Observations (3): Satellite Radiance Data Assimilation

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Outline

- Principle of satellite measurements
- Radiative Transfer
- Variational Bias Correction and All-sky radiance DA
- Radiance DA setting with MPAS-JEDI

Environmental monitoring satellites

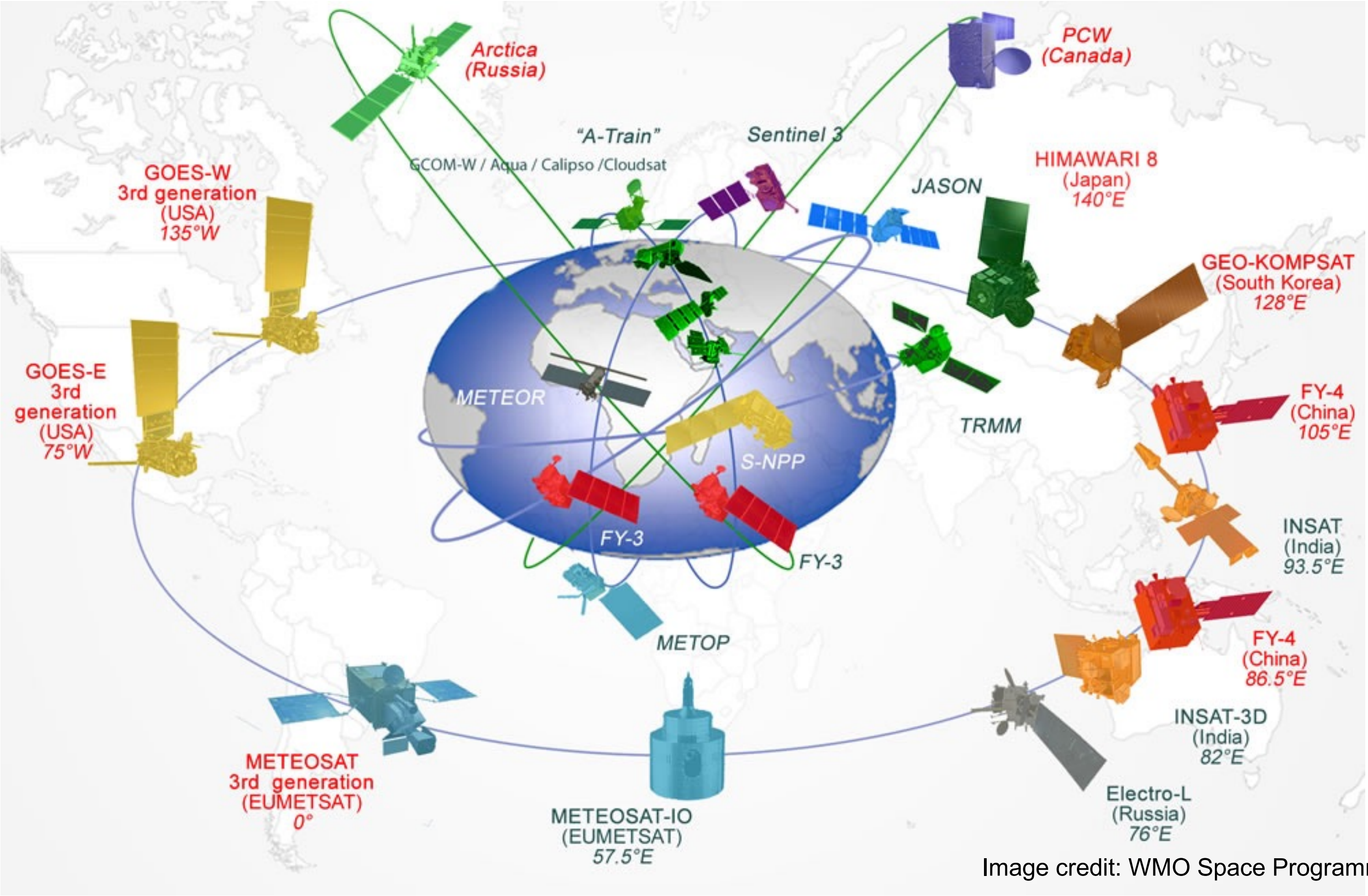
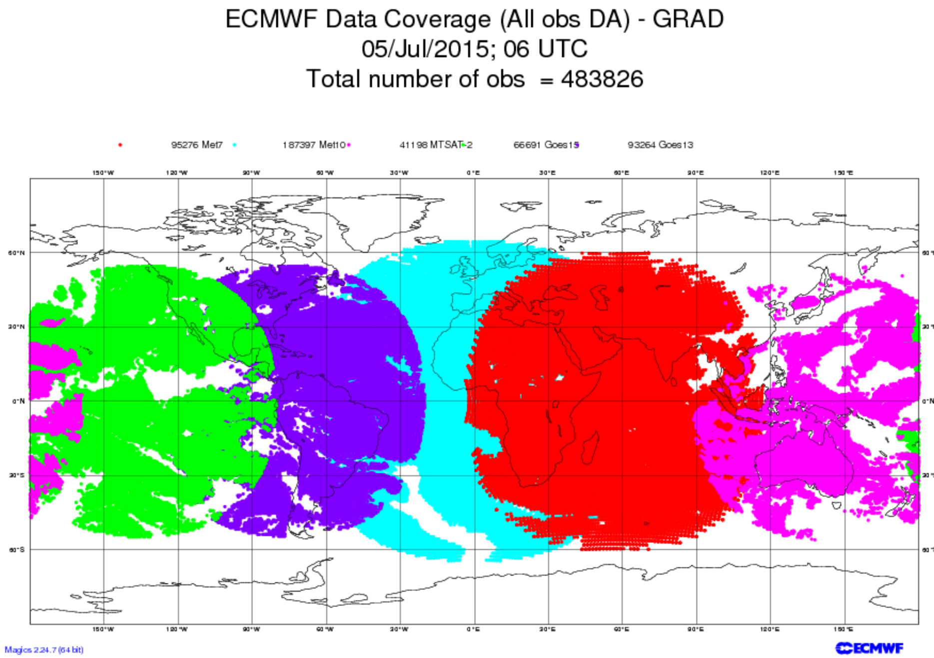


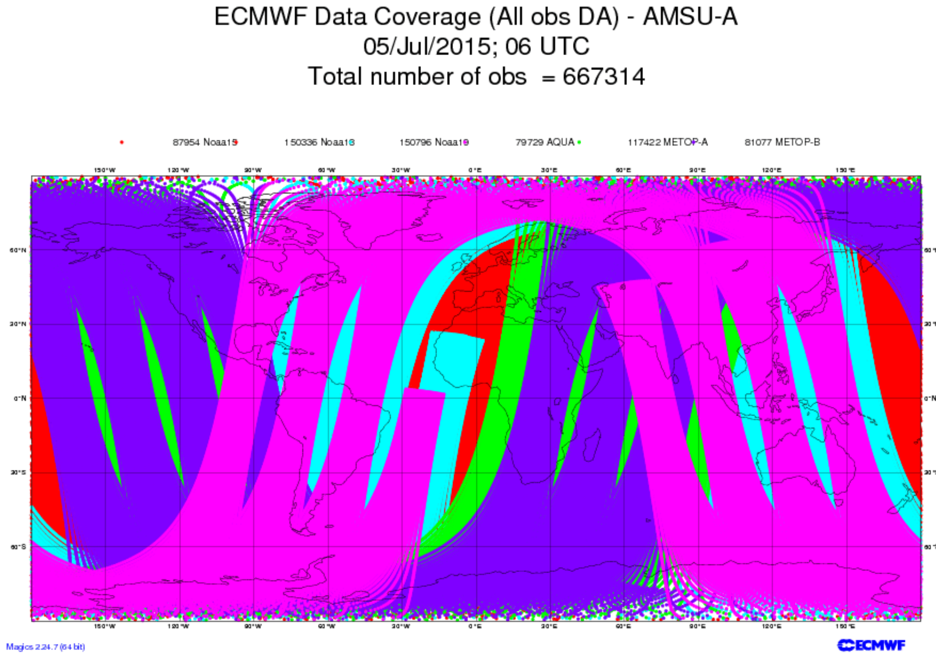
Image credit: WMO Space Programme

Polar-orbiting satellites vs. Geostationary satellites

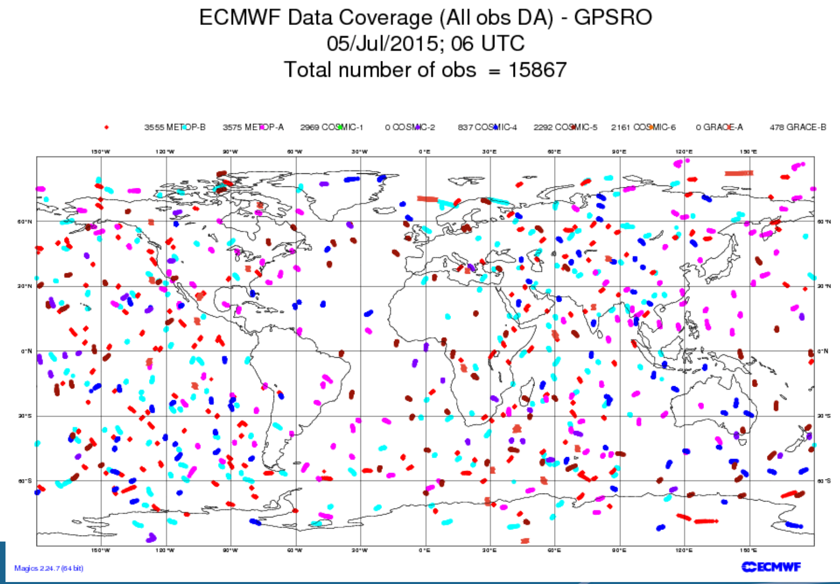
AMV from Geostationary satellites



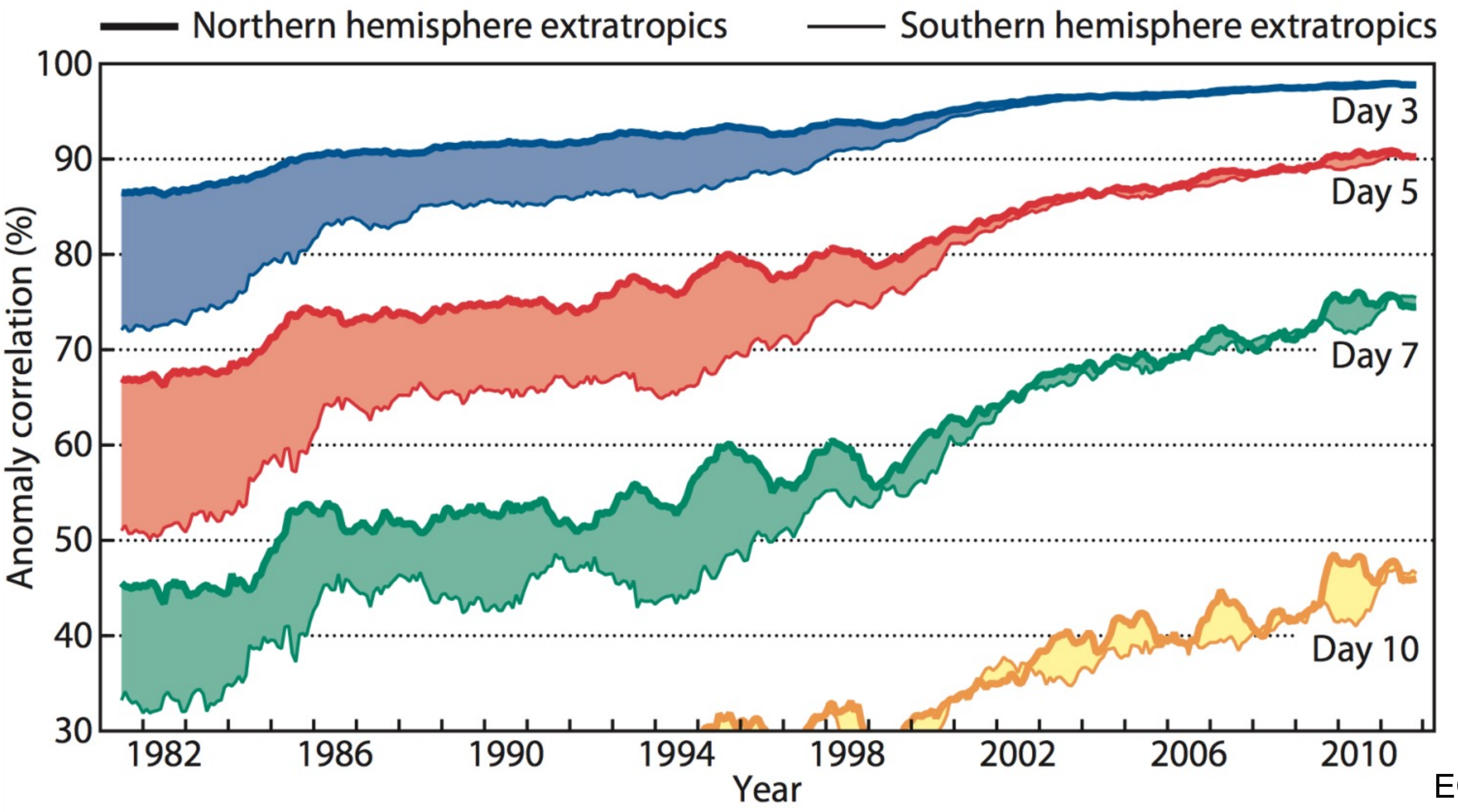
Polar-orbiting satellites



GNSS Radio Occultation



Global forecast improvement over time at ECMWF



ECMWF 2012

A – Assimilated; P – Passively monitored; E – Under evaluation; X – Failed or data excluded due to quality/transmission issues; 🌦 – All-sky treatment
Changes since ITSC-23 are highlighted through orange shading.

Satellite	Present orbit position (LTAN, approx.)	MW temperature sounder	MW humidity sounder	MW imager	IR broadband sounder or imager	IR hyper-spectral sounder
NOAA-15	19:30	A 🌦	X		X	
NOAA-18	22:30	A 🌦	X		X	
NOAA-19	20:30	A 🌦	A 🌦		P	
NOAA-20	13:30	A	A			A
NOAA-21	13:30	E	E			
Aqua	13:30	X	X			A
S-NPP	13:30	A	A			A
Metop-B	21:30	A 🌦	A 🌦		X	A
Metop-C	21:30	A 🌦	A 🌦			A
FY-3C	19:00	X	A 🌦	X		
FY-3D	14:00	P 🌦	A 🌦	P 🌦 & X		E
FY-3E	17:30	E 🌦	A 🌦			
DMSP-F17	18:30		A 🌦	A 🌦		
DMSP-F18	16:00		A 🌦	P 🌦 & E		
GCOM-W1	13:30			A 🌦		
GPM	Mid-incl.		A 🌦	A 🌦		
Meteosat-9	45.5°E				A	
Meteosat-11	0°				A	
GOES-16	75.2°W				A	
GOES-18	137°W				A	
Himawari-9	140.7°E				A	
FY-4A	104.7°E					E
FY-4B	133°E					E

Current status (2023) of satellite radiance DA at ECMWF

Niels Bormann, ITSC-24

Satellite instruments/sensors

Types of sensors

- Passive
- Active
- Radio Occultation

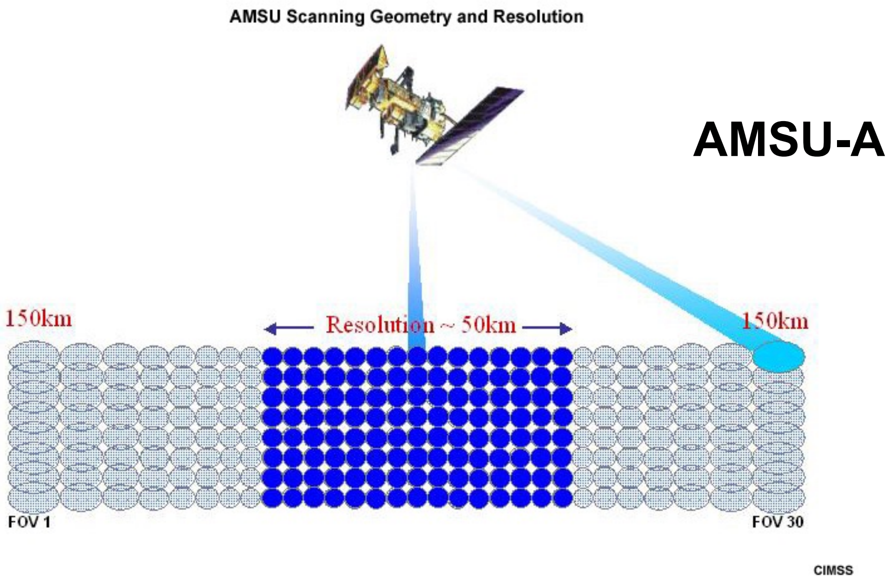
Scan strategies and viewing geometry affect coverage and field-of-view (FOV) resolution

<u>cross-track scan</u>

- Resolution degrades toward the edge of the swath because the viewing angle changes across the swath

<u>conical scan</u>

- Constant ground resolution
- Generally narrower swaths than cross-track scan swaths



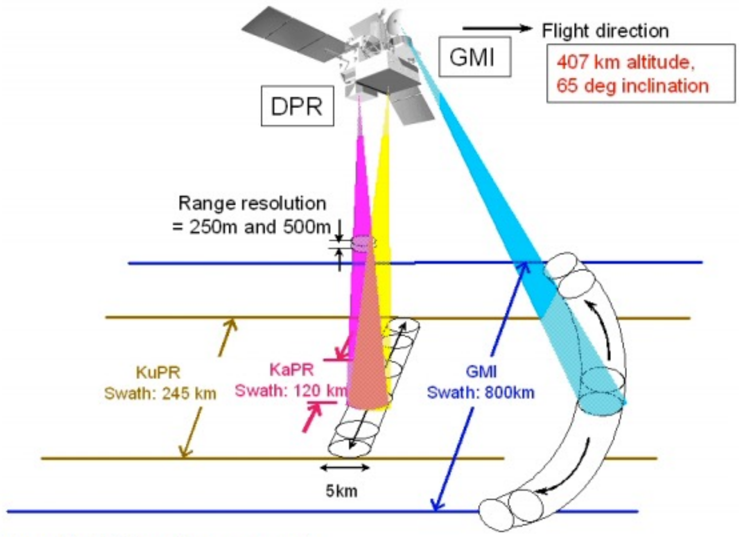
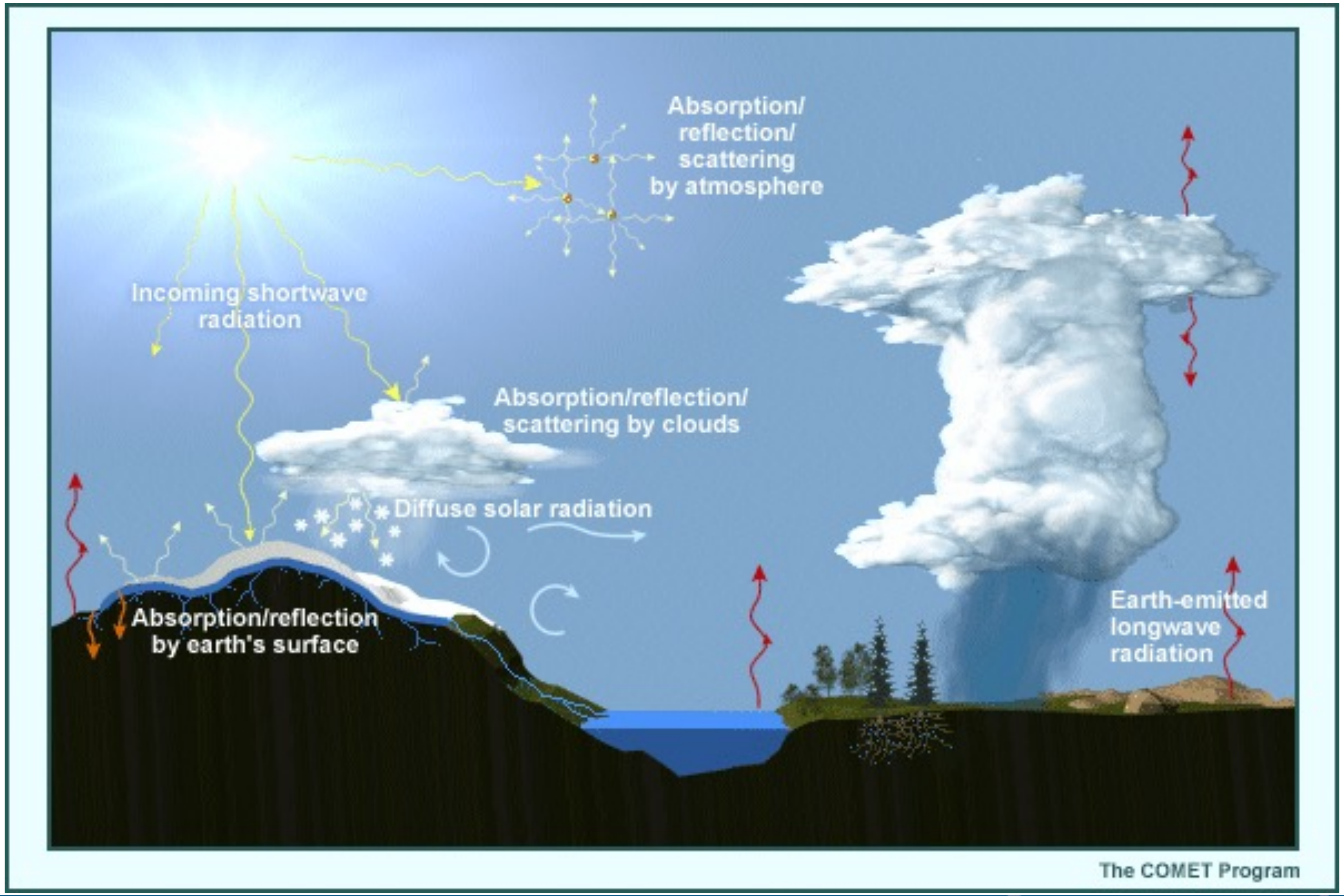


Figure 2. GPM swath measurements

What do satellite instruments measure?

- **Satellite passive sensors** observe radiation emitted and scattered from Earth's surface and atmosphere at discrete wavelength intervals



Passive Sensors from Weather/Environment Satellites

AMSU-A
AMSU-B
MHS
SSMI
SSMIS
ATMS
TMI
AMSR-E
AMSR-2
GMI

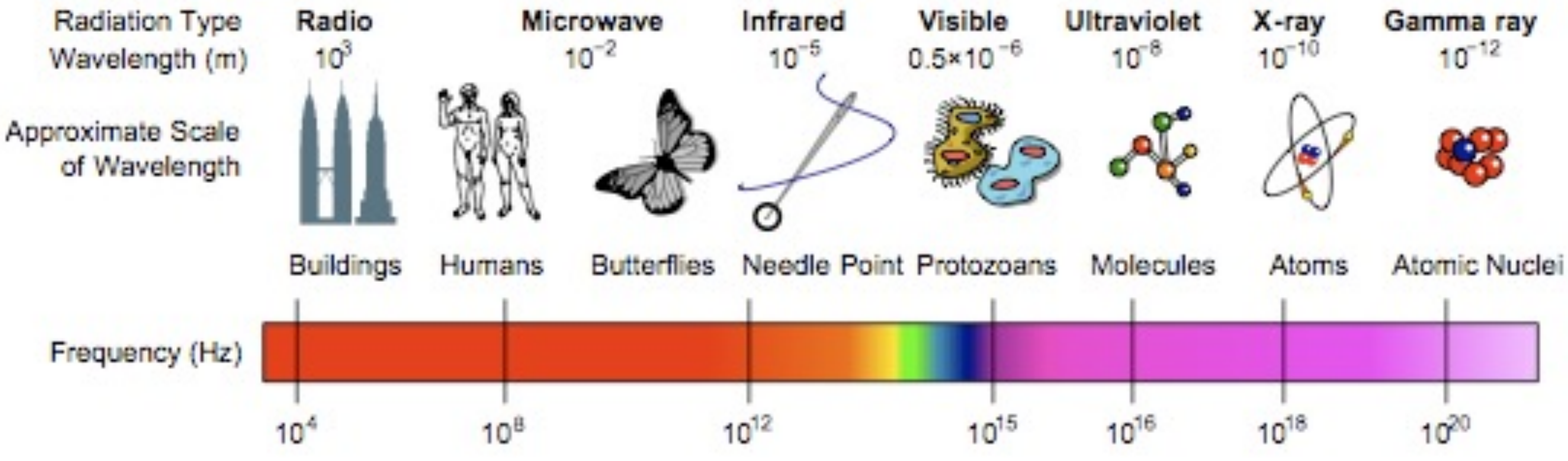
AHI
ABI

HIRS
AIRS
IASI
CrIS

AVHRR
MODIS
VIIRS

SBUV

Different sensors measure radiation at different wavelengths (e.g., microwave, Infrared, visible)



Electromagnetic Spectrum

What is radiance?

- Radiance (L) is the amount of energy per unit area per unit time per unit solid angle emitted at a wavelength λ (or frequency v)
  - Recall, $c = \lambda v$, where c is the speed of light.
- Physically, can think of radiance as the "brightness" of an object
- Radiance is related to geophysical atmospheric variables by the radiative transfer equation
- Radiances are often converted to **brightness temperature** (equivalent blackbody temperature, by inverting Plank function)

Liou 2002.

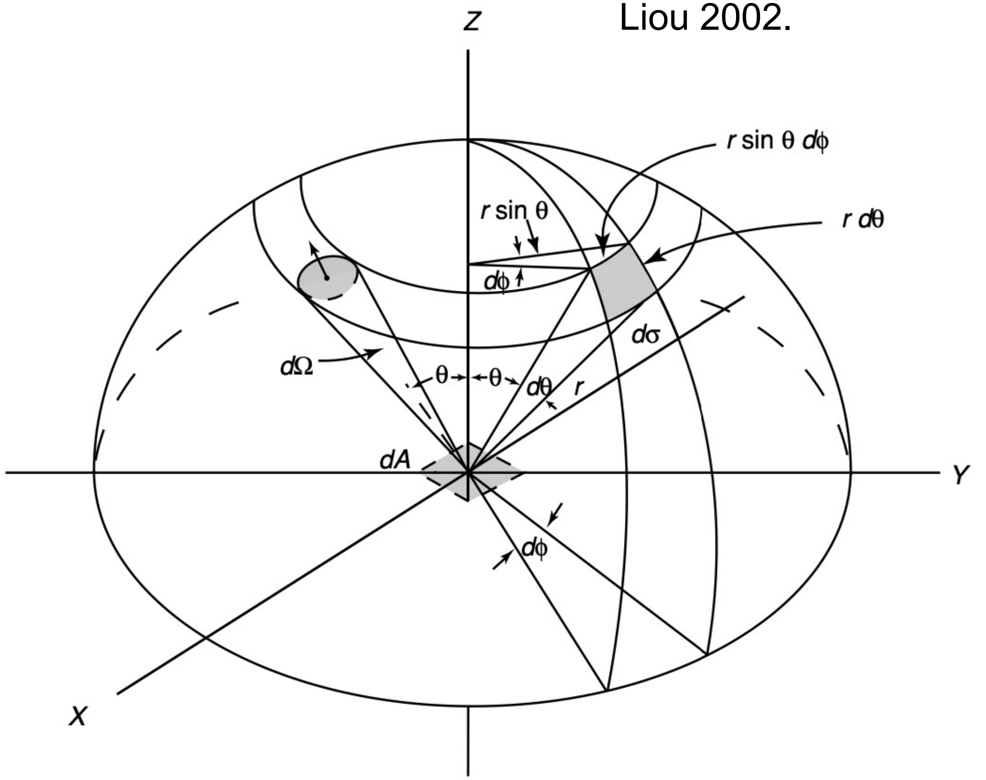


Figure 1.3 Illustration of a differential solid angle and its representation in polar coordinates. Also shown for demonstrative purposes is a pencil of radiation through an element of area dA in directions confined to an element of solid angle $d\Omega$. Other notations are defined in the text.

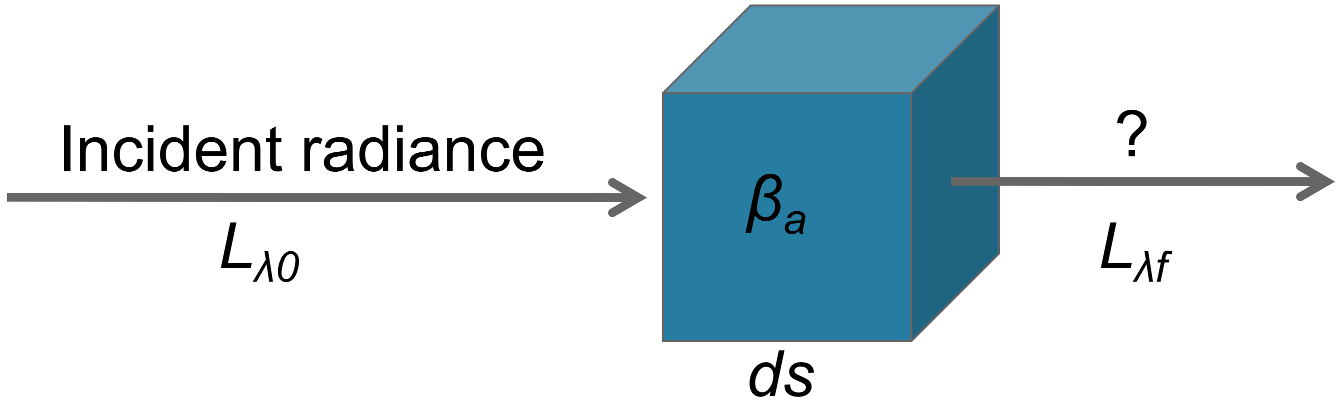
Hence, the differential solid angle is

$$d\Omega = d\sigma/r^2 = \sin\theta \, d\theta \, d\phi, \qquad (1.1.5)$$

where θ and ϕ denote the zenith and azimuthal angles, respectively, in polar coordinates.

Atmospheric Transmittance

- Consider radiation at wavelength λ with radiance $L_{\lambda 0}$ incident upon an absorbing medium of thickness *ds*
  - Use an absorption coefficient (β_a ; units m^{-1}) to quantify degree of absorption
- Ignore emission from the medium and scattering
- What is the radiance on the other side of the surface?



Atmospheric Transmittance

- Beer's Law gives the amount of radiation emerging from the material:

$$L_{\lambda f} = L_{\lambda 0} \exp\left[-\int_{s_1}^{s_2} \beta_a(s)\,ds \right]$$

- The ratio of the amount of radiation that emerges from the cube to the amount that entered is the transmittance:

$$\tau_\lambda = \frac{L_{\lambda f}}{L_{\lambda 0}} = \exp\left[-\int_{s_1}^{s_2} \beta_a(s)\,ds \right]$$

- Transmittance in the real atmosphere varies in space (especially in the vertical) and time

- Letting a_λ denote the absorption of the medium at wavelength λ, then in the absence of scattering

$$a_\lambda + \tau_\lambda = 1$$

Radiative Transfer

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz + \text{Surface} + \text{Cloud/Rain Aerosol}$$

TOA radiance at frequency ν

Planck function

Atmospheric Absorption (weighting function)

Emission/reflection

Diffusion/scattering

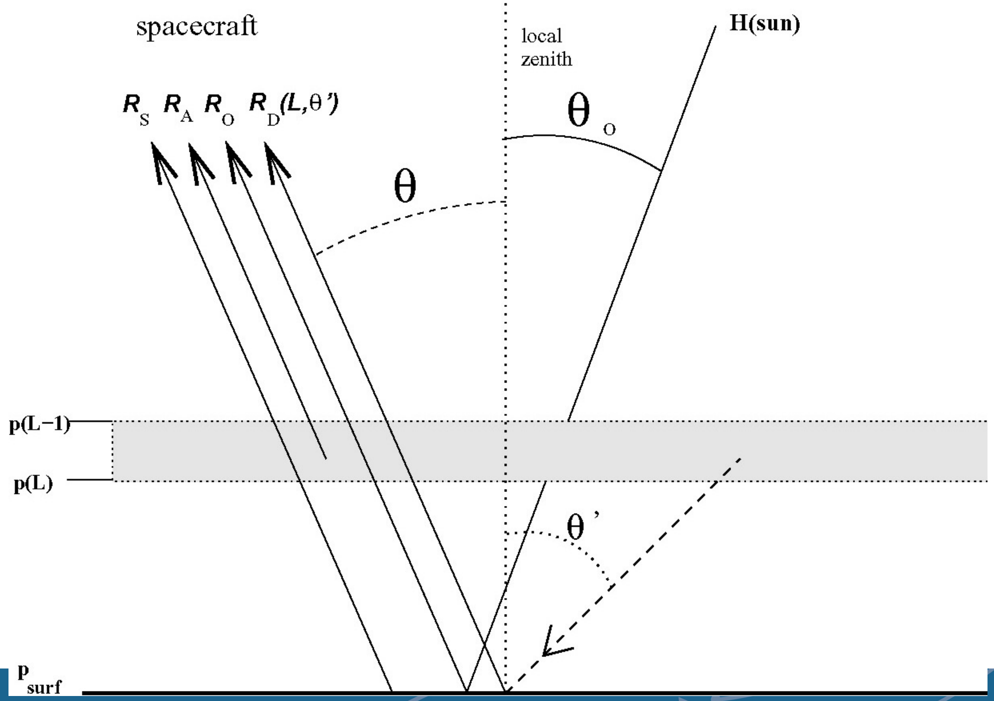
Surface emission R_s

Up-welling atmosphere emission R_A

Reflected solar radiation R_O

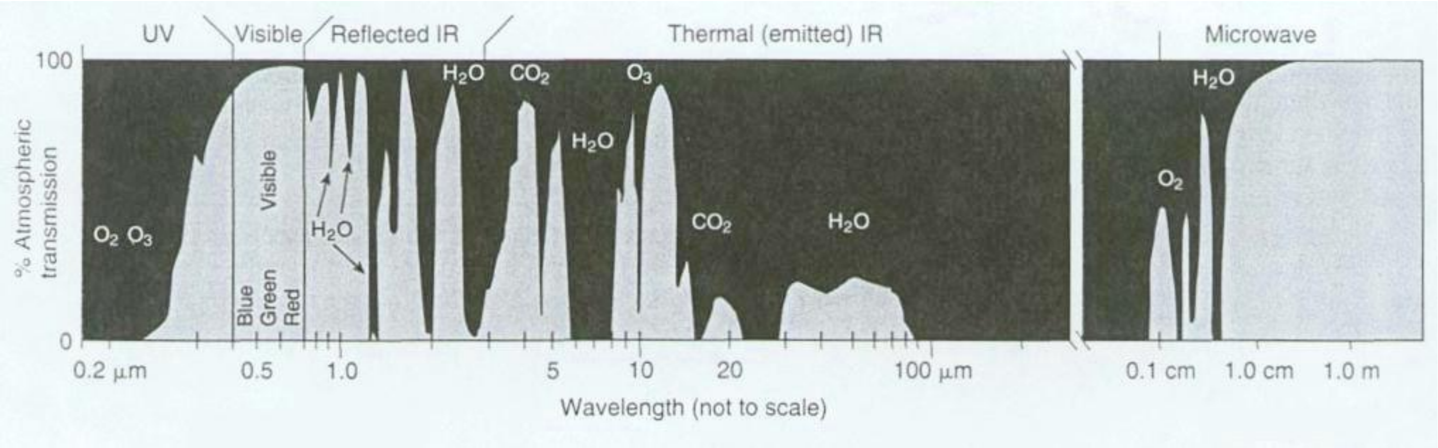
Down-welling & reflected atmos.

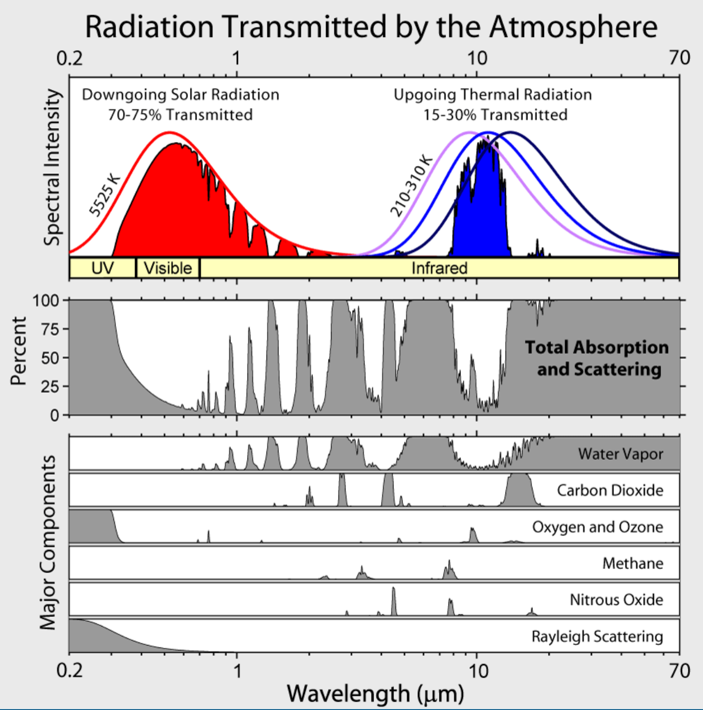
Emission (R_D)

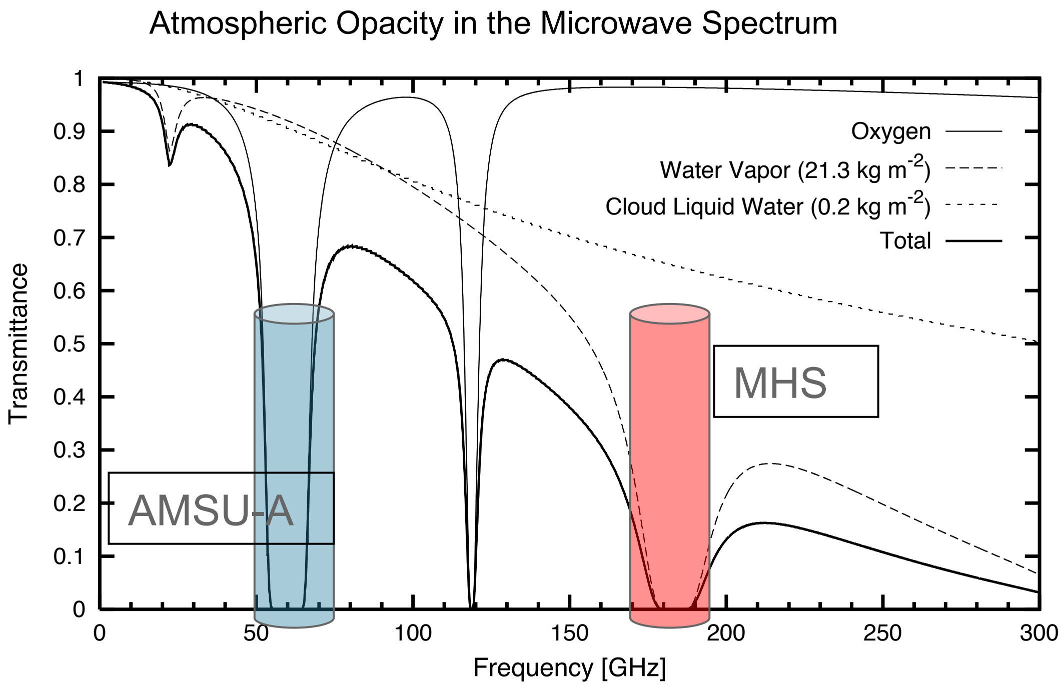


Atmospheric gas absorption-transmission

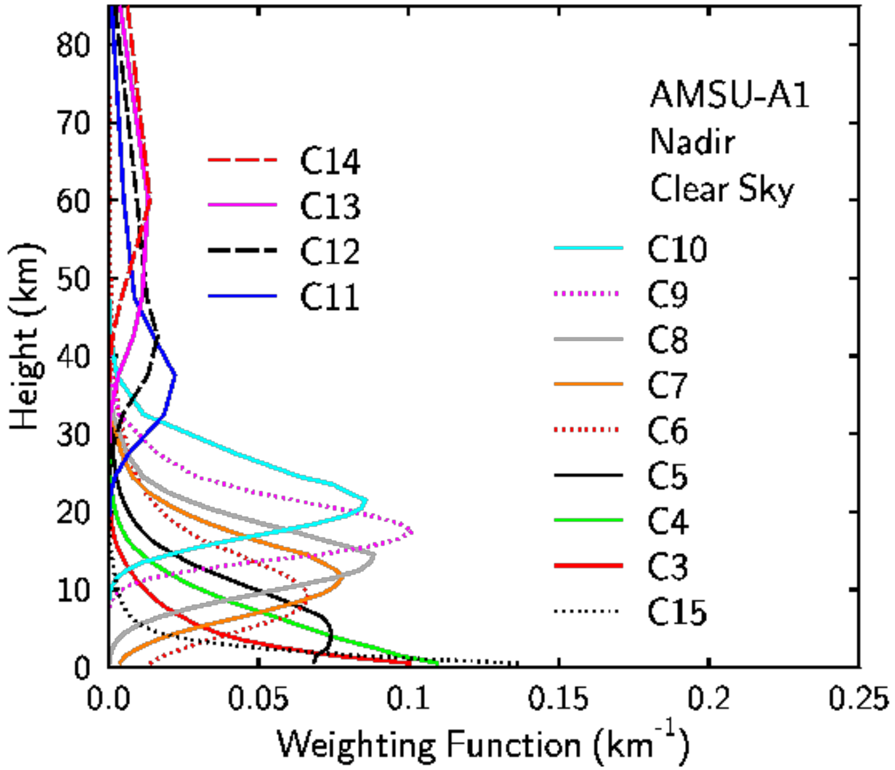
Satellite sensors are designed to make use of the frequency-dependent atmospheric absorption







Weighting functions



Weighting functions indicate the contribution to the outgoing radiance from various layers of the atmosphere

Weighting functions are frequency (channel) dependent

<u>Channel selection for NWP data assimilation</u>

- **Atmospheric sounding channels** (measured radiance has no contribution from the surface)
- **Window channels** are sensitive to properties associated with earth and ocean surfaces as well as clouds

yaml setting for radiative transfer model

```yaml
_clear crtm: &clearCRTMObsOperator
  name: CRTM
  SurfaceWindGeoVars: uv
  Absorbers: [H2O, O3]
  linear obs operator:
    Absorbers: [H2O]
  obs options: &CRTMObsOptions
    EndianType: little_endian
    CoefficientPath: ./crtm_coeffs_v2/
    IRVISlandCoeff: USGS
```

```yaml
- obs space:
    <<: *ObsSpace
    name: amsua_n18
    obsdatain:
      engine:
        type: H5File
        obsfile: ./amsua_n18_obs_2018041500.h5
    obsdataout:
      engine:
        type: H5File
        obsfile: ./obsout_da_amsua_n18.h5
    simulated variables: [brightnessTemperature]
    channels: &amsua_n18_channels 1-15
  obs error: *ObsErrorDiagonal
  obs operator:
    <<: *clearCRTMObsOperator
    obs options:
      <<: *CRTMObsOptions
      Sensor_ID: amsua_n18
  get values:
```

Settings for channel selection and quality control

```yaml
obs filters:
- filter: PreQC
  maxvalue: 0
#  Useflag check #amsua-n18
- filter: Bounds Check
  filter variables:
  - name: brightnessTemperature
    channels: *amsua_n18_channels
  test variables:
  - name: ObsFunction/ChannelUseflagCheckRad
    channels: *amsua_n18_channels
    options:
      channels: *amsua_n18_channels
      use_flag: [-1, -1, -1, -1,  1,
                  1,  1,  1,  1, -1,
                 -1, -1, -1, -1, -1 ]
  minvalue: 1.0e-12
  action:
    name: reject
- filter: Background Check
  threshold: 3.0
  <<: *multiIterationFilter
```

Much more you can set
for quality control, but not able
to cover too much this time

Variational Bias Correction (VarBC)

Modeling errors for satellite radiances:

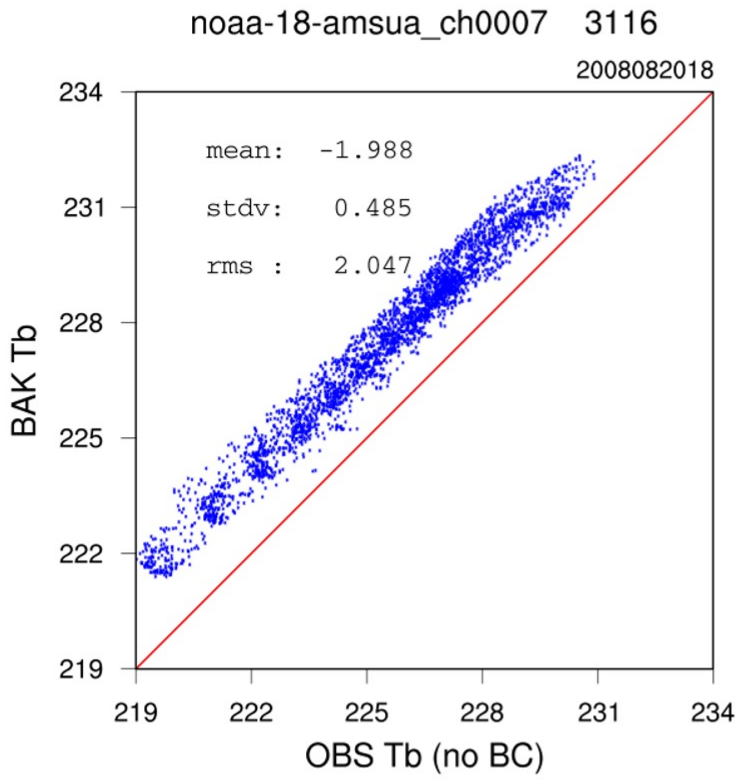
$$y = H(x_t) + B(\beta) + \varepsilon$$

$$\langle \varepsilon \rangle = 0$$

$$B(\beta) = \sum_{i=1}^{N} \beta_i p_i$$

Bias-correction coefficients

Predictors: e.g.,
- **Offset (i.e., 1)**
- **Temperature lapse rate**
- **Scan, Scan^2, Scan^3**



J_b: background term for x

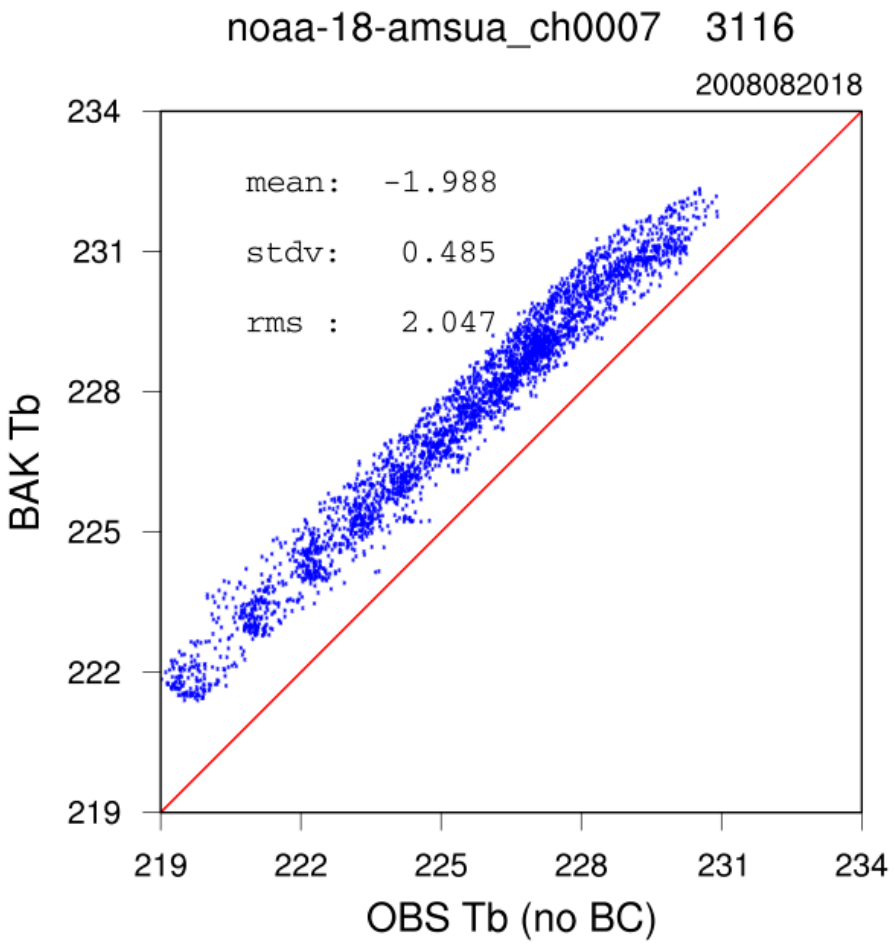
J_o: corrected observation term

$$\mathbf{J}(\mathbf{x},\beta) = (\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1} (\mathbf{x}_b - \mathbf{x}) + [\mathbf{y} - H(\mathbf{x}) - B(\beta)]^T \mathbf{R}^{-1} [\mathbf{y} - H(\mathbf{x}) - B(\beta)]$$

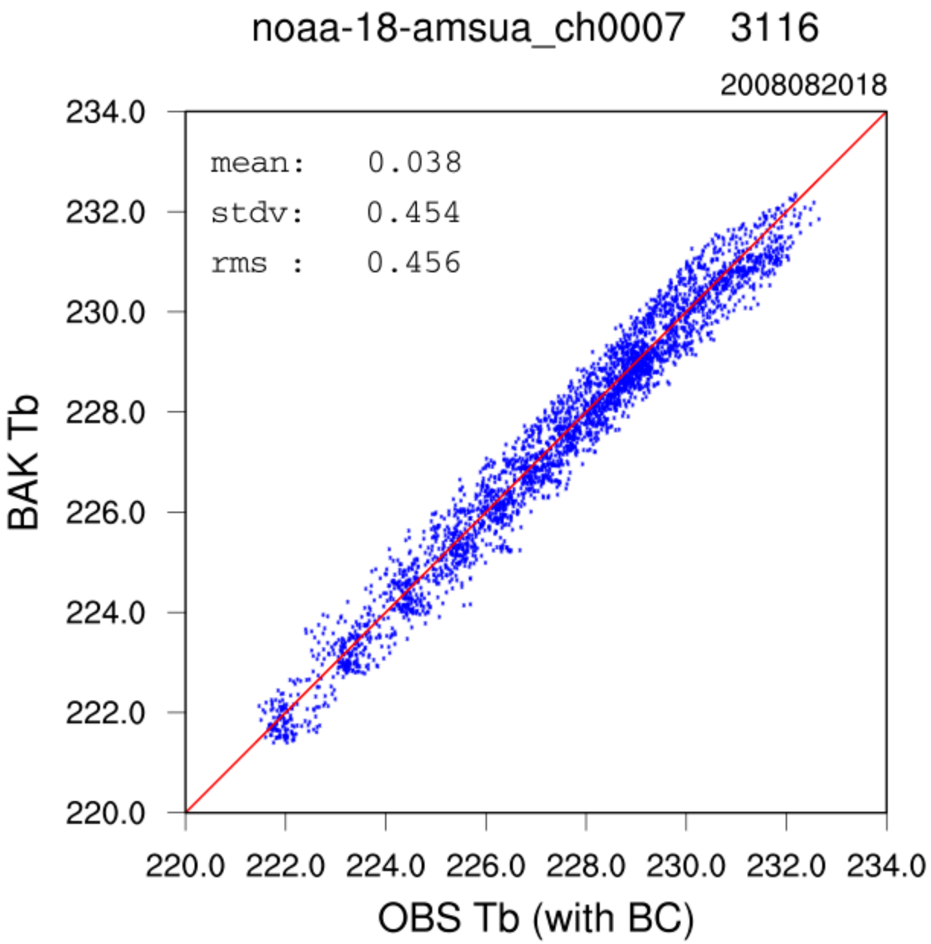
$$+ (\beta_b - \beta)^T \mathbf{B}_\beta^{-1} (\beta_b - \beta)$$

J_p: background term for β

Bias Correction



No bias correction



With bias correction

NCAR | UCAR

```
netcdf satbias_amsua_n18 {
dimensions:
        nchannels = 15 ;
        npredictors = 12 ;
variables:
        float bias_coeff_errors(npredictors, nchannels) ;
        float bias_coefficients(npredictors, nchannels) ;
        int channels(nchannels) ;
        int nchannels(nchannels) ;
                nchannels:suggested_chunk_dim = 15LL ;
        int npredictors(npredictors) ;
                npredictors:suggested_chunk_dim = 12LL ;
        float number_obs_assimilated(nchannels) ;
        string predictors(npredictors) ;

// global attributes:
                string :_ioda_layout = "ObsGroup" ;
                :_ioda_layout_version = 0 ;
```

```
predictors = "constant", "zenith_angle", "cloud_liquid_water",
   "lapse_rate_order_2", "lapse_rate",
   "cosine_of_latitude_times_orbit_node", "sine_of_latitude", "emissivity",
   "scan_angle_order_4", "scan_angle_order_3", "scan_angle_order_2",
   "scan_angle" ;
```

JEDI's bias correction coefficient file

yaml setting for VarBC

```yaml
obs bias:
  input file: {{biasCorrectionDir}}/satbias_amsua_n18.h5
  output file: {{OutDBDir}}{{MemberDir}}/satbias_amsua_n18.h5
  variational bc:
    predictors: &predictors3
    - name: constant
    - name: lapse_rate
      order: 2
      tlapse: &amsua18tlap {{fixedTlapmeanCov}}/amsua_n18_tlapmean.txt
    - name: lapse_rate
      tlapse: *amsua18tlap
    - name: emissivity
    - name: scan_angle
      order: 4
    - name: scan_angle
      order: 3
    - name: scan_angle
      order: 2
    - name: scan_angle
 covariance:
   minimal required obs number: 20
   variance range: [1.0e-6, 10.]
   step size: 1.0e-4
   largest analysis variance: 10000.0
   prior:
     input file: {{biasCorrectionDir}}/satbias_cov_amsua_n18.h5
     inflation:
       ratio: 1.1
       ratio for small dataset: 2.0
   output file: {{OutDBDir}}{{MemberDir}}/satbias_cov_amsua_n18.h5
```

$$B(\beta) = \sum_{i=1}^{N} \beta_i p_i$$

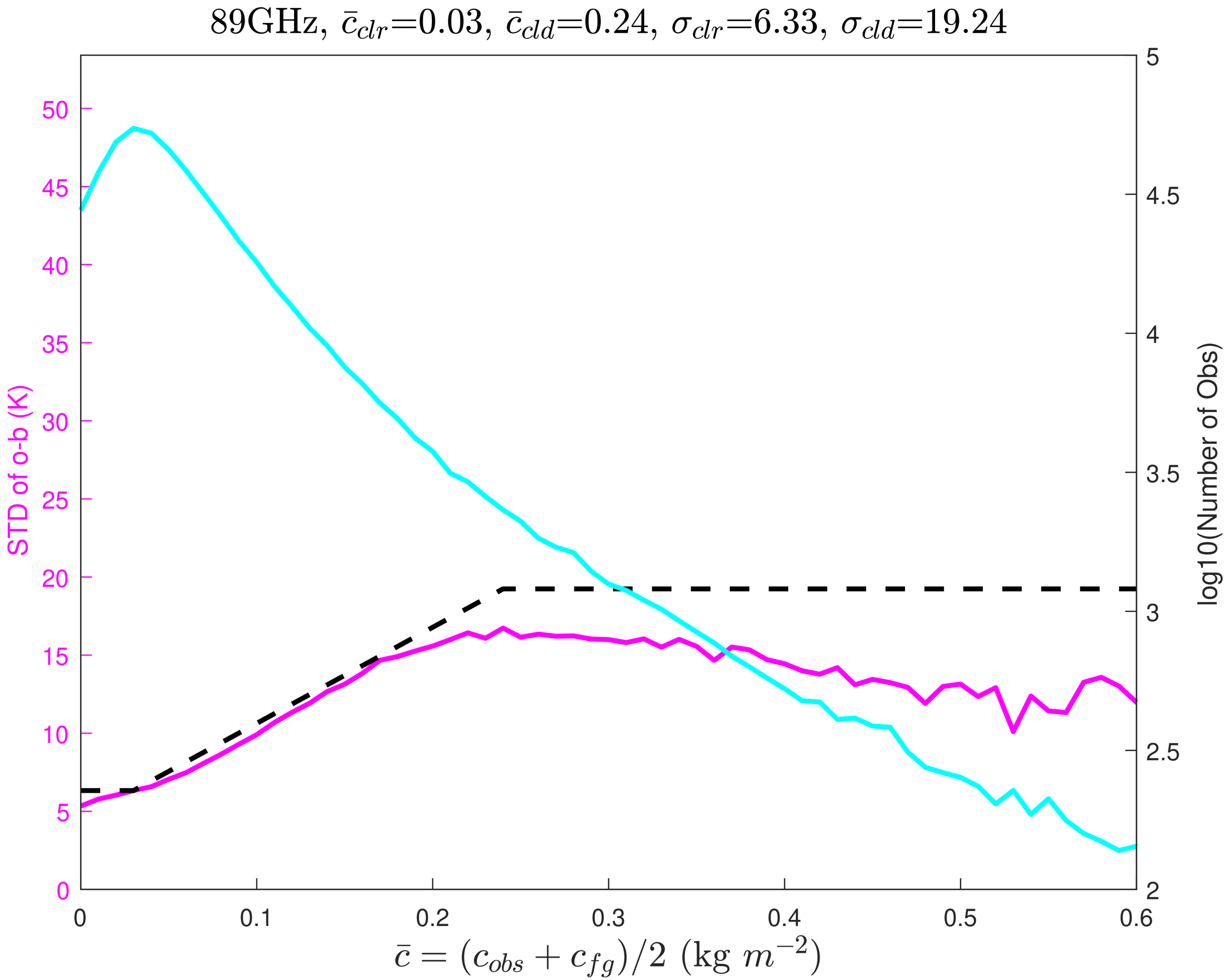
$\mathbf{J}_b$: background term for x

$\mathbf{J}_o$: corrected observation term

$$\mathbf{J}(\mathbf{x},\beta) = (\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1} (\mathbf{x}_b - \mathbf{x}) + [\mathbf{y} - H(\mathbf{x}) - B(\beta)]^T \mathbf{R}^{-1} [\mathbf{y} - H(\mathbf{x}) - B(\beta)]$$
$$+ (\beta_b - \beta)^T \mathbf{B}_\beta^{-1} (\beta_b - \beta)$$

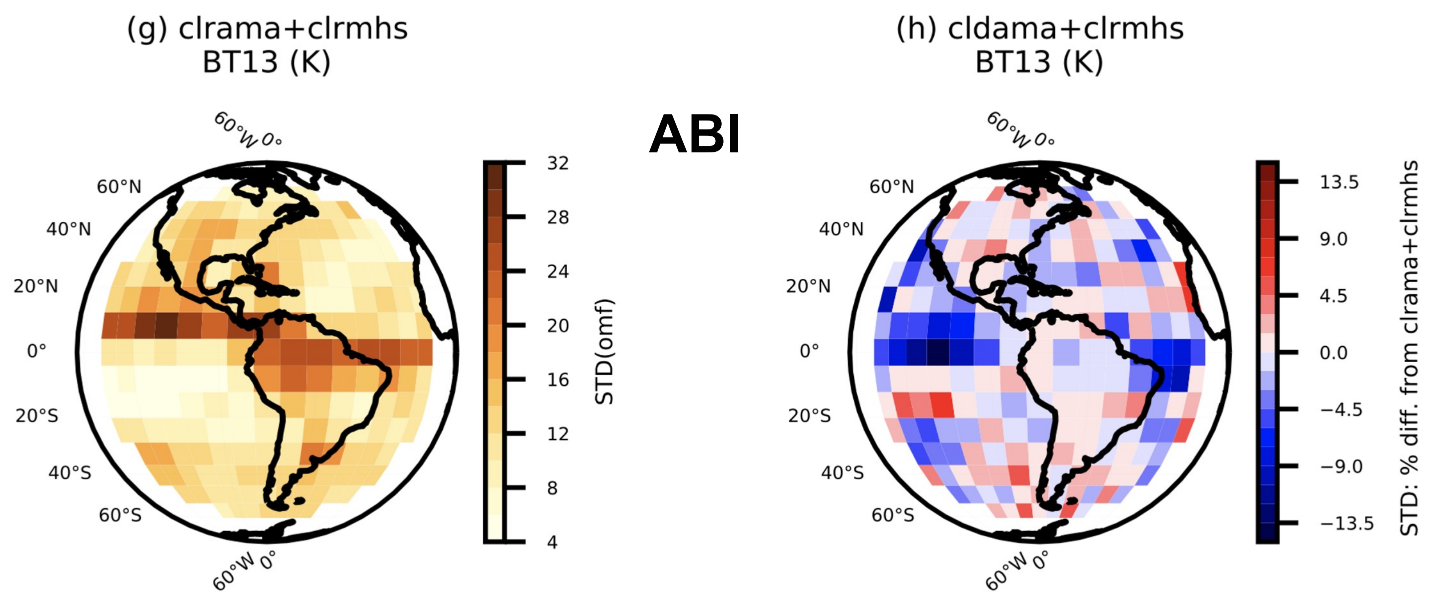
$\mathbf{J}_p$: background term for β

Situation-dependent all-sky obs error model

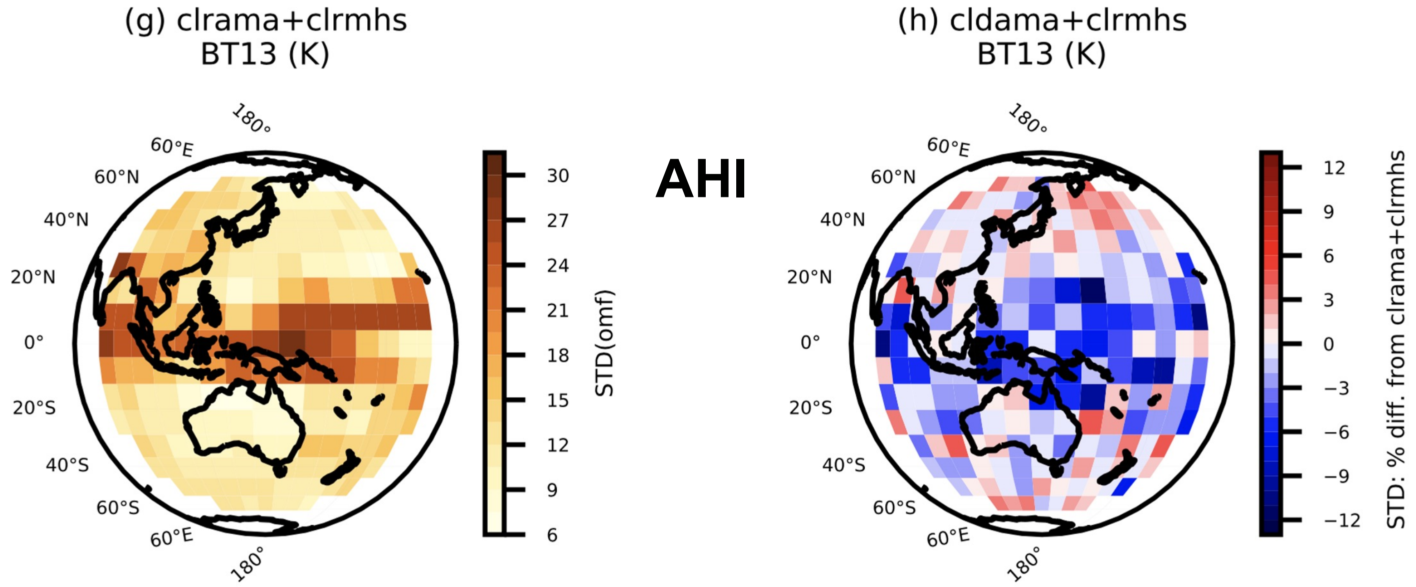


All-sky obs error model for AMSU-A ch15:

Obs error is a function of cloud liquid water path retrieved from channel 1 and 2's brightness temperature



ABI



AHI

Added value of all-sky AMSU-A

Day-1 forecast

Error STD reduction

Improvement concentrated in cloudy regions of Tropics
Up to 12-14%

Concluding Remarks

- Radiance DA is complex
  - Cloudy radiative transfer, QC, bias correction, all-sky obs error model
  - Different complexity for assimilating different sensors' data
- Much more to explore for satellite DA in general
  - Visible band, near IR, active sensors, small satellites, …
- JEDI framework allows much greater flexibility to configure/tune without code change, ease science discovery
  - e.g., you can combine the use of CRTM and RTTOV in the same run!