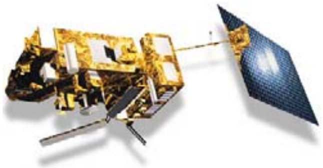
Special : Satellite Data

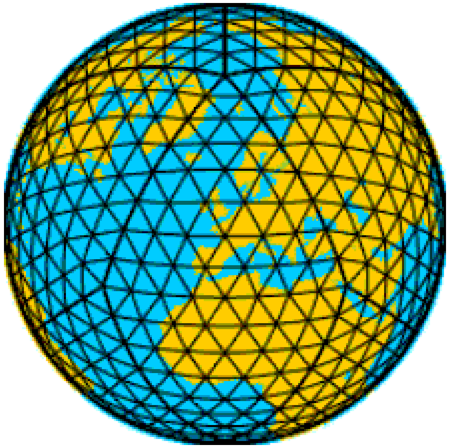
Part I: Introduction to satellite observations for NWP

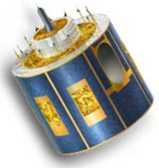
Christina Köpken-Watts, Robin Faulwetter

Data assimilation FE12/Satellite data



Part II: Processing and assimilation of satellite radiances (at DWD)





Robin Faulwetter, Christina Köpken-Watts
Data assimilation FE12/Satellite data

Outline

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

The path of a satellite measurement through a NWP model

I. **Measurement and transmission to NWP centers**
   a) Satellite orbits
   b) Meteorological instruments, measurement principles
   c) Measurement geometry
   d) Transmission of data to earth
   e) Level-0 preprocessing
   f) Transmission to NWP center

II. **Pre-processing in DWD**
   a) Retrieve data from bank, conversion
   b) Quality control
   c) Mapping
   d) Further stuff

III. **Assimilation**
   a) Radiative transfer
   b) Bias correction
   c) Cloud detection
   d) Thinning/quality control
   e) Assimilation

IV. **Monitoring**

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IV. Monitoring

Satellite orbits: classification

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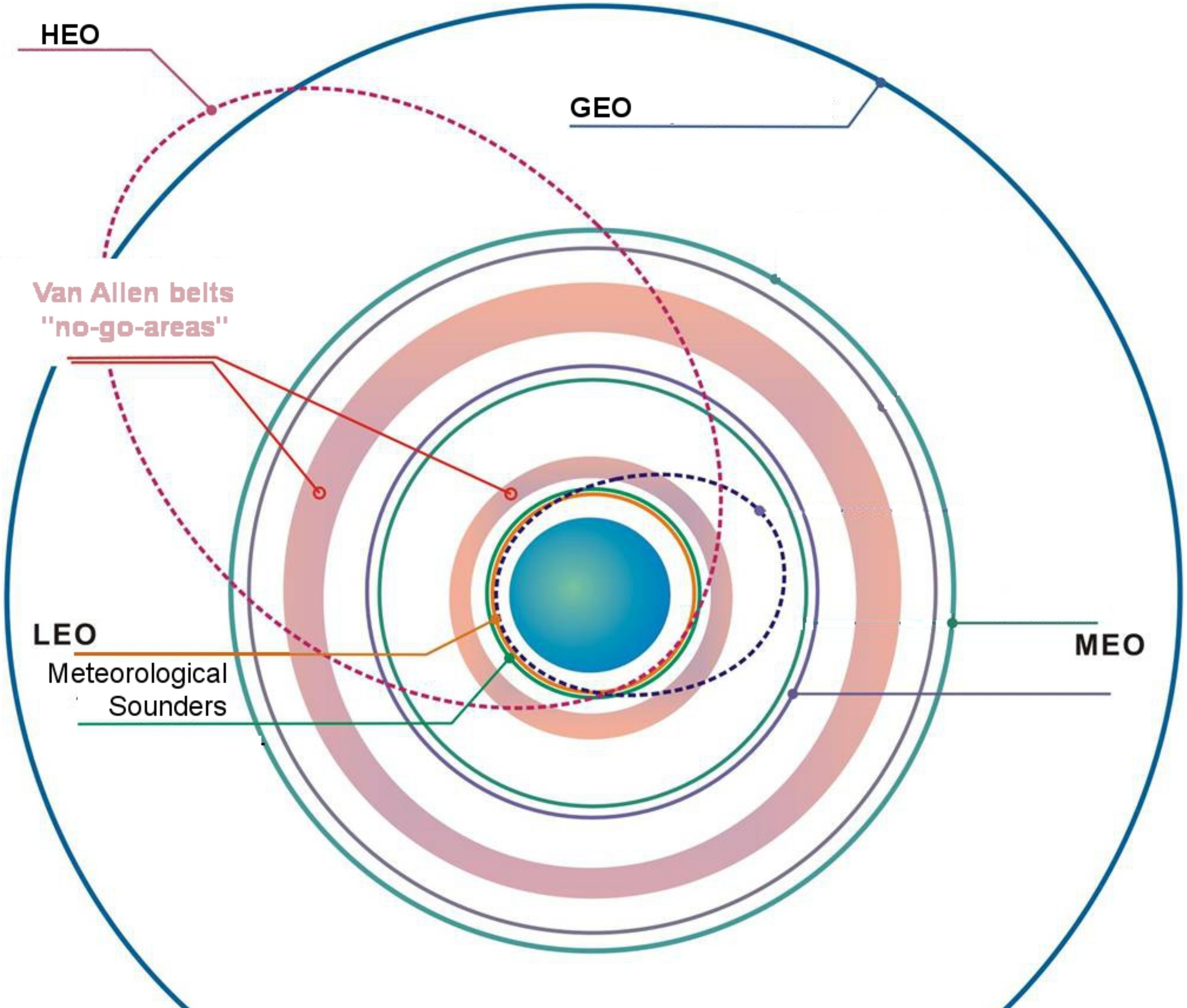


GEO (**Geo**-stationary orbit)
- Height ~ 36000km
- Period: 1 day

MEO (**M**edium **E**arth **O**rbit)
- Height: 1200 – 36000 km
- Period: ~ several hours

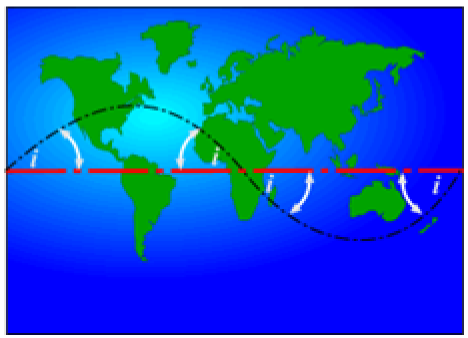
LEO (**L**ow **E**arth **O**rbit)
- Height: 200 – 1200 km
- Period: ~ 100 min

HEO (**H**ighly **E**lliptical **O**rbit)

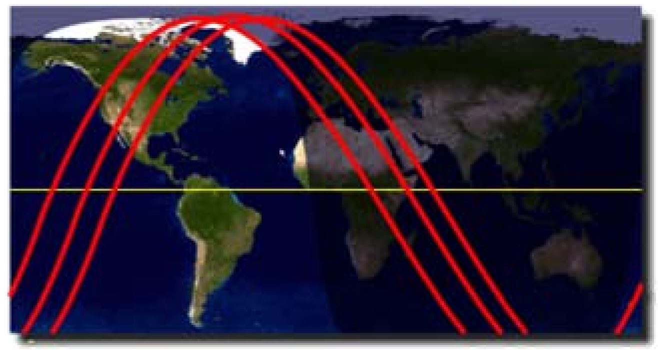
http://anityonugroho.blogspot.com/2011/04/satellite-communication-part-1.htm

Satellite orbits: LEO

In the absence of external forces satellite orbits are confined to fixed planes in an inertial system.
For LEO satellites the „orbital plane“ is usually inclined with respect to the equator.
i : inclination
i near to 90° → “polar orbiter“



Satellite track for a non-rotating Earth



Satellite tracks for the rotating Earth

As the Earth rotates, the satellite tracks move westwards.
Therefore, the satellite tracks cover a large fraction of the Earth.

http://www.asc-csa.gc.ca/eng/educators/resources/orbital/tracks_ground.asp

Satellite orbits: Sun Synchronous Orbit (SSO)

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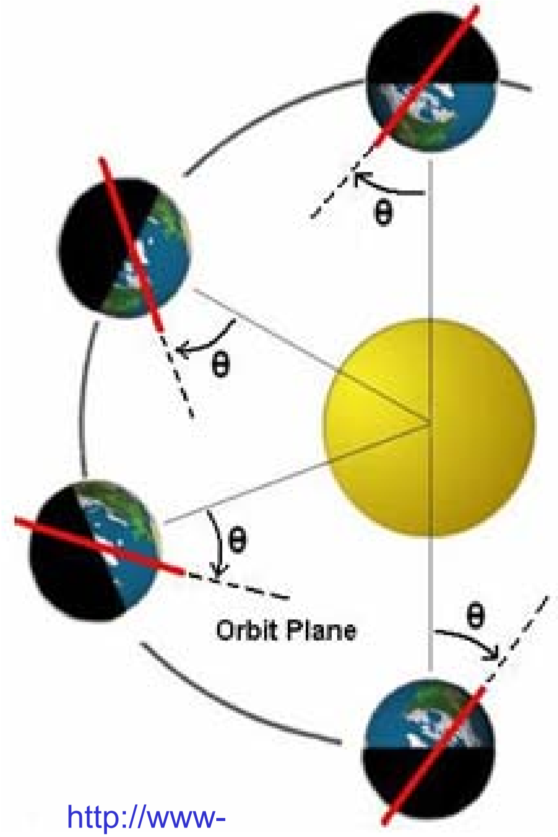
- Due to the Earths **extra mass near the equator**, orbits with inclinations > 0° are not fixed in the inertial system.
- They **precess** with a period that is determined by the height and inclination.
- If the precession period is one year, the orbit is **sun-synchronous**, i.e. the angle θ is fixed.

  The satellite crosses the equator at a fixed local time → **equator crossing time**

  - **Advantage**: solar effects are constant
  - **Disadvantage**: the diurnal cycle is not resolved.



http://www-personal.umich.edu/~mjregan/MCubed/Images/M-Cubed Photos/Extra/O&C/orbit1.PNG

Sun Synchrounous Orbit animation

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Meteorological instruments
Measurement principles

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Active:

- Radar
- Lidar
- Radiooccultations

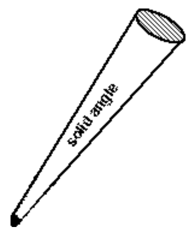
Passive:

- Radiance measurements
  - Resolution: Sounders, Imagers
  - Wavelength: Visible, Infrared, Microwave
  - Measurement principle: radiometers, interferometers

- AMVs (derived from radiance measurements)

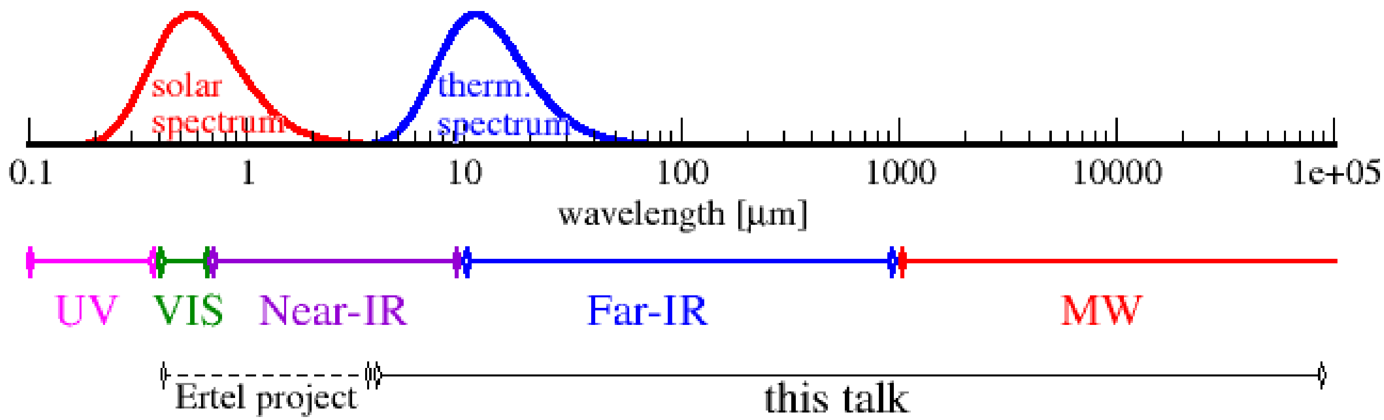
What is measured?

L : radiance in units of W / (m^2 cm sr)

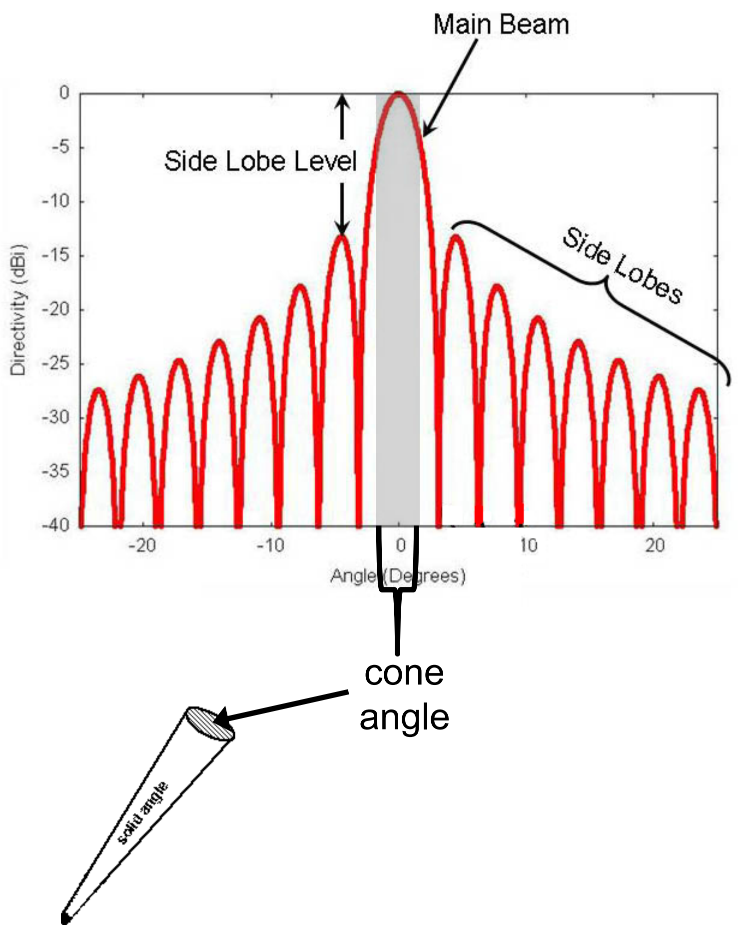


$$L = \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda k T_B}} - 1\right)}$$

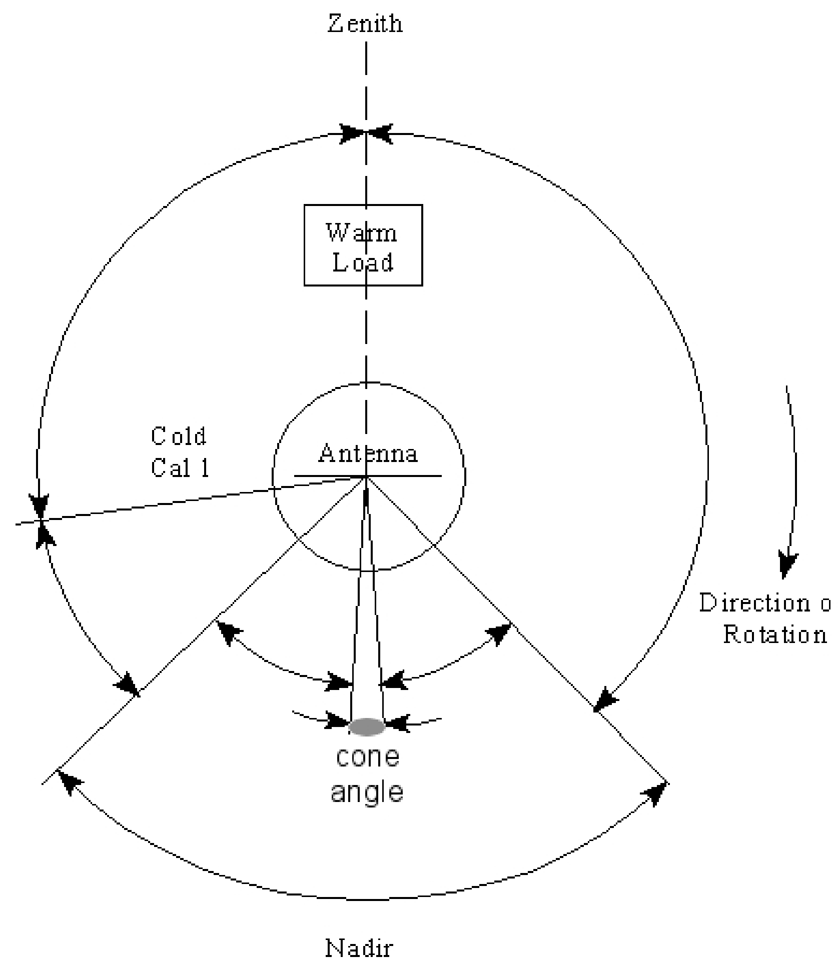
Brightness temperature



How is measured?



http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/podug/html/c1/sec1-1.htm



http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/klm/images/fj3-5.gif

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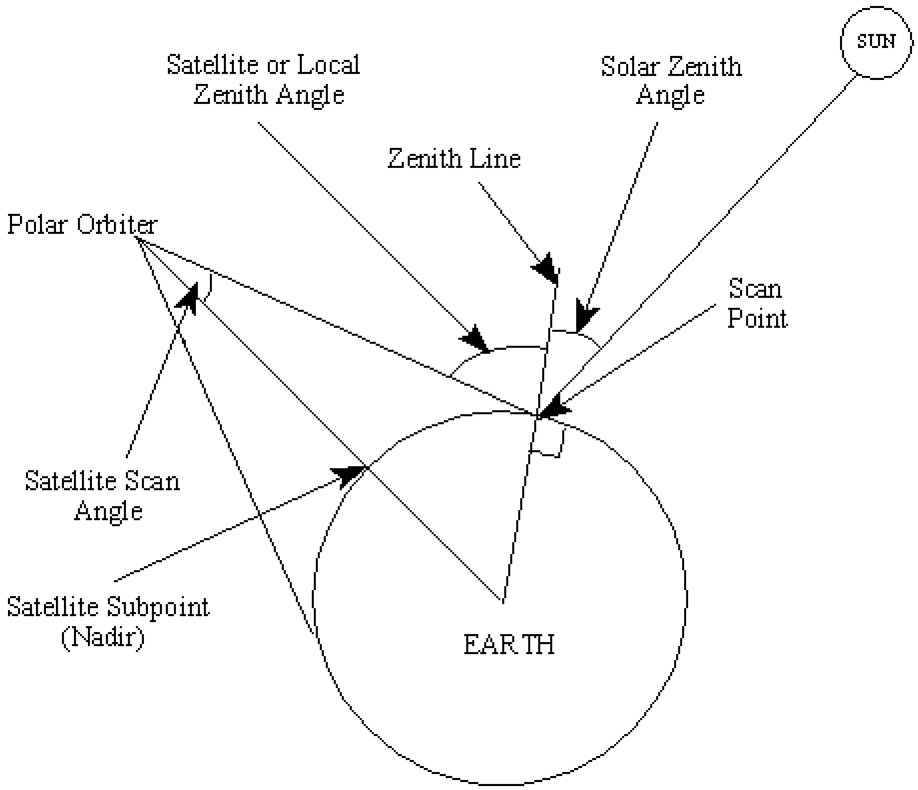
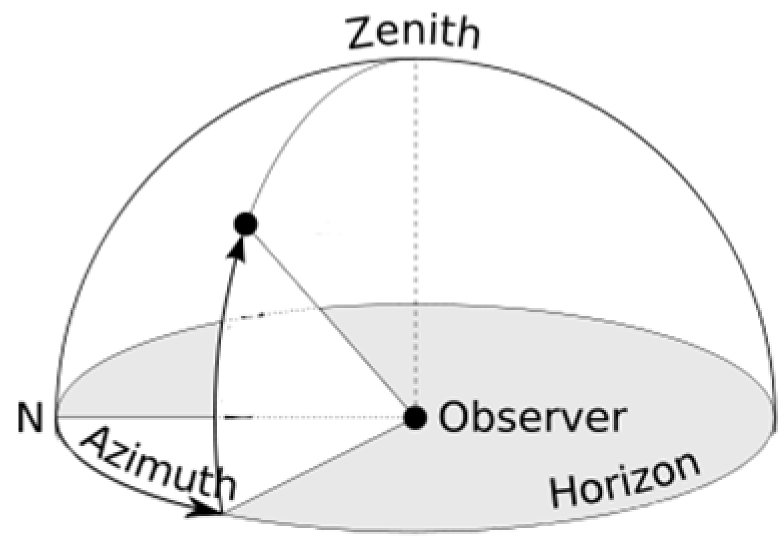
IV. Monitoring

Measurement geometry

Zenith and scan angle



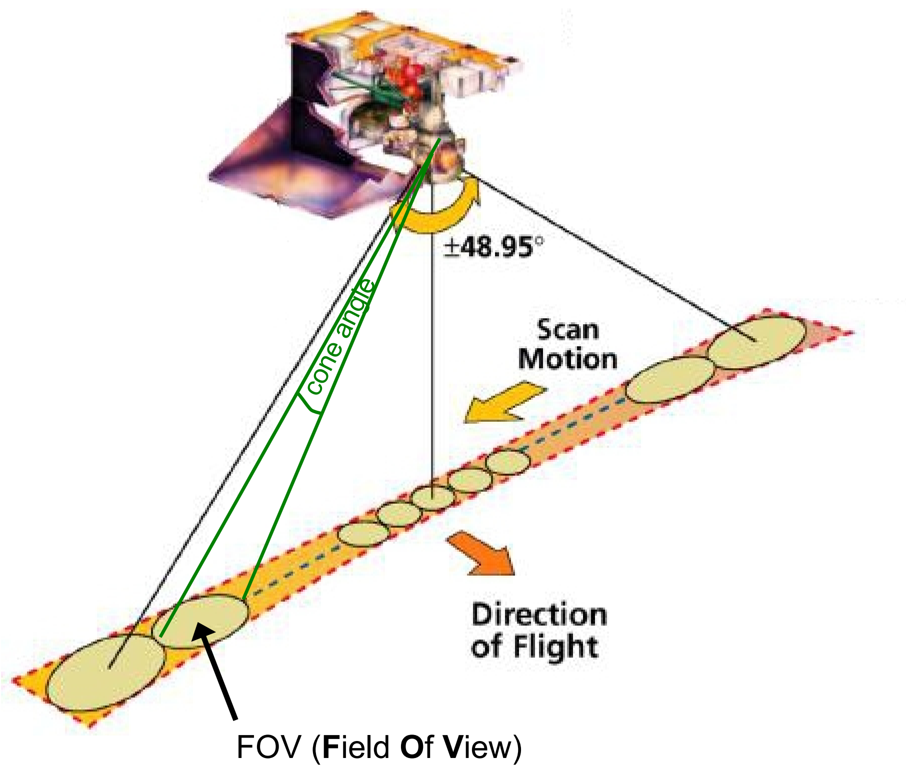
Azimuth angle



http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/podug/html/c1/sec1-1.htm

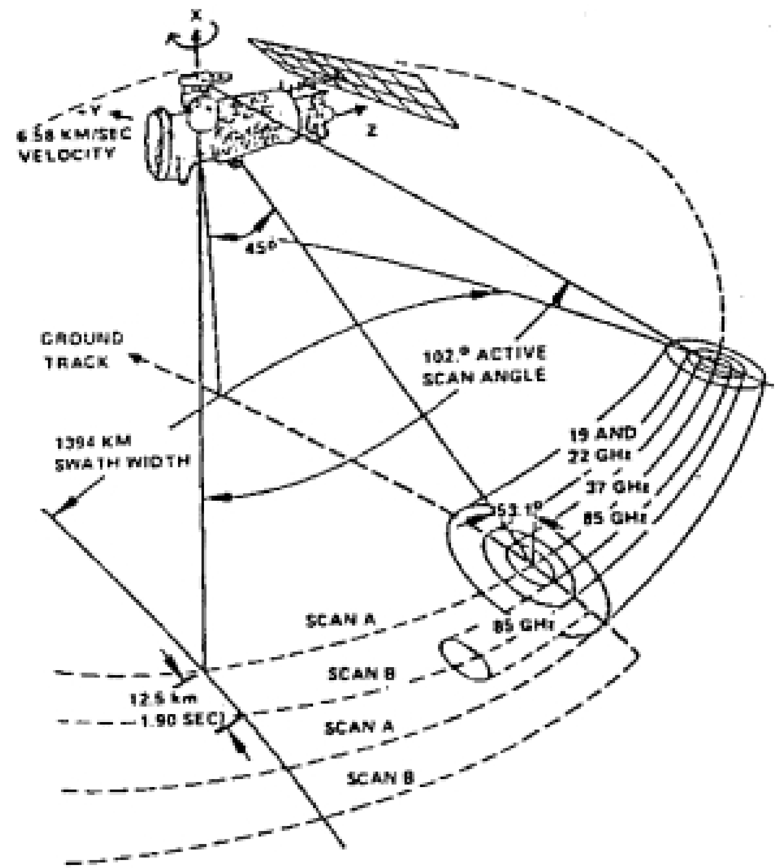
Measurement geometry

Across-track scan
(AMSU, IASI, ATMS, CrIS …)



http://www.star.nesdis.noaa.gov/smcd/spb/LANDEM/website/instr_AIRS.php

Conical scan
(SSMI/S)



http://www.star.nesdis.noaa.gov/smcd/spb/LANDEM/website/instr_SSMI.php

Measurement geometry

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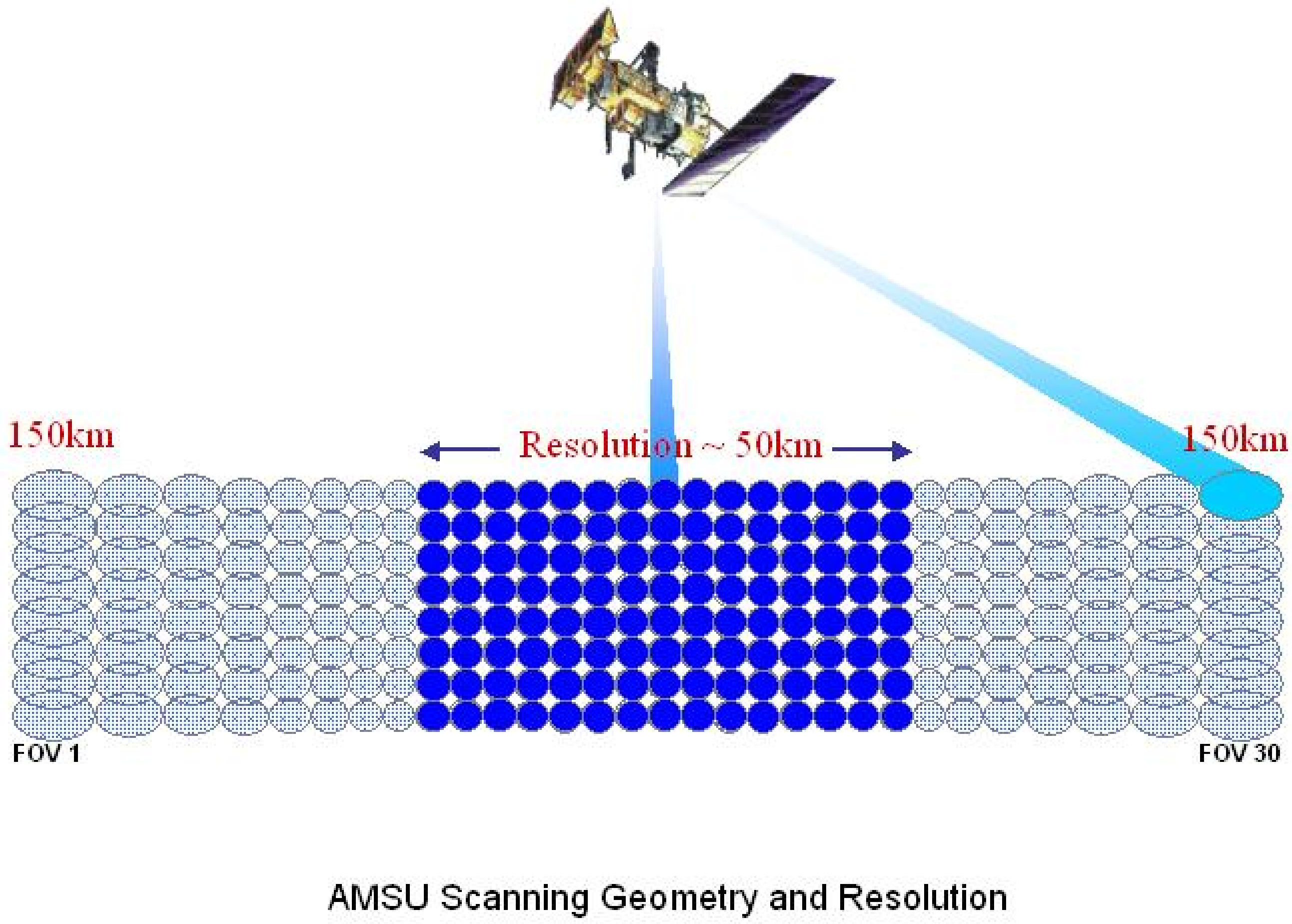

http://amsu.ssec.wisc.edu/explanation/amsua_scan_res.jpg

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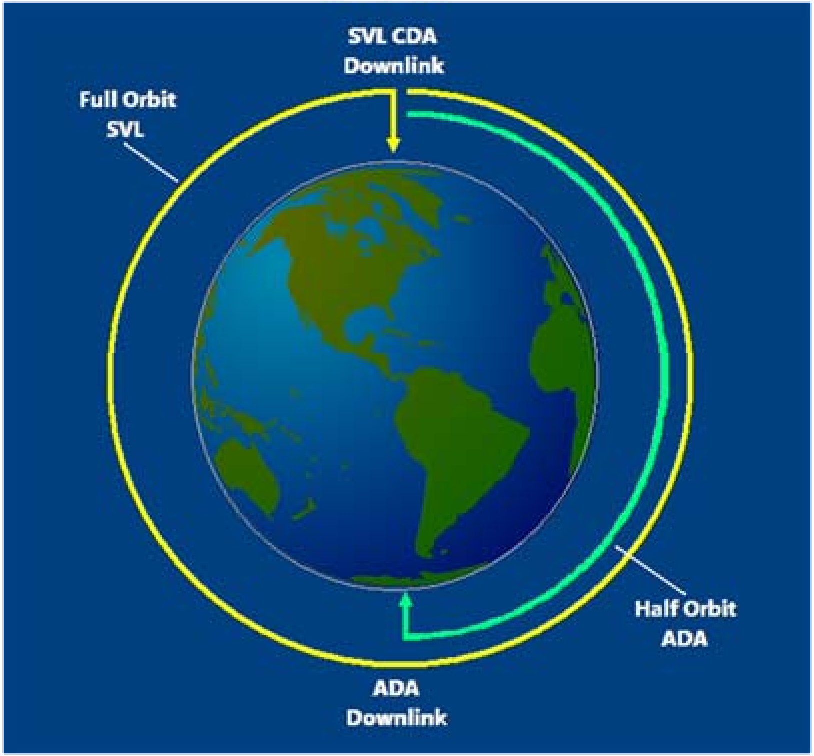
IV. Monitoring

Transmission of data to Earth

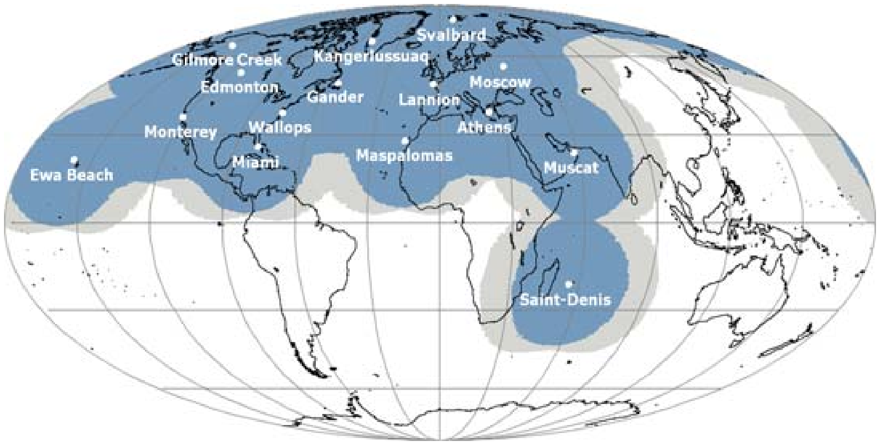
Complete global datasets



http://www.eumetsat.int/groups/ops/documents/image/img_ada_data_dump.org

Local datasets

RARS – Regional **A**dvanced **R**etransmission **S**ervice



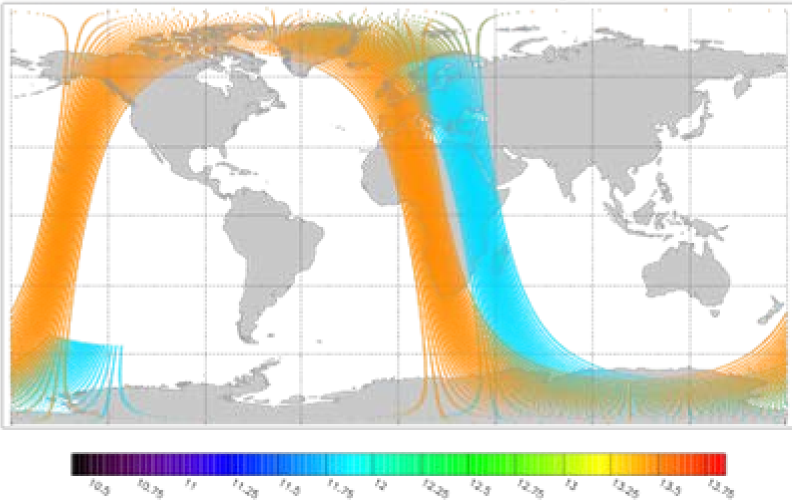
http://www.eumetsat.int/groups/public/documents/image/img_ears_atovs_news.jpg

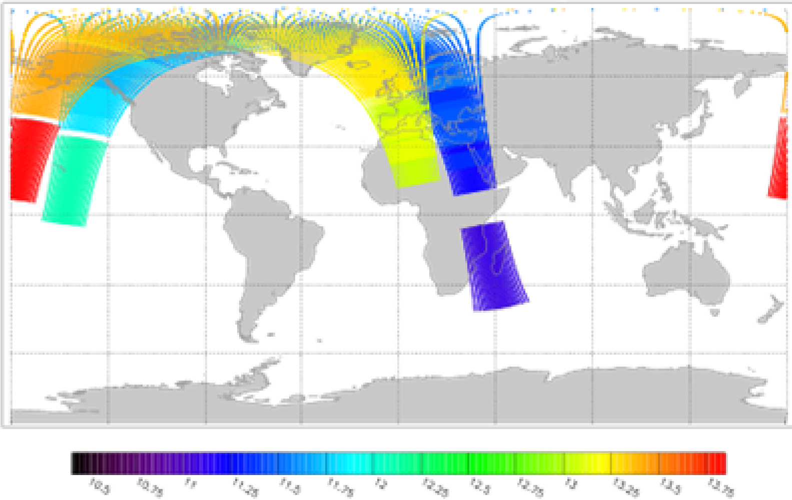
Transmission of data to Earth

Complete global dataset

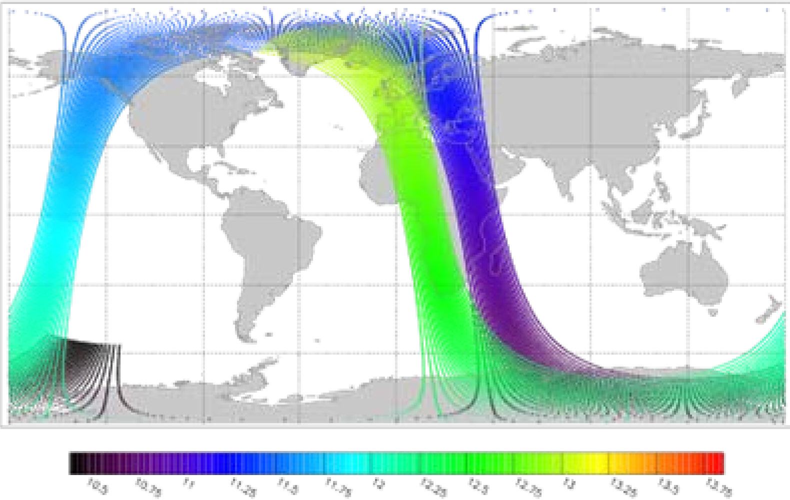
Local datasets (RARS)

Arrival time (in DWD)





Measurement time



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IV. Monitoring

Level-0 preprocessing: Level-0 -> Level-1b

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- **Decommutation**: split data into separate datasets for each instrument
- **Calibration**: compute calibration coefficients
- **Navigation**: compute position of satellite on its orbit, compute geolocation of measurements (latitude, longitude, scan angle, satellite/sun zenith/azimuth angles, …
- **Conversion**: convert radiances to brightness temperatures
- **Flagging**: flag data for which the computation of calibration coefficients or geolocation failed or is suspicious, …

Software package: **AAPP** (**A**TOVS and **A**VHRR **P**re-processing **P**ackage)
OPS-LRS, ATOVPP, ATOVIN are parts of AAPP
Provided by **NWPSAF**

Level-0 preprocessing: data levels

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Level 0	**Raw data**	Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artifacts (e. g., synchronization frames, communications headers, duplicate data) removed.
Level 1a	**Raw data + calibration info**	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e. g., platform ephemeris) computed and appended but not applied to the Level 0 data (or if applied, in a manner that level 0 is fully recoverable from level 1a data).
Level 1b	**Calibrated data**	Level 1a data that have been processed to sensor units (e. g., radar backscatter cross section, brightness temperature, etc.); not all instruments have Level 1b data; level 0 data is not recoverable from level 1b data.
Level 1c/1d	**Quality control**	Level 1b data that have been quality controlled. If required, data from other instruments can be „mapped“ onto the data. Input to NWP models.
Level 2	**Derived variables**	Derived geophysical variables (e. g., ocean wave height, soil moisture, ice concentration) at the same resolution and location as Level 1 source data.
Level 3	**Gridded data**	Variables mapped onto uniform spacetime grid scales, usually with some completeness and consistency (e. g., missing points interpolated, complete regions mosaicked together from multiple orbits, etc).
Level 4	**Model data**	Model output or results from analyses of lower level data (i. e., variables that were not measured by the instruments but instead are derived from these measurements).

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IV. Monitoring

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Data formats:

• …sentation of meteorological data. Table

Excerpt from BUFR table D:

```
340001 (IASI Level 1c data)
       001007 Satellite identifier
       001031 Identification of originating/generating centre
       002019 Satellite instruments
       002020 Sate
       004001 Year
       004002 Mont
       004003 Day
       004004 Hour
       004005 Minu
       004006 Seco
       005001 Lati
       006001 Long
       007024 Sate
       005021 Bear
       007025 Sola
       005022 Sola
       005043 Fiel
       005040 Orbi
       005041 Scan
       025070 Majo
       007001 Heig
       033060 GQis
       033061 QGis
       033062 QGis
       033063 QGis
       033064 QGis
       033065 GQis
       101010 Repe
       340002 IASI
       101087 Repeat next 1 descriptor 87 times
       340003 IASI Level 1c 100 channel sequence
       002019 Satellite instruments
       025051 AVHRR channel combination
       340004 IASI Level 1c AVHRR single scene sequence
```

Excerpt from BUFR table 002019:

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220	ESA/EUMETSAT	Spectrometer	GOME-2	Global ozone monitoring experiment-2
221	CNES/EUMETSAT	Atmospheric temperature and humidity sounder	IASI	Infrared atmospheric sounding interferometer
240	CAST	Communications	DCP	Data-collection platform transponder
.				
.				
.				
570	NOAA	Radiometer	AMSU-A	Advanced microwave sounding unit-A
574	NOAA	Radiometer	AMSU-B	Advanced microwave sounding unit-B
580	NOAA	Radiometer	ATOVS	Advanced TIROS operational vertical sounder
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620	NOAA	Atmospheric temperature and humidity sounder	CrIS	Cross track infrared sounder/NPOESS
621	NOAA	Atmospheric temperature and humidity sounder	ATMS	Advanced technology microwave sounder

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Process chain

Part II:
- Retrieve data from bank
- Conversion
- Quality control (sat_pp)
- Mapping (sat_pp)
- Quality control (sat_pp)

Part III:
- Bias correction (var3d)
- Cloud detection (var3d)
- Quality control (FG checks) (var3d)
- Thinning (var3d)
- Assimilation (var3d)

Part IV:
- Monitoring

sat_pp

var3d

First guess required

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IV. Monitoring

Retrieve data from bank, conversion

- **Retrieve data from bank**:
  - In experiments make sure that the datasets are equal to those, that were used in the routine forecasts.
  - For additional datasets make sure, that the routine cutoff times are applied.

- **Conversion**: BUFR -> NetCDF

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Quality control: motivation

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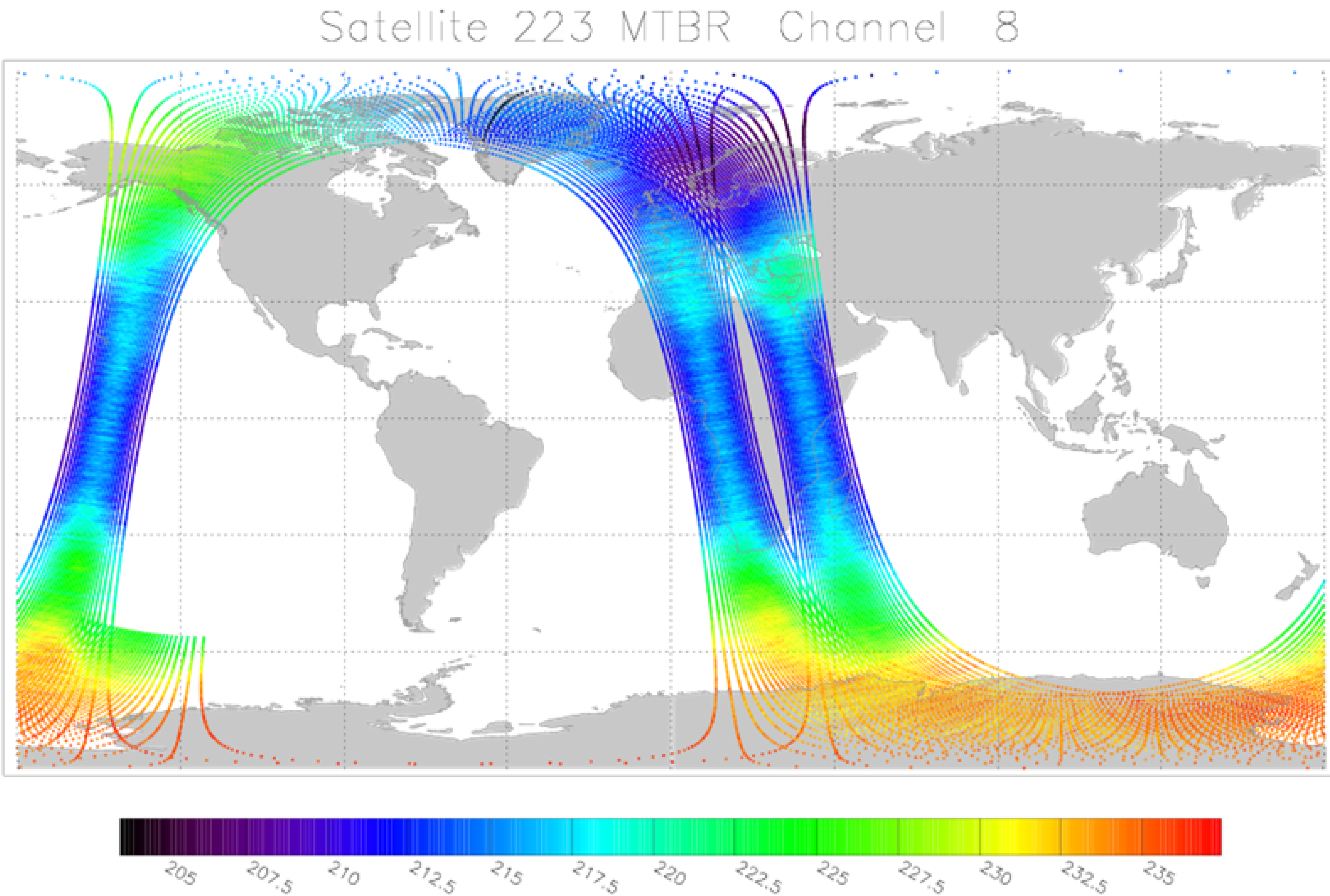

Quality control

- **Missing values:** check for missing values in variables, that are required later
- **Suspicious values:** Unrealistic brightness temperatues, latitudes, longitudes
- **Time:** suspicious time sequences and times outside of the assimilation window are discarded
- **Redundancy:** check for redundant data
- **Data flags:** check for data flags, that indicate that a measurement should not be used.
- **Physical tests:**
  - from microwave data the **surface type** can be estimated. If it is not consistent with the actual surface type, the measurement can be discarded.
  - Various **scattering indices** exist, that indicate whether a measurement is disturbed by clouds/rain/aerosols.
  - If a **1dvar** retrieval of temperature does not converge, the measurement is discarded (not operational).

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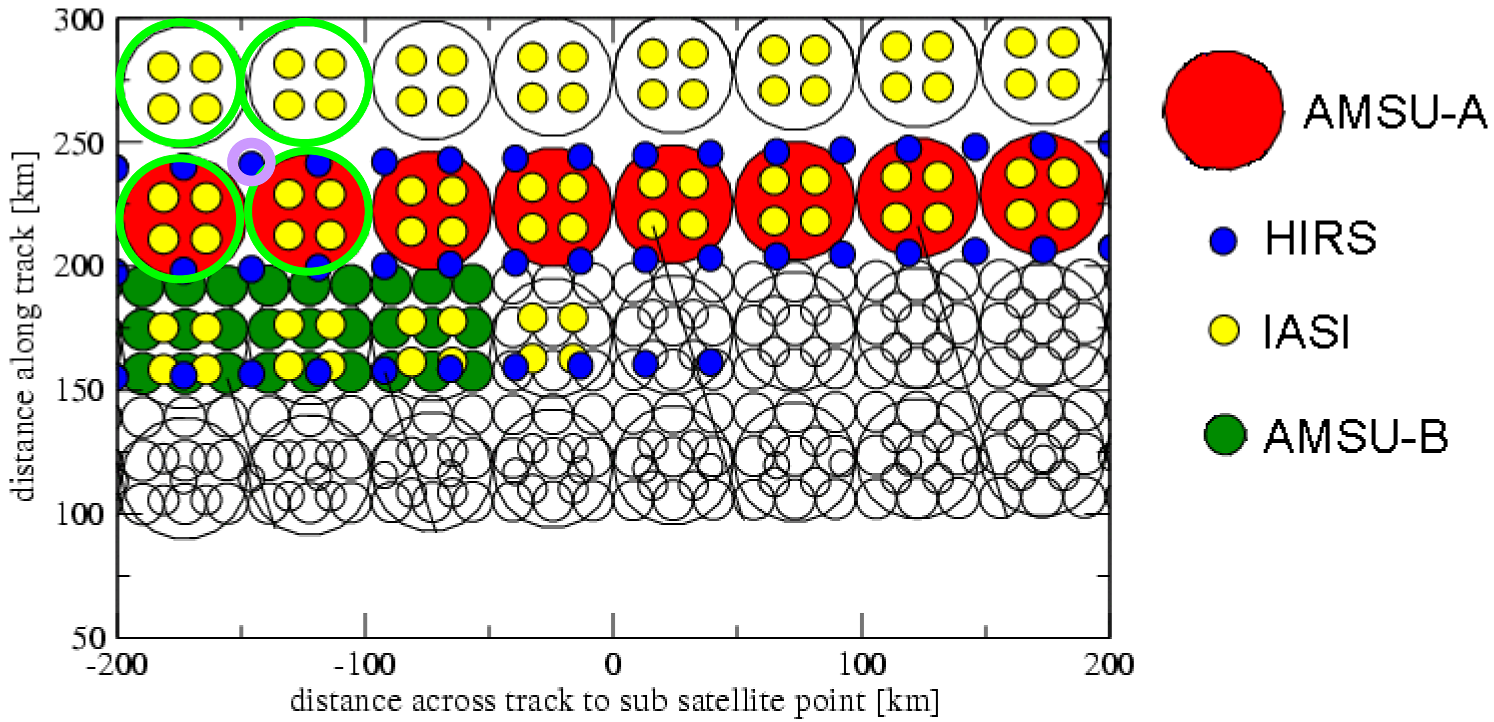
IV. **Monitoring**

Mapping

It can be useful, if measurements of another instrument are available at the measurement locations

- **Quality control:** use results from physical tests (e.g. surface type test)
- **Bias correction:** see later



http://oiswww.eumetsat.int/WEBOPS/eps-pg/IASI-L2/images/IASI_AMSU_HIRS_MHS_SCAN_PG.gif

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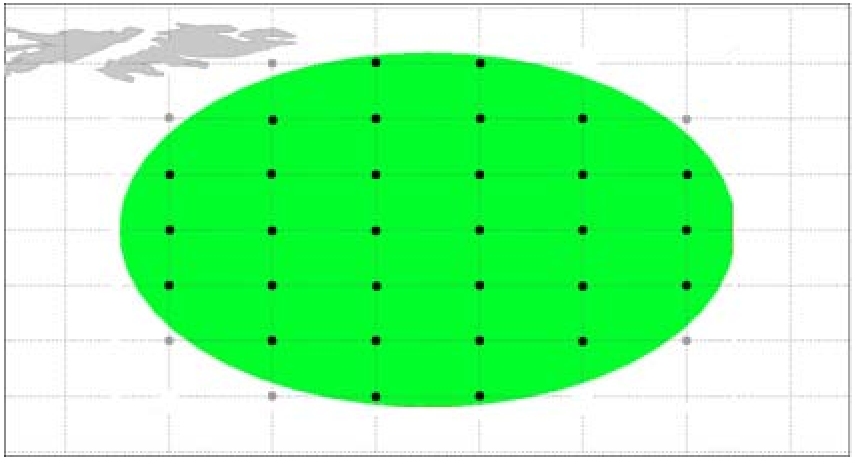
IV. Monitoring

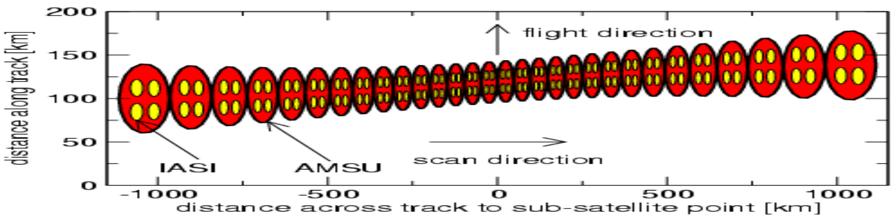
Further stuff

- **Topography within FOV** (**FOV**=**F**ield **O**f **V**iew): land fraction, surface type, altitude…



Interferometers (IASI, CrIS):

- **Radiances → brightness temperatures**
- **Thinning:** for each observation time measurements from multiple equal detectors (IASI:4, CrIS:9) are available. The best one is selected for futher use.



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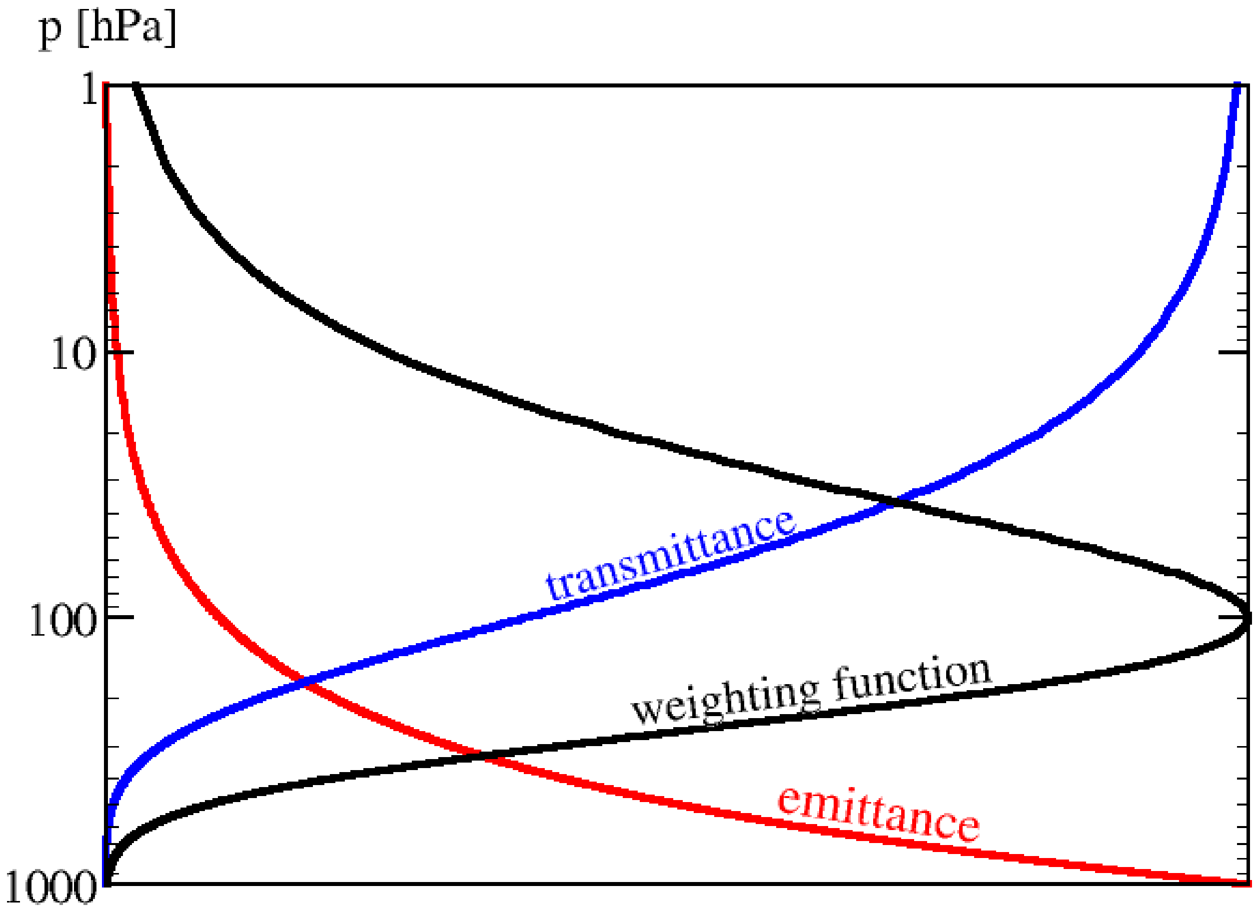
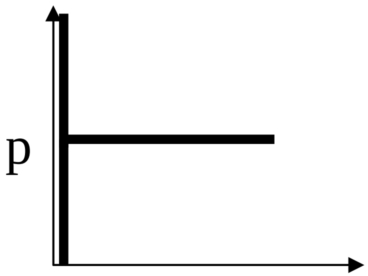
IV. Monitoring

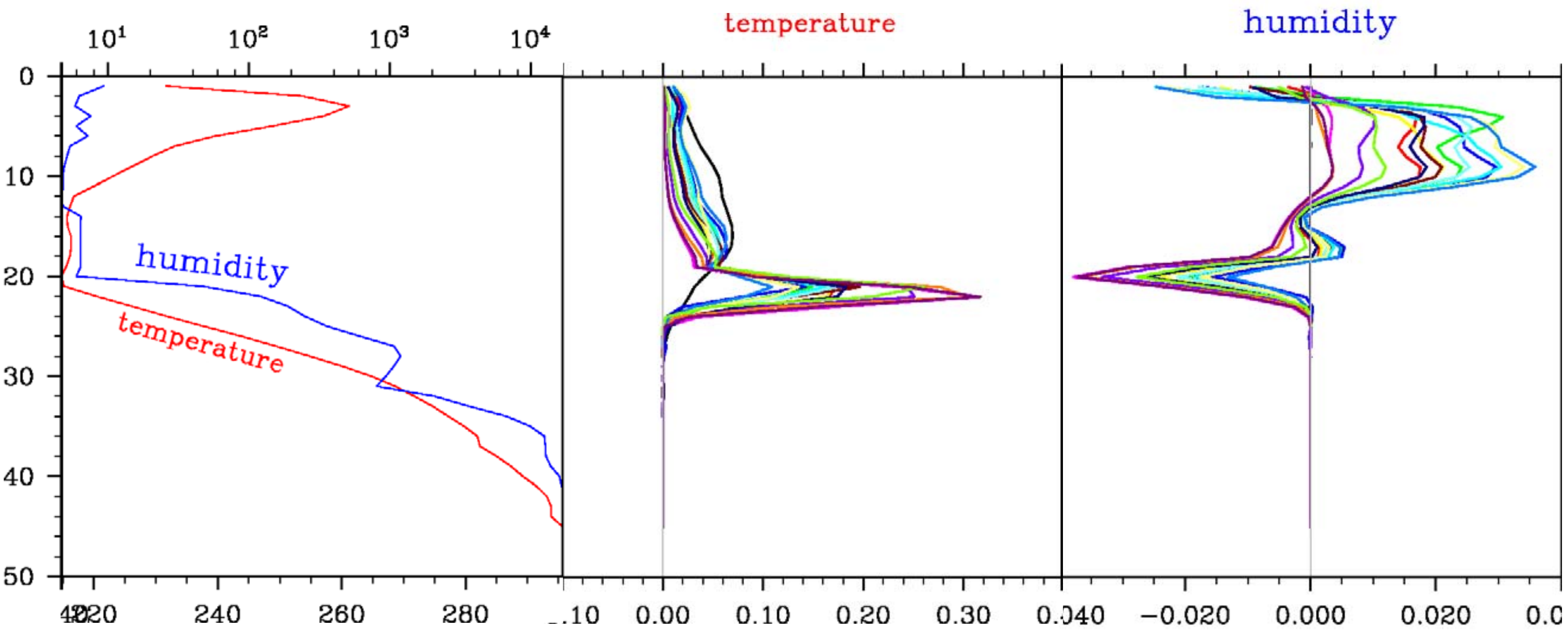
What does the instrument „see“?





Radiative transfer: weighting functions

Profiles **Weighting functions**



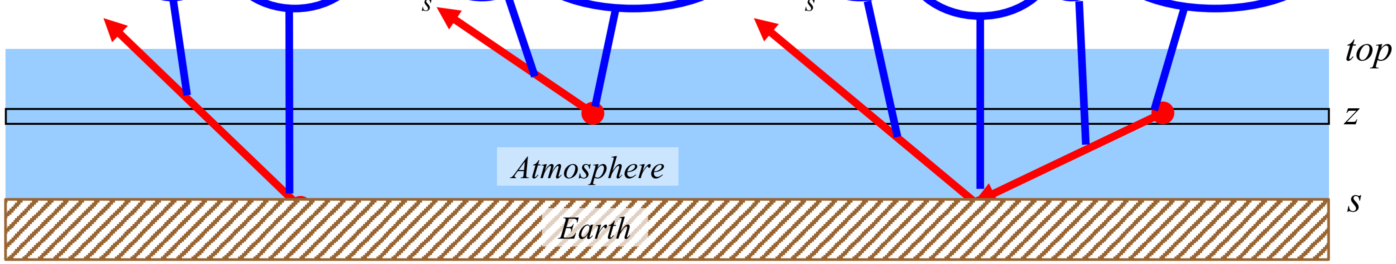
How to assimilate such observations?

$$J = \ldots + \| \mathbf{y} - \mathrm{H}(\mathbf{x}) \|^2_{\mathbf{R}^{-1}}$$

$\mathbf{y}$: observations $\mathbf{x}$: model state $\mathrm{H}(\mathbf{x})$: simulated observations

Radiative transfer equation:

$$L = \tau_{s,\,top}\, \varepsilon_s\, B(T_s) + \int_s^{top} \tau_{z,\,top}\, B(T)\, k_{abs}\, dz + \int_s^{top} \tau_{s,\,top} (1-\varepsilon_s)\, \tau_{z,\,s}\, B(T)\, k_{abs}\, dz$$



L: upwelling radiation

B: Planck-function

τ: transmittance

k_{abs}: absorption coefficient

ε_s: surface emissivity

T_s: surface skin temperature

Minimization of J $\leftrightarrow$ $\dfrac{\partial H}{\partial \mathbf{x}}$ $\leftrightarrow$ $\dfrac{\partial L}{\partial \mathbf{x}}$ $\leftrightarrow$ **weighting functions**

Radiative transfer

$$L = \tau_{s,\,top}\,\varepsilon_s\,B(T_s) + \int_s^{top} \tau_{z,\,top}\,B(T)\,k_{abs}\,dz + \int_s^{top} \tau_{s,\,top}\,(1-\varepsilon_s)\,\tau_{z,\,s}\,B(T)\,k_{abs}\,dz$$

$$k_{abs}dz = -dD \qquad \tau = e^{-D}$$

$$L = e^{-D_{s,top}}\varepsilon_s B(T_s) - \int_s^{top} e^{-D_{z,top}} B(T)\,dD_{z,top} - \int_s^{top} e^{-D_{s,top}}(1-\varepsilon_s)\,e^{-D_{z,s}} B(T)\,dD_{z,top}$$

L: upwelling radiation

B: Planck-function

ε_s: surface emissivity

τ: transmittance

k_{abs}: absorption coefficient

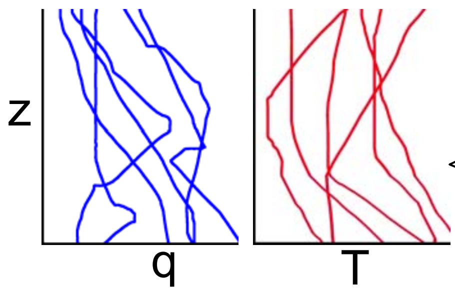
D: optical depth

$$D = D(\nu, \text{chemical composition}, p, T)$$

can be calculated with line-by-line models, but this is computationally extremely expensive.

Radiative transfer: RTTOV

RTTOV (**R**adiative **T**ransfer for **TOV**S, fast radiative transfer model)**:**



LBL-model → $D_{j,j\text{-}1}$: optical depths

$P_{k,j}$: predictors

$D_{j,j\text{-}1}$: optical depths → Linear regression ← $P_{k,j}$: predictors

Linear regression → $D_{j,j-1} = \sum_k a_{j,k} P_{k,j}$

$$\rightarrow D_{z,top}, D_{z,s}, D_{s,top}$$

FASTEM $\rightarrow \varepsilon_s$

$$\rightarrow L = e^{-D_{s,top}} \varepsilon_s B(T_s) - \int_s^{top} e^{-D_{z,top}} B(T)\, dD_{z,top} - \int_s^{top} e^{-D_{s,top}} (1-\varepsilon_s)\, e^{-D_{z,s}} B(T)\, dD_{z,top}$$ + Scattering

Precision: ~0.1K

Radiative transfer: RTTOV

Clouds, Scattering

RTTOV7
Explicit multiple scattering

RTTOV9/10
Scaling approximation

$$D_{j,j-1} = D^{clear}_{j,j-1} + D^{scatt}_{j,j-1}$$

Precision: ~1K

Radiative transfer: RTTOV

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Input

- Atmospheric profiles: *T, q, [cloud cover, water content, type, height]*
- (Near) surface conditions: T_{skin}, T_{2m}, q_{2m}, u_{10m}, v_{10m}, *sfc. type*

↓

RTTOV (with FASTEM)

↓

Output

- Clear and cloudy brightness temperatures and radiances $\rightarrow \boldsymbol{L} \rightarrow \boldsymbol{H}$
- Weighting functions $\rightarrow \dfrac{\partial H}{\partial \mathbf{x}} \rightarrow \dfrac{\partial L}{\partial \mathbf{x}}$
- Surface emissivity $\rightarrow \varepsilon_s$
- Optical depth $\rightarrow D$

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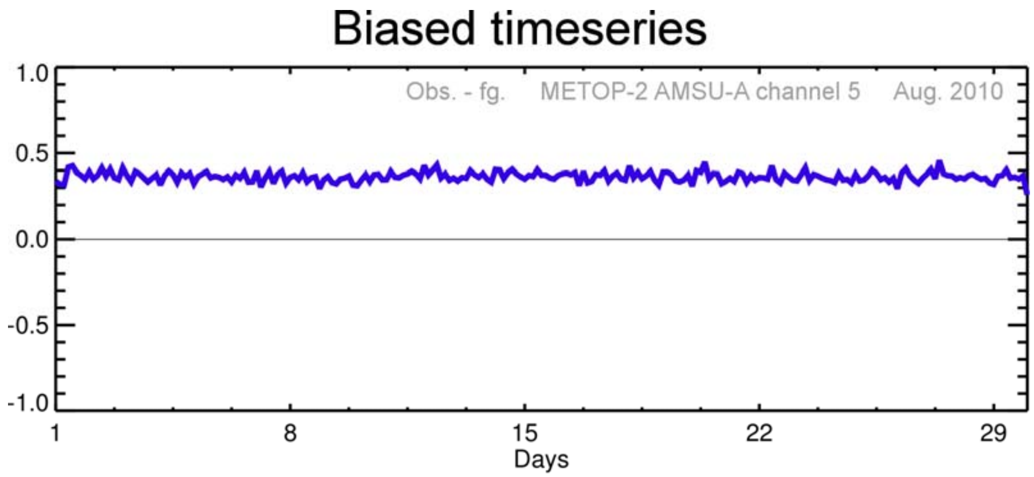
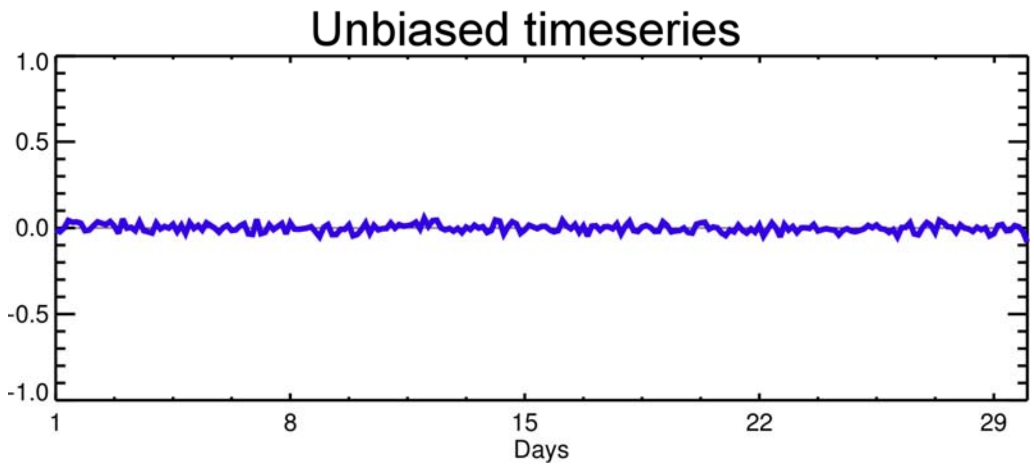
IV. Monitoring

What is a bias?



$$E(y) \neq 0$$



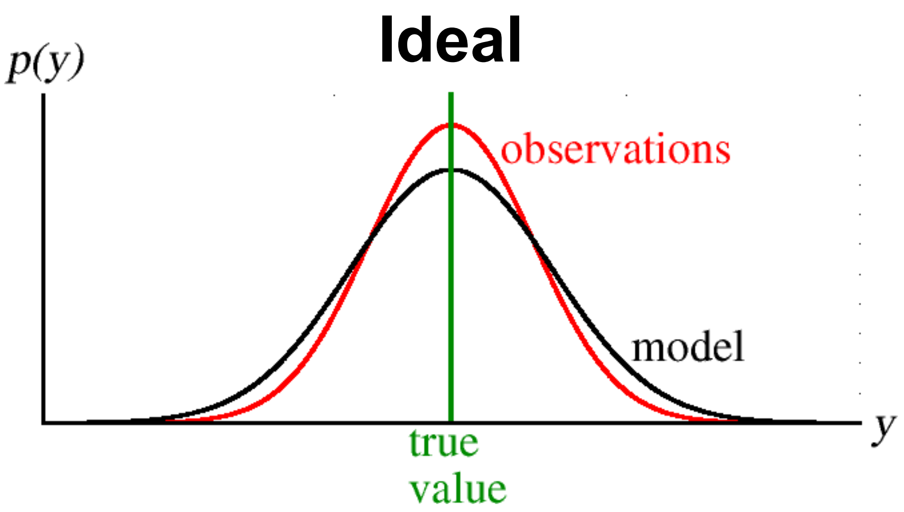
$$E(y) = 0$$

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

The problem of biases

Assumptions in 3D-Var:

$$E(\varepsilon_o) = E(y_o - y_{true}) = 0$$
$$E(\varepsilon_f) = E(y_f - y_{true}) = 0$$

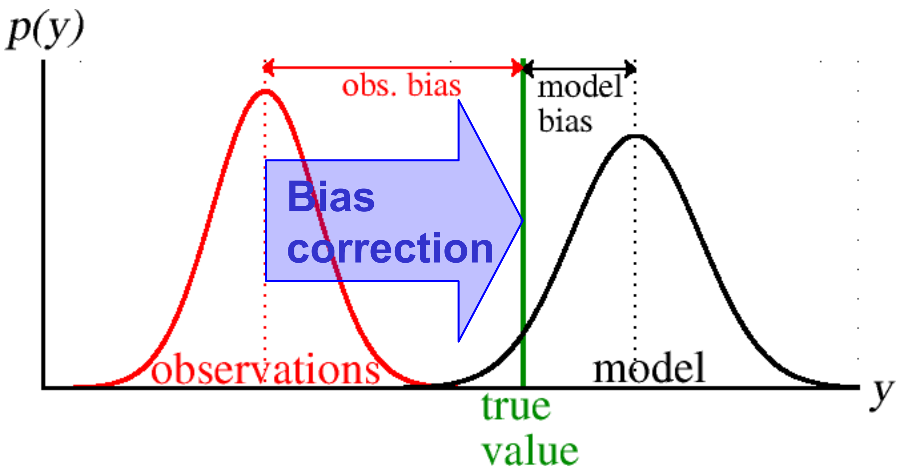


Obs. Bias has to be corrected

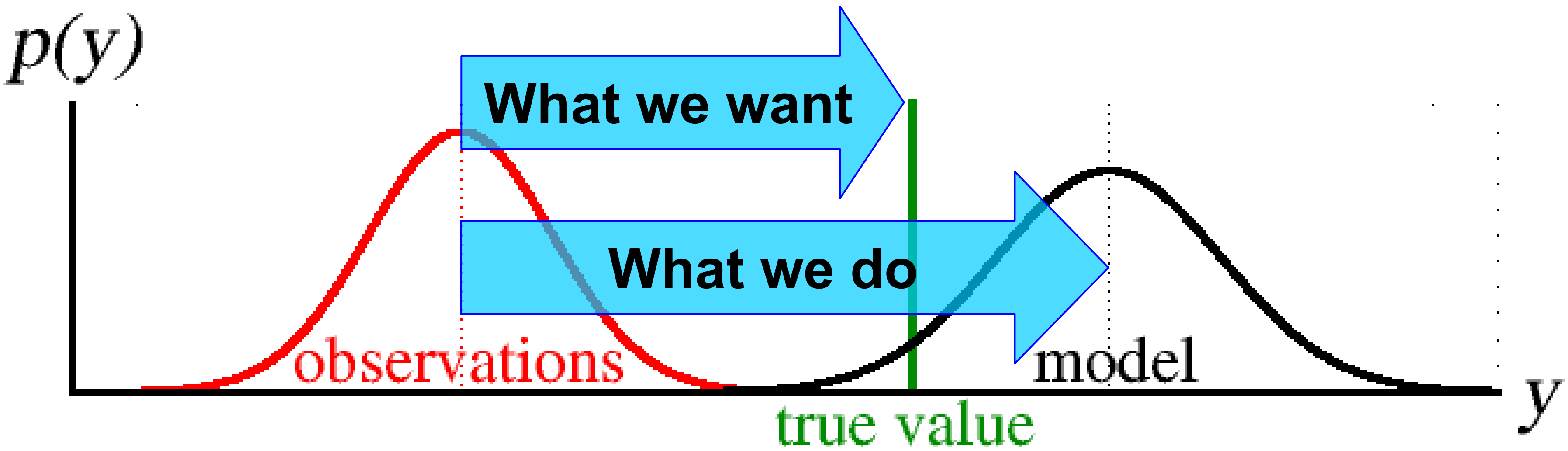
$\varepsilon_o = y_o - y_{true}$ **not known!**

→ **Consider obs. – fg.**

$$\varepsilon_o \approx y_o - y_f$$



Bias correction

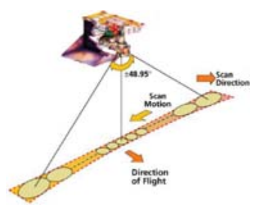


- Correction of obs. biases heavily suffers from model bias
- This is a desired effect. Due to the overcorrection the model is not pulled away from its climate.

Bias correction

Types of biases:

- Constant offset
- Situation dependent bias
- Scanline bias



Sources of biases:

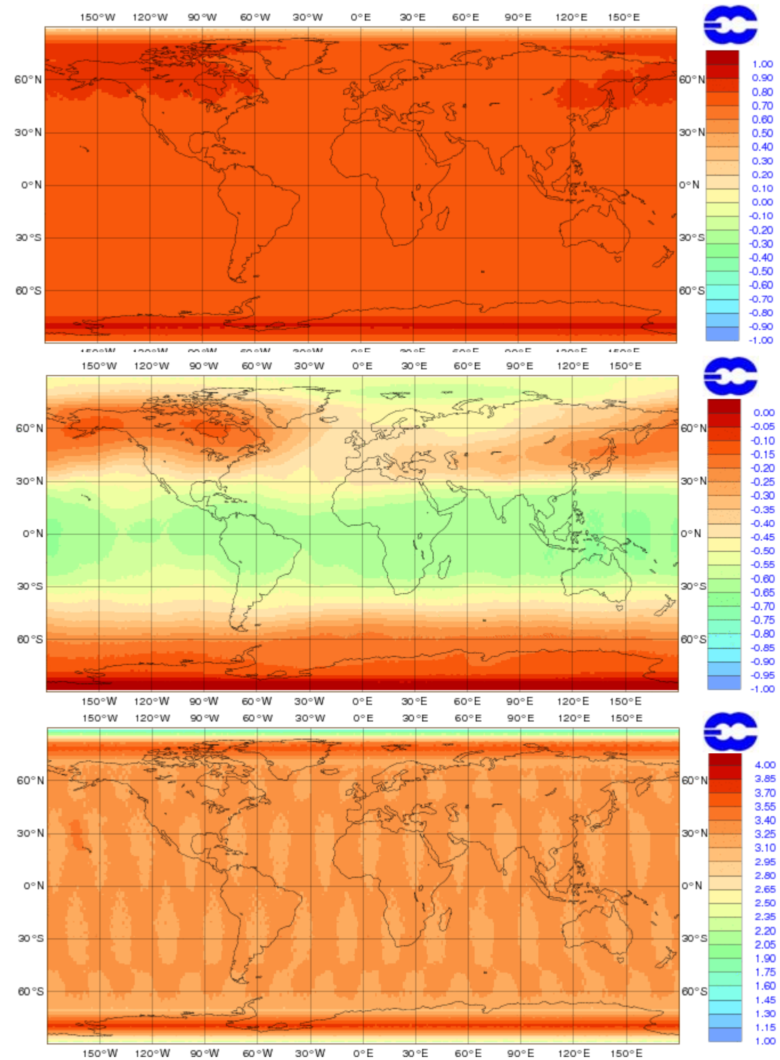
- Instrument problems
- Forward model problems
  (→ air-mass bias)
- Model bias

Remark:

These error sources are also taken into for the "observation error" covariance matrix:

$$J = [\mathbf{Y} - \mathrm{H}(\mathbf{X})]^{T} \mathbf{R}^{-1} [\mathbf{Y} - \mathrm{H}(\mathbf{X})] + \ldots$$

$$\mathbf{R} = \mathbf{O} + \mathbf{F}$$



http://www.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/atovs/amsua/

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c) **Cloud detection**
d) Thinning/quality control
e) Assimilation

IV. Monitoring

Cloud detection: motivation

Microphysical properties of individual clouds are not well known,
Multiple scattering code not very precise

↓

Radiative transfer calculations are not good enough

↓

Discard cloudy scenes

Cloud detection: AMSU-A

AMSU-A has so-called „window-channels“, i.e. the weighting functions have their maxima at the Earth‘s surface.

$$T_B \approx \varepsilon_{sfc}\, T_{skin}$$

- **Over sea:**

  determine ice fraction

  $$T_B \approx \varepsilon_{sfc}\, T_{skin} \longrightarrow \varepsilon_{obs} = f_{ice}\,\varepsilon_{ice} + (1 - f_{ice})\,\varepsilon_{water}$$

- **Over ice and land:**
  determine surface type by comparison of ε_{obs}‘s with emissivity model.

- **Check for rain/clouds:**
  - Over sea: estimate LWP (Liquid Water Path):

    $$LWP > 0.3\text{mm} \rightarrow \text{rain}$$

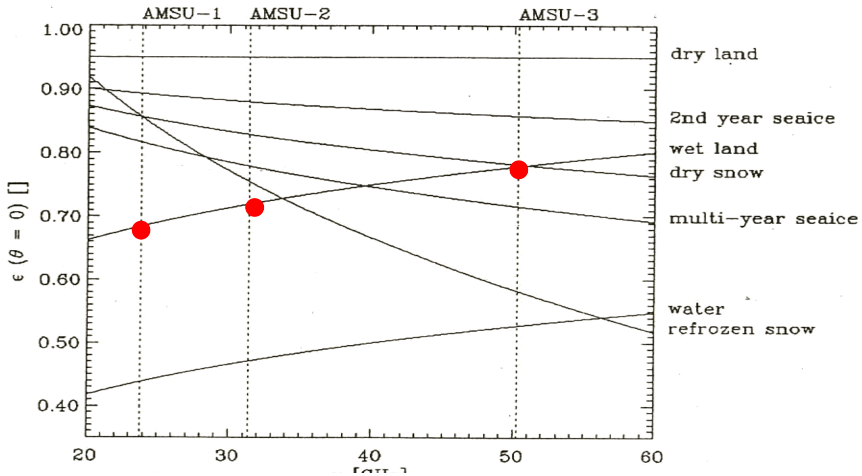
    $$LWP > 0.1\text{mm} \rightarrow \text{clouds}$$

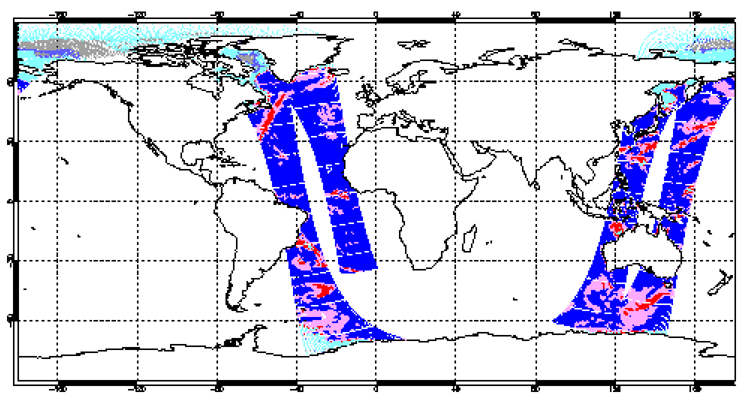
  - Over snowfree land:

    $$T_B^{(1)} - T_B^{(15)} > 3\text{K} \rightarrow \text{rain}$$

  - No check over snow

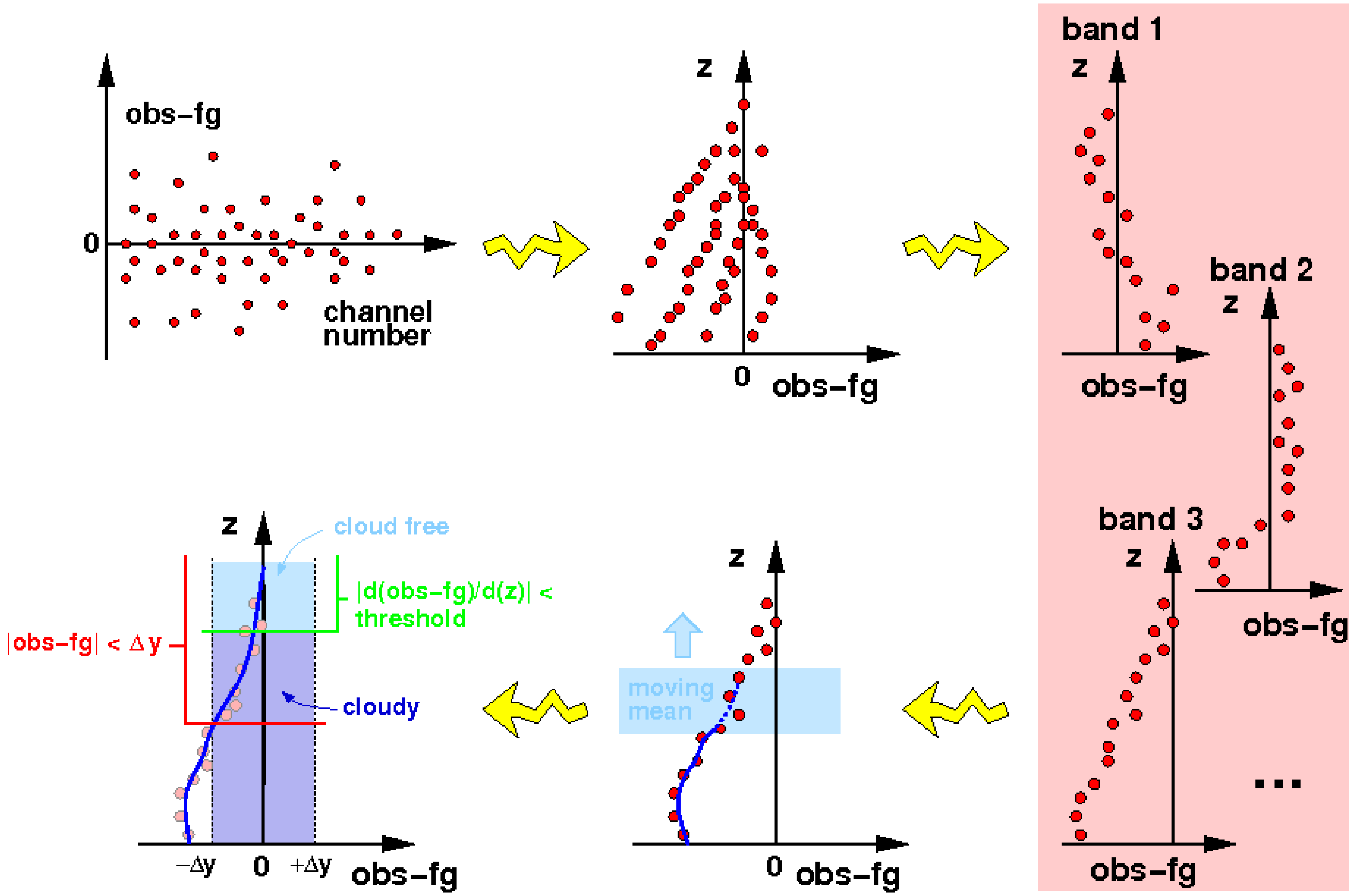
Emissivity of different surface types





Sea, Ice, cloud, rain

Cloud detection: IASI (McNally-Watts)



Courtesy Detlef Pingel

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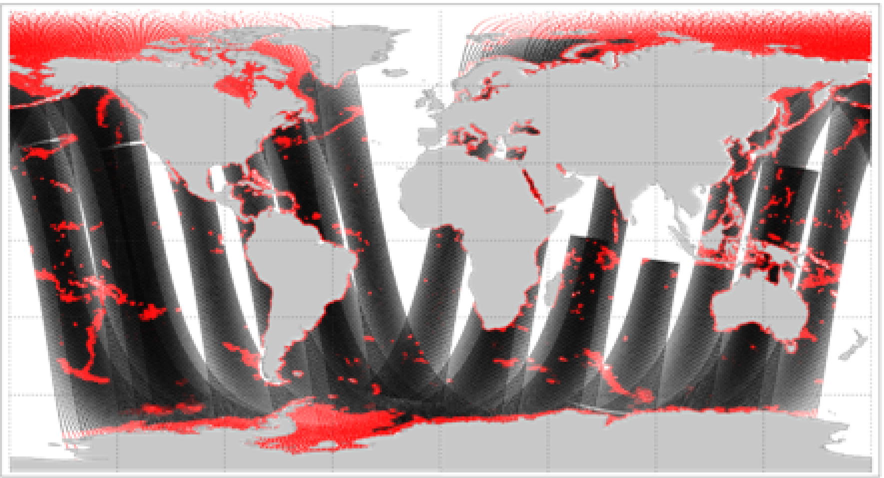
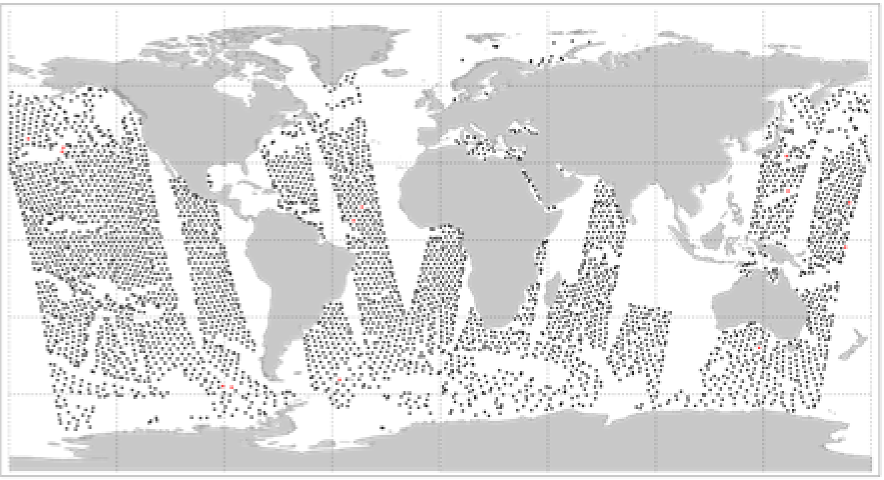
Thinning/quality control

Available observations



Assimilated observations



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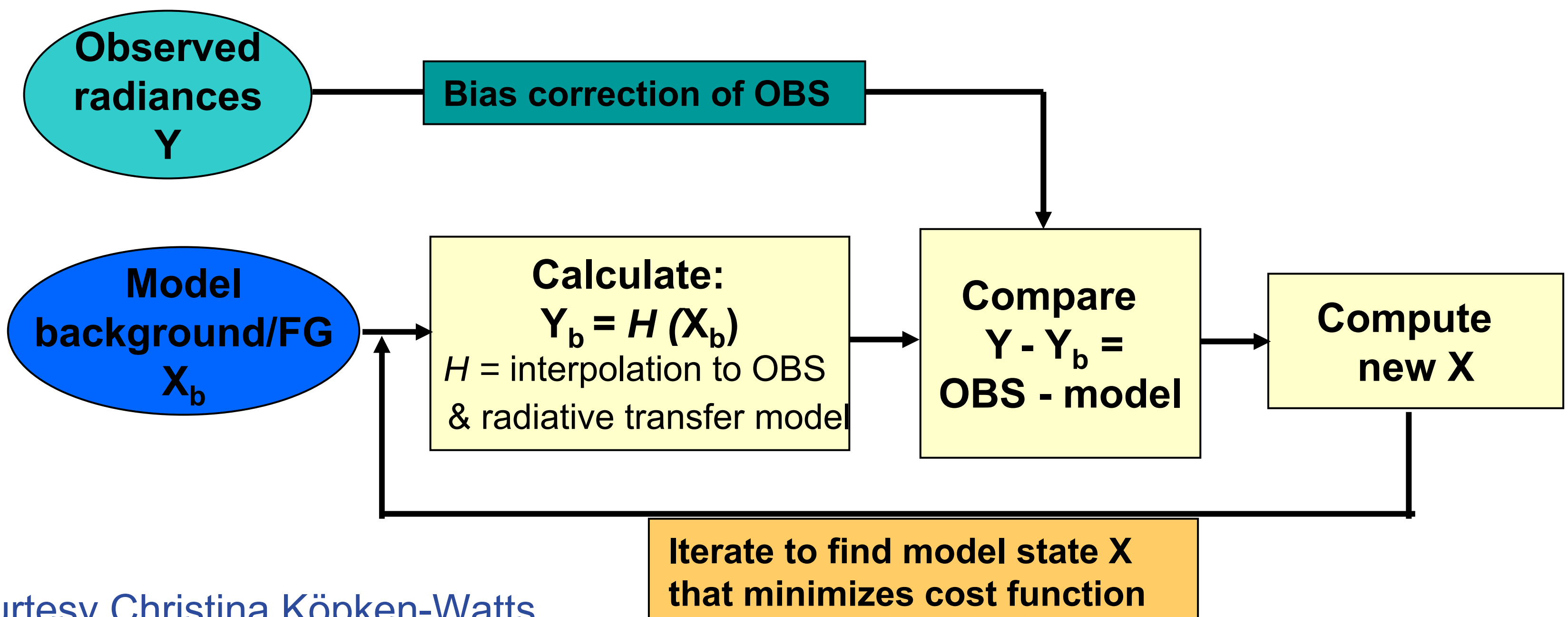
IV. Monitoring

Assimilation

Radiances are non-linearly related to model parameters

- **OI method** (linear analysis scheme):
  - Radiances have to be converted into T(p), q(p): External retrieval scheme.
  - Error characteristics of retrievals are complicated
- **Variational methods (e.g. 3DVar)**:
  - Can take non-linear relationships into account
  - Use radiances/brightness temperatures -> errors are easier to quantify



Courtesy Christina Köpken-Watts

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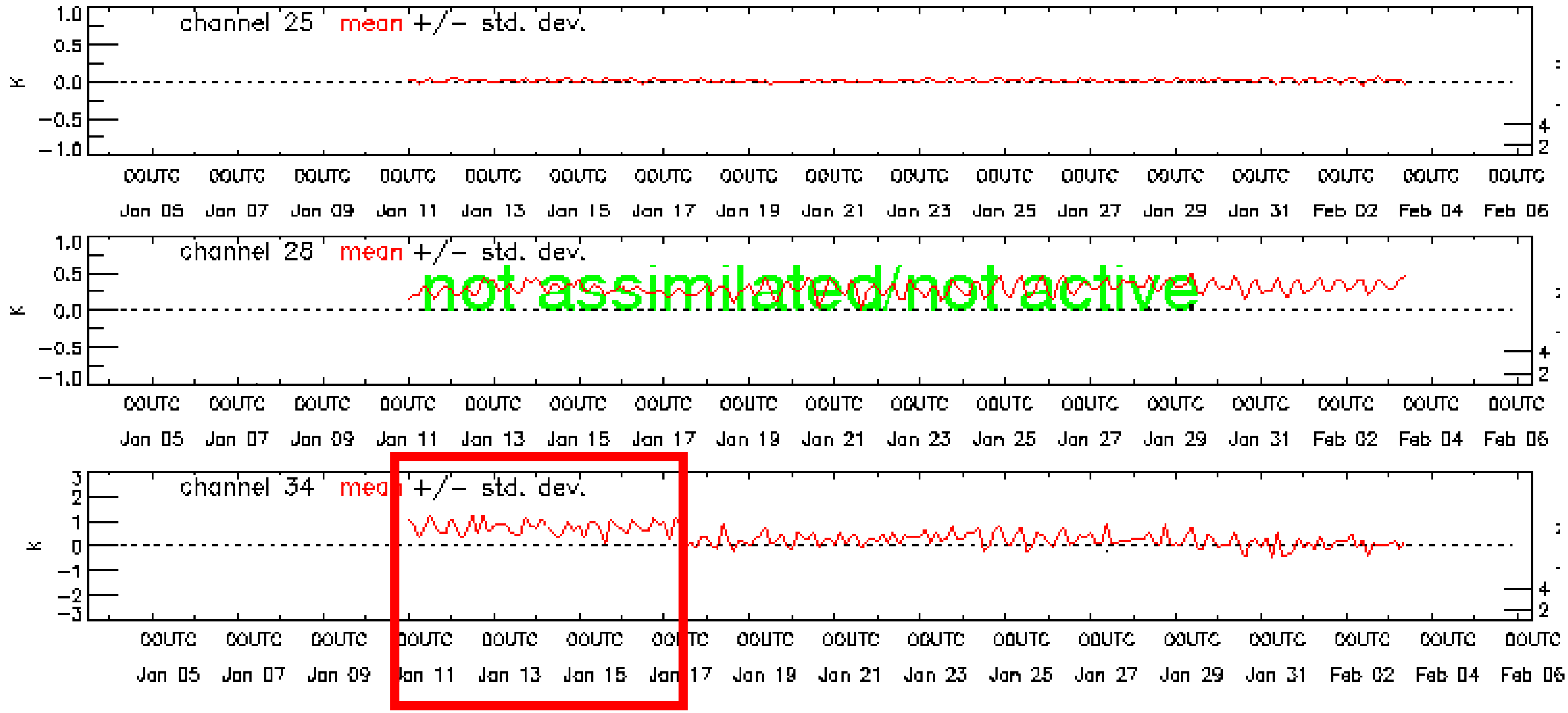
IV. Monitoring

Monitoring

Bias corrected observations minus first guess

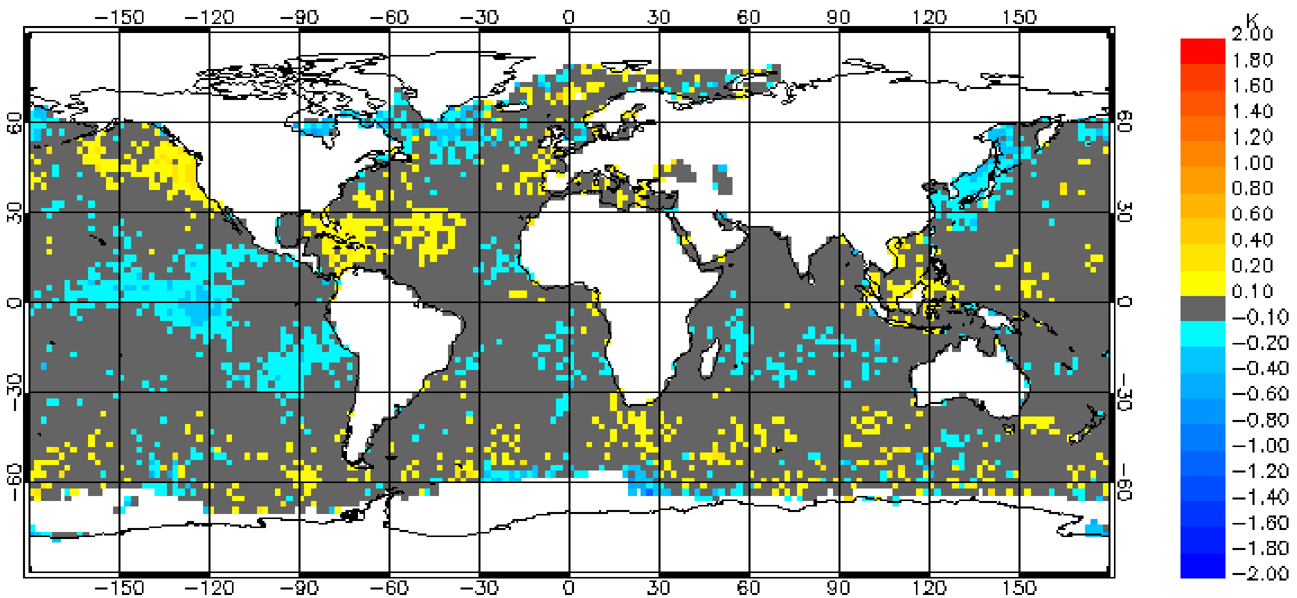


Statistics for Radiances from NOAA-15 / AMSU-A - 8

Mean First Guess Departure (OBS-FG), bias corr. (used)

EXP = rou

Time period: 20111201 00UTC - 20111213 21UTC, Hour = all



units = K
min = -1.01
max = 0.53
mean = -0.01

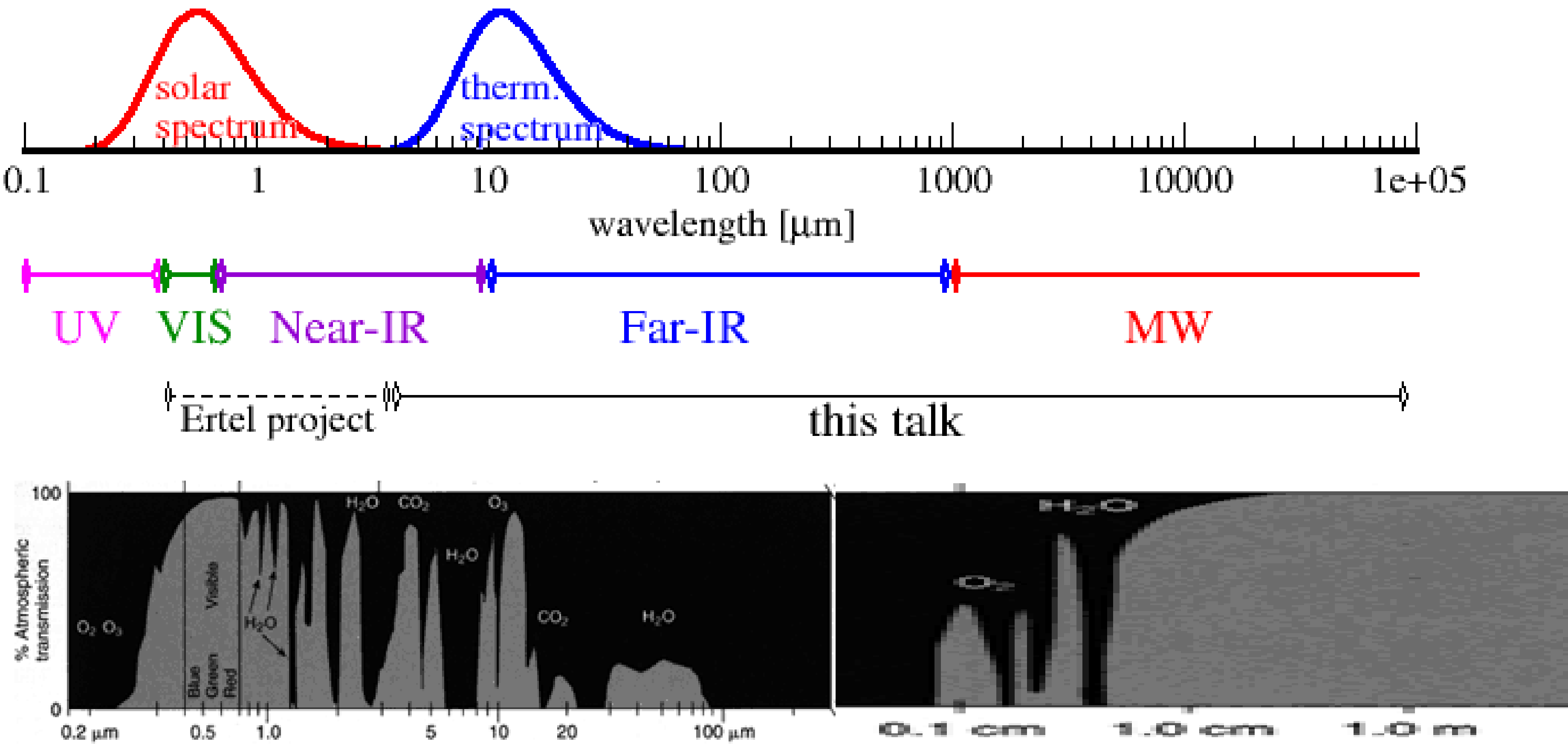
Summary

- Sun-synchronous orbits
- Satellite tracks
- Measurement geometry
- BUFR
- RTTOV
- Bias correction
- Cloud detection

Questions?

Backup slides

What is measured?



How to remove obs. biases?

$y_o \longrightarrow y_o + b$ $\qquad b = c + \sum_i \beta_i P_i$

c, β_i : coefficients

P_i : state dependent predictors

→ Minimization problem: $\left\langle \left(y_o + b - y_f \right)^2 \right\rangle = \min$

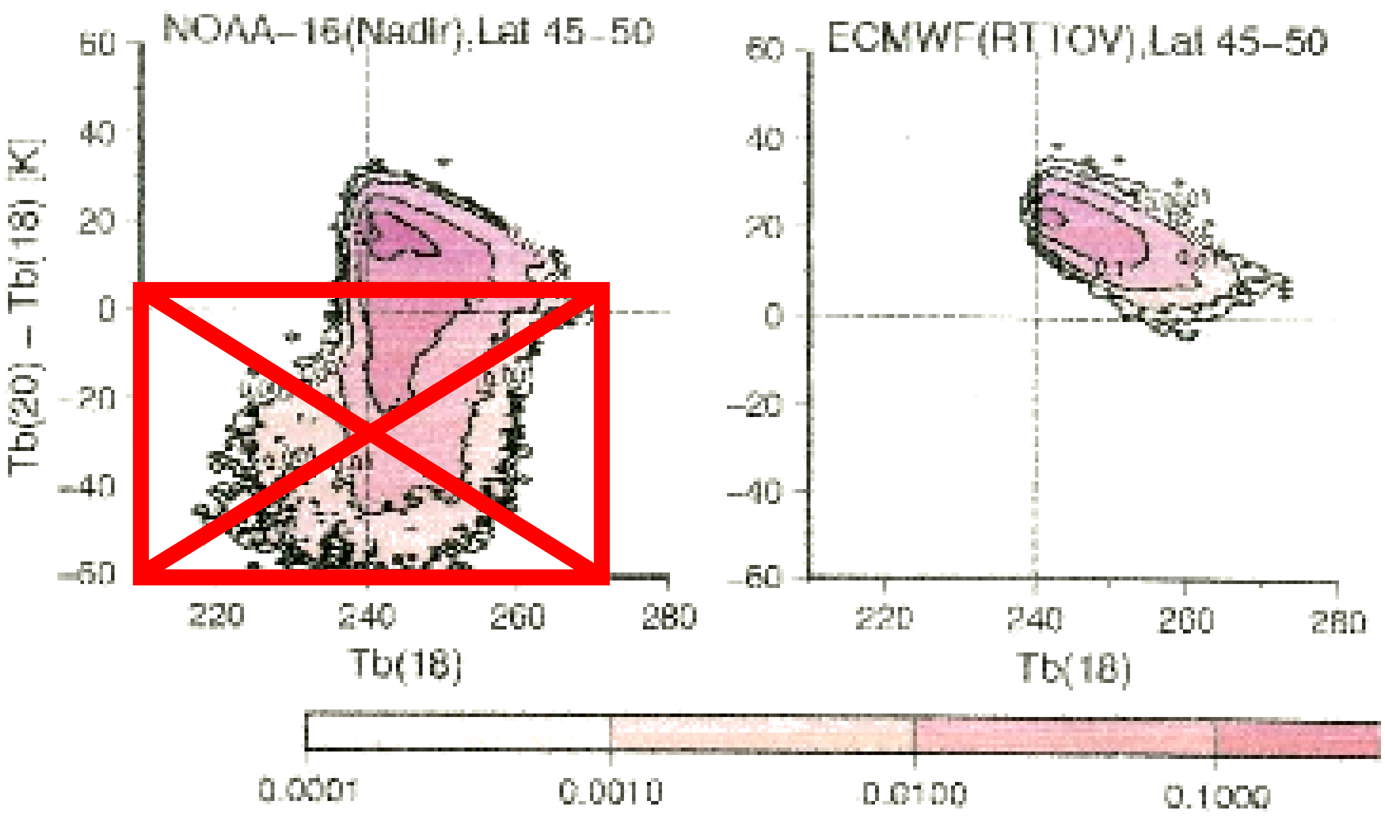
→ solved by linear regression → c, β_i

Strategies to update coefficients:

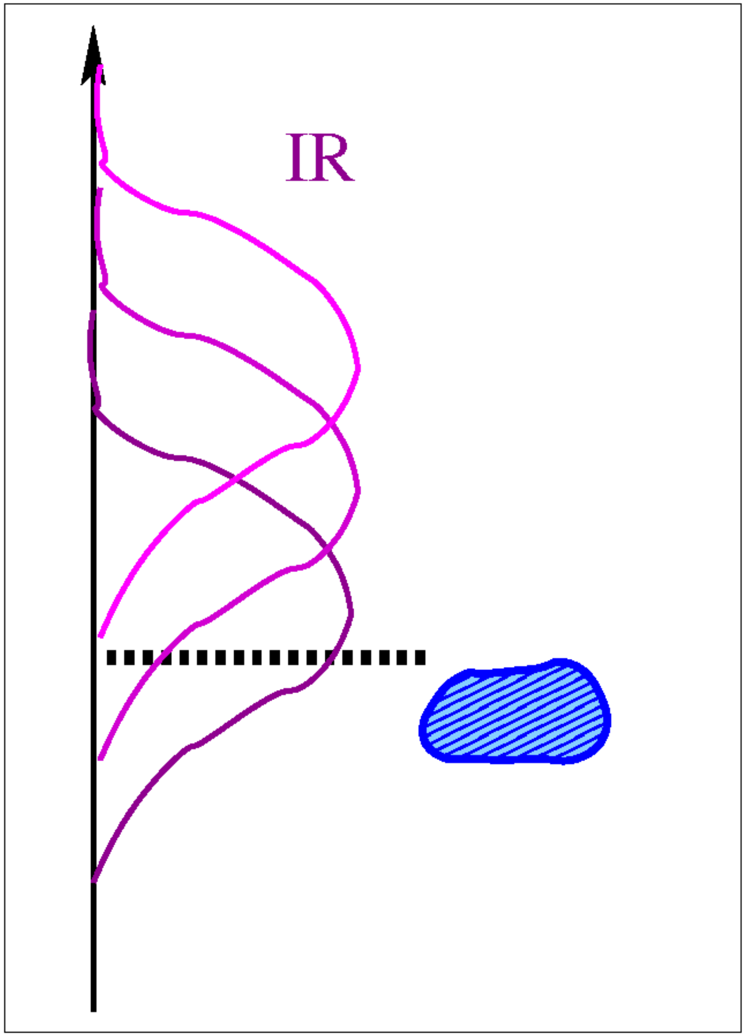
- Manually, "*static*", operational
- Automatic, "*online*", experimental
- Within 3D-Var minimization, "*variational*", in progress

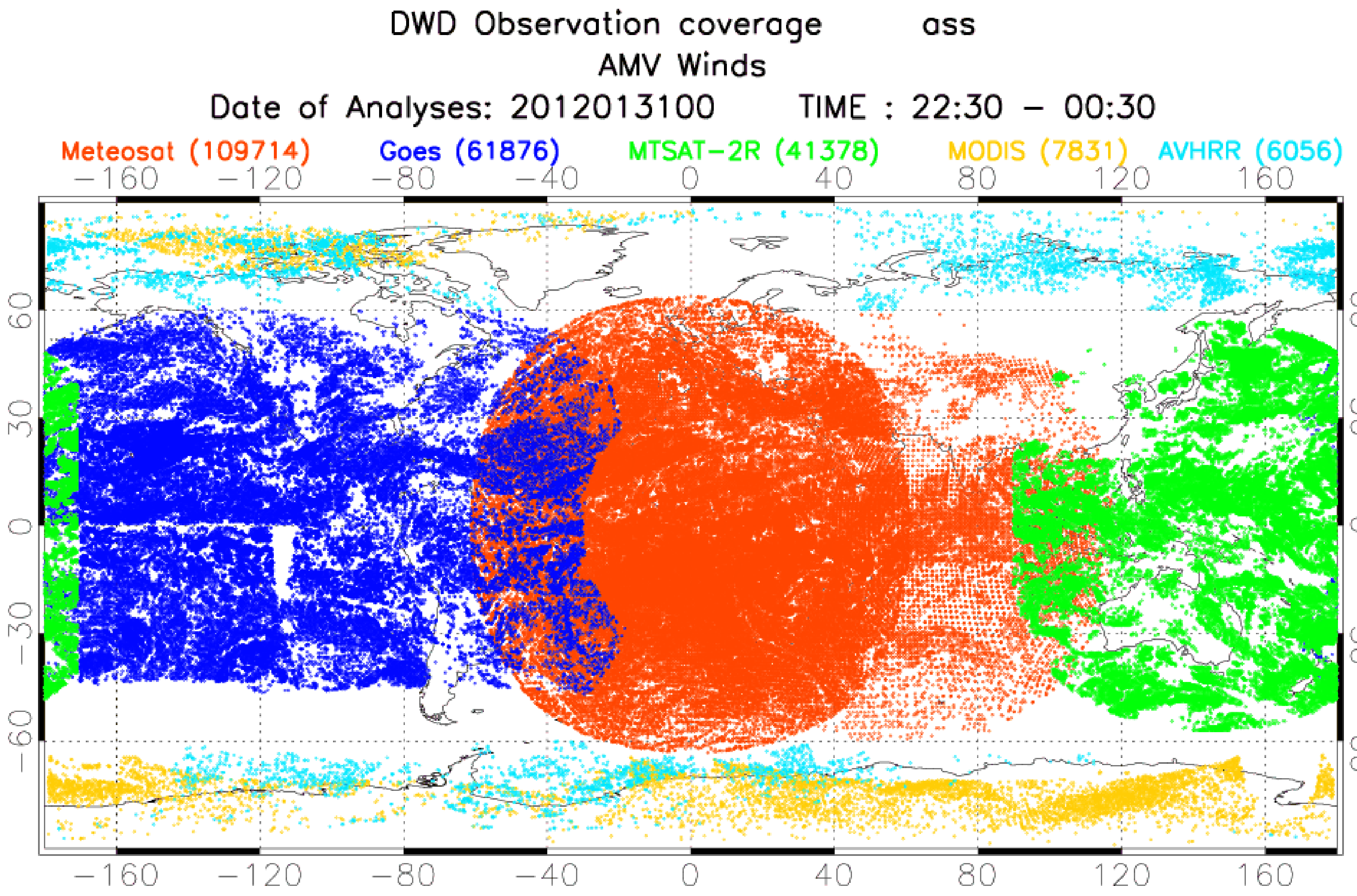
Cloud detection: AMSU-B

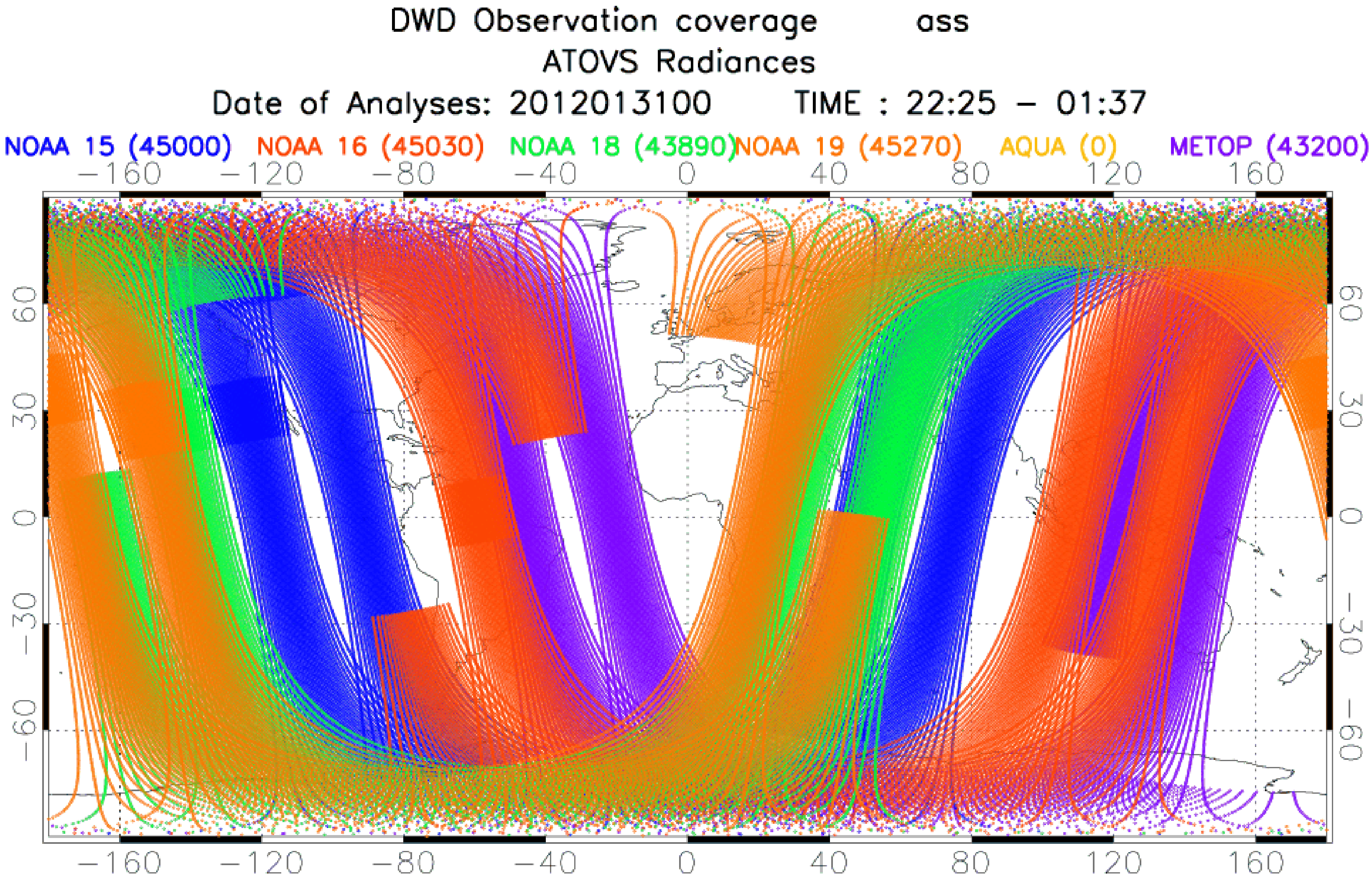
Deutscher Wetterdienst
Wetter und Klima aus einer Hand



Cloud detection: IR

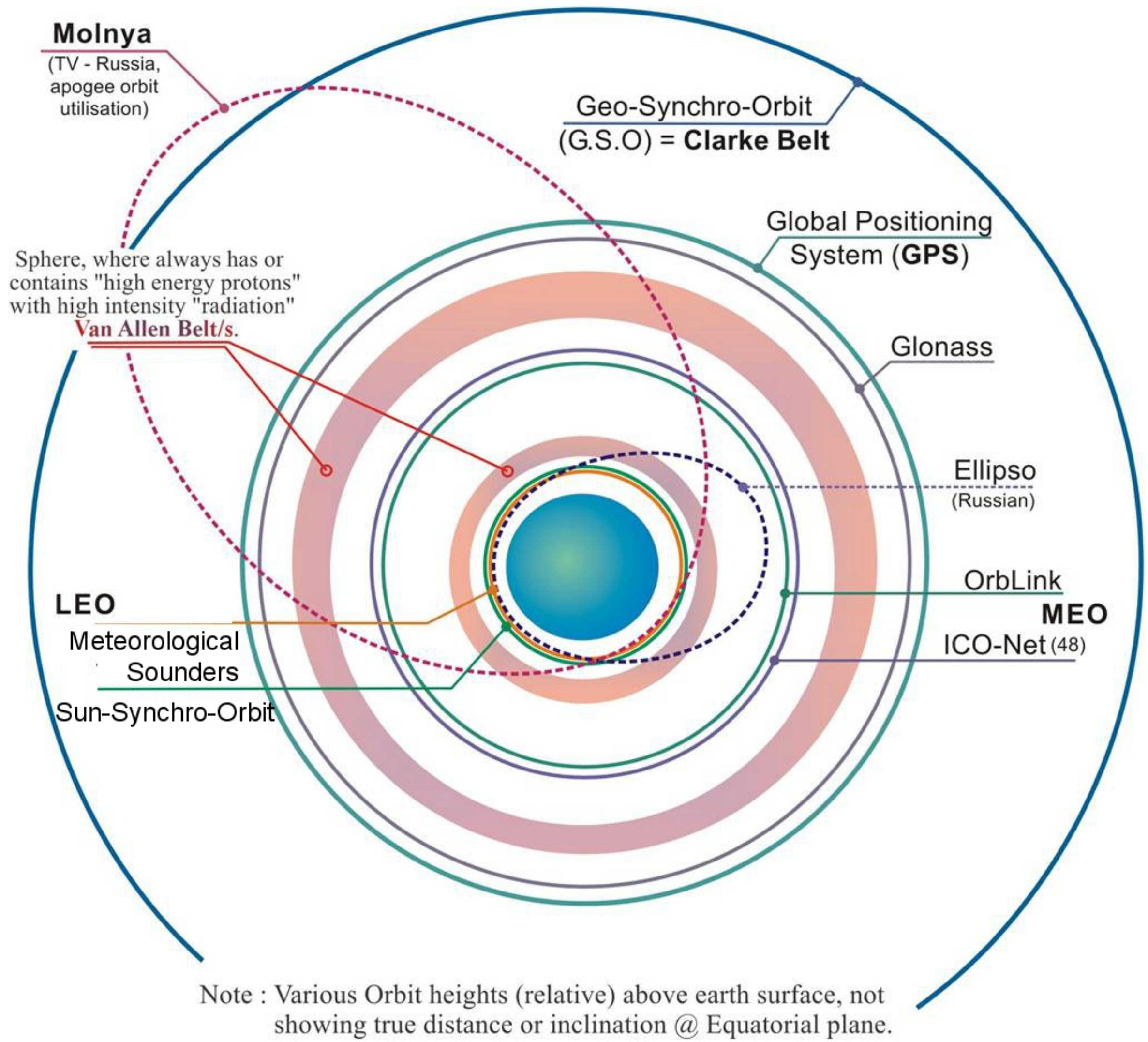



DWD Observation coverage ass
AMV Winds
Date of Analyses: 2012013100 TIME : 22:30 – 00:30
Meteosat (109714)
Goes (61876)
MTSAT-2R (41378)
MODIS (7831)
AVHRR (6056)
–160 –120 –80 –40 0 40 80 120 160
60 30 0 –30 –60


DWD Observation coverage ass
ATOVS Radiances
Date of Analyses: 2012013100 TIME : 22:25 – 01:37
NOAA 15 (45000) NOAA 16 (45030) NOAA 18 (43890) NOAA 19 (45270) AQUA (0) METOP (43200)
−160 −120 −80 −40 0 40 80 120 160
60 30 0 −30 −60

Satellite orbits: classification

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



http://anityonugroho.blogspot.com/2011/04/satellite-communication-part-1.htm

Geo **S**ynchronous **O**rbit (GSO)
Geo-stationary orbit

- Height: 35786km
- Period: 23h56m04s
- Meteorological satellites: Meteosat, GOES, …

Medium **E**arth **O**rbit (MEO)

- Height: 1200 – 35786 km
- Period: ~ several hours
- Navigation satellites: GPS, Galileo, GLONASS, …

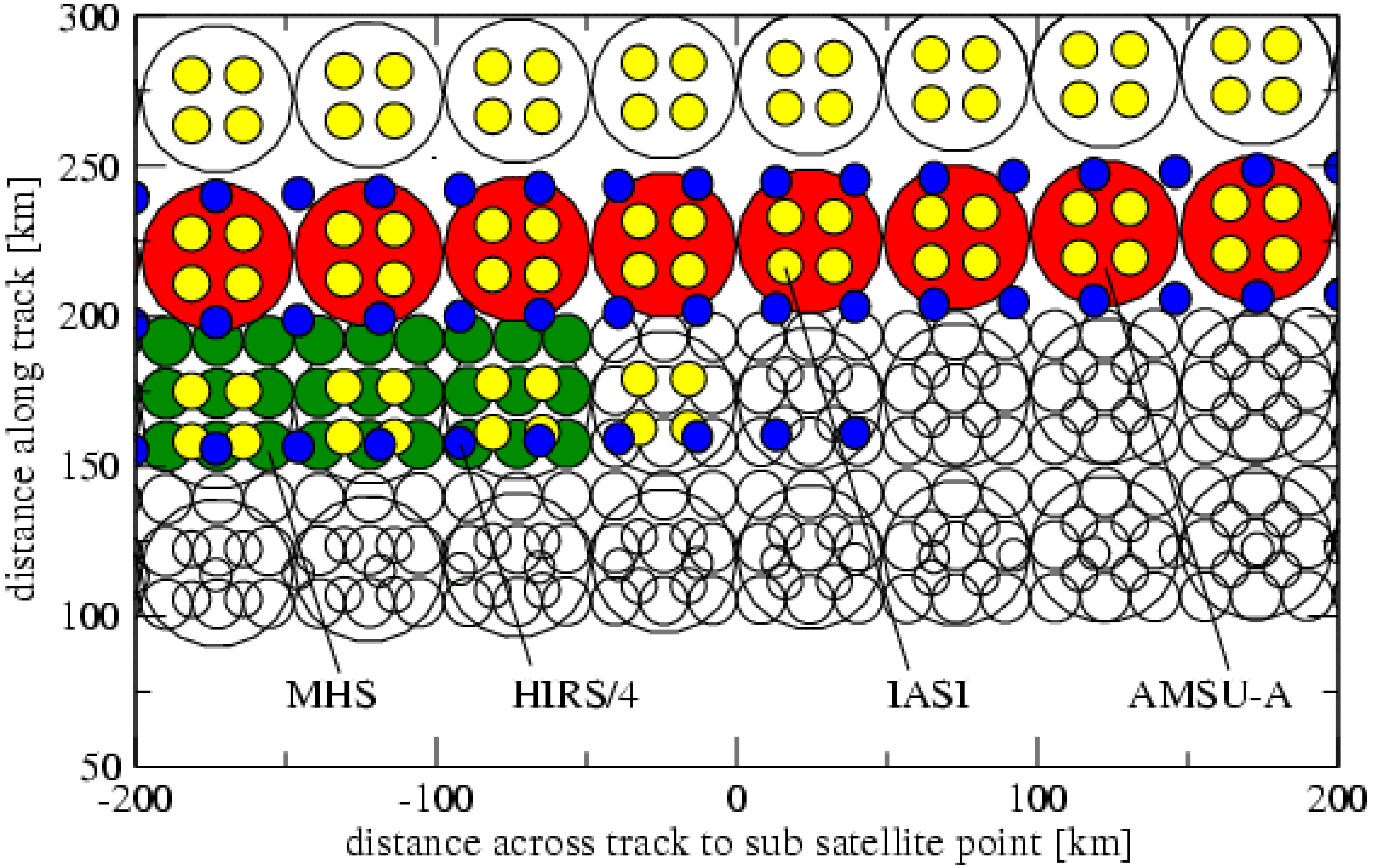
Low **E**arth **O**rbit (LEO)
Sun **S**ynchronous **O**rbit (SSO)

- Height: 200 – 1200 km
- Period: ~ 100 min
- Meteorological satellites: NOAA, METOP (EPS, JPSS), …

Highly **E**lliptical **O**rbit (HEO)

- Height: variable
- Future meteorological satellites

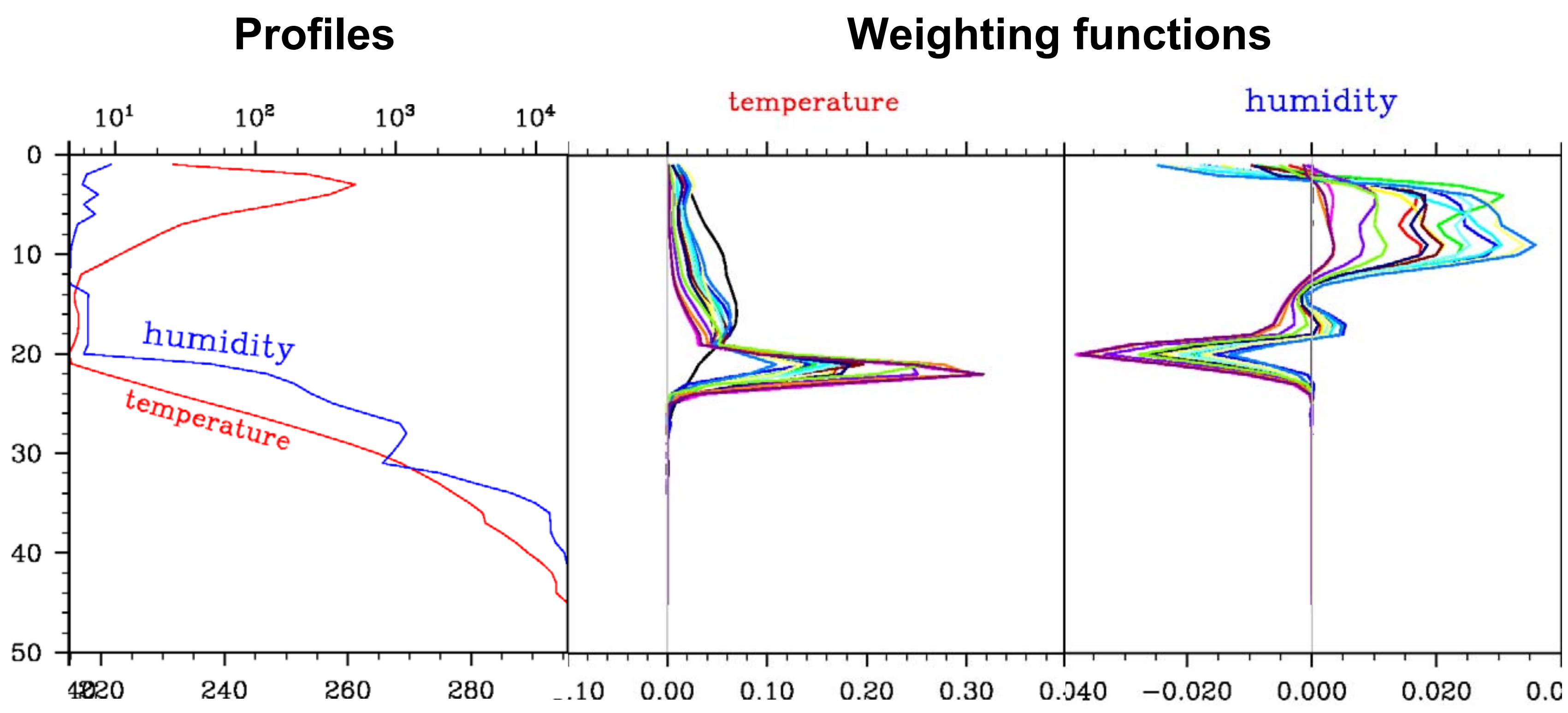
Measurement geometry



http://oiswww.eumetsat.org/WEBOPS/eps-pg/IASI-L1/images/IASI_AMSU_HIRS_MHS_SCAN_PG.gif

Radiative transfer: weighting functions

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



Thinning/quality control

Available observations	Assimilated observations