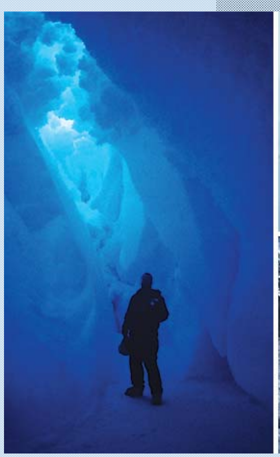
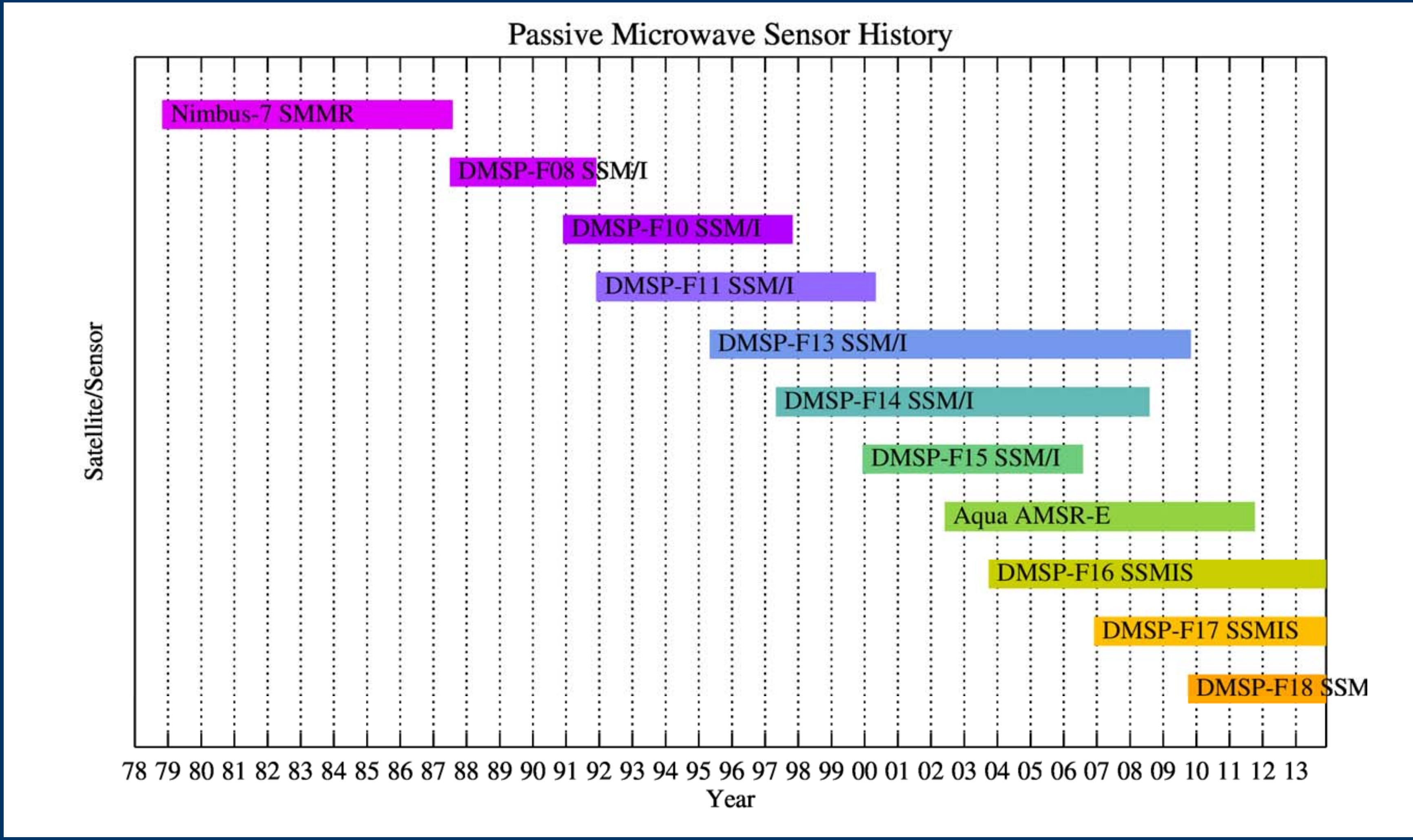


A Climate Record of Enhanced Spatial Resolution Microwave Radiometer Data

D. G. Long, A. Paget*, and M. J. Brodzik†*

* Brigham Young University
† National Snow and Ice Data Center

Earth-observing Passive Microwave (PM) sensors (radiometers)



Availability of SMMR, AMSR-E, SSM/I and SSMIS sensors (dates are approximate); DMSP-F19 launched 3 Apr 2014 and F20 is not yet launched.

The State of Gridded Passive Microwave (PM) Data

Current state of gridded PM data

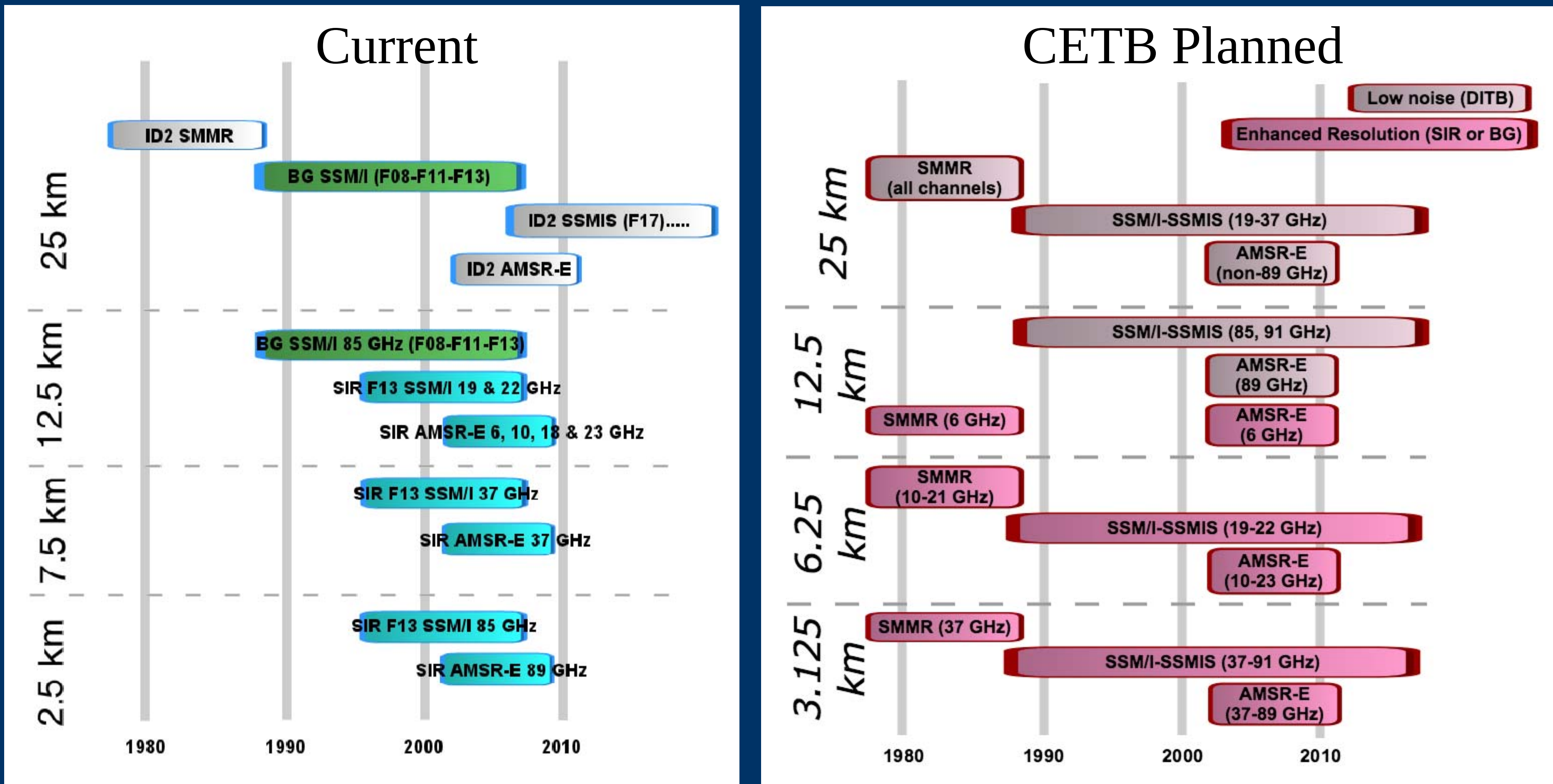
- Various gridding techniques (Ditb, ID2, BG, rSIR image reconstruction)
- Various temporal sampling (daily avg, daily asc/des, daily ltod)
- Mix of Level 2 source data versions (whatever was available at the time it was gridded)
- Mix of resolutions, 25, 12.5 km, some finer to 2.25 km
- Not all data from all sensors has been processed completely any given consistent way

NASA MEaSUREs CETB Project Goals

The *Calibrated, Enhanced-Resolution EASE-Grid 2.0 Brightness Temperature (CETB)* project will:

- Leverage recent work to recalibrate Level 2 PM data record from SSM/I-SSMIS as FCDRs
- Use improved *EASE-Grid 2.0* projection definition
- Use developments in image reconstruction to enhance spatial resolution in addition to conventional gridded
- Process all data (instead of only 1 month sensor overlaps) from SMMR, all SSM/I-SSMIS and AMSR-E
- Data distribution will be from NSIDC DAAC
- Software to be turned over to the DAAC for ongoing processing

CETB: Calibrated, Enhanced-Resolution EASE-Grid 2.0 TBs



Time series of current (left) set of gridded passive microwave data sets, compared to planned (right) CETB ESDR. The various processing methods are indicated by colors; lengths of colored bars approximate respective periods of record. Note the consistency of the processing of the proposed products.

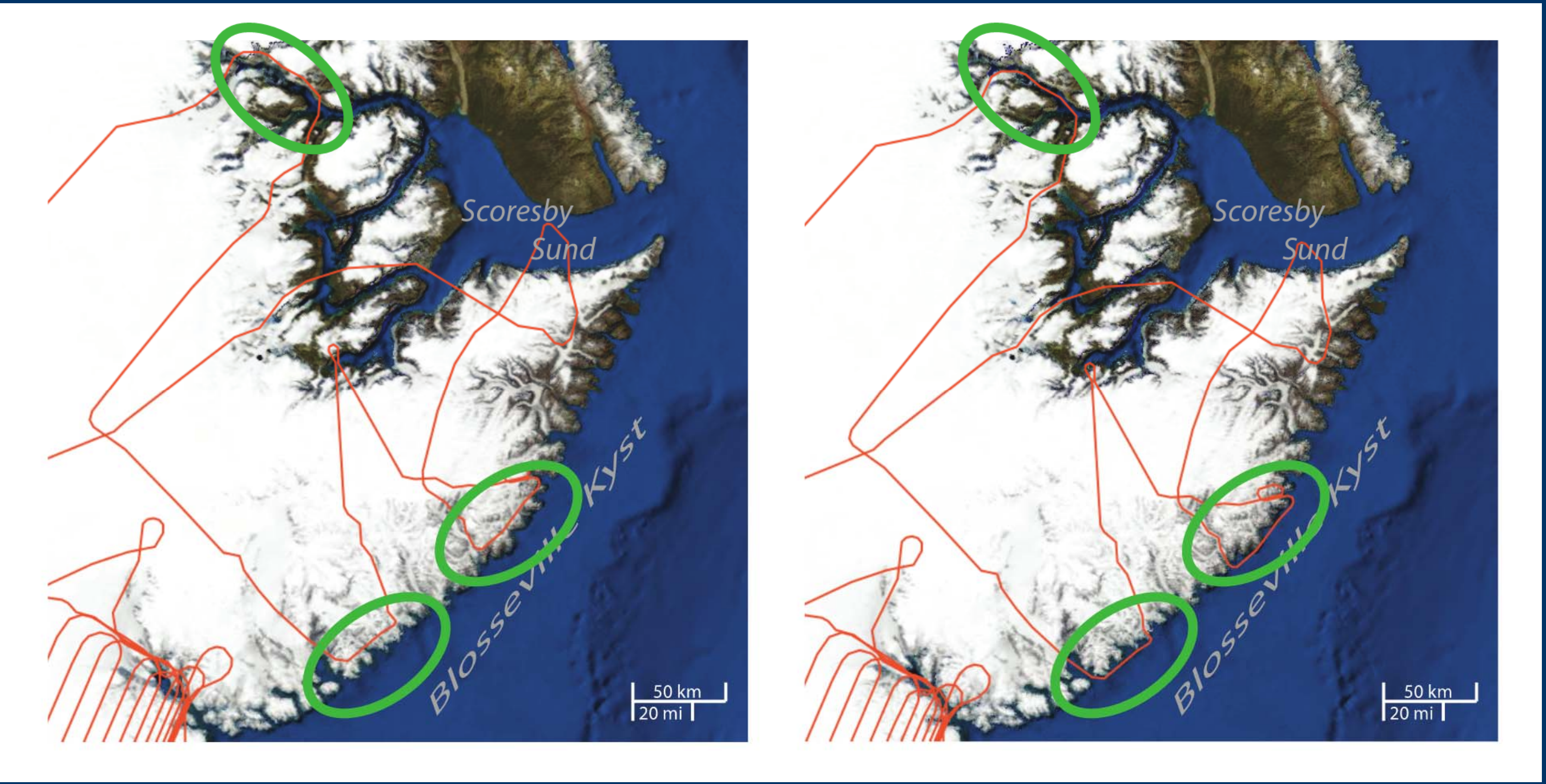
Input swath data

CETB product uses the latest available reprocessing/recalibration available by sensor:

Sensor	Years	Swath Data	Source	Reference
SMMR	1978-1987	Nimbus-7 SMMR Pathfinder TBs	NSIDC	Njoku, 2003
SSM/I-SSMIS*	1987-present	CSU FCDR, V1	CSU	Berg et al., 2013; Sapiano et al, 2013
SSM/I-SSMIS*	1987-present	RSS FCDR, V7	RSS	Hilburn and Wentz, 2008
AMSR-E	2002-2011	AMSR-E/Aqua L2A Global Swath Spatially-Resampled TBs, V3	NSIDC	Ashcroft and Wentz, 2013

*CETB will choose between CSU and RSS, depending on feedback from Early Adopters.

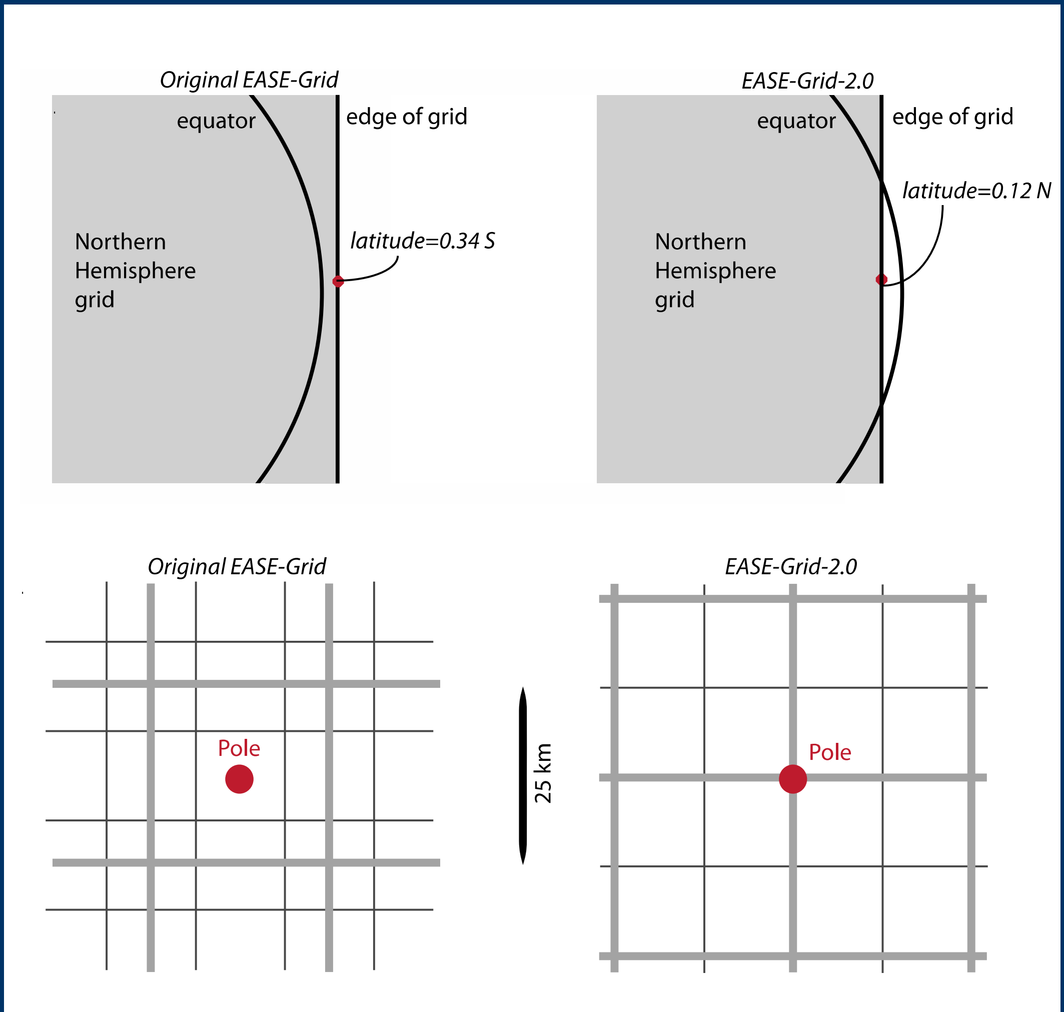
The trouble with EASE-Grid (1.0)



EASE-Grid defined a spherical projection ellipsoid with data referenced to WGS84 datum, but this makes reprojection tricky, because most software assumes the ellipsoid and datum are the same.

Brodzik, M. J., B. Billingsley, T. Haran, B. Raup and M. Savoie. 2012. EASE-Grid 2.0: Incremental but Significant Improvements for Earth-Gridded Data Sets. ***ISPRS Int. J. Geo-Inf.***, 1(32-45).

EASE-Grid 2.0 improvement details



Defines the equator barely outside the grid extent, to ensure corner pixels are well-defined.

Changes higher-resolution grid definitions from bore-centered to nested.

Brodzik, M. J., B. Billingsley, T. Haran, B. Raup and M. Savoie. 2012. EASE-Grid 2.0: Incremental but Significant Improvements for Earth-Gridded Data Sets. ***ISPRS Int. J. Geo-Inf.***, 1(32-45).

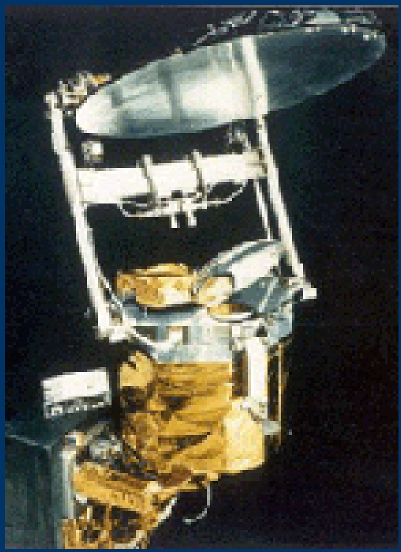
EASE-Grid (1.0) vs. EASE-Grid 2.0

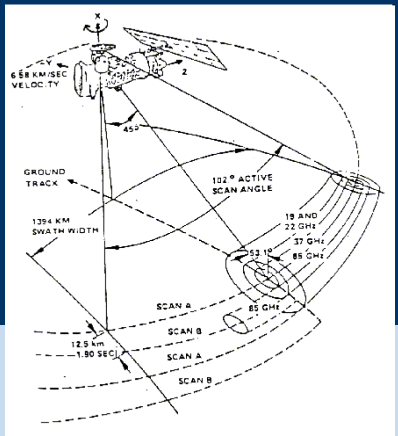
	EASE-Grid (1.0)	**EASE-Grid 2.0**
Projection spheroid	International 1924 Authalic Sphere	WGS84*
Pole location	Center of center cell	Intersection of center cells
Scale (data-set specific)	Azimuthal/Cylindrical coupled, e.g. Nl/Sl/Ml 25.067525 km	Azimuthal: exact, e.g. 25.0 km or 36.0 km, etc.; Cylindrical: integer-multiples across latitude of true scale
Dimensions	Odd-numbered	Even-numbered
Nested Grids	Force choices between total coverage and nested cells	Coverage can stay the same, only number of cells changes
Corner Points	Undefined: azimuthal grids "wrapped beyond" opposite pole	No undefined corner cells
GeoTIFF	Requires reprojection	Supported w/o reprojection*
Software Issues	Usually requires user to understand "custom projection" settings	Most software will "do the right thing"*

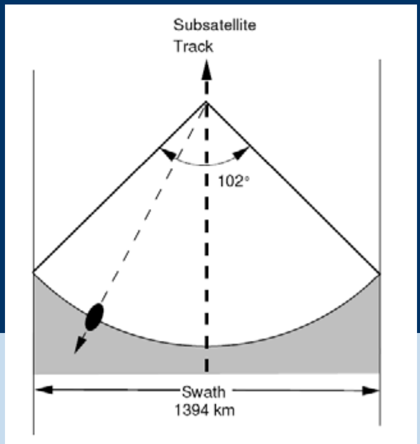
Footnote: ***** *Key to success for geoTIFF is setting projection ellipsoid to the reference datum.*

Special Sensor Microwave/Imager (SSM/I)

- Microwave radiometer operated on a series of DMSP weather satellites
  - Almost continuously since 1987
- Seven channels at ~51 deg incidence angle
  - Variable resolution/channel
  - Three dual-polarized channels (19.35, 37, 85.5 GHz)
  - One single polarization channel (22.2 GHz)
- 1400 km wide swath
- Cross-calibration issues



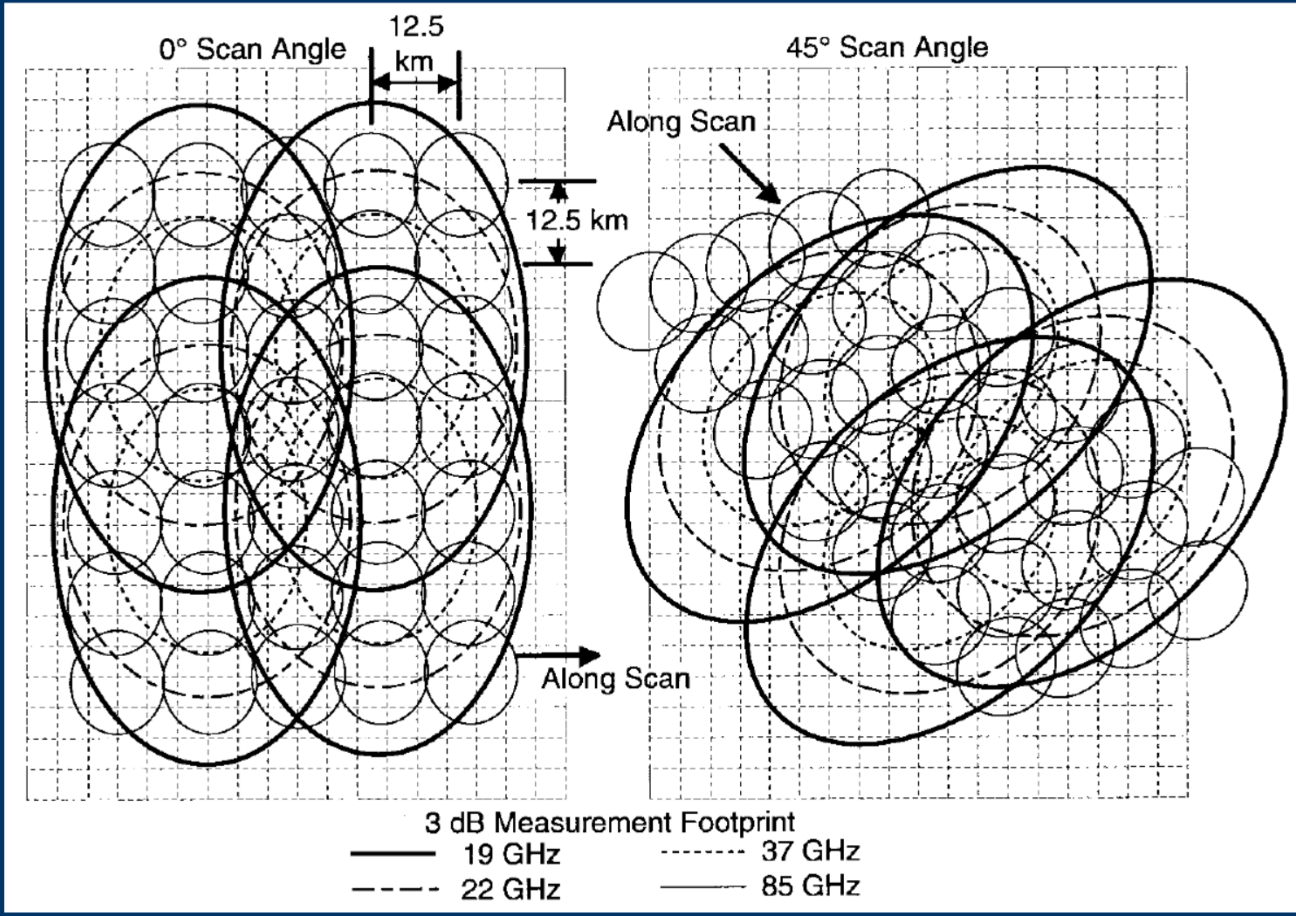




Comparison of footprints between channels

In addition to conventional processing, the CETB Product uses oversampled measurements to enhance gridded spatial resolution

SSM/I measurement footprints



Antenna Temperature

Apparent antenna temperature distribution

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

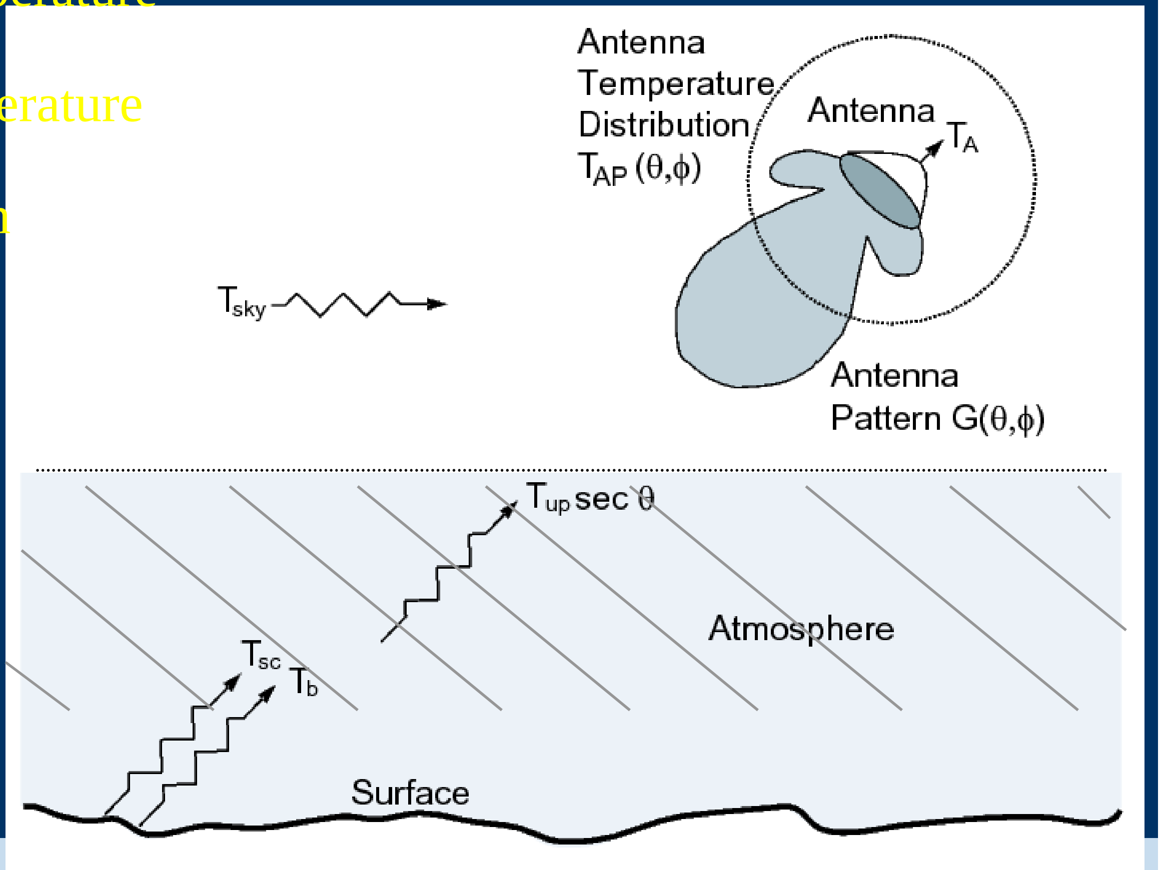
$T_b = \varepsilon T_p$ Surface brightness temperature

T_{sc} Surface scattering temperature

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

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

T_{sky} Sky temperature



Antenna temperature

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

Image Reconstruction

Typical SSM/I measurement density improvement with multiple passes. Image reconstruction techniques take advantage of irregular sampling locations.

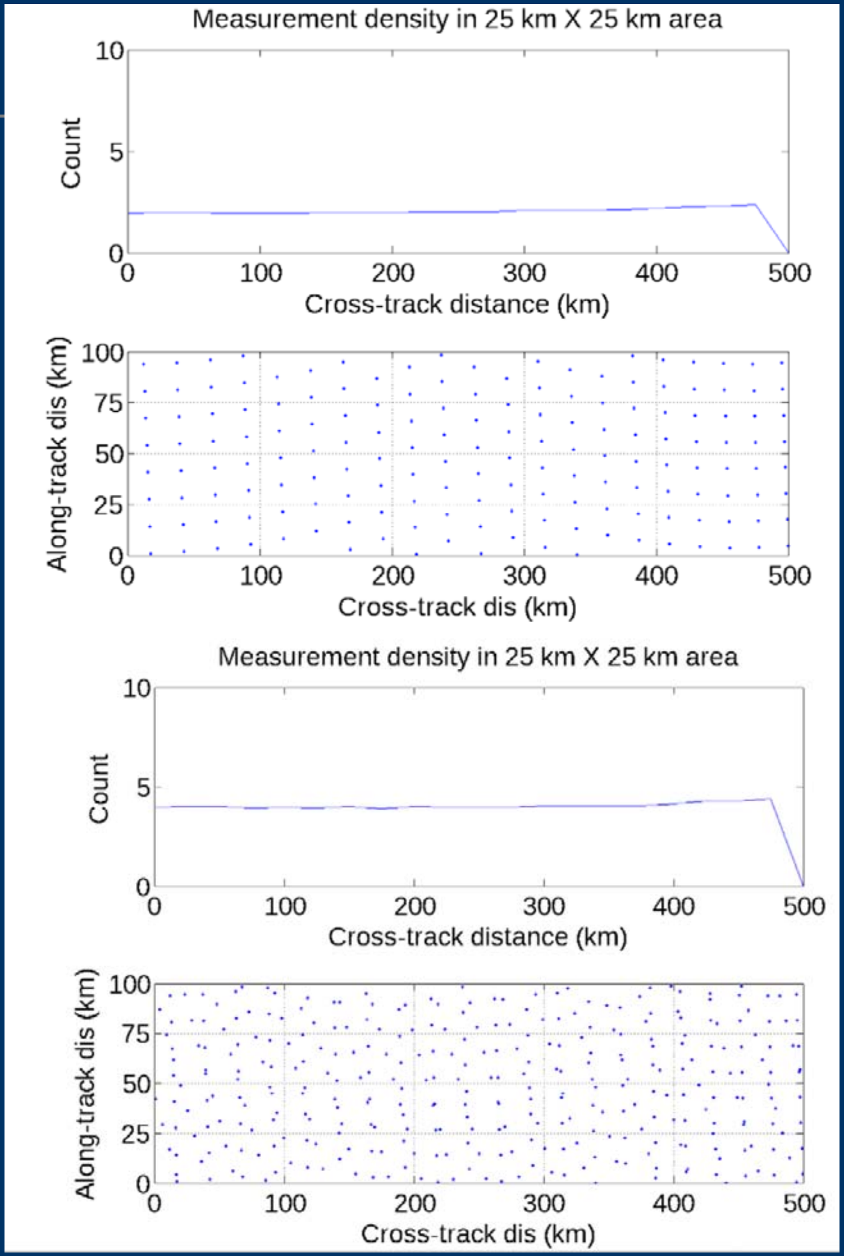
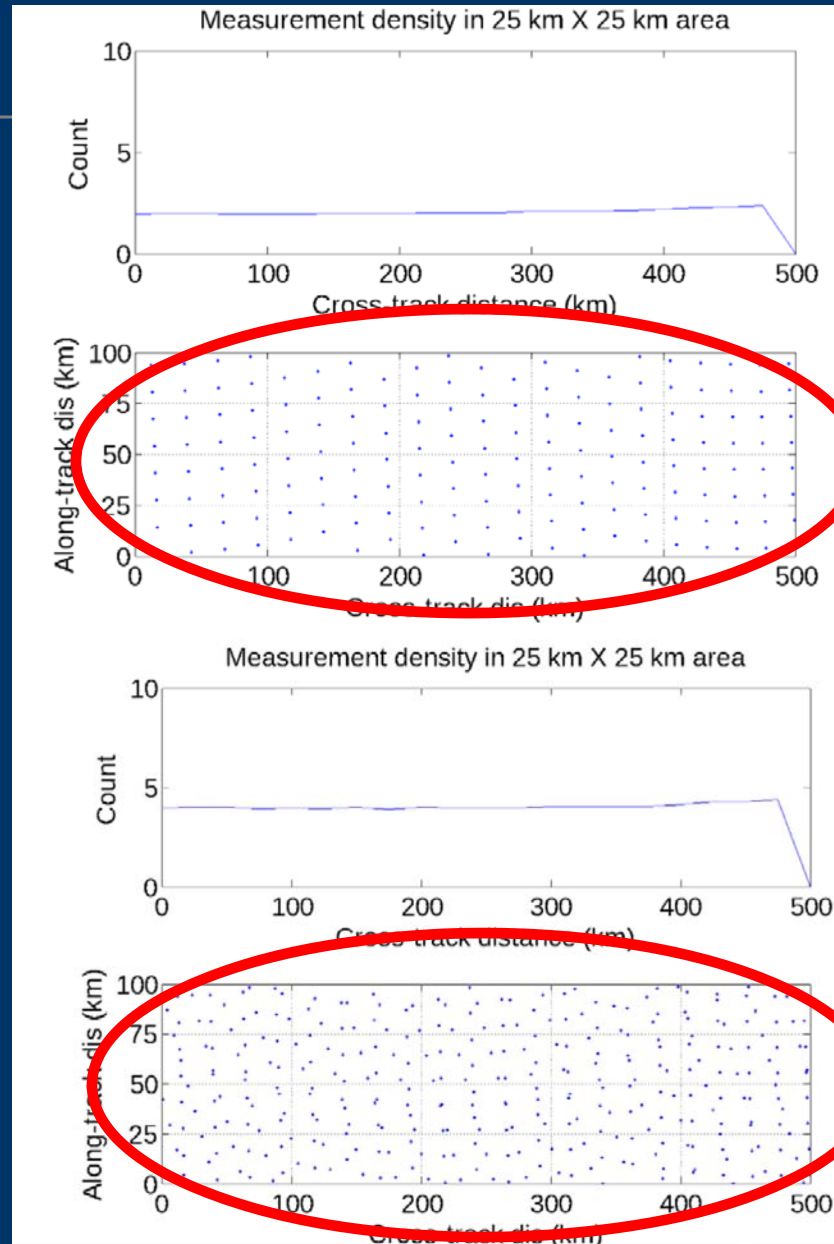


Image Reconstruction

Typical SSM/I measurement density improvement with multiple passes. Image reconstruction techniques take advantage of resulting irregular sampling locations.



Backus Gilbert and rSIR

Backus Gilbert (BG) and *radiometer version of Scatterometer Image Reconstruction (rSIR)* both can be tuned for either enhanced spatial resolution or low noise—but not both.

Both techniques require a reasonable knowledge of the instrument antenna pattern, which determines the Measurement Response Function (MRF) to weight the contribution of overlapping measurements to a given gridded pixel TB.

	BG	**rSIR**
Technique	Matrix Inversion (slow)	Iterative (at least 10x faster)
Tuning Parameter	"gamma" (dimensionless)	N=number of iterations

MRFs

Exact knowledge of the antenna pattern is not required: a reasonable approximation is a 2-D Gaussian.

(Good: we don't know all of them!)

(Long, 2015, An Investigation of Antenna Patterns for CETB. http://nsidc.org/pmesdr)

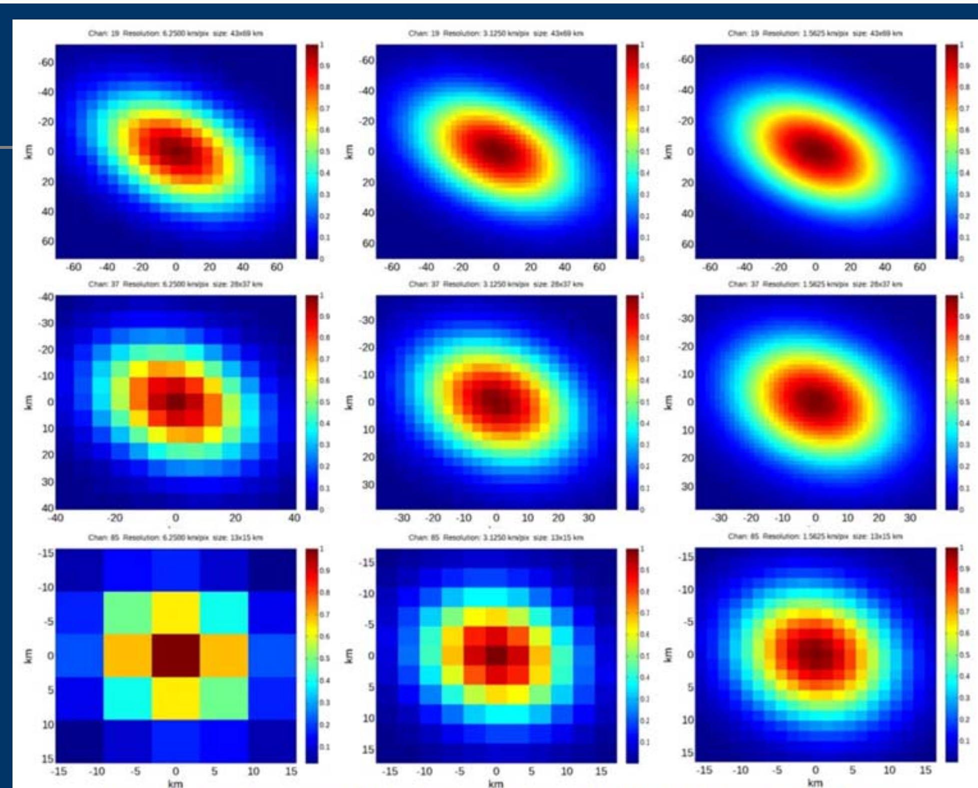
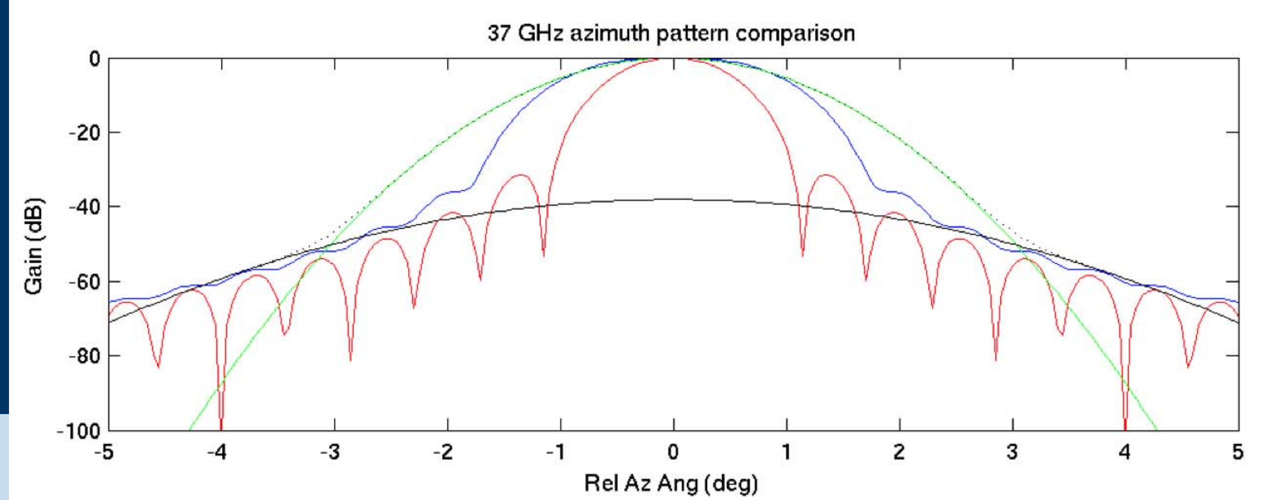


Figure 13. Illustrative sampled MRF for channels (top row) 19 GHz, (middle row) 37 GHz, (bottom row) 85 GHz and pixels sizes (left column) 6.25 km, (middle column) 3.125 km, (right column) 1.5625 km. The MRF size in km is the same for a given channel (row). The pixel sizes are the same in each column, though the area covered by the image varies. The axes are in km and vary by image. The color scale is unit-less gain. In the plots shown here, the MRF is normalized to one at the peak.



Backus Gilbert and rSIR

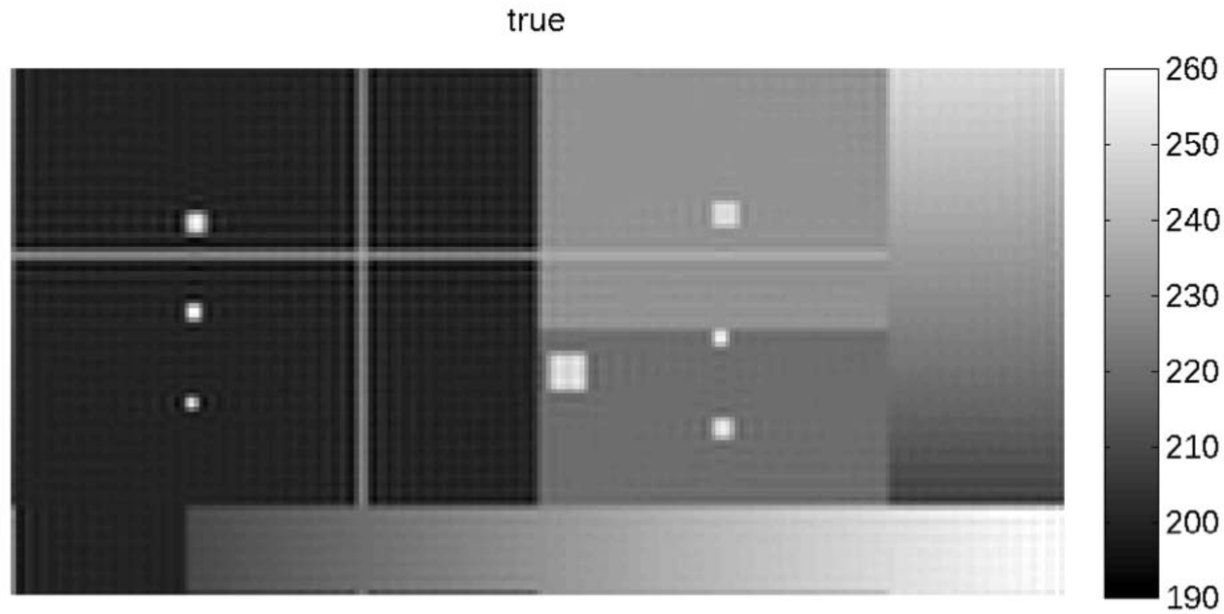


Figure 12. Example synthetic "truth" image for Ps=3.125 km. Units are K. Image has been bandpass filtered to 10 km effective resolution, which accounts for the Gibbs phenomena at boundaries. Features where were arbitrarily selected to illustrate different target sizes.

We determined (subjective) "best" BG/rSIR tuning parameters using a synthetic truth image.

(Long, 2015, Selection of Reconstruction Parameters. http://nsidc.org/pmesdr)

D.G. Long and D.L. Daum, "Spatial Resolution Enhancement of SSM/I Data," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 36, No. 2, pp. 407-417, Mar. 1998.

Backus Gilbert and rSIR

Qualitative comparison of "truth" vs. BG and rSIR result

(Quantitative statistics in white paper)

(Long, 2015, Selection of Reconstruction Parameters. http://nsidc.org/pmesdr)

rSIR produced in a fraction of the computational time of BG

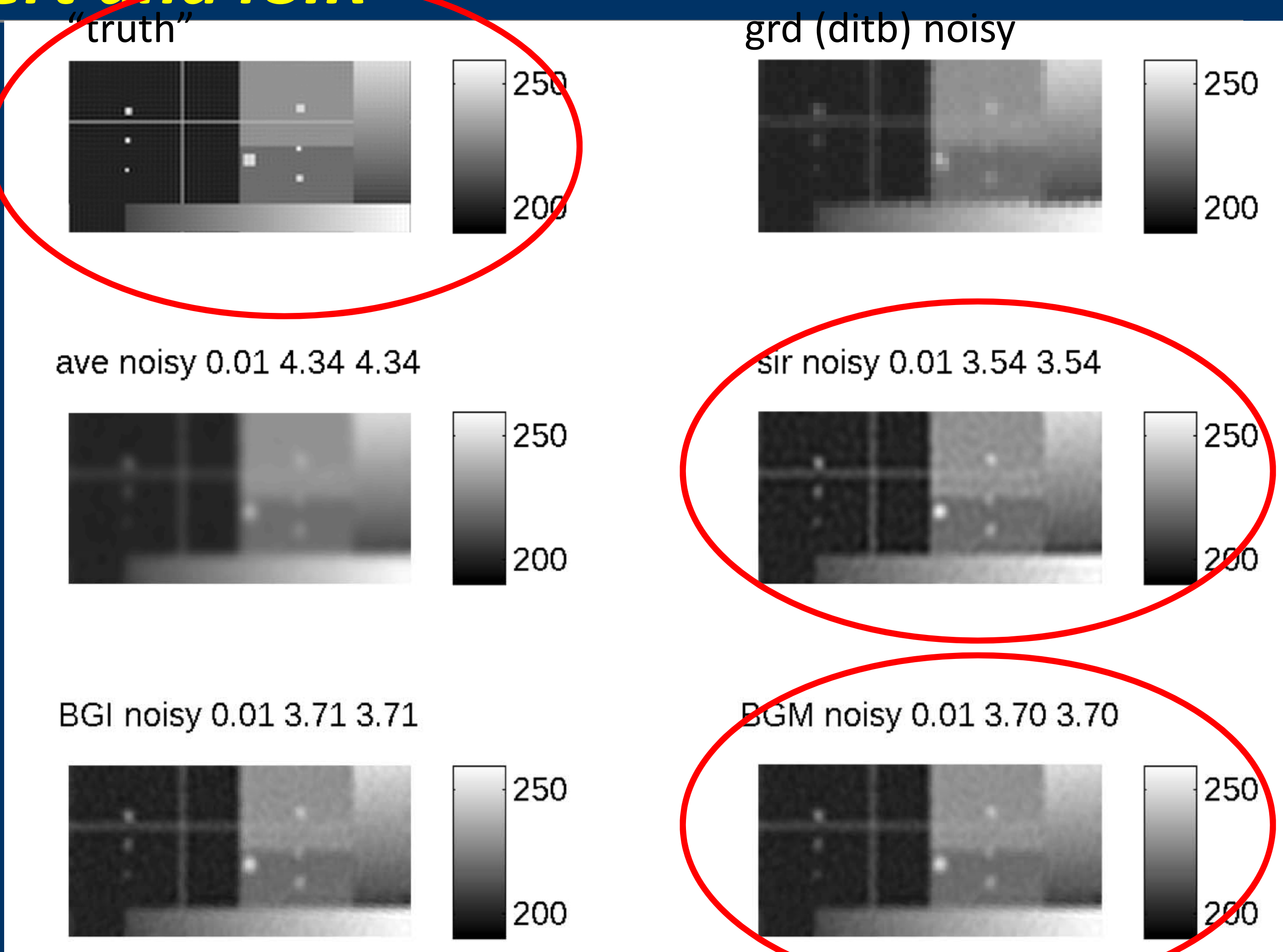


Figure 26. Comparison of true, Non (Grd), Ave, SIR, and BGI images with γ'=0.45 and BGI with median filter for the 37 GHz channel with N_s=3. Note the reduction in RMS error in BGI after median filtering.

D.G. Long and D.L. Daum, "Spatial Resolution Enhancement of SSM/I Data," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 36, No. 2, pp. 407-417, Mar. 1998.

Conventional versus rSIR results

SIR results for N=20 iterations,

at various frequencies.

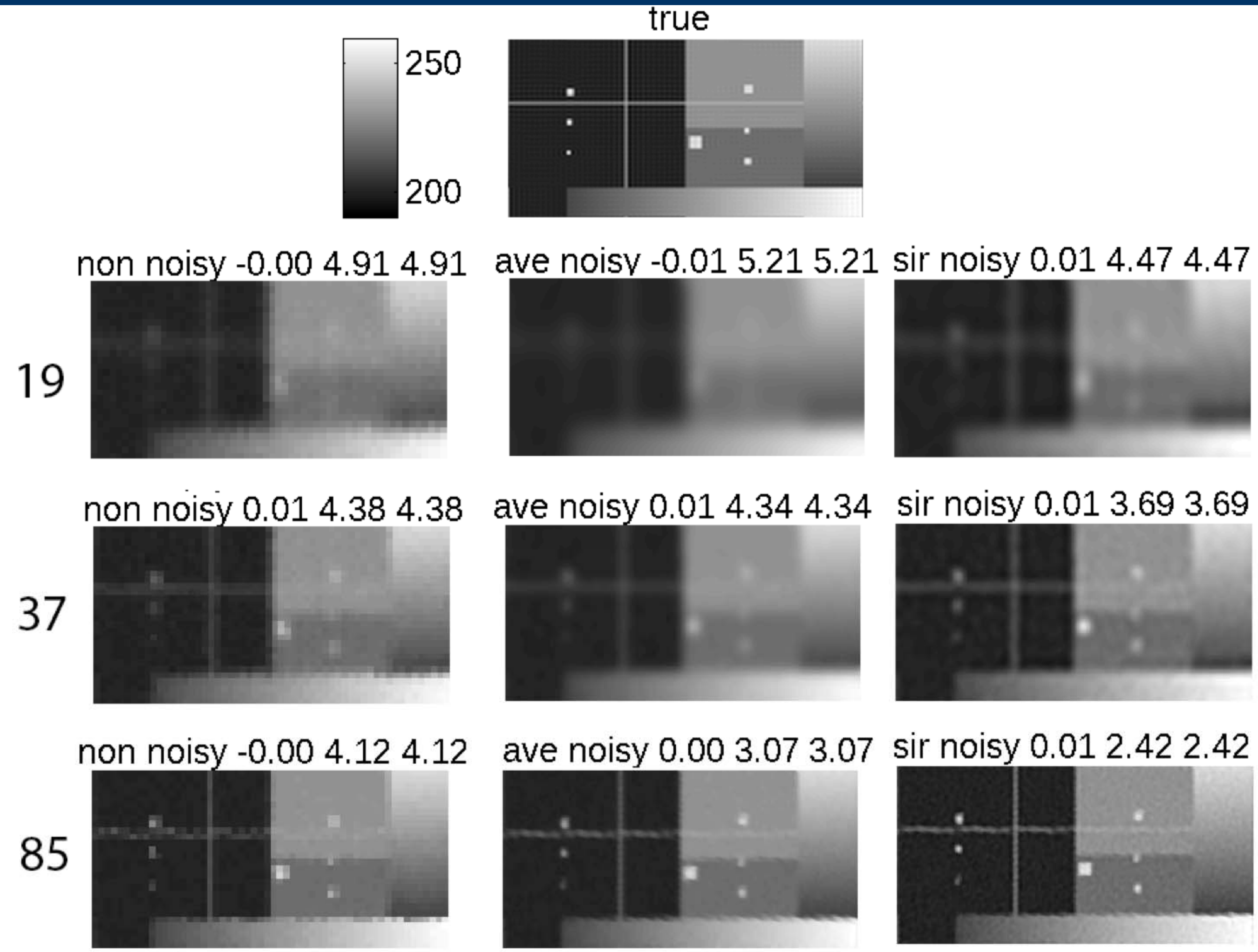


Figure 21. Comparison of (left column) NON, (center column) AVE, and (right column) SIR images for the (top full row) 19, (center full row) 37 and (bottom row) 85 GHz channels for N_s =3, 20 SIR iterations, and two passes. The top row image shows the true synthetic image.

(Long, 2015, Selection of Reconstruction Parameters. http://nsidc.org/pmesdr)

Backus Gilbert and rSIR

Tuning parameters for prototype data, (details in Enhancement Tradeoffs white paper)

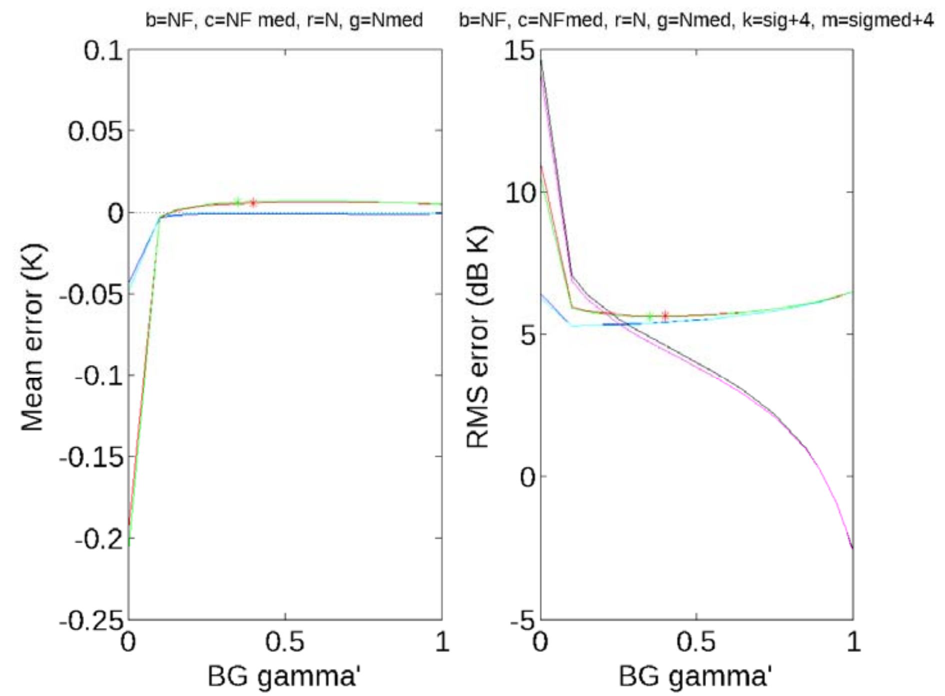


Figure 24. RMS error versus γ' for the 37 GHz channel with *Ns=3*.

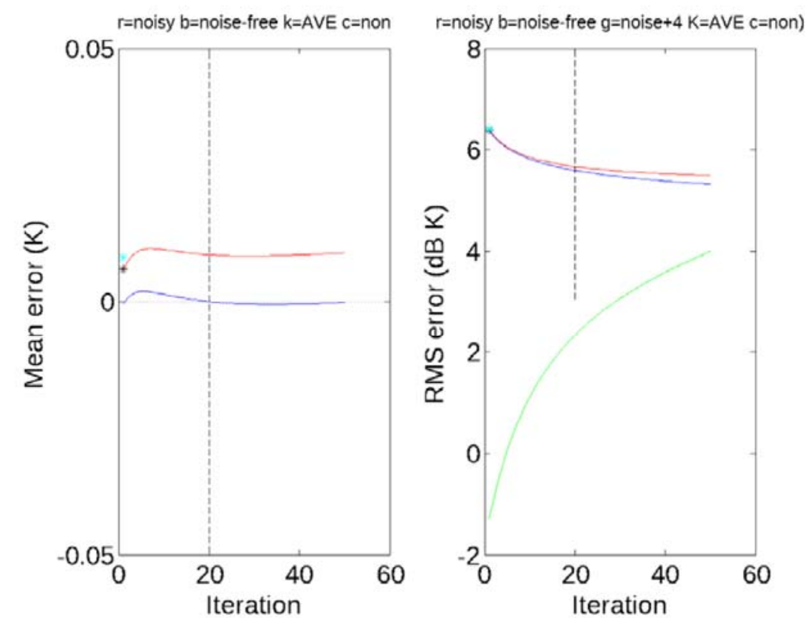
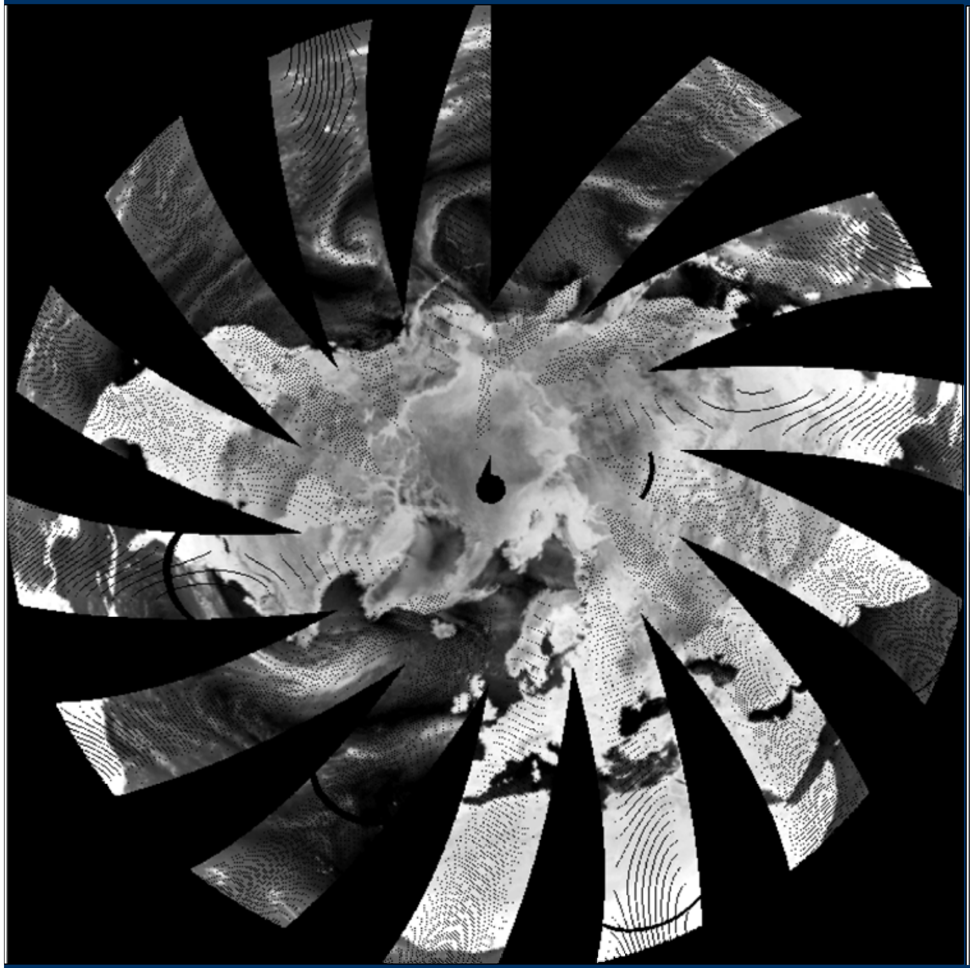


Figure 16. 37 GHz, dual-pass, Ns=3 SIR image error versus iteration number. (left) mean error. (right) RMS error. The red line is the noisy measurement case, while the blue line is the noise-free

(Long, 2015, Selection of Reconstruction Parameters. http://nsidc.org/pmesdr)

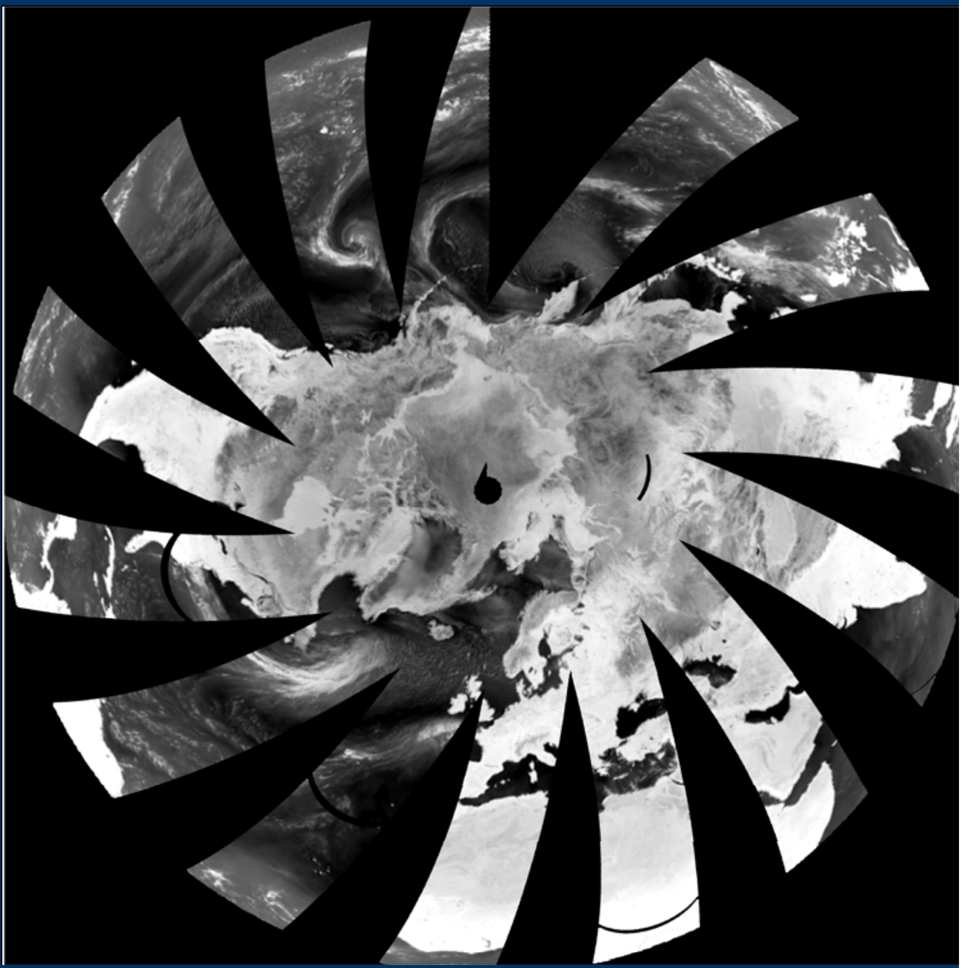
Sample Images

GRD (Low-noise, 25 km) vs. SIR (3.125 km), 1997 day 061 morning passes



Ditb (non) Conventional

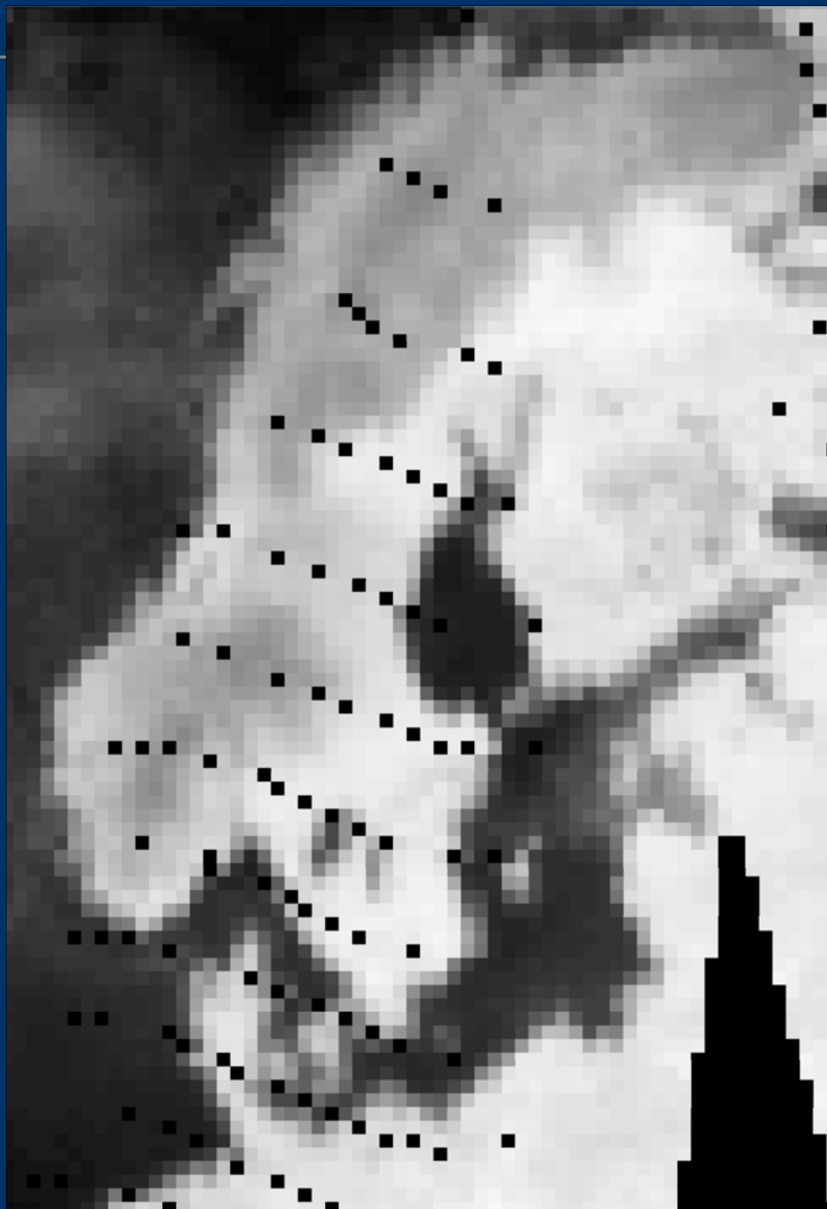
25 km pixels

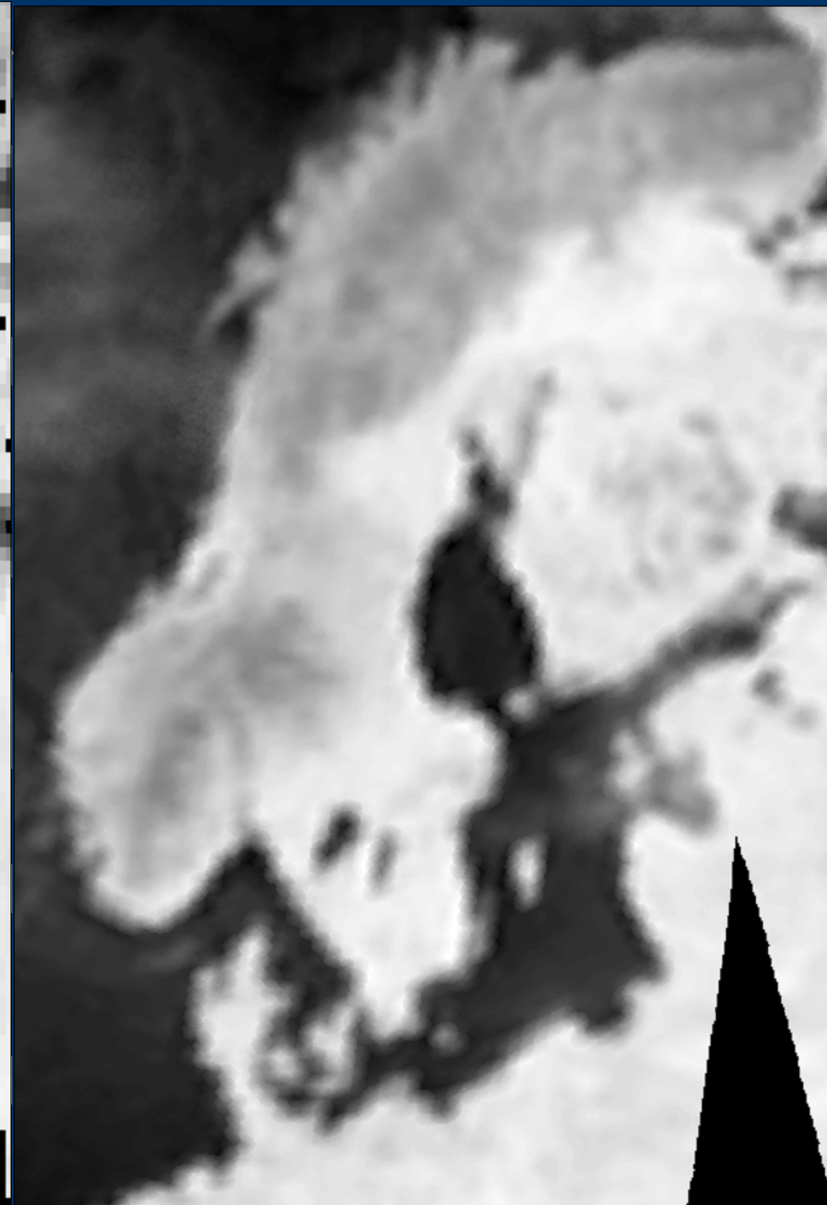


rSIR Enhanced resolution

3.125 km pixels

GRD (Low-noise, 25 km) vs. SIR (3.125 km), 1997 day 061 morning passes

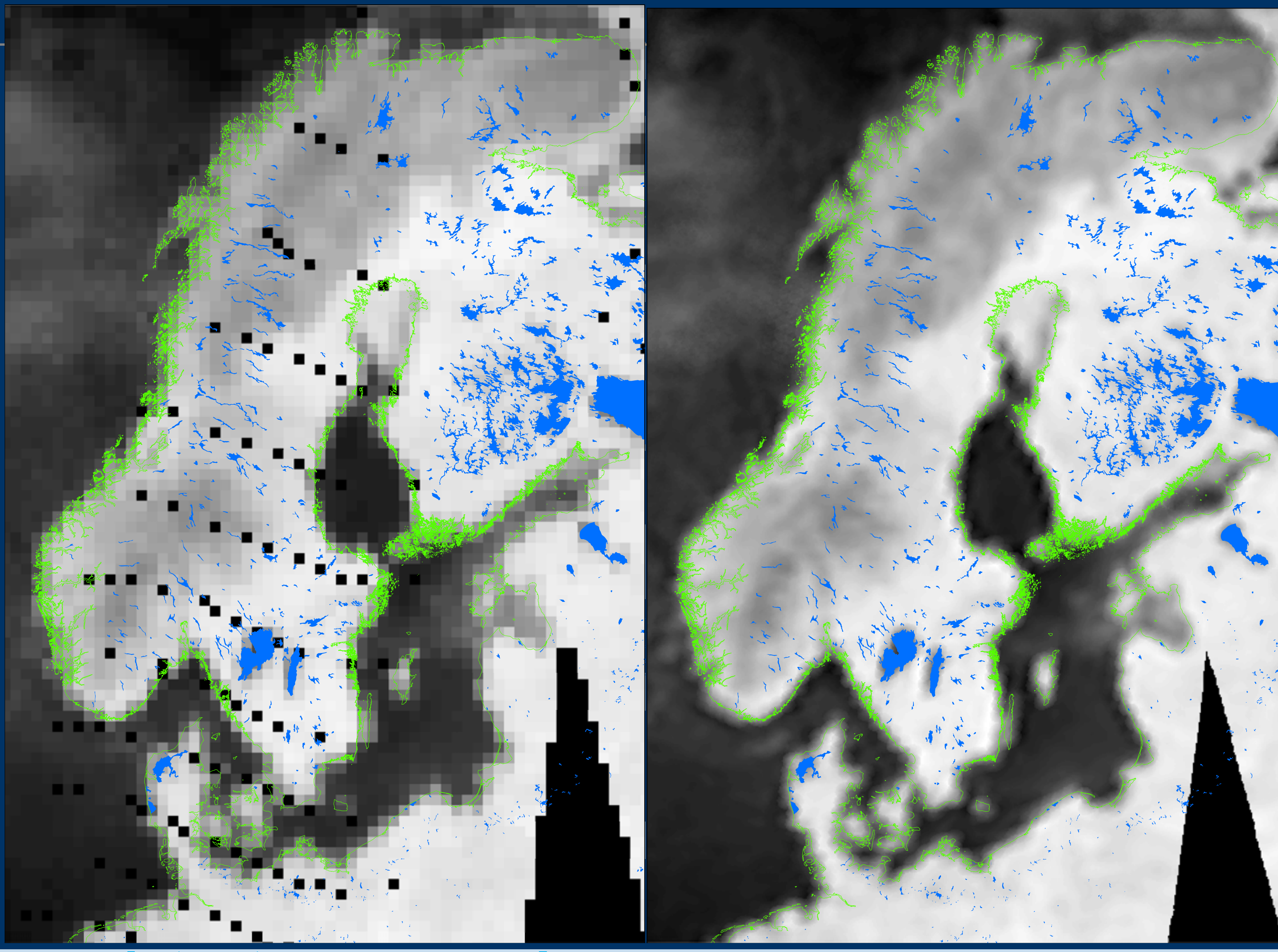




Ditb (non) Conventional
25 km pixels

rSIR Enhanced resolution
3.125 km pixels

GRD (Low-noise, 25 km) vs. SIR (3.125 km), 1997 day 061 morning passes



Ditb (non) Conventional
25 km pixels

rSIR Enhanced resolution
3.125 km pixels

Ltod (Gunn and Long, 2008)

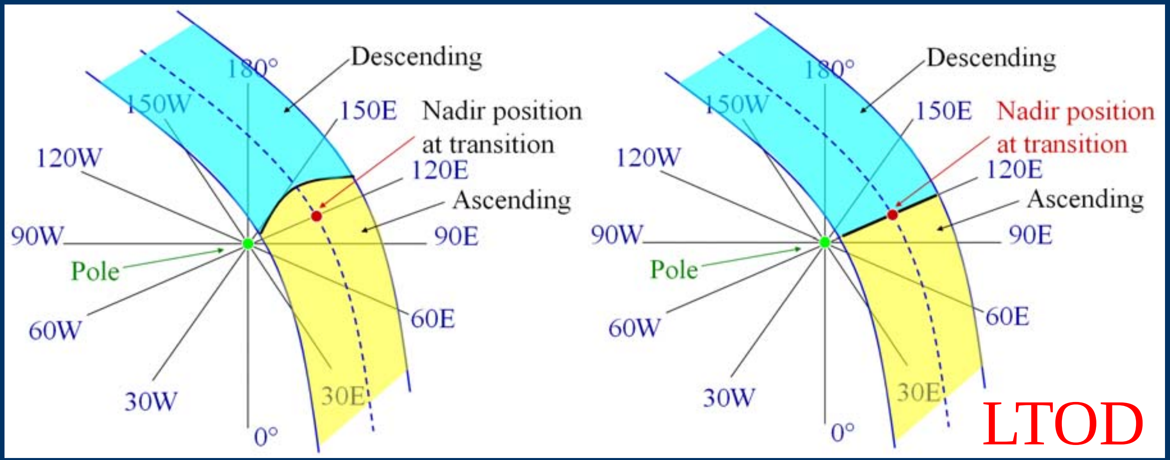
Due to sun-synchronous orbit, a given location is observed at a set of discrete times over the 2-4 day orbit cycle

At equator, this is two measurements 12 hours apart

- – Separate by ascending or descending orbit passes

At the poles, the orbits overlap, resulting in multiple times per day

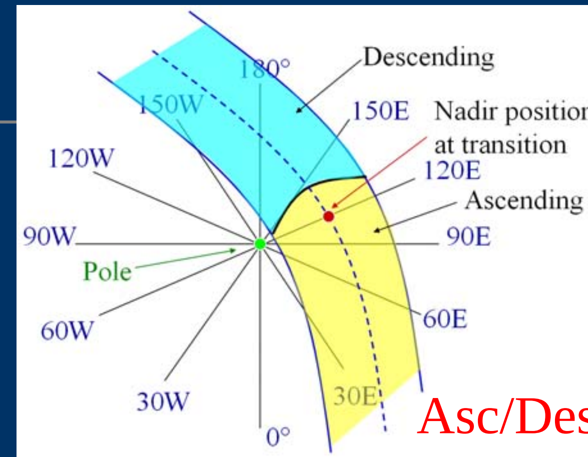
- – Ascending/Descending does not work well
- – Use local time of day (ltod) division instead



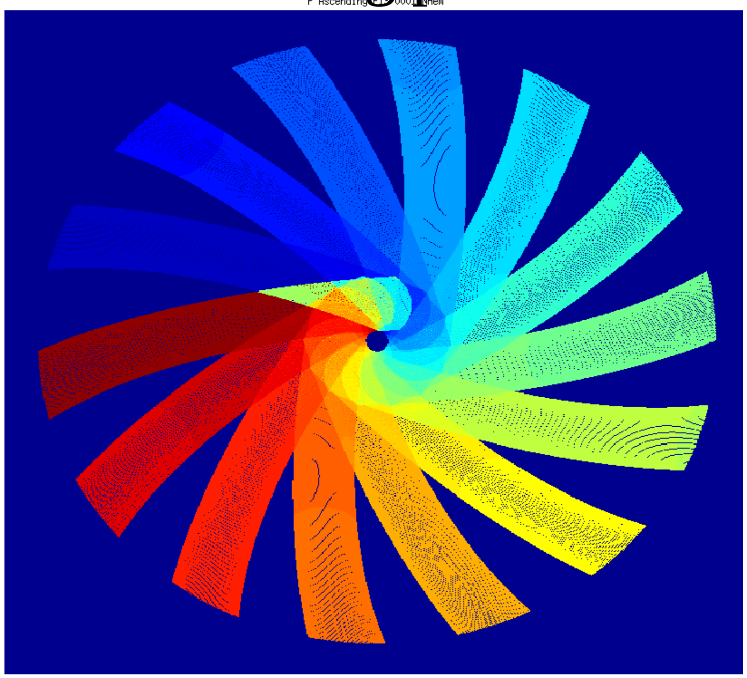
Ascending/Descending

Asc/Dsc Division

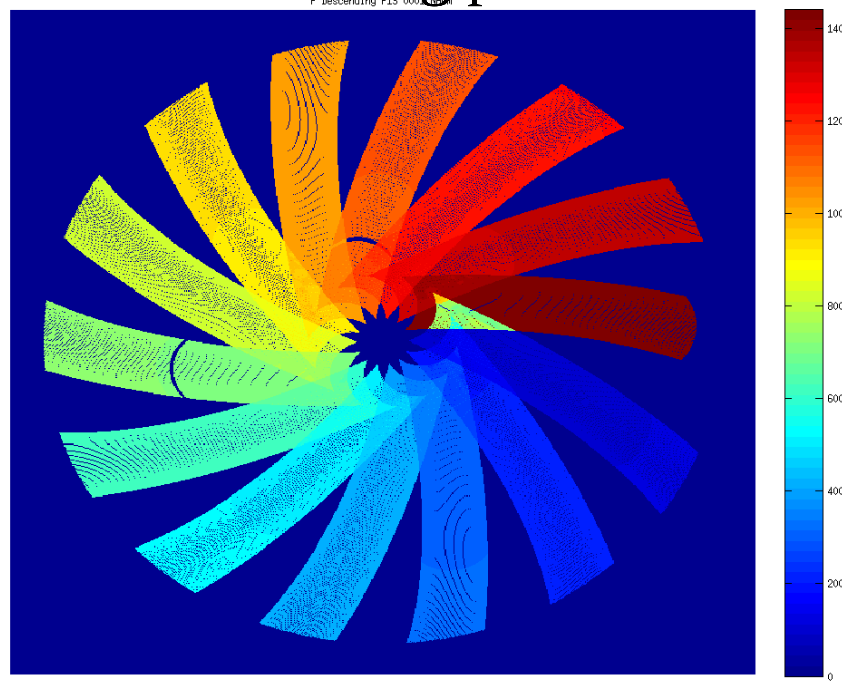
Ascending/Descending



Ascending passes



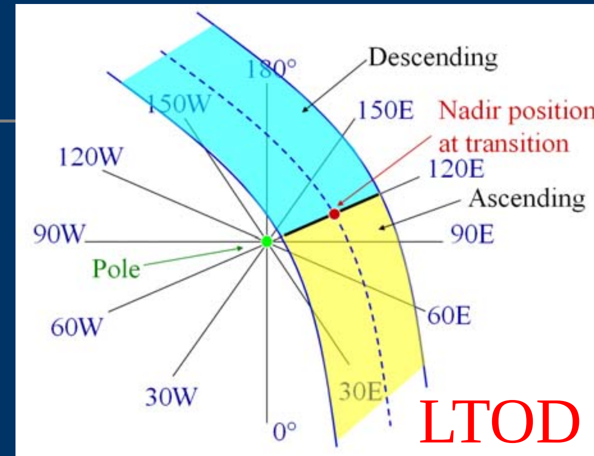
Descending passes



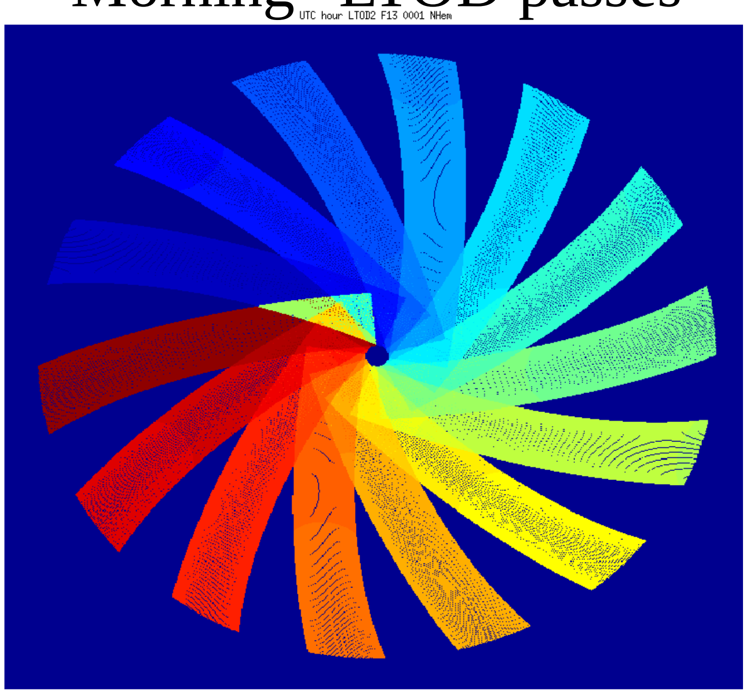
Pass time in minutes from start of UTC day

LTOD Division

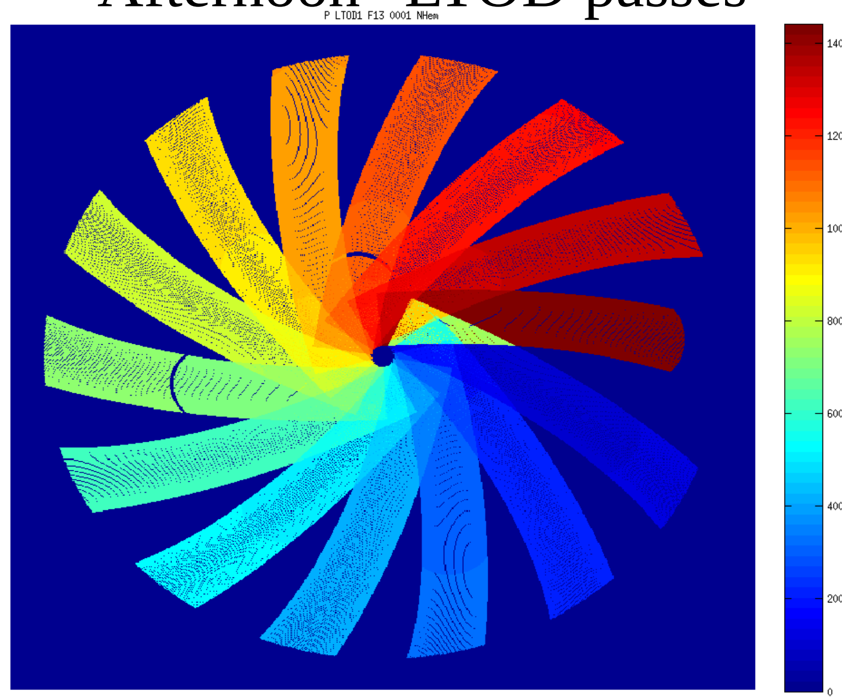
LTOD



“Morning” LTOD passes



“Afternoon” LTOD passes

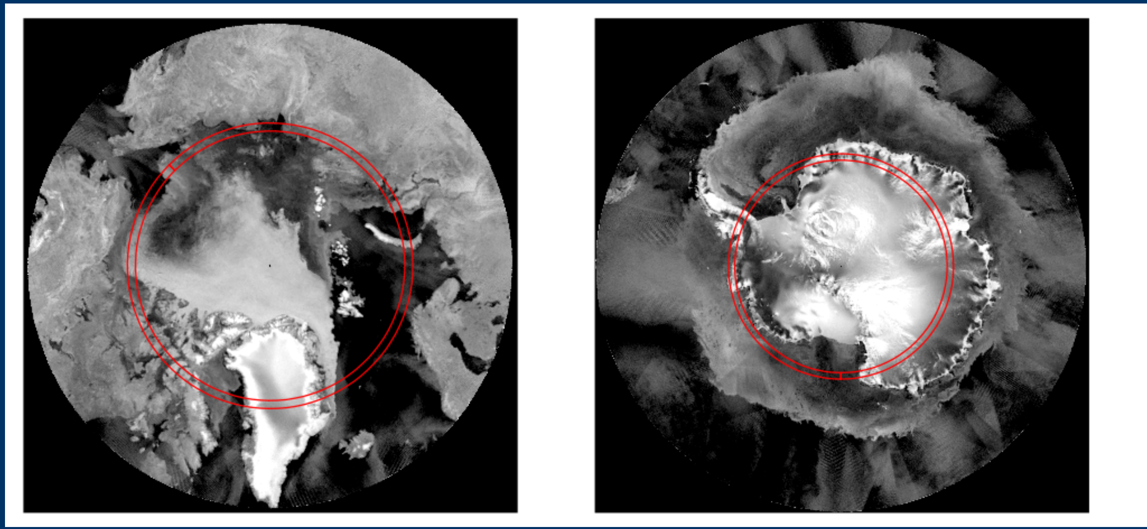


Pass time in minutes from start of UTC day

Ltod (Gunn and Long, 2008)

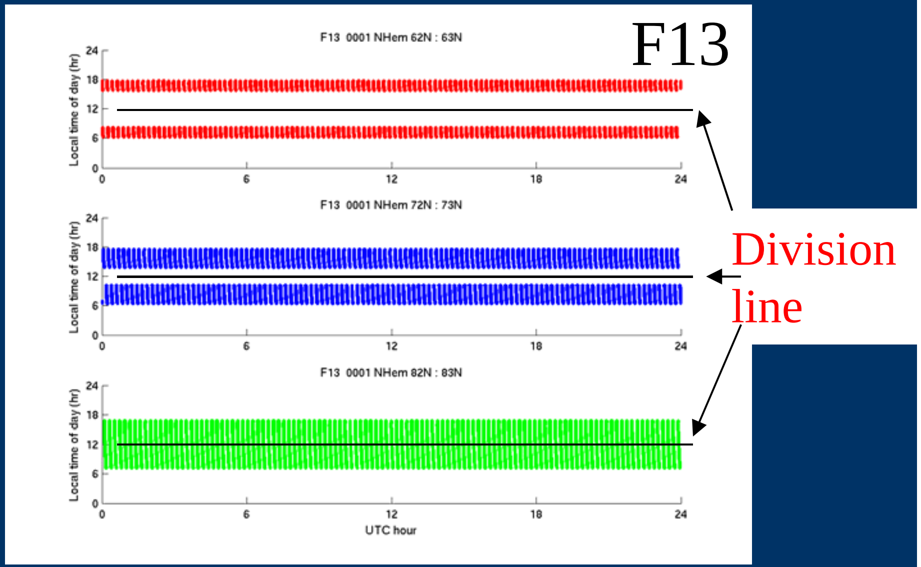
Histogram of LTOD of measurements

Two LTOD groupings:
- Morning, Afternoon within < 8 hours

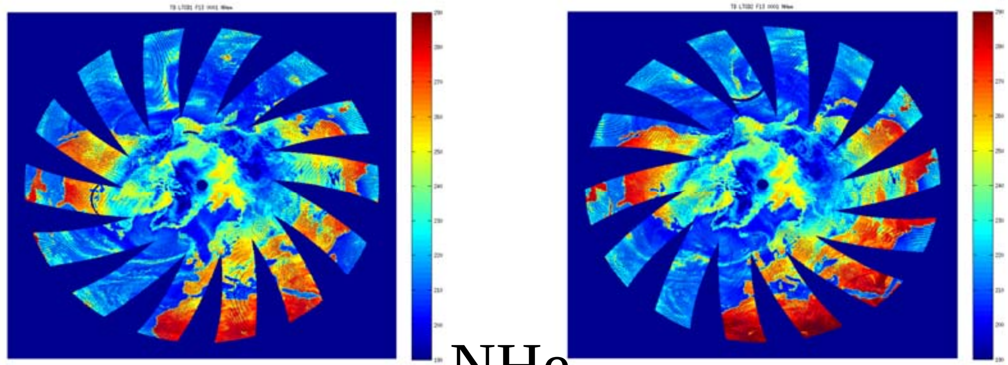


Combine measurements within same LTOD
- At equator, LTOD and Asc/Dec same

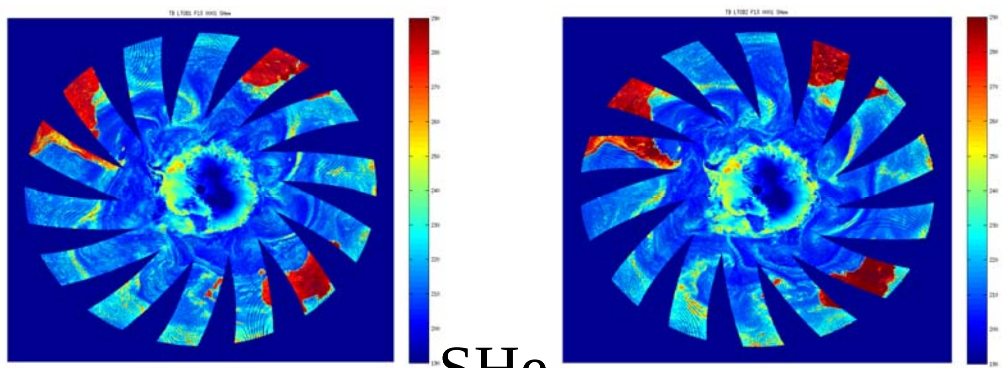
Two images per day



LTOD Image Examples

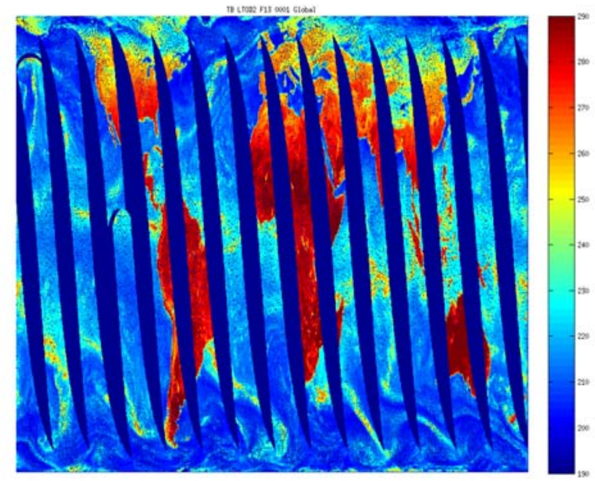


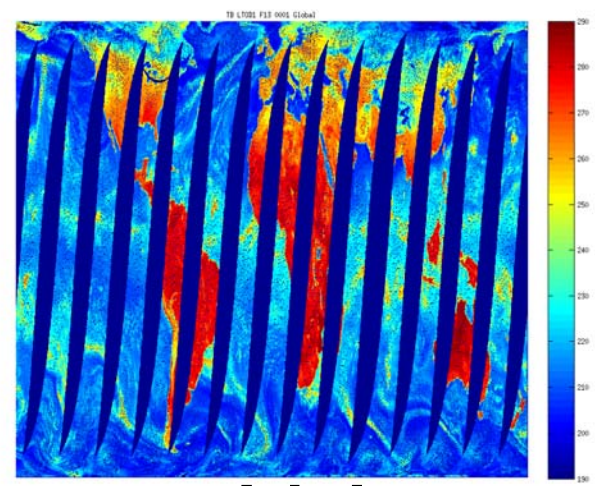
NHe



SHe

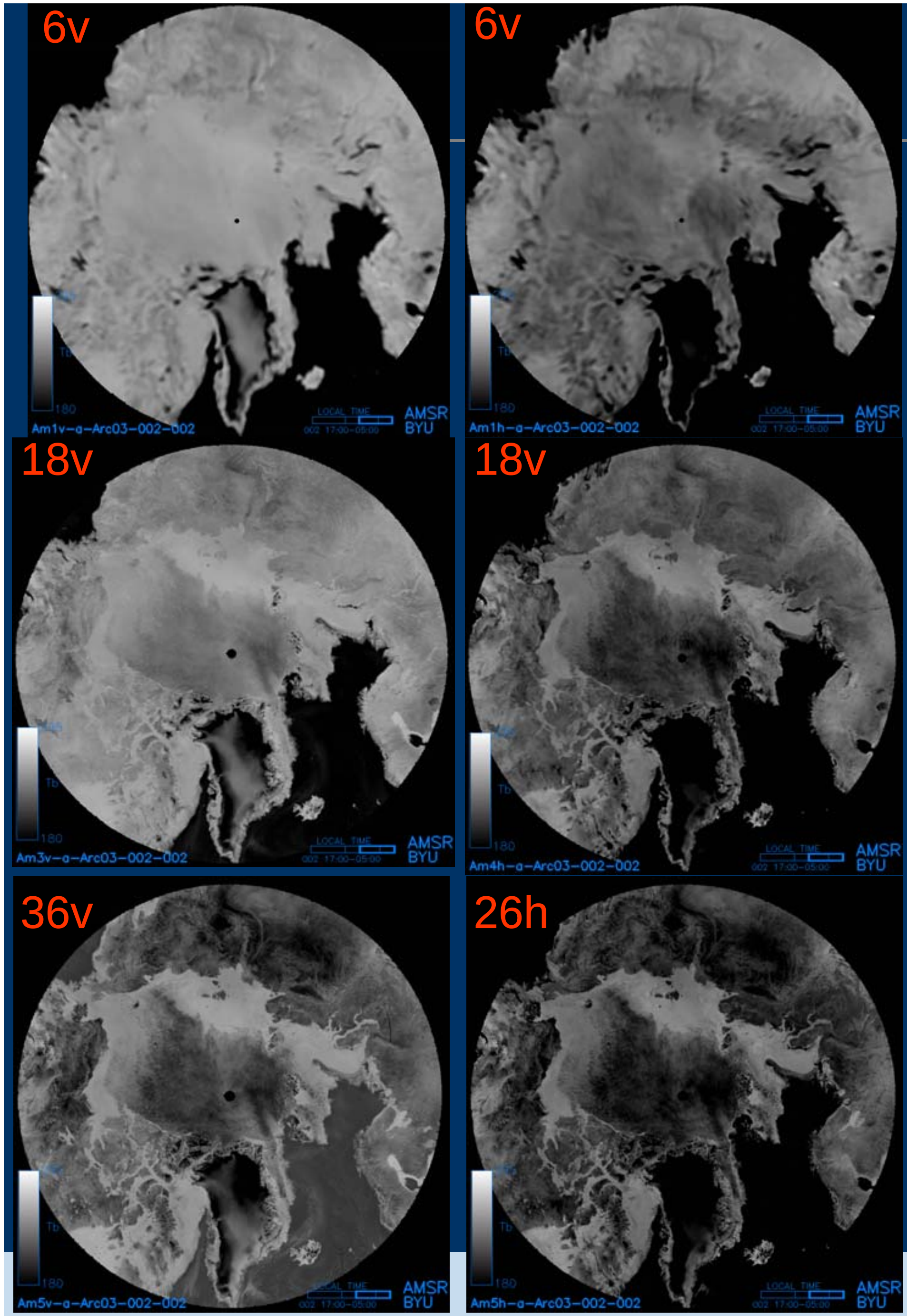
Image examples (Dib)





Global

AMSR-E Images



- JD 002, 2007

- Enhanced resolution image examples
  - Radiometer Scatterometer Image Reconstruction (sSIR) (T_b)
  - Sample applications
    - Sea ice extent
    - Sea ice age
    - Snow coverage

CETB Project Status – Aug 2015 nsidc.org/pmesdr

- Available now:
  - ATBD available for comment now
  - Prototype data (SSM/I and AMSR-E for 2003) available for Early Adopter feedback and evaluation
    - SSM/I data from both CSU and RSS for comparison
    - "GRD" (ditb) (25, 12.5 km) low-noise grids
    - BGI, SIR (6.25, 3.125 km) enhanced-resolution grids
  - Early adopters welcome! (contact brodzik@nsidc.org)
- Coming:
  - SMMR and SSMIS, eventually AMSR
  - Data content/format finalized
  - Complete historical record available at NSIDC DAAC
- **http://nsidc.org/pmesdr**

A Climate Record of Enhanced Spatial Resolution Radiometer Data

David G. Long (long@byu.edu), Aaron Paget, Mary J. Brodzik

Operational satellite radiometers, such SMMR, SSM/I, SSMIS, and AMSR-E, provide a multi-decadal time series of observations of the globe that can support studies of climate change. Unfortunately, spatial resolution and sampling characteristics differ between sensors, which complicate compiling a single climate record. Resolution concerns can be ameliorated by reconstructing radiometer brightness temperature measurement (Tb) data onto daily-averaged compatible grids. We consider and contrast two widely used methods for image reconstruction: a radiometer version of the scatterometer image reconstruction (SIR) algorithm and Backus-Gilbert (BG). Both require the spatial response function (antenna gain pattern) and the sampling geometry. We discuss considerations for an optimum gridding scheme based on the EASE-Grid 2.0 map projection. The EASE-Grid 2.0 simplifies the application of the Tb images in derived products since the reconstruction for each radiometer channel is implement on the same grid. This has the effect of optimally interpolating low-resolution measurements to locations of the highest resolution measurements. By employing reconstruction techniques rather than traditional "drop in the bucket" (dib) gridding, the effective resolution of the images is spatially enhanced compared to dib images, at the expense of additional computation required for the reconstruction processing. We evaluate the sensitivity of the radiometric accuracy of the resulting Tb images to uncertainties in the antenna gain pattern as well as variations in local-time-of-day. We briefly consider a number of applications of reconstructed Tb images. As part of the NASA-MEASUREs project "An improved, enhanced-resolution, gridded passive microwave ESDR for monitoring cryospheric and hydrologic time series" we are processing all available satellite radiometer data to generate a consistently calibrated and processed time series of gridded images spanning from the 1970's to the present that will be available from the National Snow and Ice Data Center starting later this year.