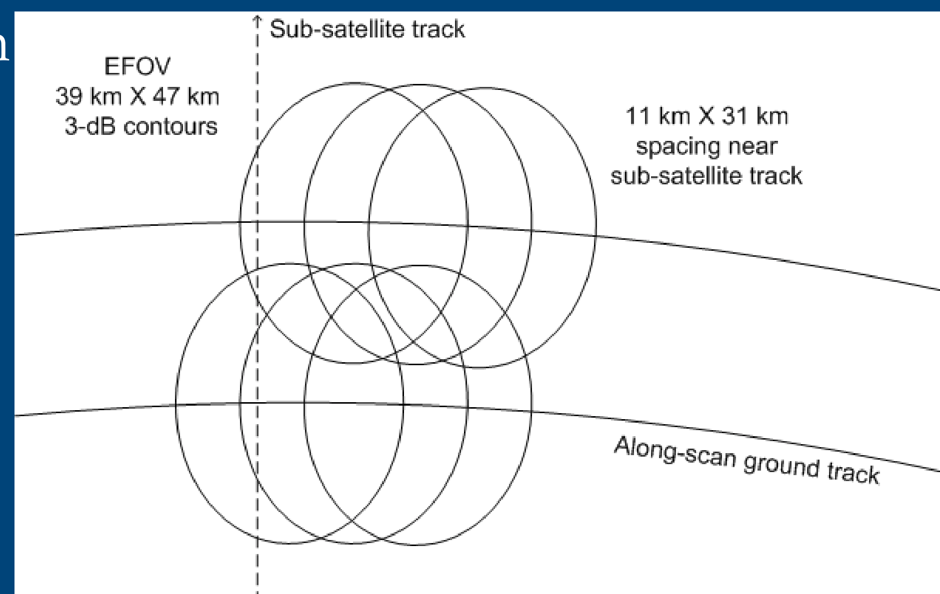
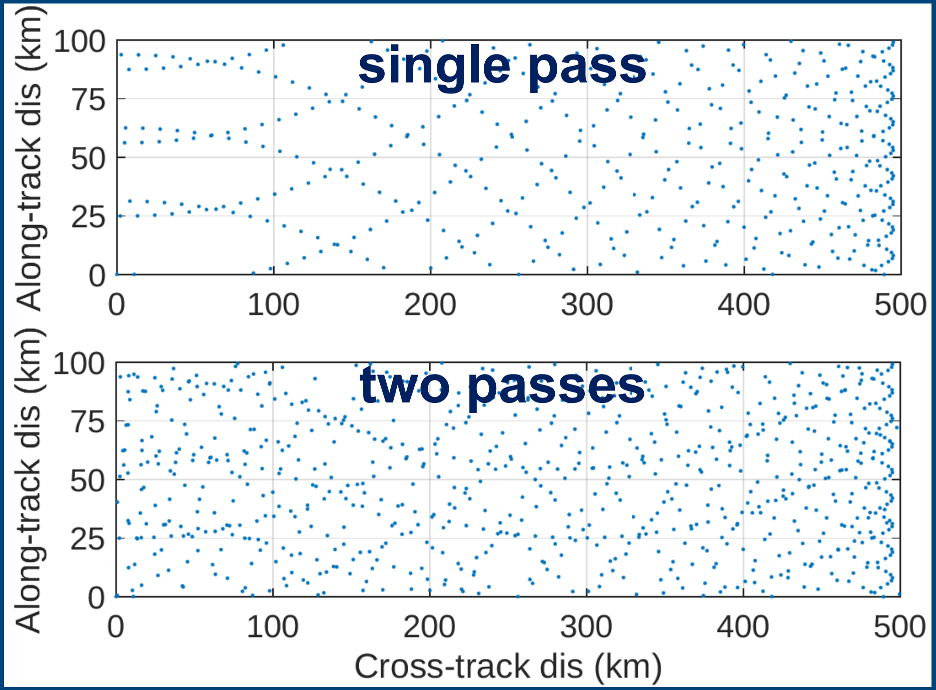


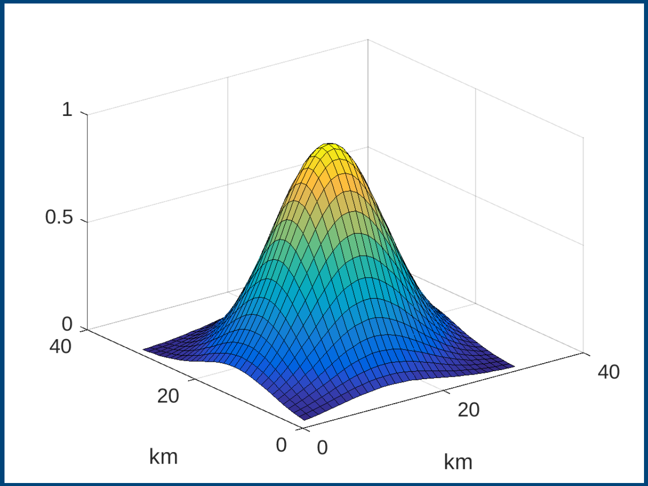
Image Reconstruction for SMAP

Measurement density increases with multiple overpasses

Image reconstruction takes advantage of irregular sampling locations

Measurement locations





Fortunately, exact knowledge of the antenna pattern is not required, since full deconvolution is not required

A reasonable approximation is a 2-D Gaussian

Antenna Temperature

$$T_{AP}(\theta,\varphi)=\left[T_b(\theta,\varphi)+T_{sc}(\theta,\varphi)\right]e^{-\tau(\theta)\sec\theta}+T_{up}(\theta)+T_{sky}(\theta,\varphi)$$

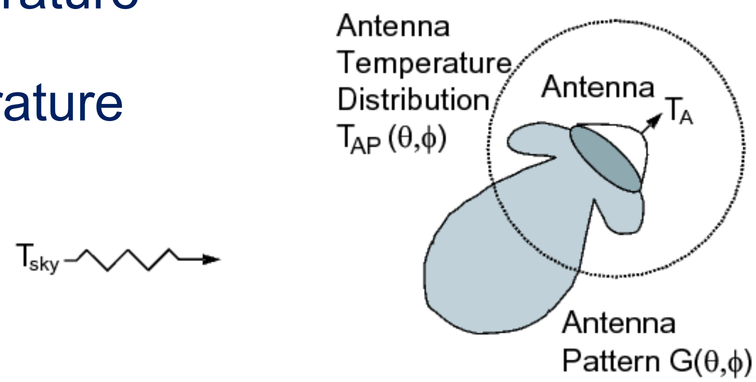
$T_b = \varepsilon T_p$ Surface brightness temperature

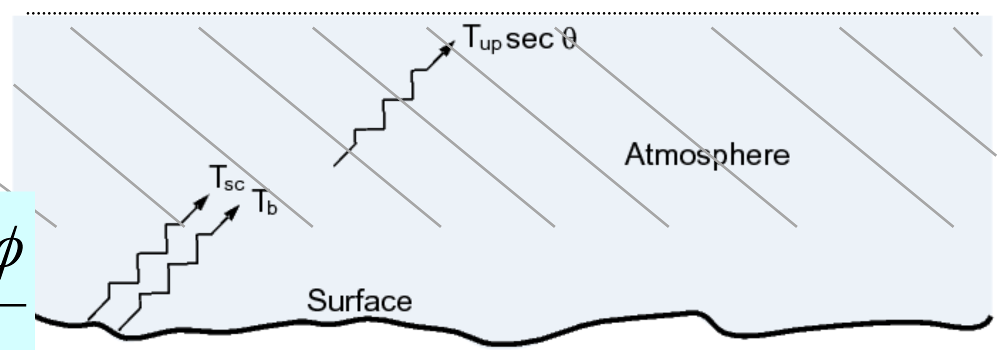
T_{sc} Surface scattering temperature

$e^{-\tau(\theta)\sec\theta}$ Atmospheric attenuation

$T_{up}(\theta)$ Upwelling signal

T_{sky} Sky temperature





Antenna temperature

$$T_A=\frac{\iint G(\theta,\phi)\,T_{AP}(\theta,\phi)\,d\theta\,d\phi}{\iint G(\theta,\phi)\,d\theta\,d\phi}$$

Spatial response function
(includes movement during integration)

Ulaby and Long, *Microwave Radiometric and Radar Remote Sensing*, 2014 (Amazon.com)

Reconstruction

Spatial sampling can be represented as a matrix equation:

$$z = Hs$$

s.t. s = signal, z = the measurements, H = the sampling and measurement aperture function,

$$z_i = \int h_i(x)\, s(x)\, dx + noise$$

Spatial response function

The reconstruction problem is then

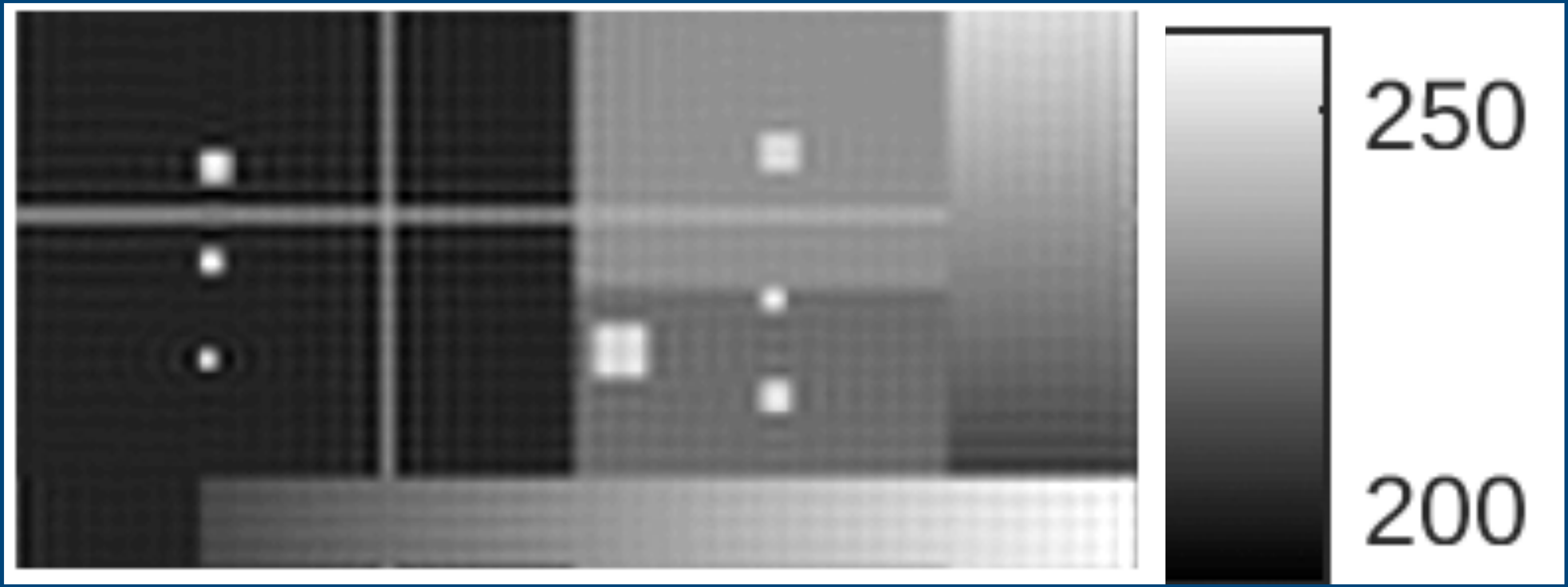
$$\hat{s} = H^{-1} z$$

Regularization techniques are applied to ensure a unique, computable inverse & to minimize adverse effects of noise

- ***BG*** (matrix inversion): is a general least-squares approximation explicitly trading signal and noise
- ***rSIR*** (iterative): regularization is done by restricting number of iterations
    - Assumes a band-limited surface consistent with the spatial sampling

D.G. Long and M.J. Brodzik, "Optimum Image Formation for Spaceborne Microwave Radiometer Products," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 54, No. 5, pp. 2763-2779, 2016.

Algorithm Tuning Using Synthetic Image

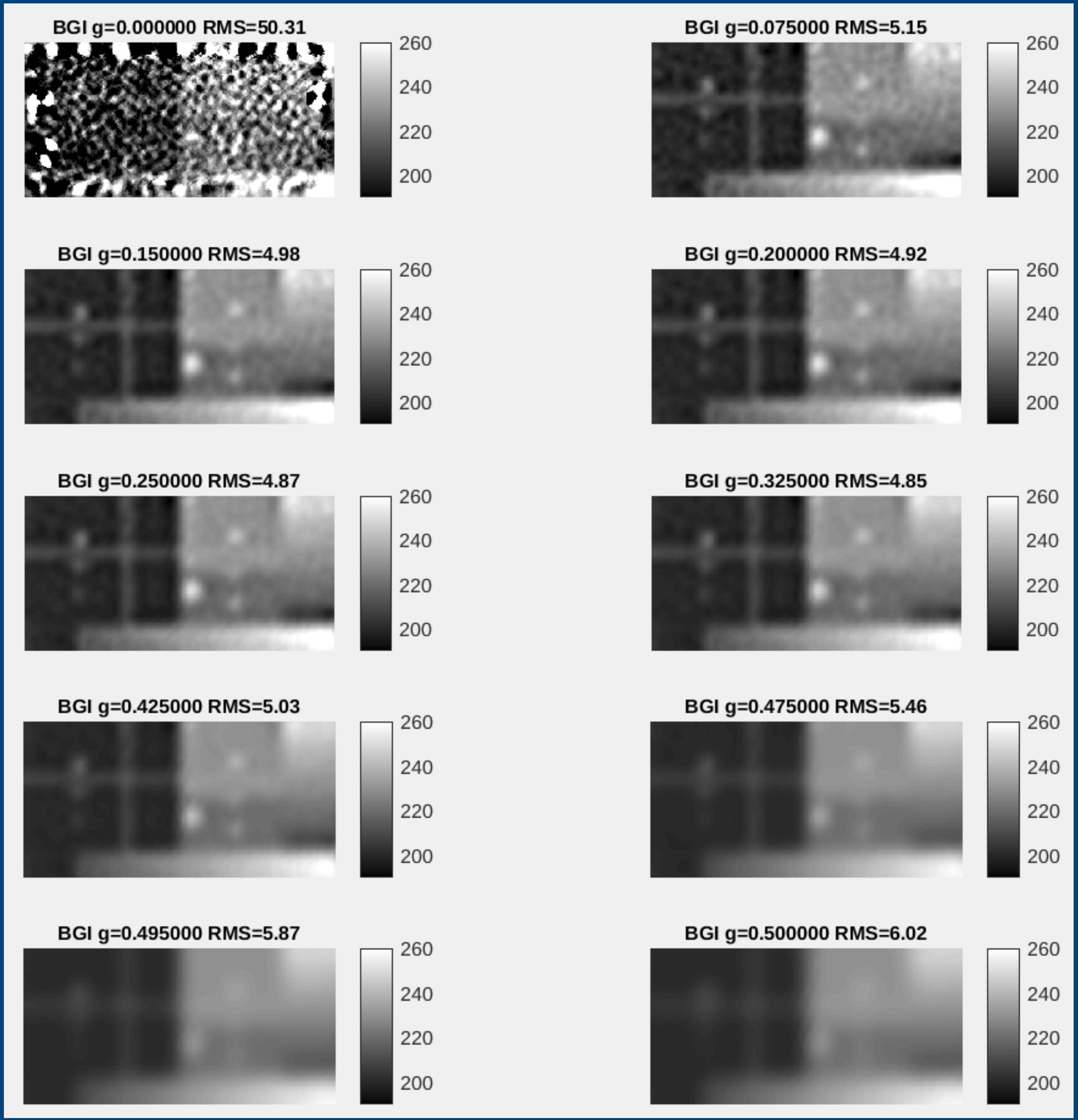


Determine the “best” BG/rSIR tuning parameters, using a synthetic truth image, real sampling geometry, and Monte Carlo noise by “minimizing RMS error in reconstructed image compared to the bandlimited synthetic image” (3 km pixels)

BG Error vs. gamma

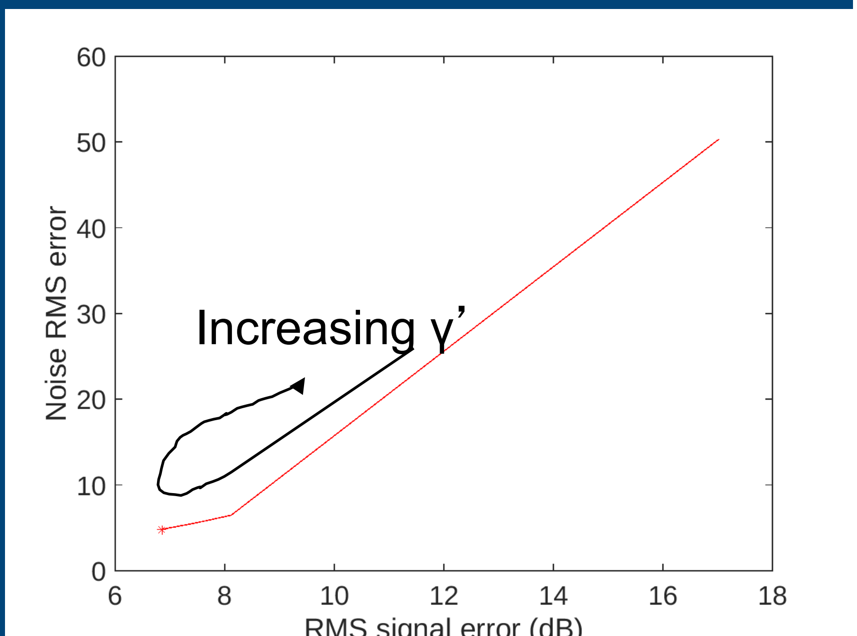
BG examples for various values of gamma: performance varies with gamma

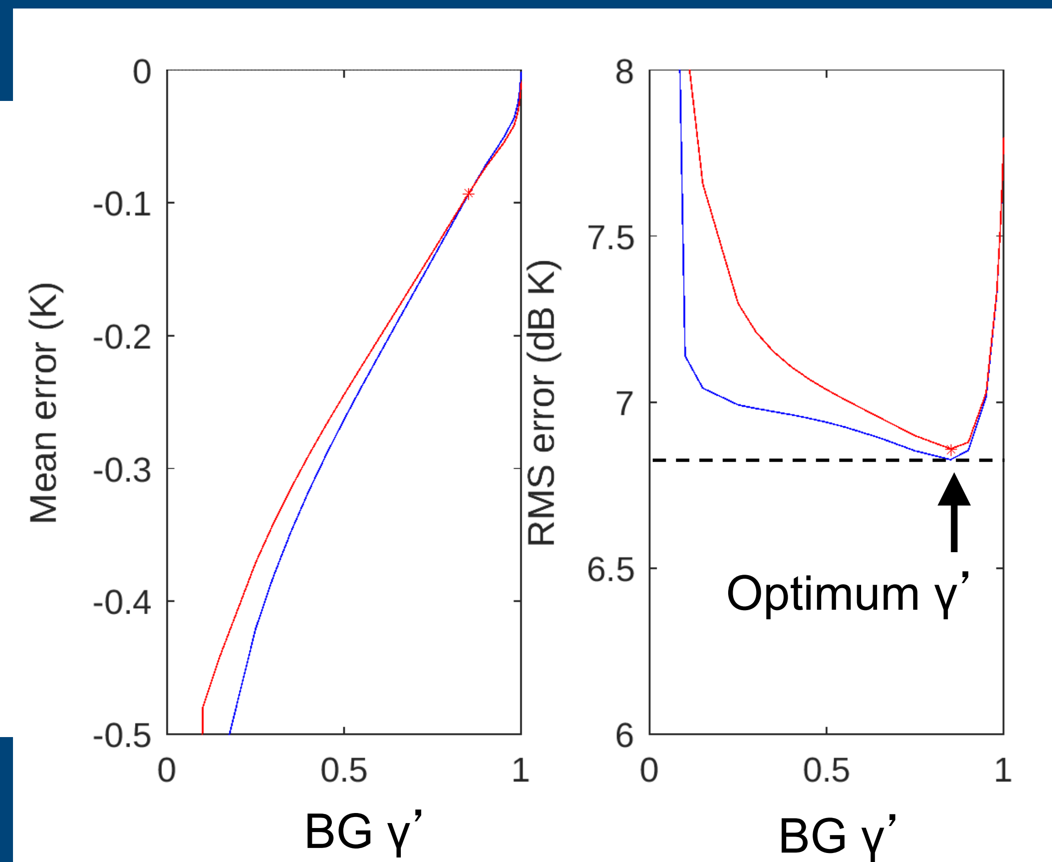
Objective is to minimize RMS error



BG Error vs. gamma

For BG, we choose gamma that minimizes RMS error

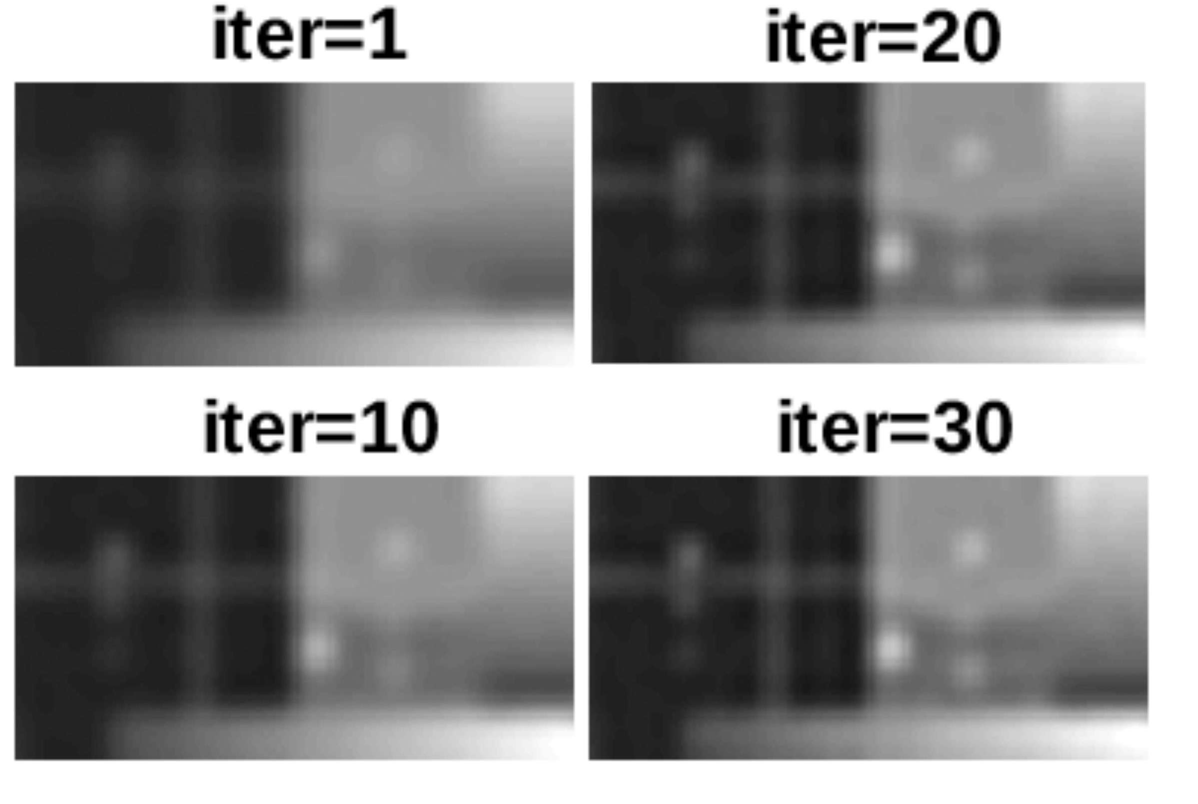




rSIR Error vs. number of iterations

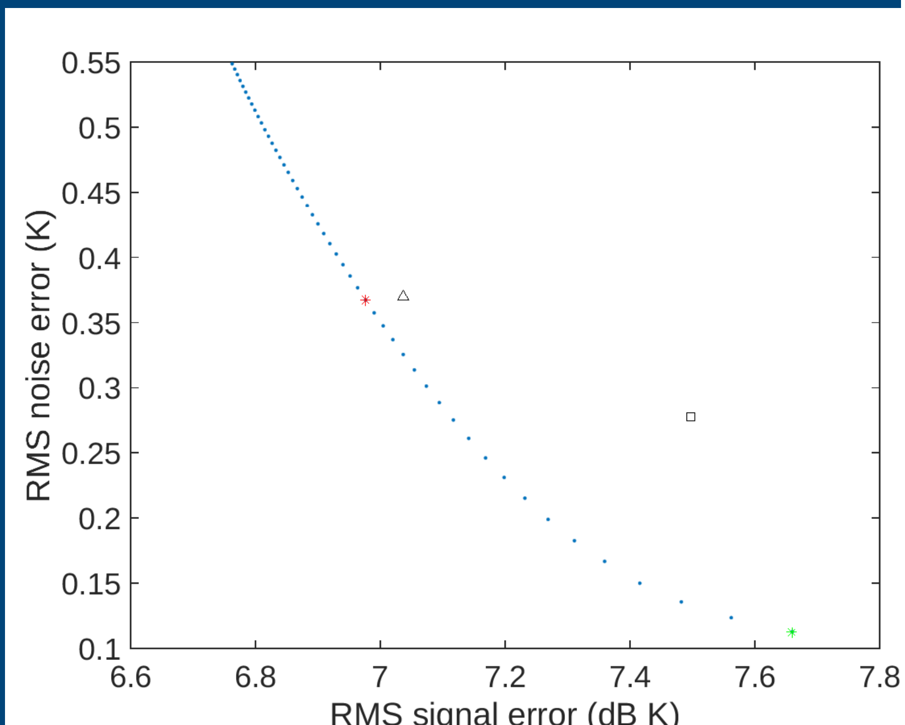
Similarly, rSIR performance varies with number of iterations, n

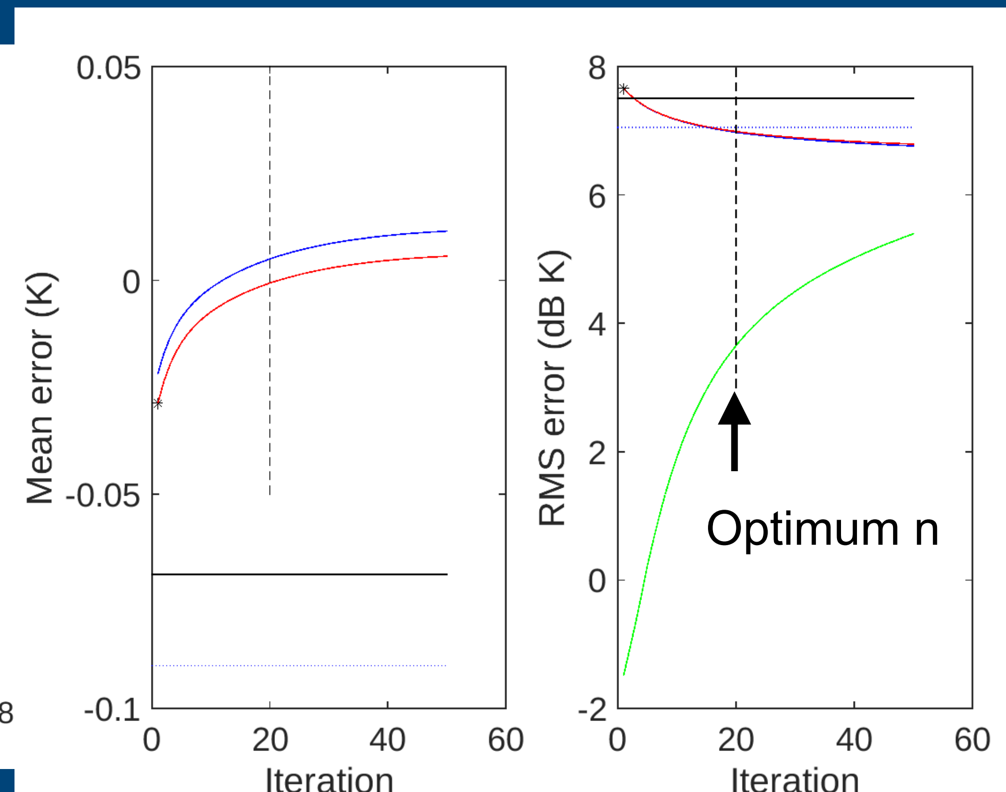
Increasing n improves signal, but increases noise (acts like a high pass filter)



rSIR Error vs. number of iterations

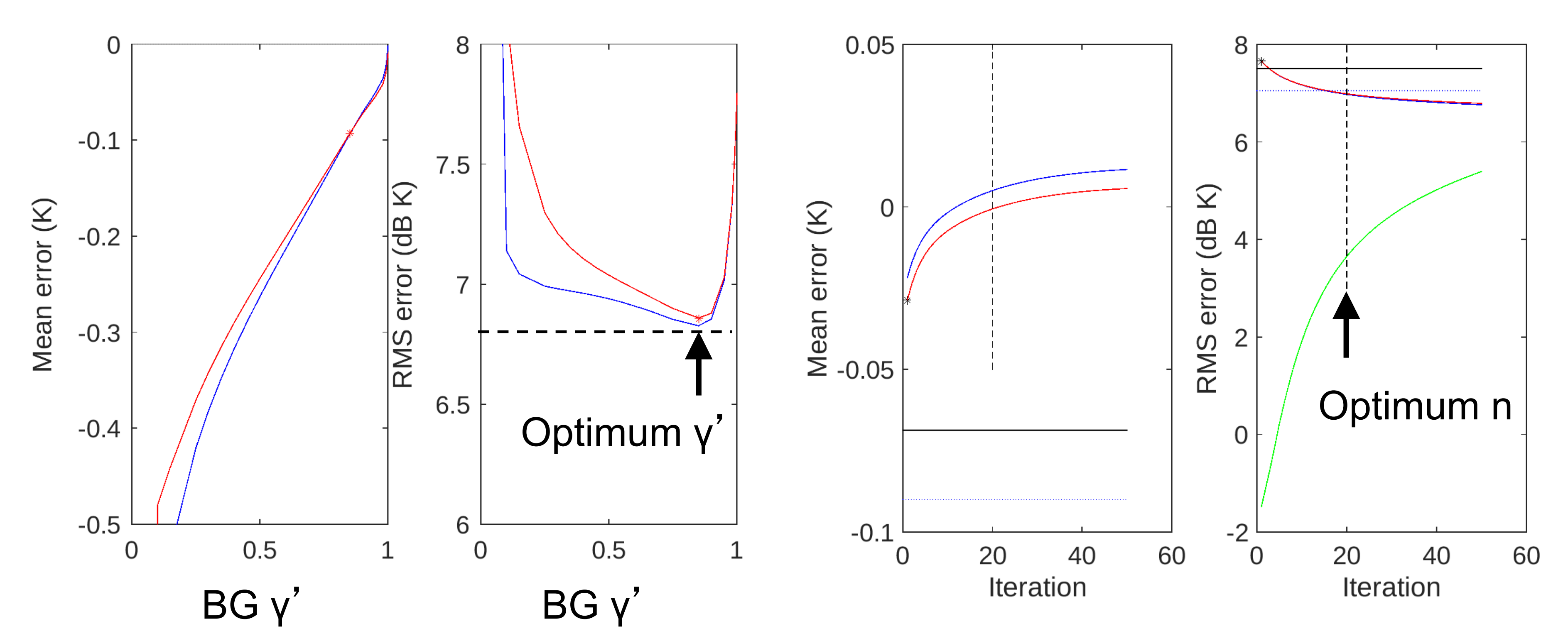
For rSIR, increasing n improves signal error, but increases noise error; excessive iteration introduces artifacts: we choose n to minimize RMS error





BG and rSIR

Performance vs. regularization tuning parameters
rSIR achieves somewhat lower RMS error than BG
(this is consistent with SSM/I results)



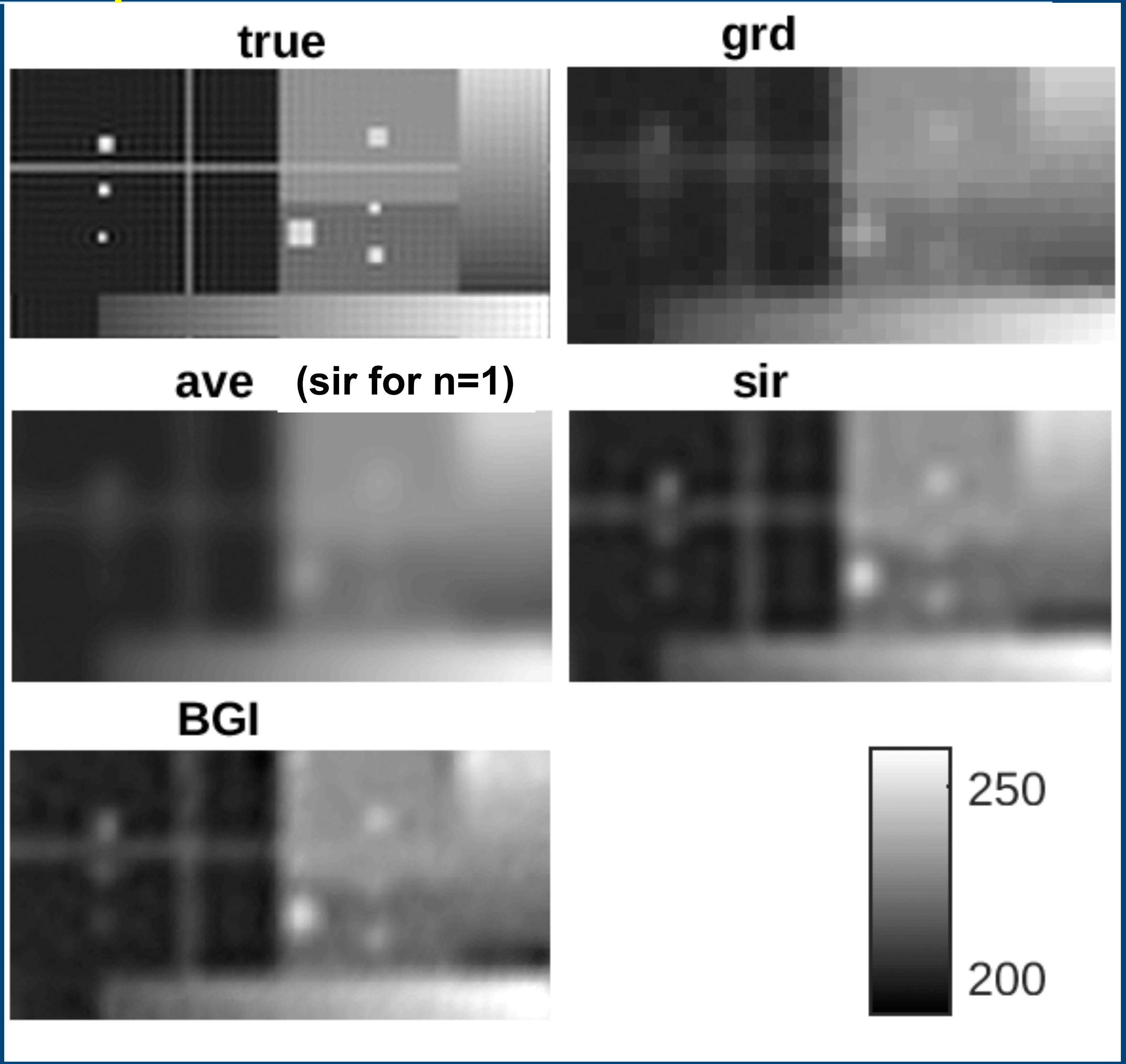
D.G. Long and M.J. Brodzik, "Optimum Image Formation for Spaceborne Microwave Radiometer Products," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 54, No. 5, pp. 2763-2779, 2016.

Optimum Results Comparison

Qualitative comparison of "truth" vs. optimal BG and rSIR results

- BG and rSIR have smaller RMS error than GRD
- Computational time:

GRD << rSIR << BG



Optimum Results Comparison

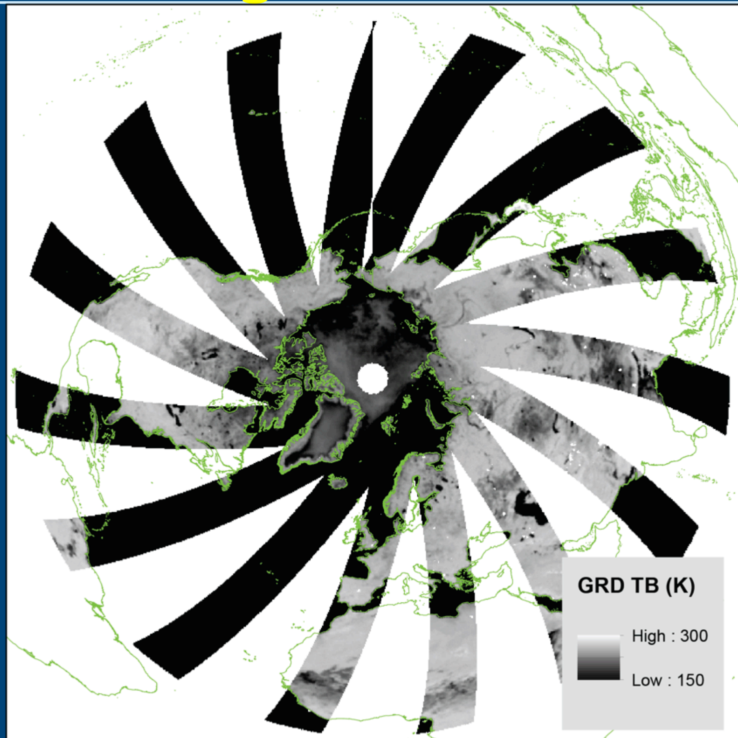
	Case	Mean	STD	RMS
Noise-free	N-F GRD	-0.06	5.62	5.62
	N-F Ave	-0.02	5.83	5.83
	N-F rSIR	0.01	4.75	4.75
	N-F BG	-0.24	4.92	4.93
Noisy	Noisy GRD	-0.07	5.63	5.63
	Noisy Ave	-0.03	5.84	5.84
	Noisy rSIR	0.01	4.78	4.78
	Noisy BG	-0.23	5.02	5.03

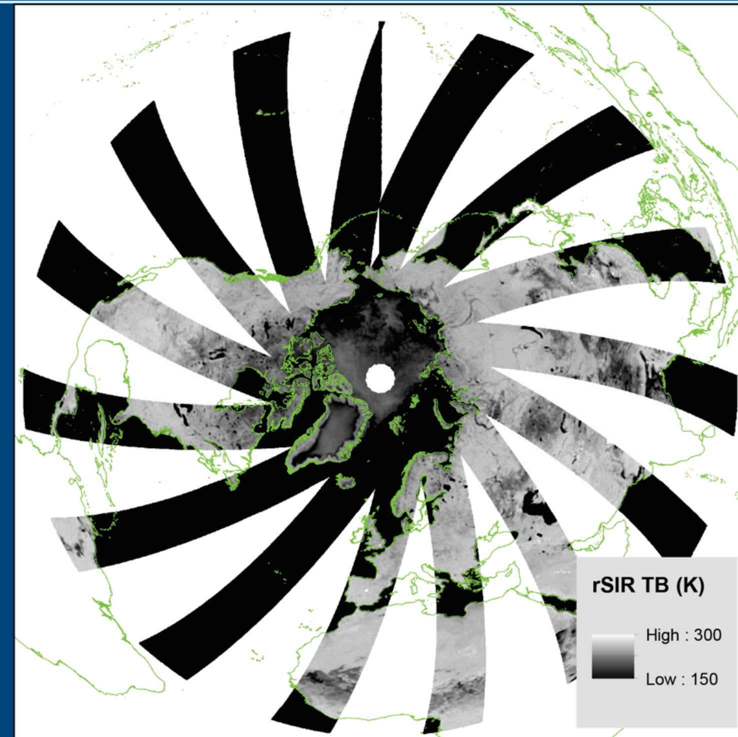
Lowest RMS Error

BG and rSIR have better performance than GRD, since they better model the surface TB: they have smaller signal error

More details in: D.G. Long, "Selection of Reconstruction Parameters for SMAP," project white paper, 2016.

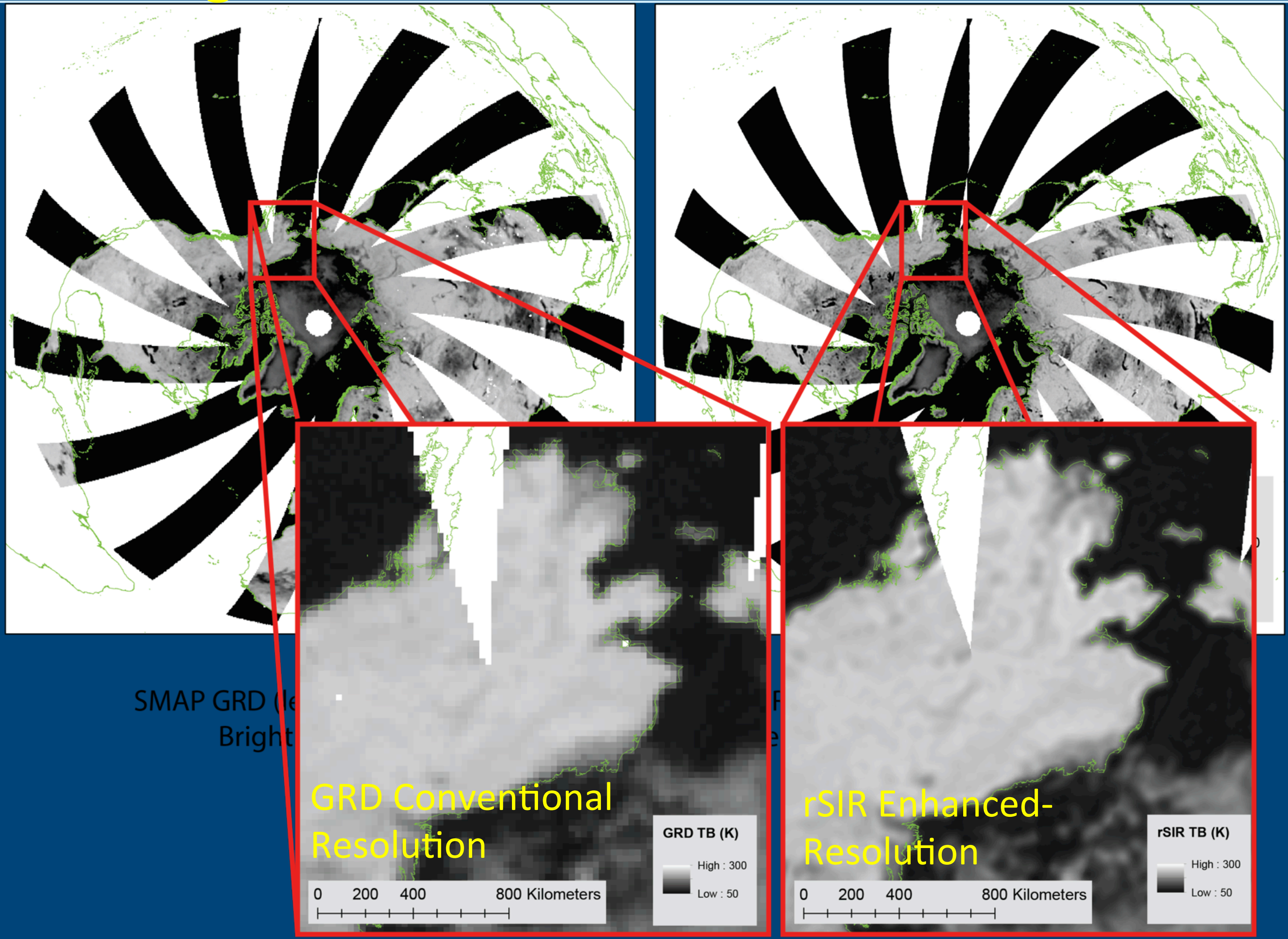
SMAP Images





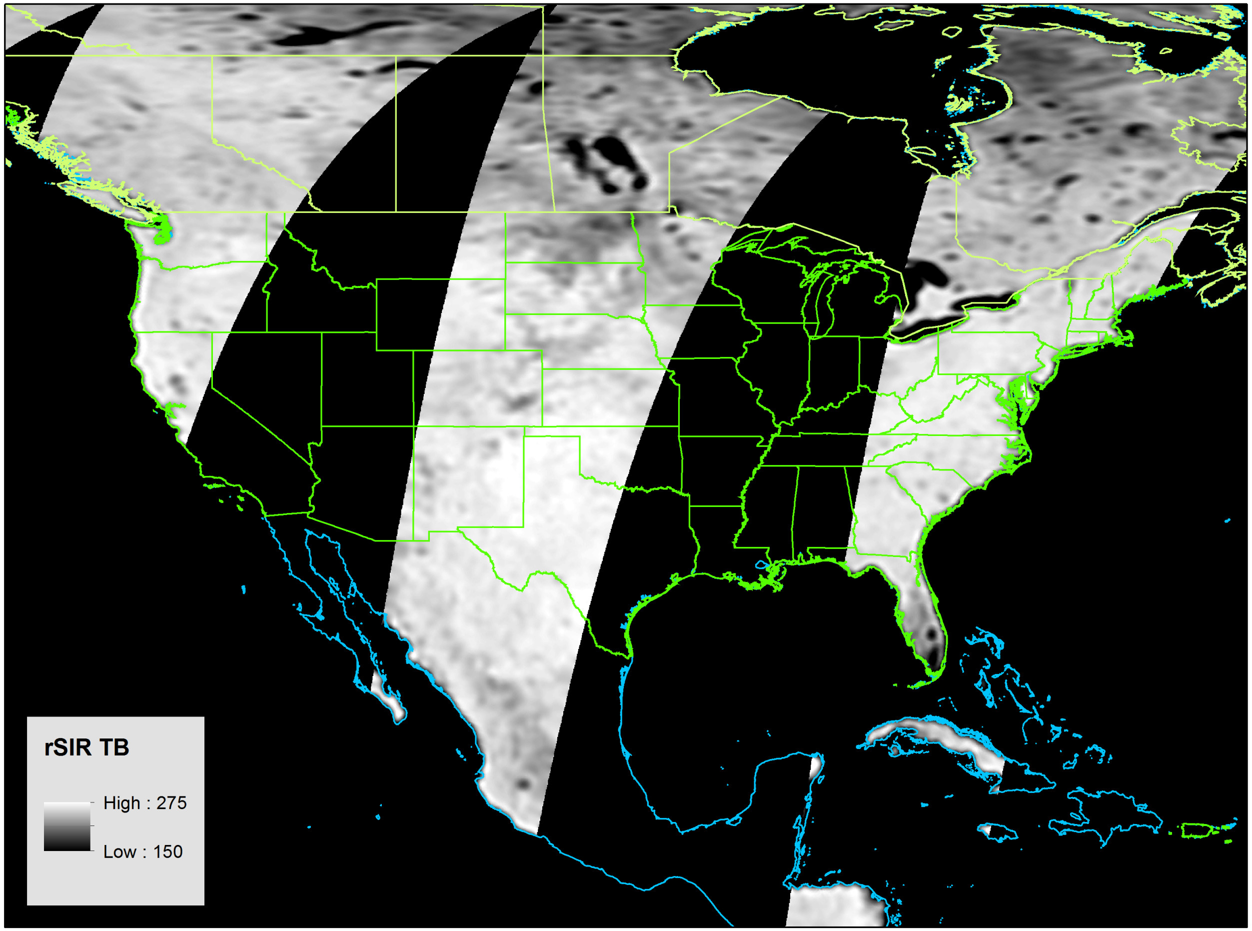
SMAP GRD (left, 25 km) and enhanced-resolution rSIR (right, 3.125 km) morning pass Brightness Temperatures, Northern Hemisphere, 2016 day of year 206

SMAP Images

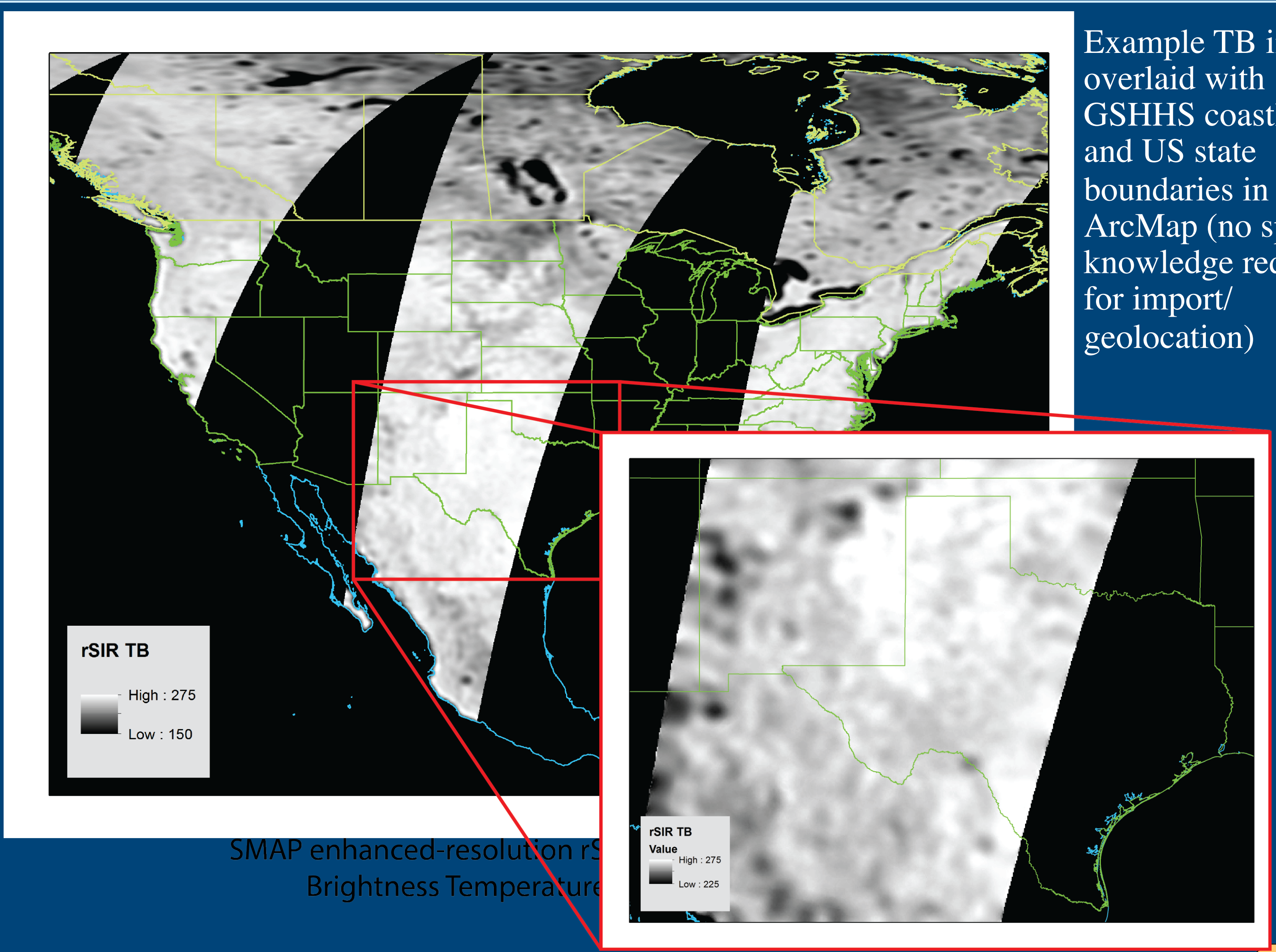


GRD Conventional Resolution
GRD TB (K)
High : 300
Low : 50
0 200 400 800 Kilometers
rSIR Enhanced-Resolution
rSIR TB (K)
High : 300
Low : 50
0 200 400 800 Kilometers
SMAP GRD (le
Bright

rSIR SMAP



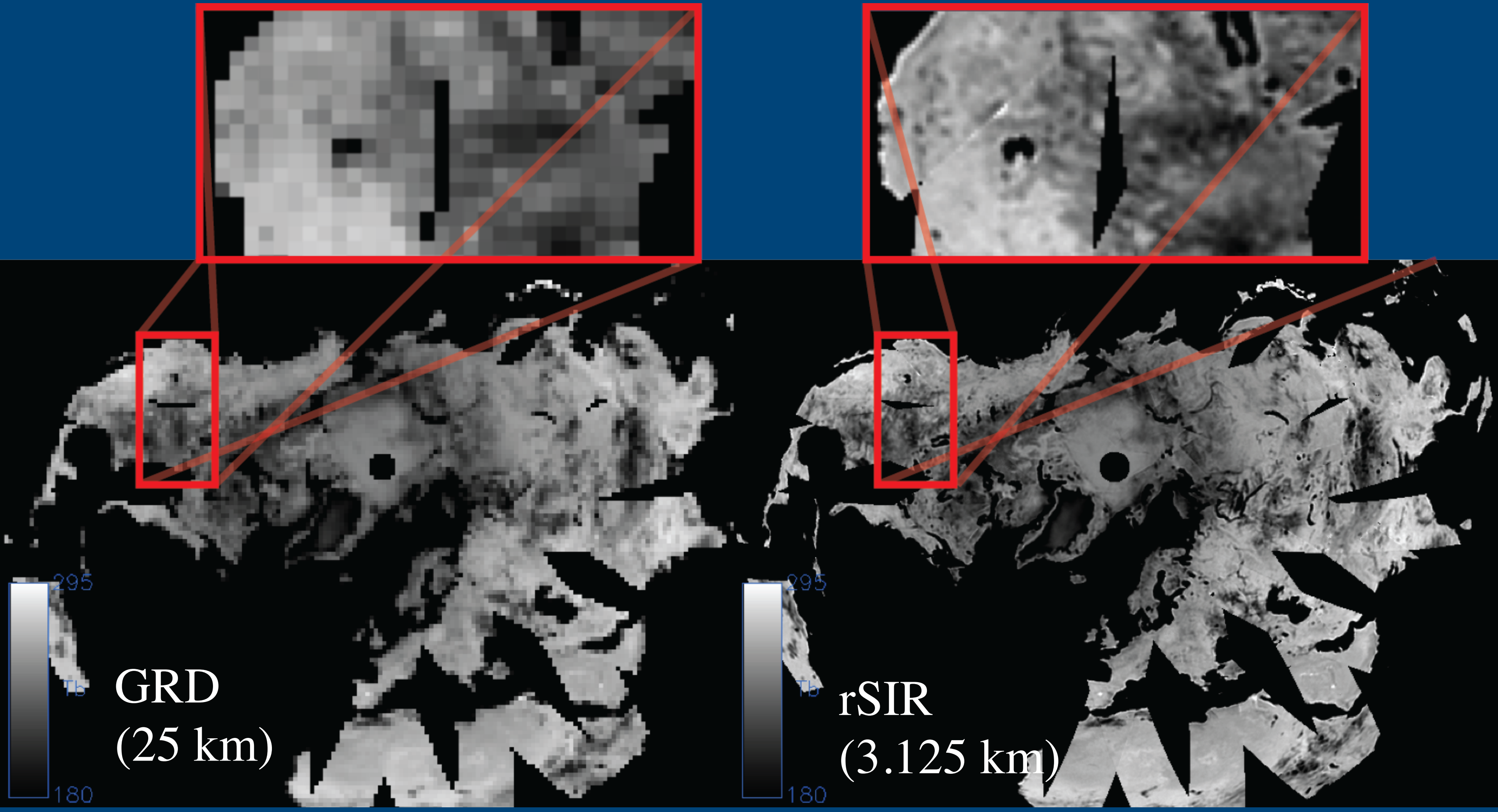
rSIR SMAP



SMAP enhanced-resolution rS
Brightness Temperature

Example TB image overlaid with GSHHS coastlines and US state boundaries in ArcMap (no special knowledge required for import/ geolocation)

SMAP with Multiple Passes



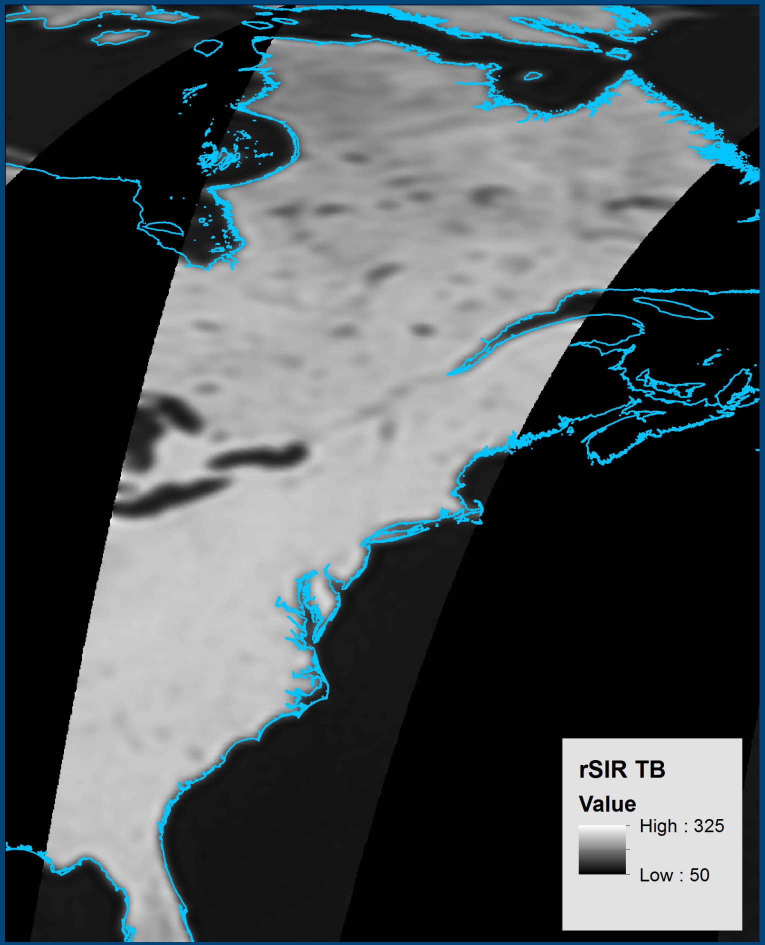
Enhanced-Resolution SMAP TB Images

SMAP L-Band TB images

- On “standard” grids
  - CETB EASE-Grid 2.0 (25 km base, powers of 2 divisors)
  - SMAP EASE-Grid 2.0 (36 km base, 9 and 3 km)
- Low-noise GRD on base grid, with rSIR at higher, enhanced-resolutions
- More work to examine trade-offs of noise with spatio-temporal resolution: How to combine multiple passes?
  - Multiple days will improve spatial resolution and reduce noise, but will smooth temporal change
    - Separate single passes? (can only benefit from measurement overlap)
    - Twice-daily local time of day? (improves spatial resolution with multiple passes at higher latitudes)
    - Daily? Multi-day?

Project Status

- (Part 1) We have demonstrated effectiveness of enhanced-resolution processing for SMAP radiometer TBs
  - rSIR has lower noise, somewhat finer effective resolution than BG
- Enhanced-resolution SMAP products in production, will be available at NSIDC
  - Standard, ltod (25 km base) grids, for comparison/fusion with other sensors
  - On SMAP (36 km base) grids for compatibility with SMAP project reqs, possible combinations: ltod, daily, multi-day
- (Part 2) Now evaluating enhanced-resolution SMAP TBs in soil moisture retrieval algorithms



SMAP 3.125 km GHz H-pol descending overpass brightness temperature GeoTIFF, 2016 doy 206, zoomed to Eastern seaboard, easily overlaid in ArcMap with GSHHS coastlines, no special steps required.

Thank you!

Project: http://nsidc.org/pmesdr

Email: brodzik@nsidc.org

Color CETB AMSR-E 36 GHz H-pol montage uses Viridis colormap (new, perceptually uniform, matplotlib default), more info: https://www.youtube.com/watch?v=xAoljeRJ3lU