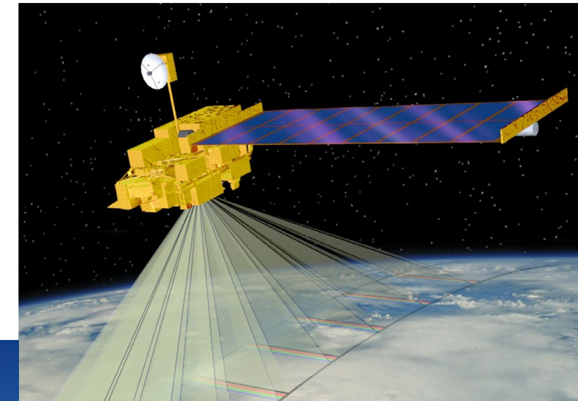
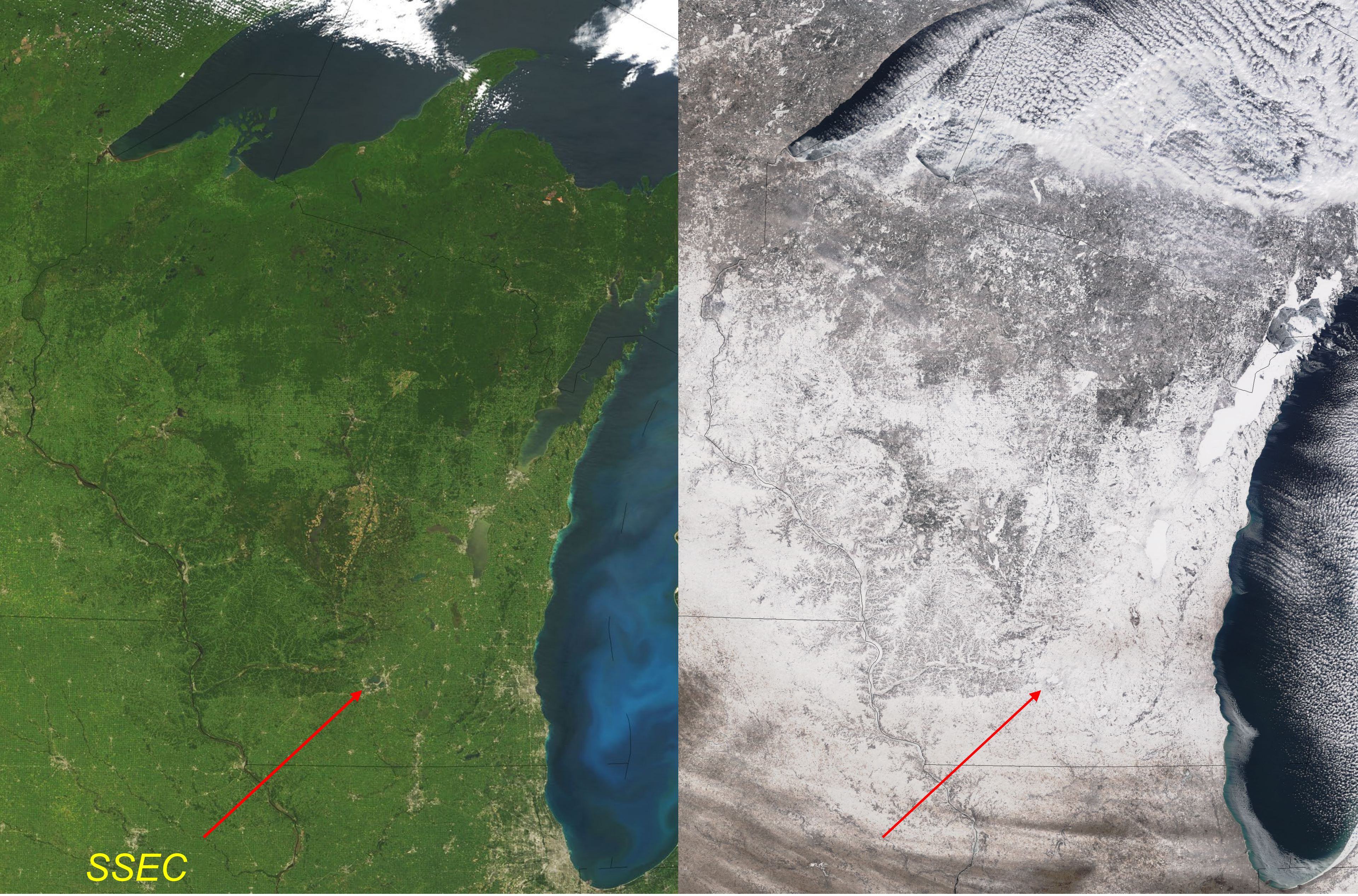
MODIS Sensor Characteristics and True Color Images



MODIS/AIRS Seminar
Benevento, Italy
June, 2007

Liam Gumley
Space Science and Engineering Center
University of Wisconsin-Madison



Visit Wisconsin: Beautiful in Summer and Winter

Slide Credits

University of Wisconsin-Madison: Paul Menzel, Steve Ackerman, Paolo Antonelli, Chris Moeller, Kathy Strabala, Bryan Baum, Suzanne Seemann.

MODIS Science Team: Michael King, Steve Platnick, Eric Vermote, Robert Wolfe, Bob Evans, Jacques Descloitres, Jack Xiong.

Other colleagues: Wenjian Zhang, Stefan Maier, Jackie Marsden, Jamie Shutler, Tim Smyth, Roger De Abreu, Gerardo Lopez.

Introduction to MODIS

Terra

Launched: Dec. 18, 1999

10:30 am descending

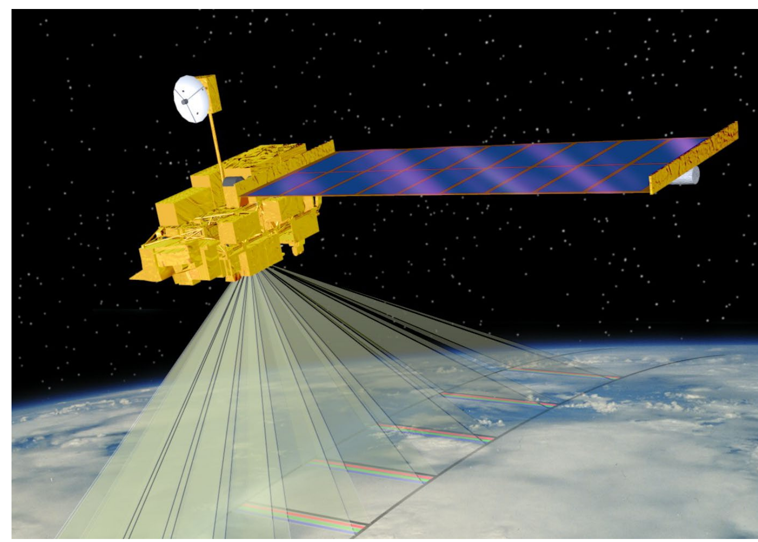
ASTER: Hi-res imager

CERES: Broadband scanner

MISR: Multi-view imager

MODIS: Multispectral imager

MOPITT: Limb sounder



Terra MODIS first light image, 24 Feb. 2000

Aqua

Launched: May 4, 2002

1:30 pm ascending

AIRS: Infrared sounder

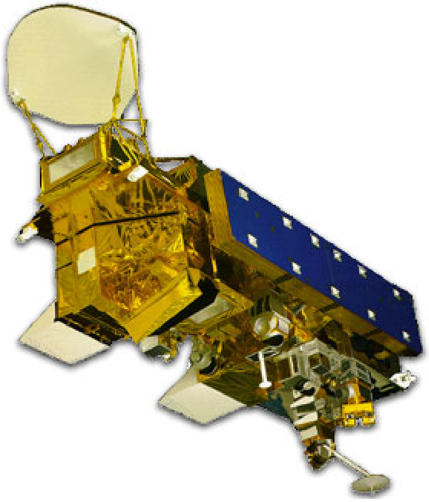
AMSR-E: Microwave scanner

AMSU: Microwave scanner

CERES: Broadband scanner

HSB: Microwave sounder

MODIS: Multispectral imager



Formation Flyers

Coordinated observations by multiple sensors
without the risk of one large platform

Morning Train (10:30 am)

- Terra (multidisciplinary)
- Landsat-7 (land)
- EO-1 (technology)
- SAC-C (GPS water vapor)
- NPP (EOS/NPOESS bridge)

Afternoon Train (1:30 pm)

- Aqua (multidisciplinary)
- Aura (chemistry)
- Cloudsat (cloud radar)
- CALIPSO (cloud lidar)
- Parasol (polarimetry)
- NOAA-16 (weather)

Moderate resolution imaging spectroradiometer (MODIS)

Heritage: AVHRR (land), SeaWIFS (ocean), HIRS (atmosphere)

Spectral coverage: 36 bands from 0.4 to 14.2 microns

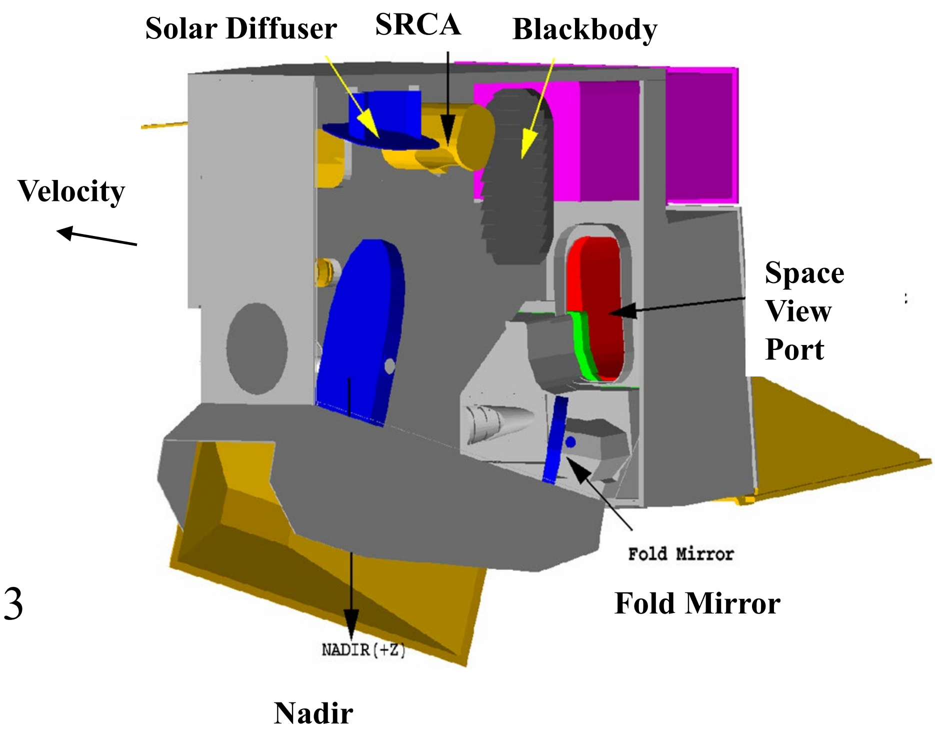
Spatial resolution: 2 bands @ 250 m; 5 @ 500 m; 29 @ 1000 m

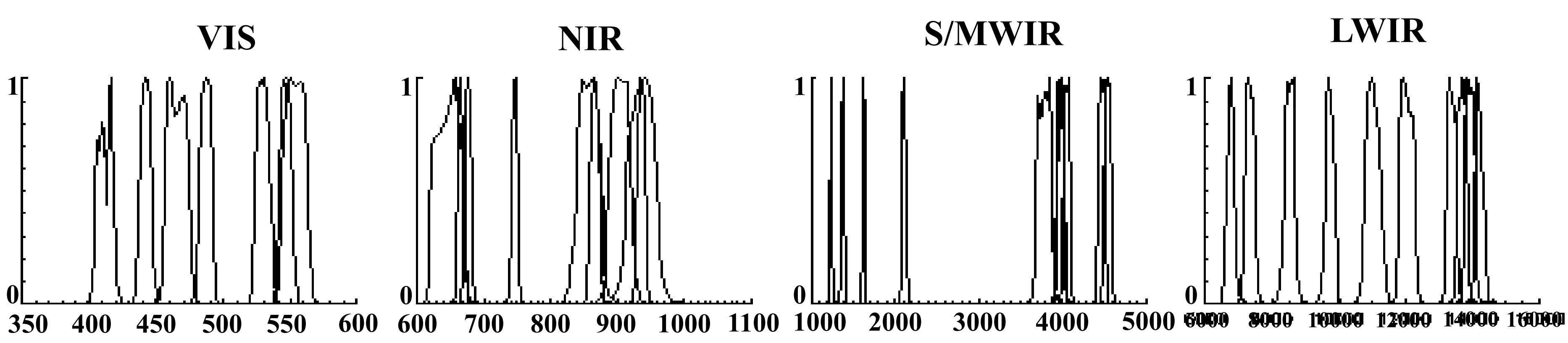
Major differences:

- More spectral bands (490 detectors)
- Multiple samples along track on each earth scan
- Higher spatial resolution
- On-orbit radiometric, spatial, and spectral calibration
- Improved radiometric accuracy and precision (12-bit)
- Improved geolocation accuracy
- Higher data rate requiring X-band direct broadcast

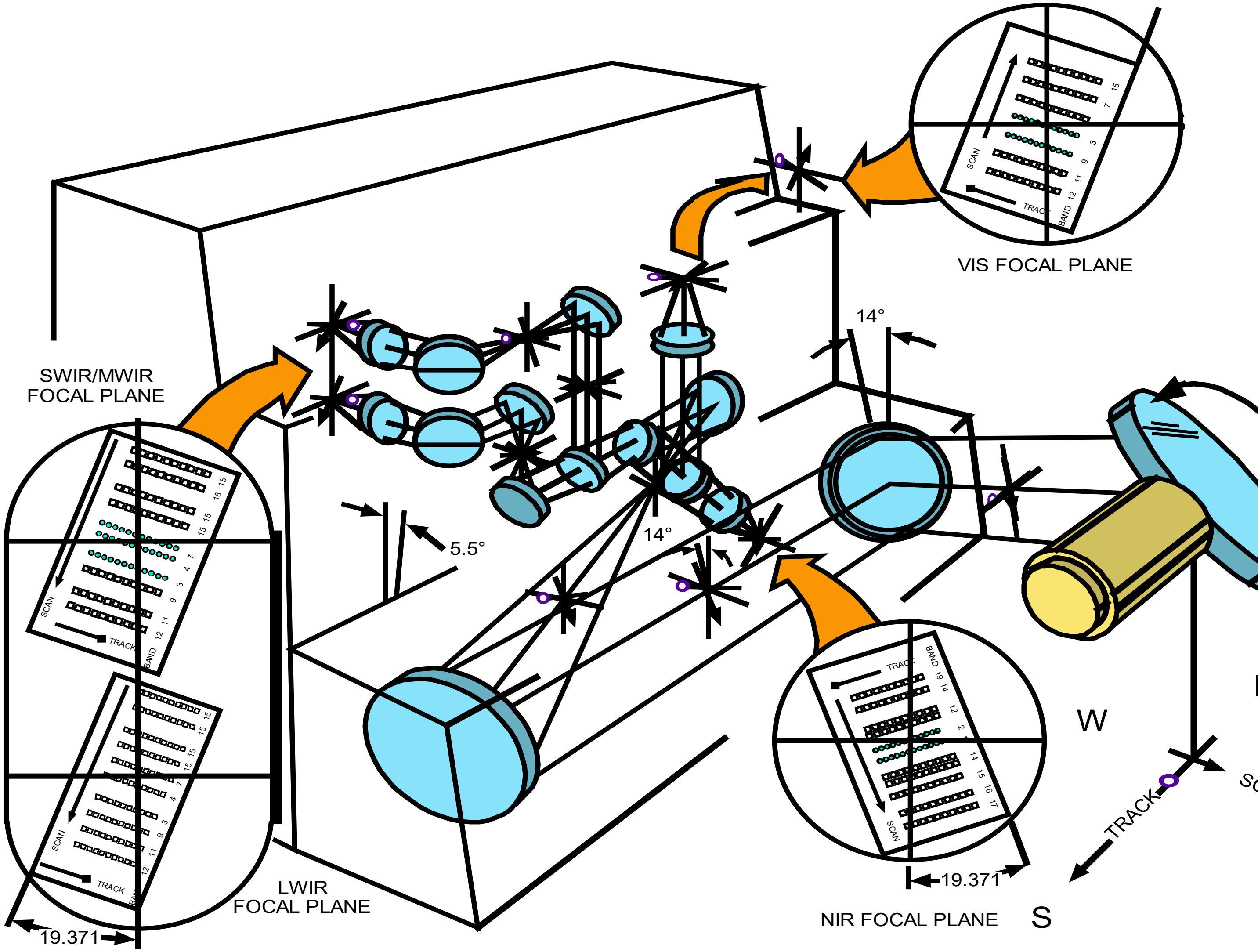
Instrument Overview

- 36 spectral bands (490 detectors) cover wavelength range from 0.4 to 14.5 µm
- Spatial resolution at nadir: 250m (2 bands), 500m (5 bands) and 1000m
- 4 FPAs: VIS, NIR, SMIR, LWIR
- On-Board Calibrators: SD/SDSM, SRCA, and BB (plus space view)
- 12 bit (0-4095) dynamic range
- 2-sided Paddle Wheel Scan Mirror scans 2330 km swath in 1.47 sec
- Day data rate = 10.6 Mbps; night data rate = 3.3 Mbps (100% duty cycle, 50% day and 50% night)





MODIS Optics System



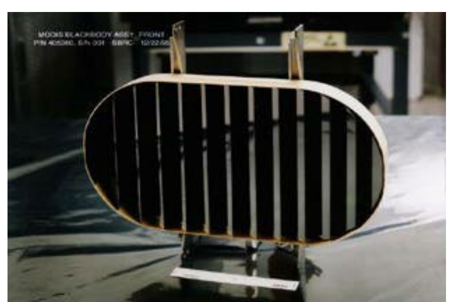
On-board Calibrators

- **SD** – Solar Diffuser for RSB calibration, SD BRDF determined from pre-launch, referenced to a transfer standard calibrated at NIST
- **SDSM** – Solar Diffuser Stability Monitor for tracking SD degradation
- **BB** – Blackbody (12 thermistors reference to NIST standard) for TEB calibration. Emissivity determined from pre-launch calibration using a blackbody calibration source.
- **SRCA** – Spectroradiometric Calibration Assembly for spectral and spatial characterization

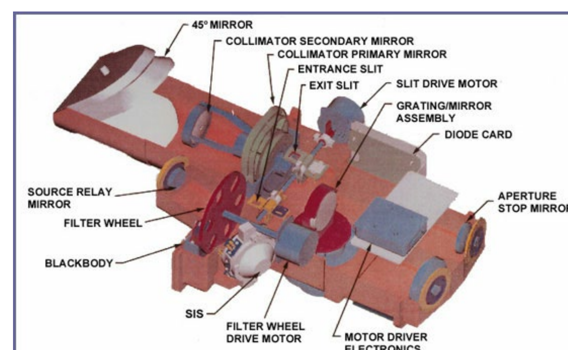
SD

SDSM

BB



SRCA



MODIS Challenges

Multiple detectors:

Detector differences are noticeable

Dead or out-of-family detectors must be handled

Multiple samples along track introduce bowtie distortion

Spectral information:

Many interdependent bands

How to utilize all the spectral information?

Data rate:

Orders of magnitude larger than heritage sensors

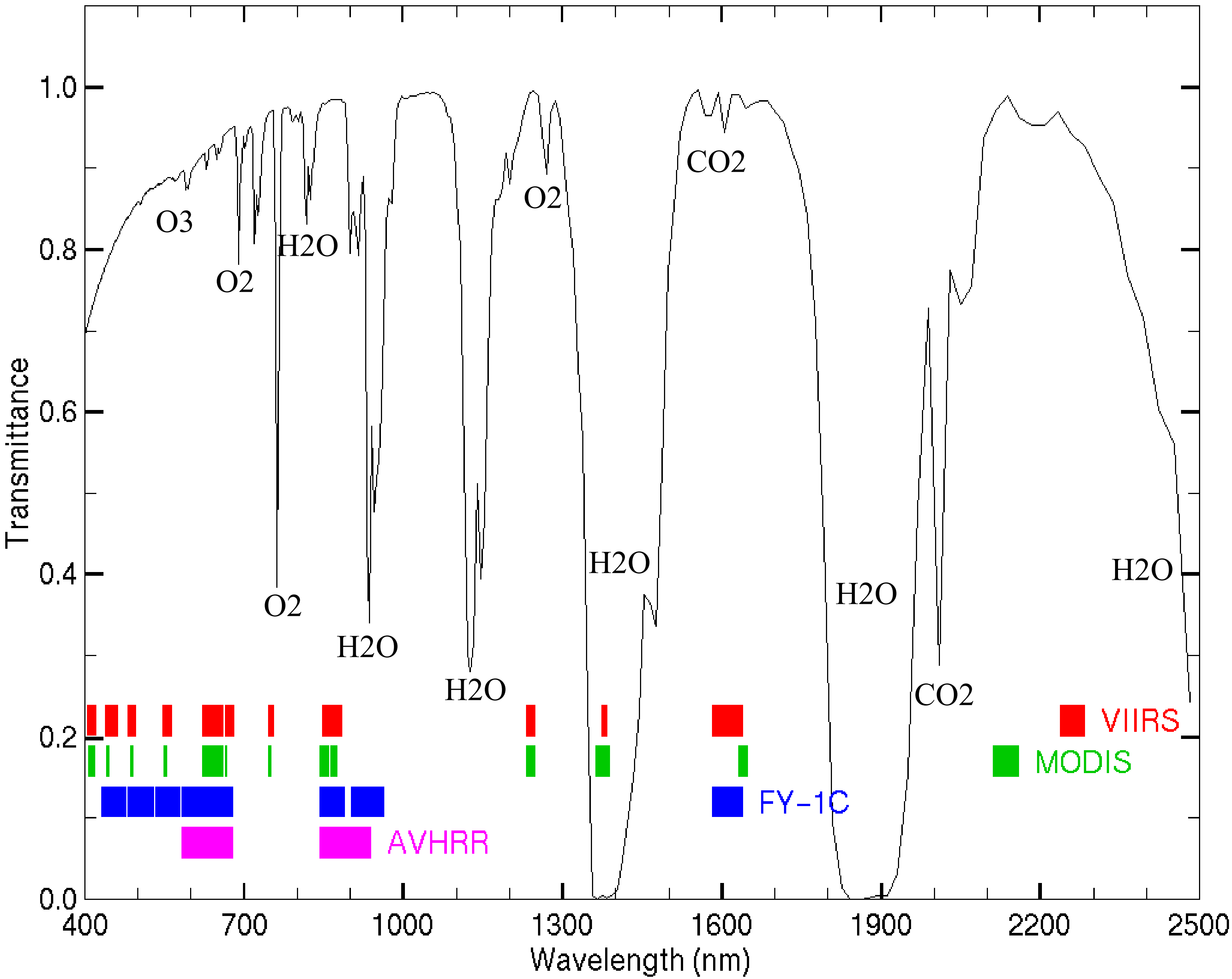
MODIS Reflected Solar Bands

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required SNR[3]
Land/Cloud/Aerosols Boundaries	1	620 - 670	21.8	128
	2	841 - 876	24.7	201
Land/Cloud/Aerosols Properties	3	459 - 479	35.3	243
	4	545 - 565	29.0	228
	5	1230 - 1250	5.4	74
	6	1628 - 1652	7.3	275
	7	2105 - 2155	1.0	110
Ocean Color/ Phytoplankton/ Biogeochemistry	8	405 - 420	44.9	880
	9	438 - 448	41.9	838
	10	483 - 493	32.1	802
	11	526 - 536	27.9	754
	12	546 - 556	21.0	750
	13	662 - 672	9.5	910
	14	673 - 683	8.7	1087
	15	743 - 753	10.2	586
	16	862 - 877	6.2	516
Atmospheric Water Vapor	17	890 - 920	10.0	167
	18	931 - 941	3.6	57
	19	915 - 965	15.0	250

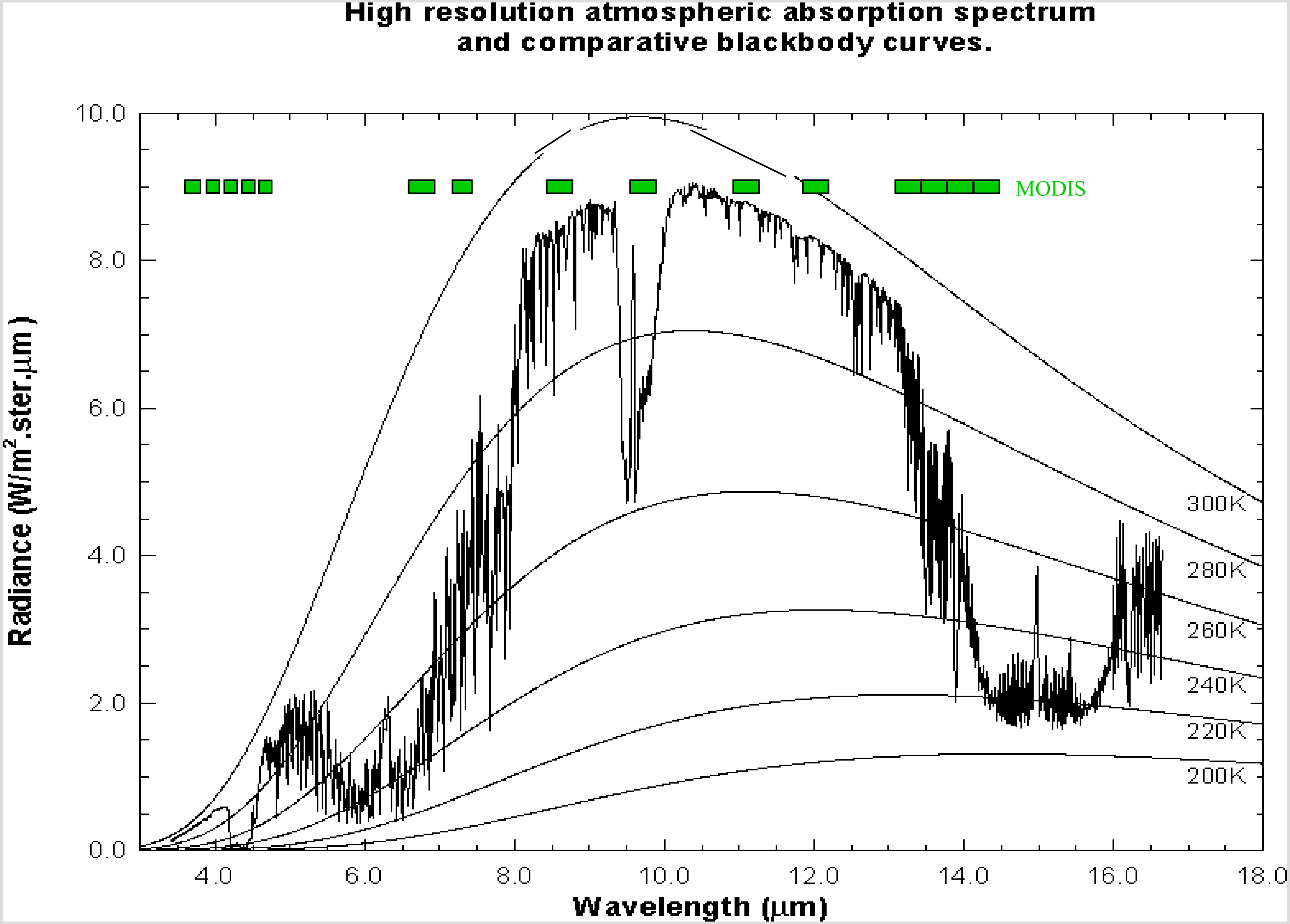
MODIS Thermal Emissive Bands

Primary Atmospheric Application	Band	Bandwidth[1]	$T_{typical}$ (K)	Radiance[2] at $T_{typical}$	NEΔT (K) Specification	NEΔT (K) Predicted
Surface Temperature	20	3.660-3.840	300	0.45	0.05	0.05
	22	3.929-3.989	300	0.67	0.07	0.05
	23	4.020-4.080	300	0.79	0.07	0.05
Temperature profile	24	4.433-4.498	250	0.17	0.25	0.15
	25	4.482-4.549	275	0.59	0.25	0.10
Moisture profile	27	6.535-6.895	240	1.16	0.25	0.05
	28	7.175-7.475	250	2.18	0.25	0.05
	29	8.400-8.700	300	9.58	0.05	0.05
Ozone	30	9.580-9.880	250	3.69	0.25	0.05
Surface Temperature	31	10.780-11.280	300	9.55	0.05	0.05
	32	11.770-12.270	300	8.94	0.05	0.05
Temperature profile	33	13.185-13.485	260	4.52	0.25	0.15
	34	13.485-13.785	250	3.76	0.25	0.20
	35	13.785-14.085	240	3.11	0.25	0.25
	36	14.085-14.385	220	2.08	0.35	0.35

VIIRS, MODIS, FY-1C, AVHRR



MODIS IR Spectral Bands



Scanner Characteristics

MODIS Orbit and Scan Geometry

Terra: 10:30 am local descending

Aqua: 1:30 pm local ascending

Orbit period: 99 minutes

Repeat cycle: 16 days (same as Landsat)

Scan mirror: Double sided, 20.3 revs/minute

Scan rate: 1.477 scans/sec

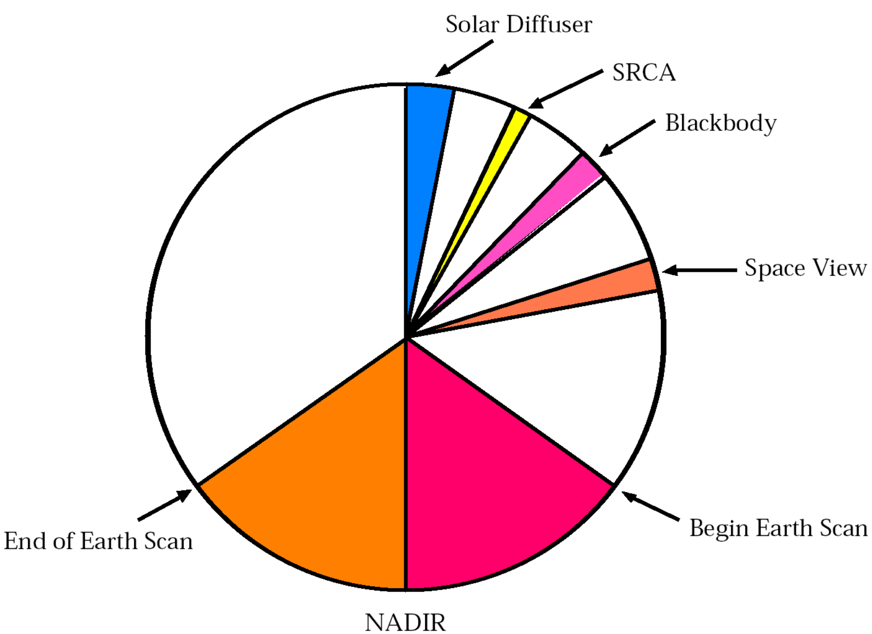
Scan angle: +/- 55 degrees

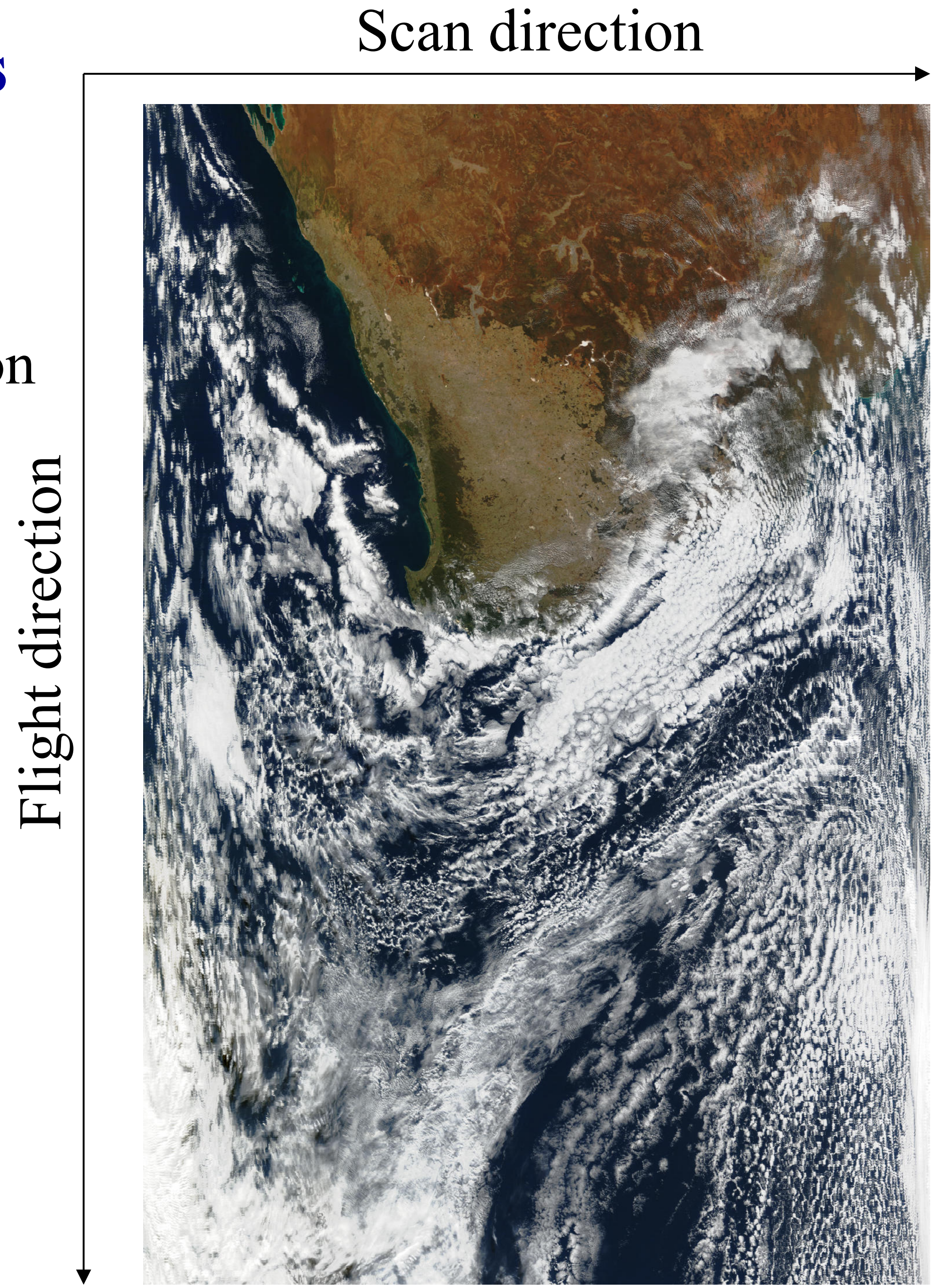
Swath width: 2330 km across track, 10 km along track

Image Acquisition Details

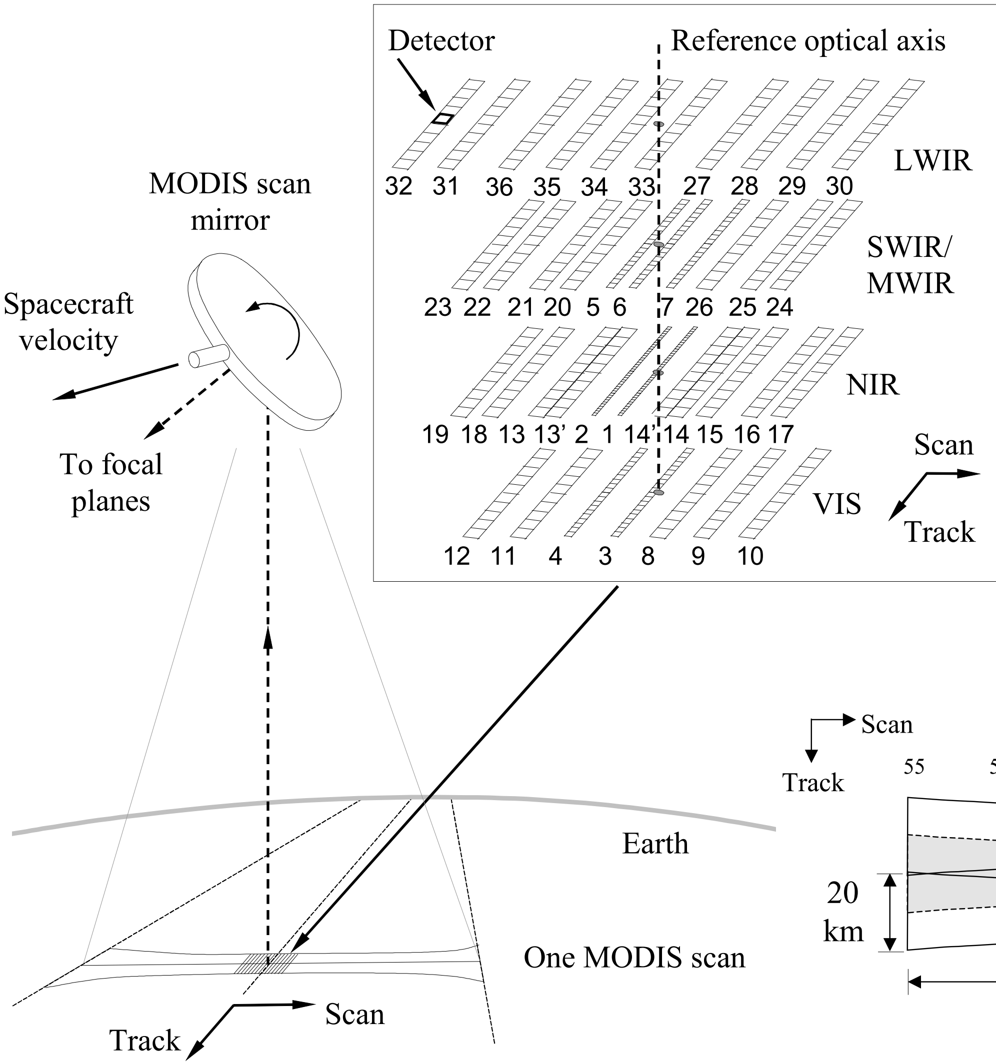
Scan sequence:

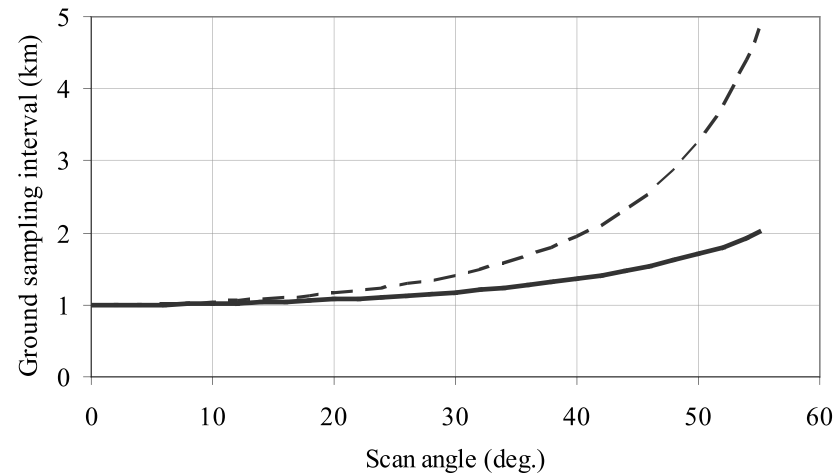
1. Solar diffuser
2. Spectroradiometric Calibration Assembly
3. Blackbody
4. Space View
5. Earth scan

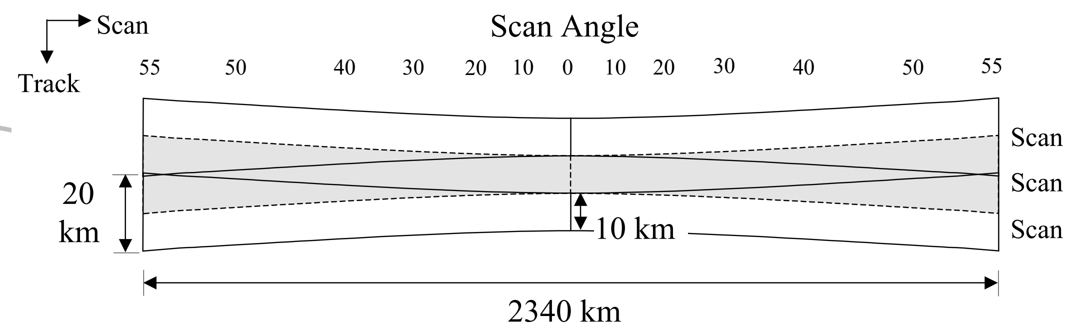




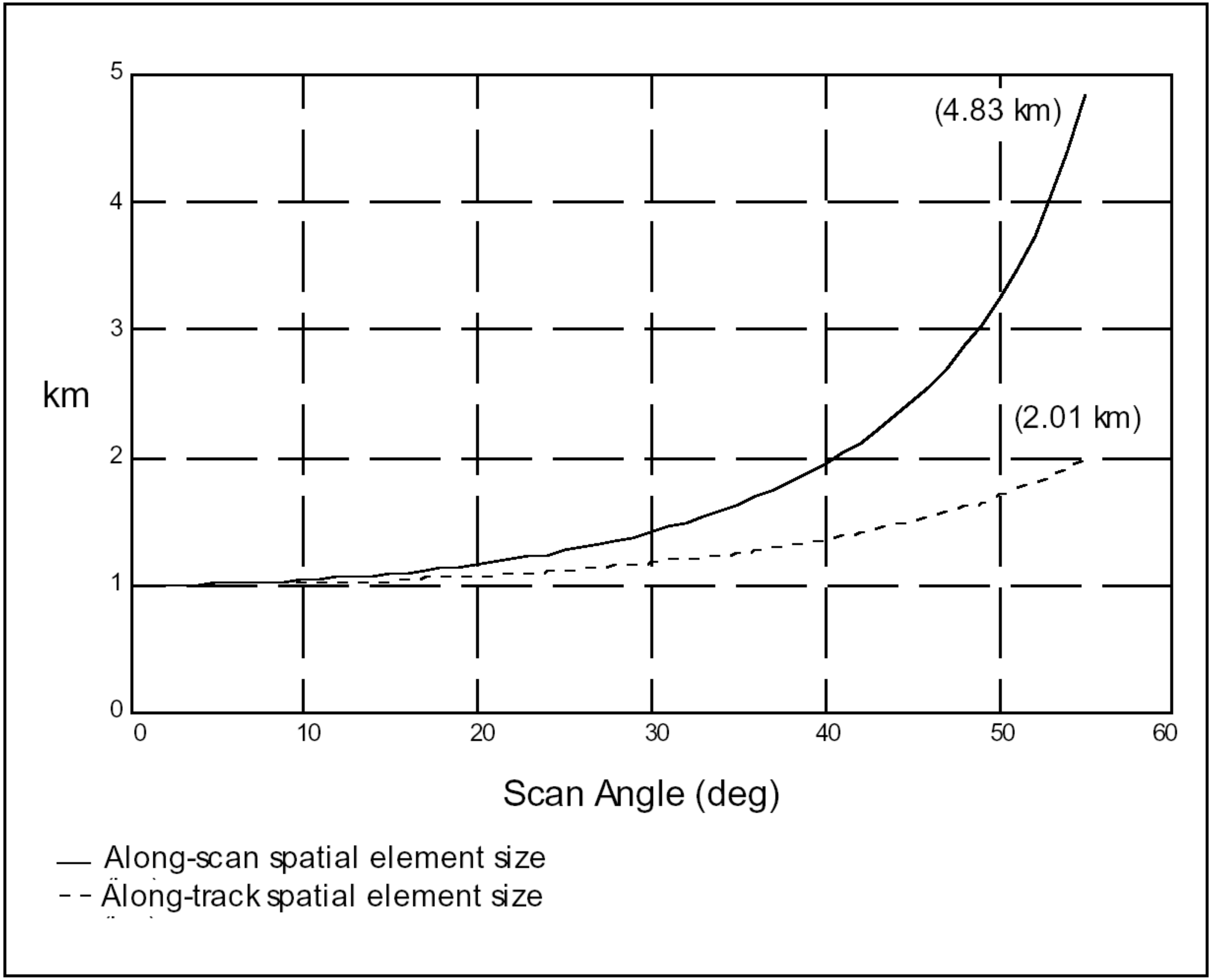
MODIS Scan Geometry





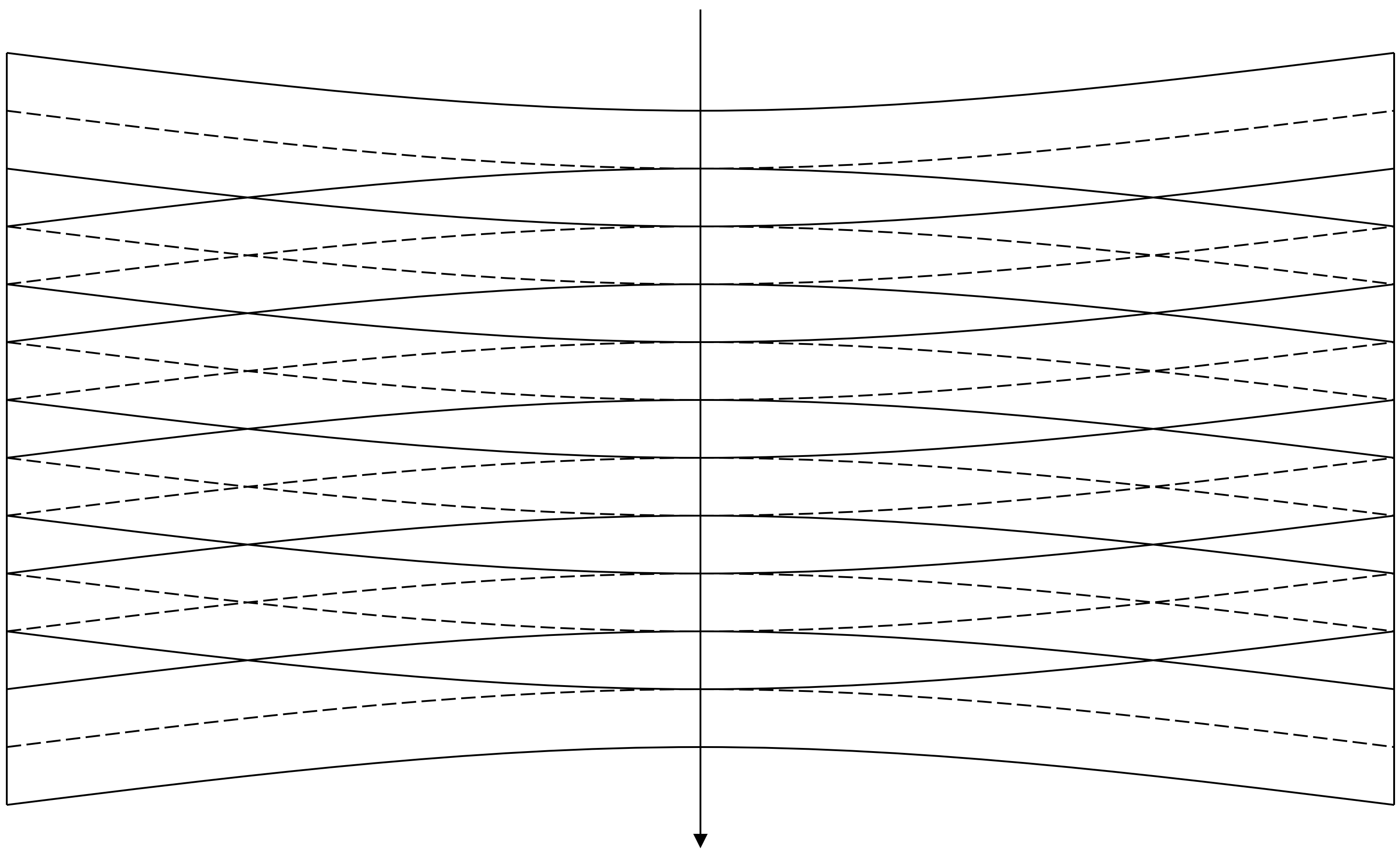


Growth of MODIS 1 km pixel with scan angle

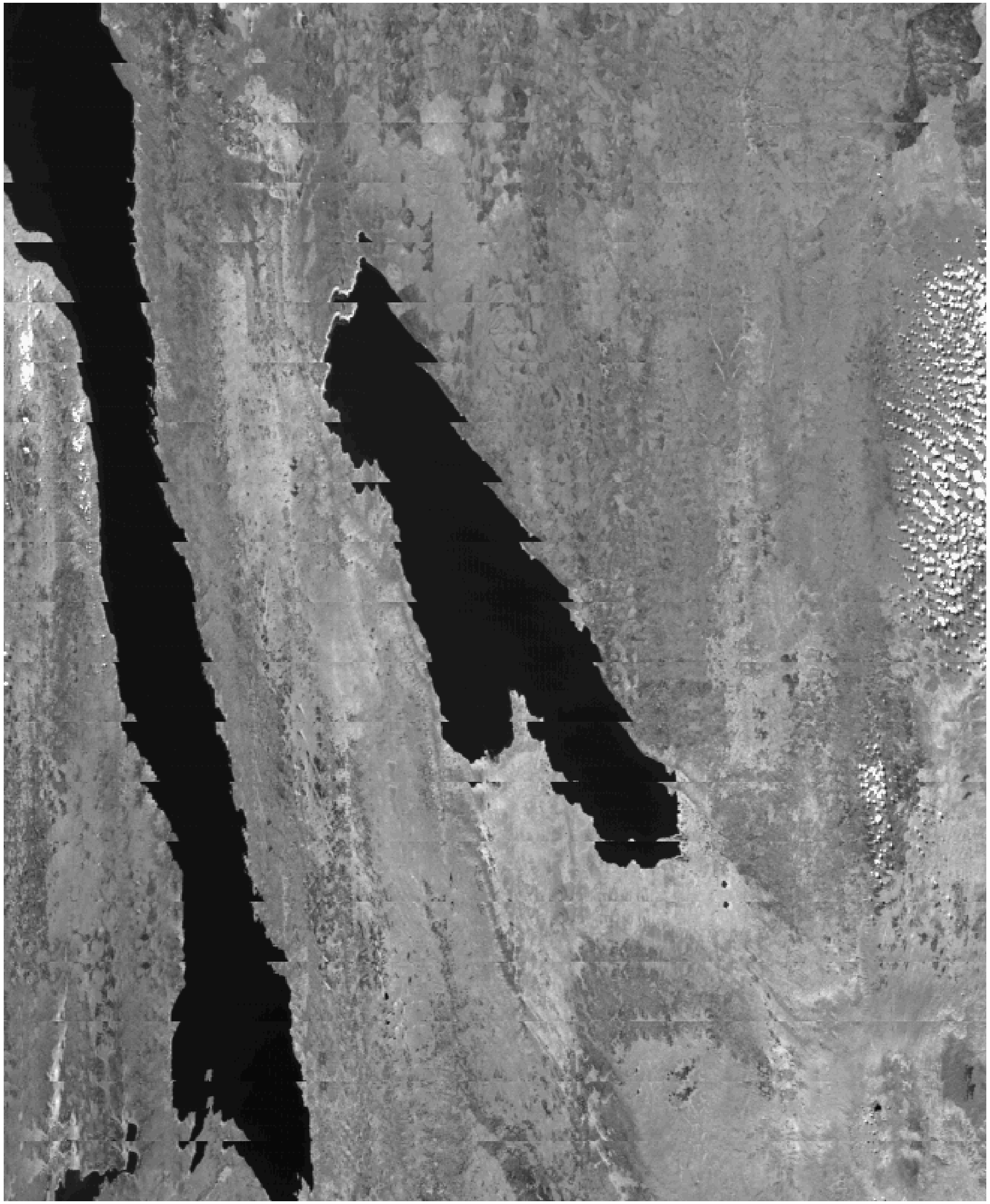


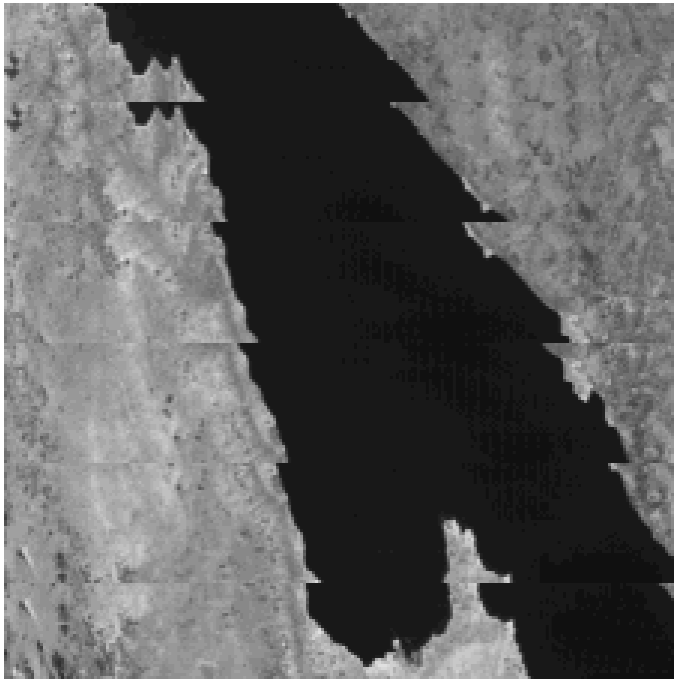
MODIS Bowtie Artifacts

Consecutive "bowtie" shaped scans are contiguous at nadir, and overlap as scan angle increases…



MODIS bowtie artifacts at edge of swath





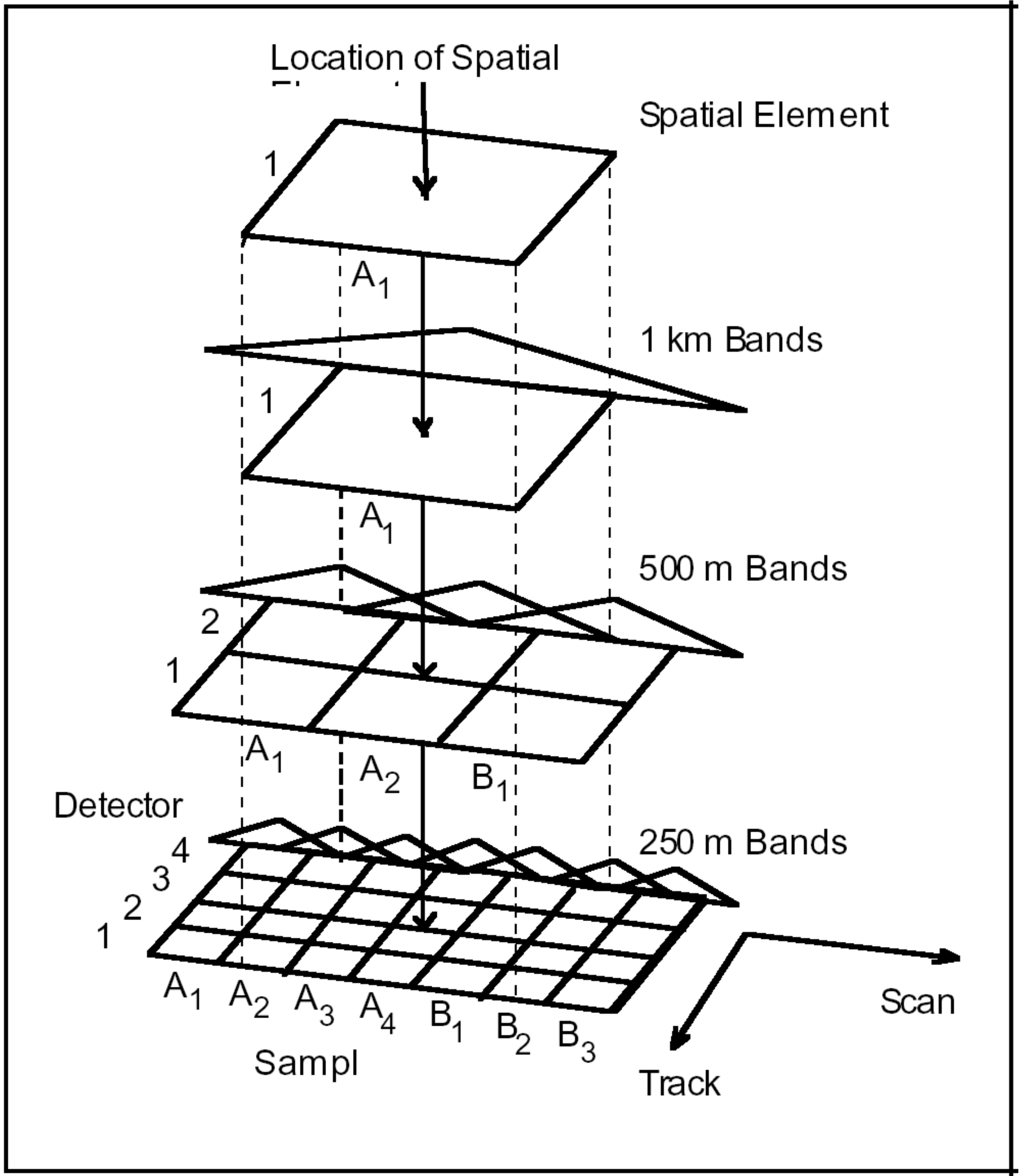
Band 2 (0.87 micron)

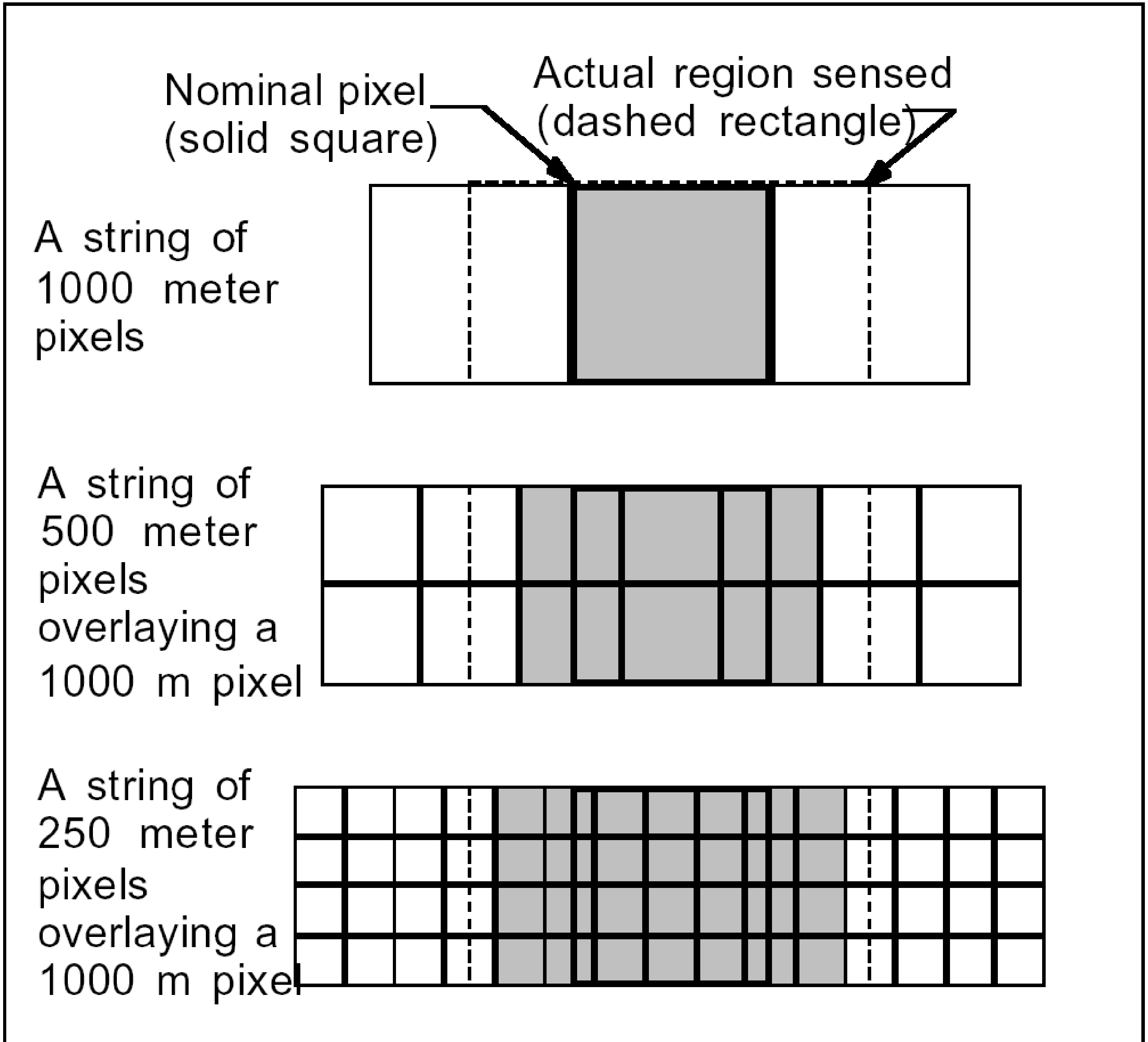
250 meter resolution

Bowtie Artifacts

1. Are not a ‘problem’: they are a consequence of the sensor design
2. Can be removed for visualization purposes by reprojecting the image onto a map
3. Do not affect science algorithms that run on a pixel-by-pixel basis or within one earth scan
4. Will be present on next generation of operational polar orbiting imagers (VIIRS on NPP/NPOESS)

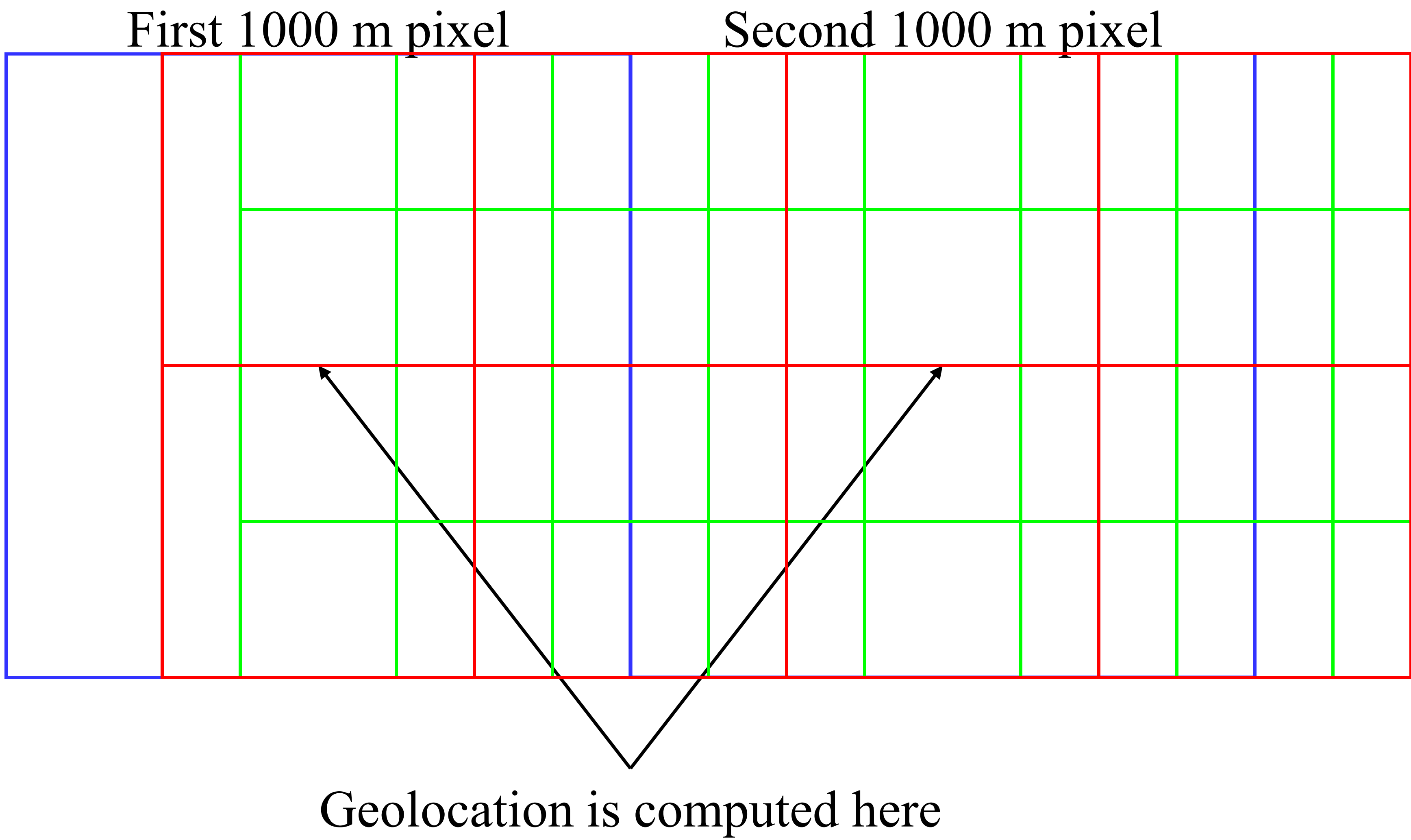
Inter-band Registration





Nominal pixel
(solid square)
Actual region sensed
(dashed rectangle)
A string of
1000 meter
pixels
A string of
500 meter
pixels
overlaying a
1000 m pixel
A string of
250 meter
pixels
overlaying a
1000 m pixel

Nominal MODIS inter-band registration

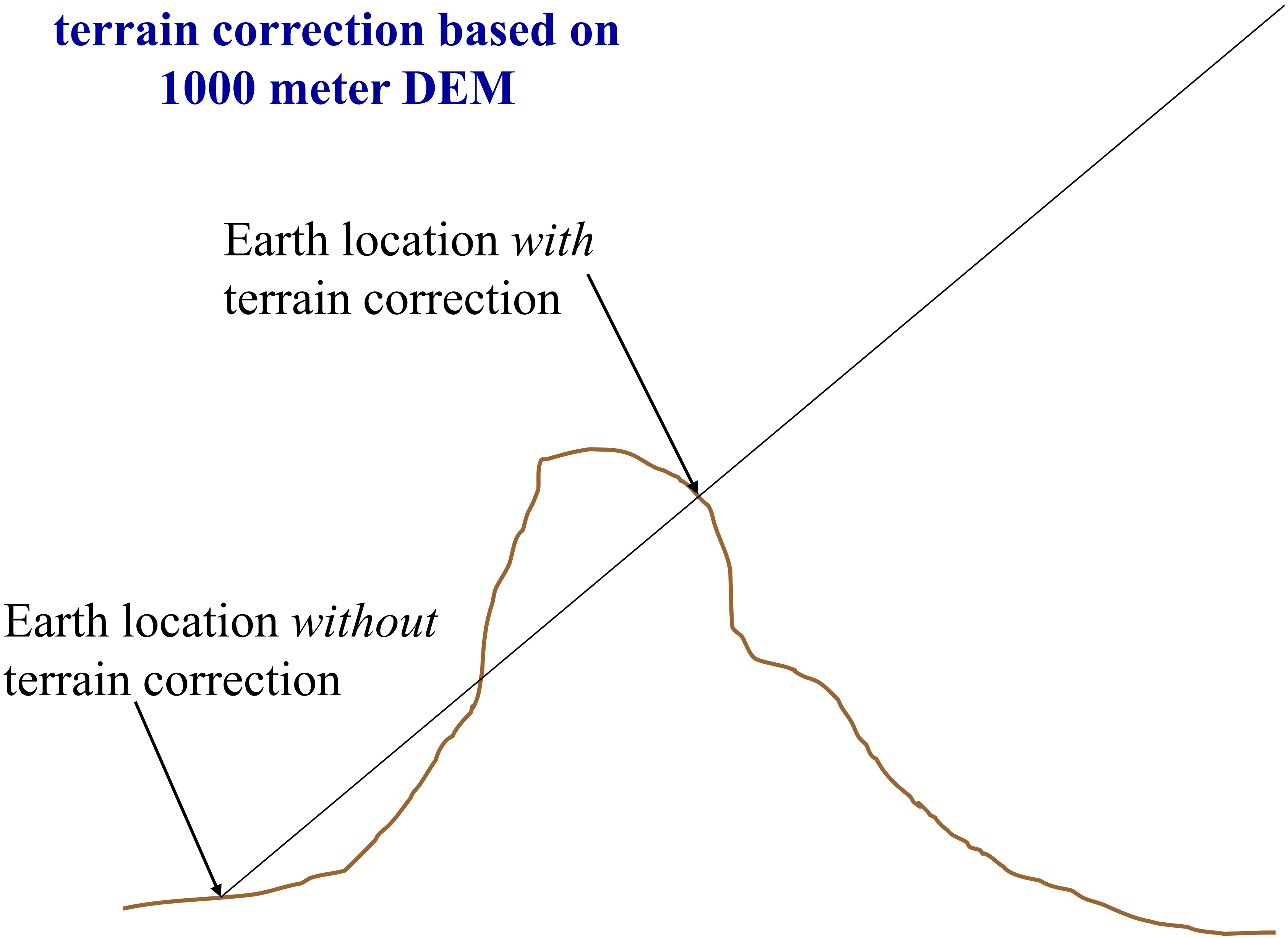


MODIS Geolocation

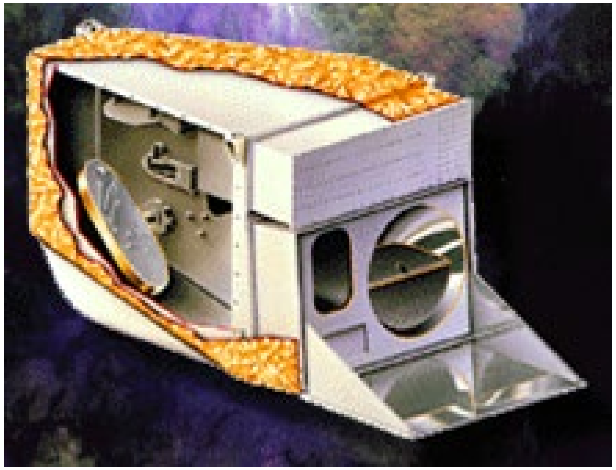
Earth locations computed for every 1000 meter pixel (WGS84):

- Geodetic latitude (degrees, -90S to +90N)
- Geodetic longitude (degrees, -180W to +180E)
- Sensor zenith and azimuth (degrees, pixel to sensor)
- Solar zenith and azimuth (degrees, pixel to sun)
- Terrain height above geoid (meters)
- Land/Sea mask
    - 0: Shallow Ocean
    - 1: Land
    - 2: Ocean Coastlines and Lake Shorelines
    - 3: Shallow Inland Water
    - 4: Ephemeral (intermittent) Water
    - 5: Deep Inland Water
    - 6: Moderate or Continental Ocean
    - 7: Deep Ocean

MODIS geolocation includes terrain correction based on 1000 meter DEM

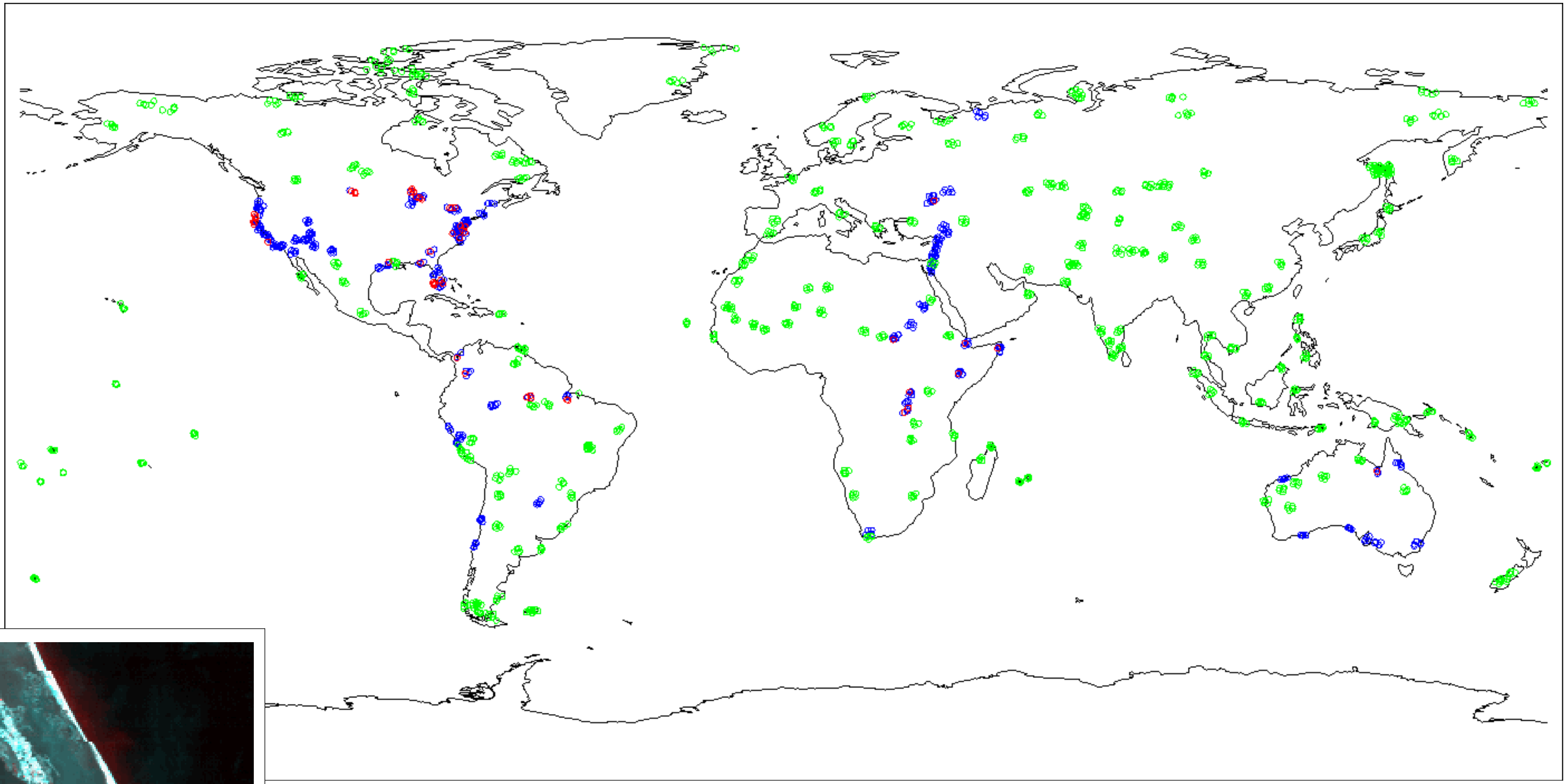


MODIS Geolocation



- Geolocation accuracy specification is 150 m (1 σ) and goal is 50 m (1 σ) at nadir
- Geolocation goal driven by Land 250 m change product requirements
- MODIS is a moderate resolution whisk-broom sensor with 36 spectral bands; 2 at 250 m, 5 at 500 m and 29 at 1 km nadir spatial resolution
- “Ideal” band is geolocated
  - 250m band 1 (645 nm, “red”)

Ground Control Points (GCPs)



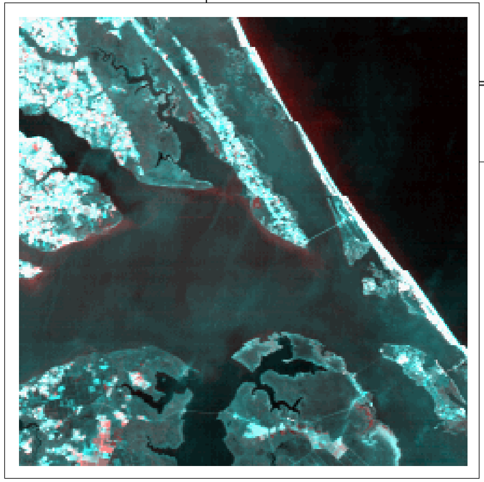


Image chips from Landsat TM/ETM scenes

366 old chips (blue)
51 chips removed (red)
990 new chips (green)

Geolocation Collection 4 (C4)

Terra

- Excellent results – Root Mean Square (RMS) error in nadir equivalent units is better than accuracy goal
- Small remaining northern/ southern hemisphere difference
- Large errors occur after orbit maneuvers (about 6 per year)
  - accuracy in following orbit suspect

Aqua

- Good results – RMS error is better than goal in track direction but slightly over goal in scan direction (but much better than specification – 150 m)
- Early post-launch coordinate system issue resolved before C4
- Definitive ephemeris is used for best results – causes up to 24 hr processing delay

	Terra	Aqua
Along-track RMS error (m)	38	43
Along-scan RMS error (m)	43	56
Years	4.0	1.6
Ground Control Point Match-ups/day	83	74

Realtime Geolocation

1. For realtime processing, ephemeris and attitude downlinked from spacecraft must be used.
2. Post-processed ephemeris and attitude from NASA GSFC Flight Dynamics may be used for non realtime processing (delay of at least 24 hours after data acquisition)
3. What is the impact on geolocation accuracy of realtime processing?

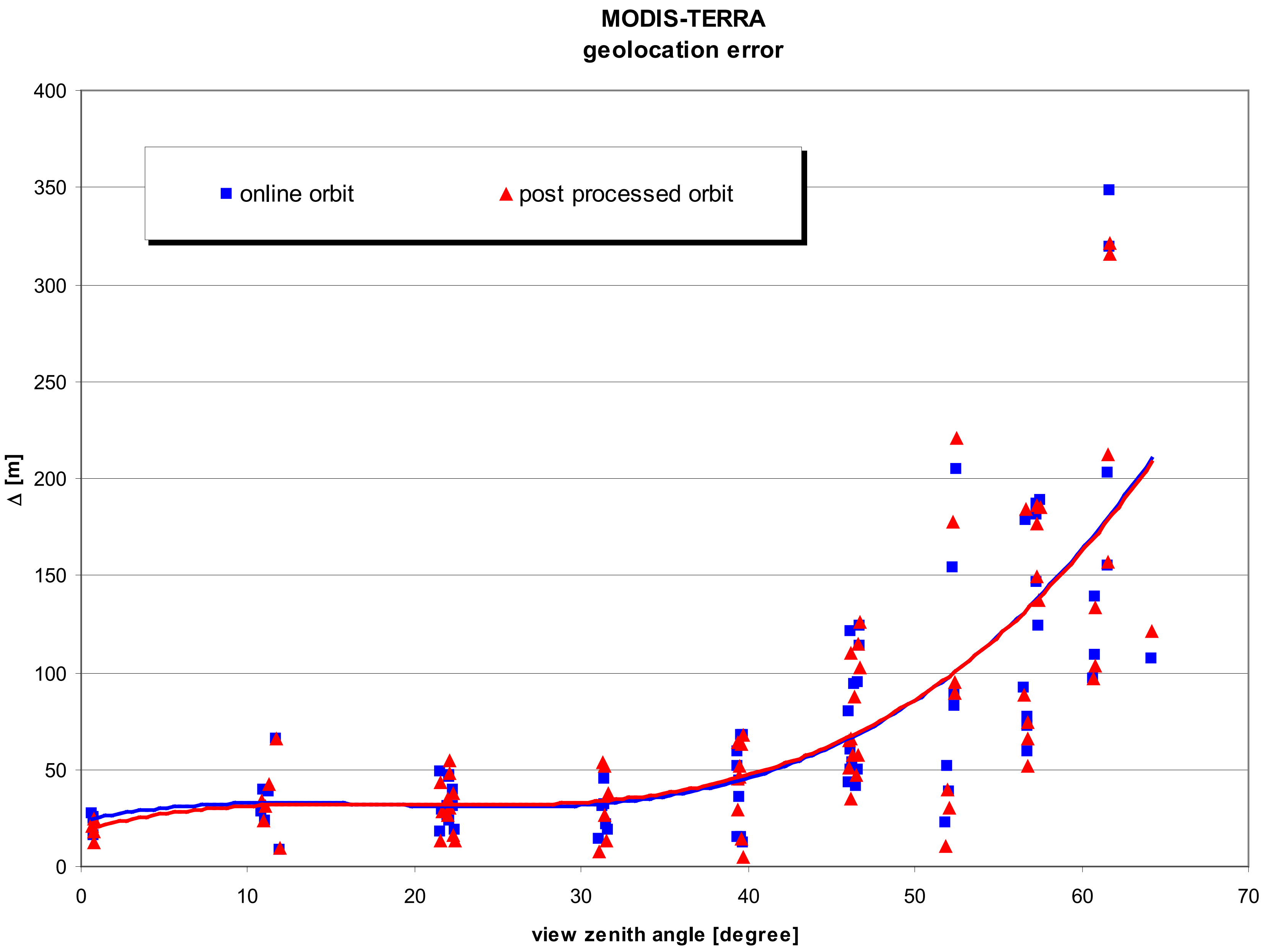


Figure courtesy of Stefan Maier, DOLA

Image Artifacts (other than Bowtie)

Mirror Side Striping (Band 8, 0.41 μm)

Side 0

Side 1

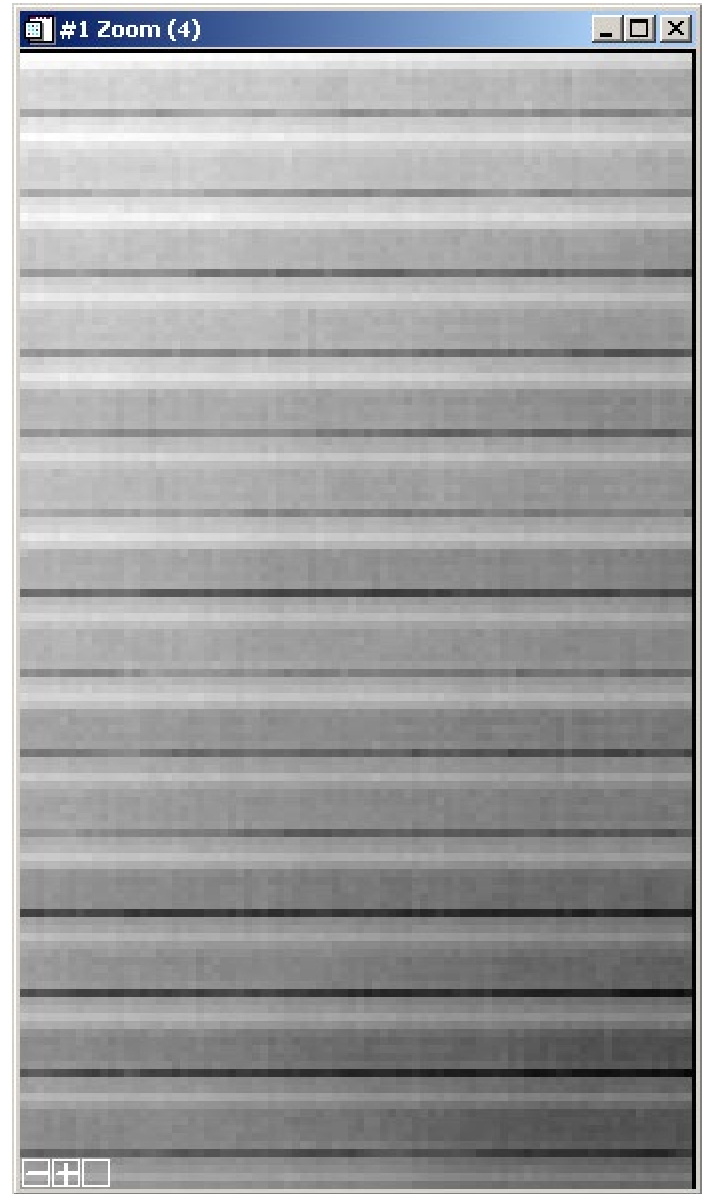
Reflectance, emissivity, or polarization of each scan mirror side not characterized correctly.

Can be corrected.

Detector Difference Striping (Band 27, 6.7 μm)

Responsivity of each detector not characterized correctly.

Can be corrected.



Noisy Detectors (Band 34, 13.6 μm)

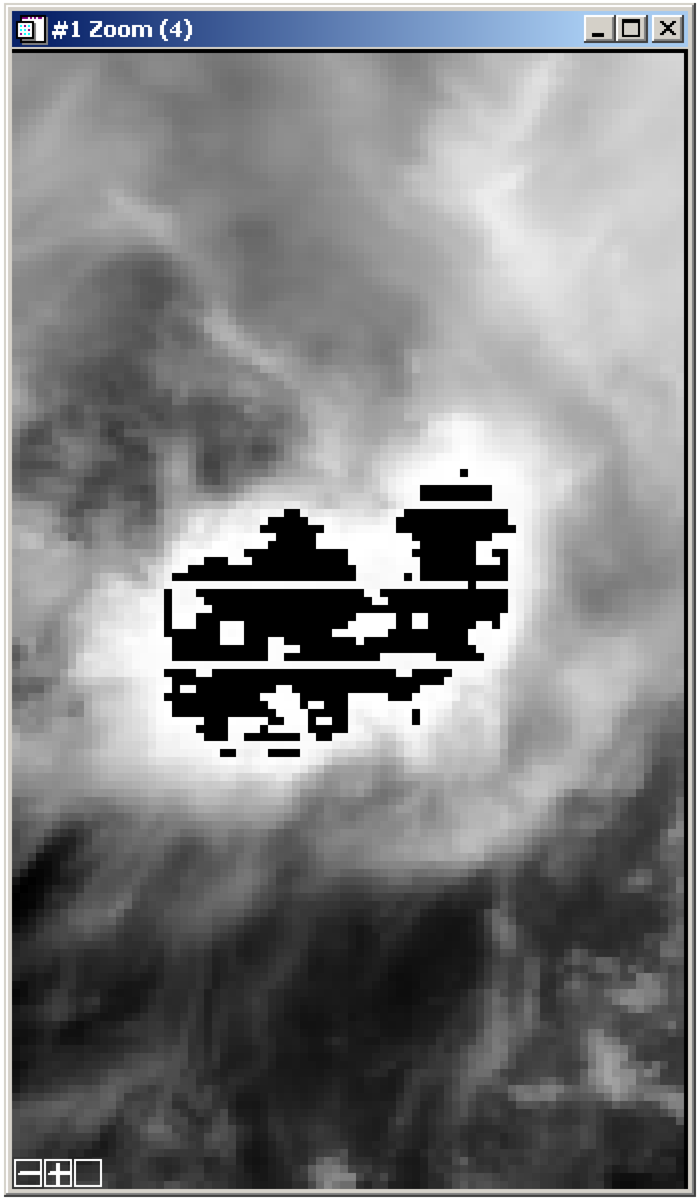
Detectors are noisy on a per frame basis and unpredictable from scan to scan.

Difficult to correct.

Saturation (Band 2, 0.87 μm)

Signal from earth scene is too large for 12 bit digitization with current gain settings.

Workaround available.



Handling Saturation in Bands 1-5

Problem:

- Bright cloud tops cause bands 1-5 to saturate, and the MODIS Cloud Mask cannot process these pixels correctly. It also makes true color image creation problematic (bands 1, 4, 3).

Approach:

- Replace saturated pixels with maximum scaled integer.

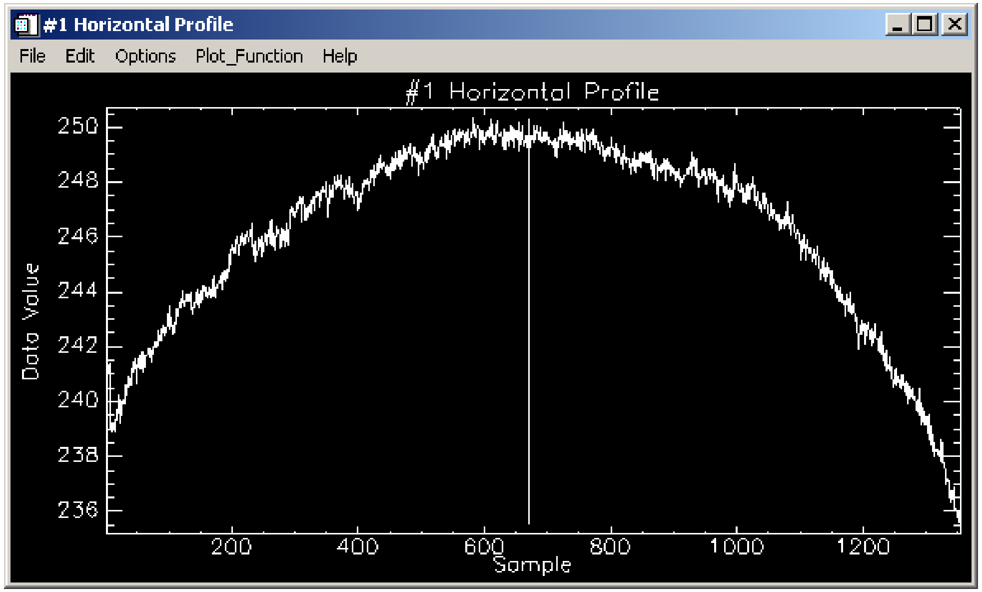
Method:

1. Check for scaled integer values corresponding to “Detector is saturated” (65533) or “Aggregation algorithm failure” (65528).
2. Replace these values with maximum allowed scaled integer (from valid_range attribute).

Response vs. Scan Angle (Band 35, 13.9 μm)

Scan mirror reflectance, emissivity, or polarization not characterized correctly as a function of scan angle.

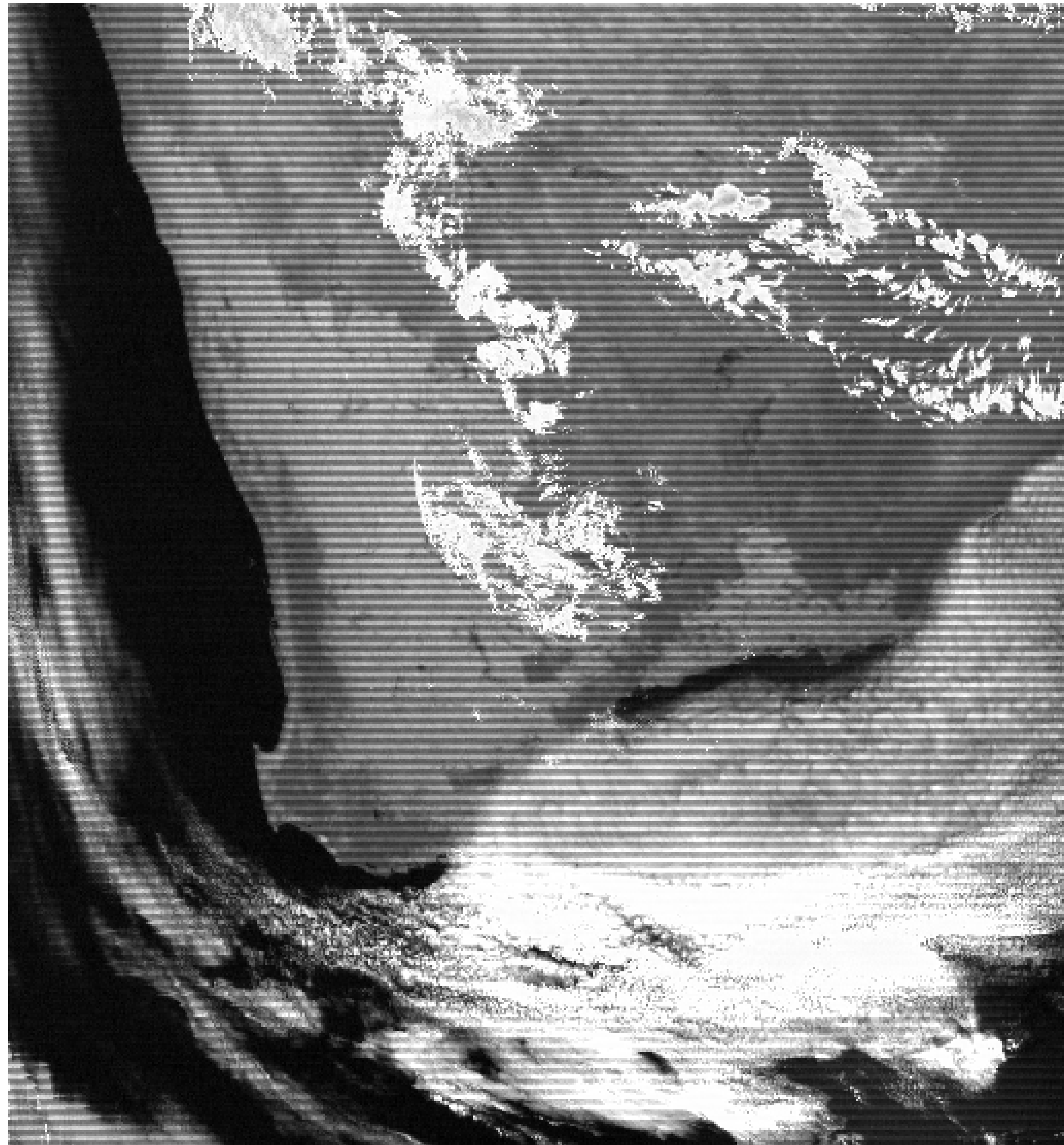
Deep Space Maneuver data on Terra incorporated for collection 5 processing.



Band 26 Optical Leak

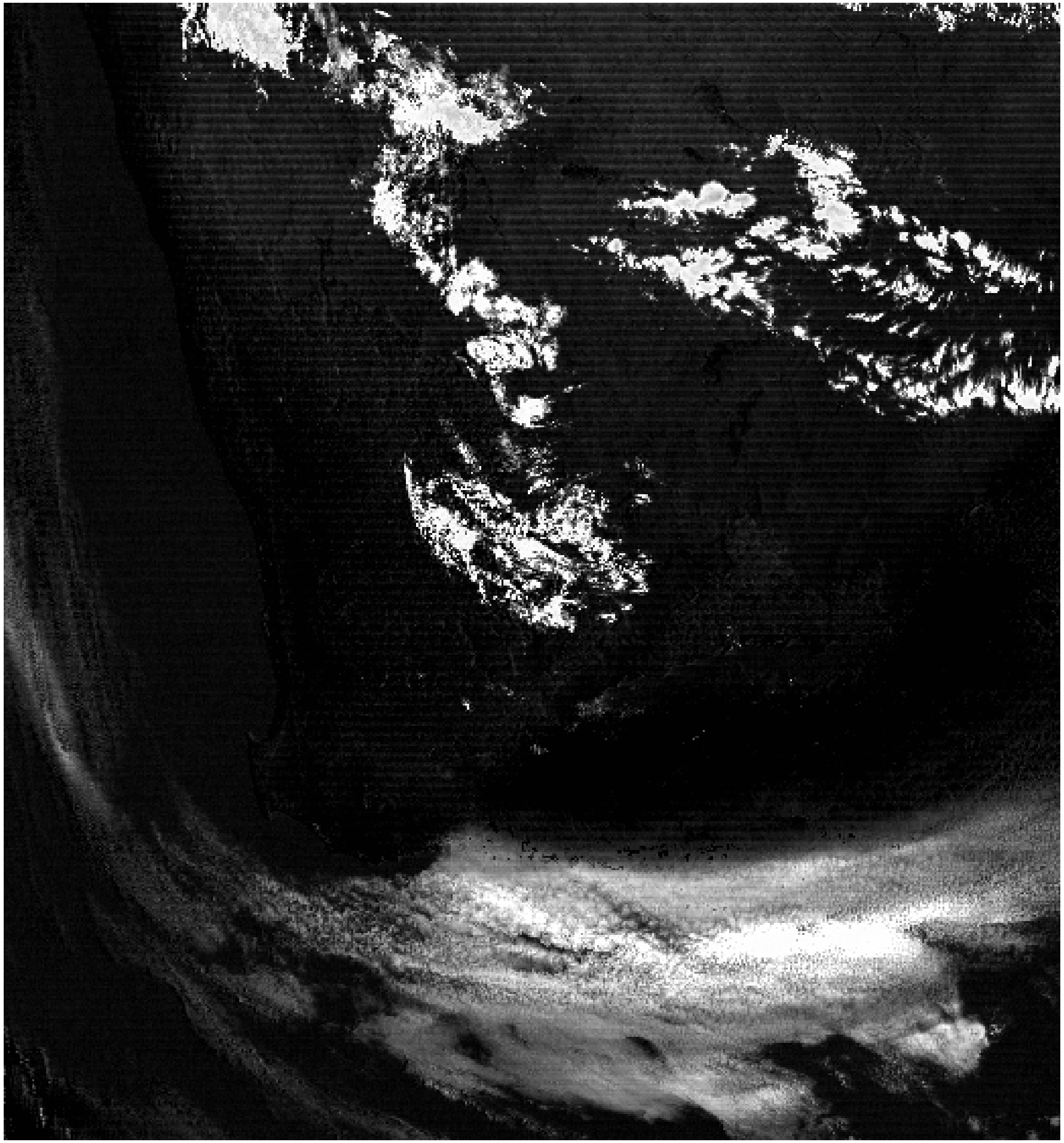
Photons intended for Band 5 detectors (1.24 μm) leak into Band 26 (1.38 μm) detectors.

Correction is operational for collection 4 processing.



Band 26 Corrected

Detector dependent correction factors remove the land surface contribution and reduce striping.



FIXED!

MODIS Performance

Performance Issue	Terra	Aqua
Band 26 Striping and elevated background signal	Correction in L1B now in place for Collect 4.	No Improvement Correction will be necessary
S/MWIR Electronic Crosstalk	An ongoing issue No on-orbit correction	Improved (reduced but not eliminated)
PC LWIR Band Optical Leak	Corrected in L1B; 1-2% uncertainty	Fixed during prelaunch
Detector Striping	Exists in several thermal IR bands. EDF algorithm now available	Improved, but still present. EDF algorithm now available.

MODIS Performance
cont.

Performance Issue	Terra	Aqua
5um thermal leak into SWIR	Small influence; Effectively Corrected in L1B	Improved; Correction in L1B TBD
SWIR Band Subsample Departure	On going issue No on-orbit correction	Much Improved
Noisy Detectors	Several in LWIR CO2 bands, one in B24, 25, 27, 28,30	Much Improved (B36 chan 5)
Saturation in Band 2	Saturation on thick water cloud, sunglint regions	Slightly Worse (lower saturation level)

MODIS Performance
cont.

Performance Issue	Terra	Aqua
Scan Mirror reflectance vs. angle of incidence	Much Improved after Deep Space Maneuver	Much Improved Good prelaunch characterization
Dead detectors in SWIR bands	None	B6 severely impacted; B5 has one dead detector

Destriping

MODIS Destriping

Striping is a consequence of the calibration algorithm, where each detector is calibrated independently. If the instrument were characterized perfectly, there would be no striping.

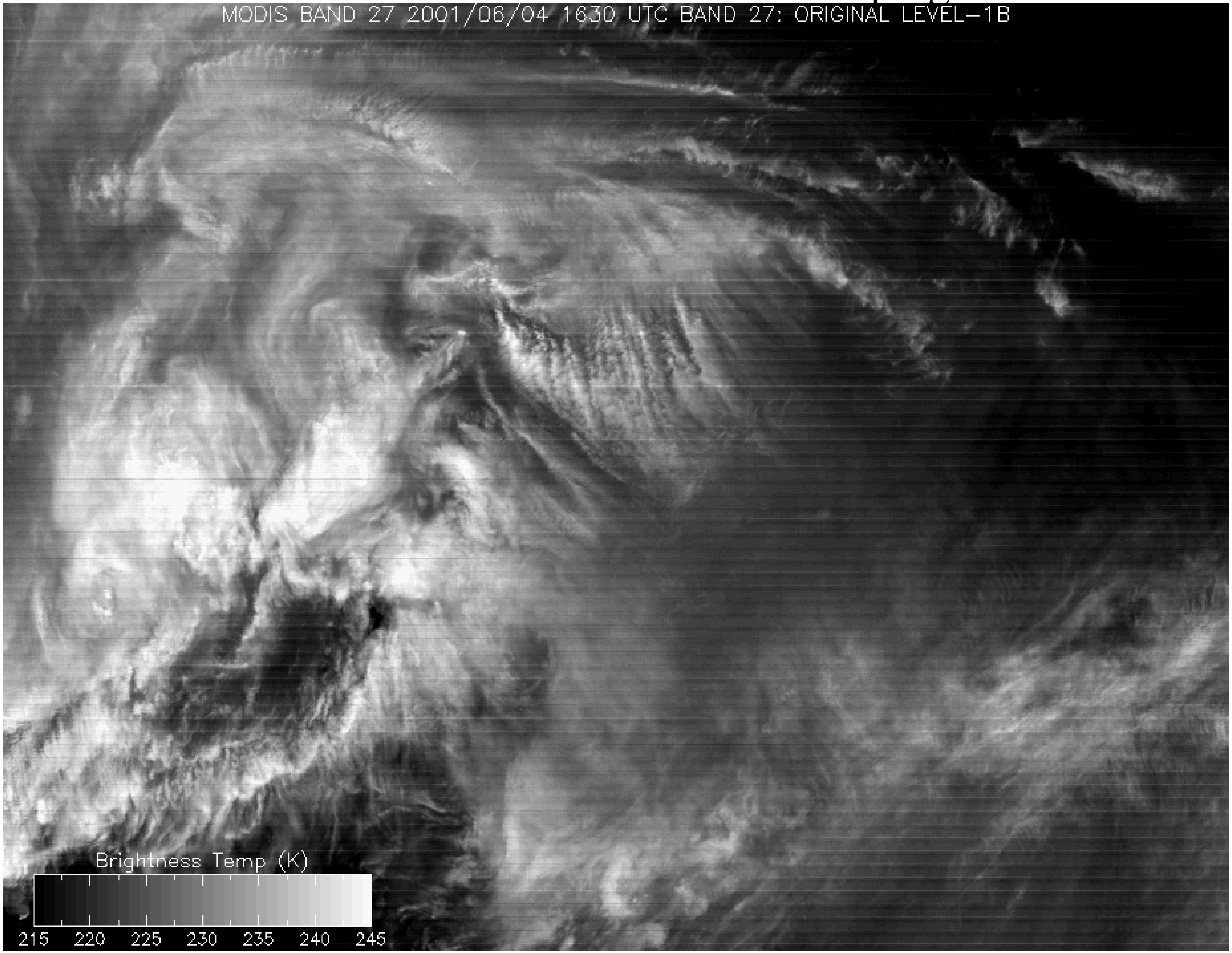
However, it is not possible to characterize the instrument perfectly because of time, cost, and schedule constraints.

As a result, striping artifacts are introduced by:

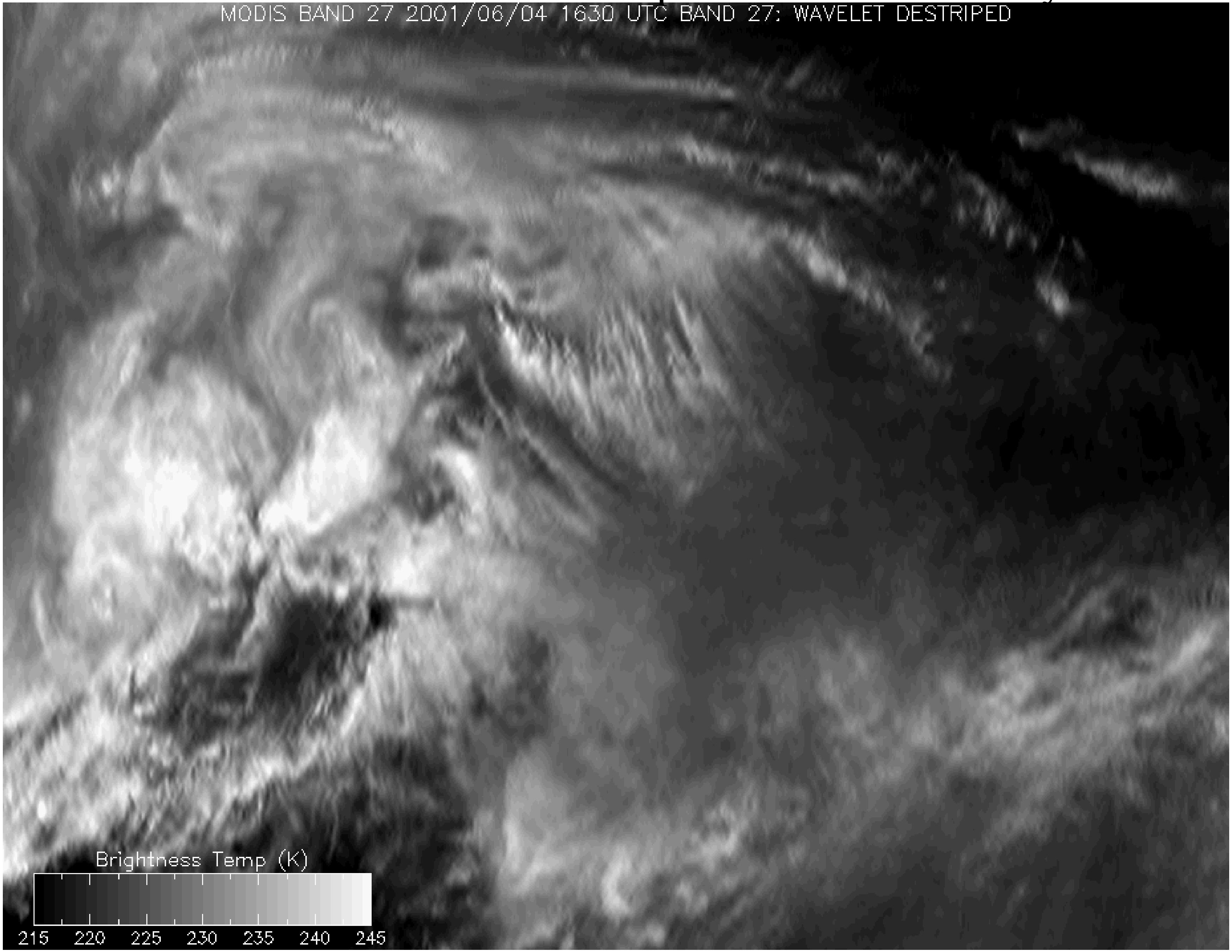
- Two-side scan mirror is not characterized perfectly
- Detectors behavior can change in orbit (bias, spectral response)
- Detectors may be noisy

The challenge is to design a destriping algorithm which is effective, fast, and insensitive to instrument changes.

Terra MODIS Band 27 With Striping



Terra MODIS Band 27 Destriped via Wavelet Analysis



Algorithm Details

Weinreb et al., 1989: "Destriping GOES Images by Matching Empirical Distribution Functions". Remote Sens. Environ., 29, 185-195.

• Accounts for both detector-to-detector and mirror side striping.

• MODIS is treated as a 20 detector instrument in the emissive bands (10 detectors on each mirror side).

• The empirical distribution function (EDF) is computed for each detector (cumulative histogram of relative frequency).

• The EDF for each detector is adjusted to match the EDF of a reference in-family detector.

• Algorithm operates on L1B scaled integers (0-32767).

• Median scaled integer value is restored following destriping.

Destriping Algorithm Implementation

- IDL, FORTRAN-90, and C code for Terra/Aqua L1B 1KM files in DAAC or IMAPP format.
- Requires about 60 seconds to run for each granule.
- Correction LUT is created for each individual granule.
- Uncorrected scaled integers are replaced with corrected scaled integers (could store the correction LUT instead).
- Bands 20, 22-25, 27-30, 33-36 are destriped.
- Impact on bands 31 and 32 is equivocal.
- For Terra MODIS, noisy detectors in some bands are replaced with neighbors (could use interpolation instead):

    27 (dets 0, 6); 28 (dets 0, 1); 33 (det 1); 34 (dets 6, 7, 8)

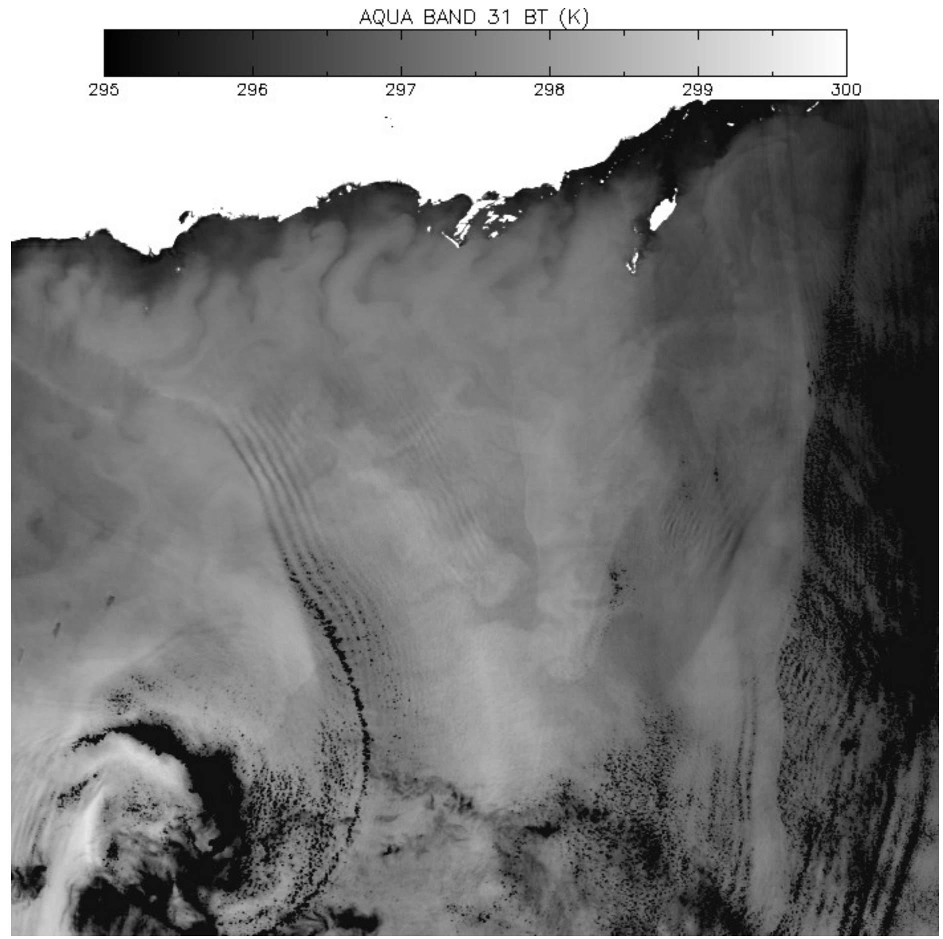
- For Aqua MODIS, no detectors are replaced.

Aqua Example

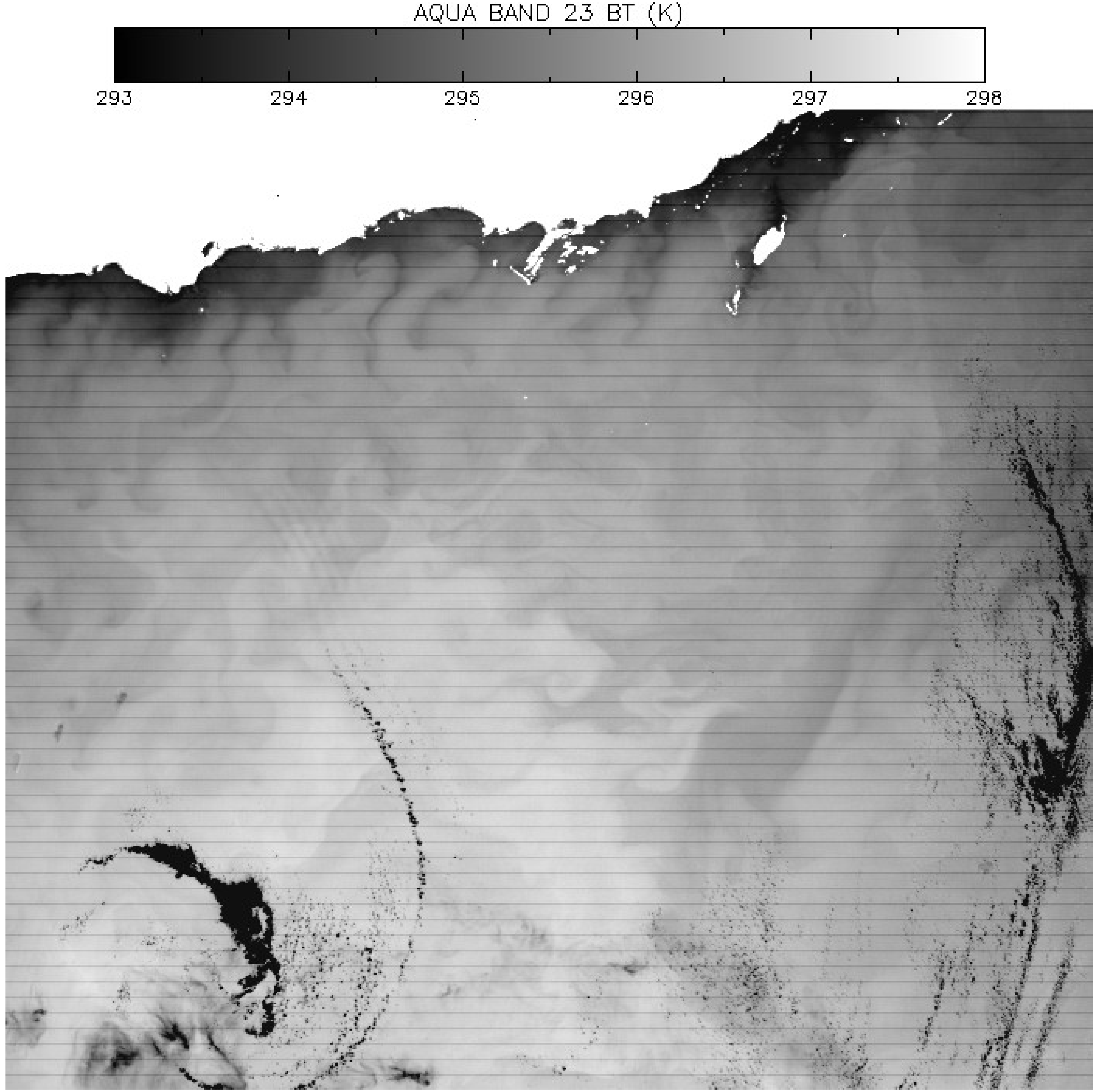
MYD021KM.A2003147.0555.003.2003149154542.hdf (May 27)

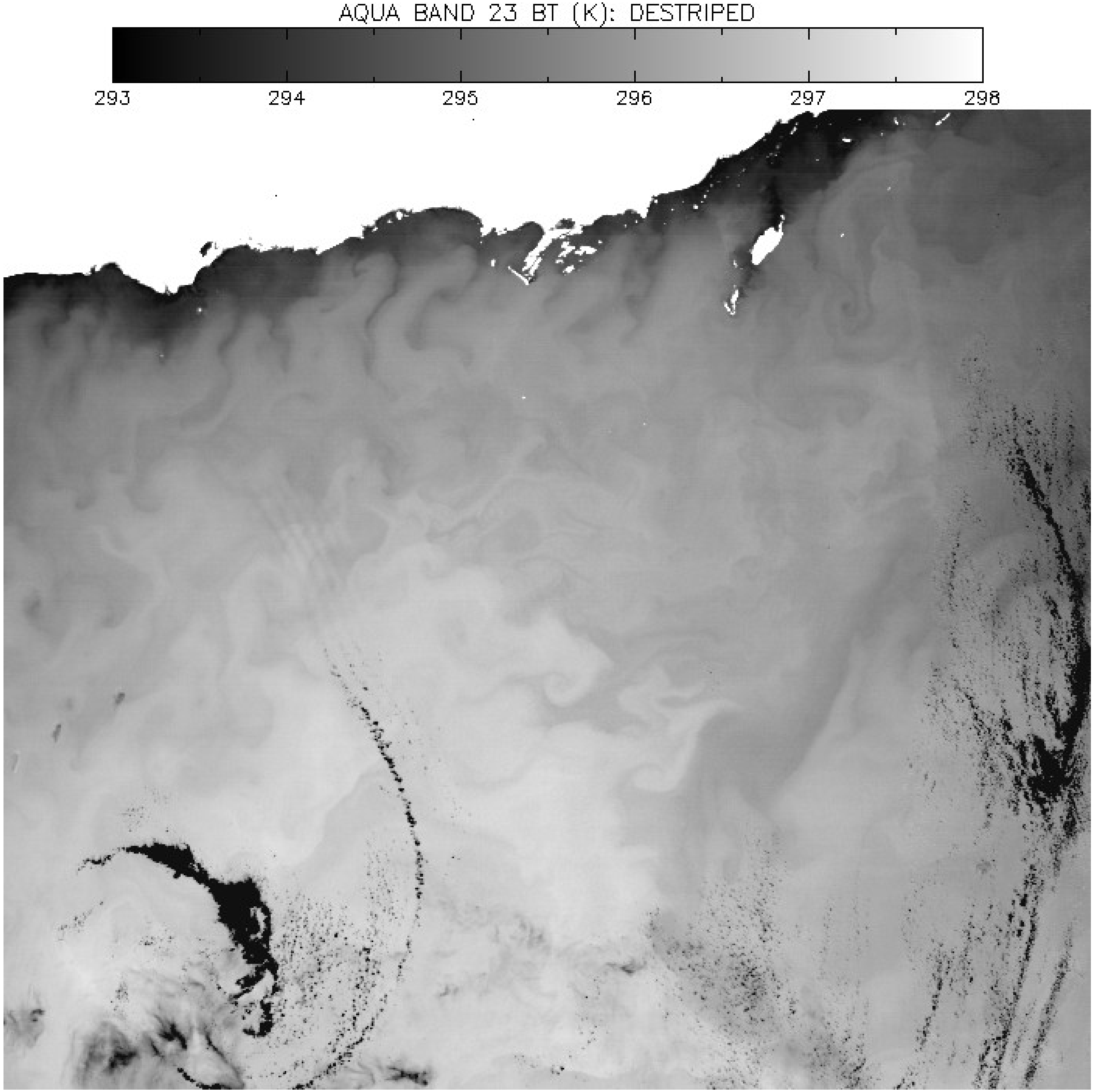
Northwest Shelf of Western Australia, 700 x 700 pixel subscene

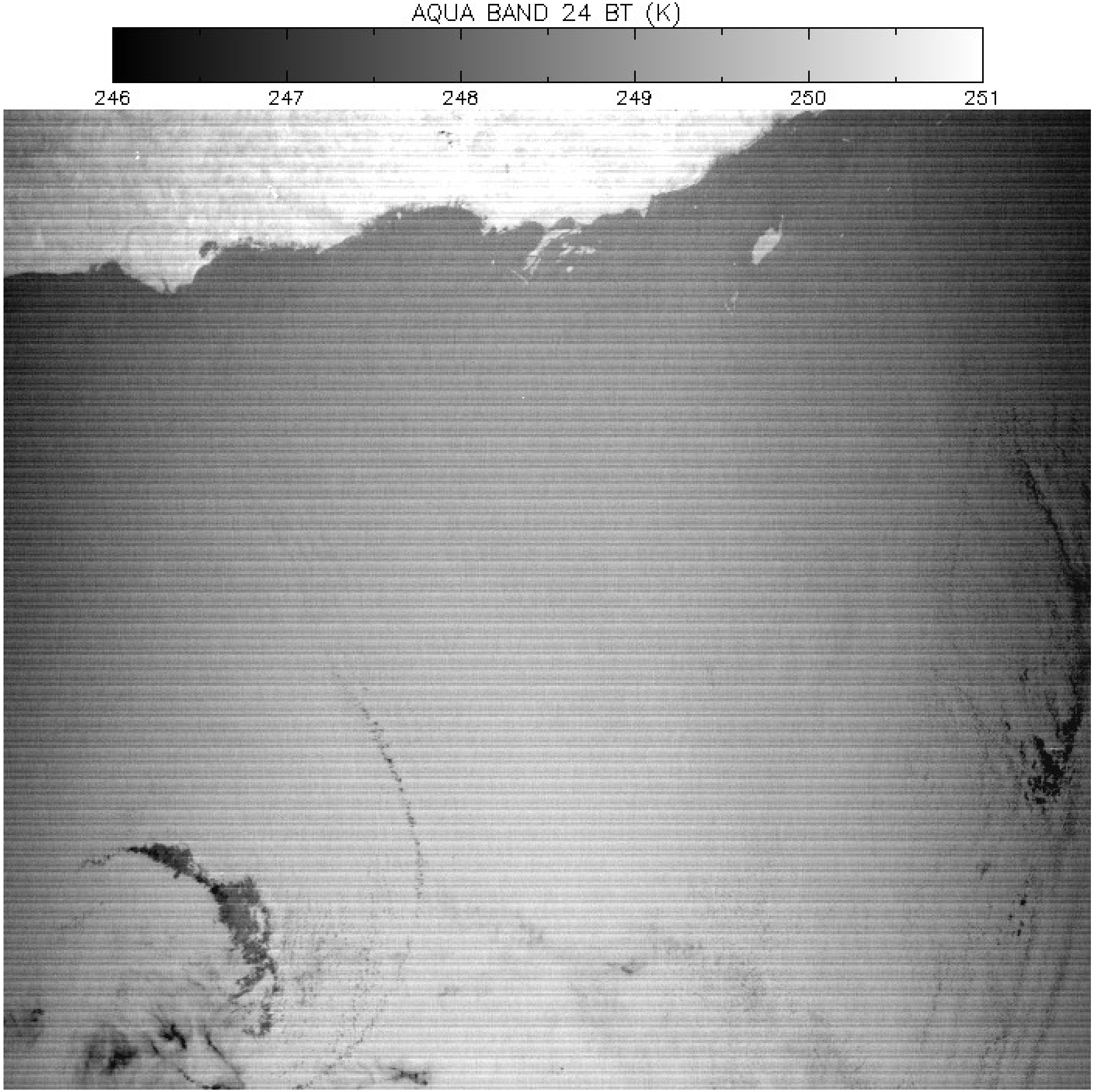
Band 2

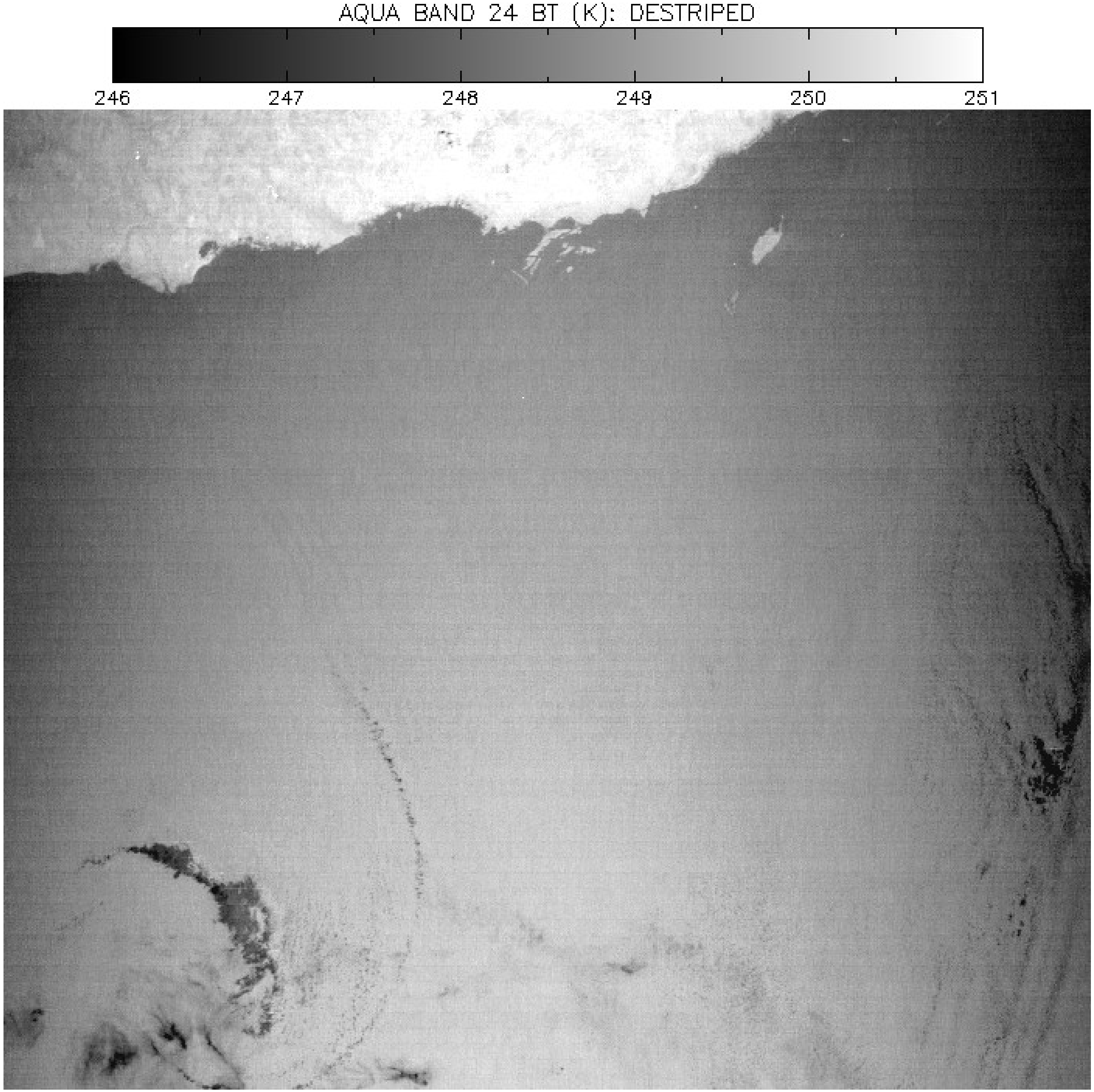


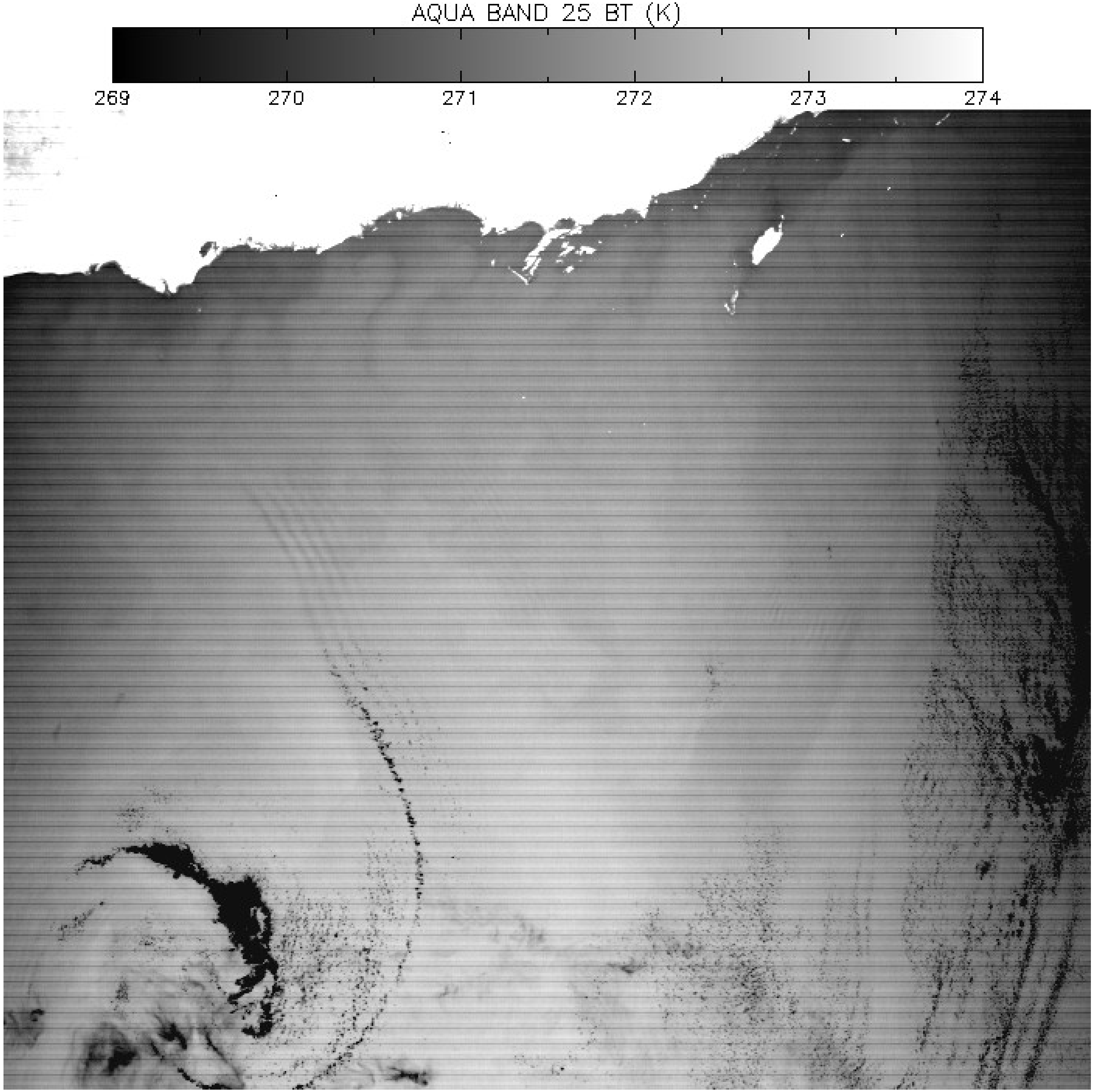
Band 31

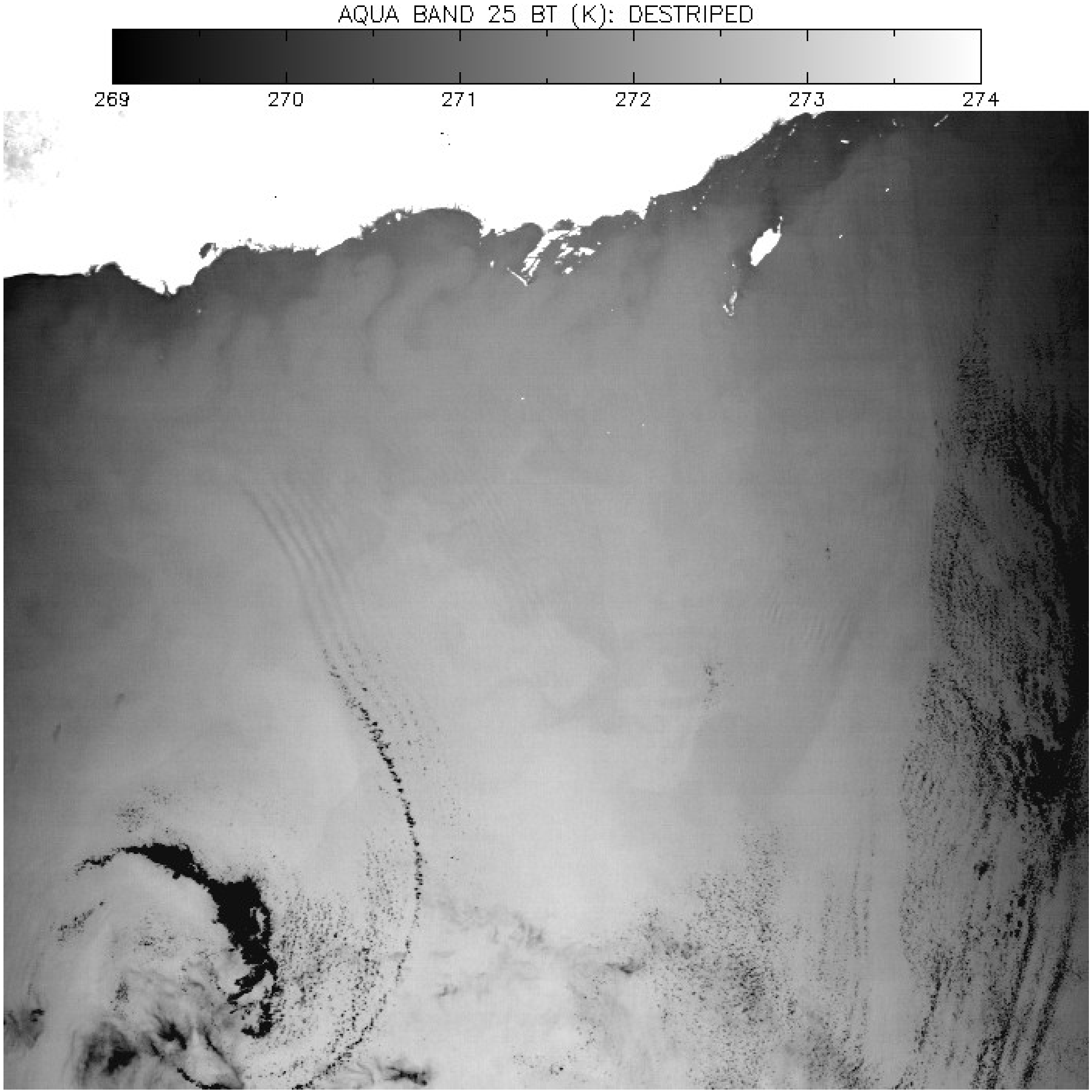

AQUA BAND 23 BT (K)
293
294
295
296
297
298

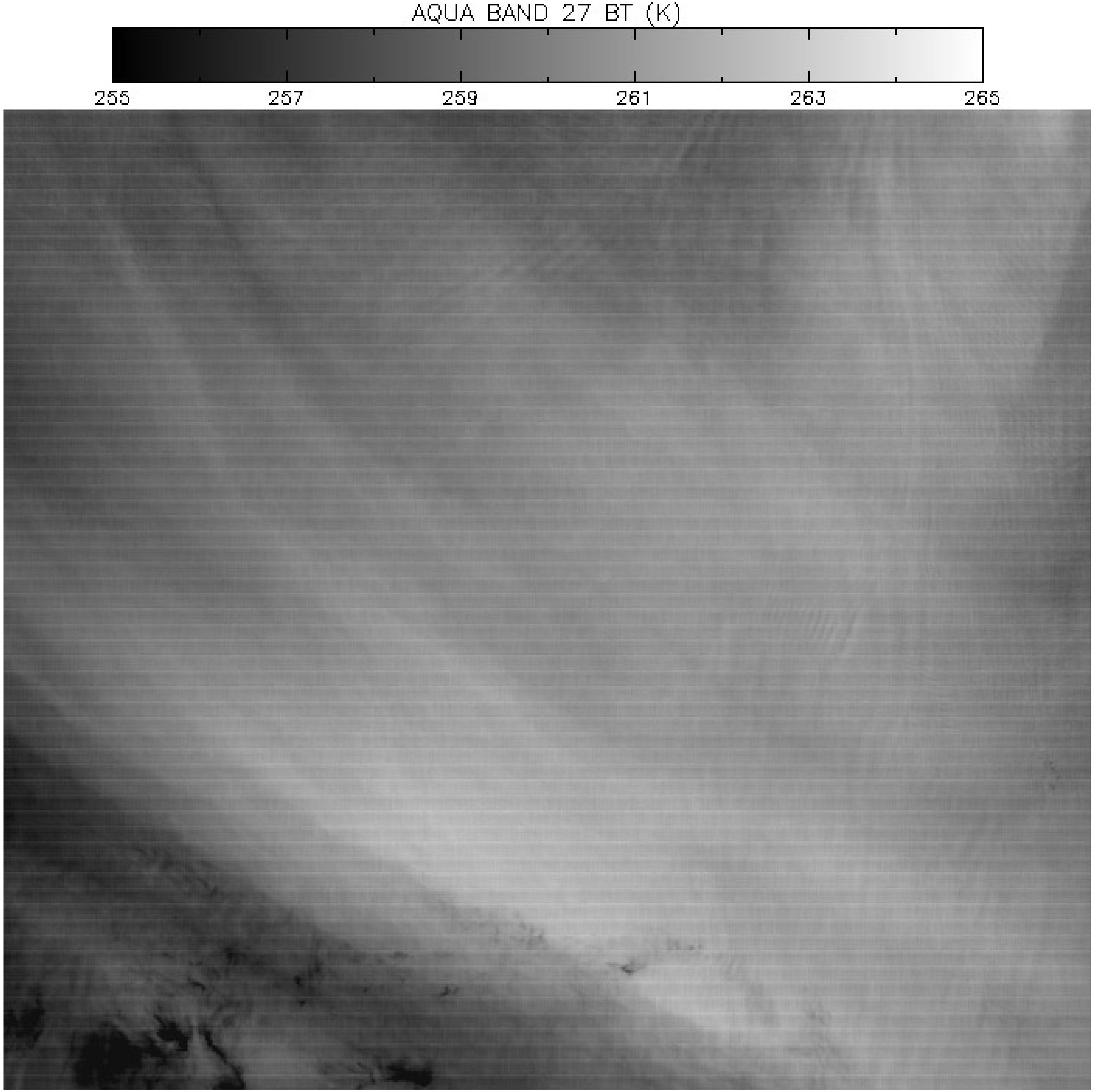

AQUA BAND 23 BT (K): DESTRIPED
293
294
295
296
297
298

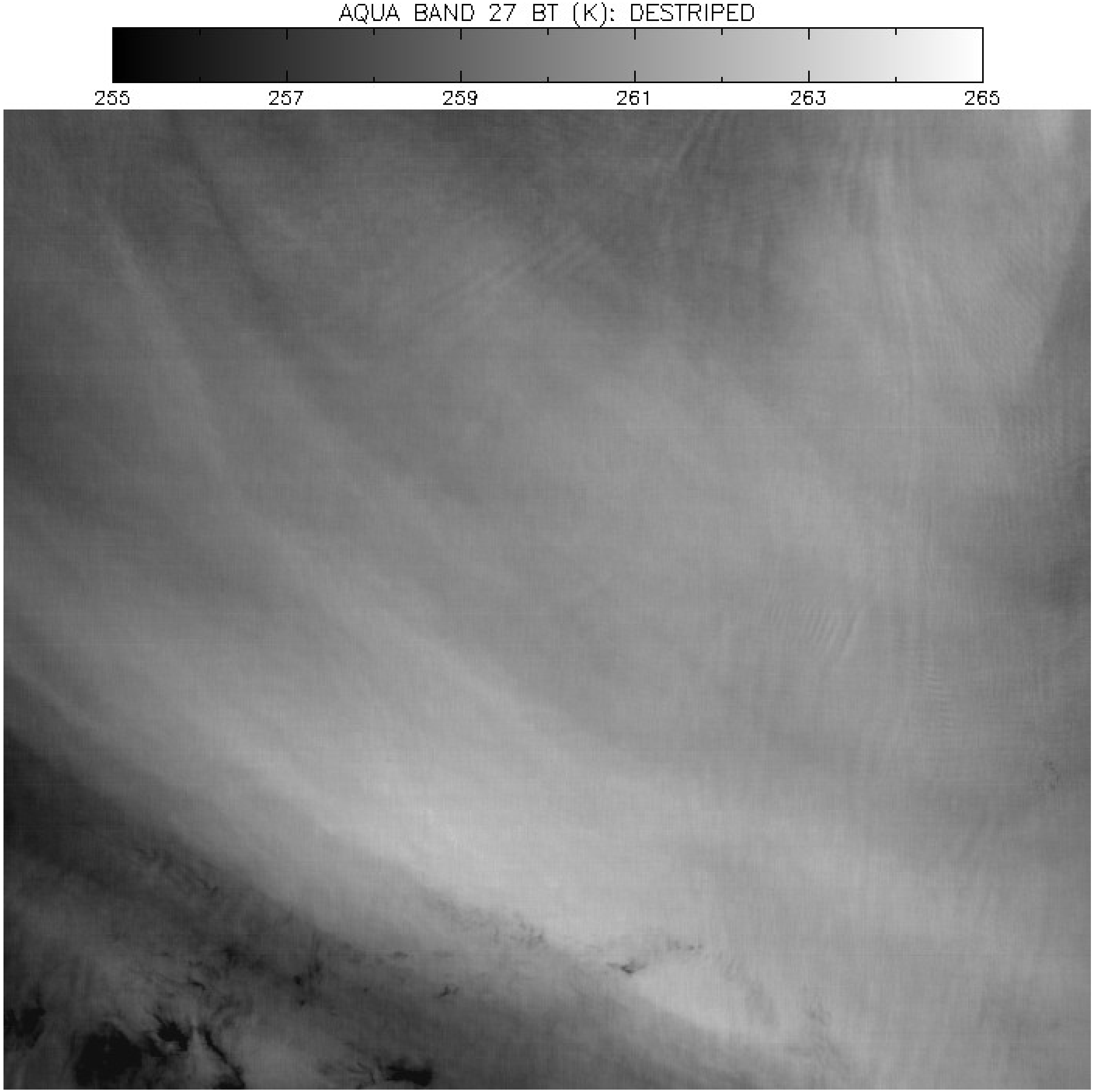

AQUA BAND 24 BT (K)
246
247
248
249
250
251

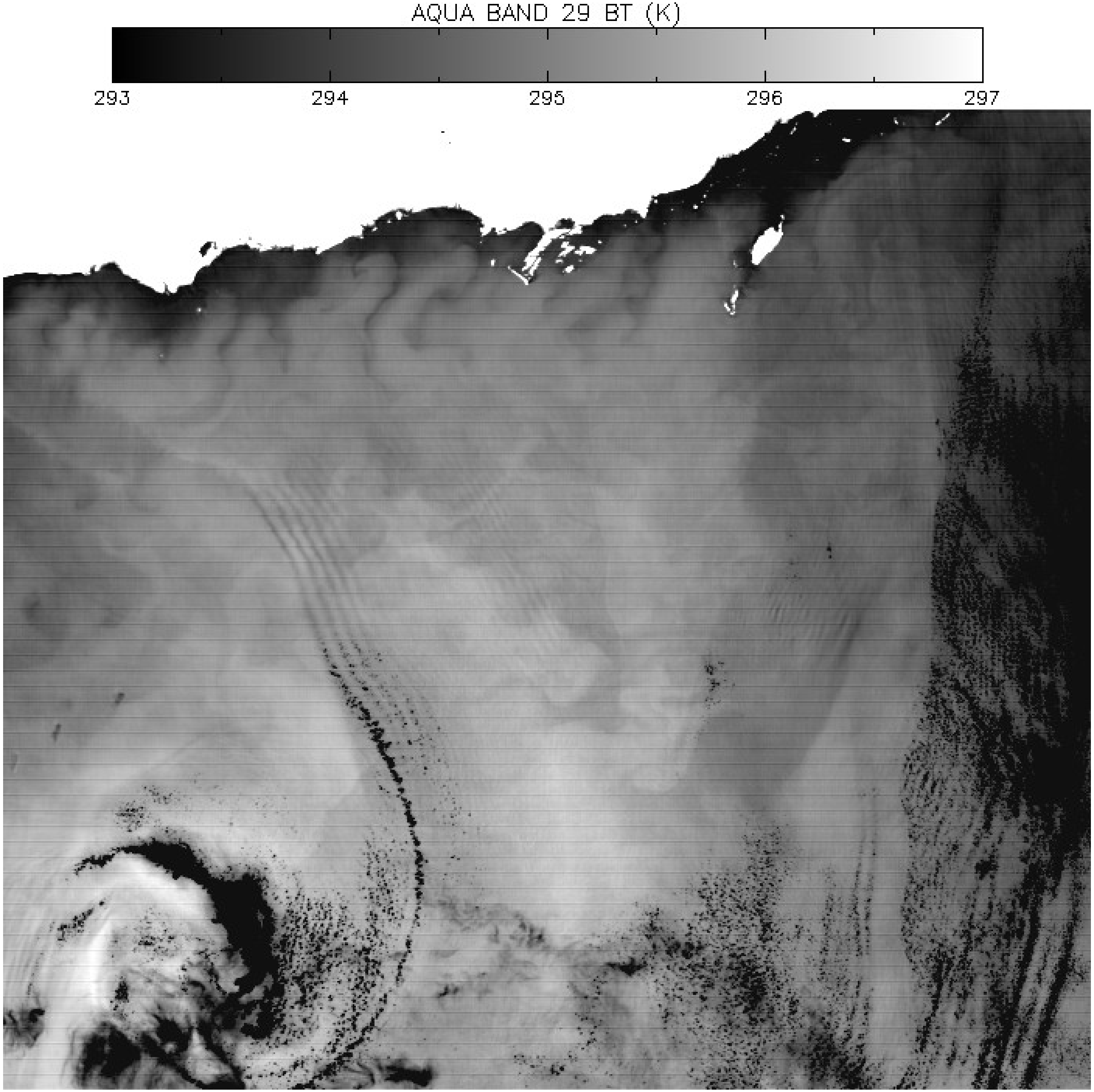

AQUA BAND 24 BT (K): DESTRIPED
246
247
248
249
250
251

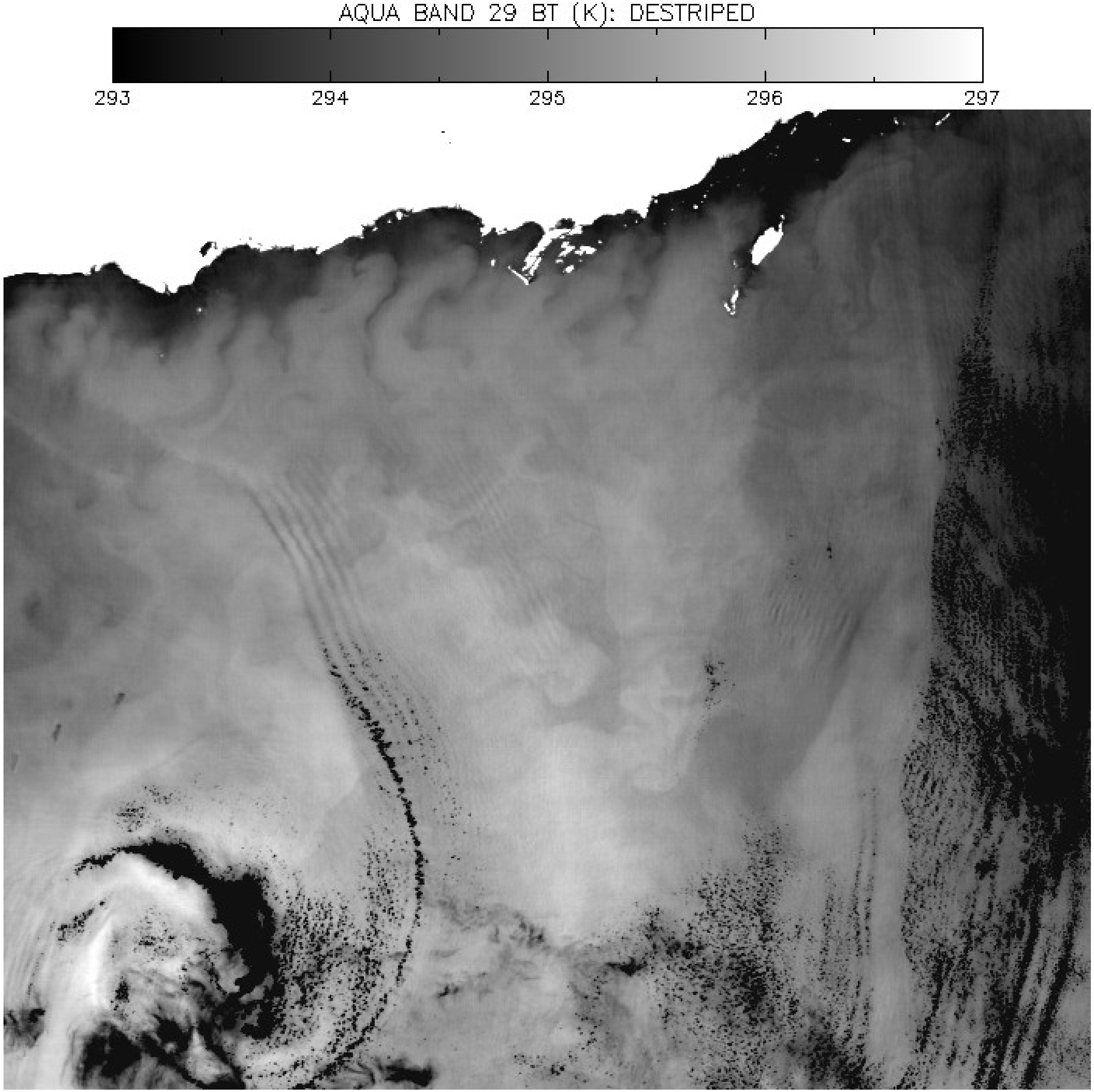

AQUA BAND 25 BT (K)
269
270
271
272
273
274

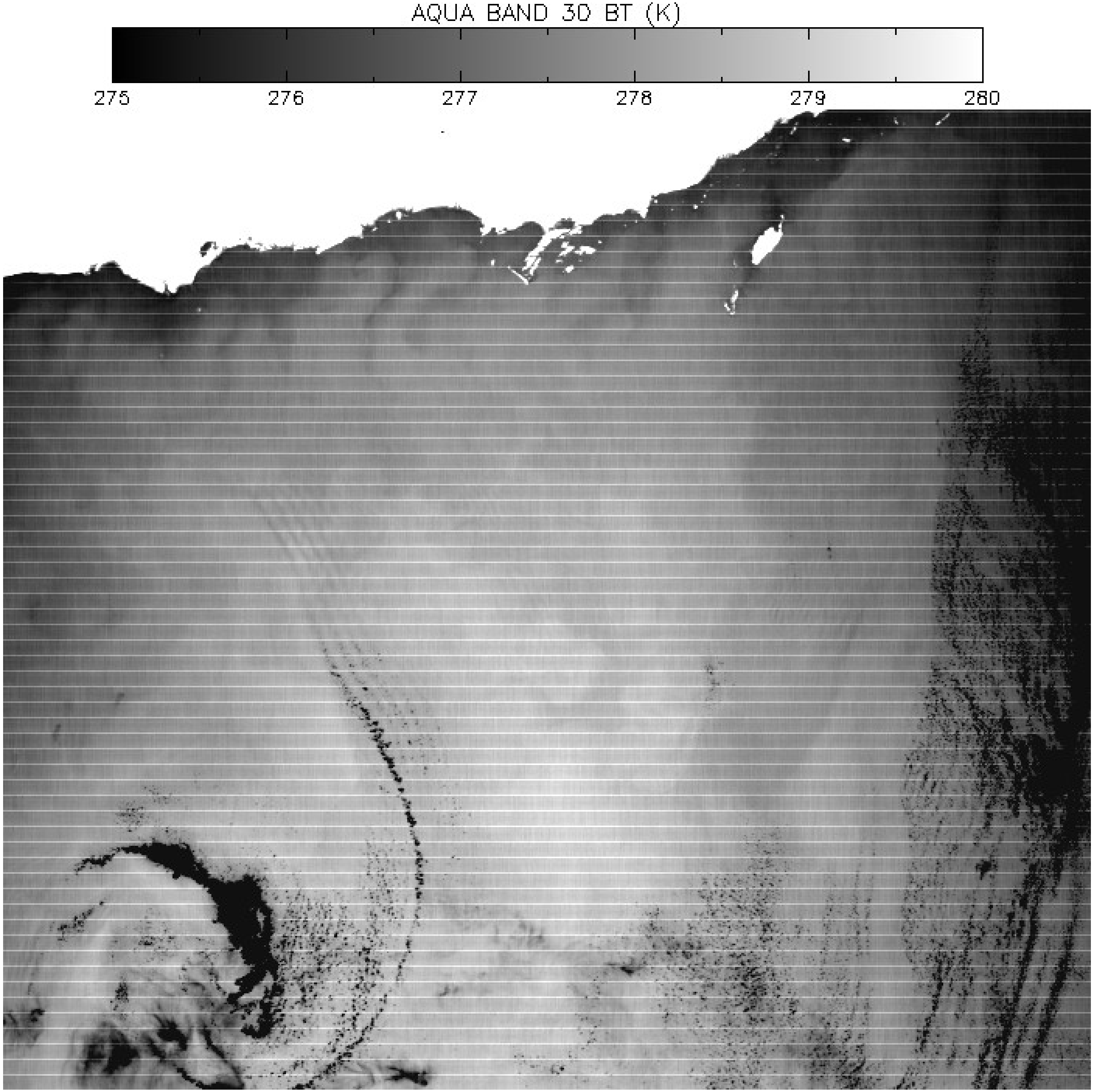

AQUA BAND 25 BT (K): DESTRIPED
269
270
271
272
273
274

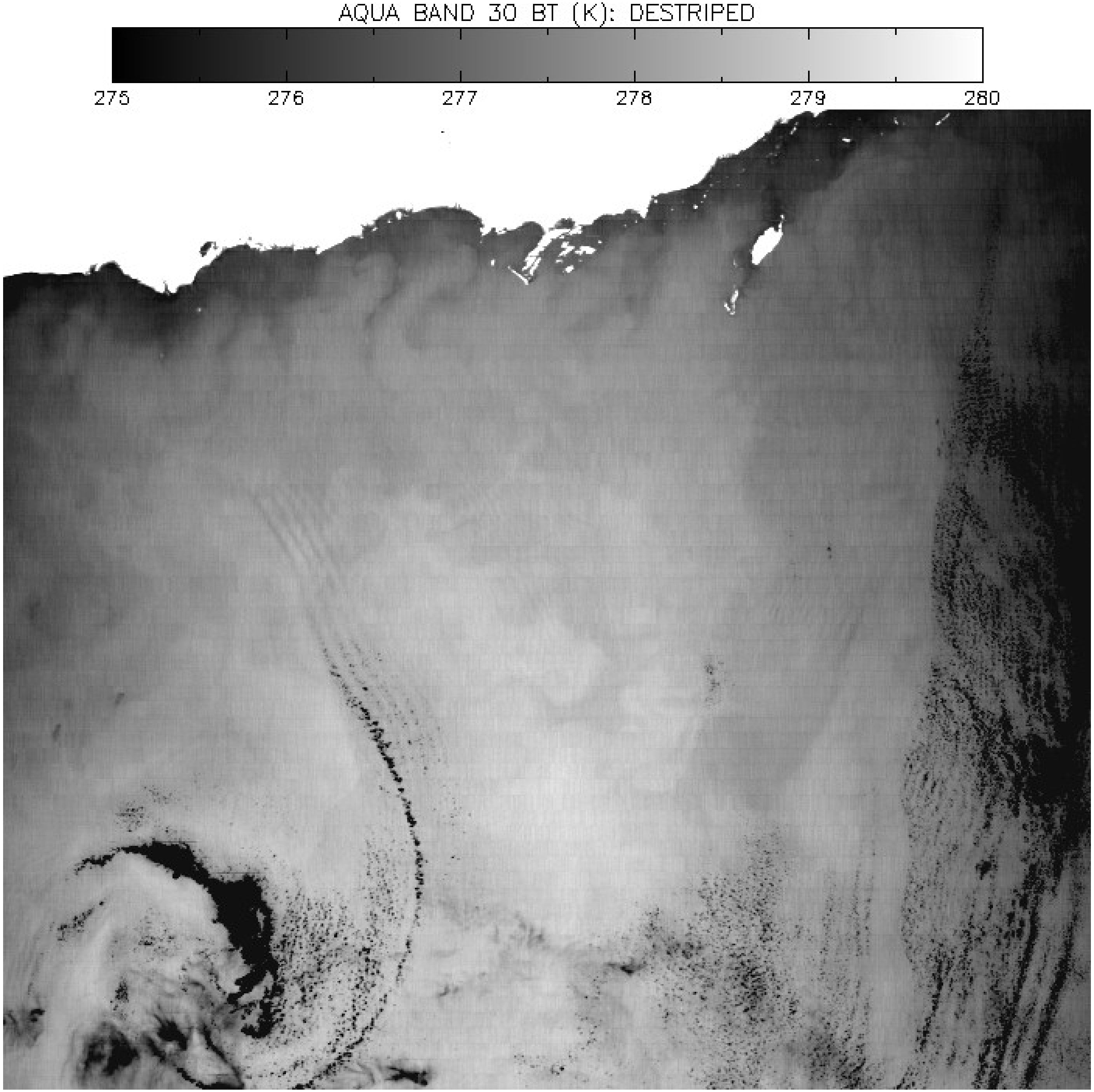

AQUA BAND 27 BT (K)
255
257
259
261
263
265

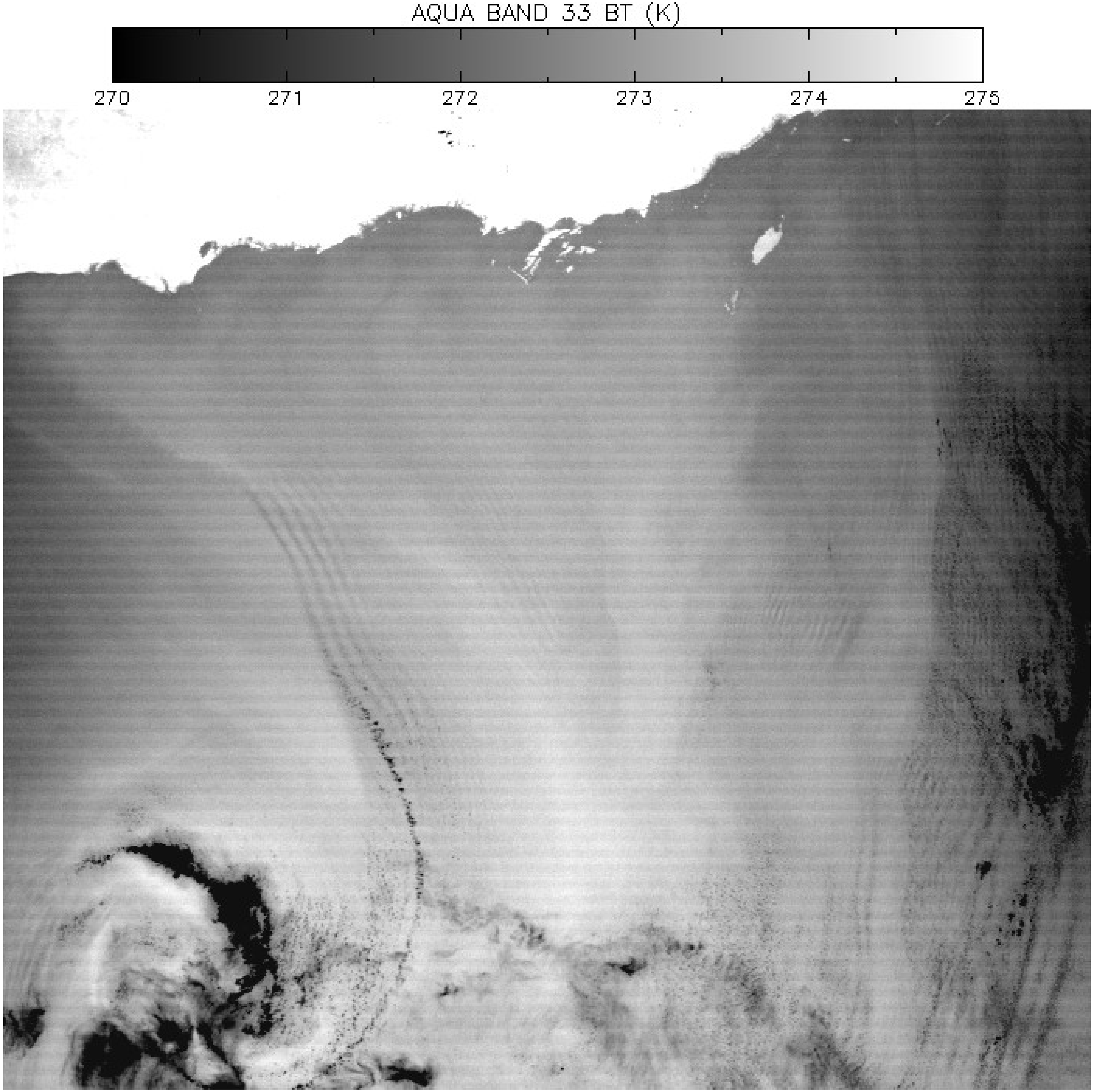

AQUA BAND 27 BT (K): DESTRIPED
255
257
259
261
263
265

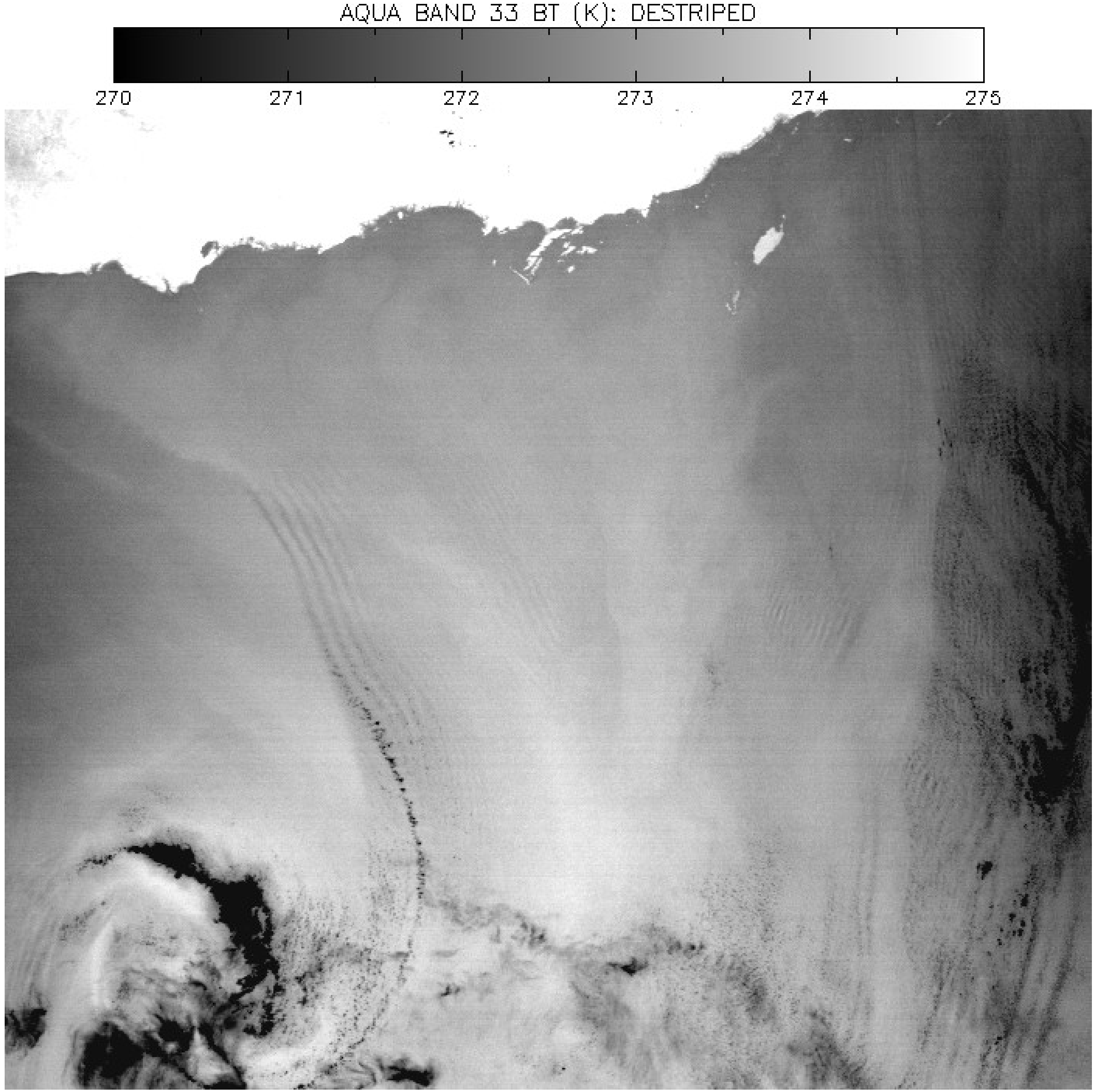

AQUA BAND 29 BT (K)
293
294
295
296
297


AQUA BAND 29 BT (K): DESTRIPED
293
294
295
296
297


AQUA BAND 30 BT (K)
275
276
277
278
279
280


AQUA BAND 30 BT (K): DESTRIPED
275
276
277
278
279
280


AQUA BAND 33 BT (K)
270
271
272
273
274
275


AQUA BAND 33 BT (K): DESTRIPED
270
271
272
273
274
275

MODIS Destriping Impact on Radiometry

Analyzed an Aqua MODIS scene from 2003/10/16 19:31-19:41 UTC acquired by SSEC direct broadcast

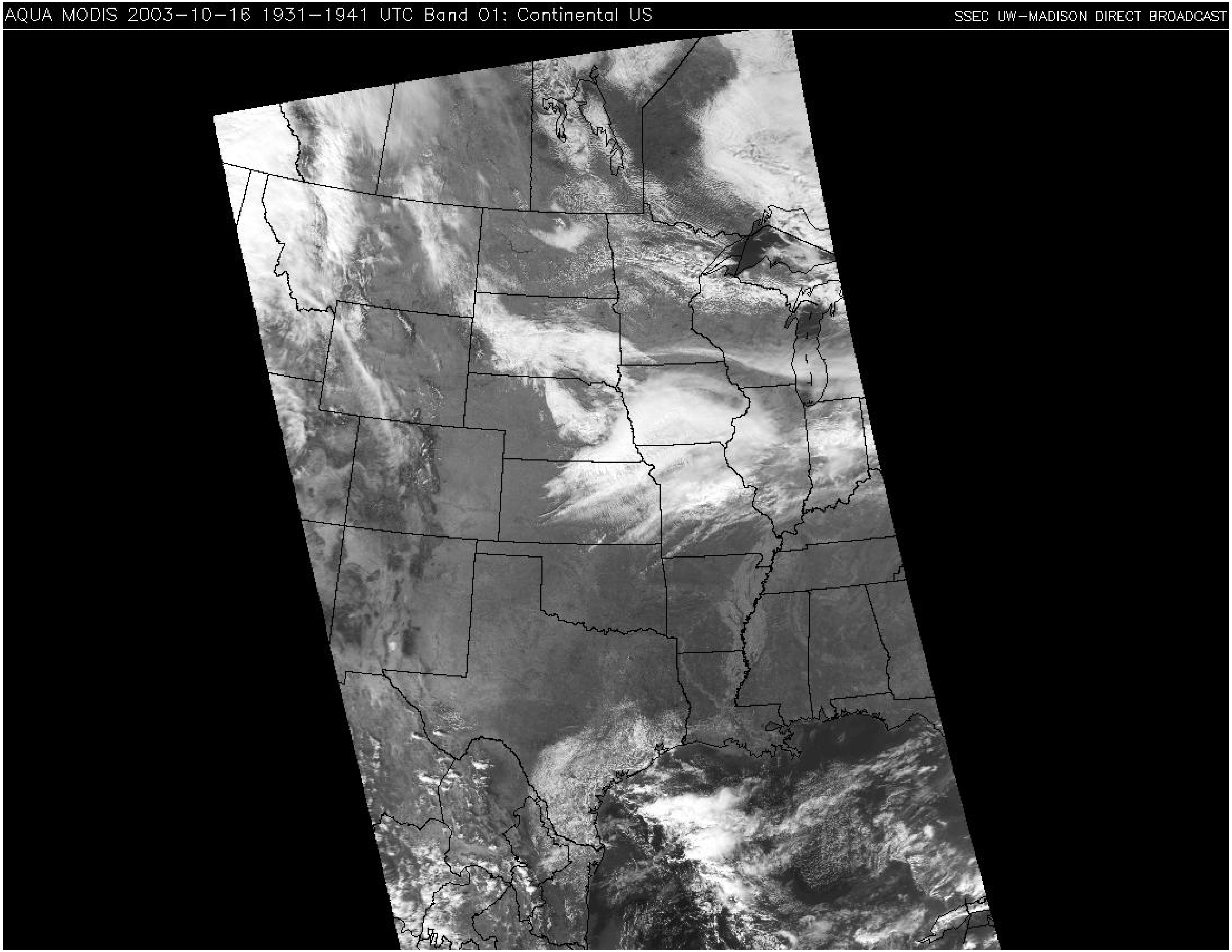
Objective 1: Assess change in overall scene radiometry as a result of destriping (with and without median restored)

Figure 1: Histograms of (Destriped – Original) brightness temperature

Objective 2: Assess magnitude of destriping correction as a function of scene temperature

Figure 2: Scatter plots of (Destriped –Original) brightness temperature vs. Destriped brightness temperature

Aqua MODIS 2003/10/16 19:31-19:41 UTC



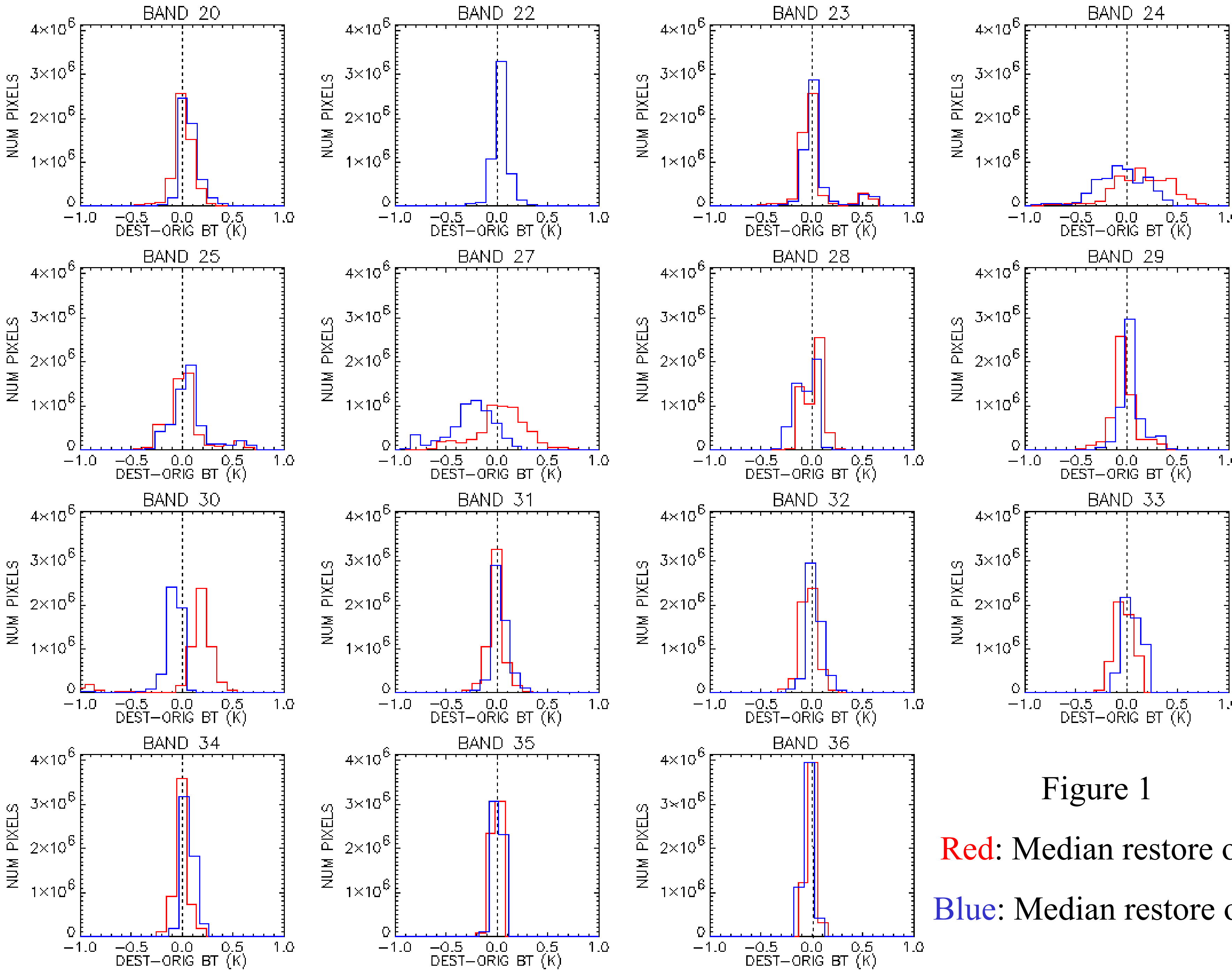


Figure 1

Red: Median restore on

Blue: Median restore off

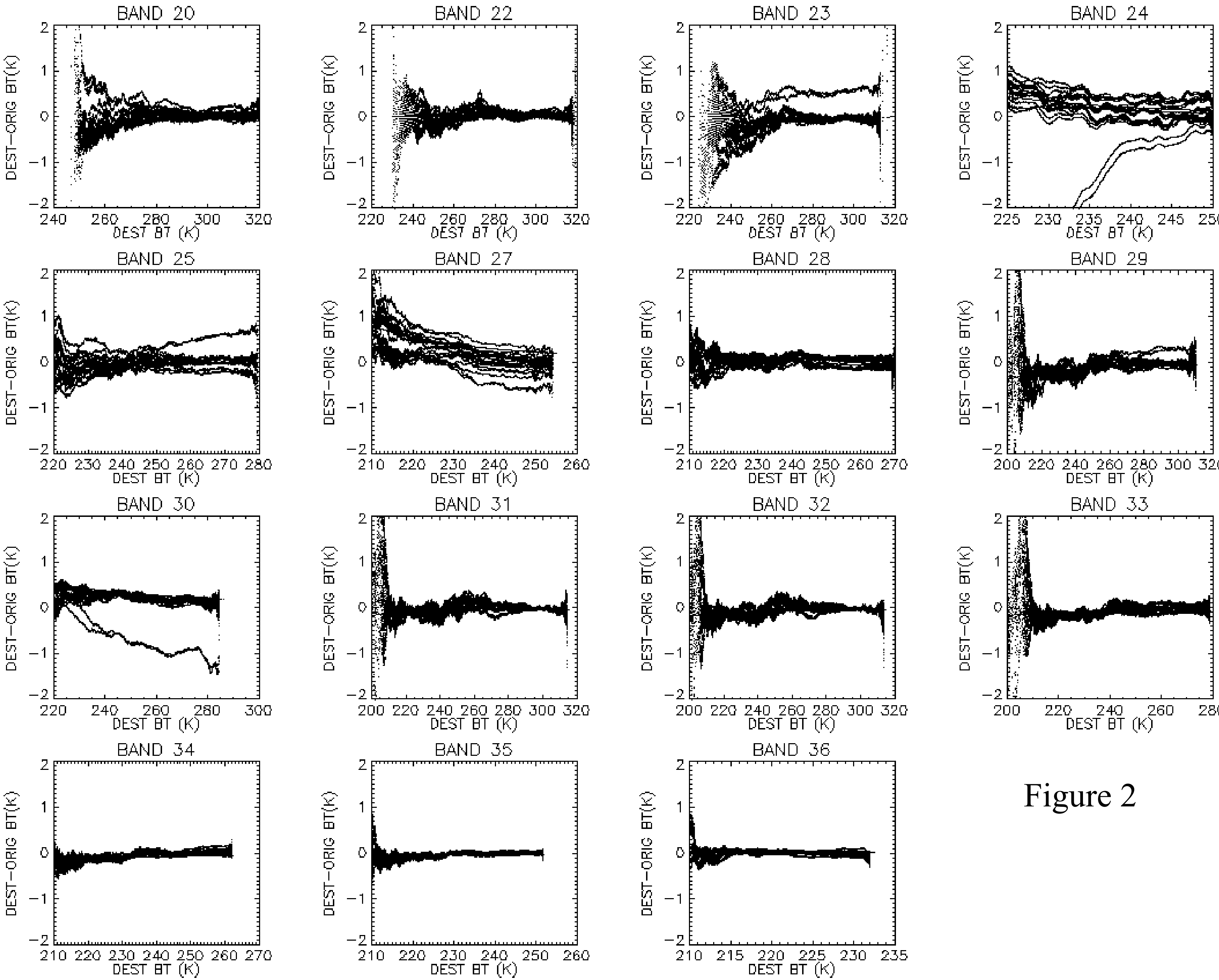

BAND 20
BAND 22
BAND 23
BAND 24
BAND 25
BAND 27
BAND 28
BAND 29
BAND 30
BAND 31
BAND 32
BAND 33
BAND 34
BAND 35
BAND 36
DEST–ORIG BT(K)
DEST BT (K)

Figure 2

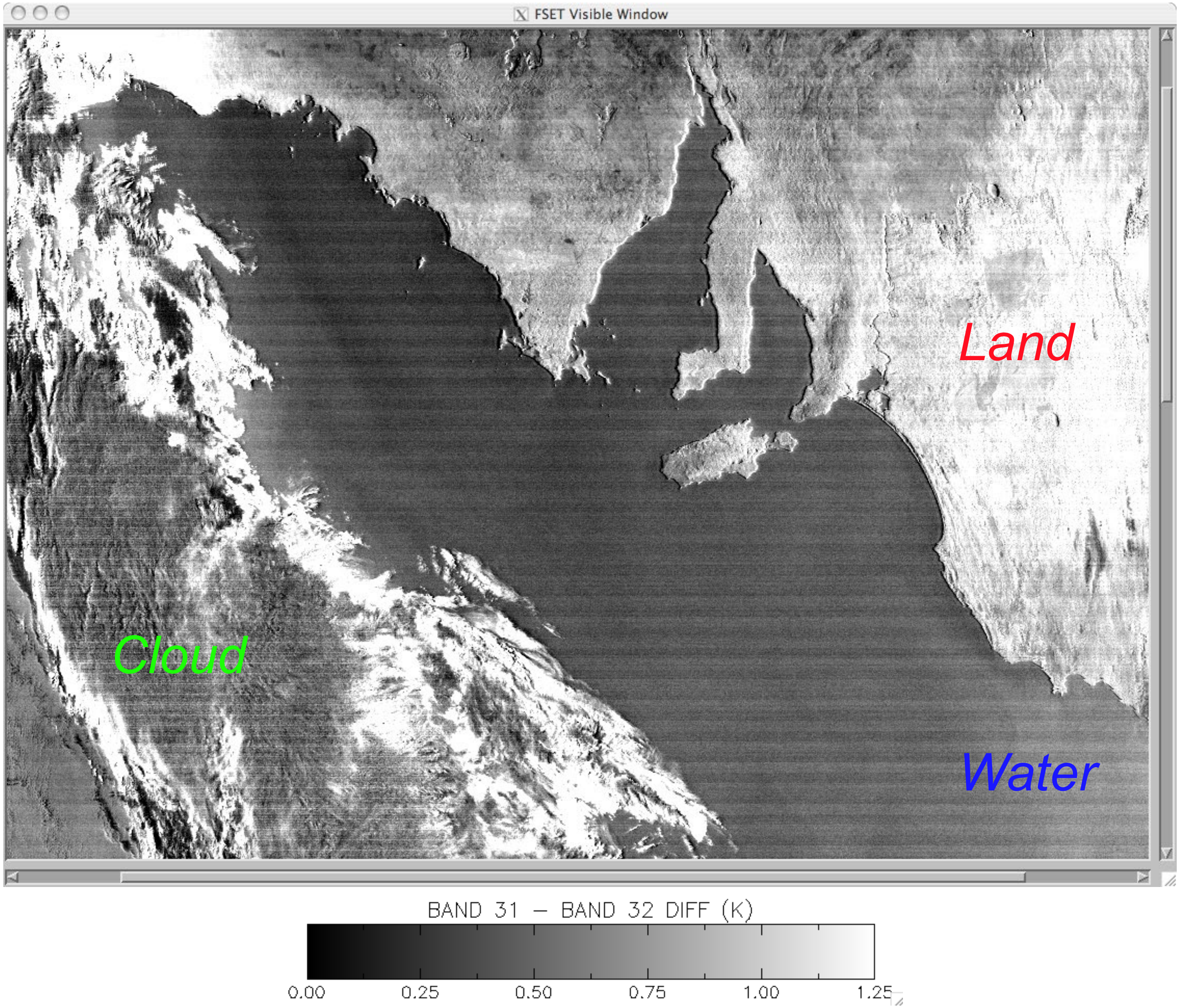
MODIS Emissive Band Destriping: Granule vs. Daily Analysis

The Atmosphere Group products for collection 5 include destriping of all emissive bands (20-25, 27-36) and band 26.

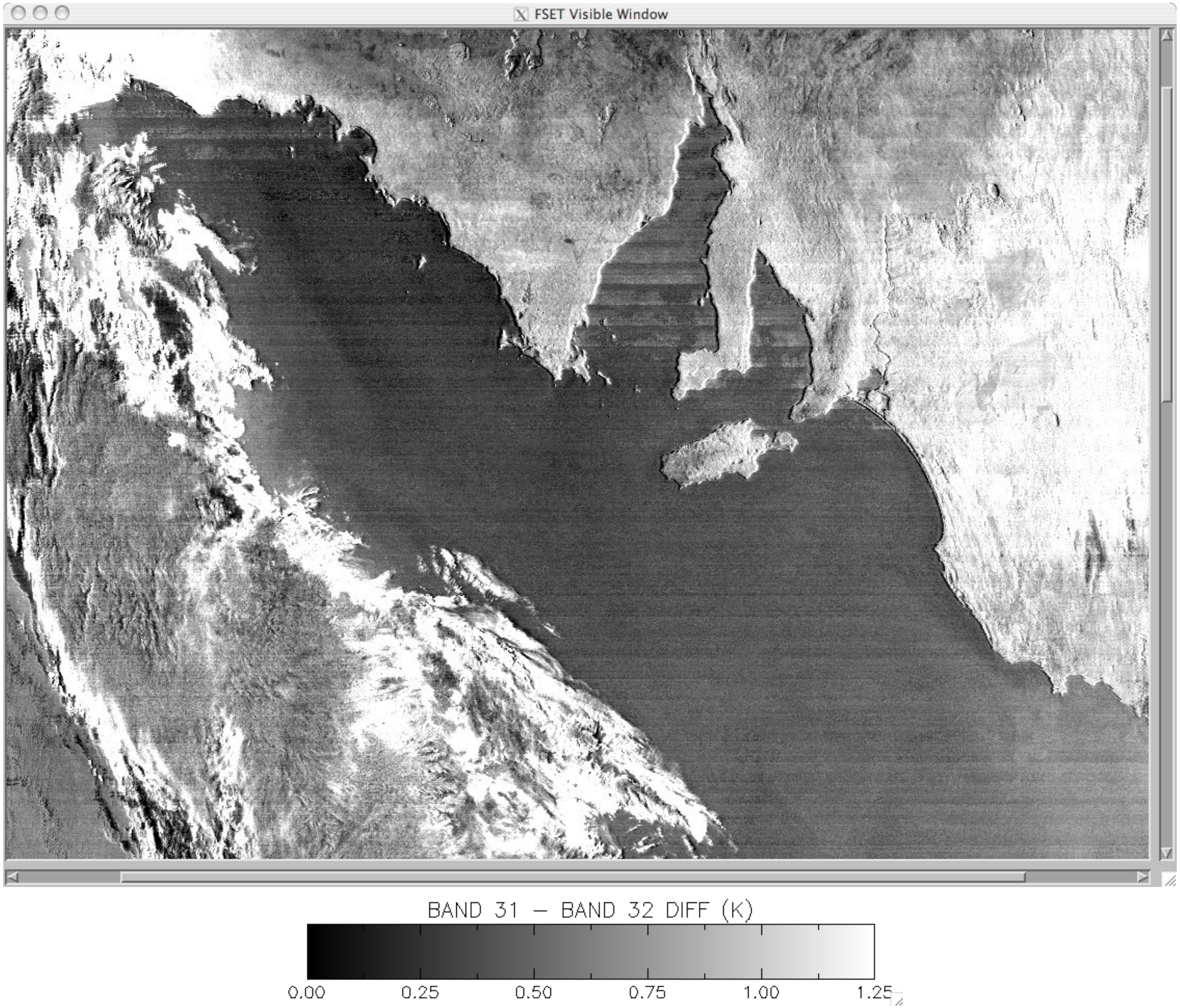
The destriping algorithm is granule-based, and for a small percentage of granules, the impact may be equivocal in bands 31 and 32. Granules with sharp transitions between warm and cool scenes (e.g. hot land, cool ocean) may have artifacts in the scene transition zone.

We analyzed a complete day of data (Terra MODIS 2000337, collection 5) to develop the destriping LUT for bands 31 and 32, with the expectation that sampling a wider range of scenes would remove the artifacts.

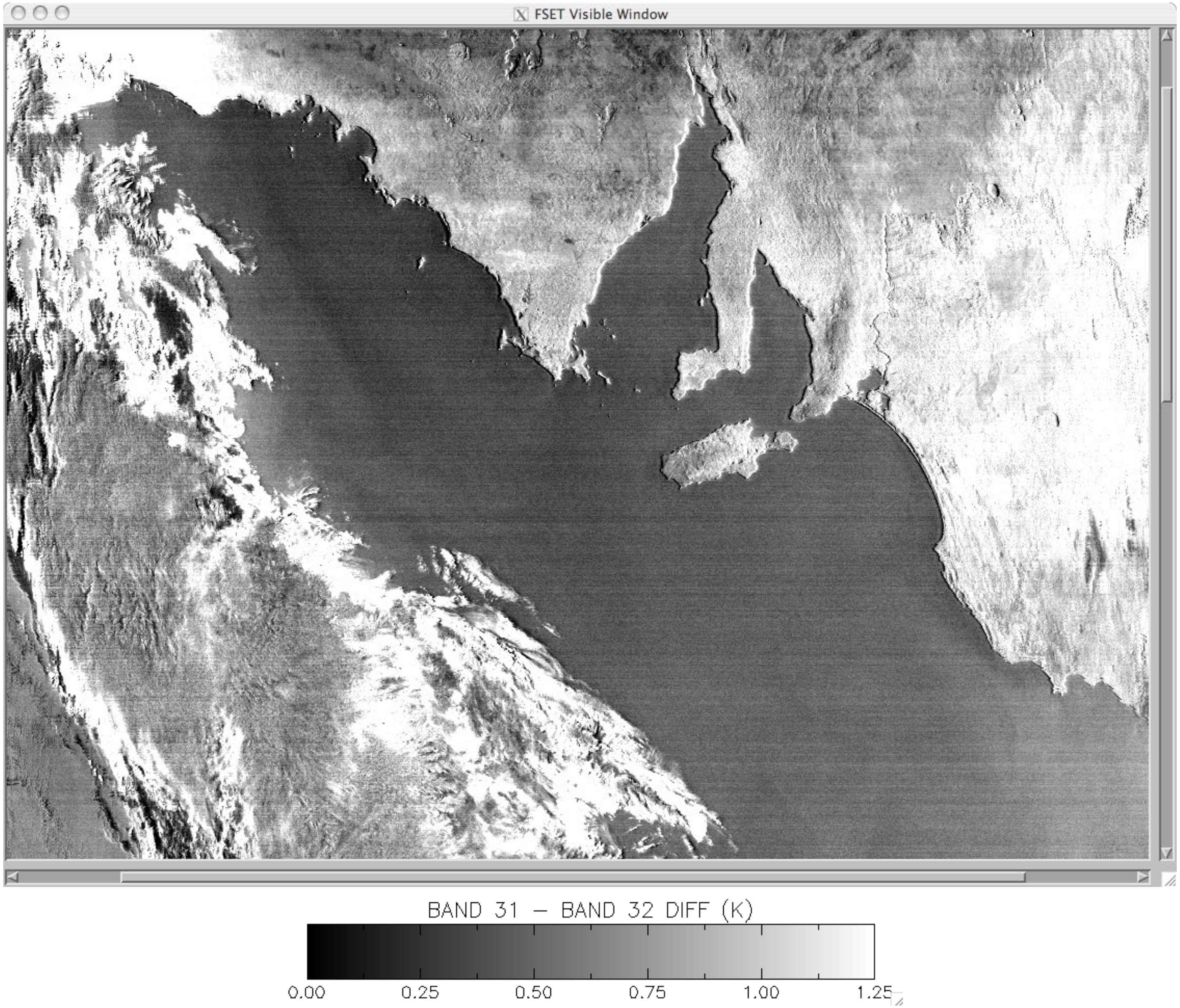
Terra MODIS 2000337 0115 UTC (South Australia)
Band 31 - Band 32 Difference, No Destriping



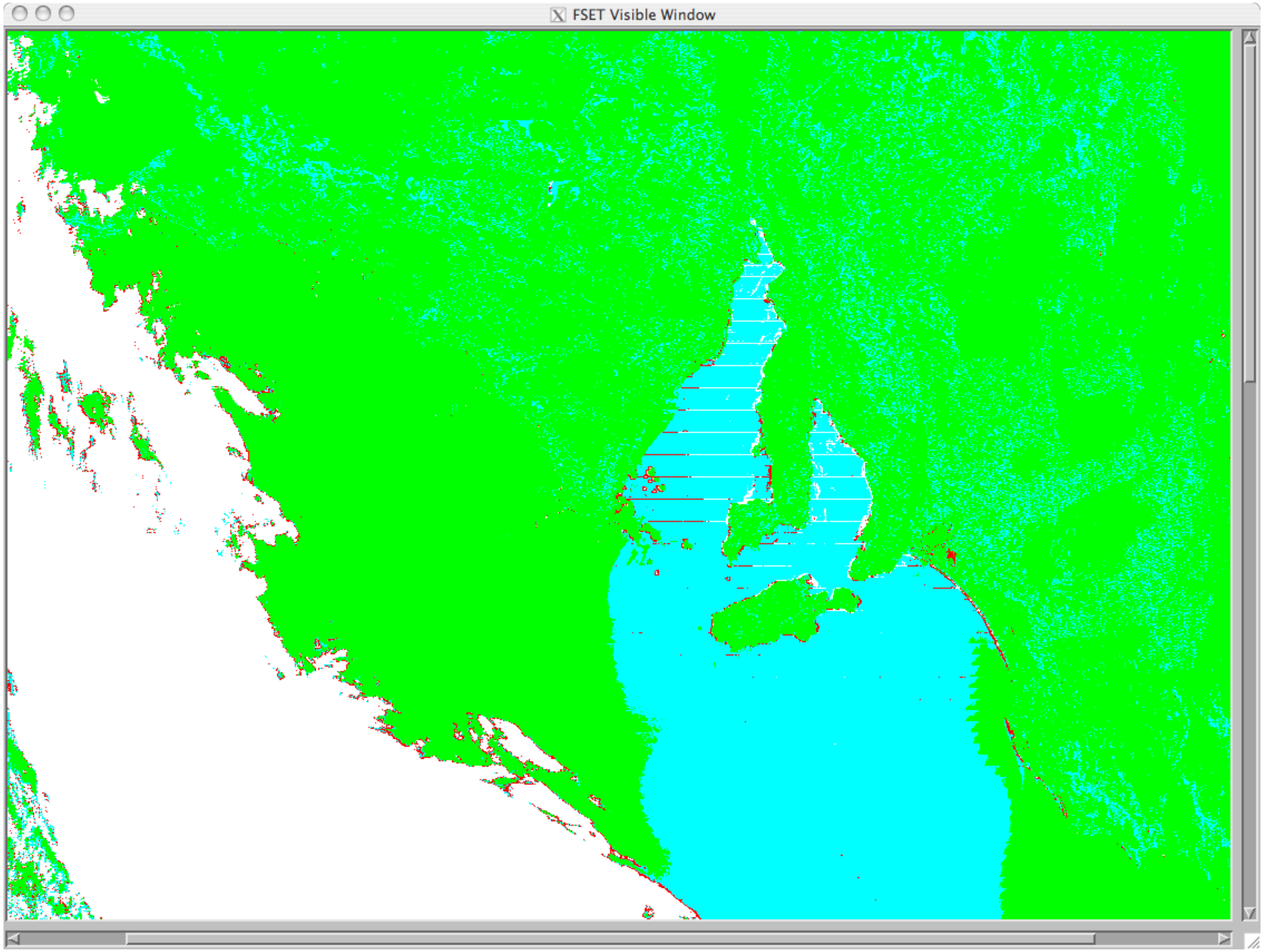
Band 31 - Band 32 Difference, Granule-Based Destriping



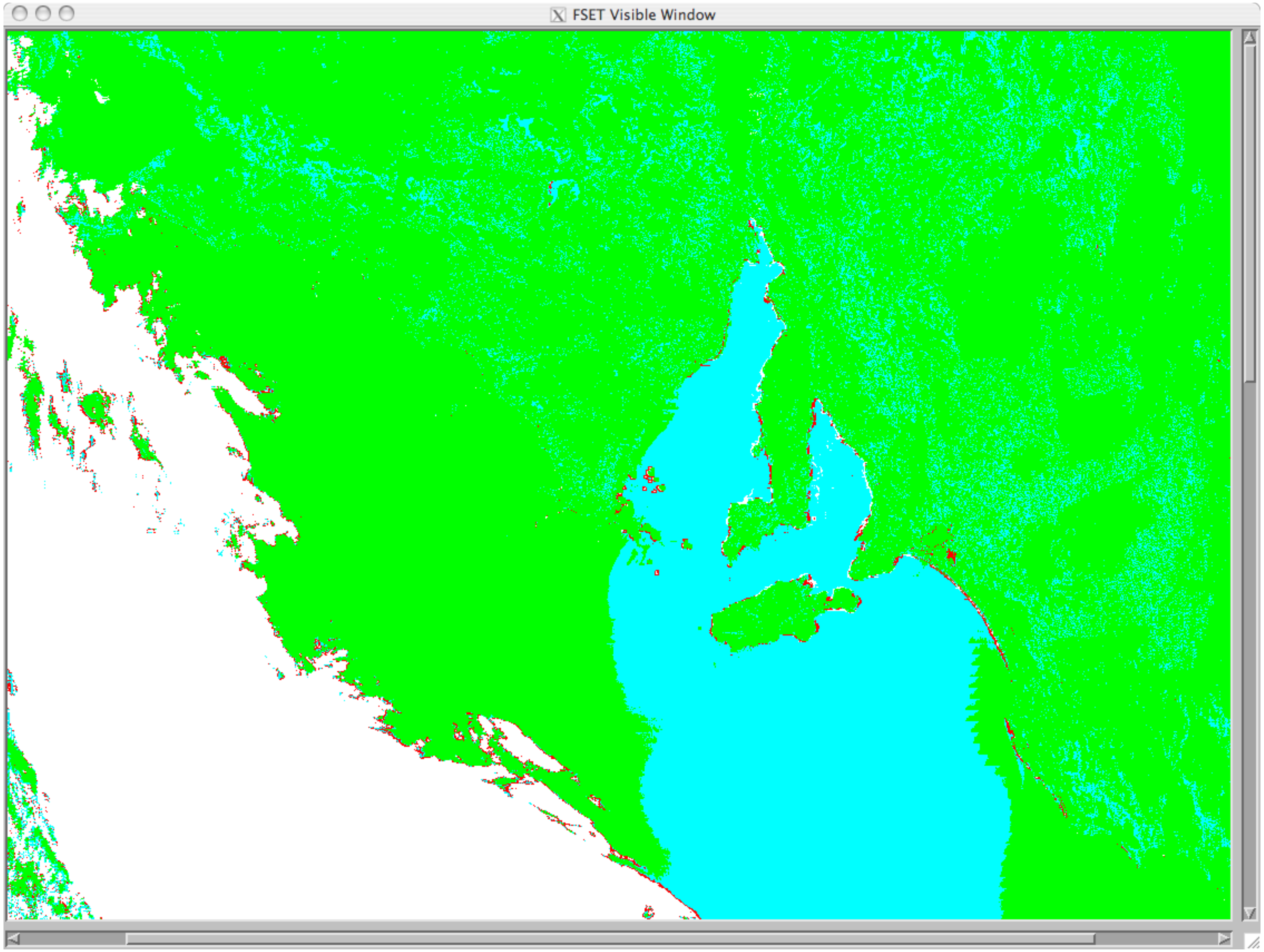
Band 31 - Band 32 Difference, Daily-Based Destriping



Cloud Mask Final Result, Granule-Based Destriping



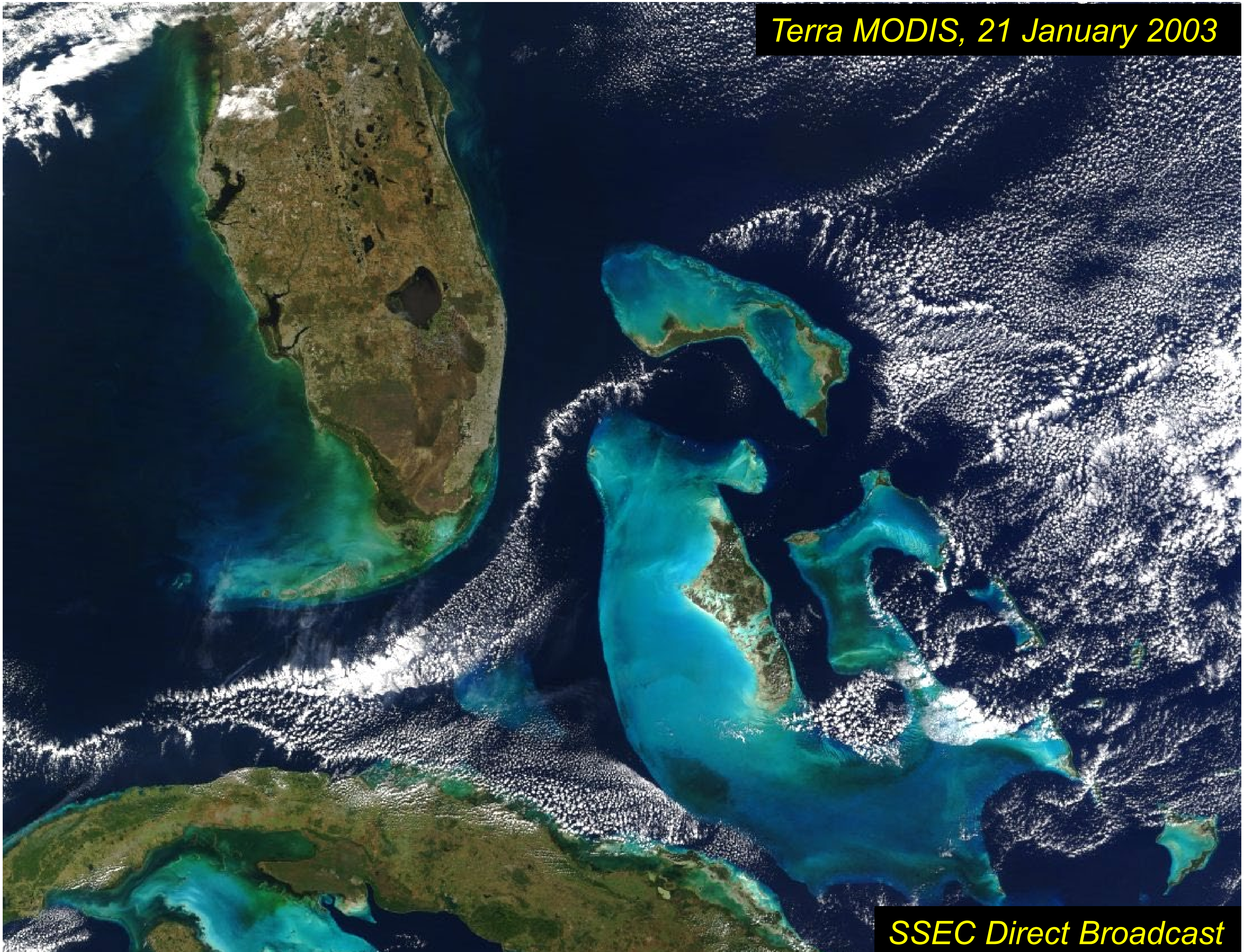
Cloud Mask Final Result, Daily-Based Destriping

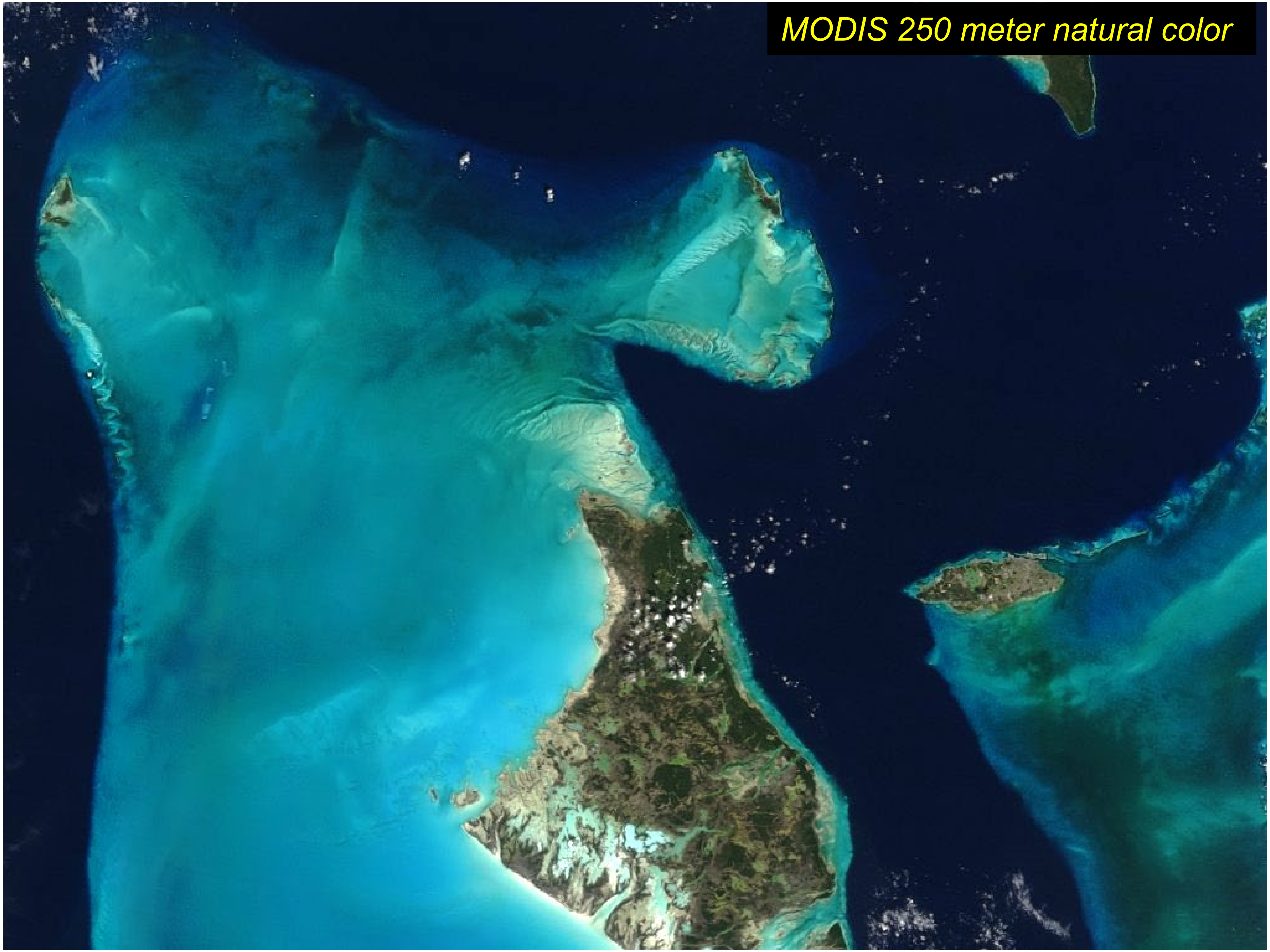


Creating Reprojected True Color MODIS Images

Liam Gumley,
Space Science and Engineering Center, Univ. of Wisconsin.

Jacques Descloitres and Jeff Schmaltz,
NASA GSFC MODIS Rapid Response System.


Terra MODIS, 21 January 2003
SSEC Direct Broadcast


MODIS 250 meter natural color

Why Reprojection?

Reasons why reprojection is desirable:

1. Removes Bowtie Artifacts
2. Allows geographic overlays (e.g. coastline, city locations)
3. Makes pretty pictures for publication on the web or in print
4. Allows collocation with other sensors or measurements
5. Prepares for ingest into GIS (e.g., GeoTIFF)

Good reprojection software is hard to find!

- Needs to understand MODIS format
- Should handle a variety of common projections
- Should be relatively easy to use and well documented
- Batch processing is a bonus
- Zero cost (i.e., free) is the icing on the cake

Software for Reprojecting MODIS Images

MRTSwath: MODIS Swath Reprojection Tool ***(Free)*** ★ ★ ★ ★ ★
http://edcdaac.usgs.gov/landdaac/tools/mrtswath/

HDFLook ***(Free)*** ★ ★ ★ ★ ★
http://www-loa.univ-lille1.fr/Hdflook/hdflook_gb.html

MS2GT: MODIS Swath to Grid Toolkit ***(Free)*** ★ ★ ★ ★ ★
http://cires.colorado.edu/~tharan/ms2gt/

ENVI: Environment for Visualizing Images ***($$$)*** ★ ★ ★
http://www.rsinc.com/envi/

HEG: HDF-EOS to GeoTIFF converter ***(Free)*** ★ ★
http://newsroom.gsfc.nasa.gov/sdptoolkit/HEG/HEGHome.html

MODIS L1B Reprojection Software Features

Software	*UNIX*	*Windows*	*GeoTIFF output*	*Batch operation*	*Output quality*	*Cost*
MRTSwath *	Yes	Yes	Yes	Yes	Excellent	Free
MS2GT*	Yes	No	Yes	Yes	Excellent	Free
HEG	Yes	Yes	Yes	Yes	Fair	Free
HDFLook	Yes	Yes	Yes	Yes	Excellent	Free
ENVI	Yes	Yes	Yes	?	Fair	$$$

* MS2GT and MRTSwath require additional software

Why True Color Images?

- Dramatic impact (more so than single band images)
- Excellent for public relations purpose
- Require comparatively little explanation
- Can use as base for displaying other products (e.g. fires)
- Daily 250 meter images in near real time are a first!

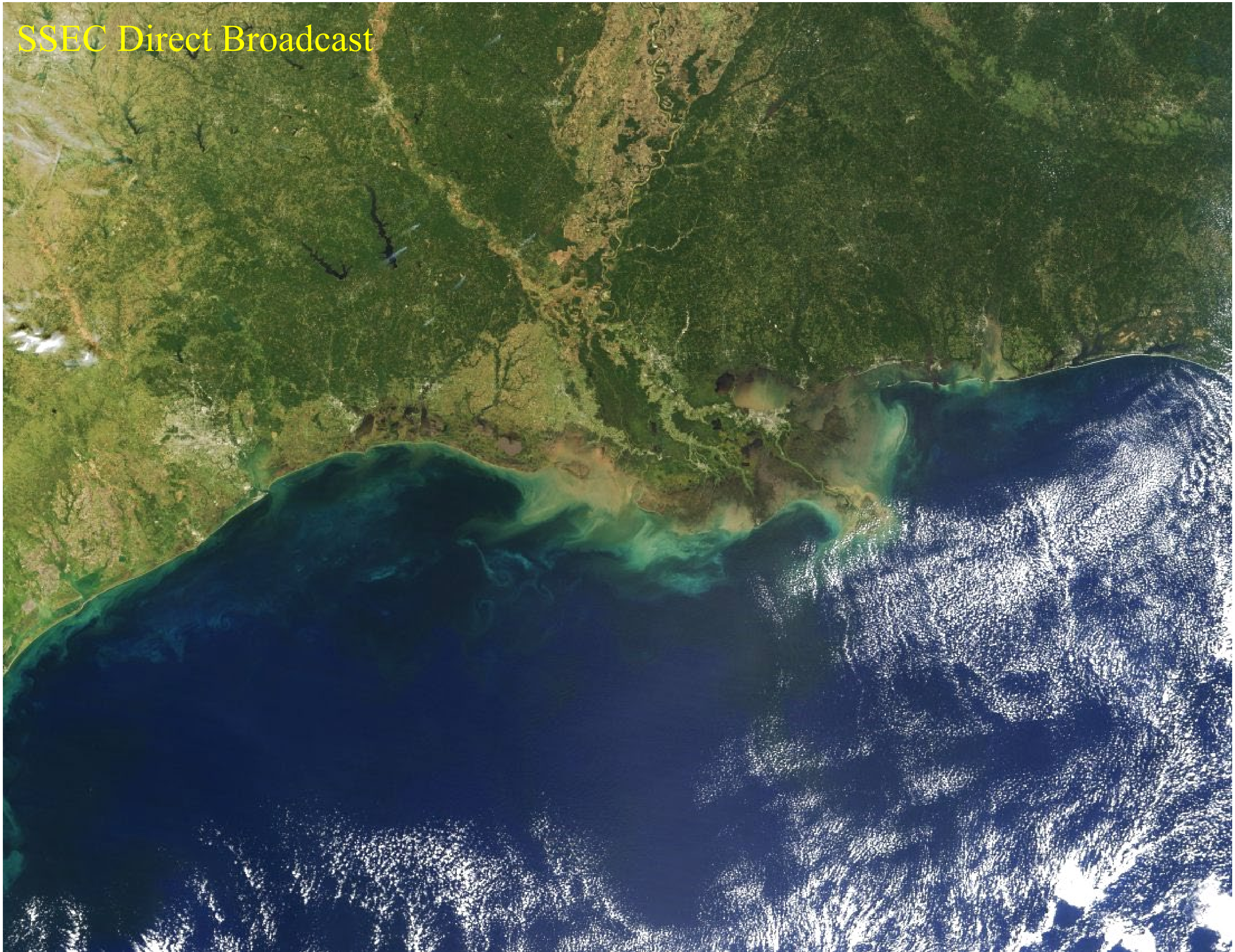
MODIS True Color Galleries:

http://rapidfire.sci.gsfc.nasa.gov/gallery/

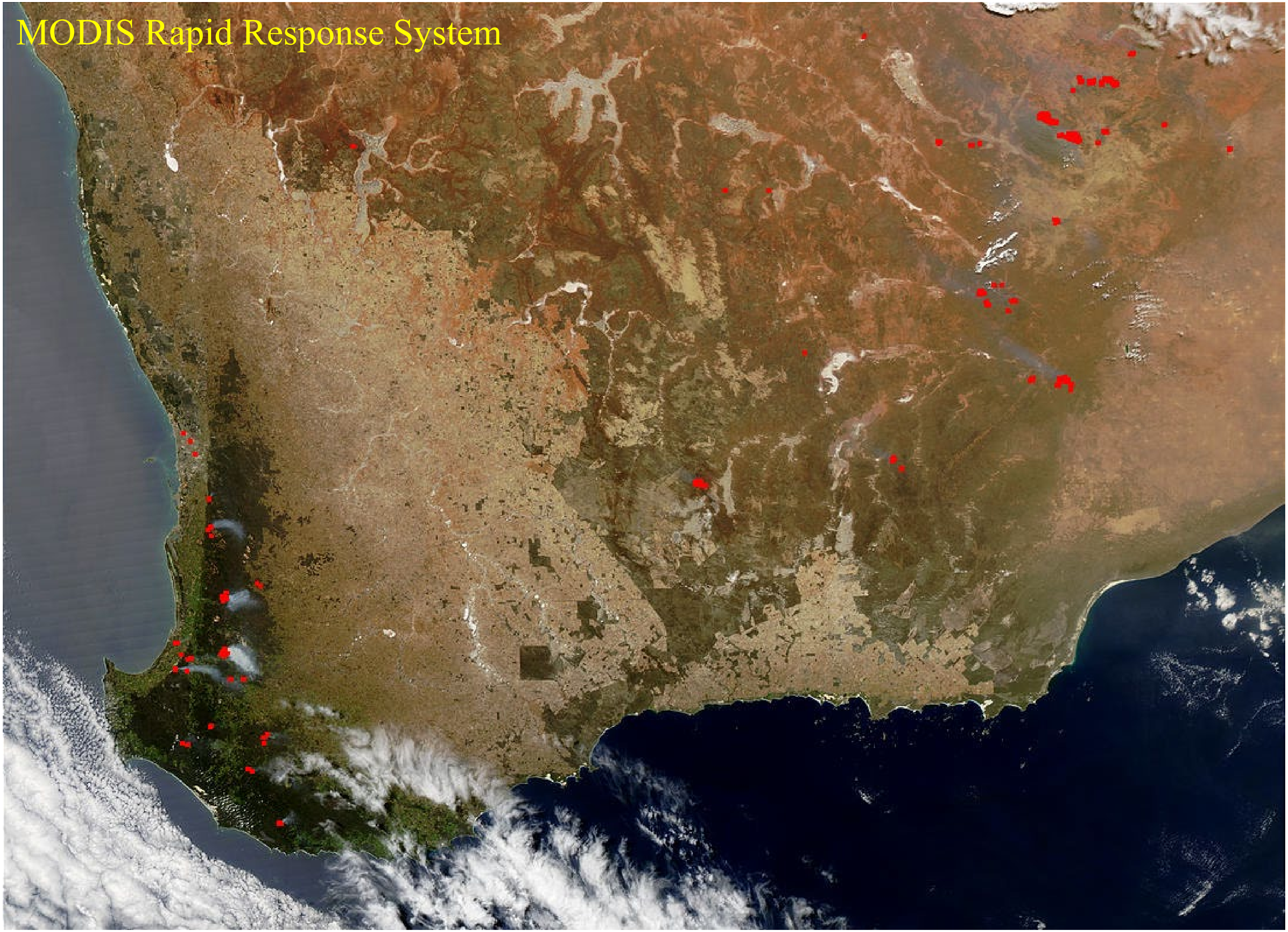
http://www.ssec.wisc.edu/~gumley/modis_gallery/

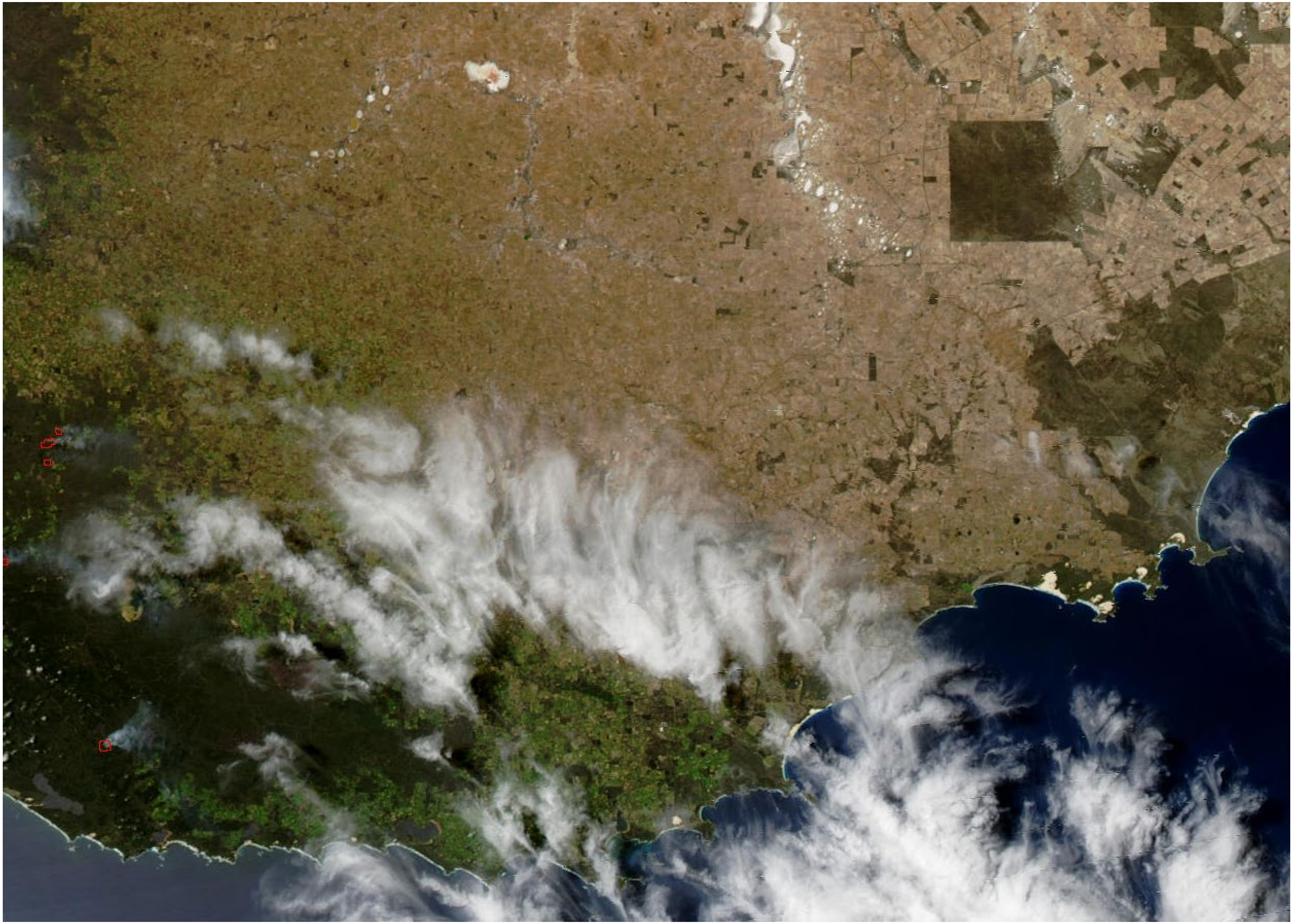
Eastern China

Mississippi Delta, Louisiana



Southwest Western Australia





True Color Bands and Resolution

- Use bands 1, 4, 3 (0.65, 0.55, 0.47 μm) for red, green, blue because of wide dynamic range.
- Band 1 is 250 meter native resolution; bands 3 and 4 are 500 meter native resolution.
- Can use the image data for input at 1000, 500, or 250 meter resolution.
- Choice of output resolution for reprojected images is up to the user (e.g., 8 or 4 km for continental, 2 or 1 km for state, 500 or 250 meter for high resolution scenes). Output resolution does not have to match the input resolution.
- Must use accurately interpolated geolocation data for reprojected images.

Tutorial Details

- Designed to run on UNIX systems (including Linux)

- Uses freely available software (no need to buy anything)

- Works with MODIS L1B 1KM, HKM, and QKM resolution data from Terra and Aqua

- Tutorial document (PDF), source code, sample data:

ftp://ftp.ssec.wisc.edu/pub/IMAPP/MODIS/TrueColor/

Software Required for Tutorial

MODIS Corrected Reflectance
http://directreadout.gsfc.nasa.gov/

MODIS Swath to Grid Toolbox (MS2GT)
http://nsidc.org/data/modis/ms2gt/

IDL
http://www.rsinc.com/
Note: License is *not* required: can use IDL 6.0 Virtual Machine

Image Magick
http://www.imagemagick.org/

Required Input Data

MODIS Level 1B radiance files at 1000, 500, and 250 meter resolution (Terra or Aqua)

and

MODIS Level 1B geolocation file at 1000 meter resolution

IMAPP or DAAC L1B format may be used!

Corrected Reflectance Algorithm

• Developed by Jacques Descloitres for MODIS Rapid Response System

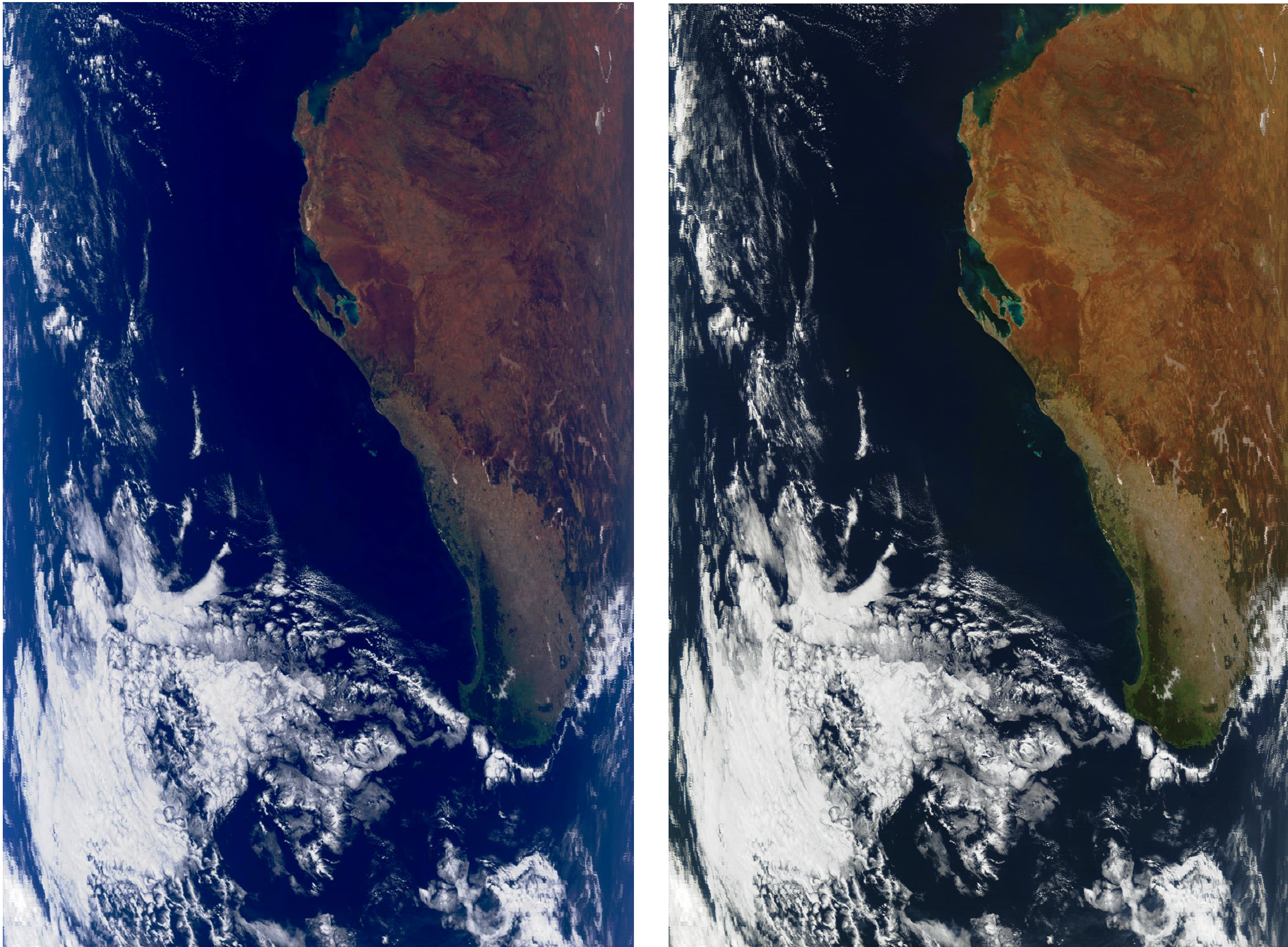
• Designed to provide natural looking true color images.

• Removes Rayleigh scattering and accounts for absorption by ozone, oxygen, and water vapor in conjunction with a low resolution terrain database. No correction for aerosol.

• Removes haze from blue band.

• Is similar to the MODIS surface reflectance product MOD09, except that it does not correct for aerosols.

TOA reflectance | Corrected reflectance



Corrected Reflectance Script

```
#!/bin/csh
# Check the input arguments
if ($#argv != 4) then
  echo "Usage: Crefl.csh MOD01KM MOD02HKM MOD02QKM MOD03"
  exit(1)
endif
echo "(Creating MODIS corrected reflectance)"
ln -f -s $1 MOD021KM.hdf
ln -f -s $2 MOD02HKM.hdf
ln -f -s $3 MOD02QKM.hdf
ln -f -s $4 MOD03.hdf
setenv ANCPATH $HOME/NDVI/run
$HOME/NDVI/NDVI.src/crefl -f -v -1km  \
  MOD02HKM.hdf MOD02QKM.hdf MOD021KM.hdf -of=crefl.1km.hdf
$HOME/NDVI/NDVI.src/crefl -f -v -500m \
  MOD02HKM.hdf MOD02QKM.hdf MOD021KM.hdf -of=crefl.hkm.hdf
$HOME/NDVI/NDVI.src/crefl -f -v -250m \
  MOD02HKM.hdf MOD02QKM.hdf MOD021KM.hdf -of=crefl.qkm.hdf
```

MS2GT (MODIS Swath to Grid Toolkit)

• Developed at National Snow and Ice Data Center (NSIDC) by Terry Haran and Ken Knowles.

• Based on **mapx** library routines that have been well tested.

• Accounts for multiple lines per earth scan.

• Comes with Perl scripts that automate reprojection procedure.

• You can call low level routines directly (**ll2cr** and **fornav**).

• Calling low-level routines gives the greatest flexibility on input and output formats.

• Flexible text file format for defining output map projection and datum.

• Gives high quality results when supplied with high quality input.

Sensor Projection (250 m pixels) | Reprojected (250 m grid)

MS2GT Input and Output Formats

When calling the low level routines **ll2cr** and **fornav**:

Input

1. Image file (8, 16, 32-bit int or 32-bit float)
2. Corresponding latitude and longitude files (32-bit float)
3. Grid Parameter Definition file (ASCII text)

Output

1. Reprojected image file (same type as input image file)
2. Optional latitude and longitude files for reprojected grid

Note: No dependence on details of MODIS L1B HDF format

MS2GT Script Example

Step 1: Convert lat/lon to col/row

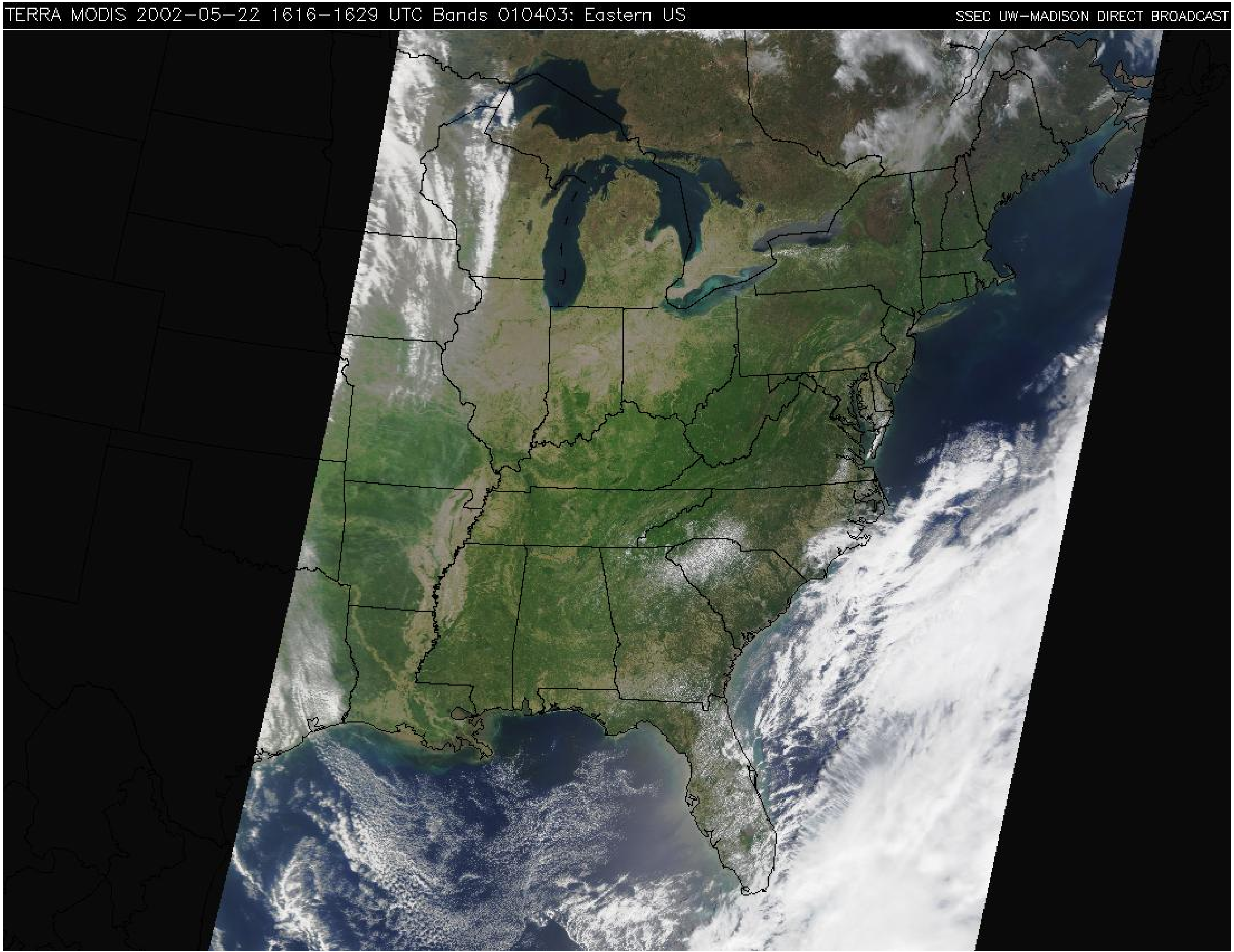
```
$ ll2cr -v -f 5416 100 40 \
  lat_5416x4000.dat lon_5416x4000.dat AquaSA.gpd AquaSA
```

Step 2: Convert lat/lon to col/row

```
$ fornav 1 -v -t f4 5416 100 40 \
  AquaSA_cols_05416_00100_00000_40.img \
  AquaSA_rows_05416_00100_00000_40.img \
  band02_5416x4000.dat 2550 3300 band02_proj_2550x3300.dat
```

Default is weighted average of pixels mapped to each grid cell (nearest neighbor is optional).

MS2GT used routinely for SSEC browse images



Geolocation Interpolation

Geolocation is defined at the nominal center of each 1000 meter pixel. To interpolate to 500 or 250 meter pixels:

1. Must handle each earth scan separately (do not process entire array with CONGRID or REBIN!).

2. Remember that centers of first 1000, 500, and 250 meter pixels across track are co-registered.

3. Can use bilinear interpolation for most (but not all) of the 500 or 250 meter pixels within each scan.

4. Must use linear extrapolation for the 500 and 250 meter pixels at the edge of each earth scan.

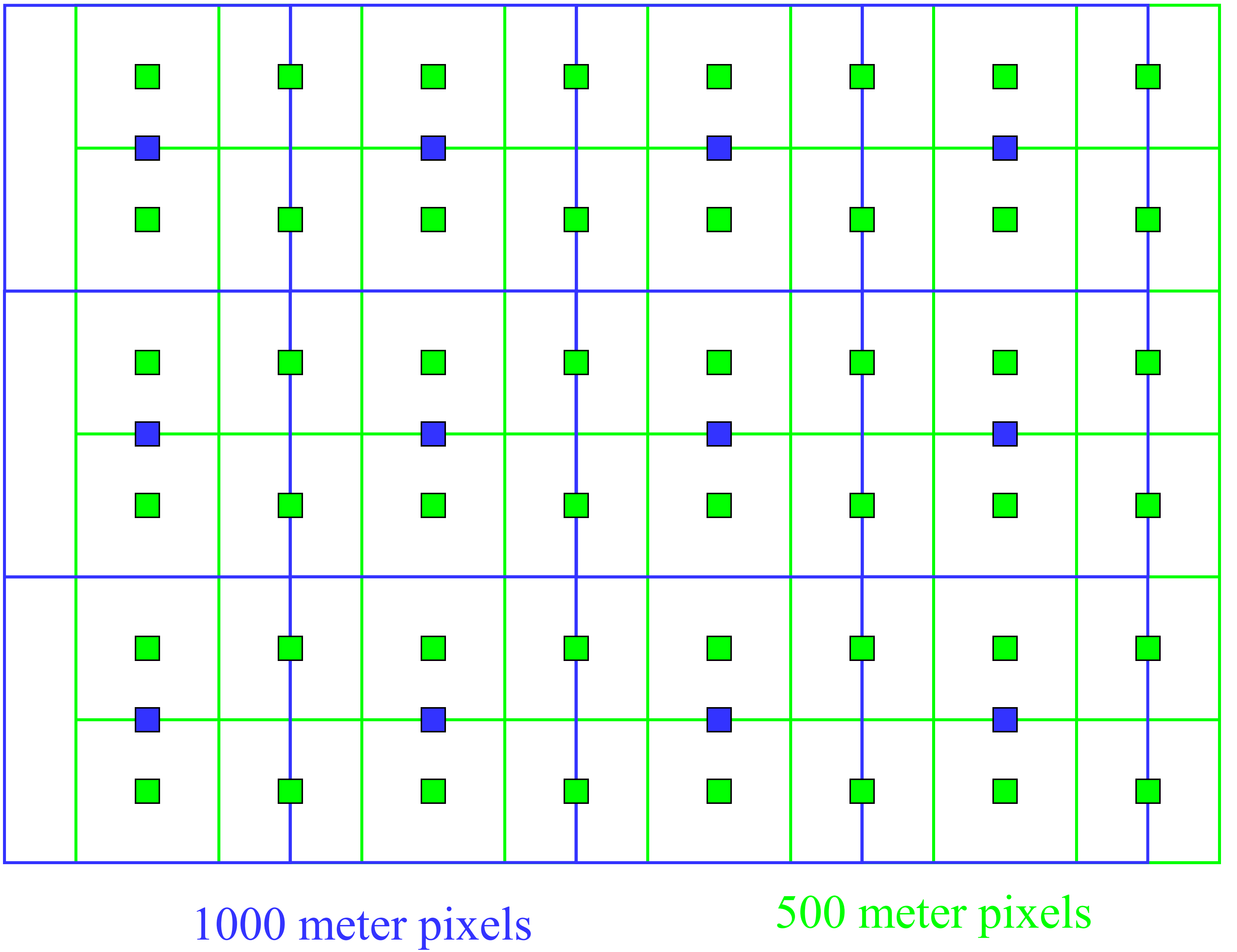

1000 meter pixels
500 meter pixels

Image Interpolation

To interpolate 500 meter resolution image pixels to 250 meter resolution:

1. Must handle each earth scan separately (do not process entire array with CONGRID or REBIN!).
2. Remember that centers of first 1000, 500, and 250 meter pixels across track are co-registered.
3. Can use bilinear interpolation for most (but not all) of the 250 meter pixels within each scan.
4. Can use pixel replication for the 250 meter pixels at the edge of each earth scan.

Resolution Sharpening

Use Band 1 to supply 250 meter resolution information for Bands 3 and 4, i.e.,

$$R = B_1^* / B_1$$

R is spatial resolution ratio

B_1^* is band 1 @ 500 m interpolated to 250 m

B_1 is band 1 @ 250 m

Then

$$B_3 = B_3^* / R$$

$$B_4 = B_4^* / R$$

B_3^*, B_4^* are bands 3, 4 @ 500 m interpolated to 250 m

B_3, B_4 are bands 3, 4 @ 250 m

True Color Enhancement: First Cut

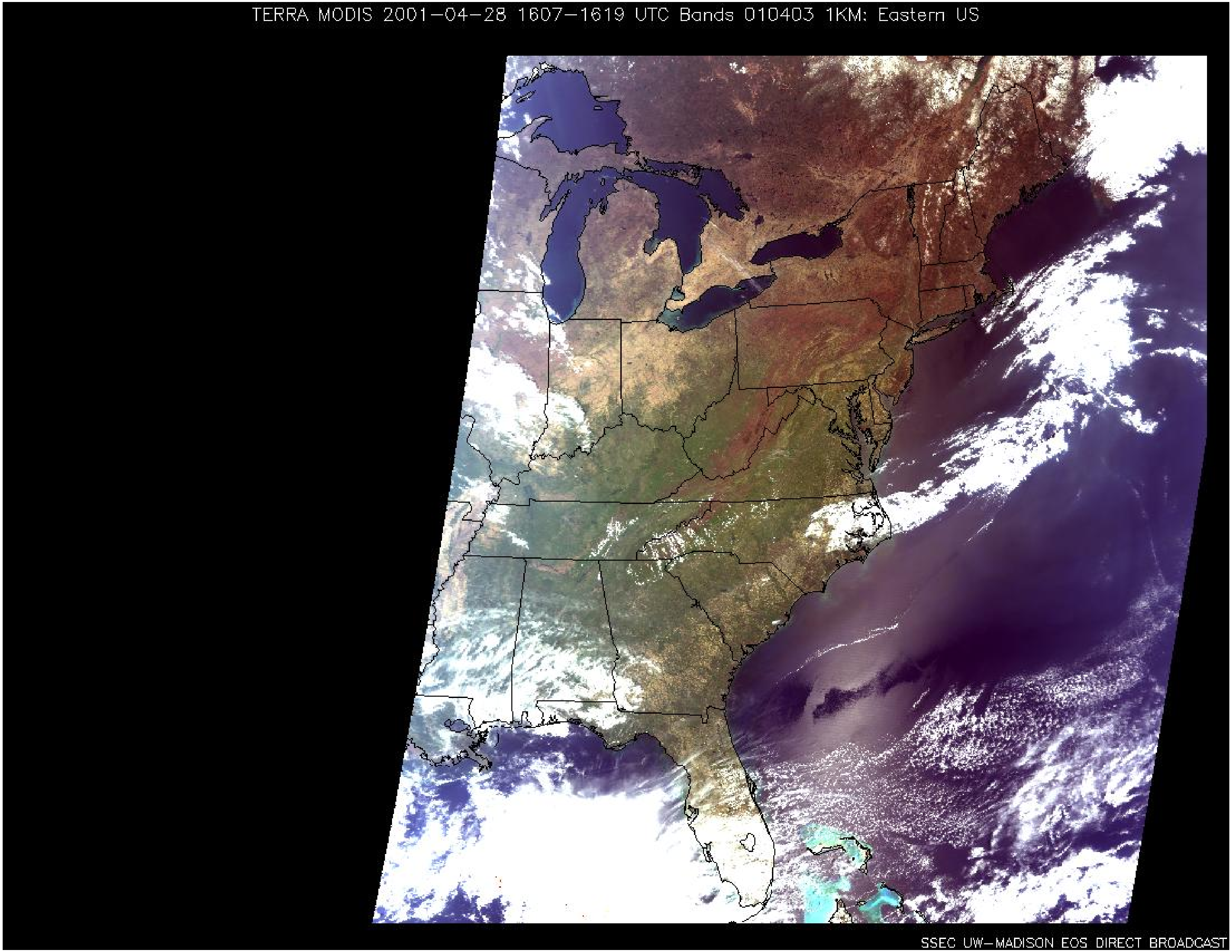
Linear enhancement of at-sensor reflectance.

Advantages:

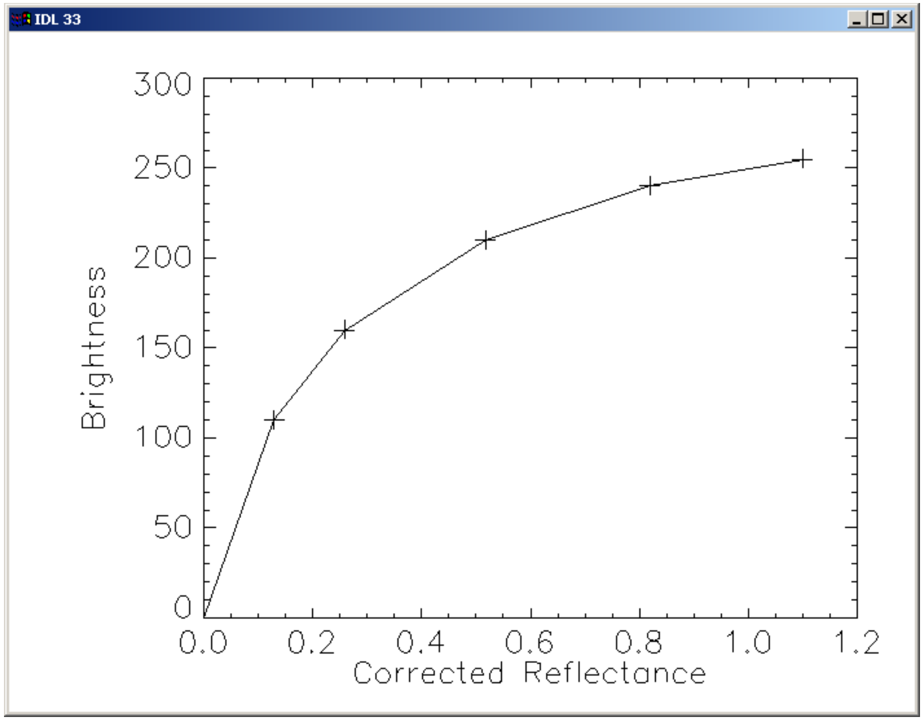
- Easy to code

Disadvantages:

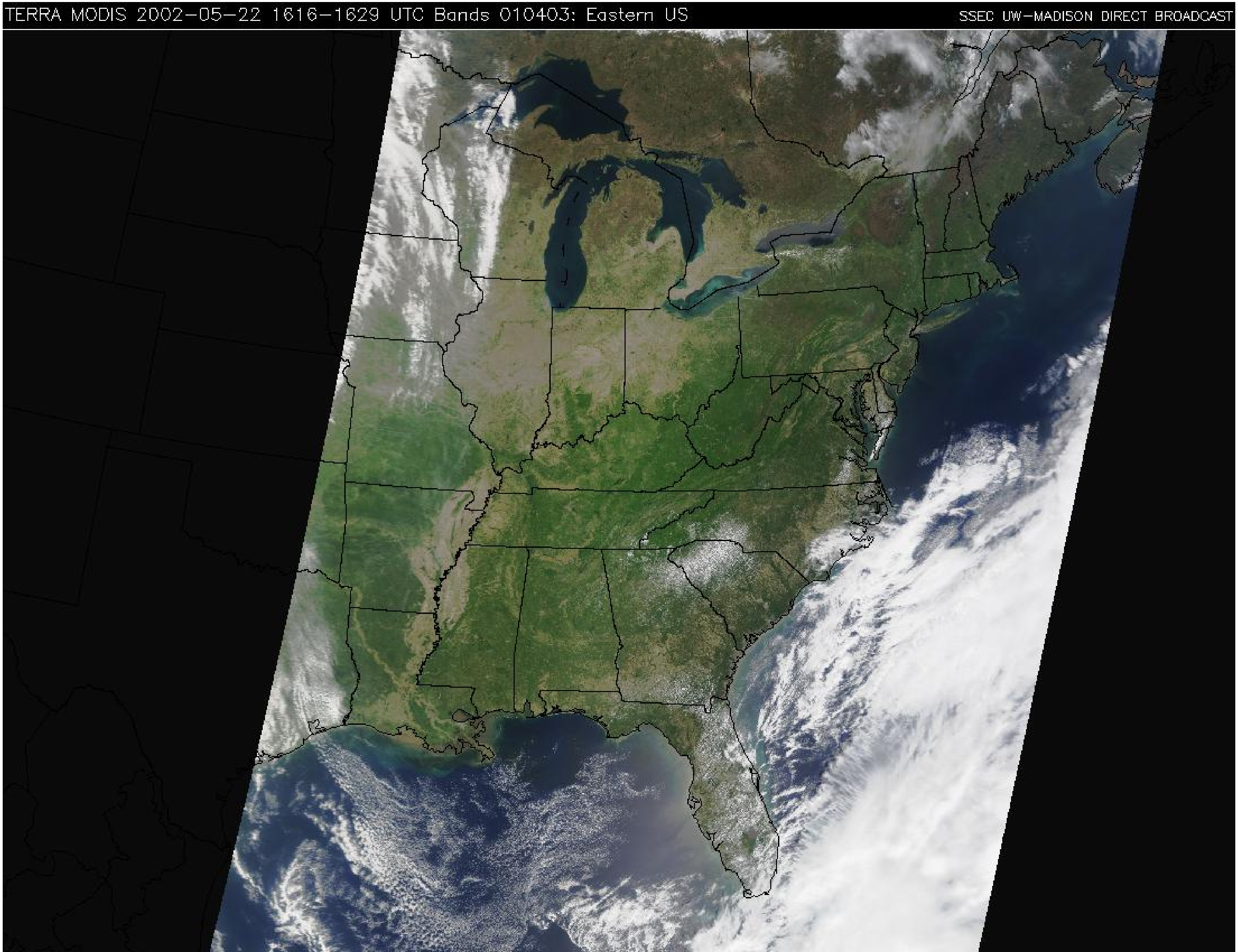
- Clouds are washed out
- Difficult to achieve balance between red, green, blue
- Bluish haze always appears at the image edges


TERRA MODIS 2001-04-28 1607-1619 UTC Bands 010403 1KM: Eastern US
SSEC UW-MADISON EOS DIRECT BROADCAST

Piecewise Linear Enhancement Curve

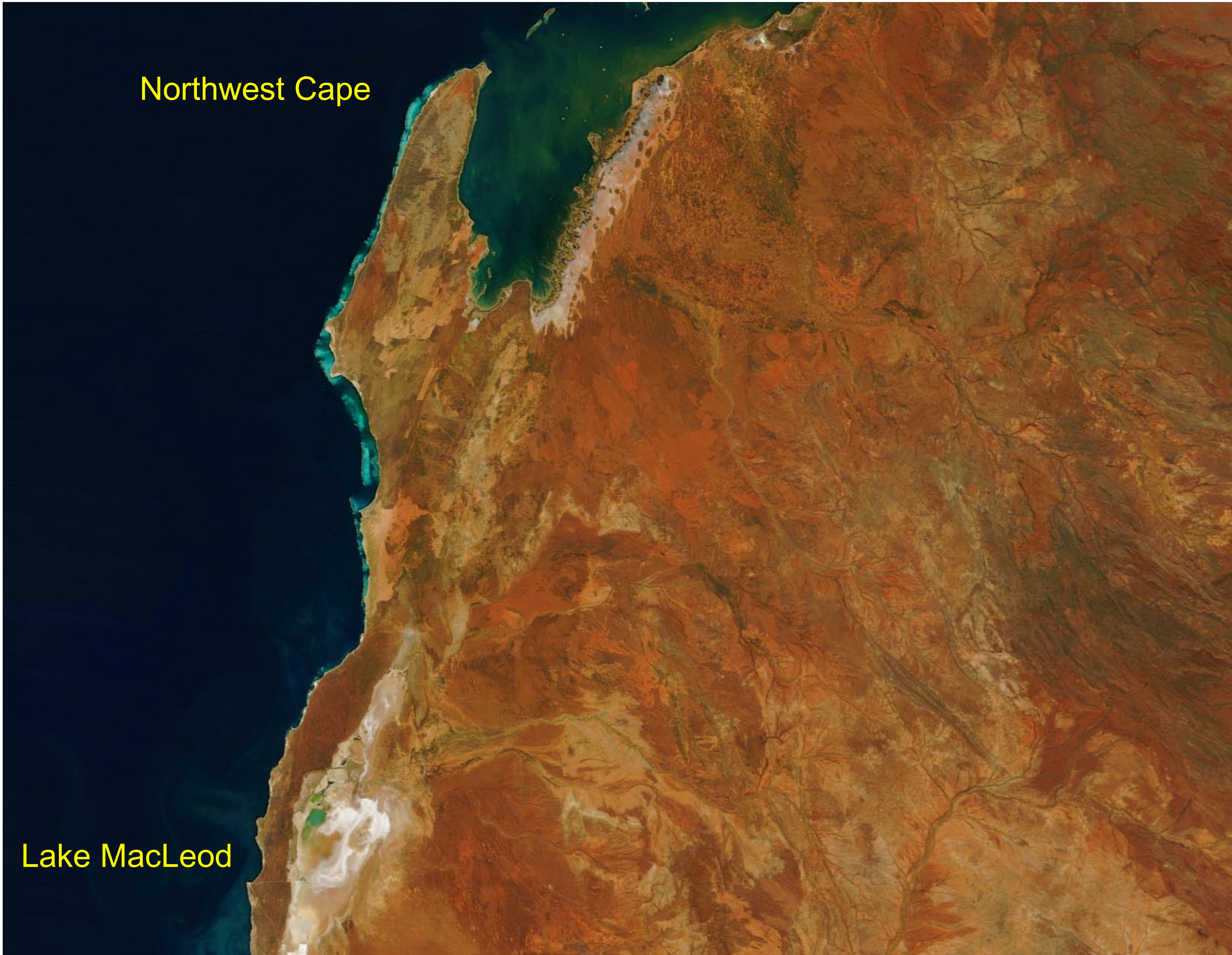


- Enhances low brightness regions (land, ocean), while de-emphasizing clouds.
- Same curve is applied to corrected reflectance in MODIS bands 1, 3, 4.
- Final step is to increase saturation by 25% and lightness by 5%


TERRA MODIS 2002-05-22 1616-1629 UTC Bands 010403: Eastern US
SSEC UW-MADISON DIRECT BROADCAST

What is the end result?

Terra MODIS, Western Australia, 2002 day 196


Northwest Cape
Lake MacLeod

Where to Get the Tutorial

Tutorial document (PDF), source code, sample data:

ftp://ftp.ssec.wisc.edu/pub/IMAPP/MODIS/TrueColor/