On the use of Simulated Photon Paths to Co-register TOA Radiances in EarthCARE Radiative Closure Experiments

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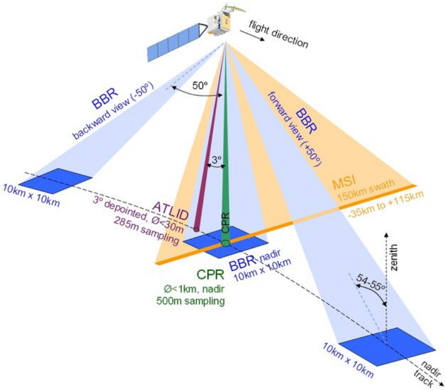
Overview of EarthCARE



- retrieval of vertical profiles of
  - cloud
  - aerosol
  - and precipitation

  parameters
  with CPR, ATLID and MSI

- verisimiltude of retrieval through Radiative Closure:
  3 along-track measurements of BBR versus simulations of 1D RTM or 3D Monte Carlo RTM

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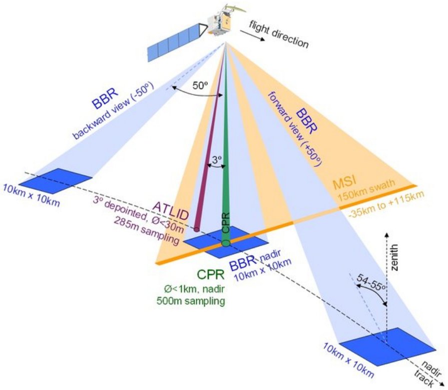

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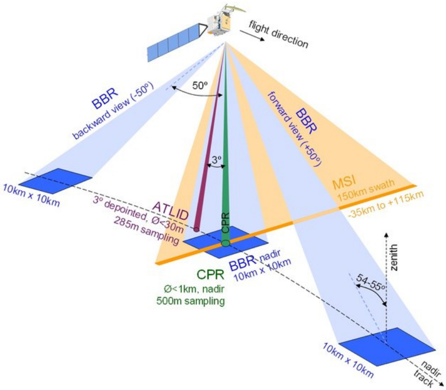

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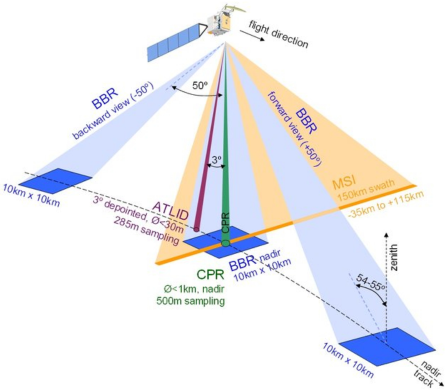

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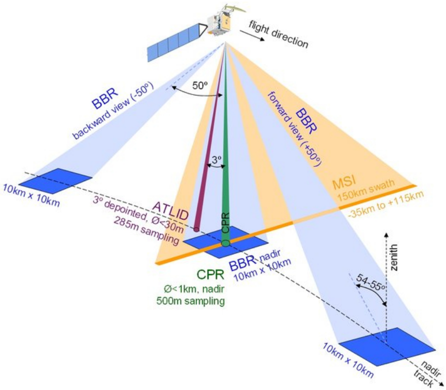

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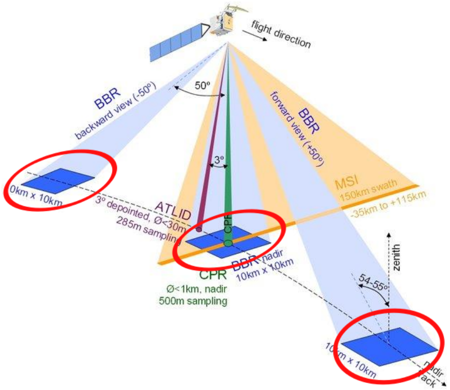

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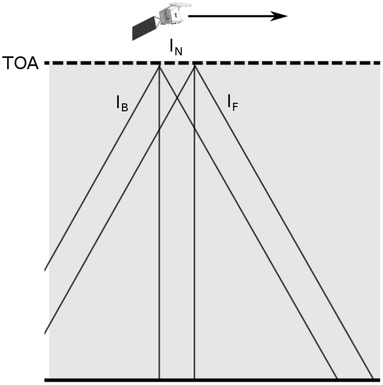

- BBR measurements
  - broadband radiances (SW and LW) at 3 along-track viewing angles
- 3D Monte Carlo RTM
  - acting on retrieved properties
  - simulating BBR TOA SW radiances (or radiative fluxes)
- measurement versus simulation
  - difference indicating inaccuaracies of retrieved properties

this study: concerning a radiative closure with SW radiances

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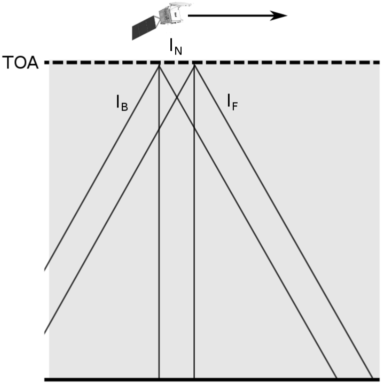

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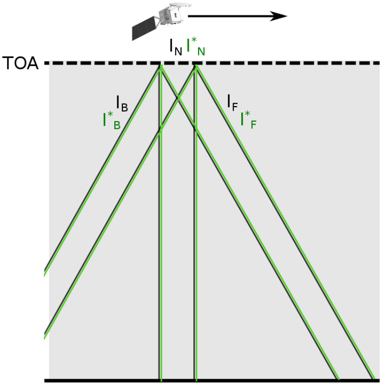

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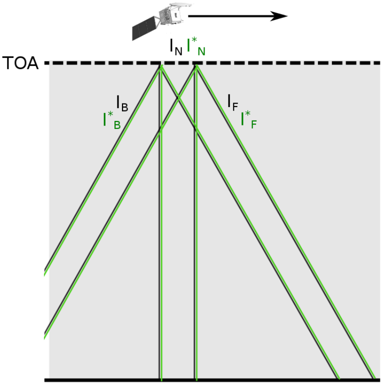

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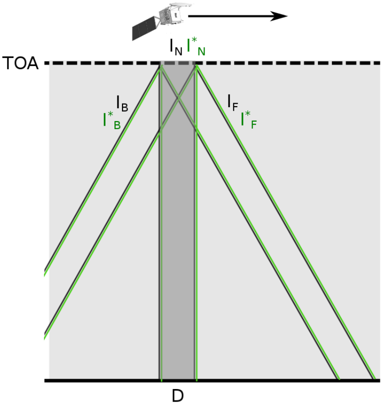

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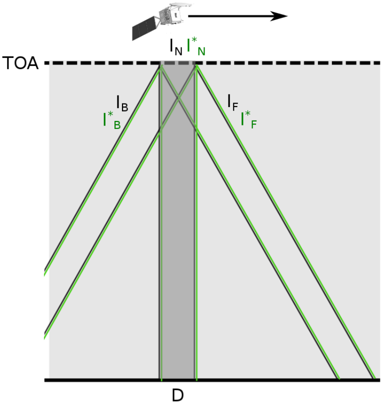

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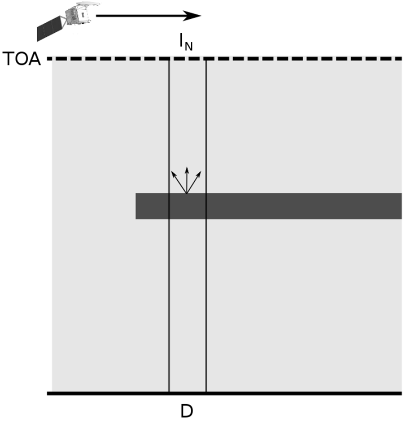
Problem of Radiance Co-registration

co-registration aims at observing the *same scene* from all 3 angles

- EarthCARE: co-registration helps to identify domains with incorrect retrieval
- up-to-date: at heighest reflecting layer
  - cloud top height
  - surface
- problematic for transparent or broken cloud layers
  - **need for more information vertical distribution of refl. layers**
  - **develope method to utilize this new information**



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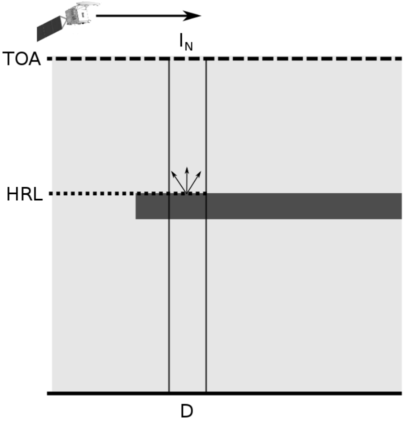

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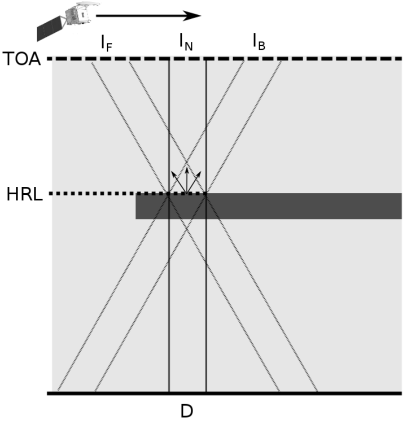

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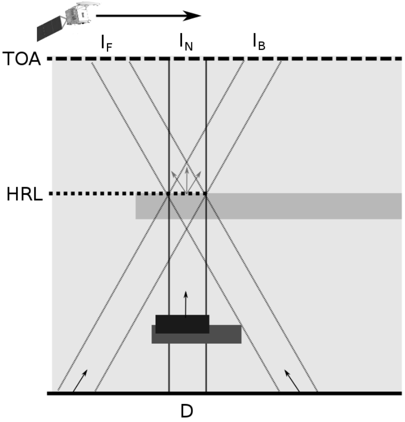

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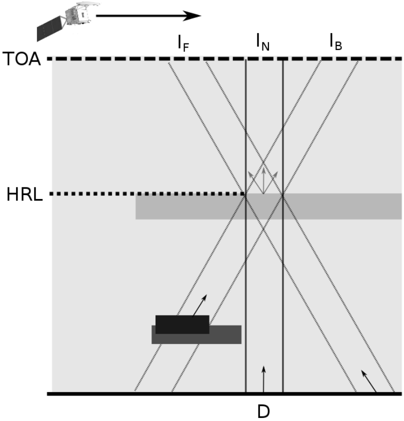

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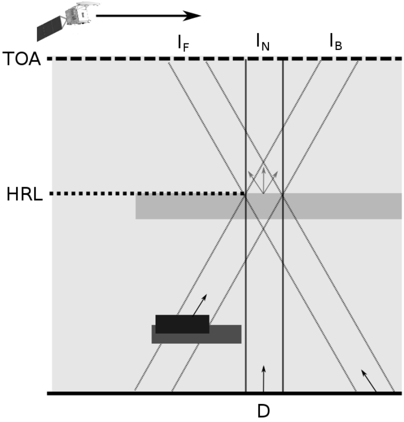

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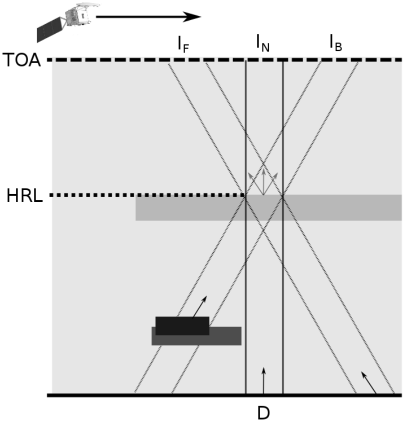

Idea of this (exploratory) work

utilize the 3D Monte Carlo RTM (simulating in the Radiative Closure)

- ▷ extract MC photon paths information
- ▷ know reflecting layer profile to each simulated radiance

- ▷ nadir profile defines scene structure
- ▷ find radiances in oblique views by:
  - comparing oblique profiles to nadir profile
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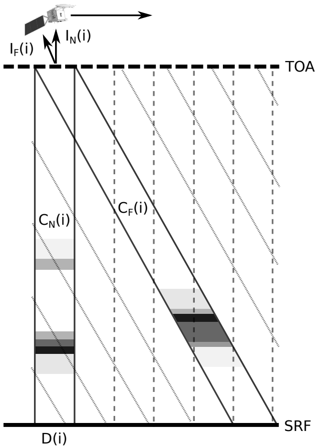
- ▷ **Maximum Similarity Co-Registration**



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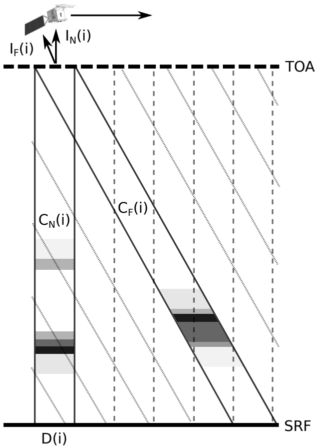

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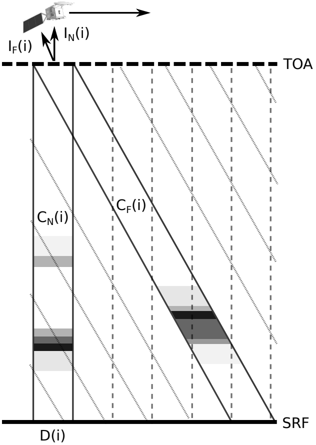

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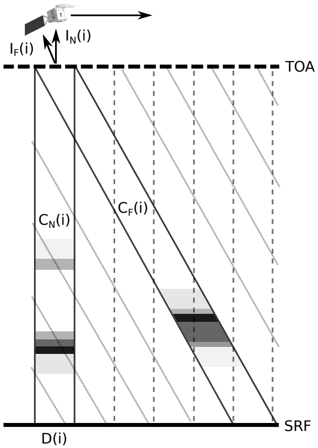

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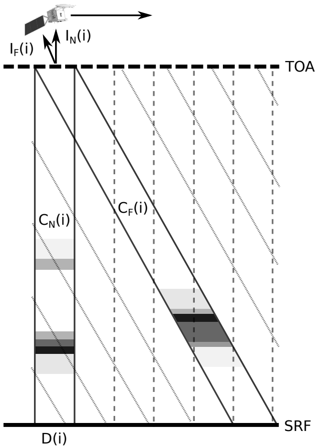

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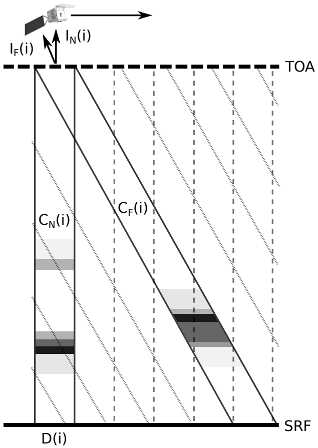
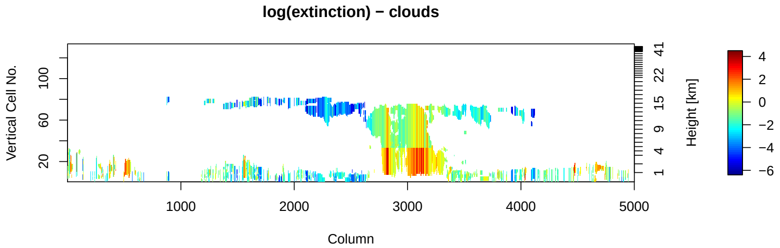


Experiments

based on CCCM data (A-Train) with vertical profiles of aerosol and cloud properties (similar to MSI, ATLID and CPR), but lacks BBR's oblique radiance measurements



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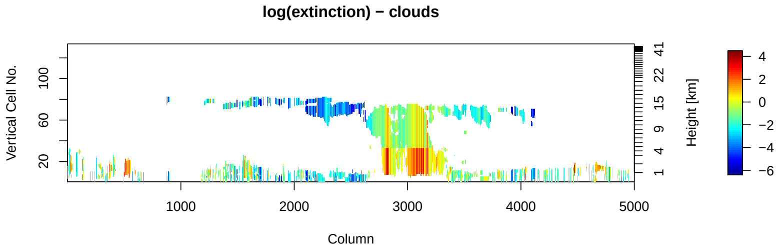

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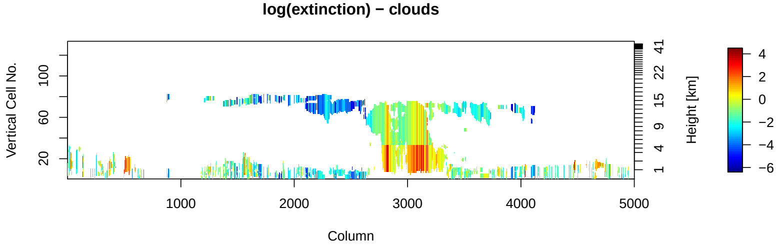

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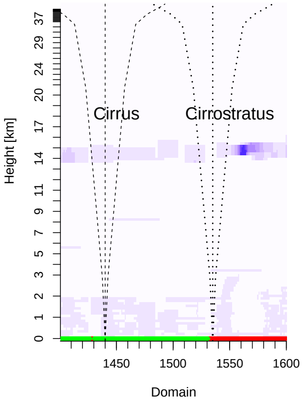

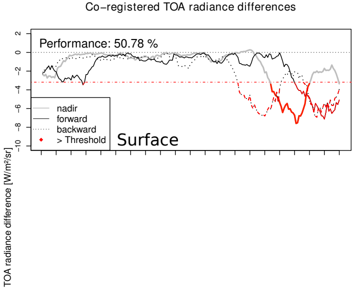

▷ Max. Sim. deals better with broken cloud fields

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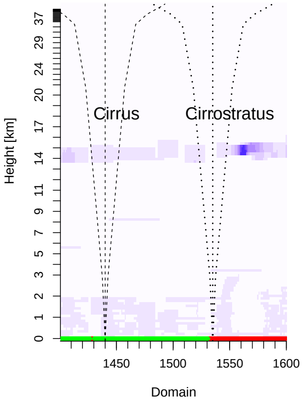

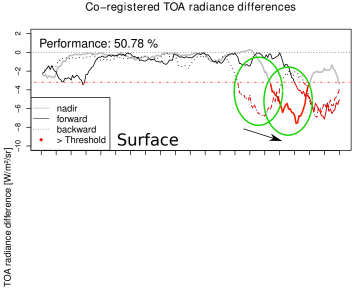

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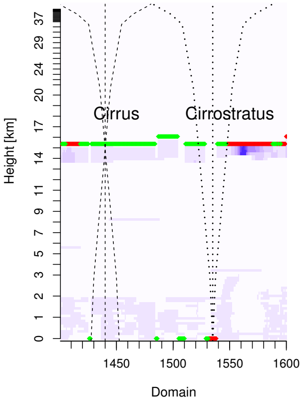

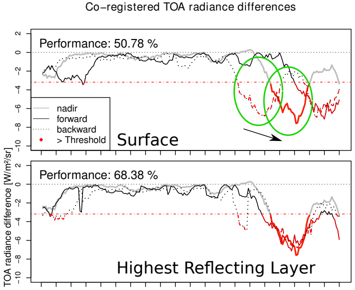

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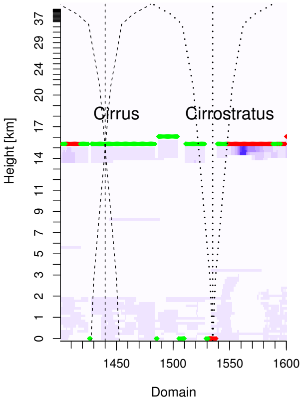

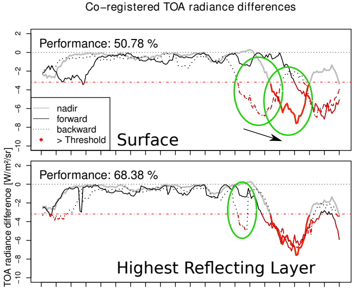

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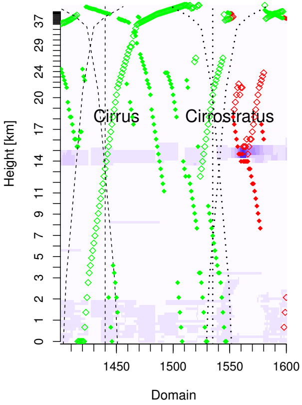

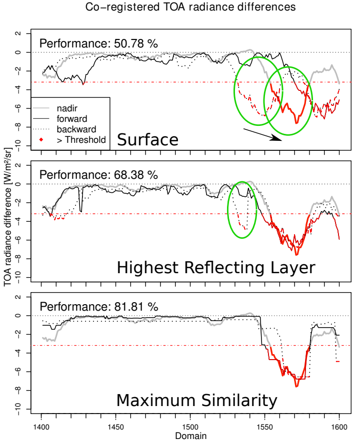

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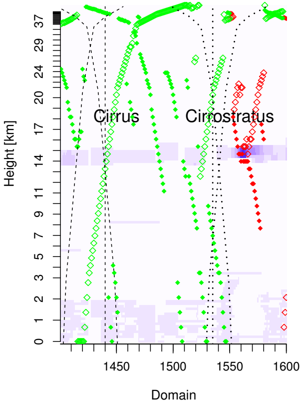

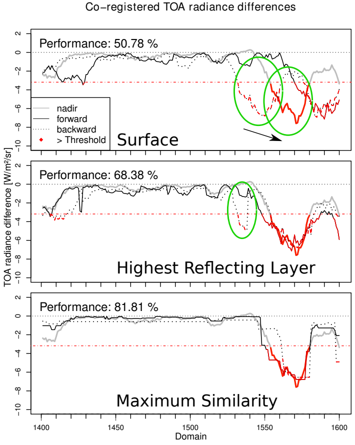

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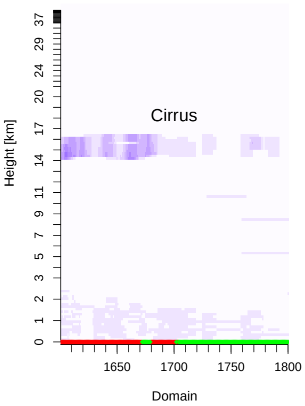

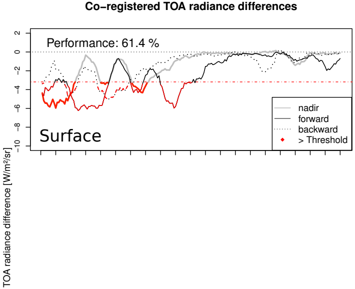

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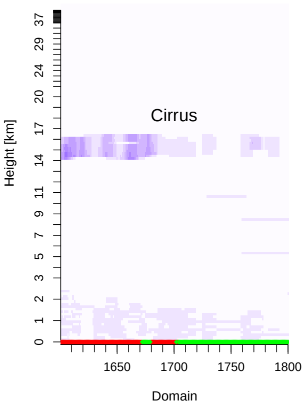

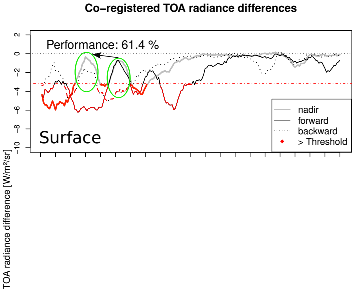

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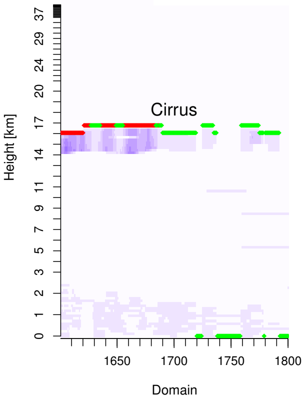

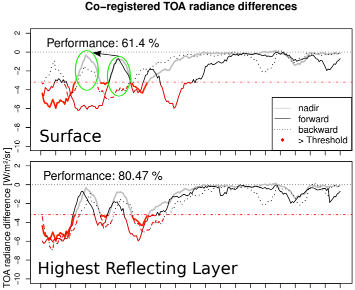

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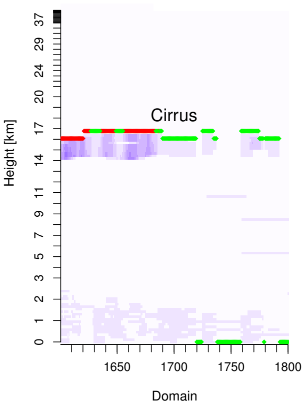

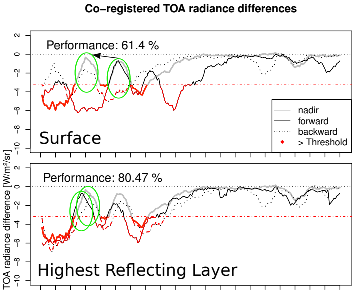

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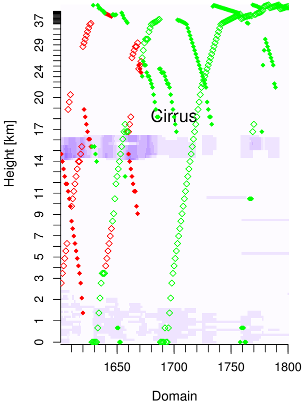

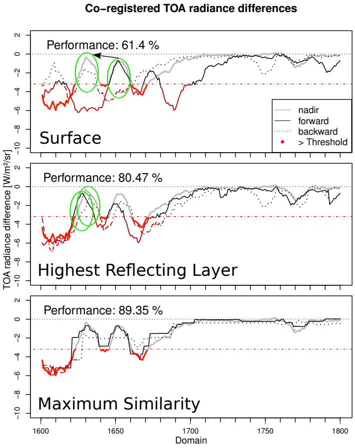

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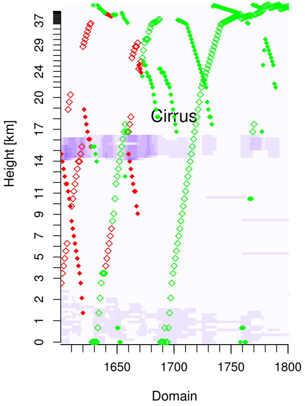

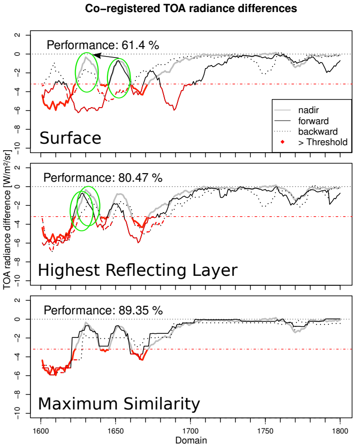

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  - against simulated counterparts by 3D Monte Carlo RTM
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  - problematic for semi-transparent or broken cloud fields
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  - use 3D MC photon paths
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Alternative: Closure with SW and LW fluxes

- BBR flux retrieval algorithm is based on the multi-view capability of the BBR and the synergy between BBR and MSI

- BBR viewing design characterizes the radiance field of the observed target from 3 AT directions → improving observation of the surface-atmosphere anisotropy
- Non-linear combination of MSI radiances provides information on the scene anisotropy of the target
- The radiance-to-flux models convert the 3 BBR measurements, collocated at the HRL of the atmosphere-surface system, into flux estimates. Then the radiative fluxes are merged, thereby enabling comparison of measurement-derived fluxes against model-derived fluxes from 1D and 3D RT models.

Methodology

- SW ADMs for every BBR viewing angle are constructed using a feed-forward back-propagation artificial neural network (ANN) technique
- CERES radiance, solar geometry, MODIS radiances over clear/cloudy FOV area, cloud cover and surface ancillary parameters are inputs of the ANN training
- CERES SW anisotropic factors are used as outputs
- election of ANN input parameters depend on the scene class observed
- LW TOA Fluxes are obtained through theoretical polynomial second order regressions on the MSI 'split-window' channels BT differences.
- Anisotropy models are classified in bins of 20 $Wm^{-2}sr^{-1}$
- A large RT-based geophysical database is used to train the data
- Anisotropic Factors are estimated from theoretical simulated thermal radiances and fluxes

Overall Results

Within the 5000km-long frame, different co-registration methods led to following results:

Domains	Characteristics	P(SRF)	P(HRL)	P(MXS)
1400-1600	Cirrus and Cirrostratus Clouds	50.78%	68.38%	**81.81%**
1600-1800	Cirrus Clouds	61.4%	80.47%	**89.35%**
2800-3000	Deep Convective Clouds (horizontally heterogeneous)	49.62%	90.23%	**92.04%**
3000-3200	Deep Convective Clouds (horizontally homogeneous)	36.14%	**82.10%**	78.17%
3600-3800	Cirrus Clouds and cloud-free zones	47.49%	87.27%	**89.32%**
1052/5000	Only domains with Cumulus Clouds	84.37%	**85.75%**	85.27%
1933/5000	Only domains with Cirrus Clouds	71.94%	87.38%	**91.98%**
181/5000	Only domains with Deep Convective Clouds	75.52%	**93.12%**	89.98%
1286/5000	Only cloud-free domains	0.45%	0.45%	**15.01%**

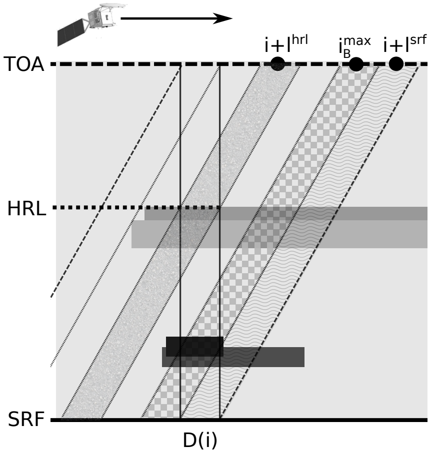
How does Maximum Similarity Co-registration work?

In order to select an off-nadir radiance

- ▷ take the nadir line-of-sight through reflecting layers of domain D
- ▷ and a subset of relevant off-nadir lines-of-sight (all intersecting with D)

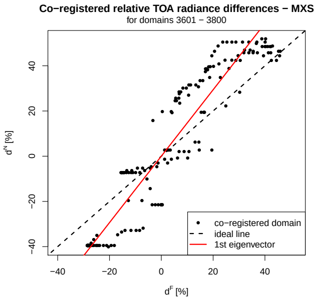
- ▷ determine pairwise similarity:
- ▷ $s = \cos\Theta = \langle \frac{C_{\text{nadir}}}{\|C_{\text{nadir}}\|}, \frac{C_{\text{oblique}}}{\|C_{\text{oblique}}\|} \rangle$

- ▷ pick the off-nadir radiance, belonging to the most similar off-nadir line-of-sight



How to measure the goodness of co-registration?

- in EarthCARE, co-registration serves to identify inaccurate retrieval
- for simplicity, we assume:
  - inaccurate retrieval of cloud parameters reduces/enhances radiances by a fraction
  - **equal relative difference between measured and simulated radiances in all 3 VZAs**



- relative difference:
  $d_i^v = \frac{I_v^M(i) - I_v^S(i)}{I_v^M(i)}$
- form a point m in $\mathbb{R}^3$:
  $m_i = \left(d_i^B, d_i^N, d_i^F\right)$
- which ideally lies on $\vec{u}$ with $n \in \mathbb{R}$:
  $\vec{u} = (1, 1, 1) \cdot n$
- hence, X should scatter around $\vec{u}$:
  $X = [m_1, \ldots, m_{n_D}]$
- or $\vec{w}_1$, the first Eigenvector of X, lines up with $\vec{u}$:
  $XX^T W = \lambda W = \lambda[\vec{w}_1, \vec{w}_2, \vec{w}_3]$
- with Eigenvalues λ:
  $\lambda = [\lambda_1, \lambda_2, \lambda_3]$
- **we measure the goodness of co-registration:**
  $P = \left(\frac{\vec{w}_1}{||\vec{w}_1||} \cdot \frac{\vec{u}}{||\vec{u}||}\right) \cdot \lambda_1 \cdot 100\%$

Caveats of using 3D photon paths

unrealistic 3D photon paths may happen because of:

- inaccurate retrieval
- inconsistent methodologies (3D scene constr., 3D MC RTM, ...)

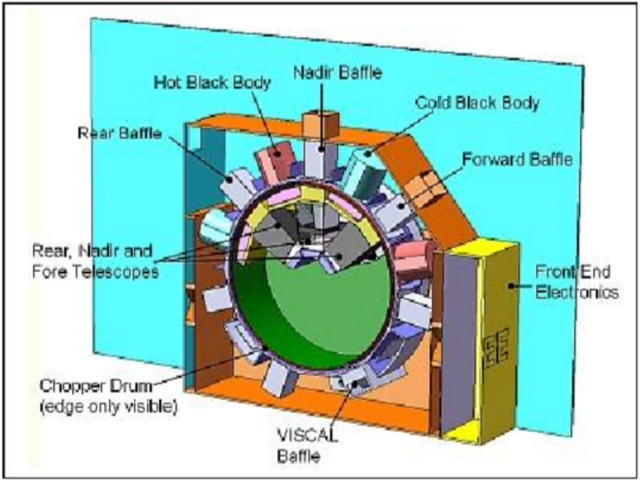
potentially:

- we expect to see something, which is not there
- we miss something, which is actually there

in case:

- the real structure is inaccurately retrieved
  - we identify it (by assigning just another errorous radiance difference)
  - we fail identifying it (by selecting a low radiance difference)
- the real structure is fine
  - we falsely identify it
  - we consider it fine

BBR - details on set-up



Overview of instruments

atmospheric lidar - ATLID

- measurements at 355nm
- molecule/cloud/aerosol separation
- every 100m with diameter of 5/12m

cloud profiling radar - CPR

- dopplerized 94GHz
- liquid/ice clouds, light rain
- resolution: vertical 500m, horizontal 750m

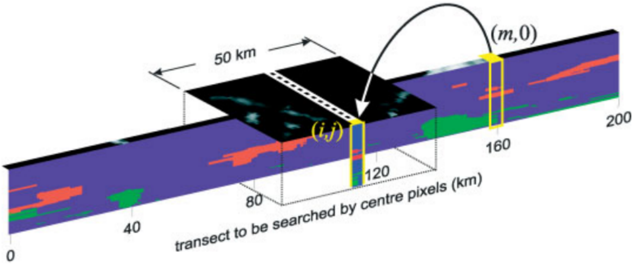
multispectral imager - MSI

- 500m pixel size, 150km swath width
- 4 solar channels, 3 thermal channels

broadband radiometer - BBR

- 3 spatialdirection - alongtrack 55°backward, nadir, 55°forward
- solar/thermal radiance
- 1km × 1km footprint in nadir
- for comparability/noise reduction transformed into 10km × 10km

Scene construction algorithm



Data

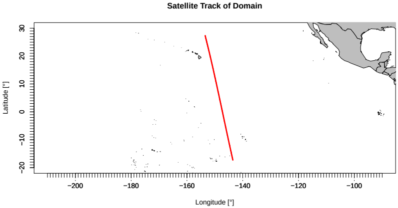
- ▷ 2D cross section (RXS)
  - vertical and horizontal information
  - clouds (liquid/ice), aerosols, gases
- ▷ 2D image of MSI (along and across track)

Algorithm

- ▷ combine RXS details and MSI info
  - donate RXS properties to off-track pixels
  - picking the most similar spectral footprint
  - in certain region around recipient pixel
- → obtain detailed information in **3D**

CCCM Data

- CERES-CALIPSO-CloudSat-MODIS (CCCM) consists of:
  - CloudSat's Cloud-Profiling Radar
  - CALIPSO's lidar
  - Terra's MODIS
  - and CERES



- CERES provides only radiances close to nadir , and lacks BBR's 2 off-nadir views
  - therefore, we generate both *BBR measurement* and *3D Monte Carlo RTS outputs*
- using a 5000km long section, measured on 5th July 2006 over equatorial Pacific

For devouring...

[Barker al., 2003]
Monte Carlo Simulation of Solar Reflectances for Cloudy Atmospheres,
Journal of the Atmospheric Sciences, 60(16):1881-1894, 2003.

[Barker al., 2011]
A 3D cloud-construction algorithm for the EarthCARE satellite mission,
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FLURB - FLUx Retrievals from EarthCARE BBR Observations,
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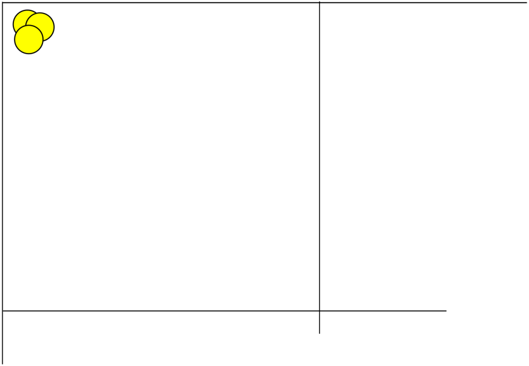
[EarthCARE Mission Advisory Group, 2006]
EarthCARE Mission Requirements Document,
ESA and JAXA, 2006.

[ESA, 2011]
EarthCARE mission instruments Fact sheet,
European Space Agency, 2011.

3D Monte Carlo RTS

- 3D radiative transfer
- distribute photons over whole domain
- follow each bunch of photons
- at each event:
  - use phase function
  - calculate rad. contribution to BBR observations



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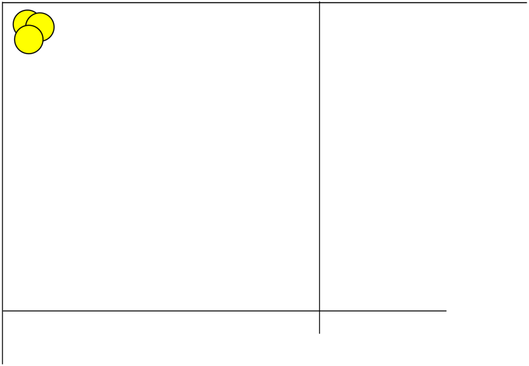

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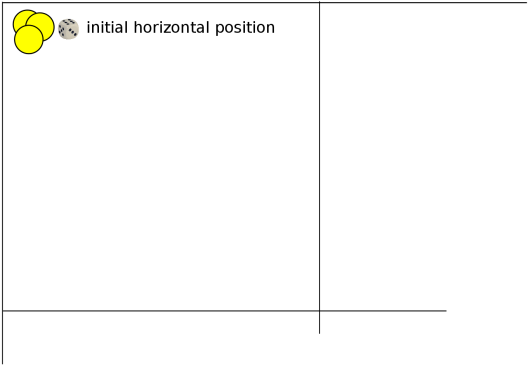

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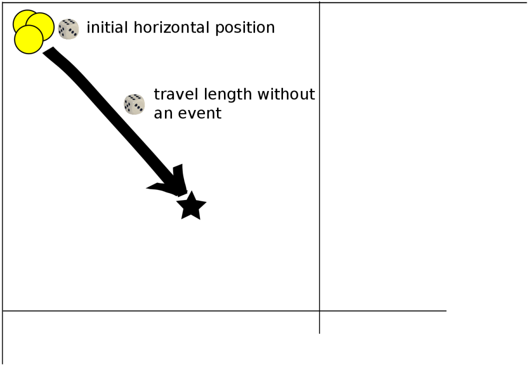

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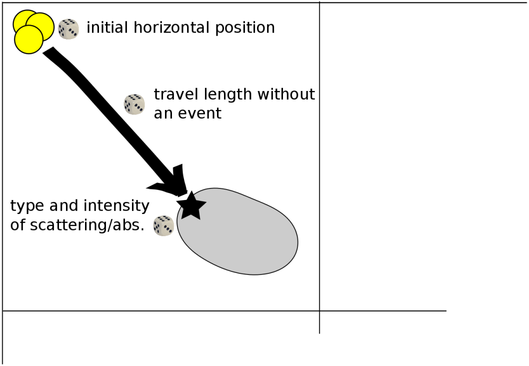

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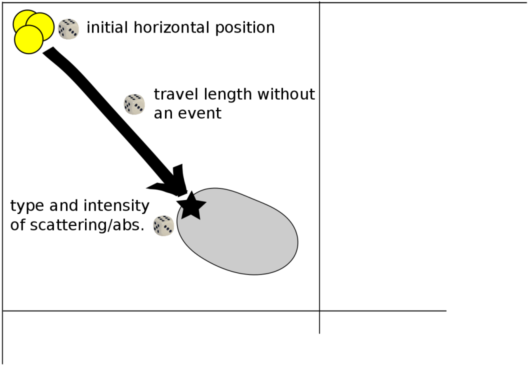

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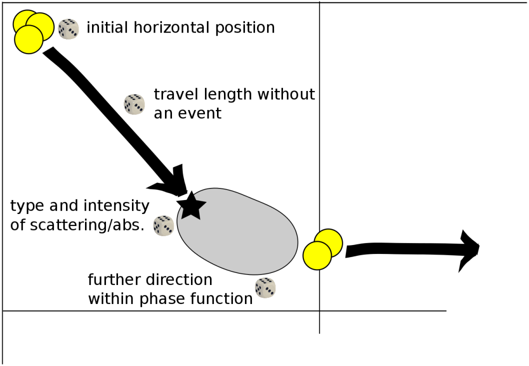

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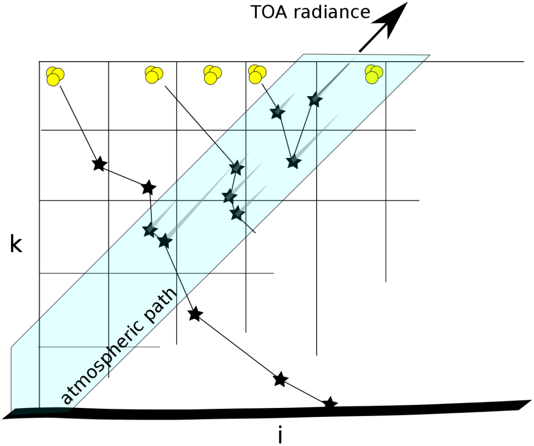
- obtain TOA radiances
  - the sum over all radiative contributions
- and full atmospheric paths for each viewing direction
  - a vector of radiative contributions for each vertical level



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