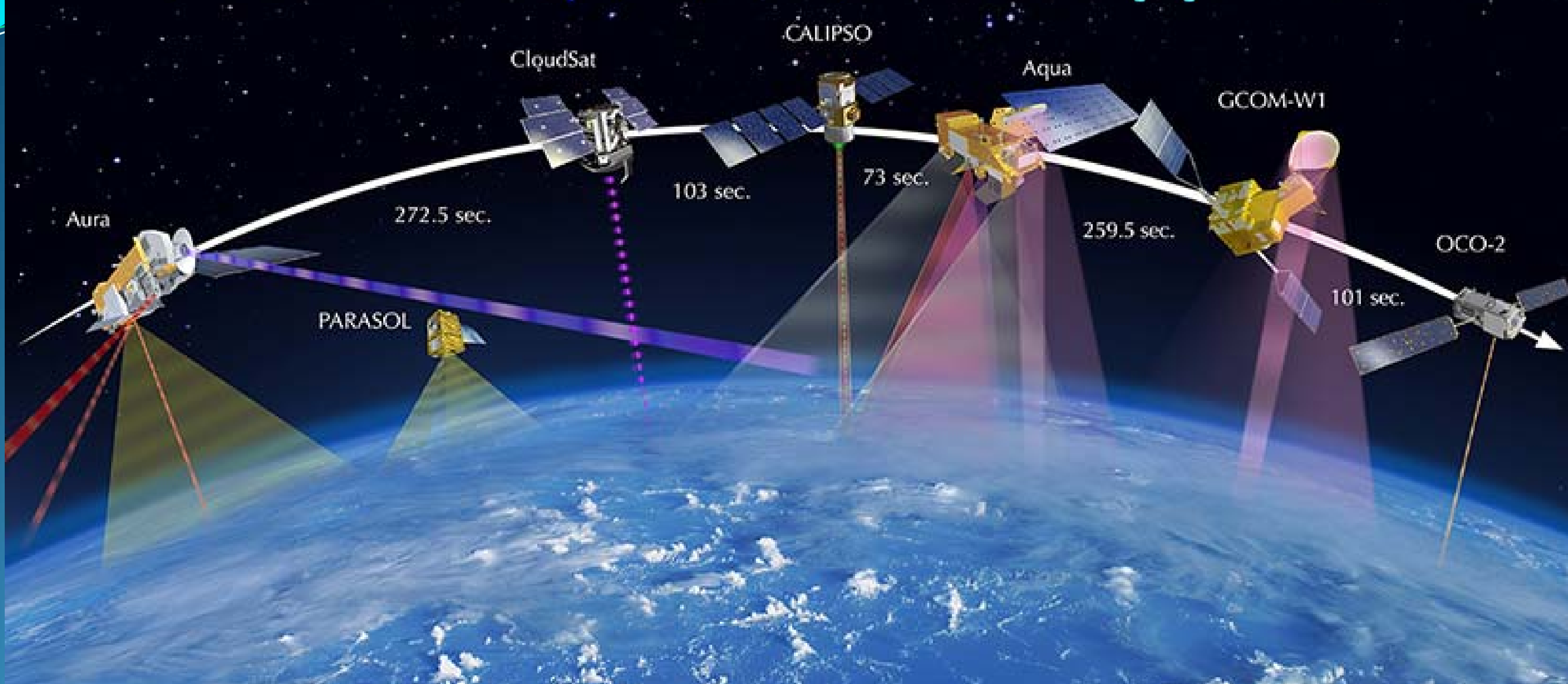
ATMO 611 – Satellite Data Applications



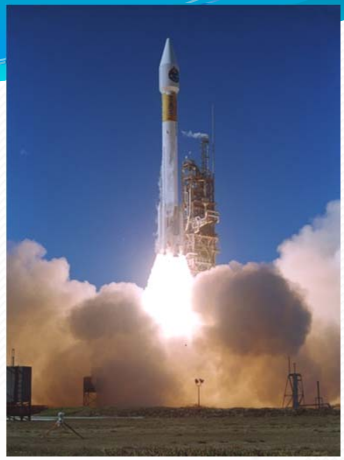
Introduction to MODIS Instrumentation

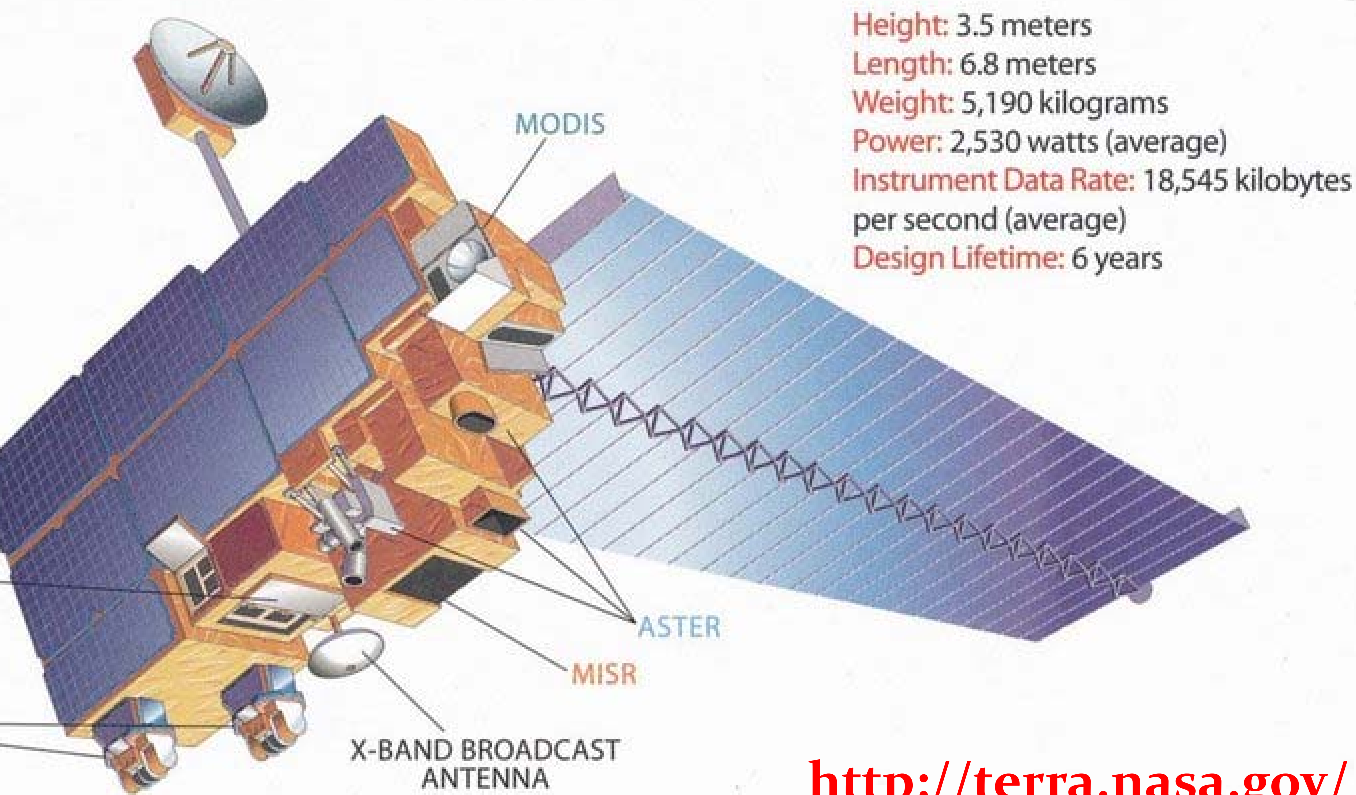
Jennifer D. S. Griswold

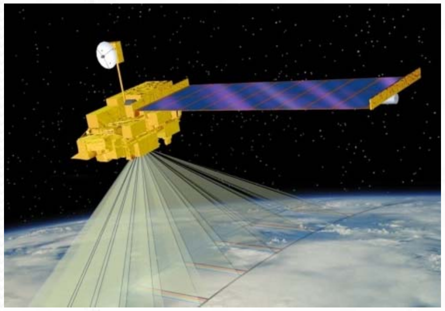
A Short History

- 1983 – NASA began to explore the concept of a polar-orbiting platform to complement a manned polar-orbiting space station
- Beginning as System Z, the idea gained momentum with NASA's proposed "Global Habitability" program
- After Challenger disaster, polar space station disappeared as did manned servicing requirement
- System Z became EOS – Earth Observing System
  - Several instrument suites were developed
  - Surface Imaging and Sounding Package (SISP) included the Moderate Resolution Imaging Spectrometer
- MODIS soon split into 2 concepts
  - MODIS-N focused primarily on land and atmosphere sensing but included some ocean bands
  - MODIS-T (tilting) focused on ocean
- Because of budget constraints, MODIS-T vanished, replaced by MODIS-N and EOS-Color (to follow SeaWiFS)
- Further budget reductions led to replacement of EOS-Color by SIMBIOS

Terra (1999-present)



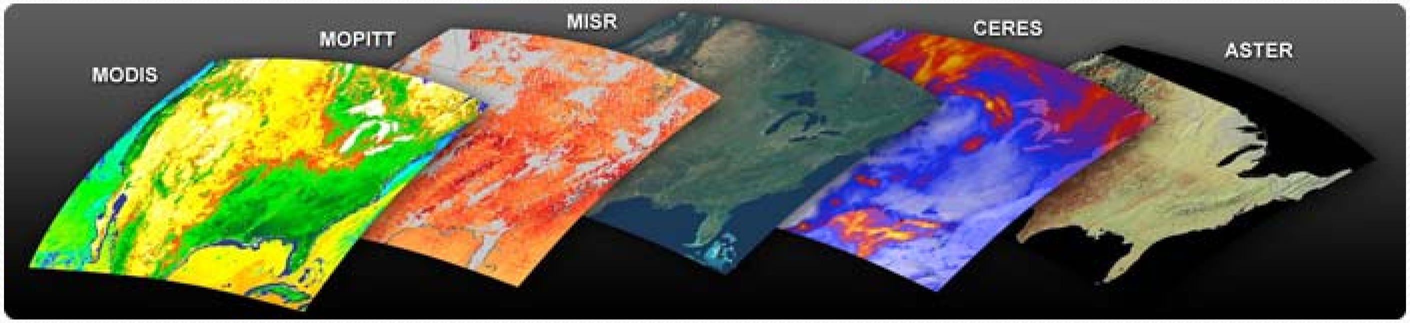




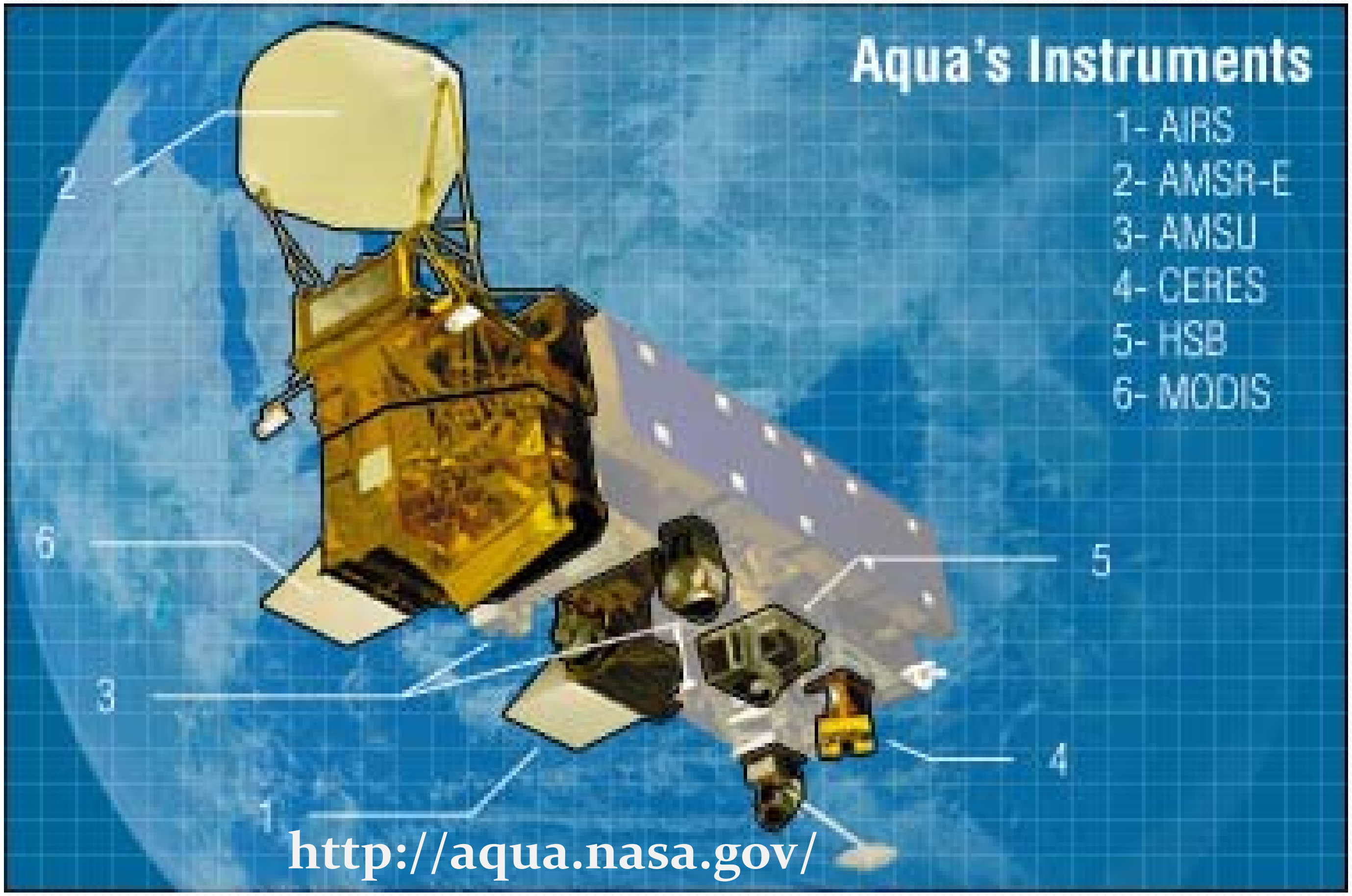
http://terra.nasa.gov/

MODIS – Terra Instruments

- **ASTER** - Advanced Spaceborne Thermal Emission and Reflection Radiometer
- **CERES** - Clouds and Earth's Radiant Energy System
- **MISR** - Multi-angle Imaging SpectroRadiometer
- **MODIS** - Moderate-resolution Imaging Spectroradiometer
- **MOPITT** - Measurements of Pollution in the Troposphere

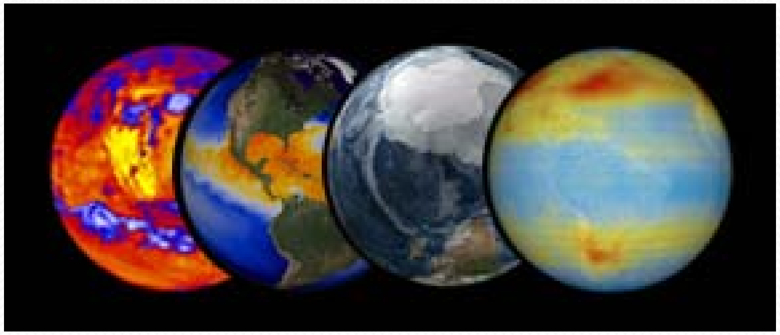


Aqua (2002-present)



Aqua Instruments

- **AIRS** - Atmospheric Infrared Sounder
- **AMSU-A** – Advanced Microwave Sounding Unit
- **HSB** – Humidity Sounder for Brazil
- **AMSR-E** – Advanced Microwave Scanning Radiometer for EOS
- **MODIS** - Moderate-resolution Imaging Spectroradiometer
- **CERES** -or Clouds and Earth's Radiant Energy System



MODIS Terra-Aqua Summary

- **Responsible Center:** NASA Goddard Space Flight Center
- **Description:** Used to understand the global dynamics and process occurring on land, in the oceans and in the atmosphere.
- **Channels:** 36-band cross-track scanning radiometer
- **Spectral Range:** Visible to thermal infrared measurements at 0.4-14.5 μm
- **Spatial resolution:** 250 m (bands 1-2), 500 m (bands 3-7), to 1 km (bands 8-36)
- **Swath width:** 2330 km (cross track) by 10 lm (along track at nadir)
- **Global coverage every 1-2 days**
- **Terra Launched:** Dec. 18, 1999
- **Aqua Launched:** May 4, 2002

Improvements on Previous Satellites

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

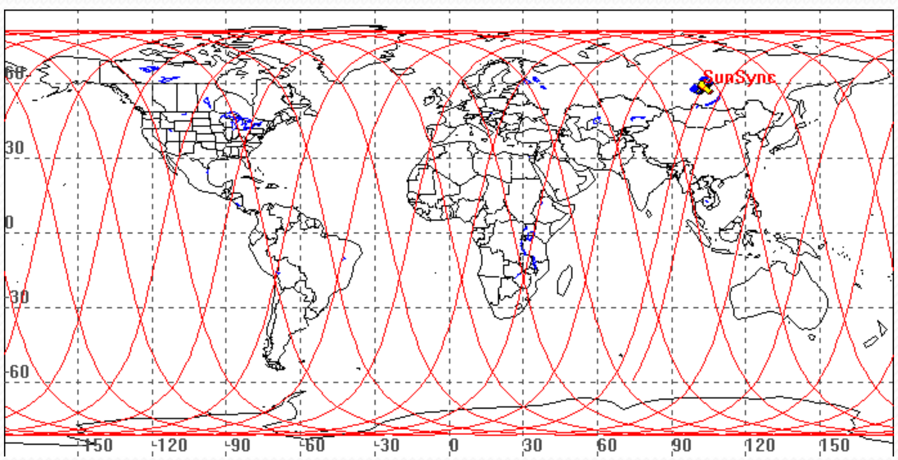
Major differences:

- 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

MODIS Orbital Characteristics

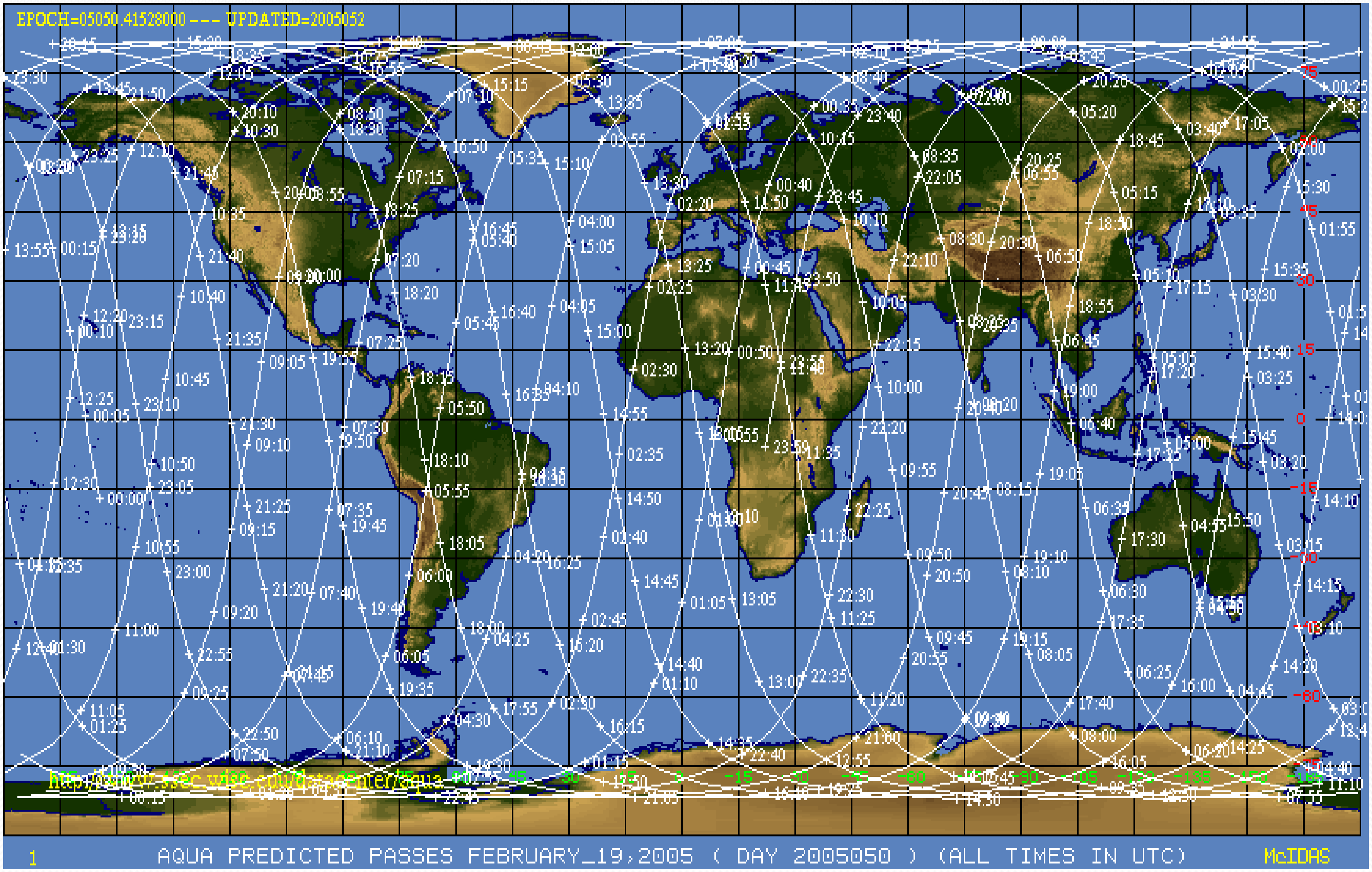
- TERRA Orbital Characteristics
  - Sun synchronous, near-polar orbit
  - Equatorial 10:30 pm, descending node crossing
  - Inclination 98.5°
  - Altitude 705 km
  - Period 99 minutes (16 orbits per day)

- AQUA Orbital Characteristics
  - Sun synchronous, near-polar orbit
  - Equatorial 1:30 pm, ascending node crossing
  - Inclination 98°
  - Altitude 705 km (438 miles)
  - Period 99 minutes (16 orbits per day)



A **Sun-synchronous orbit** (sometimes called a heliosynchronous **orbit**) is a geocentric **orbit** which combines altitude and inclination in such a way that an object on that **orbit** will appear to **orbit** in the same position, from the perspective of the **Sun**, during its **orbit** around the Earth.

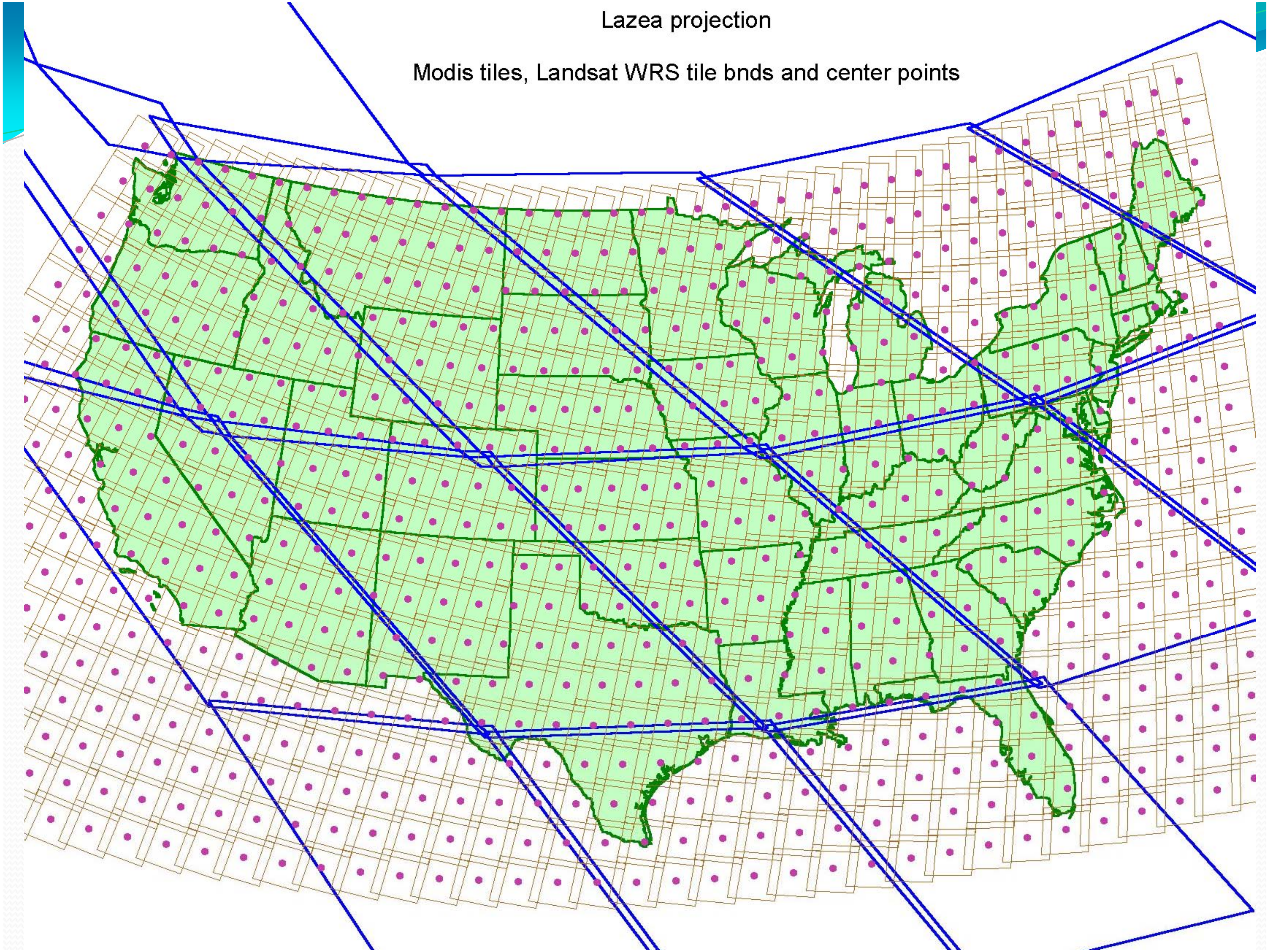
MODIS Aqua coverage (2330 km swath)



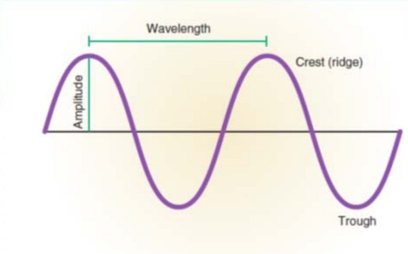
Space Science and Engineering Center (SSEC) http://www.ssec.wisc.edu/datacenter/aqua/

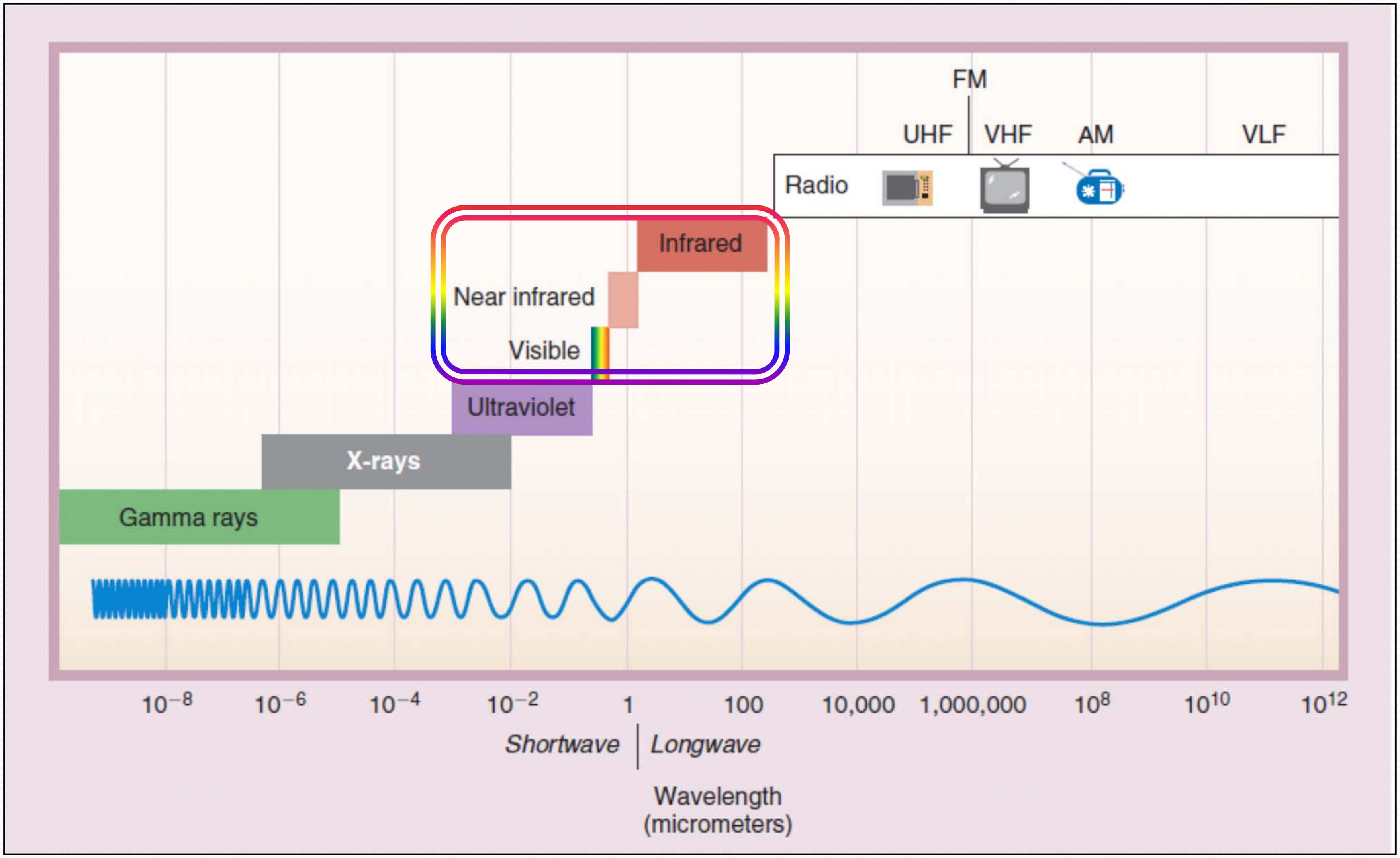
Lazea projection

Modis tiles, Landsat WRS tile bnds and center points



Where is the Electromagnetic Spectrum can MODIS "see"?





Primary Use for Reflected Solar Band

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

2/3 of the data output comes from bands 2-7

Bands 1 to 19 are in nm; Bands 20 to 36 are in µm

Spectral Radiance values are (W/m^2-µm-sr)

Primary Use for Each Thermal Band

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required NE[delta]T(K)
Surface/Cloud Temperature	20	3.660 - 3.840	0.45(300K)	0.05
	21	3.929 - 3.989	2.38(335K)	2.00
	22	3.929 - 3.989	0.67(300K)	0.07
	23	4.020 - 4.080	0.79(300K)	0.07
Atmospheric Temperature	24	4.433 - 4.498	0.17(250K)	0.25
	25	4.482 - 4.549	0.59(275K)	0.25
Cirrus Clouds Water Vapor	26	1.360 - 1.390	6.00	150(SNR)
	27	6.535 - 6.895	1.16(240K)	0.25
	28	7.175 - 7.475	2.18(250K)	0.25
Cloud Properties	29	8.400 - 8.700	9.58(300K)	0.05
Ozone	30	9.580 - 9.880	3.69(250K)	0.25
Surface/Cloud Temperature	31	10.780 - 11.280	9.55(300K)	0.05
	32	11.770 - 12.270	8.94(300K)	0.05
Cloud Top Altitude	33	13.185 - 13.485	4.52(260K)	0.25
	34	13.485 - 13.785	3.76(250K)	0.25
	35	13.785 - 14.085	3.11(240K)	0.25
	36	14.085 - 14.385	2.08(220K)	0.35

*Bands 1 to 19 are in nm; Bands 20 to 36 are in µm NE(delta)T = Noise-equivalent temperature difference

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:

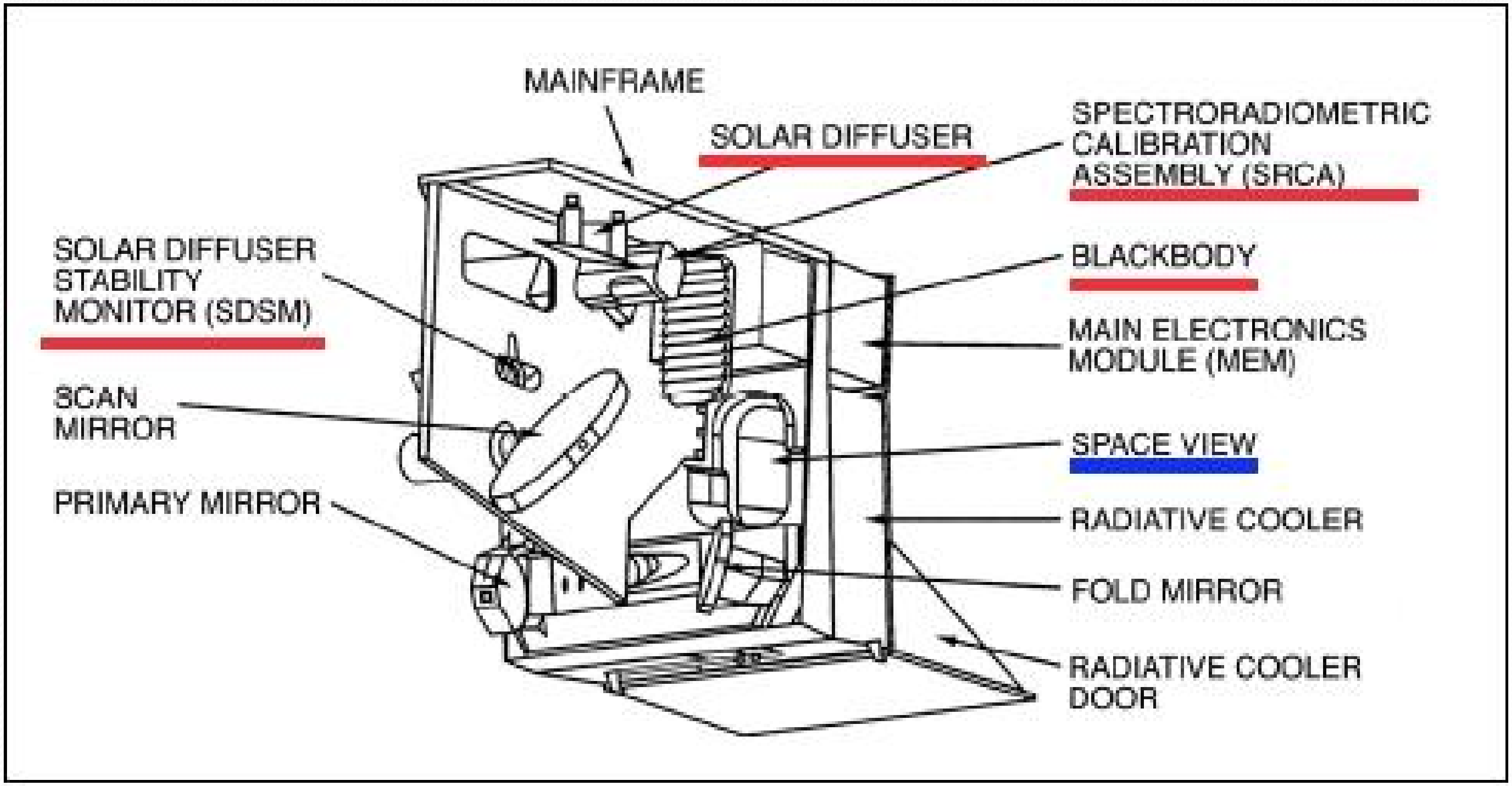
Many interdependent bands

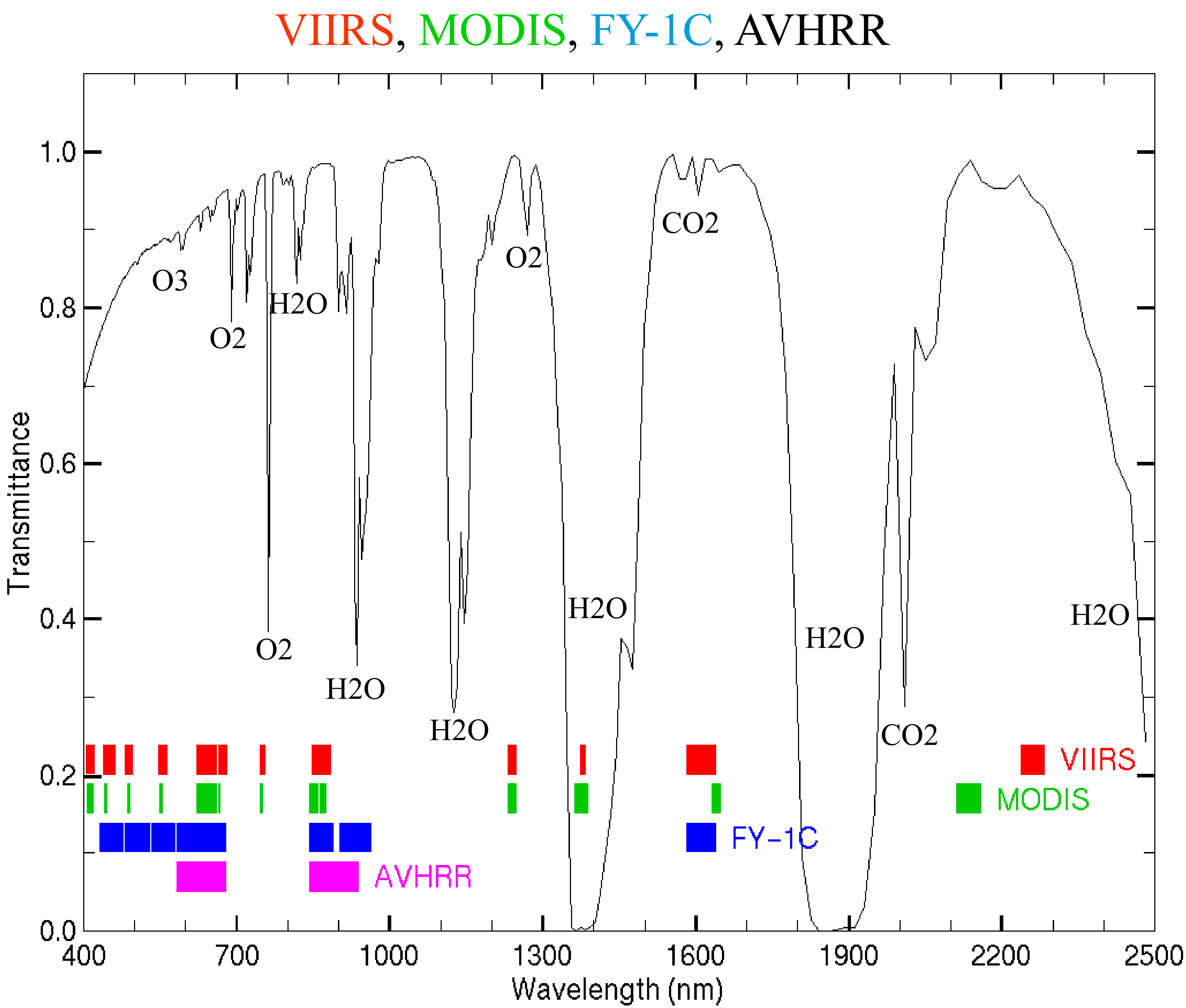
How to utilize all the spectral information?

Data rate:

Orders of magnitude larger than heritage sensors

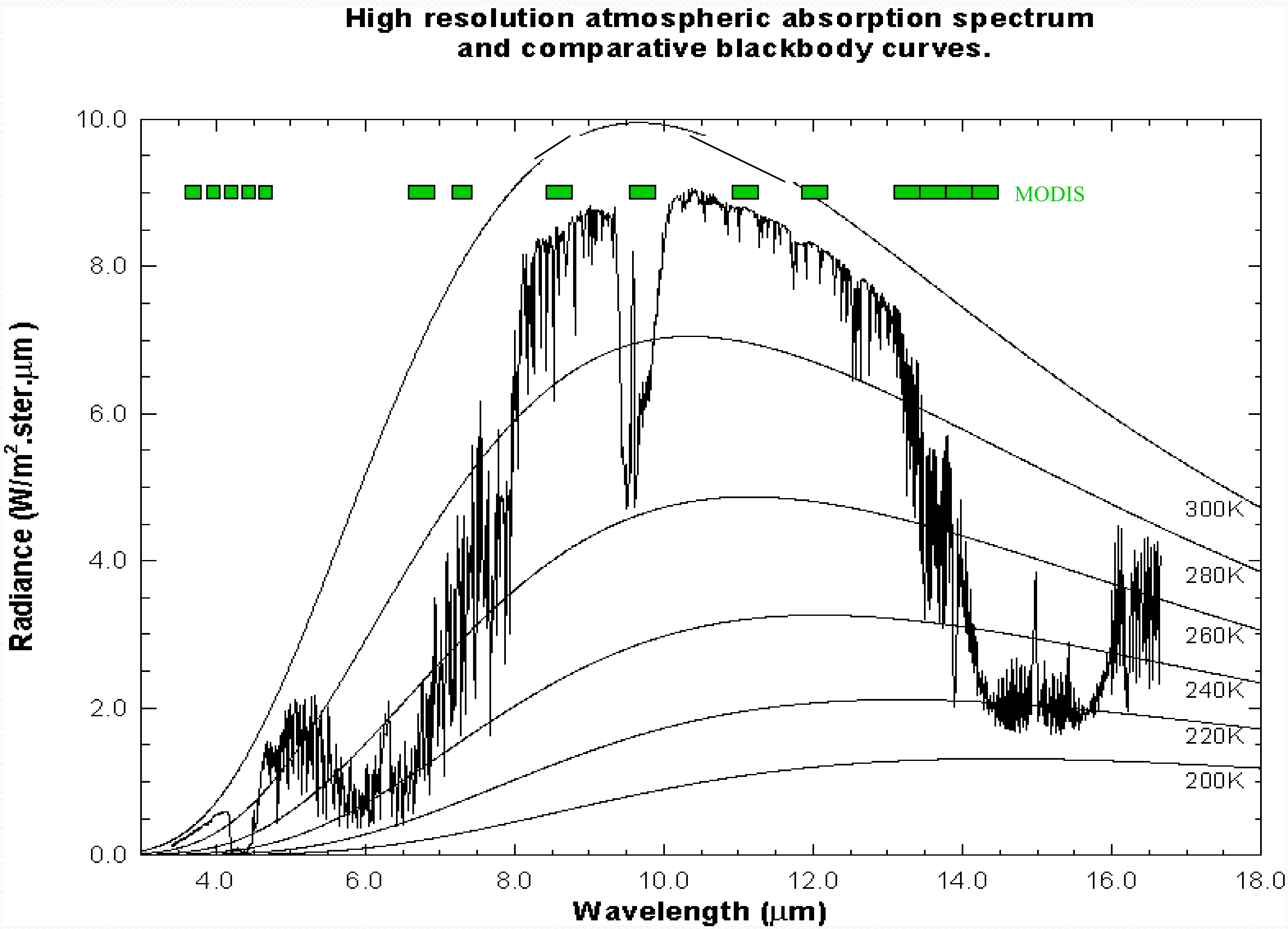
The MODIS sensor and its major subsystems



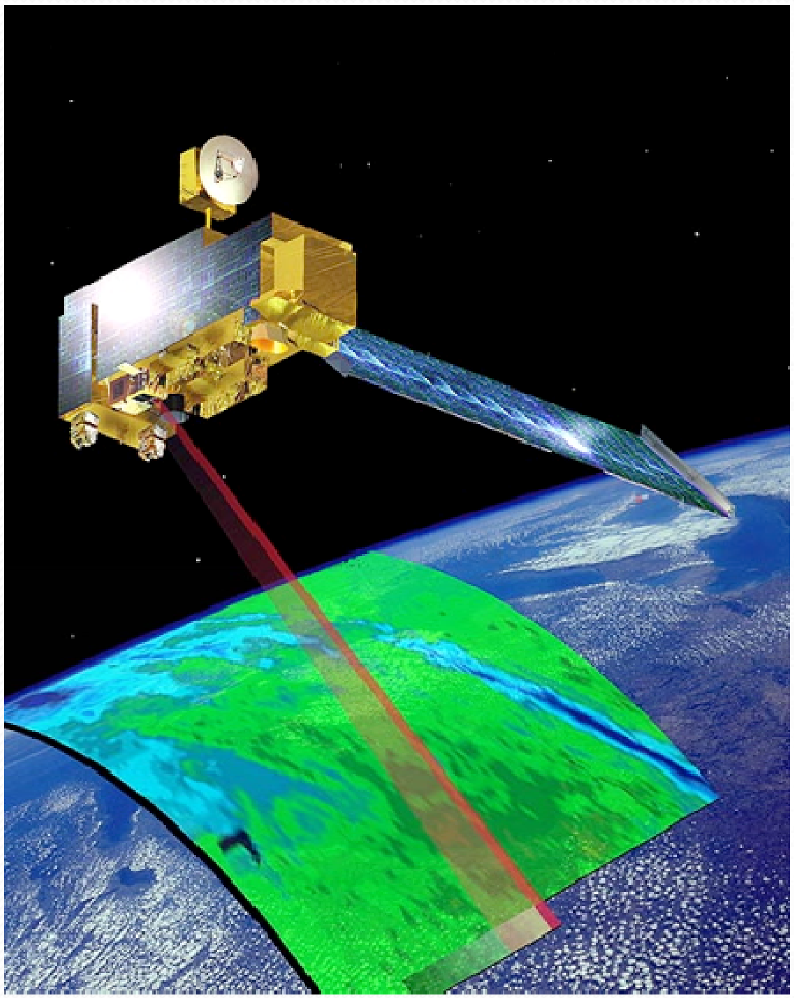


VIIRS, MODIS, FY-1C, AVHRR
Transmittance
Wavelength (nm)
1.0
0.8
0.6
0.4
0.2
0.0
400
700
1000
1300
1600
1900
2200
2500
O3
O2
H2O
O2
H2O
H2O
O2
H2O
CO2
H2O
CO2
H2O
VIIRS
MODIS
FY-1C
AVHRR

MODIS IR Spectral Bands



MODIS Scanner Characteristics



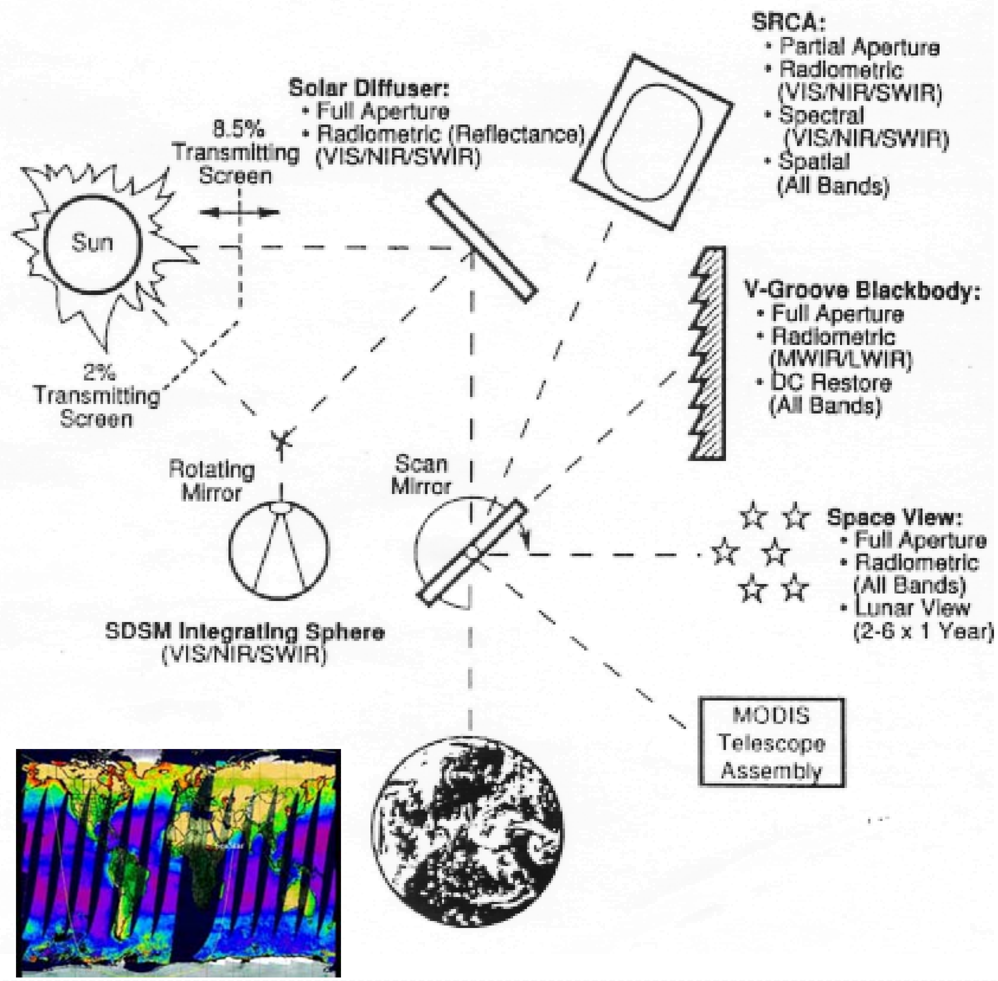
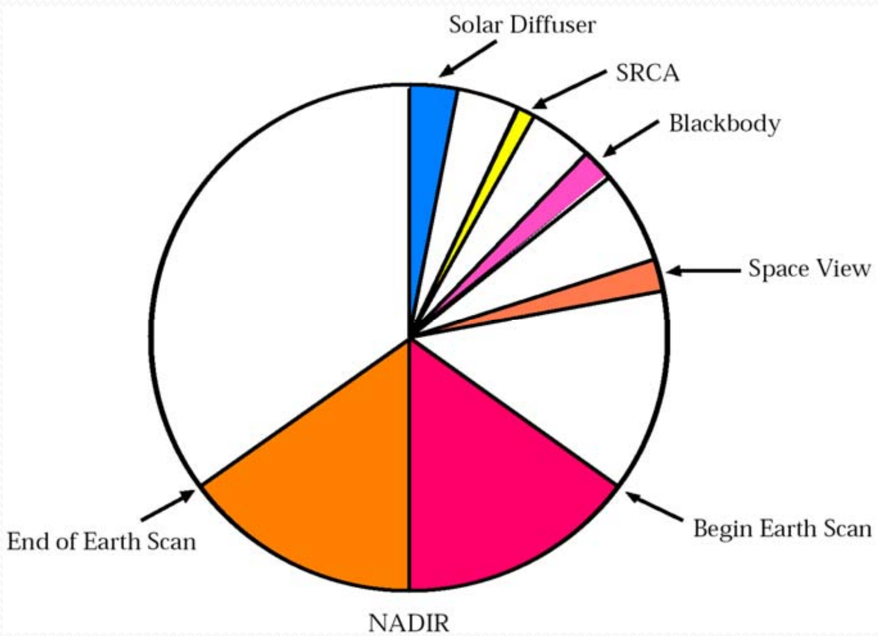


Image Acquisition Details

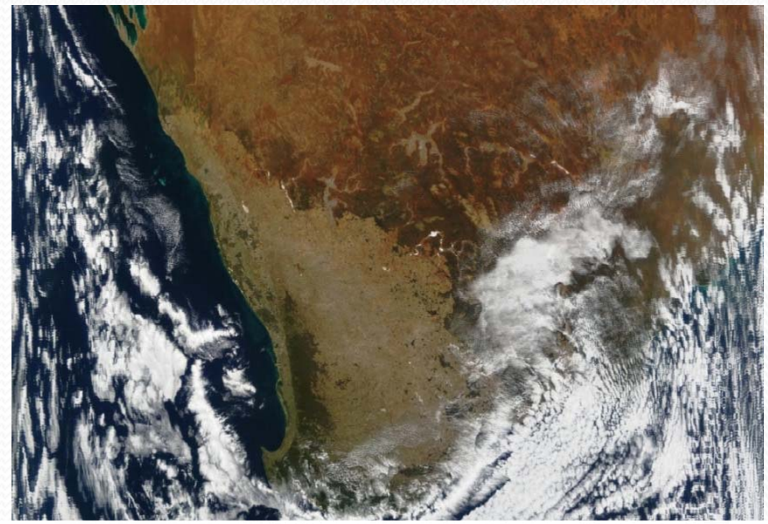
Scan sequence:

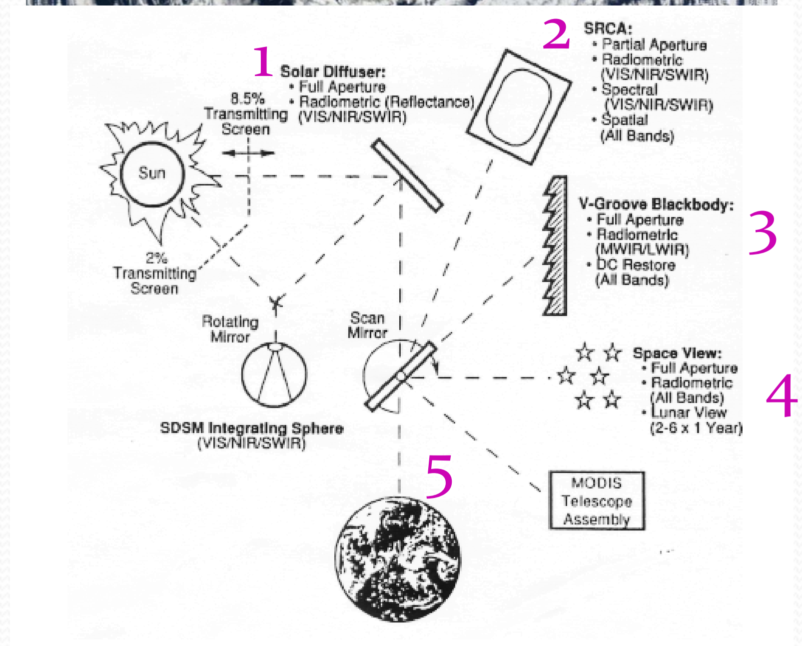
1. Solar diffuser
2. Spectroradiometric Calibration Assembly
3. Blackbody
4. Space View
5. Earth scan



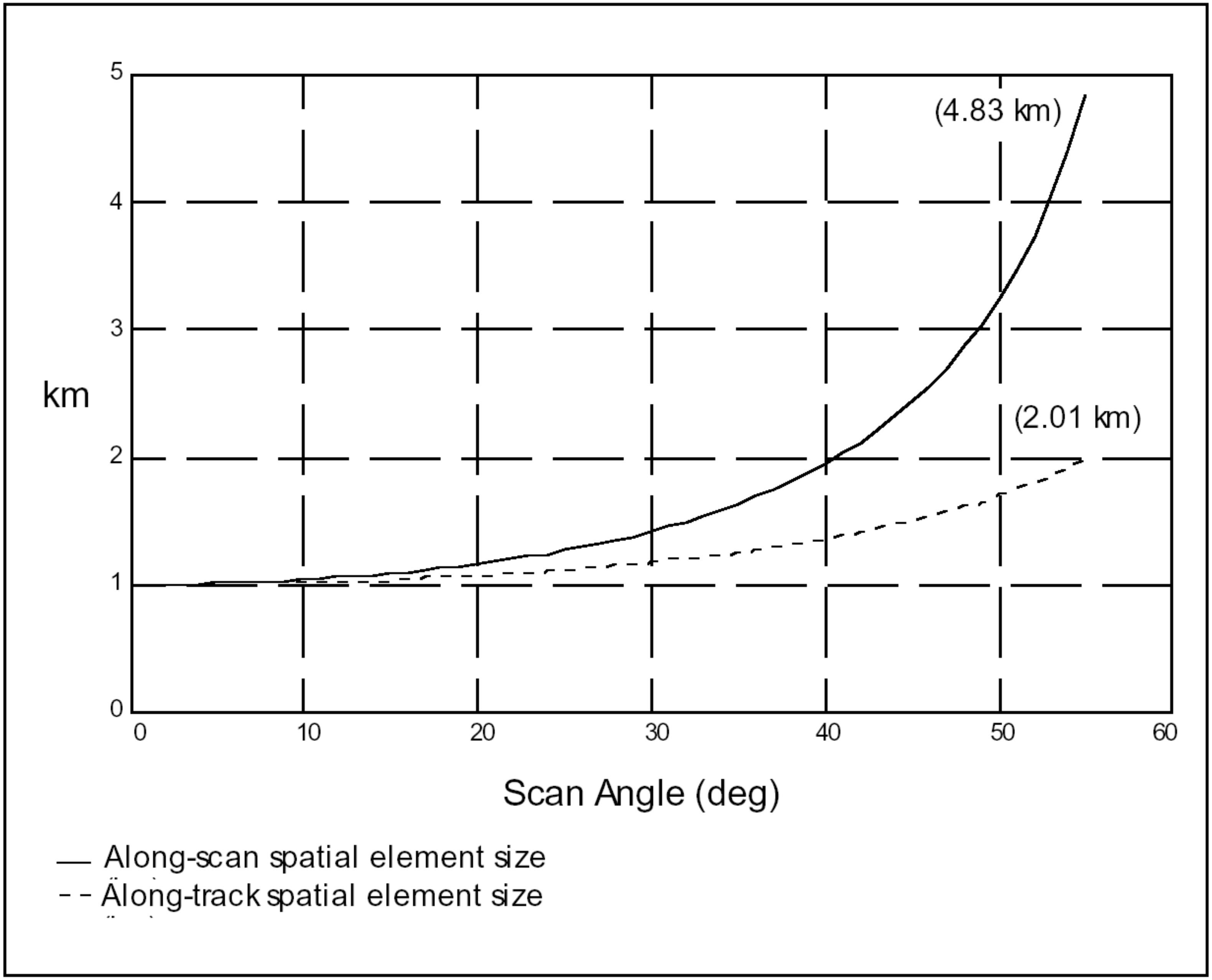
Scan direction

Flight direction



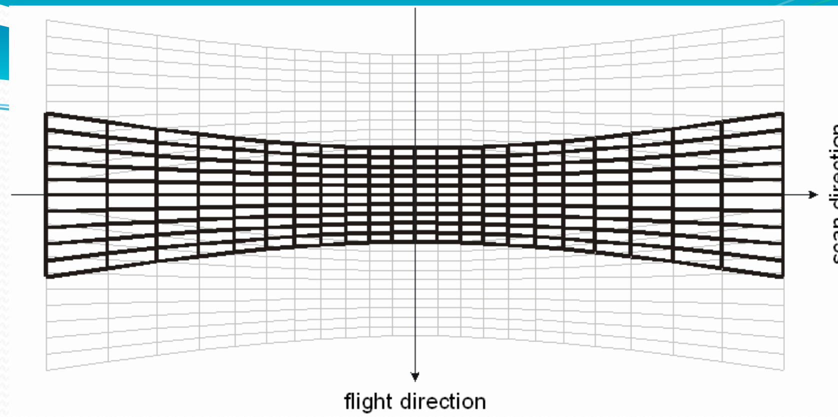


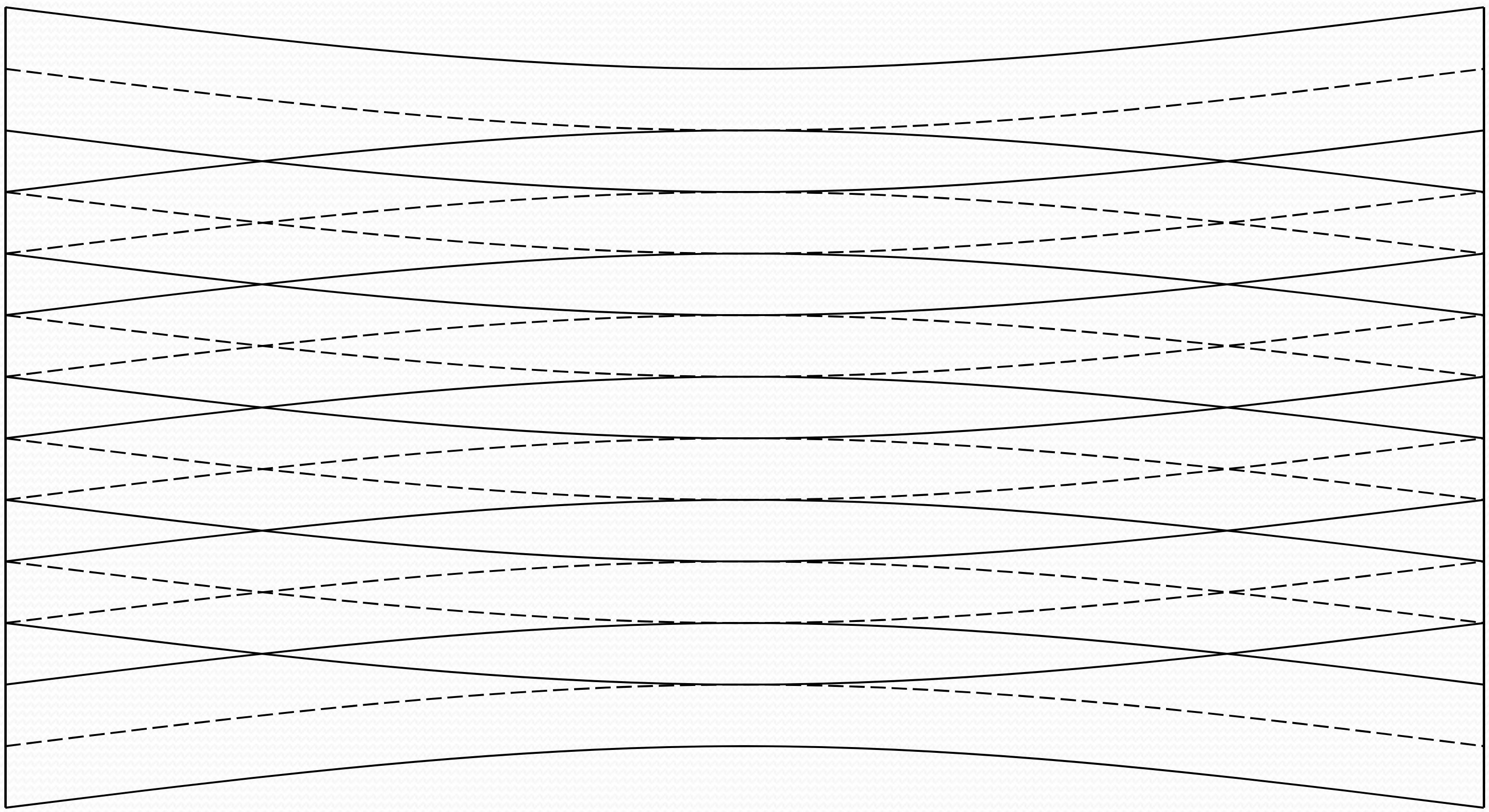
Growth of MODIS 1 km pixel with scan angle



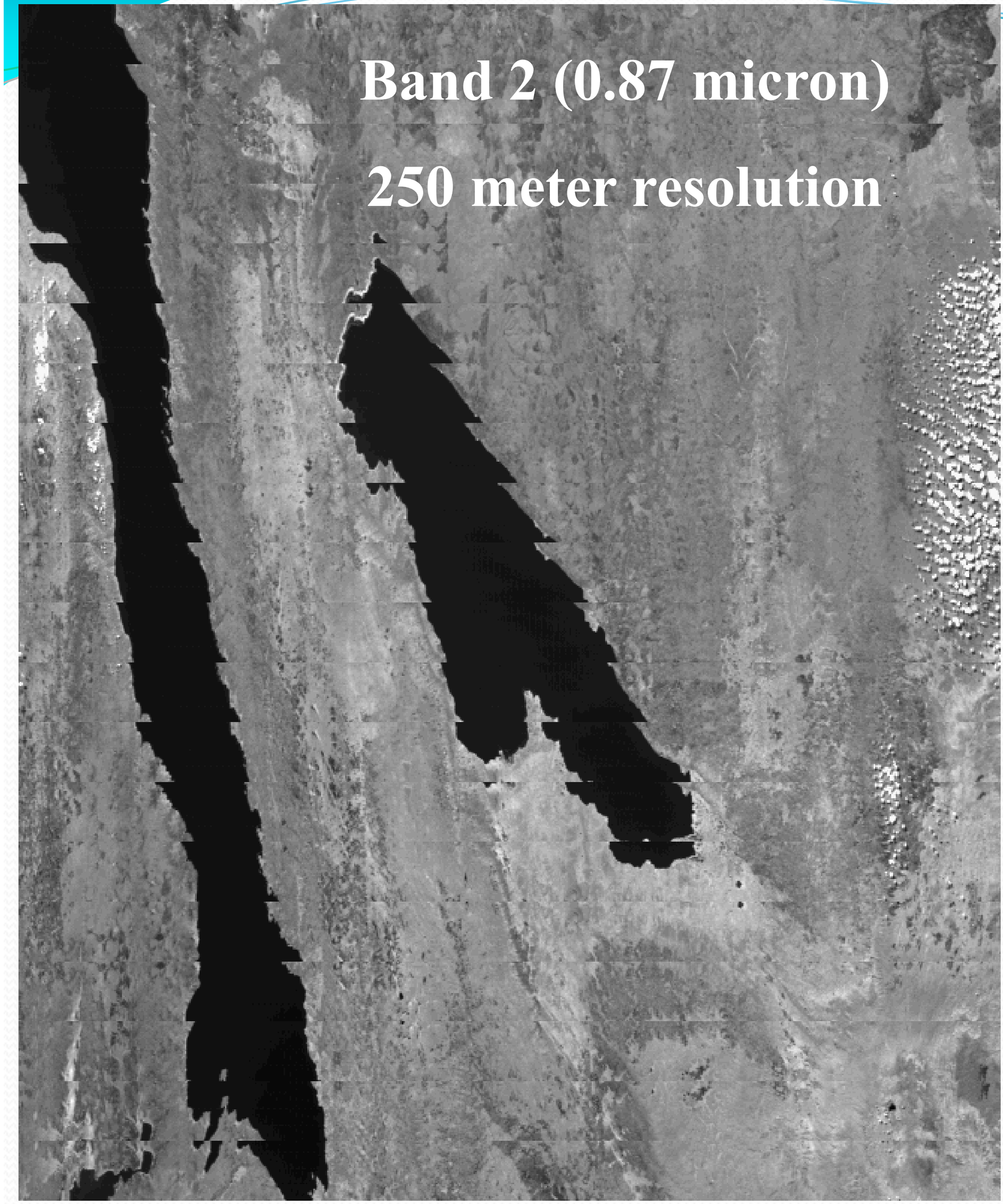
MODIS Bowtie Artifacts

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





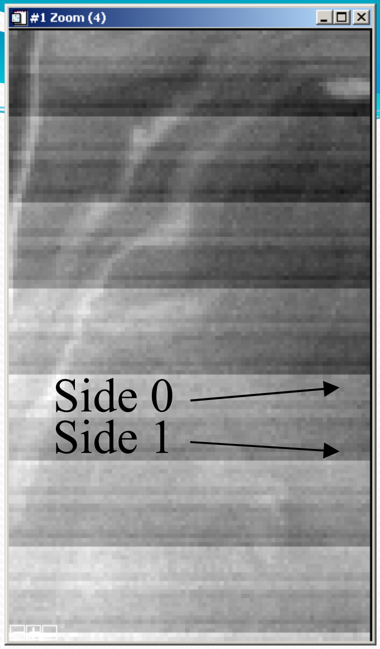
MODIS bowtie artifacts at edge of swath

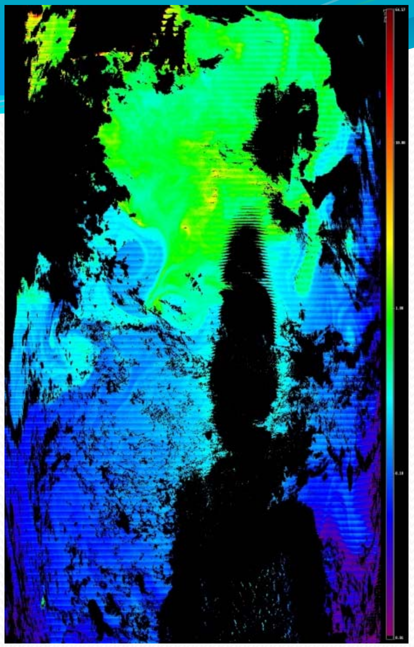


- Are not a 'problem': they are a consequence of the sensor design
- Can be removed for visualization purposes by reprojecting the image onto a map
- Do not affect science algorithms that run on a pixel-by-pixel basis or within one earth scan

Image Artifacts

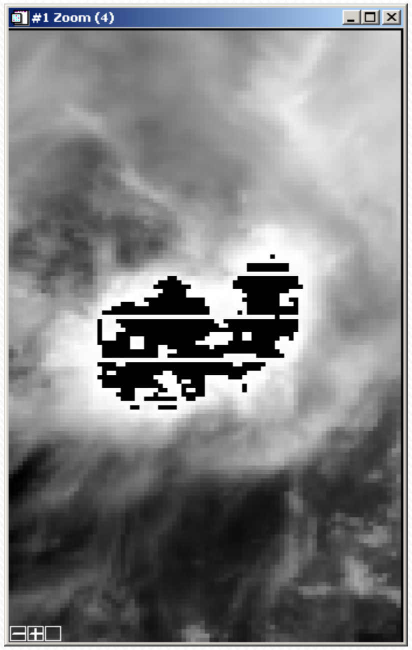
- Mirror Side Striping (Band 8, 0.41 µm)
  - Reflectance, emissivity, or polarization of each scan mirror side not characterized correctly.
  - *Can be corrected.*





- 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.*



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 bring 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.

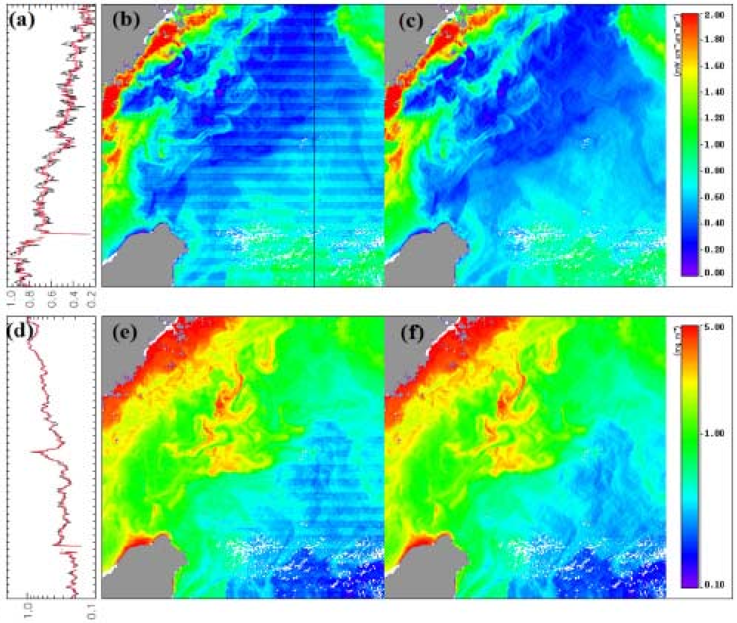
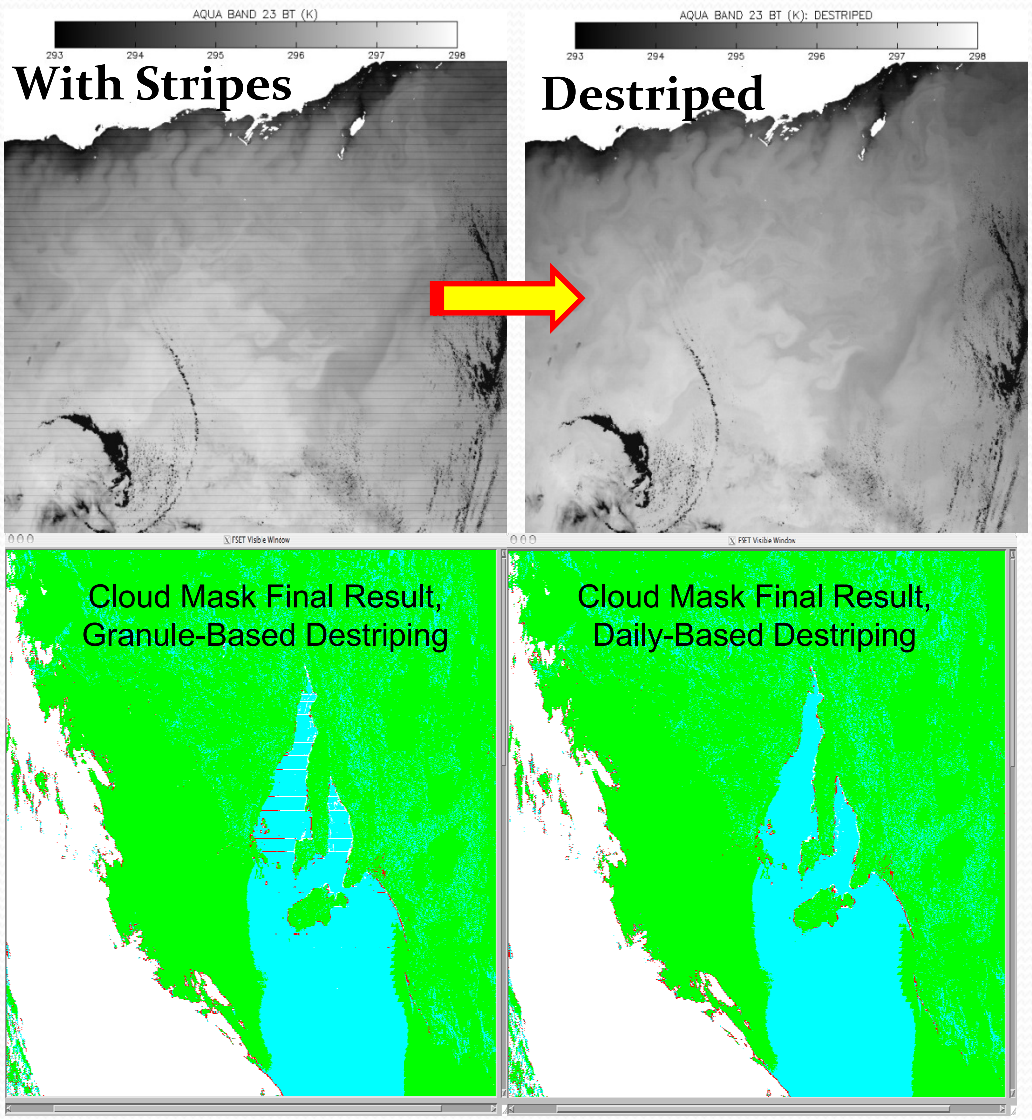


Fig. 2 Destriping of ocean color products $nL_w(412)$ (upper panels: (a)–(c)) and Chl-a concentration (lower panels: (d)–(f)) obtained by MODIS-Aqua on December 3, 2013 at around 05:05 UTC near (26°N, 123°E). The original data are shown in panels (b) and (e), while the destriped data are shown in panels (c) and (f). The values along the black line in panel (b) are plotted in panels (a) and (d) with black lines from original images (panels (b) and (e)) and red lines from destriped images (panels (c) and (f)).

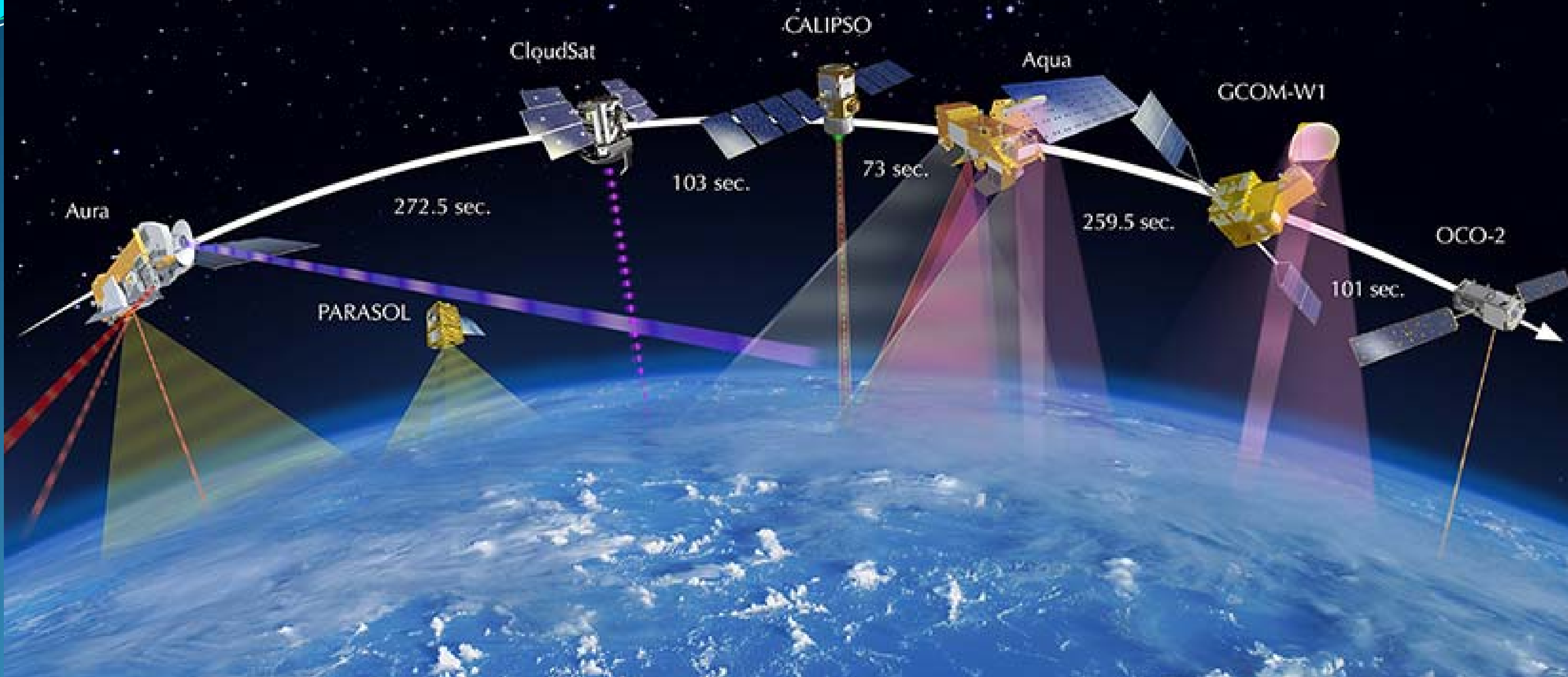
Karlis Mikelsons, Menghua Wang, Lide Jiang, and Marouan Bouali, "Destriping algorithm for improved satellite-derived ocean color product imagery," Opt. Express **22**, 28058-28070 (2014) http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-22-23-28058

MODIS Emissive Band Destriping: Granule vs. Daily Analysis



- The Atmosphere Group products for Collection 5 and 6 include detriping 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 cold scenes (e.g. hot land, cool ocean) may have artifacts in the scene transition zone.

ATMO 611 – Satellite Data Applications



MODIS Cloud Products

Jennifer D. S. Griswold

MODIS Atmosphere Team Product Organization and People

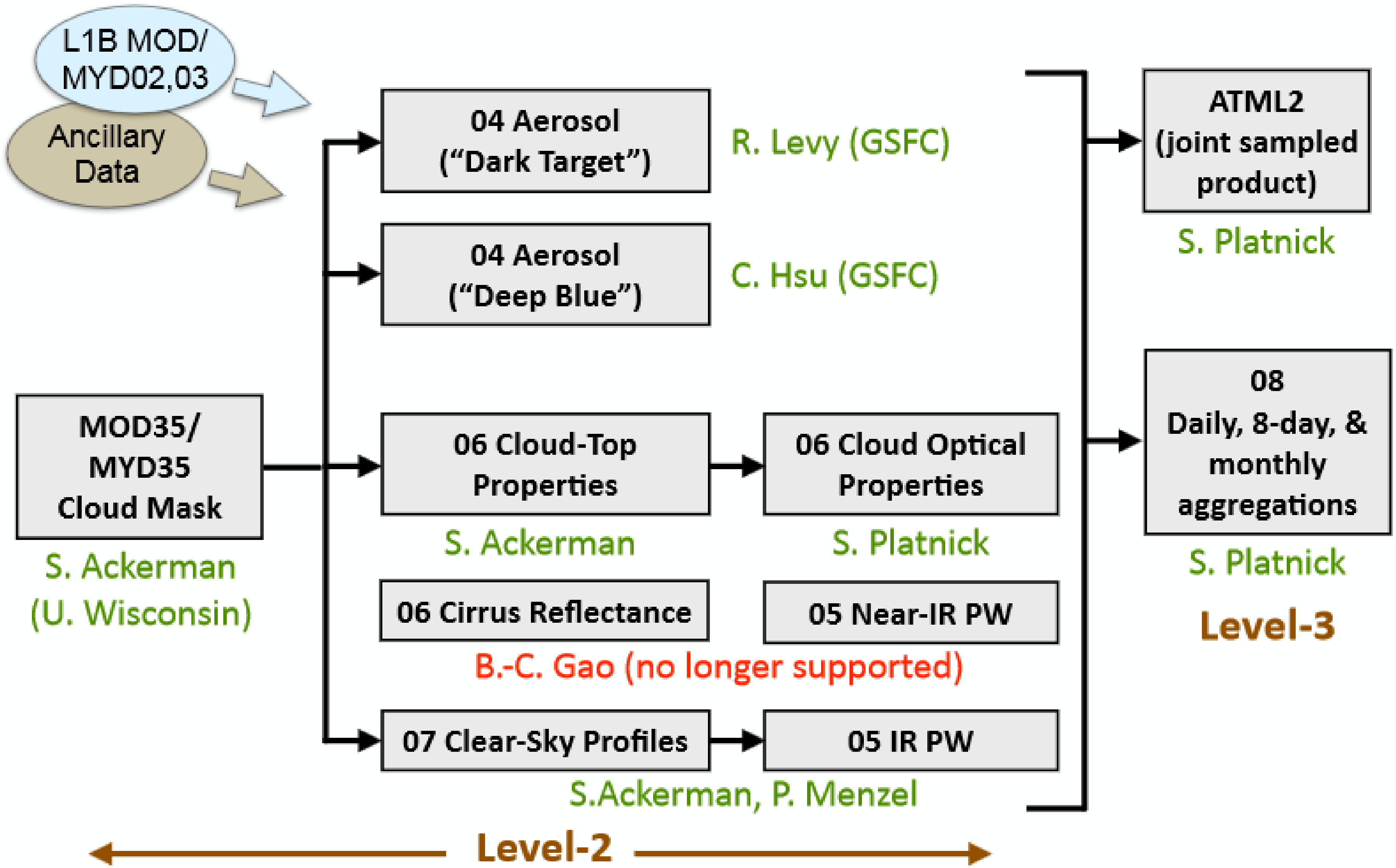


Table 1 –Platnick et al 2003

TABLE I

SUMMARY OF MODIS PIXEL-LEVEL (LEVEL-2) CLOUD PRODUCTS AND THEIR CURRENT DEPENDENCIES. * TERRA DESIGNATION (AQUA IDs ARE MYD35, MYD06, ETC.); [a] NSIDC NISE AND/OR NCEP SEA ICE CONCENTRATION; [b] NCEP GDAS SIX-HOUR DATASET; [c] NCEP REYNOLDS BLENDED SST PRODUCT; [d] AGGREGATION of MODIS ECOSYSTEM CLASSIFICATION PRODUCT (MOD12) WITH MODIS DIFFUSE SKY SURFACE ALBEDO PRODUCT (MOD43). SEE TEXT FOR FURTHER DETAILS

Retrieved parameter	Earth Science Data Designation Product ID*	Investigators	MODIS spectral bands used	Spatial resolution (km)	MODIS ancillary input	Non-MODIS ancillary input
CLOUD MASK	**MOD35**	Ackerman *et al.*	up to 20 bands, VIS thru IR	0.25, 1		snow/sea ice mask [a]
CLOUD PROPERTIES	**MOD06**					
CLOUD TOP PROPERTIES						
Cloud-top pressure (p_c), cloud-top temperature (T_c), effective emissivity ($f\varepsilon$)		Menzel *et al.* Thermal IR	11 μm and CO_2 bands (31–36)	5	**MOD35**	model/assimilated T, p profiles [b], SST [c]
CLOUD OPTICAL AND MICROPHYSICAL PROPERTIES:		Solar Reflectance				
Cloud optical thickness (τ_c), particle effective radius (r_e), water path		King *et al.*	VIS, NIR, SWIR, MWIR (bands 1, 2, 5, 6, 7, 20)	1	**MOD35, MOD06** (p_c, T_c), ecosystem + surface albedo [d]	snow/sea ice mask [a], model/assimilated T, p profiles [b], SST [c]
Thermodynamic phase (IR algorithm)		Baum *et al.* Thermal IR	8.5, 11 μm bands (bands 29, 31)	5		

Primary Use for Reflected Solar Band

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
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Bands 1 to 19 are in nm; Bands 20 to 36 are in µm

Spectral Radiance values are (W/m² -µm-sr)

Primary Use for Each Thermal Band

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	28	7.175 - 7.475	2.18(250K)	0.25
Cloud Properties	29	8.400 - 8.700	9.58(300K)	0.05
Ozone	[illegible]	[illegible]	[illegible]	[illegible]
Surface/Cloud Temperature	31	10.780 - 11.280	9.55(300K)	0.05
	32	11.770 - 12.270	8.94(300K)	0.05
Cloud Top Altitude	33	13.185 - 13.485	4.52(260K)	0.25
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	36	14.085 - 14.385	2.08(220K)	0.35

*Bands 1 to 19 are in nm; Bands 20 to 36 are in µm   NE(delta)T = Noise-equivalent temperature difference

Example Granule (Platnick et al, 2003)

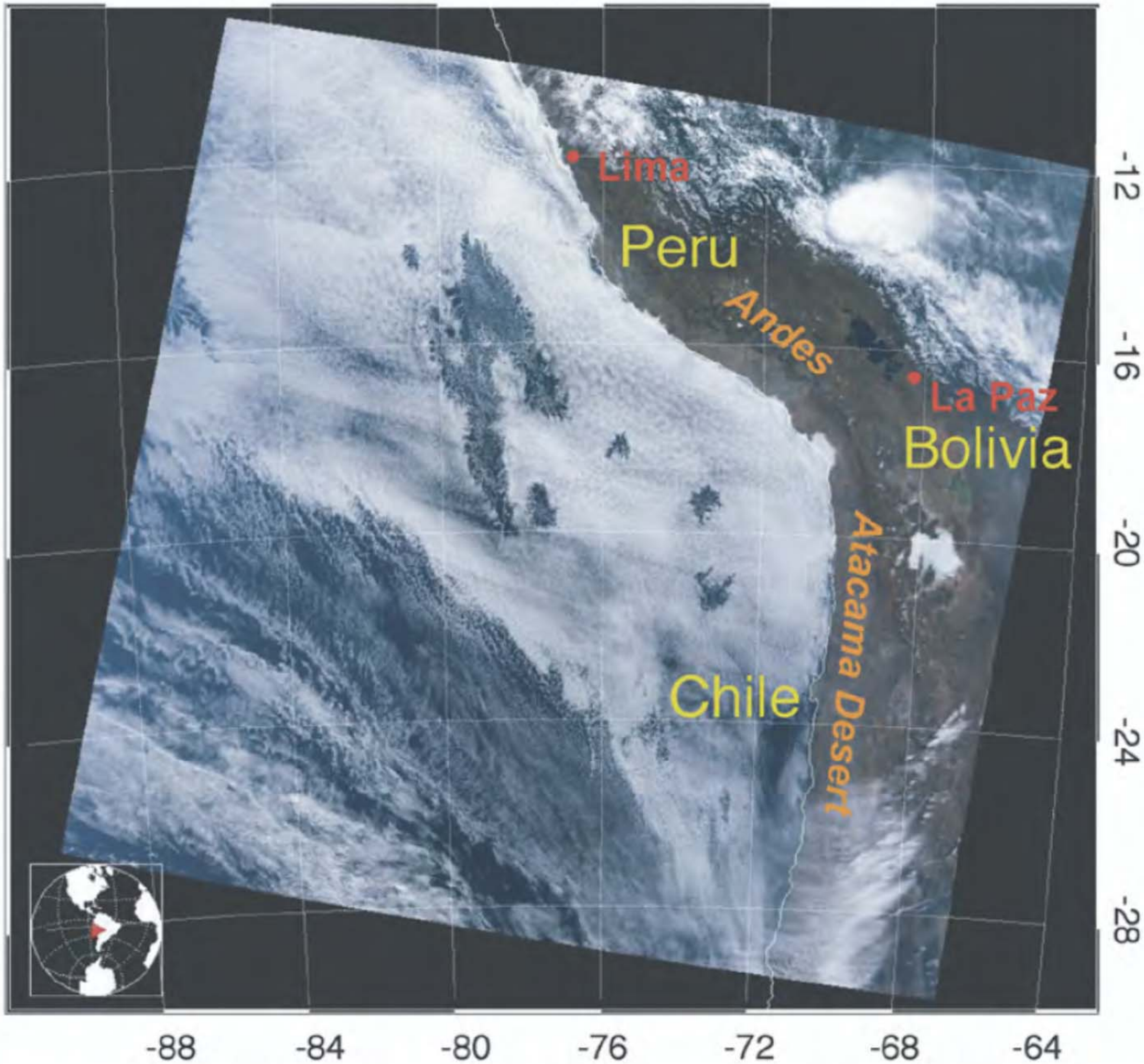
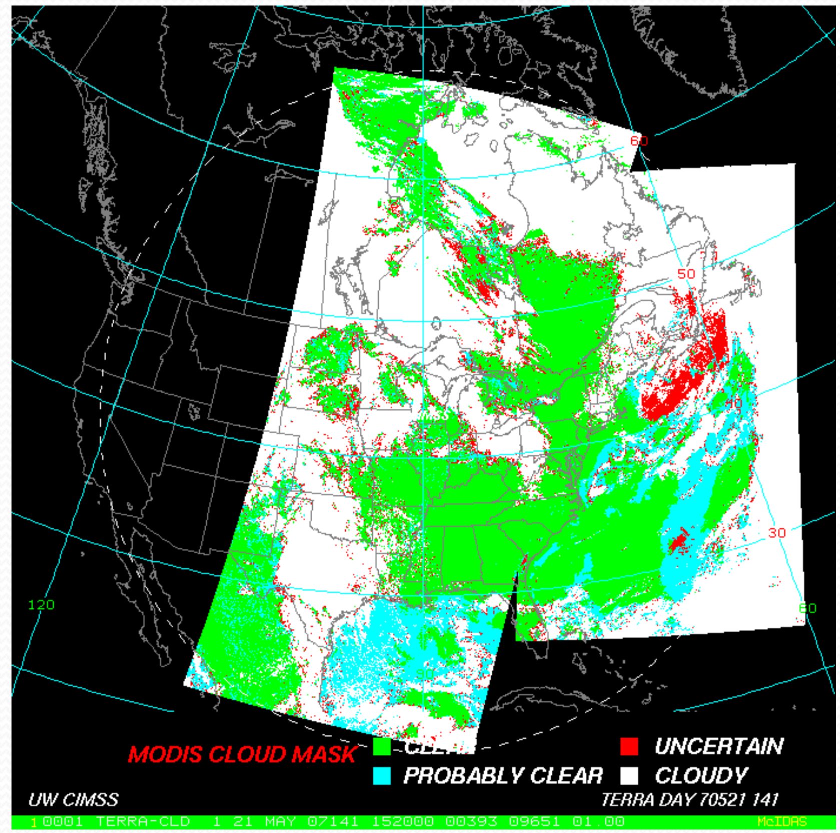


Fig. 1. True-color composite of a granule of Terra MODIS data from July 18, 2001, 1530 UTC. The image shows widespread boundary layer stratocumulus clouds off the coasts of Peru and Chile, associated with cool upwelling water along the Humboldt current.

Cloud Mask

Ackerman, Frey, UW MODIS Group

- Is the primary ancillary input to other algorithms
- Produced globally day and night
- 1 km-pixel resolution
- Uses as many as 20 (of 36) bands
- Assesses the likelihood of a pixel being obstructed by clouds
- Allows for “clear sky confidence” – i.e. varying degrees of cloudiness instead of “yes cloud-no cloud”

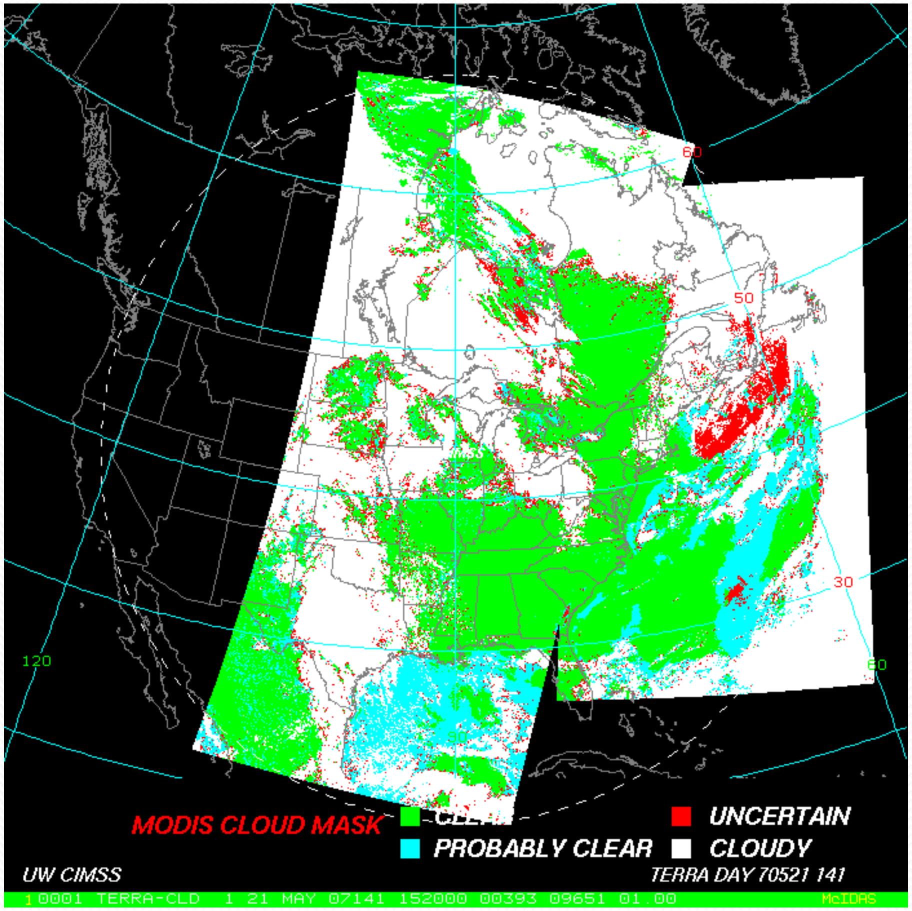


Cloud Mask - Algorithm Development

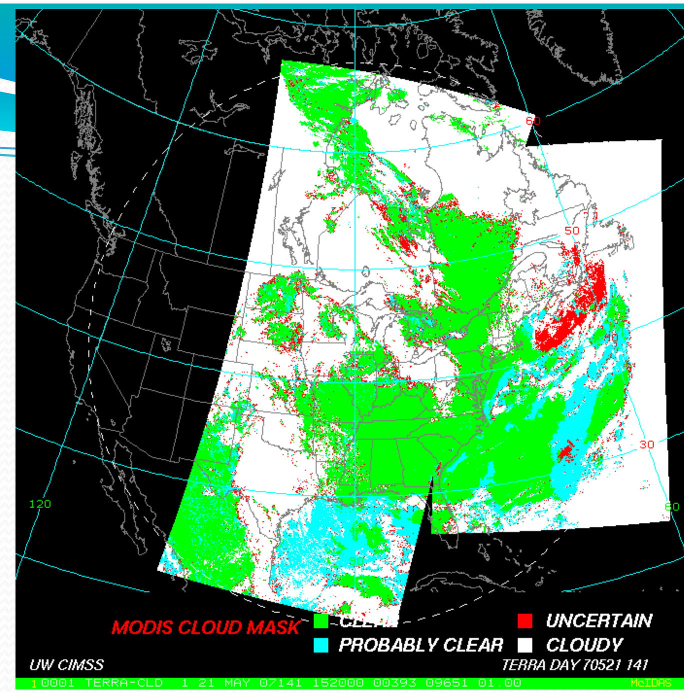
- **Built upon work done by others:**
  - ISCCP – Rossow and Garder 1993
  - CLAVR – Stowe et al. 1991
  - APOLLO – Saunders and Kriebel 1988
- **New spectral channels – new tests**
  - 1.38 micron high cloud reflectance test
- **Many spectral channels (more later)**
  - more tests go into final product
  - first platform with 8-11 (can use tri-spectral tests)

Cloud Mask

- **48 bits of output per pixel**
- **Individual cloud test results**
- **Processing path**
- **Land/Sea Tag**
- **Classification of Cloud Contamination**
  - Confident Clear
  - Probably Clear
  - Uncertain/Probably Cloudy
  - Cloudy



Cloud Mask



1. **Determine surface type (both Day and Night)**
   - Land, water, snow/ice, desert, coast
2. **Threshold Tests**
   - Clouds, aerosol in FOV
3. **"Clear" Confidence Level**
   - 1 = high confidence clear
   - 0 = low confidence clear
4. **Different tests**
   - Detection of different cloud conditions
   - Grouped together for detecting similar cloud conditions

Minimum Confidence of Each Group

$$G_{j=1,N} = \min\,[F_i]_{i=1,m}$$

- F_i = the confidence level of an individual spectral test
- m = number of tests in a given group
- j = the group index
- N = Number of groups

Cloud Mask

Final Cloud Mask Confidence

$$Q = N\sqrt{\prod_{i=1}^{N} G_j}.$$

- Q = final cloud mask confidence
- N = Number of Groups
- G_j = Minimum confidence of group

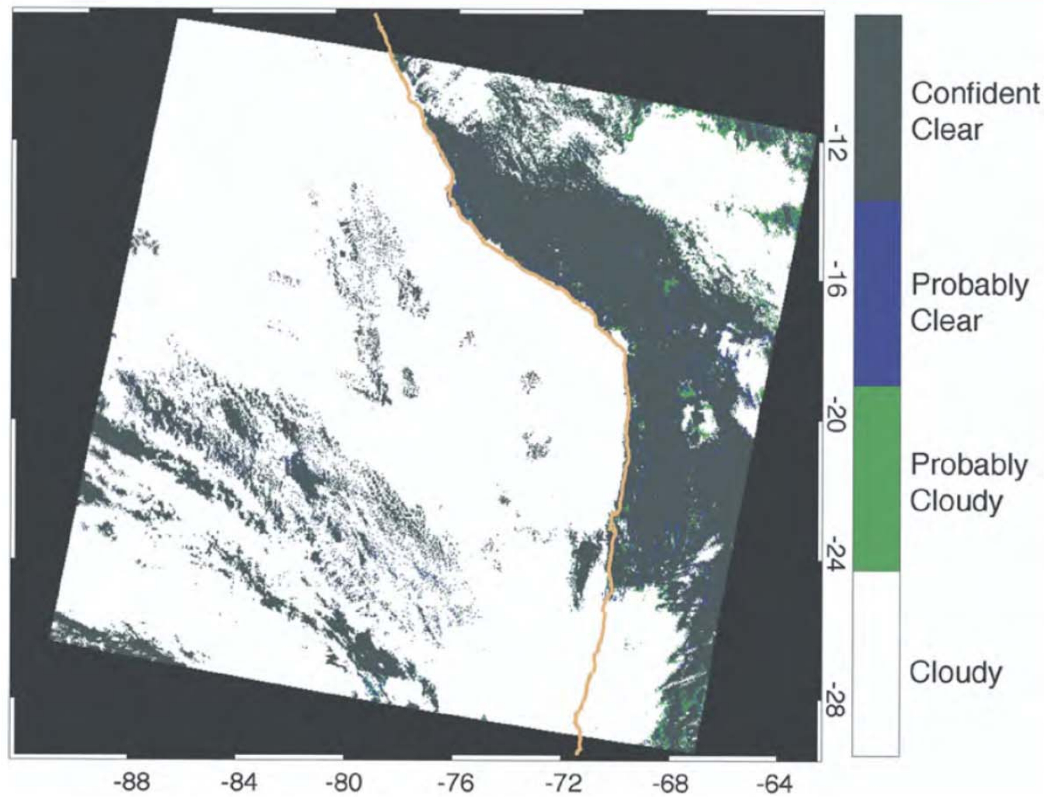


Fig. 2. The overall assessment from the MODIS cloud mask for the image of Fig. 1 as given by the first two bits of the mask.

- **Clear-Sky Conservative**
  - **If highly confident it is cloudy (Fi = 0) then the final clear-sky confidence is 0.**

- **Confidence Levels (OF BEING CLEAR!!)**
  - **Confident Clear (Q > 0.99)**
  - **Probably Clear (Q > 0.95)**
  - **Uncertain/Probably Cloudy (Q > 0.66)**
  - **Cloudy (Q ≤ 0.66). (*not clear*)**

FIRST TWO BITS of the MASK

Cloud Mask

- ***Difficult Over***
  - Non-vegetated surfaces
  - Transitional areas (Desert-Vegetation)
  - High-elevations
    - Mountains
    - Antarctica plateau
  - Sunglint regions (later)
  - Nighttime masking during strong temp inversions

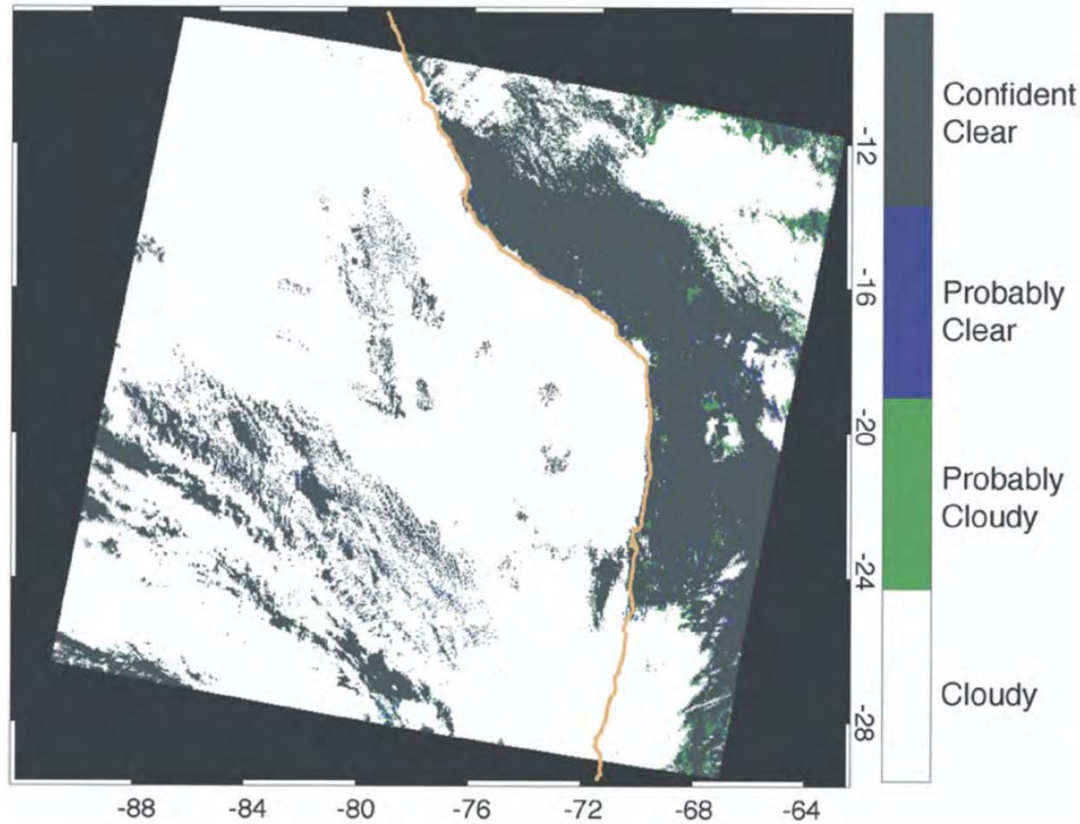
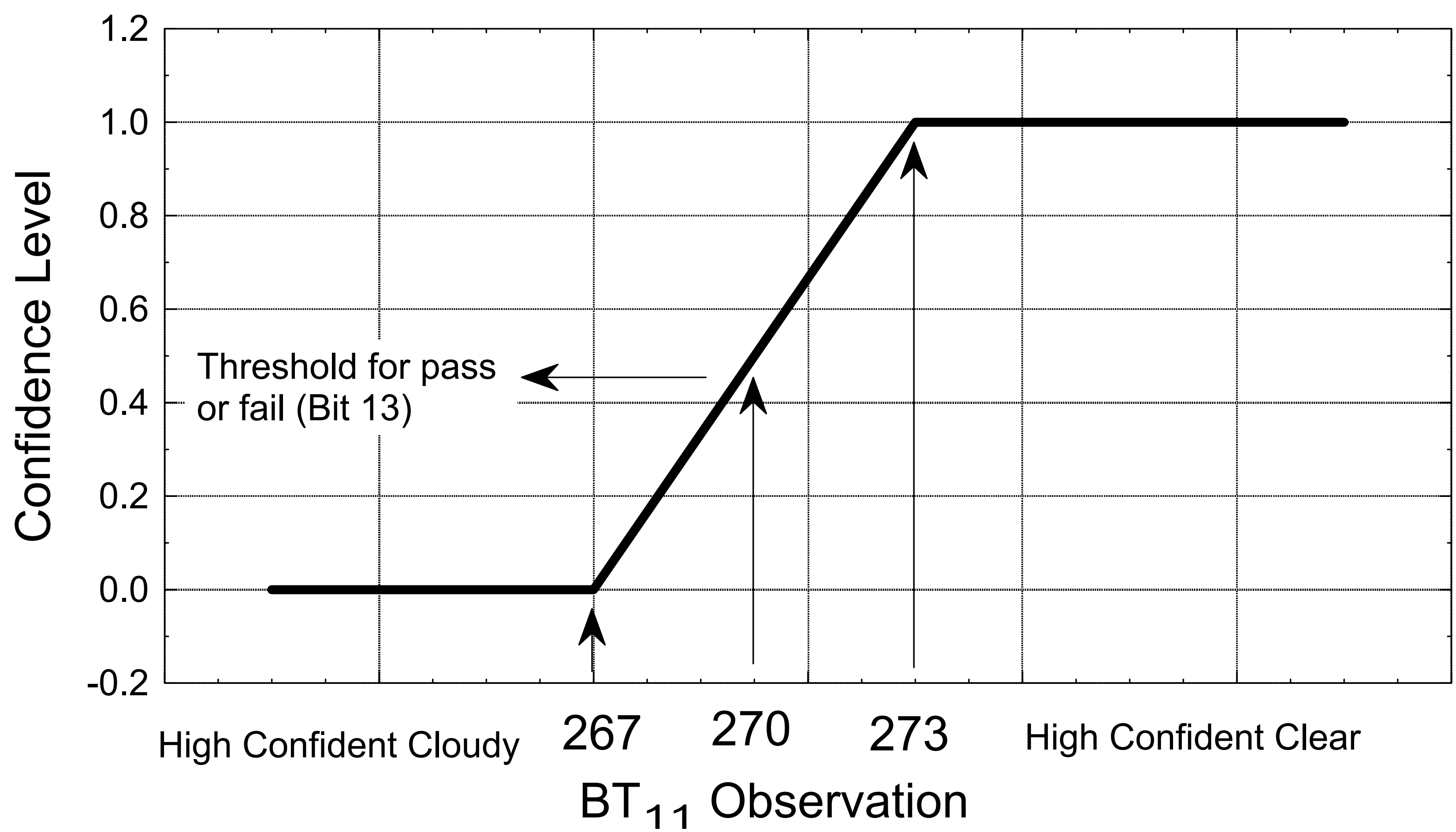


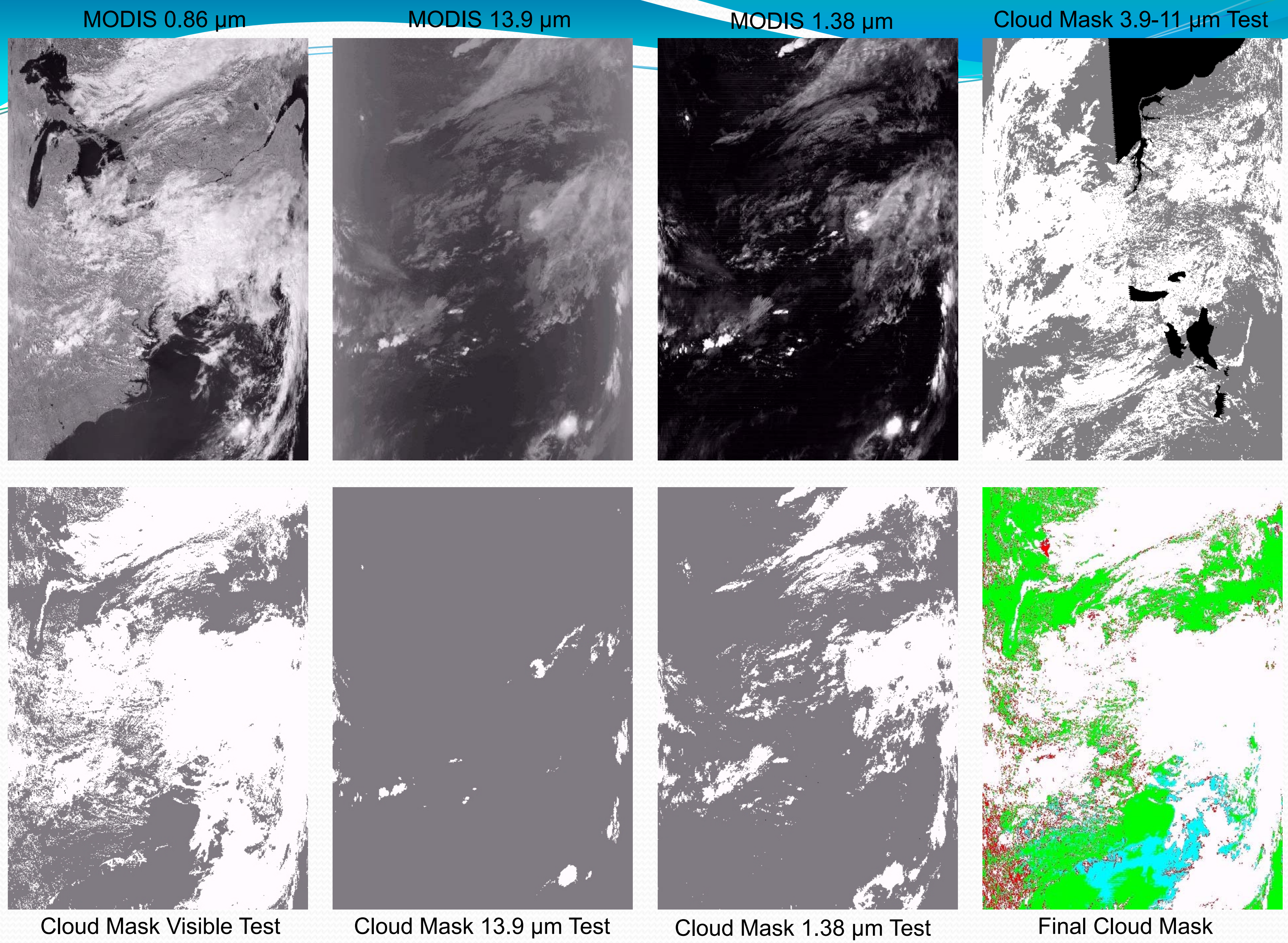
Fig. 2. The overall assessment from the MODIS cloud mask for the image of Fig. 1 as given by the first two bits of the mask.

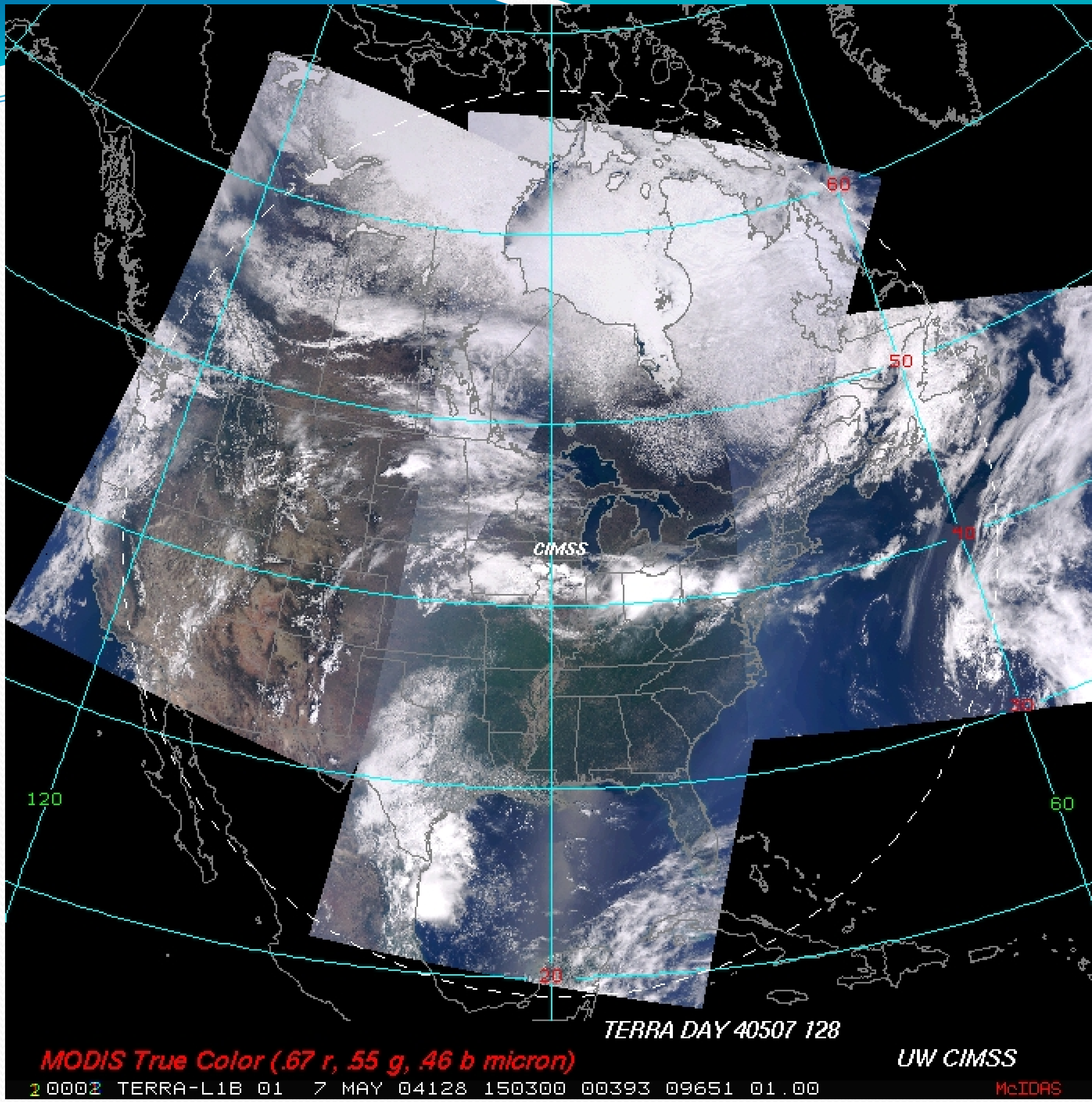
- ***Uncertain/Probably Cloudy***
  - Usually near cloud edges
- ***Probably Clear***
  - Isolated regions over land, away from cloud edges

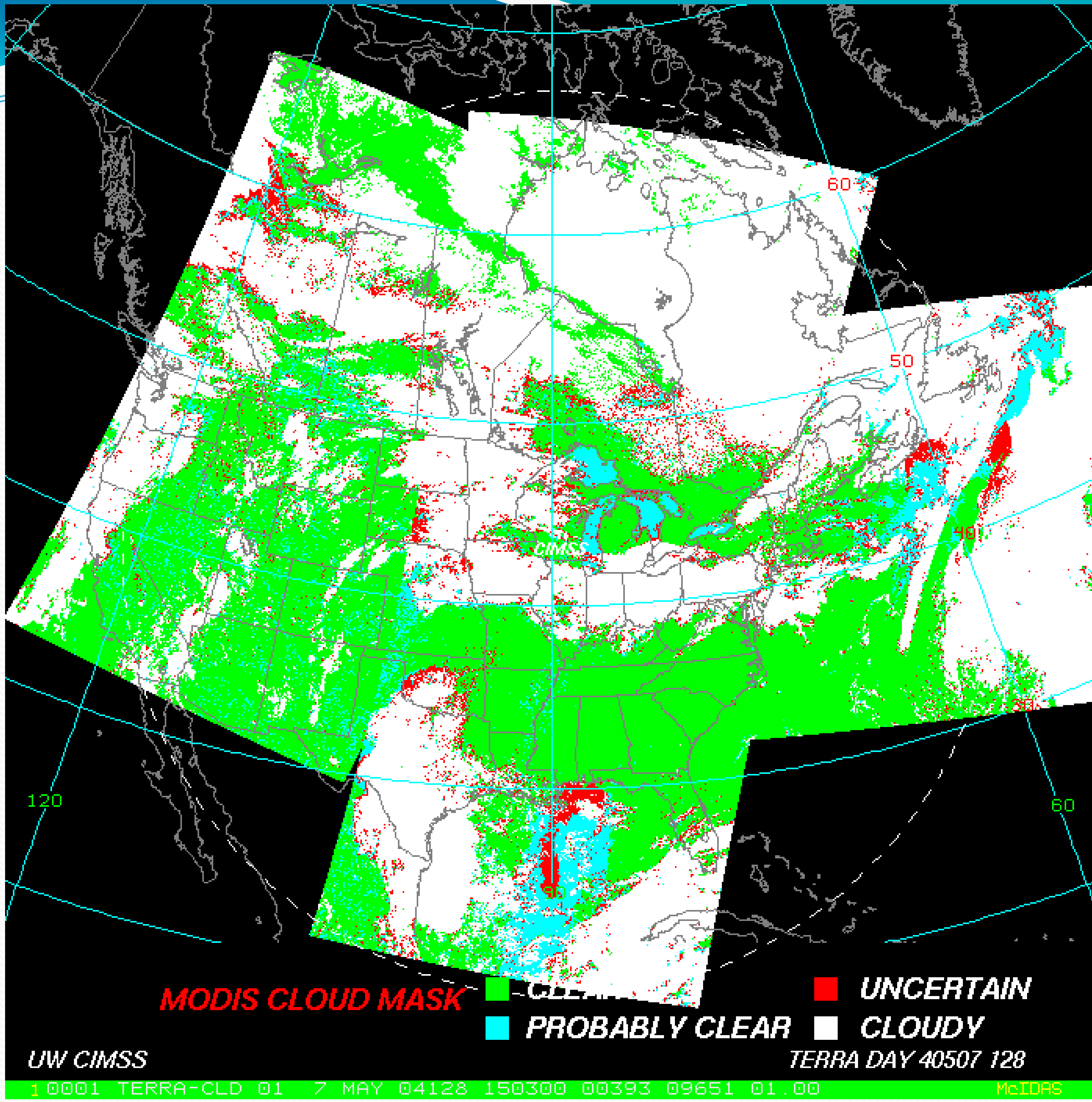
Confidence Level of Clear



Example thresholds for the simple IR window cold cloud test.


MODIS 0.86 μm
MODIS 13.9 μm
MODIS 1.38 μm
Cloud Mask 3.9-11 μm Test
Cloud Mask Visible Test
Cloud Mask 13.9 μm Test
Cloud Mask 1.38 μm Test
Final Cloud Mask


60
50
40
30
20
120
60
CIMSS
TERRA DAY 40507 128
MODIS True Color (.67 r, .55 g, .46 b micron)
UW CIMSS
2 0002 TERRA-L1B 01 7 MAY 04128 150300 00393 09651 01.00
McIDAS


MODIS CLOUD MASK
UNCERTAIN
PROBABLY CLEAR
CLOUDY
UW CIMSS
TERRA DAY 40507 128
1 0001 TERRA-CLD 01 7 MAY 04128 150300 00393 09651 01.00
McIDAS
60
50
40
120
60