The EarthCARE Simulator: A unified Active and Passive Atmospheric Remote sensing End-to-End Simulation System

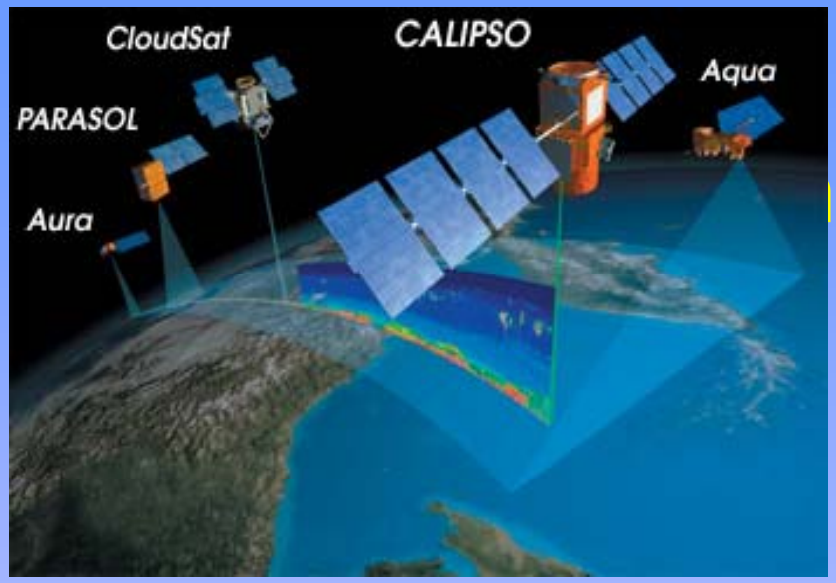
D.Donovan KNMI

Contributions from many others….

Outline

- The Earth Clouds and Radiation Explorer Mission
- The EarthCARE simulator.
- Sample Applications.
- New (ground-based) developments
- Future of the simulator.
- Conclusion

Active Atmospheric Cloud/Aerosol/Rad. missions

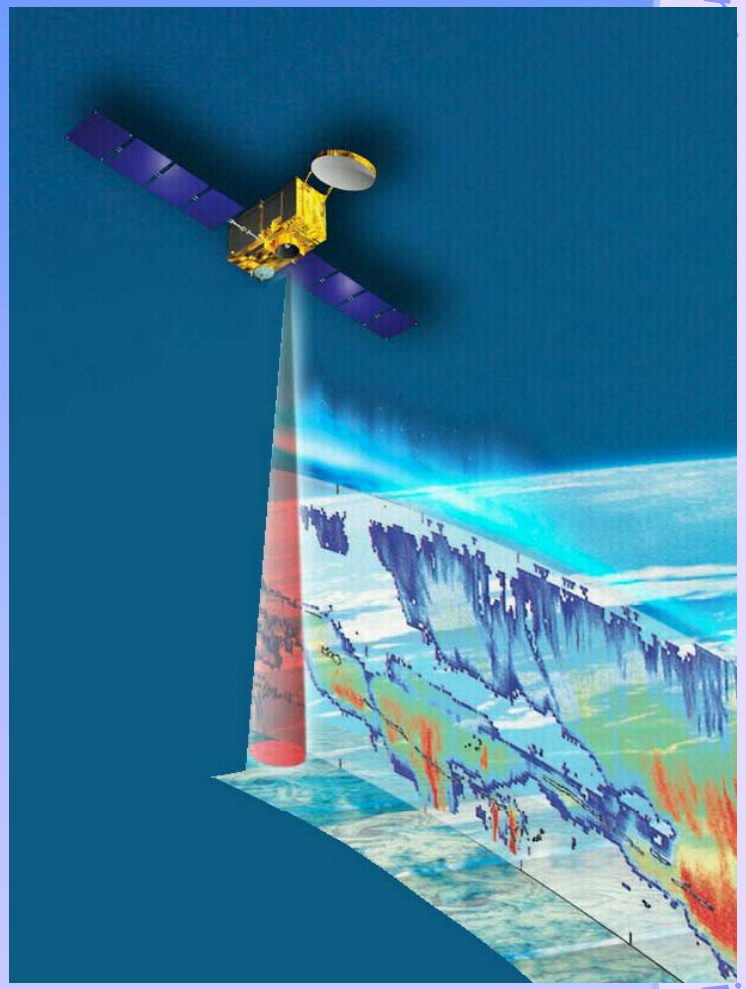


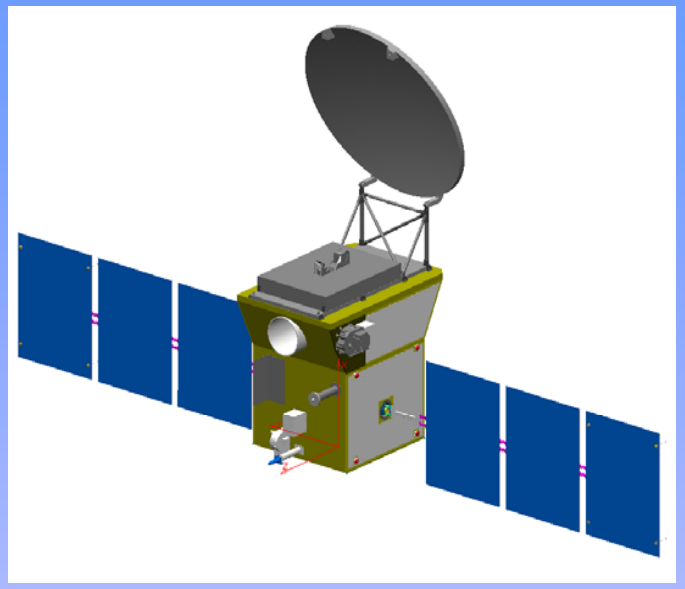
- CloudSAT (Cloud radar)
- CALIPSO (Lidar)
- Launched !

- **ADM (Atmospheric Dynamics Mission)**
- **Doppler Lidar. Wind is primary product but cloud/aerosol products will be generated.**
- **Launch 2008**

- **EarthCARE (Earth Clouds And Radiation Explorer**
- **Lidar+Radar+MSI+BBR on one platform**
- **ESA/Japan Effort**
- **Launch (2012)**

Make vertically resolved measurements of the cloud and aerosol distribution such that the radiative flux profiles can be modeled with an accuracy consistent with TOA accuracy of 10 W/m^2





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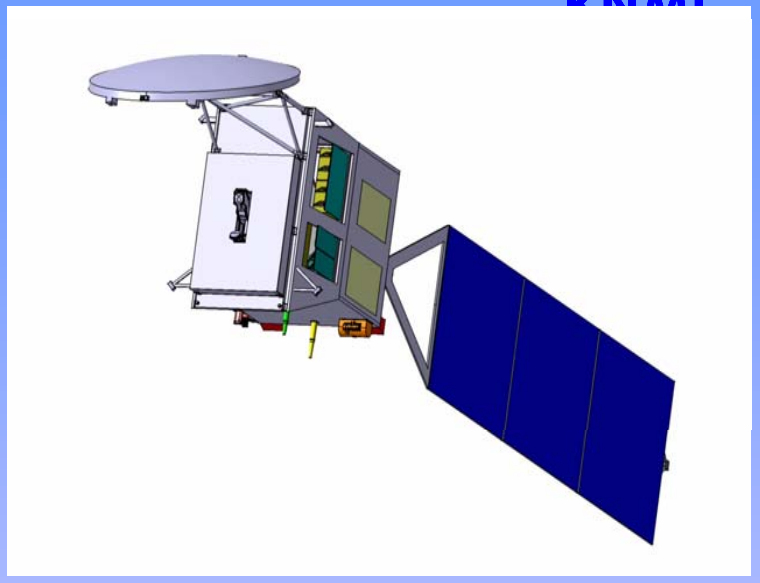
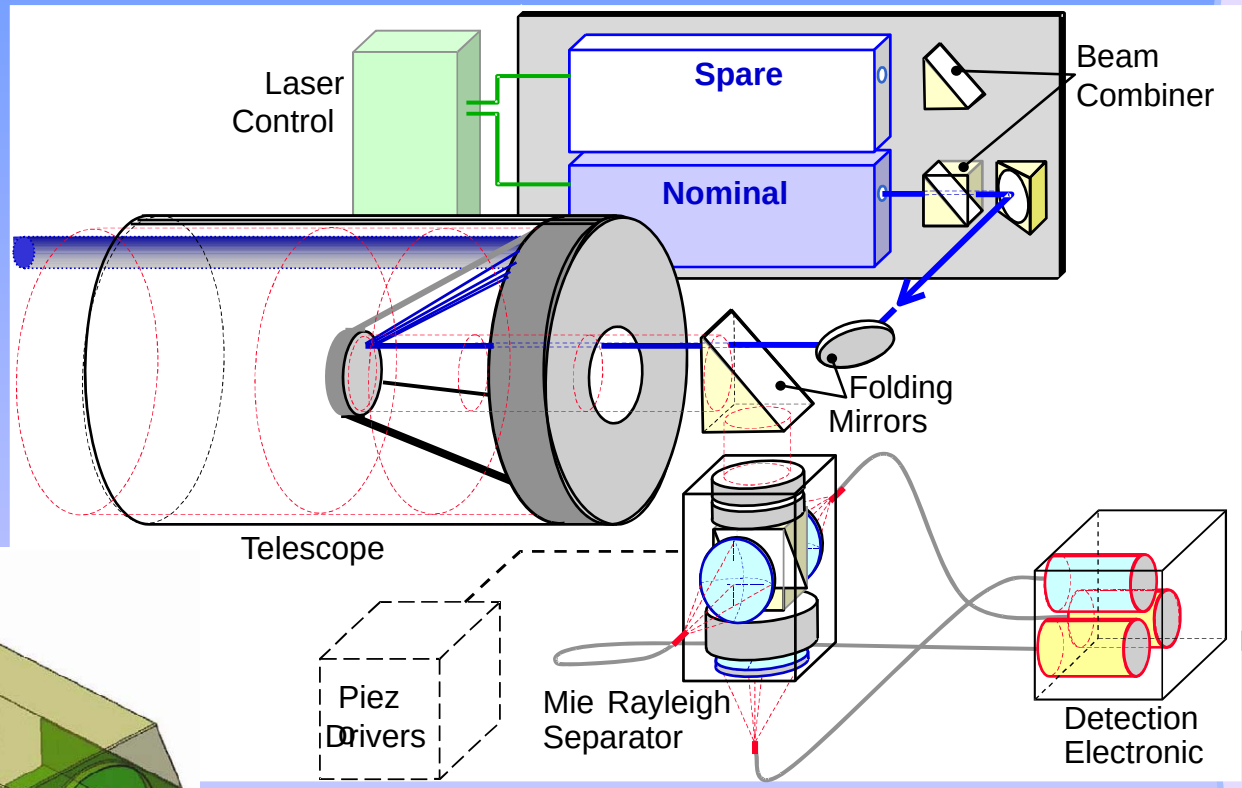
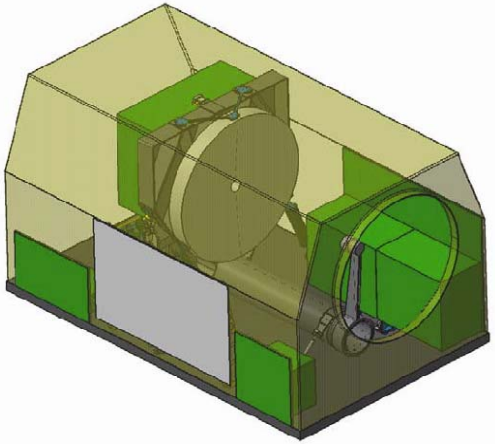


- High Spectral Resolution Lidar
- Doppler Cloud Radar
- Multi-spectral Imager
- 3 view Broad-band radiometer

ATLID Configuration

A UV backscatter lidar with High Spectral Resolution Receiver



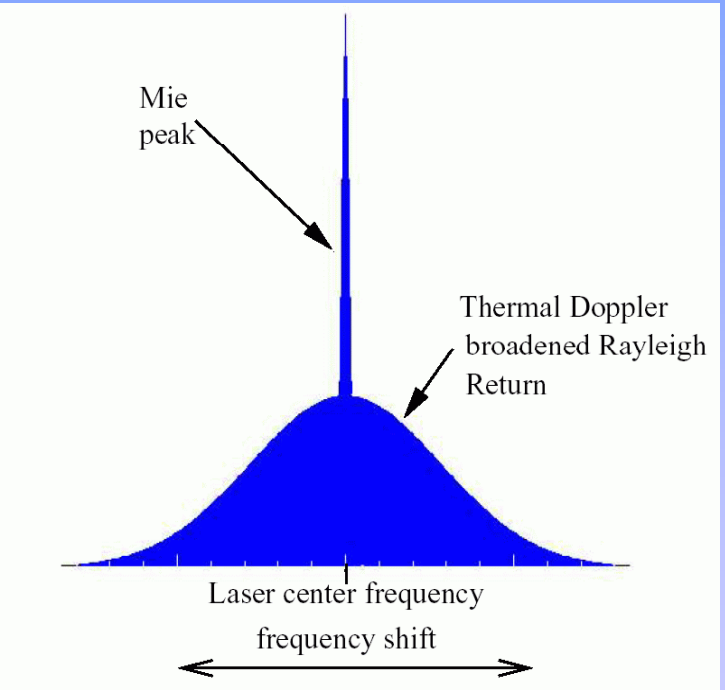


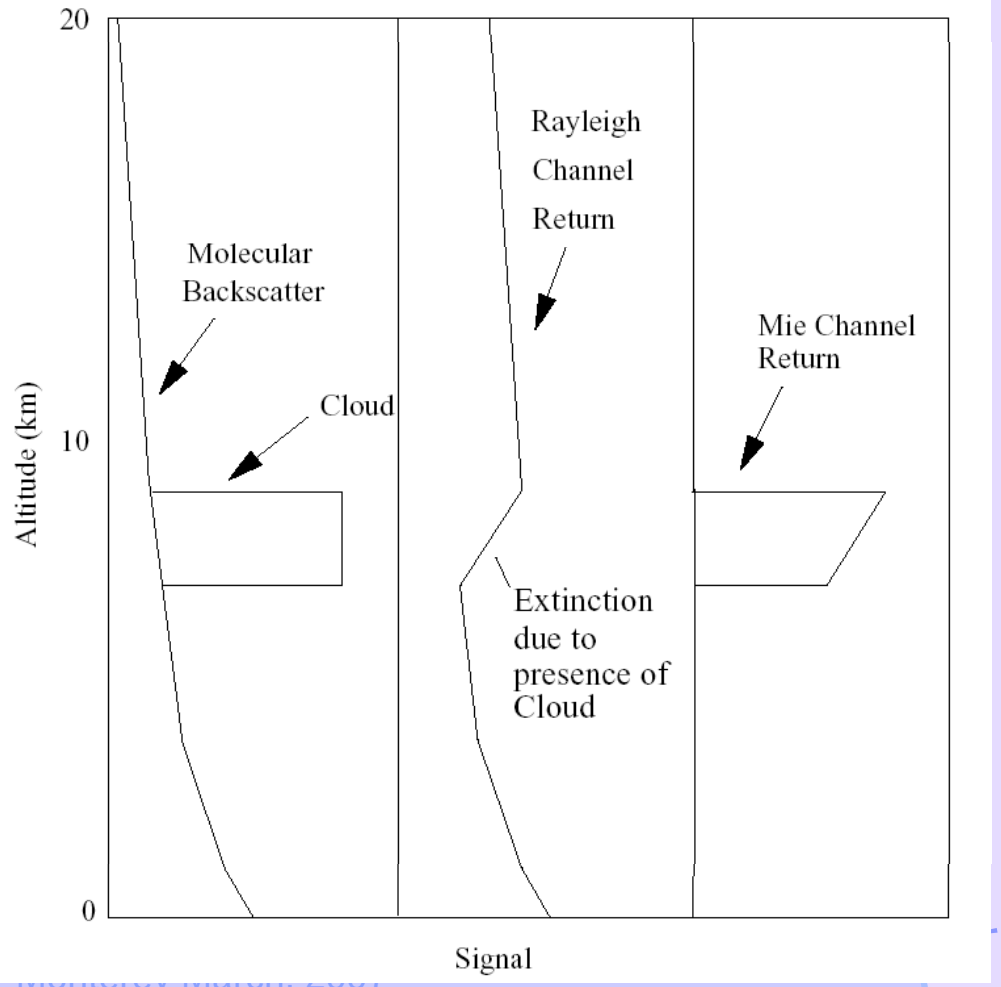
Mass: **< 230 kg**

Power: **< 308 W**

Data rate: **< 822 kb/s**

High Spectral Resolution Lidar

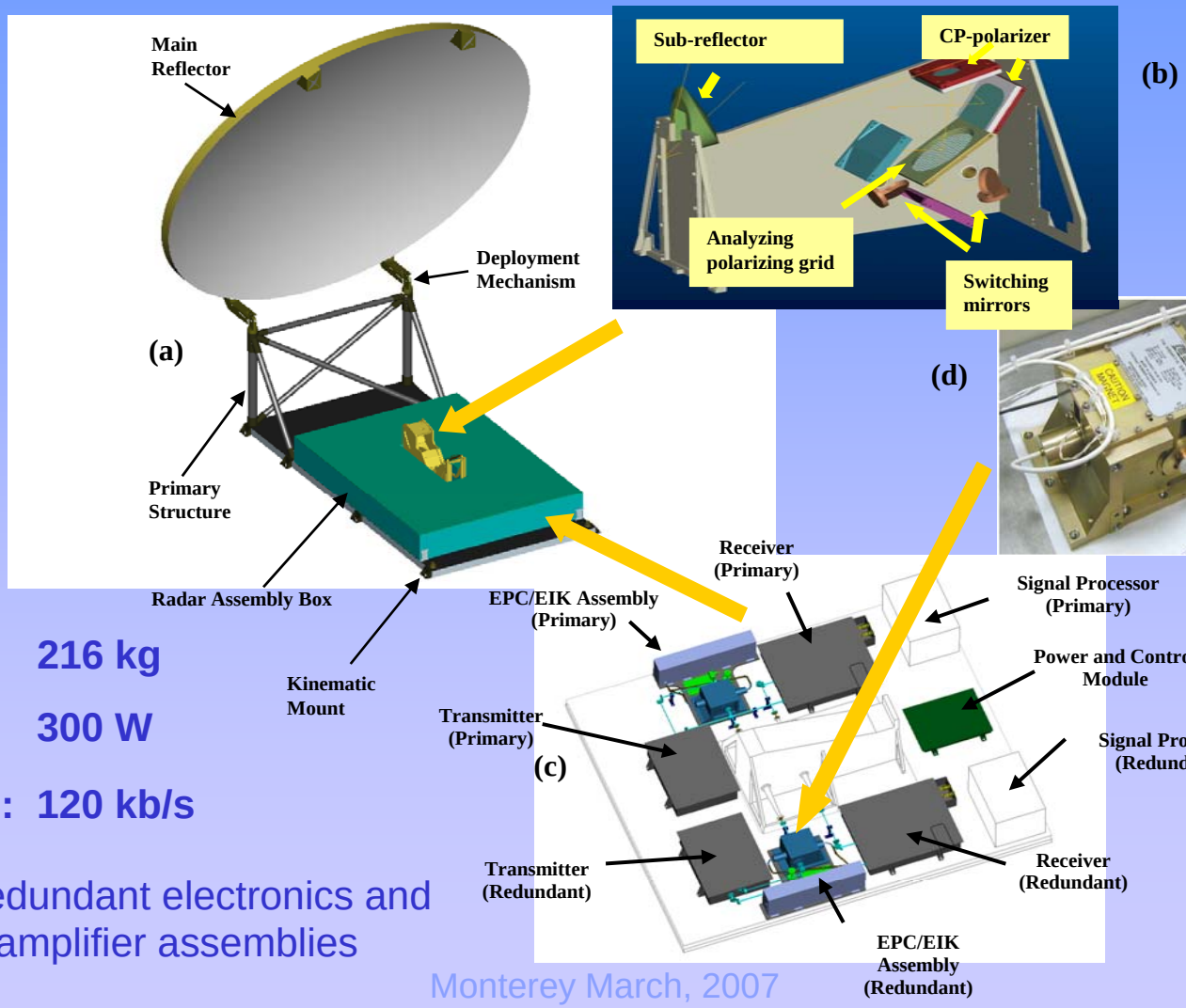




Cloud Profiling 94 GHz Doppler Radar

- Provided by NiCT JAXA -

KNMI



Mass: 216 kg

Power: 300 W

Data rate: 120 kb/s

- Fully redundant electronics and power amplifier assemblies

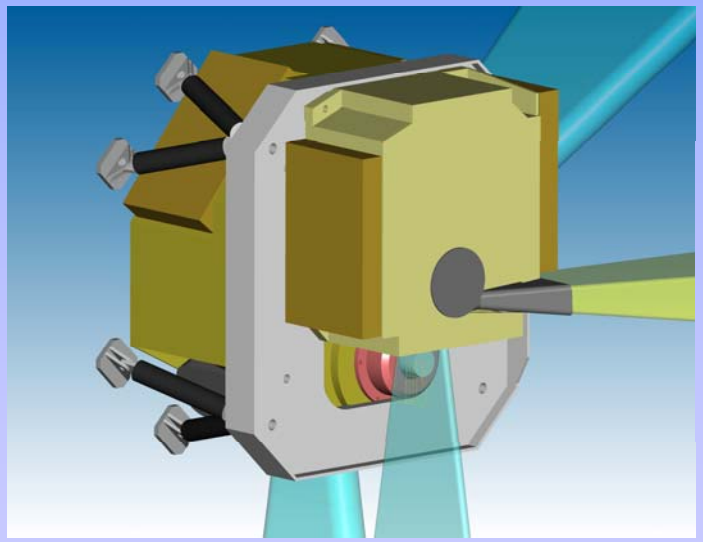
PASSIVE Instruments

Multi-spectral imager (MSI)

150 km swath with

7 channels from visible (0.6 um) to the thermal infrared (12.0 um) and 500m resolution

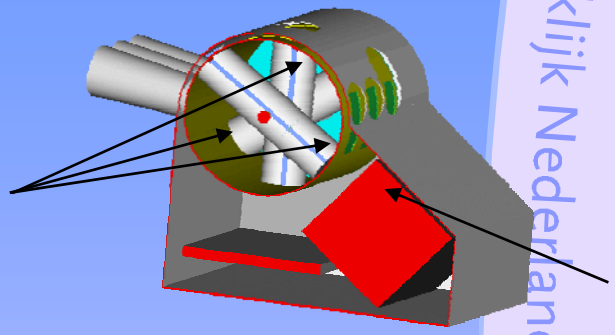
Cloud types
Ice/Water phase
Cloud optical thickness
Effective radius
Aerosol optical thickness
Surface reflectance
Surface temperature

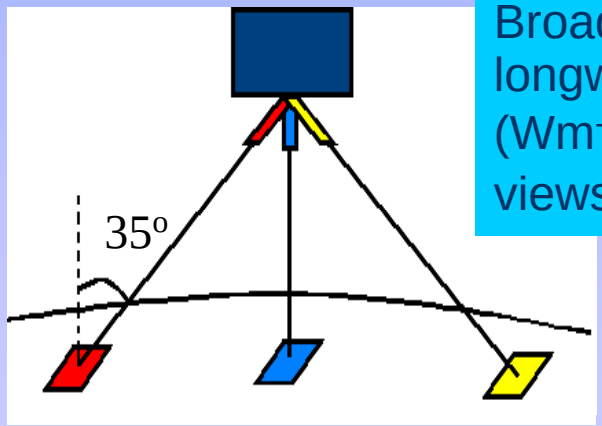


Name	λ (microns)
Vis:	0.659
NIR:	0.865
SWIR1:	1.61
SWIR2:	2.2
TIR1:	8.8
TIR2:	10.8
TIR3:	12.0

Broad-Band Radiometer (BBR)

3 -views, 2 channels
SW: 0.2-4.0 microns
LW: 4.0-50.0 microns





Broadband short- and longwave radiances ($Wm^{-2}sr^{-1}$) with 3 along-track views for 10 km pixels

Instantaneous **SW, LW TOA fluxes**

The EarthCARE (+) Simulator

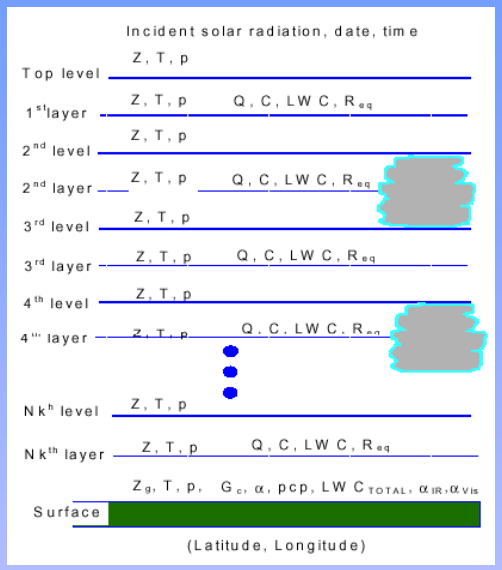
D.Donovan[1], P.Baptista[2], H. Barker[3], A. Bealune[4], J-P Blanchet[4], M. Quante[5], N. Schutgens[1], J. Testud[6], W. Szyrmer[4].
with input from. J. Cole[7], S. Kato[8]

1-KNMI the Netherlands
2-ESA/ESTEC the Netherlands
3-MSC, Canada
4-UQAM, Canada
5-GKSS, Germany
6-CETP/IPSL France.
7-Penn State, USA
8-NASA langely USA

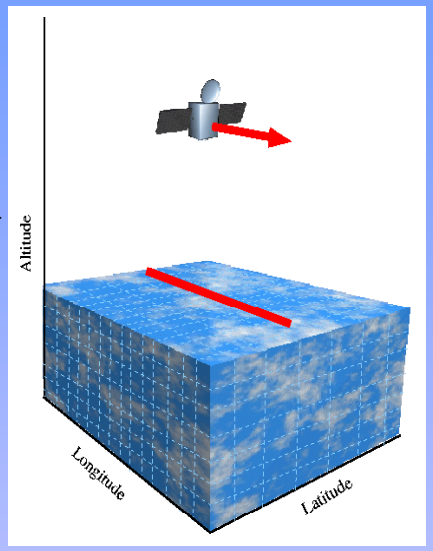
Mission Simulator

- Quantify the performance of the individual instruments.
- Quantify the performance of the platform as a whole w.r.t. mission science goals.
- Tool to help develop novel synergetic approaches to dealing with the data (algorithm development).
- End-to-end simulation capability.

- Model Atmosphere



Forward model(s)



Synthetic observations

Inversions

Compare

- - - -

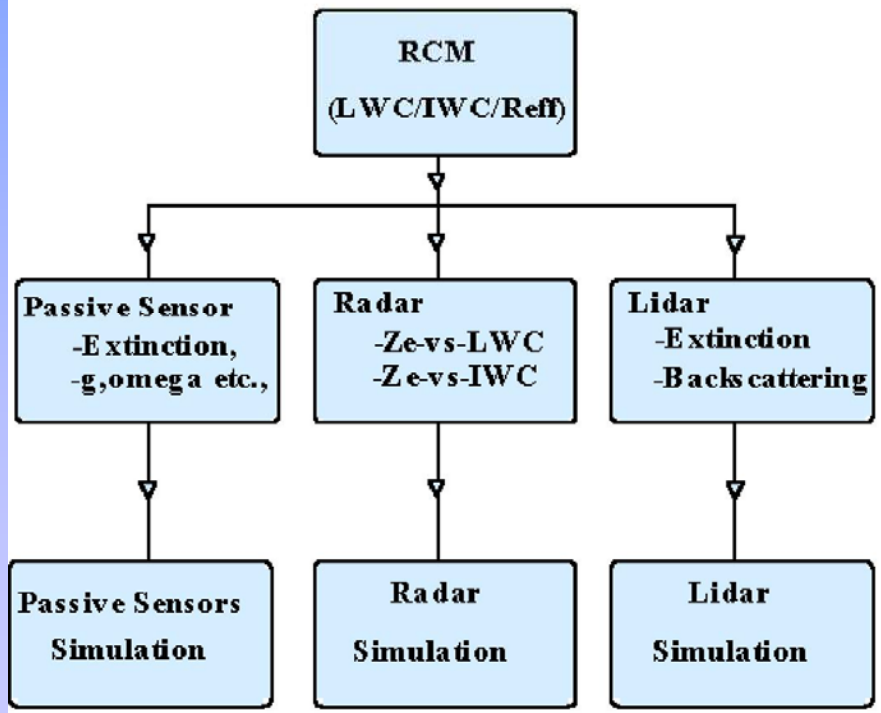
Monterey March, 2007

Features

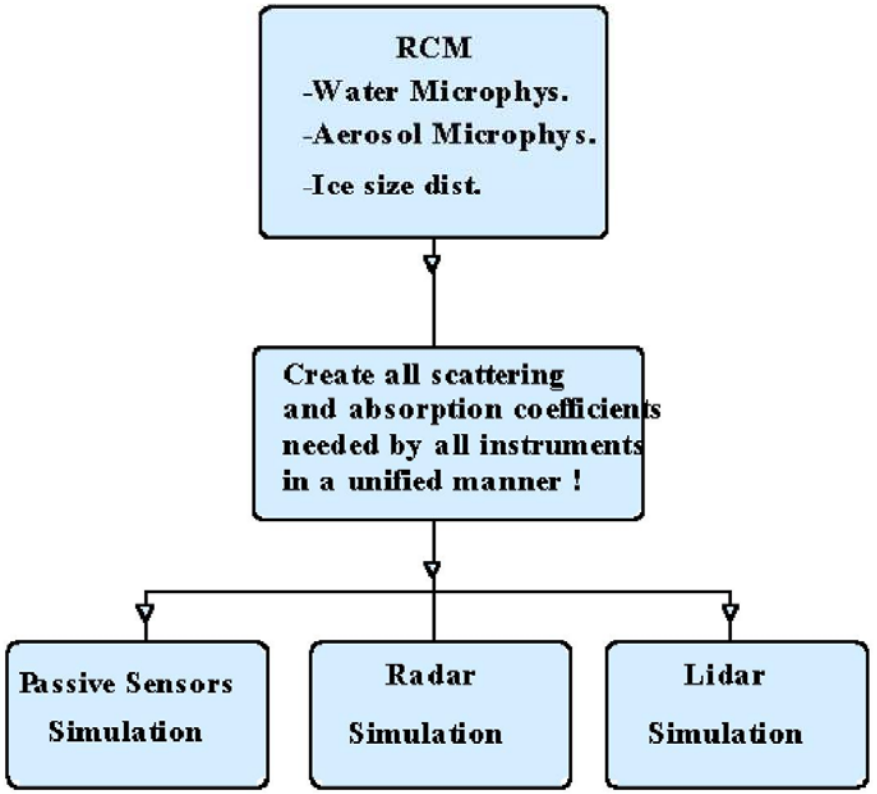
- 3-D Monte Carlo Radiative transfer codes used for Passive instrument simulations.
- 3-D Monte Carlo simulation of Lidar returns.
- Realistic Noise levels calculated via instrument parameters
- All instrument treated in a consistent fashion. Crude instrument specific parameterisations have been avoided.
- Both simple user defined scenes can be treated as well as complex scenes derived from cloud resolving model data.

Built primarily for Ecare but is inherently adaptable to other platforms and instruments !!

Fragmented Approach -Vs- Unified Approach

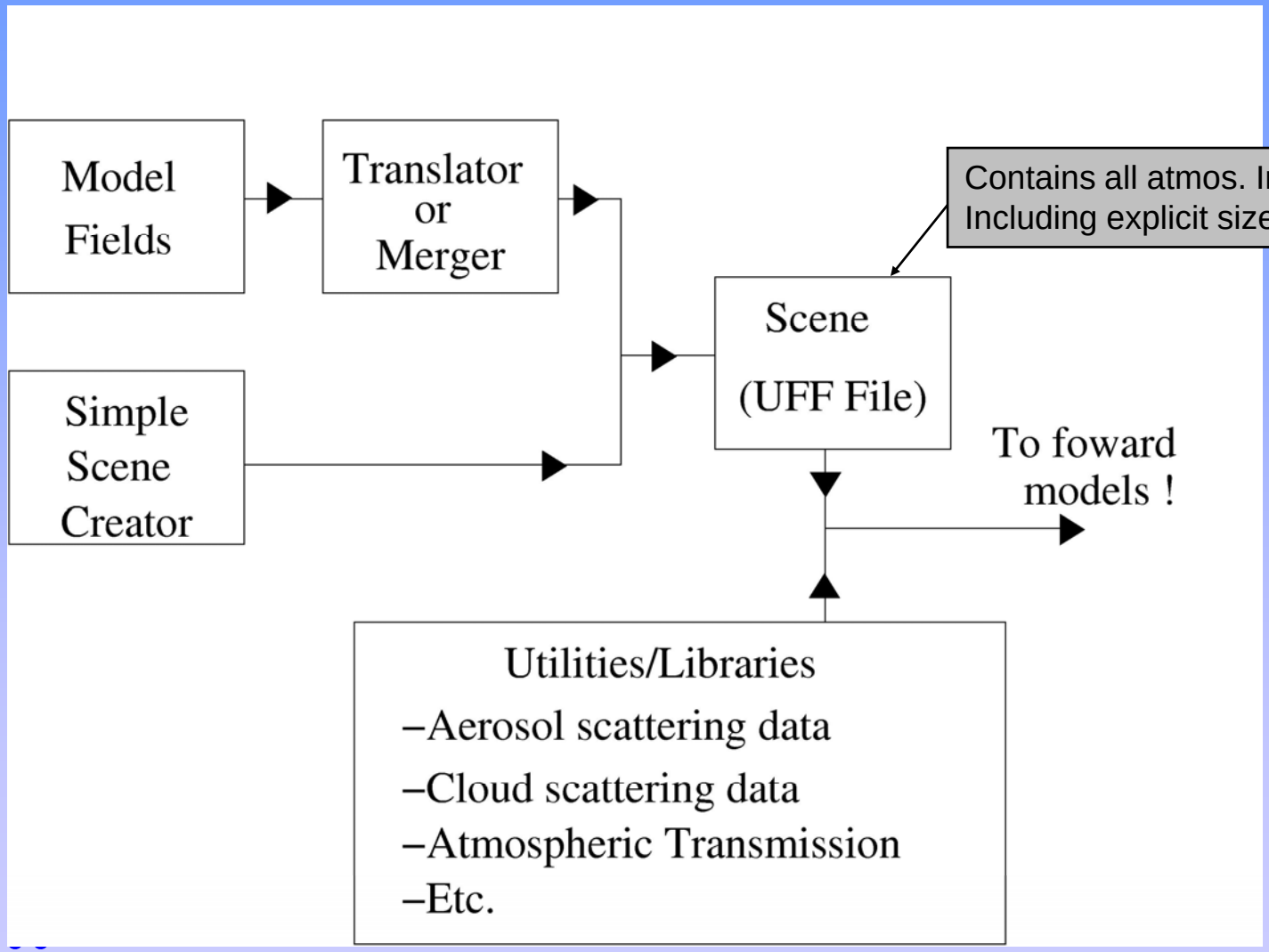


SYPAI
(ERM Simulator)



EarthCARE
Simulator

Modular unified approach



Collection of application meant to be used individually or linked together by any scripting environment

More of a `toolbox' type approach than anything else

Coded mainly in F90 making heavy use of its `modern' features.

Main Components

Forward Model Programs	
`lid_filter`	A 3-D Monte-Carlo lidar multiple-scattering engine. The code accounts for polarization and spectral effects
`lidar`	A lidar instrument module which simulates the lidar optical filtering and other instrument effects. This application relies on the output of `lid_filter`
`rad_filter`	Creates idealized radar reflectivity (Z) and radar Doppler velocity (V_d) fields.
`radar`	Samples the output of `rad_filter` and accounts for radar sampling and instrument effects.
`MC_sim_main`	A 3-D Monte-Carlo code for calculating Top-of-Atmosphere (TOA) short-wave radiances as well as Fluxes throughout the domain.
`MC_LW_sim_main`	A 3-D Monte-Carlo code for calculating Top-of-Atmosphere (TOA) long-wave radiances as well as TOA Fluxes

Retrieval Programs	
`lidar_ret1`	Processes data from `lidar` and `radar` and generates level 1 profile output products.
`msi_ret`	Uses the output of **MC_sim_main** and **MC_LW_sim_main** to generate standard MSI level 1 2-D cloud and aerosol products.
`lw_msi_lidar_radar`	Combines the output of `lidar_ret1` together with **MC_LW_sim_main** in order to retrieve the 3-D cloud property field.

And Further…..

Utility Programs	
scene_creator	Generates a *scene file* in the so-called simulator *Universal File Format* (UFF). The UFF file generated can be a 'simple-scene' based on direct user input. scene_creator can also be used to facilitate the translation of more complex cloudy scenes (i.e. those derived from cloud resolving atmospheric models) into a UFF file.
extract_quantity	A utility for extracting 2-D 'slices' of various quantities from a UFF file
extract_quantity_hor	A utility for extracting 2-D integrated column values of various quantities from a UFF file
extract_quantity_3d	A utility for extracting 3-D fields of various quantities from a UFF file
uff_merger	A utility for merging two UFF files together in the vertical
uff_averager	A utility for creating a lower resolution version of a UFF file.

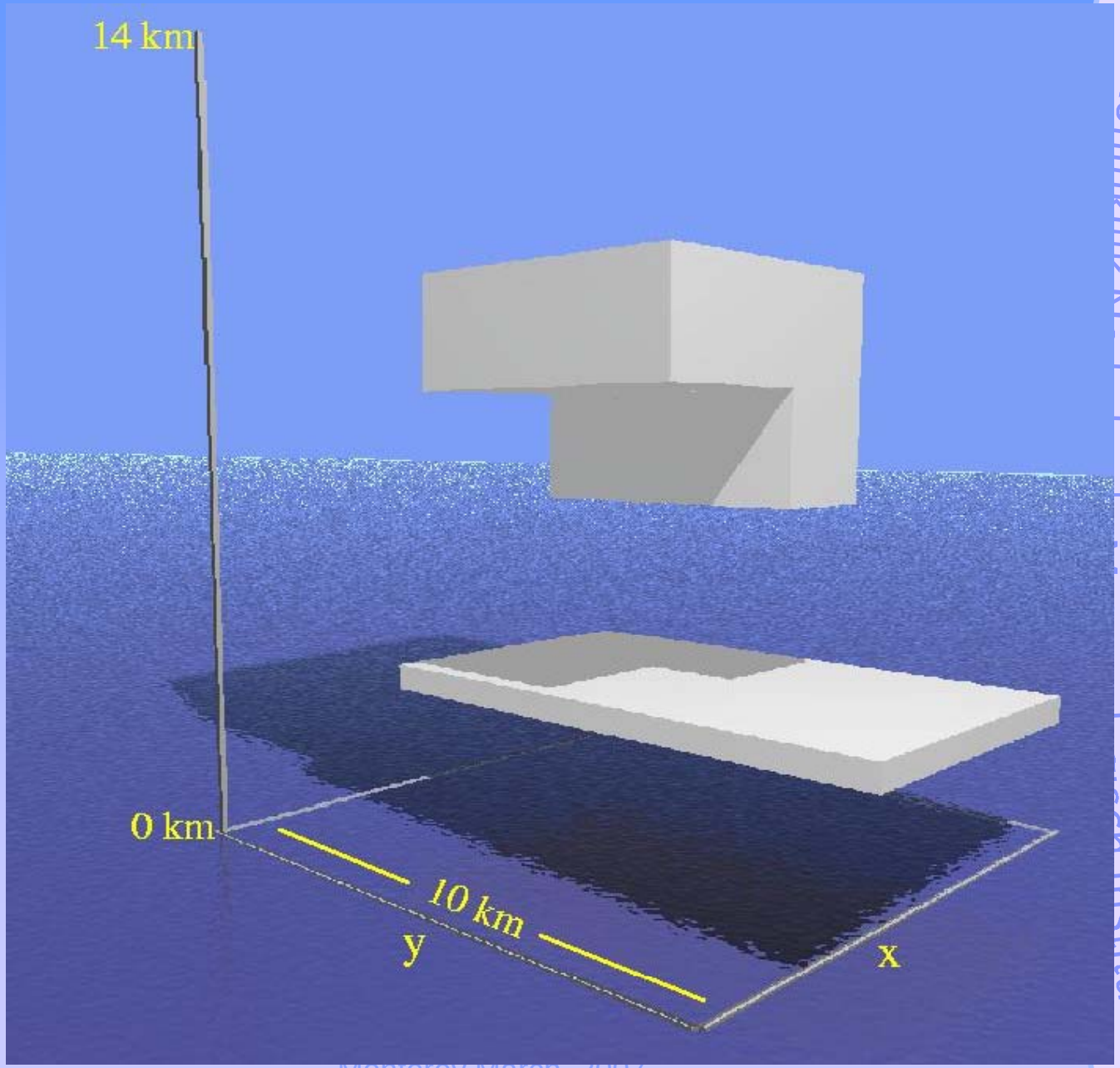
Graphics Programs	
plot_slice	A utility for plotting the results of **extract_quantity**, **lidar**, **radar** and , lidar_ret1.
plot_hor	A utility for plotting the results of **extract_quantity_hor** and , msi_ret.
plot_3d	A utility for producing 3-D plots from the results of **extract_quantity_3d**.
plot_profile	As plot_slice but plots vertical profiles.
plot_profile_comp	As plot_slice but plots vertical profiles from two different data files together
mcrad_quick_plot	A utility for plotting the results of MC_sim_main and MC_LW_sim_main.

Present Retrieval Algorithms

- Single Instrument products (for example..)
  - Lidar Cloud mask and extinction
  - Radar Cloud mask
  - MSI SW optical depth
- Synergetic products (for example…)
  - Lidar+Radar cloud mask (target classification)
  - Profiles of ice cloud effective particle radius
  - Lidar+Radar+MSI 3D scene reconstruction

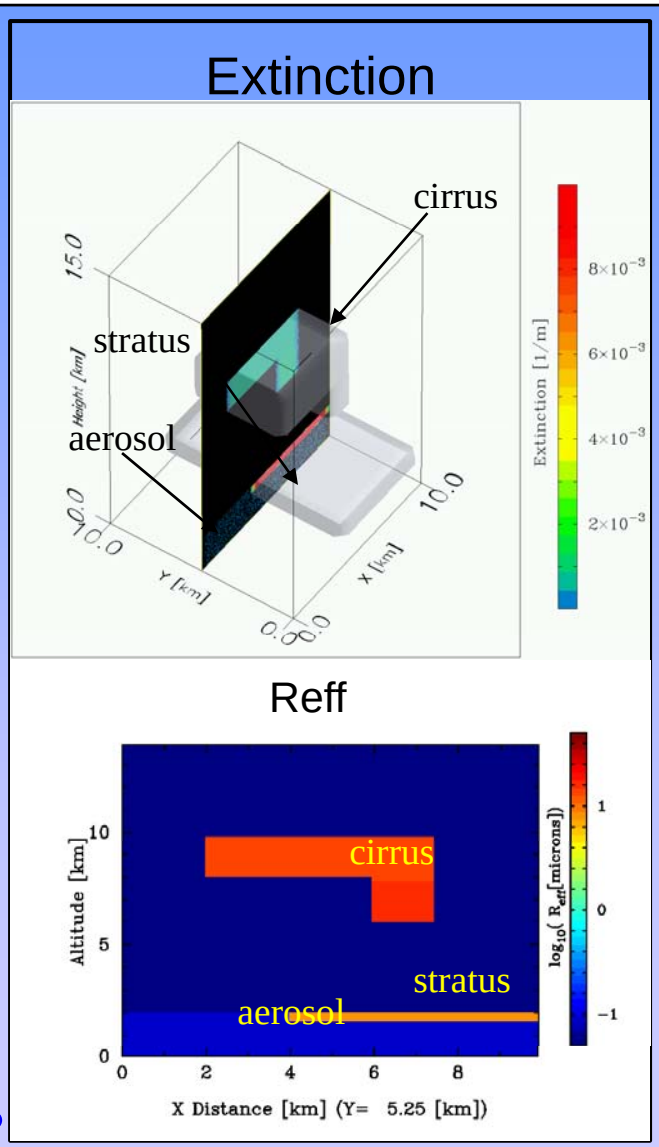
Many more could be added !!

A Sample*
`Simple' scene



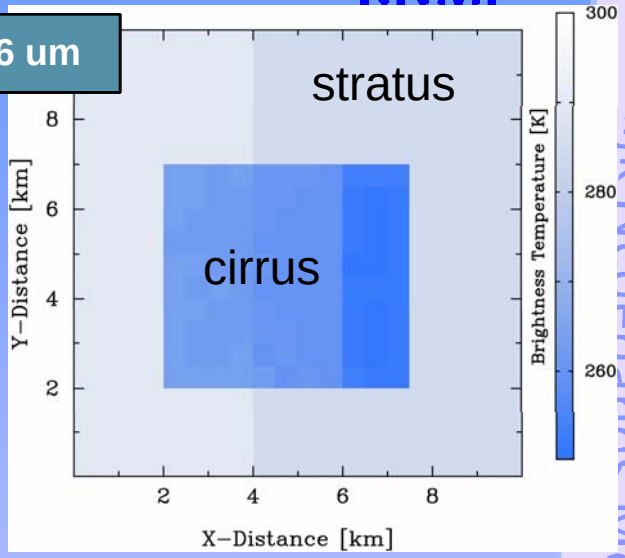
*Artistic impression only

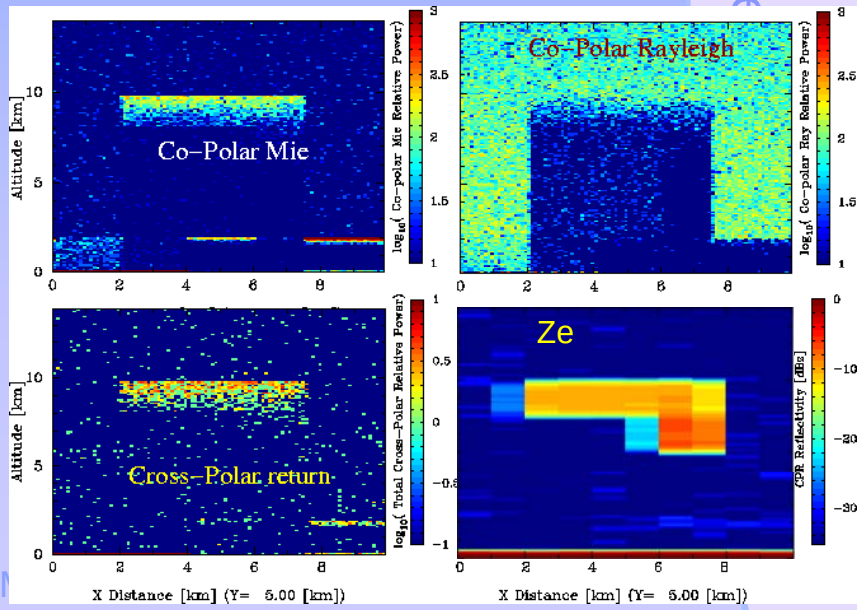
Mission Performance
EarthCARE Simulator - Example atmospheric scene



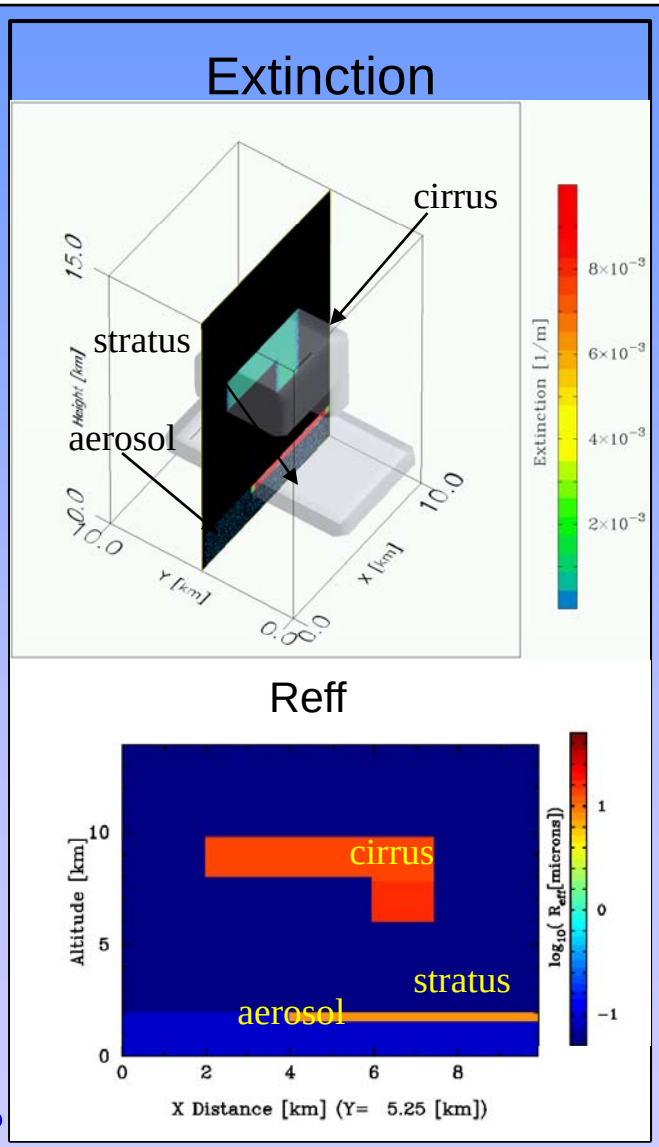
Lidar + Radar

MSI 8.6 um



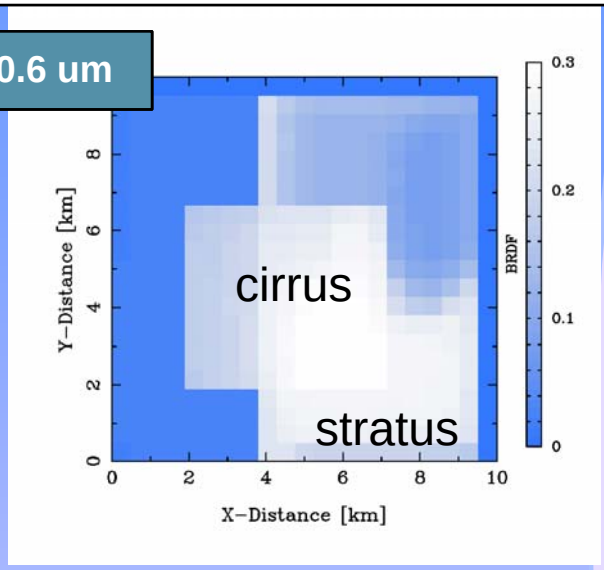


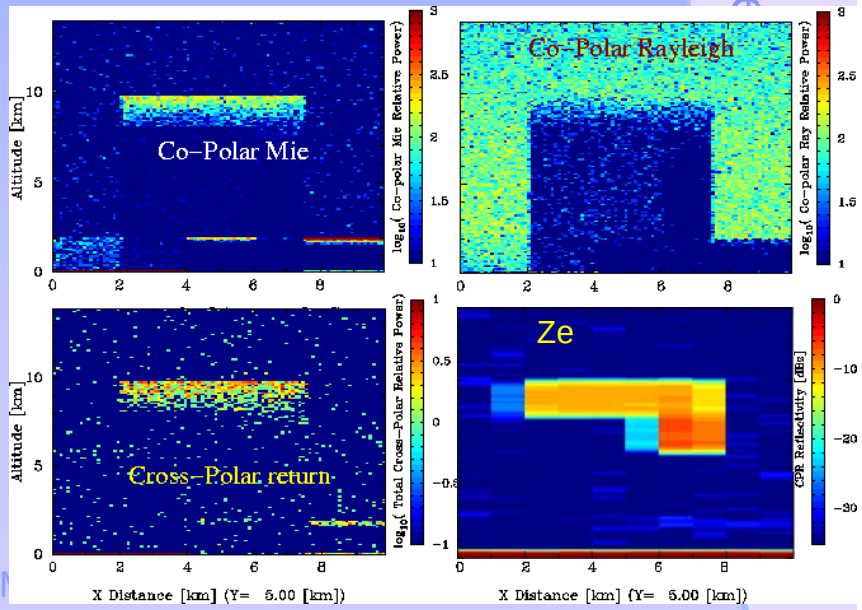
Mission Performance
EarthCARE Simulator - Example atmospheric scene



Lidar + Radar

MSI 0.6 um





How to combine things.....

- How to put things together in a useful (optimal) fashion. ?
- Lots of room for new ideas.
- Optimal estimation combination of separate products ?
- Neural networks ?
- Model to observation approaches ?

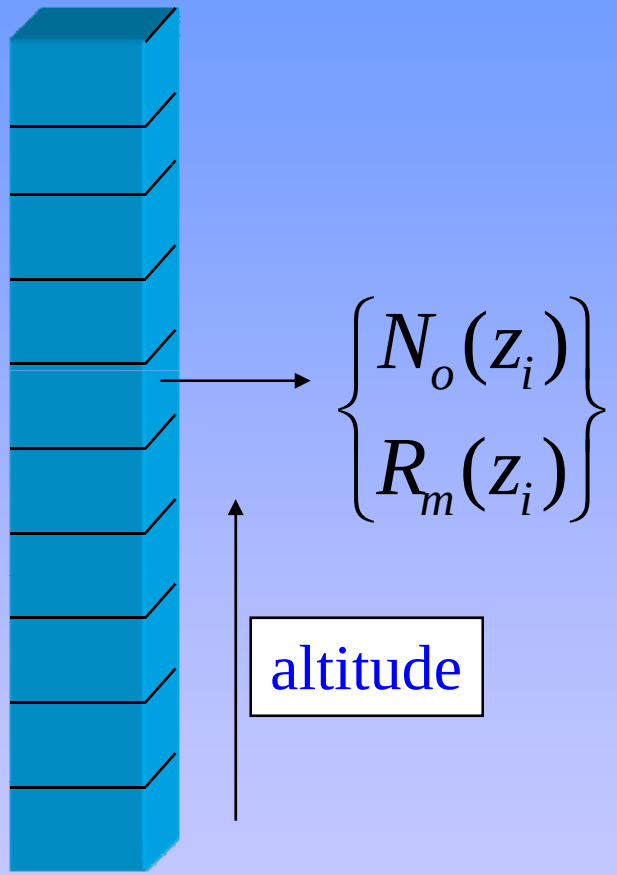
- Can only hope to find a range of possible atmospheric states that fit your observations which are likely not `complete'

- Treat the problem explicitly as a optimisation problem using an underlying model !

Putting it all Together (end-to-end)

- Use lidar+radar + IR MSI channels.
- Model with free-parameters related to height resolved mode radii and scattering type+temperature+smoothness+a priori
- Use ICA to calculate brightness temperatures
- Solve for nadir columns using an optimisation procedure
- Use off nadir MSI radiances to expand the nadir information outwards.
- Compute BBR radiances and compare to BBR measurements.
- Do you get closure ?

`Best' estimate of nadir columns



$$\begin{Bmatrix} N_o(z_i) \\ R_m(z_i) \end{Bmatrix}$$

altitude

Retrieval Forward models

MSI Views

Lidar profile

Radar profile

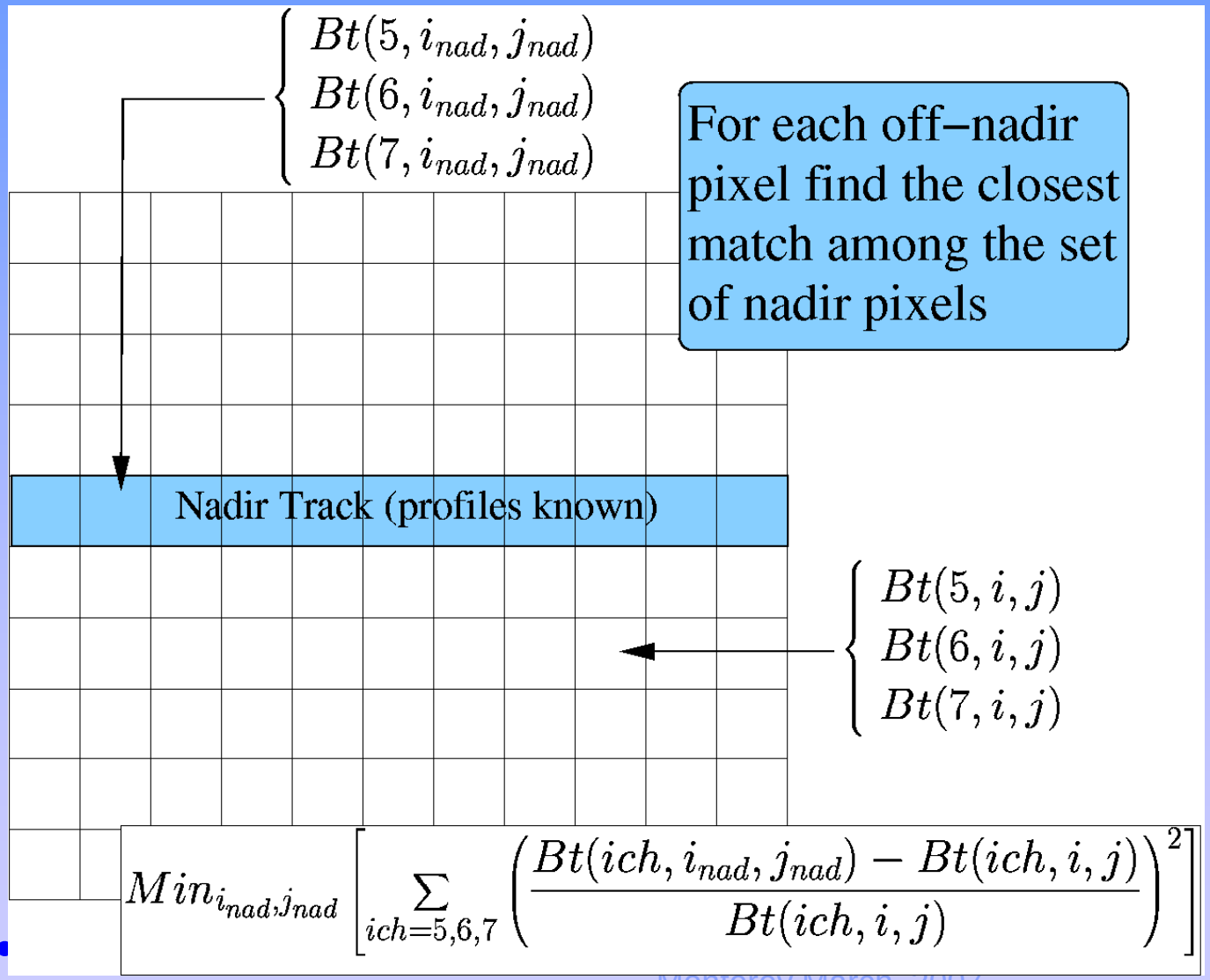
Adjust cloud Size. Dist parameters
So that results match obs.

Cost function:

$$
\begin{aligned}
C(N_{is}, R_{m,is}) = & \sum_{iz} \left(\frac{(Z_{obs}(iz) - Z_{calc}(iz))}{\delta Z_{obs}(iz)} \right)^2 + \\
& + \sum_{iz} \left(\frac{(\beta_{lid,obs}(iz) - \beta_{lid,calc}(iz))}{\delta \beta_{lid,obs}(iz)} \right)^2 \\
& + \sum_{iz} \left(\frac{(\alpha_{lid,obs}(iz) - \alpha_{lid,calc}(iz))}{\delta \alpha_{lid,obs}(iz)} \right)^2 \\
& + \sum_{is} \sum_{iz} \left(\frac{Rm_{l(s),is}(iz) - Rm^*_{l(s),is}(iz)}{\delta Rm^*_{l(s),is}(iz)} \right)^2 \\
& + \sum_{is} \sum_{iz} \left(\frac{d \log(Rm_{l(s),is}(iz))}{dz} \right)^2 \\
& + \sum_{is} \sum_{iz} \left(\frac{d \log(ext_{l(s),is}(iz))}{dz} \right)^2 \\
& + \sum_{ic=5}^{7} \left(\frac{Bt_{obs,ic} - Bt_{calc,ic}}{\delta Bt_{obs,ic}} \right)^2
\end{aligned}
$$

Inversion obtained by minimizing the cost function

2D track to 3D domain



MSI images

synthetic 3D scene

extinction

simulated measurements

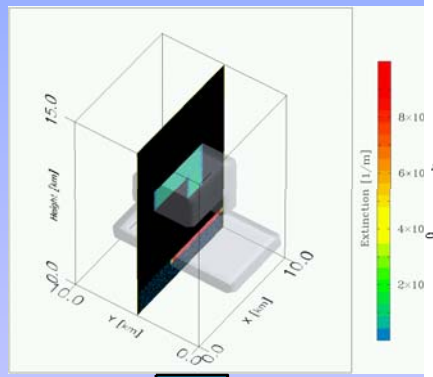
co-polar Mie

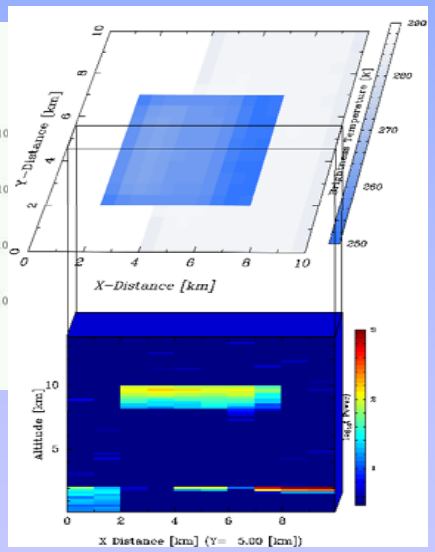
Retrieval profiles

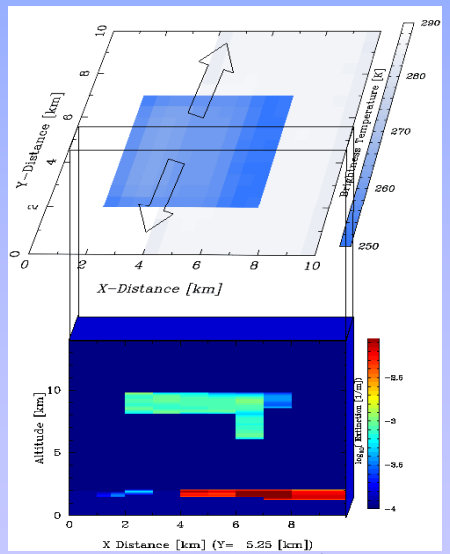
extinction

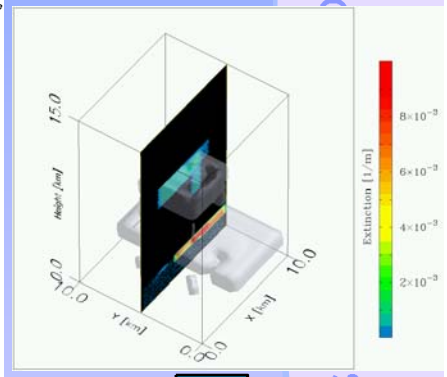
reconstructed 3D scene

extinction







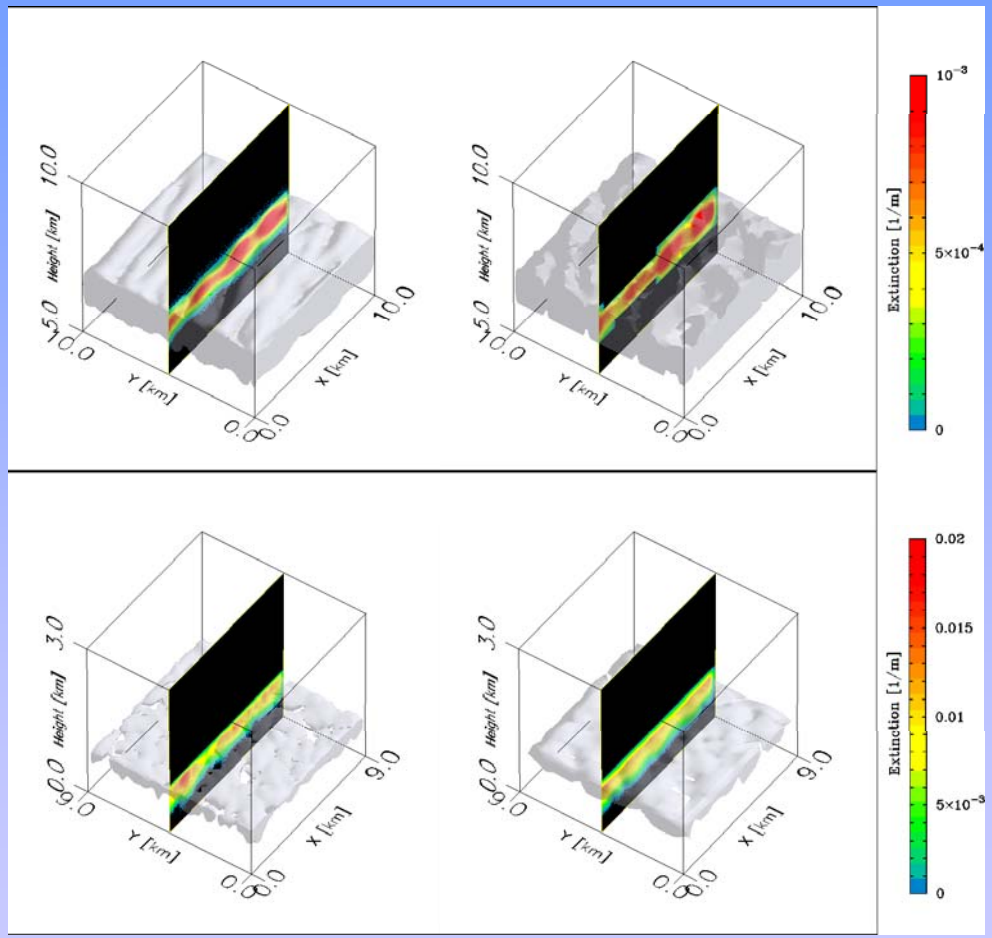


TOA FLUX
SW: 244 W/m²
LW: 238.6 W/m²

Difference :
SW: 5 W/m²
LW:2.3 W / m²

TOA Flux
SW: 249 W/m²
LW: 236.3 W/m²

Model 3D scene Reconstructed scene



Thin cirrus case

	True	Retrieved
SW TOA (W/m²)	*116*	*121*
LW TOA (W/m²)	*206.5*	*213.0*

Differences: SW TOA 5 W/m²
LW TOA 6.5 W/m²

Stratus case

	True	Retrieved
SW TOA (W/m²)	*286*	*290*
LW TOA (W/m²)	*274.9*	*273.9*

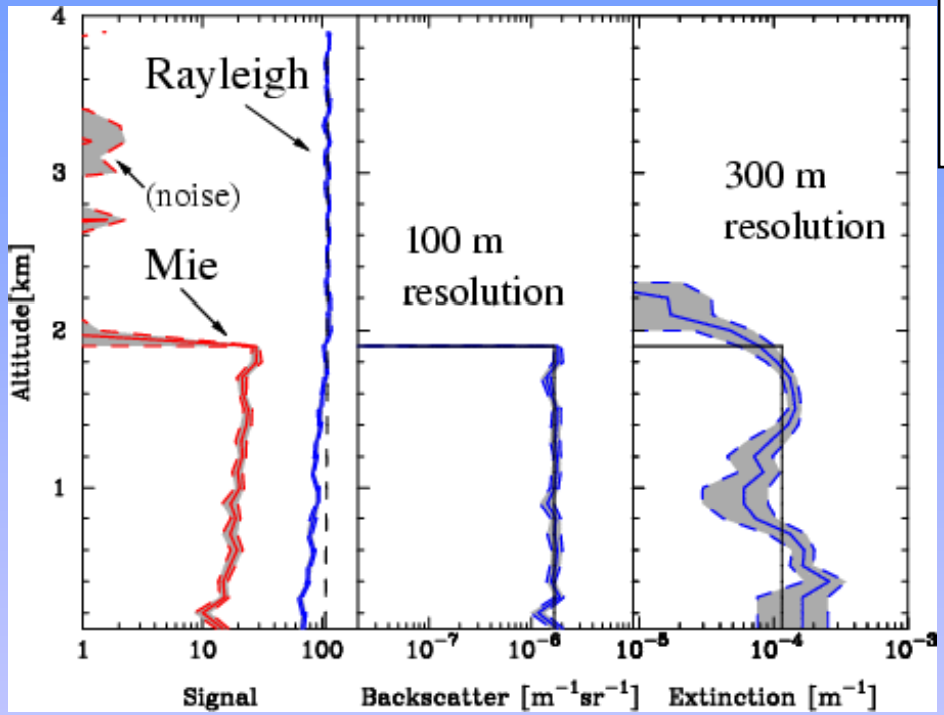
Differences: SW TOA 4 W/m²
LW TOA 1 W/m²

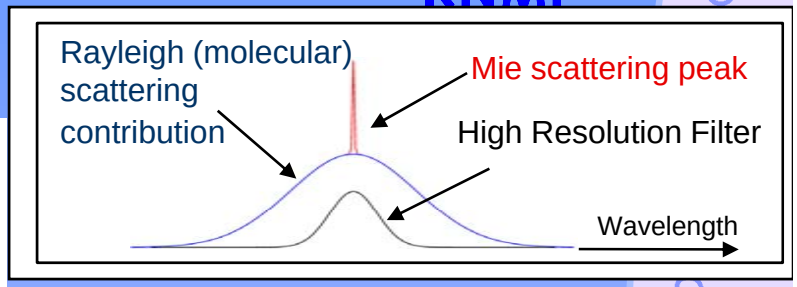
Some further miscellaneous examples….

HSR lidar aerosol soundings

High Spectral Resolution 355 nm Lidar

PBL Aerosol (10 km horizontal integration)





1. **Compare observed molecular return with expected non-attenuated value**
   True extinction coefficient (α) and/or optical depth (τ)
2. **Use α to correct the attenuated backscatter (β_{OBS}) ⇨ (β_{TRUE})**
3. **Derive the true lidar ratio α/β ~ ice crystal habit and aerosol size / composition**

Additional information:

- Shape of ice particles and aerosols: from cross-polarisation channel
- Distinguish anthropogenic from natural aerosol: from cross-polarisation channel and lidar ratio

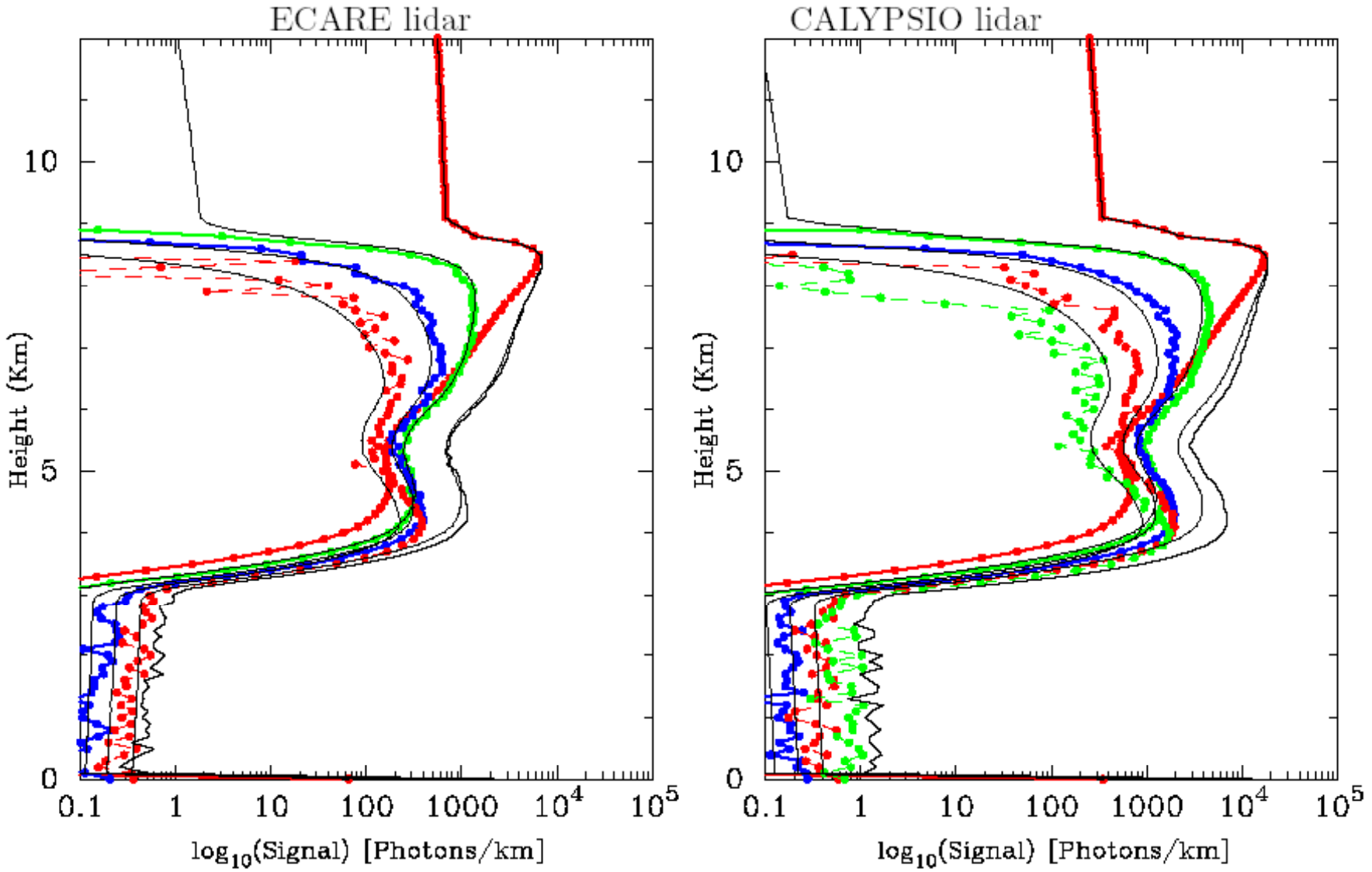
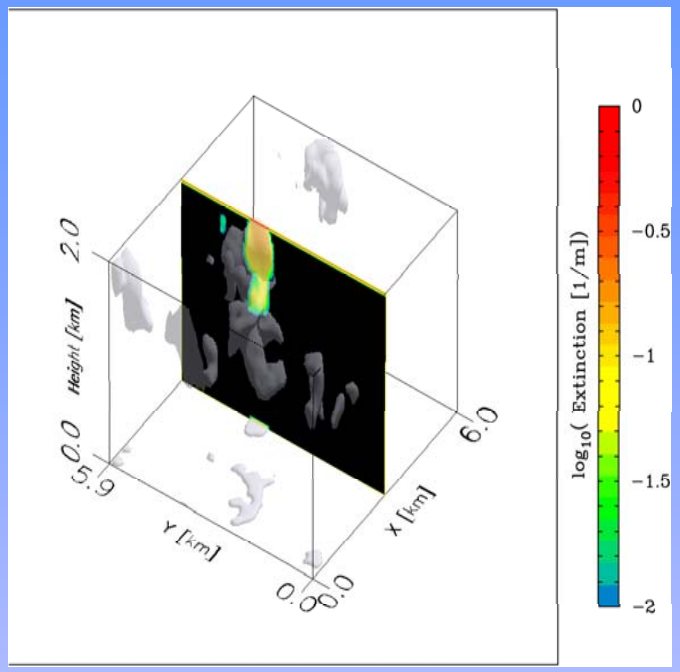


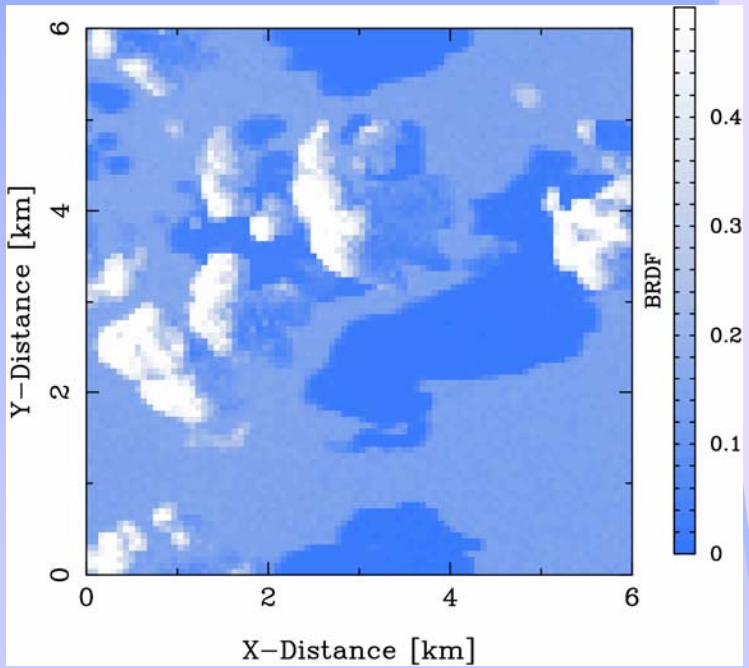
Figure 71: *Comparison between the MC results of total power and the results predicted by the model of Eloranta for (Left) the EarthCARE configuration (altitude of 450 km and a full-angle fov of 0.0735 mrads) and (Right) a configuration similar to CALYPSIO ($\lambda = 532nm$, altitude=705 km, full-angle fov 0.26 mrads). Here the Cirrus cloud is based upon in-situ measurements made during EUCROS.*

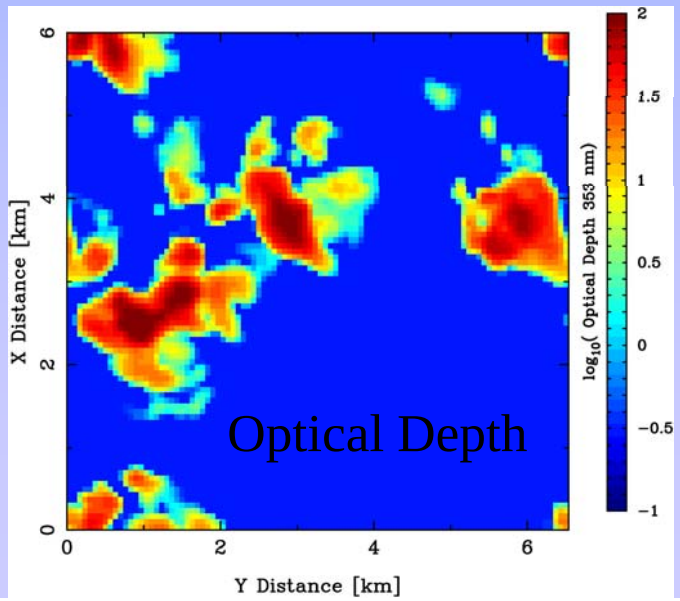
Cu scene



(Taken from I3RC test cases)

Visible nadir reflectance
At 25 m resolution (low sun angle for dramatic effect)





Optical Depth

Monterey March, 2007

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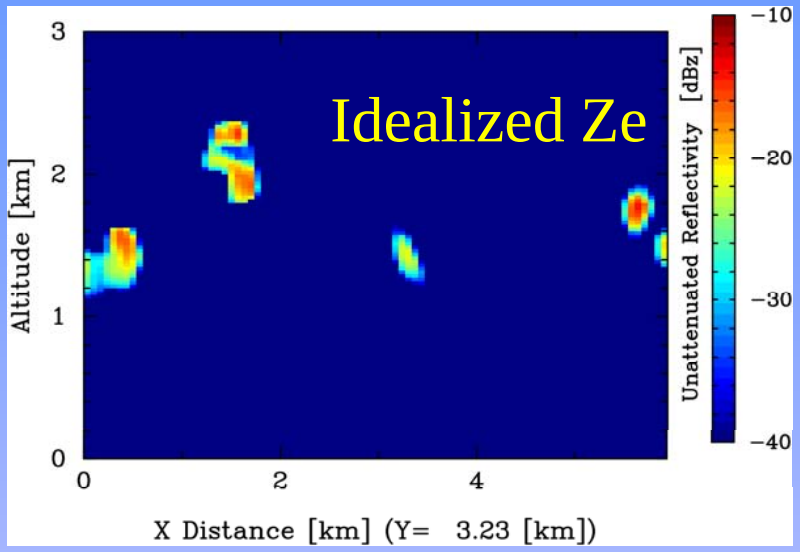
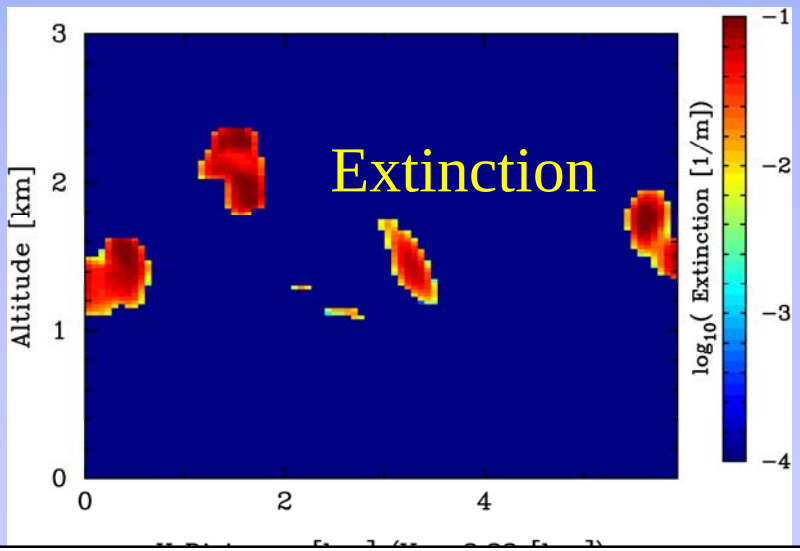
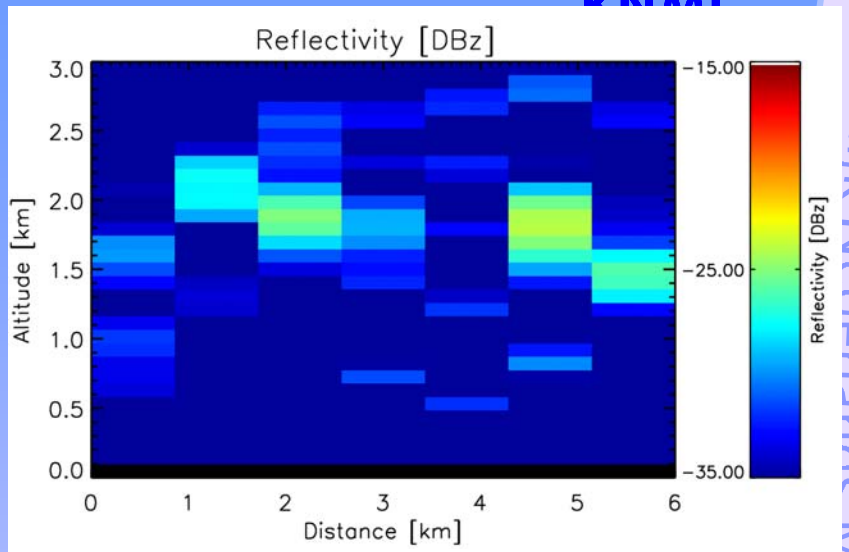
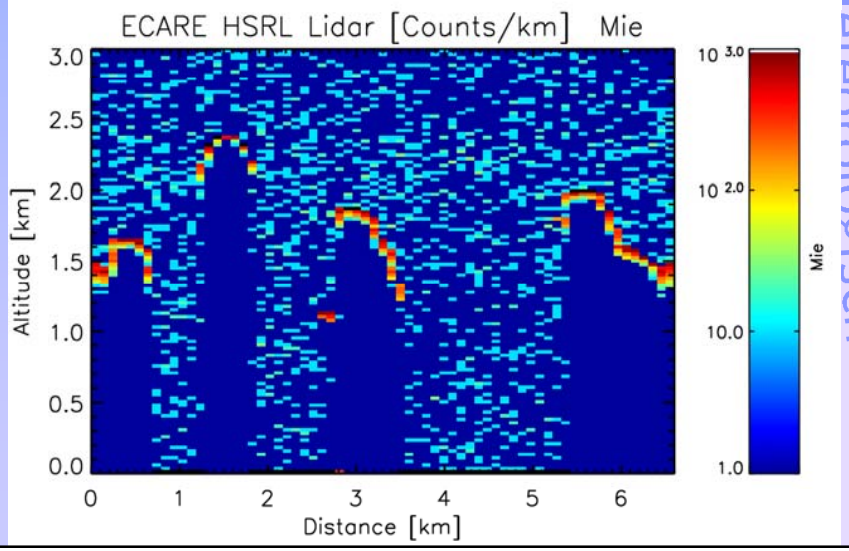
.... Example CU views EarthCARE









Larger particle sizes near Cld. top➔ But still Difficult for Radar. Lidar only penetrates few range gates into clouds but many holes➔ Aerosol soundings

Ecare-vs-Csat Stratocummulus

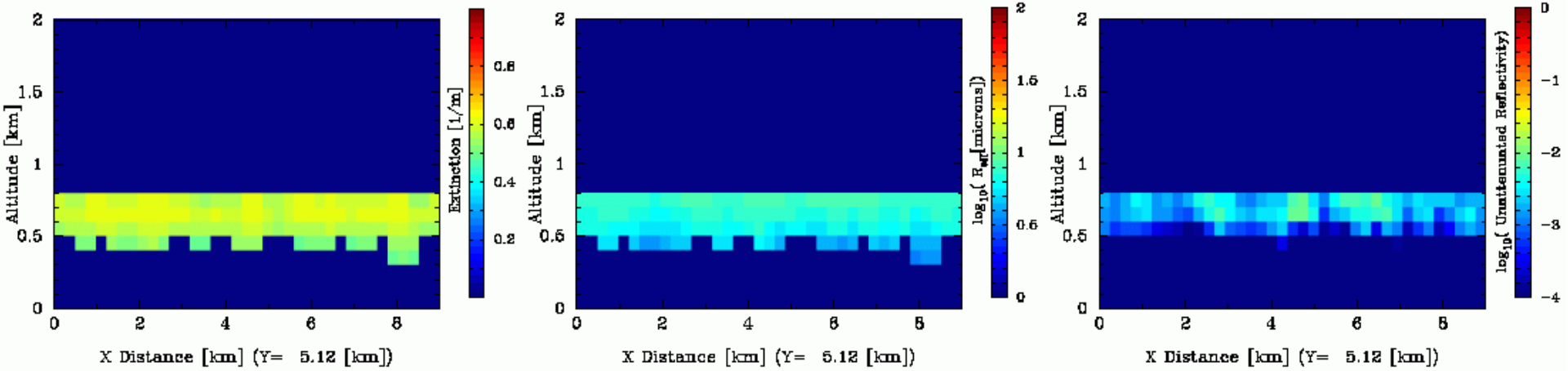
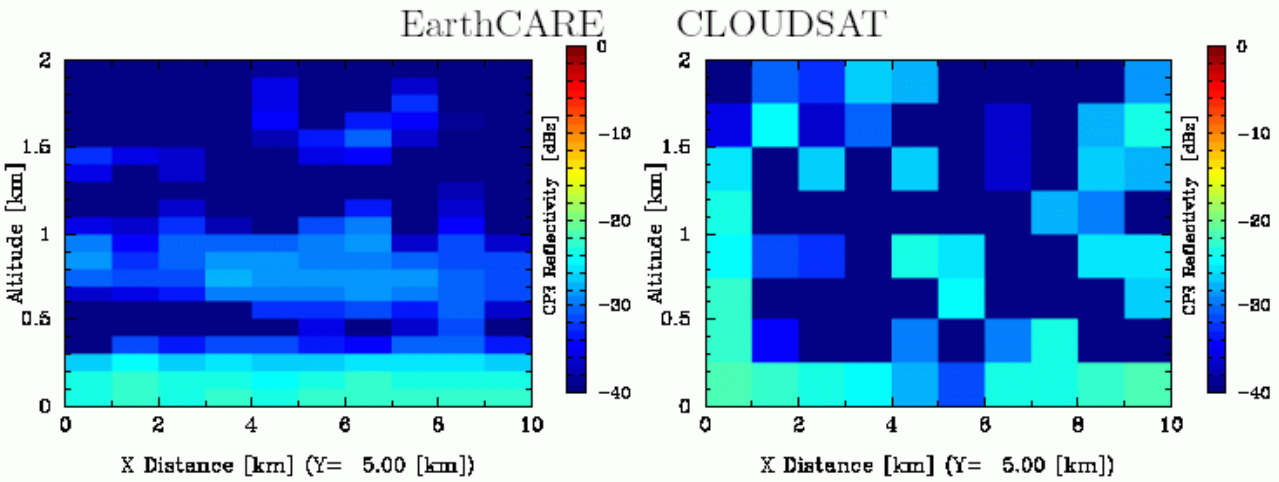


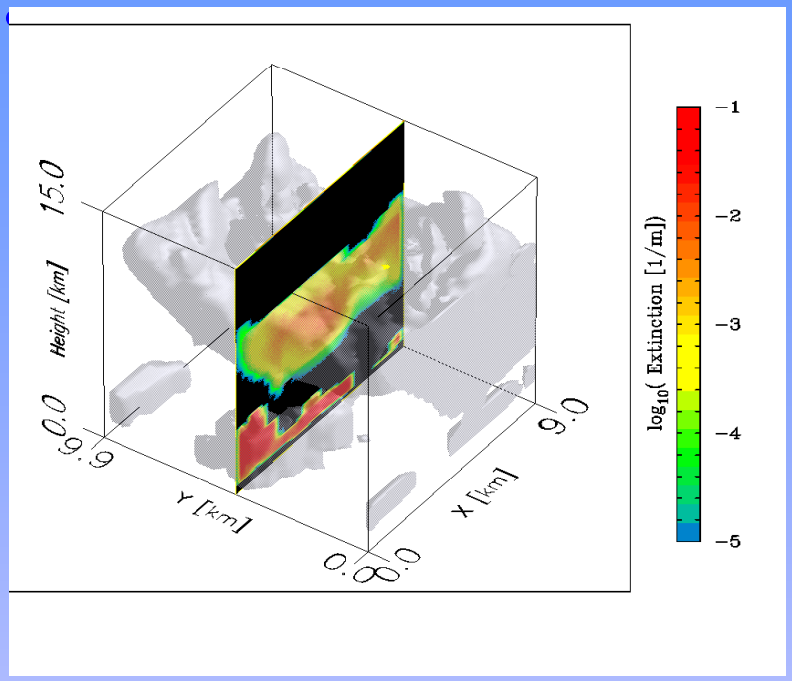
Figure 72: Extinction, effective radius and reflectivity for the UQAM ASTEX1_1 scene.



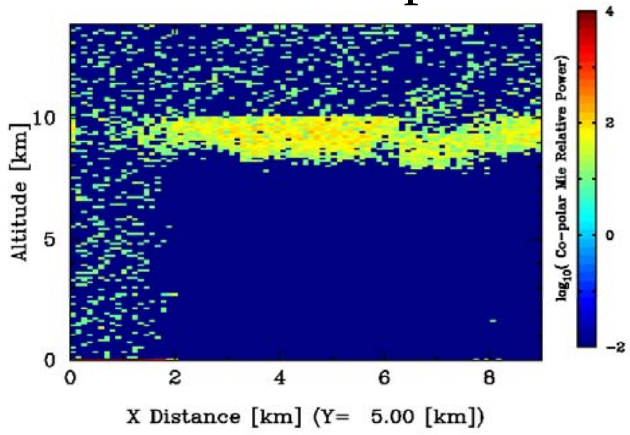
Recent work

- MSC sponsored work to extent codes to ground/aircraft based platforms.
- Partly in support of CSAT/CALIPSO validation campaign
- Parallel version of the SW MC code
- Met. Radar module

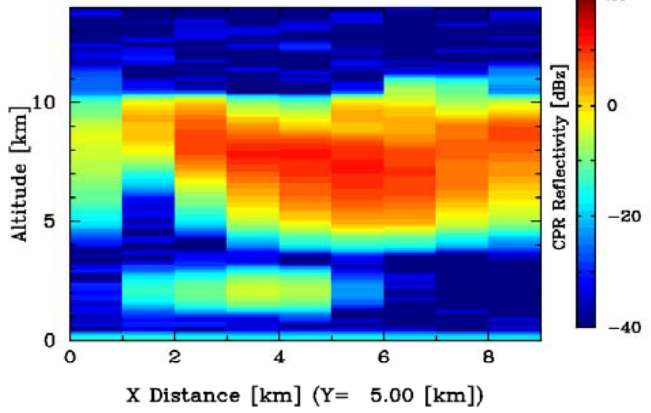
CASE of frontal ice cloud



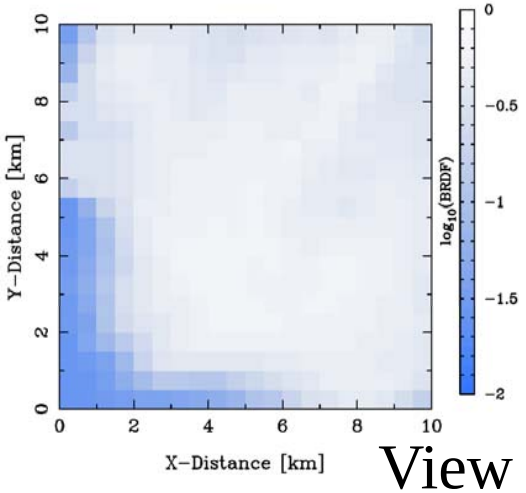
Lidar from Space



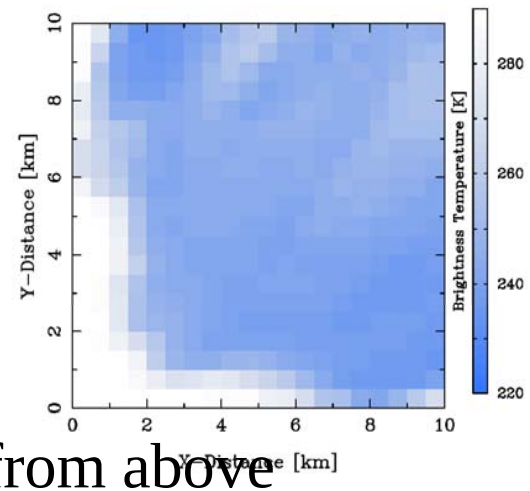
Radar From Space



0.6 microns

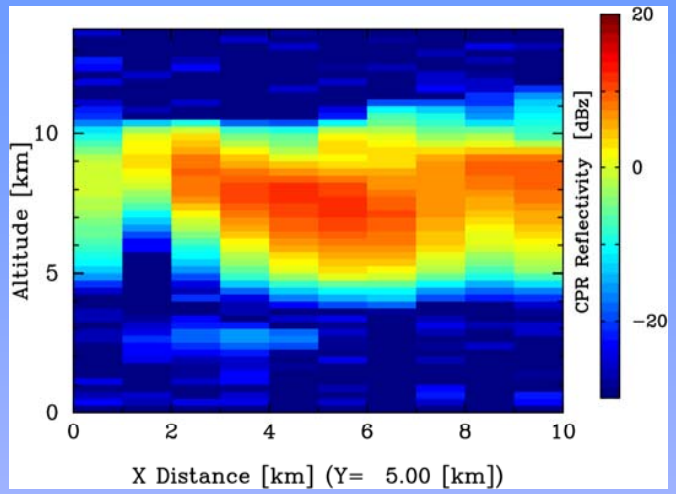


12 microns

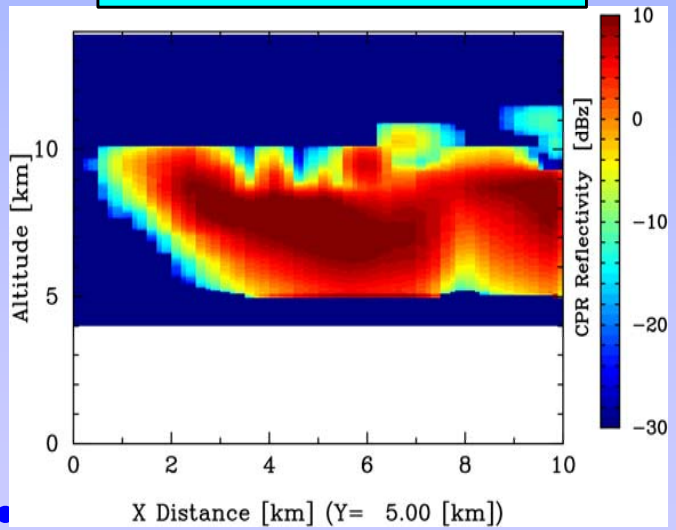


View from above

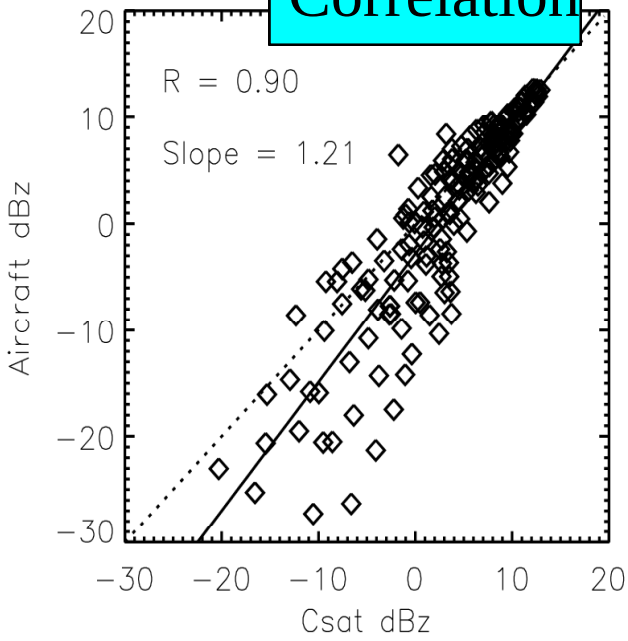
Csat measured



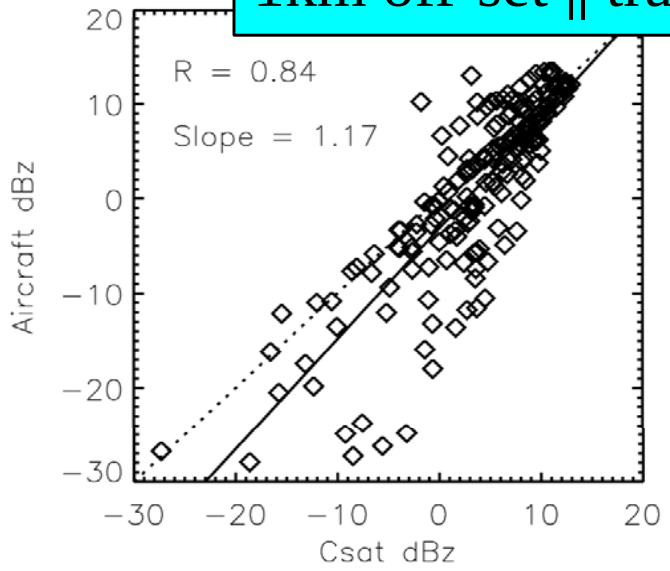
Aircraft measured



Correlation



1km off-set || track



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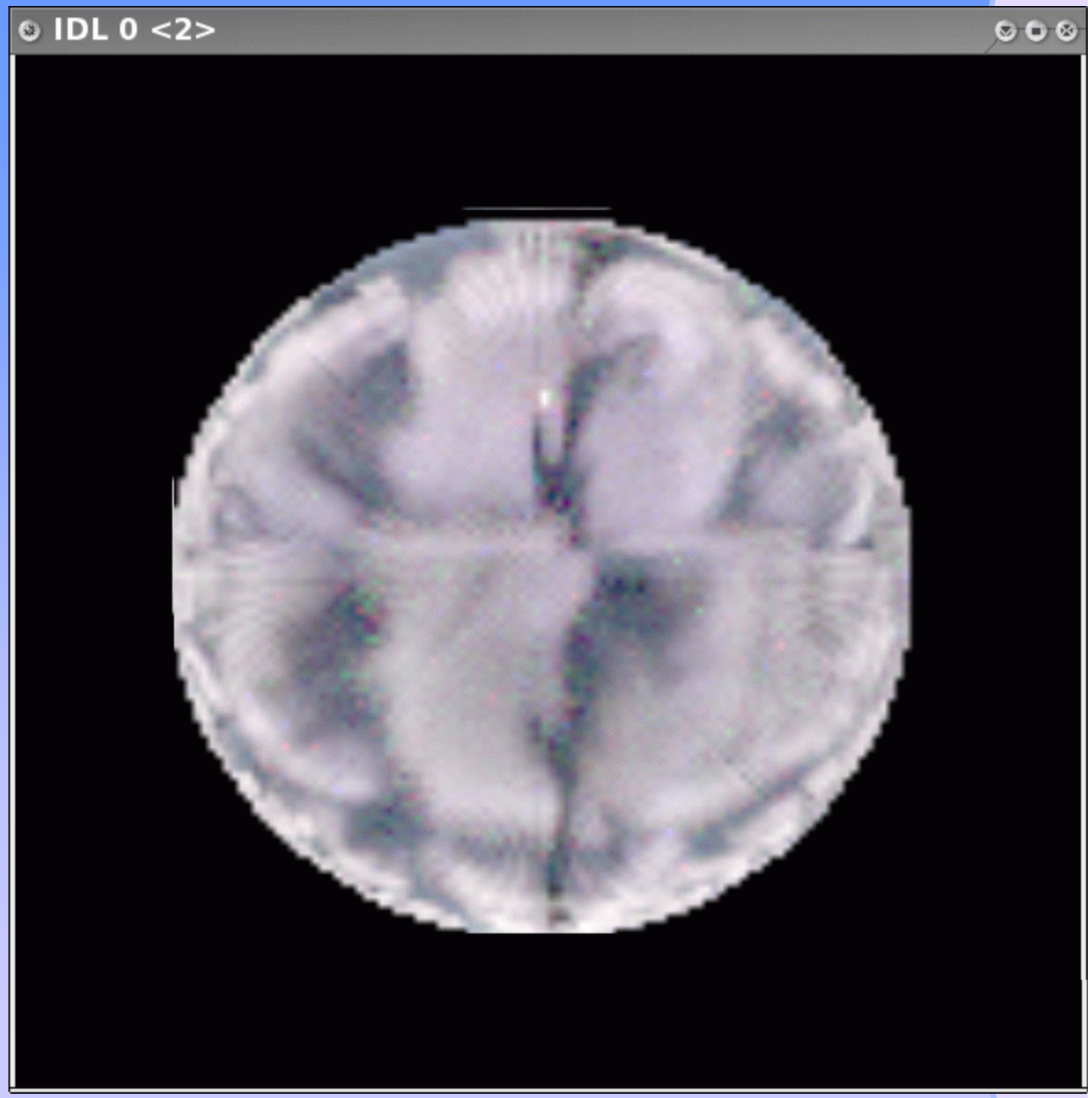
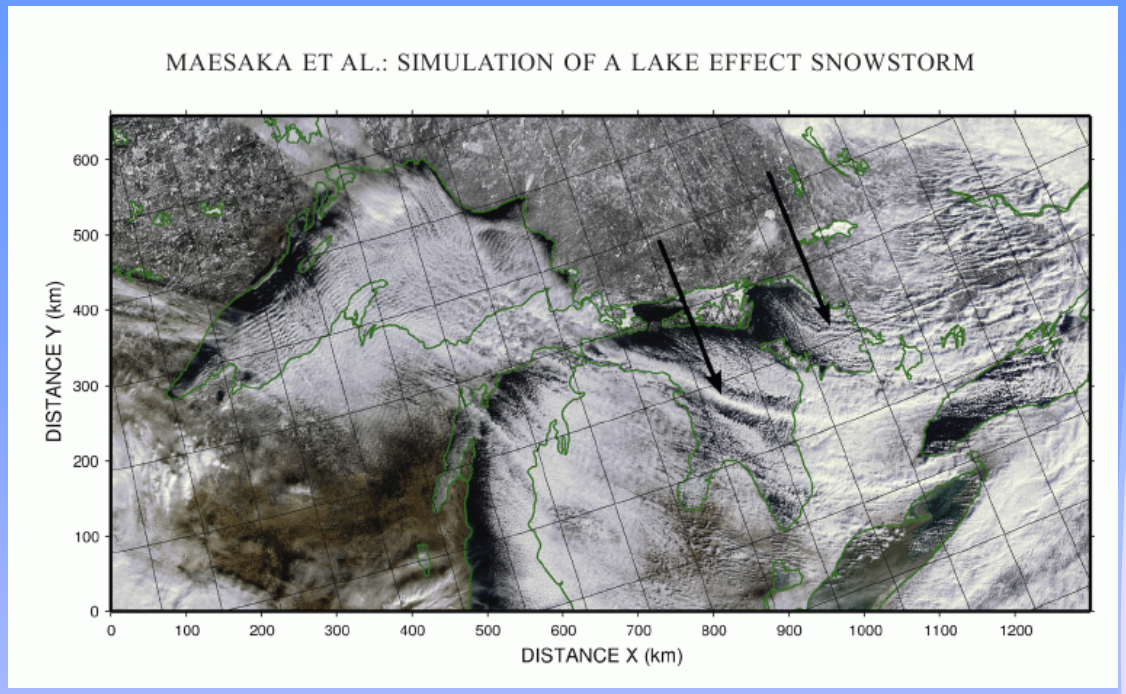
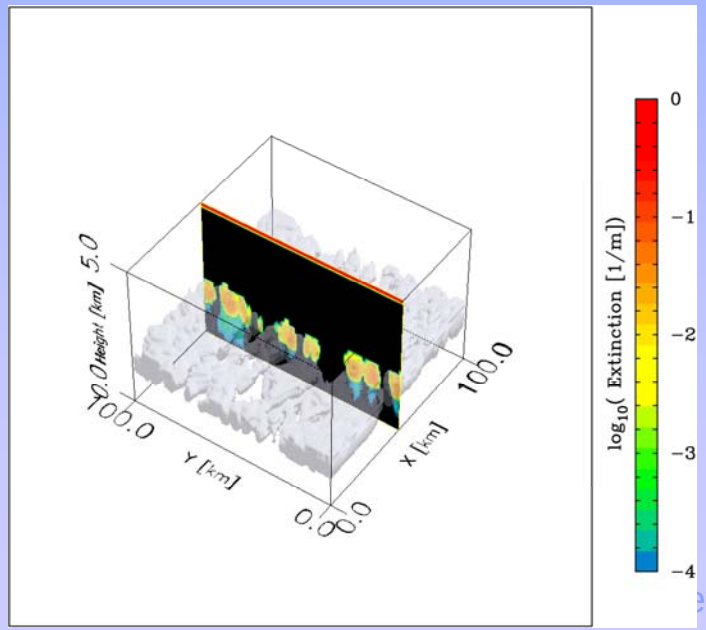
Total sky imager RGB image

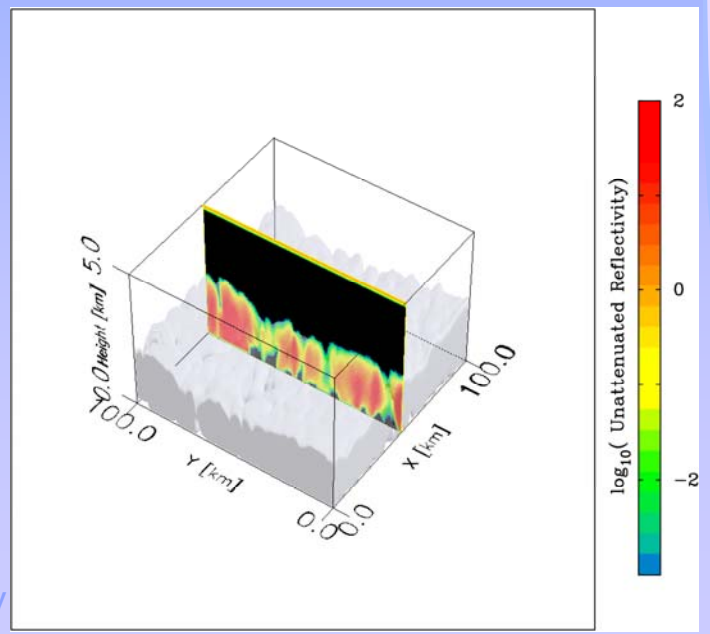
Composite of red, blue and green radiance images



- Snow squalls as simulated using Japanese CrESS model







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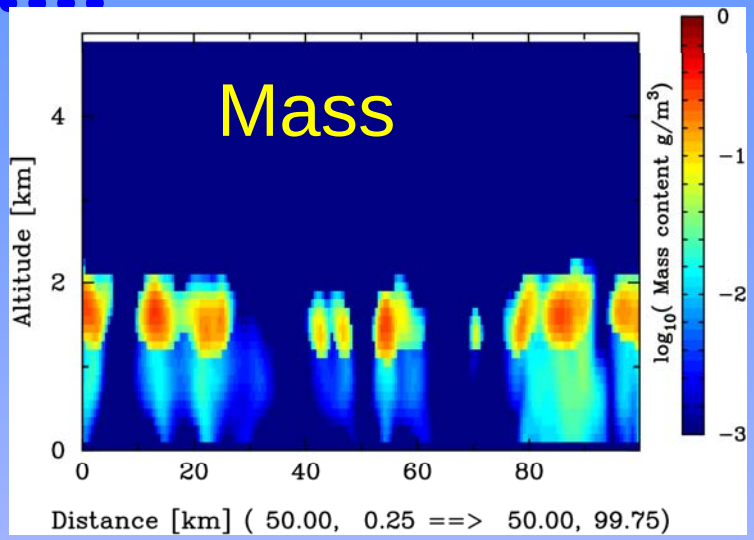
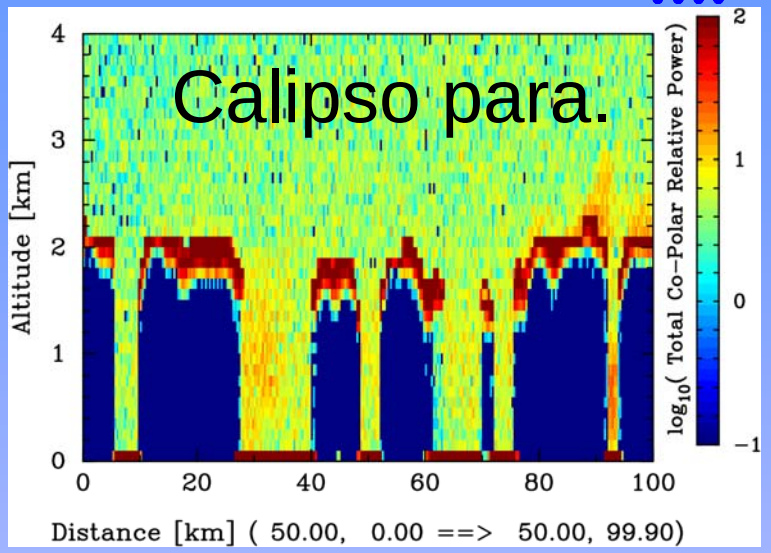
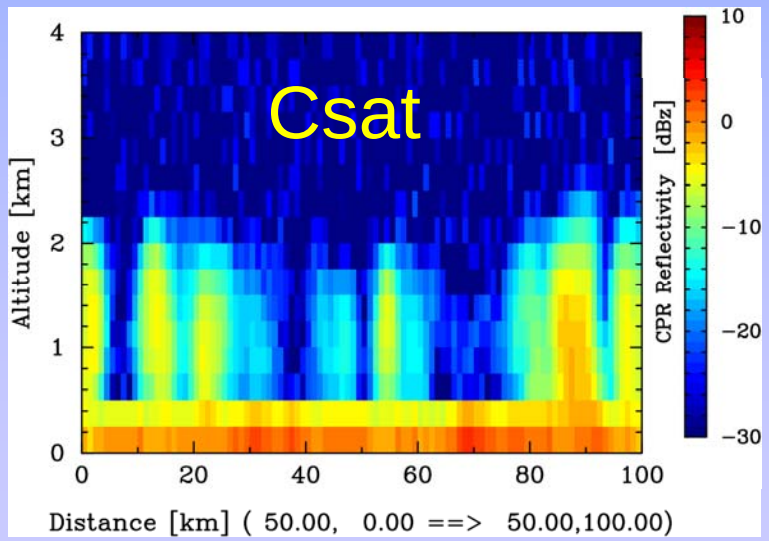
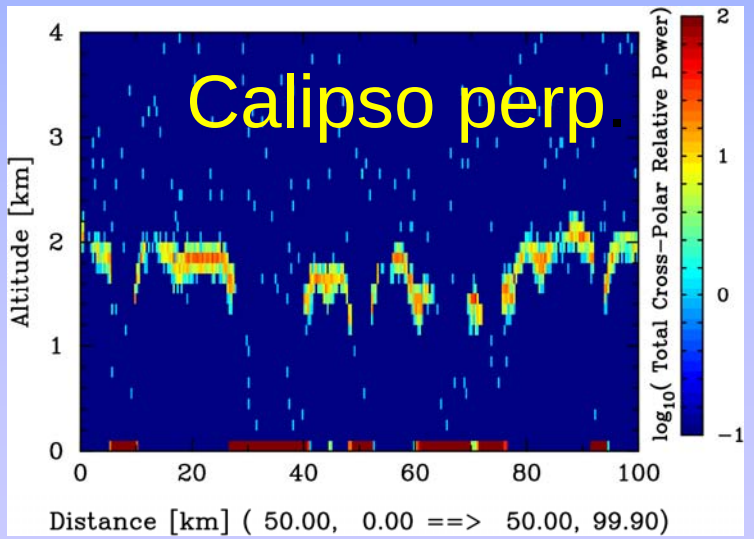
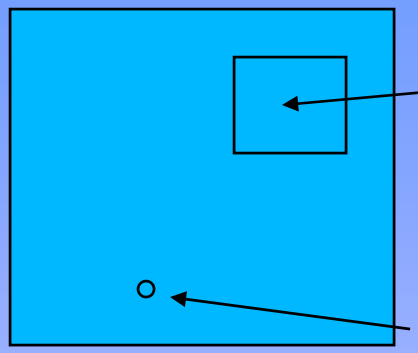






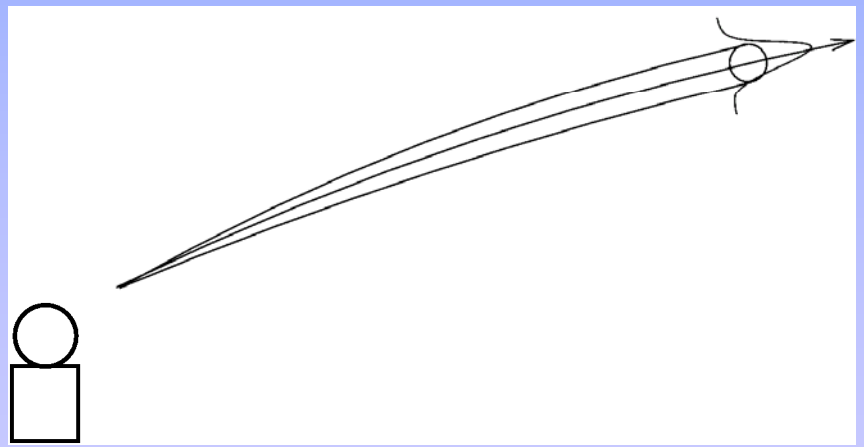


Met. Radar Module

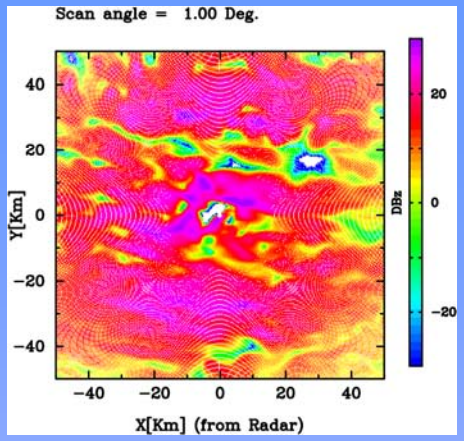


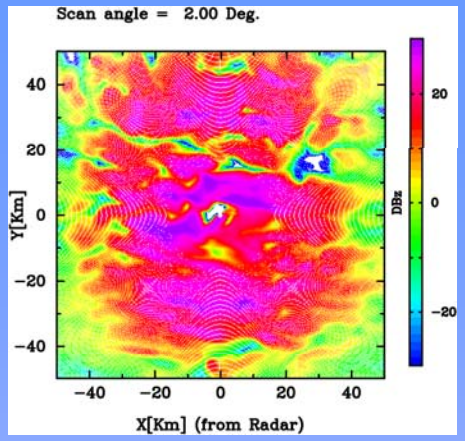
High res area embedded in lower res `background'.

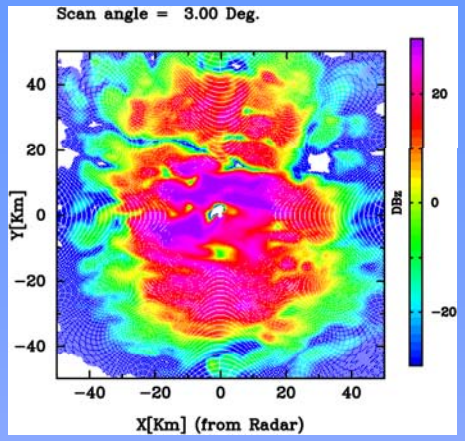
Radar



- Refraction and Earth's curvature effects included.
- Non-Rayleigh scattering is included
- No Pol. (yet ?)

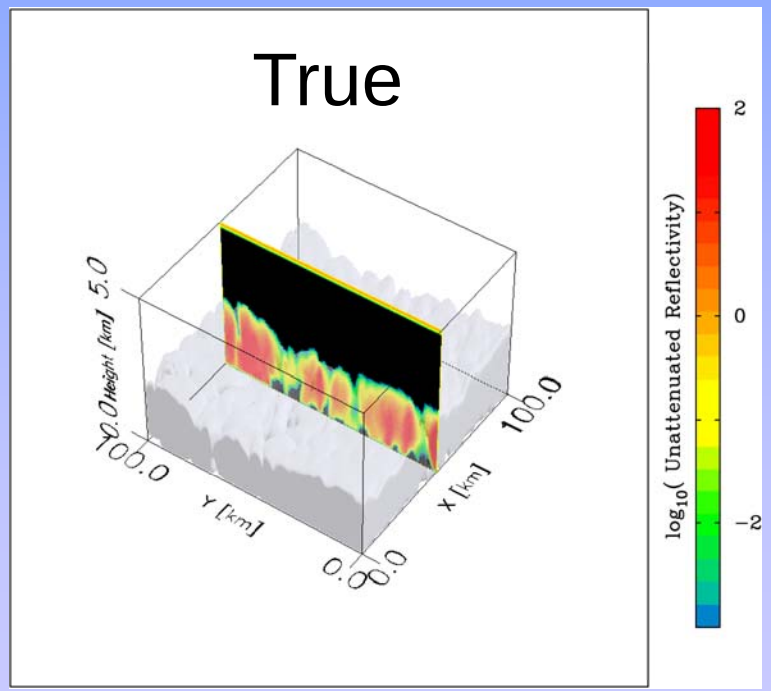


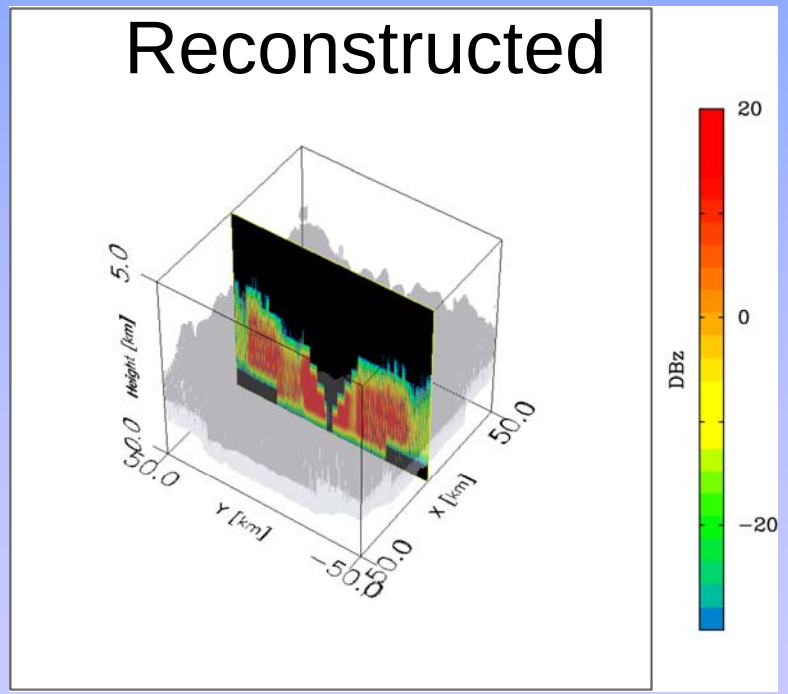




KNMI

Etc..





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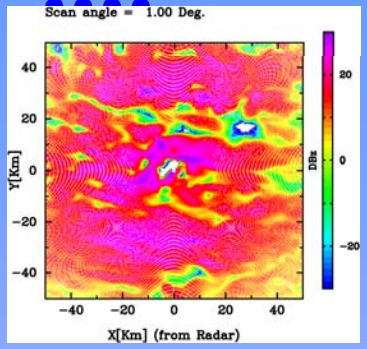
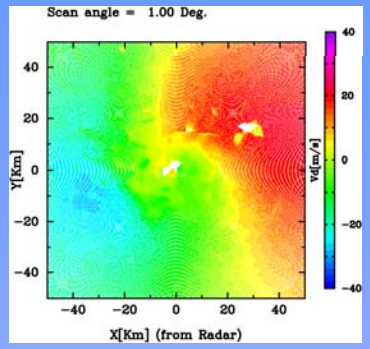
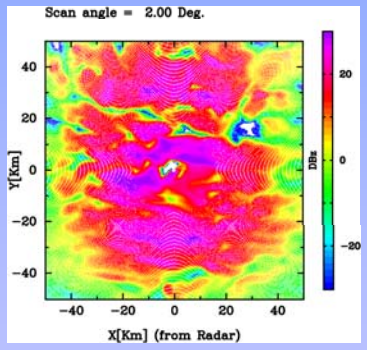
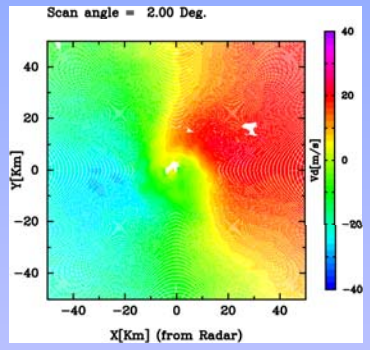
Ze

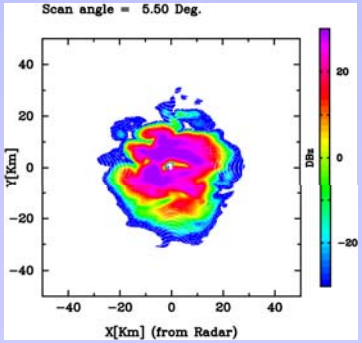
Vd

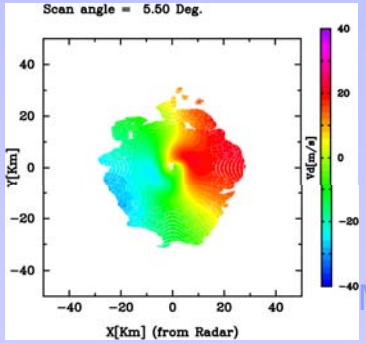








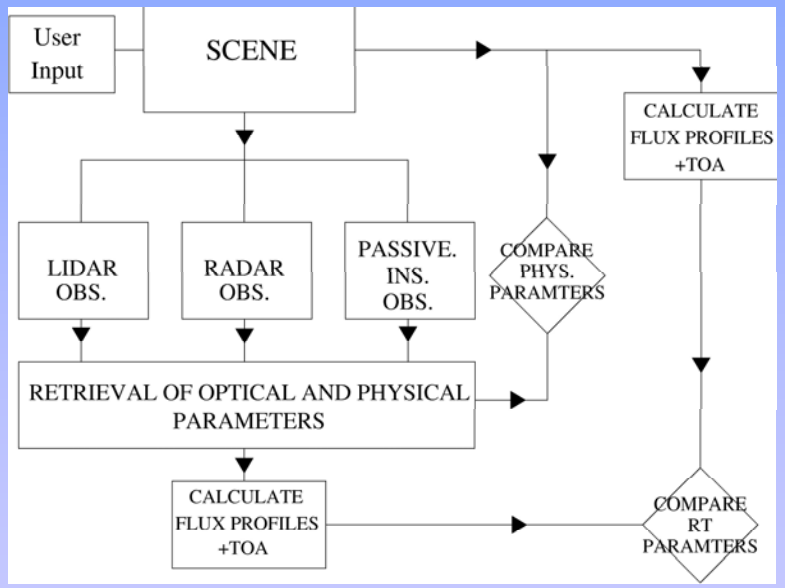




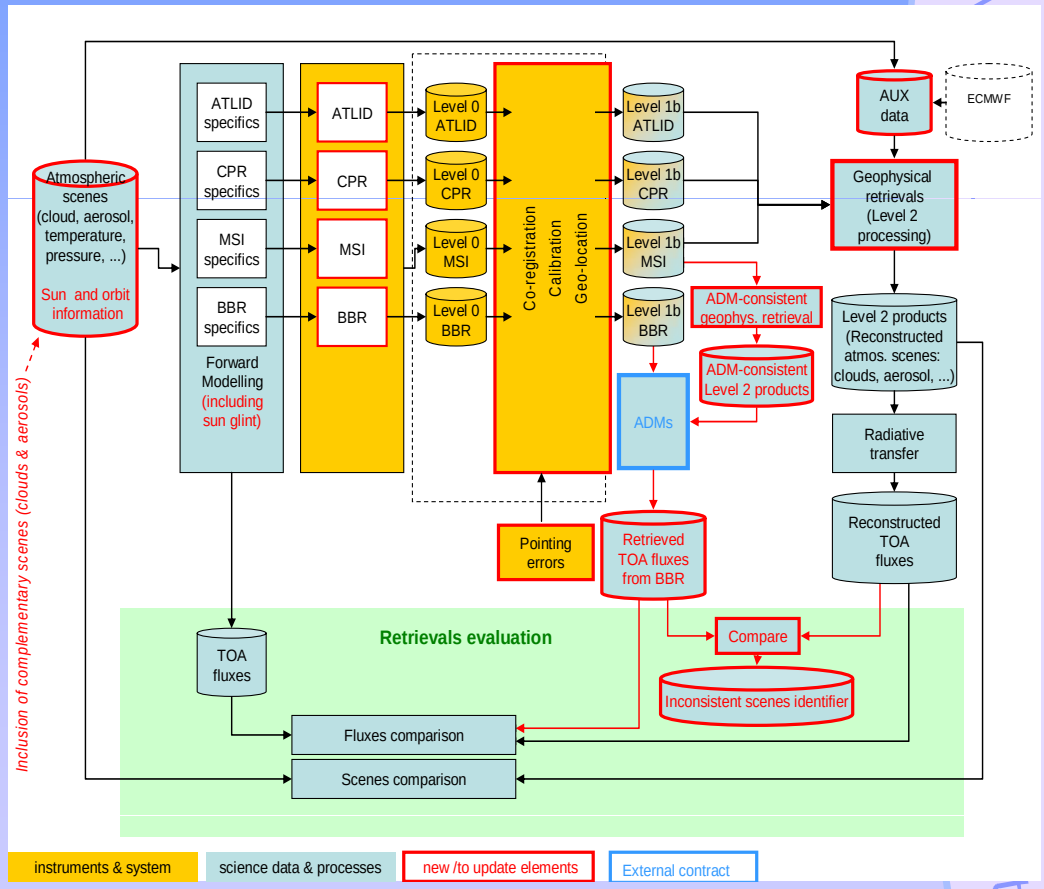
Same kind of studies can be done looking at Vd

Future Ongoing Developments (under ESA contract)

Before



After



Conclusions

- EarthCARE can be viewed as CSAT+CALIPSO+ but on a single platform.
- Will provide important information on global cloud and aerosol properties. Continue the Csat/Cal record.
- The EarthCARE simulator represents a new approach for multi-sensor simulation studies.
- It should prove very useful for the development of new synergetic retrieval techniques.
- Useful tool but it is not magic. One still have to ask good questions to use such tools effectively !
- New ESA project underway to upgrade the simulator. Source code to be (mainly) free and open

Short-Wave Bands

Broad-Band Short Wave 0.2-4.0 μ m							
Center λ	Gasses	Center λ	Gasses	Center λ	Gasses	Center λ	Gasses
0.254998	O_3	0.277389	O_3	0.294507	O_3	0.317148	O_3
0.344614	O_3	0.384187	O_3	0.428872	O_3	0.482614	O_3
0.528597	O_3	0.544707	H_2O	0.557927	O_3	0.585172	H_2O O_3
0.614836	O_3	0.645182	H_2O O_3	0.675333	O_3	0.694179	H_2O O_3 O_2
0.723040,	H_2O	0.766254	O_2	0.817094	H_2O	0.866138	H_2O
0.929973	H_2O	1.00908	H_2O	1.11501	H_2O	1.33592	H_2O
1.56311	H_2O CO_2	1.77179	H_2O	2.05465	H_2O CO_2	2.21263	H_2O
2.58866	H_2O CO_2	3.28839	H_2O O_3	3.80445	H_2O CO_2	4.27991	H_2O CO_2

Table 8: Center wavelengths used for broad-band short-wave calculations and relevant gasses.

Long Wave bands

Long-Wave 4.0-400.0 μ m									
Center λ	Gasses	Center λ	Gasses	Center λ	Gasses	Center λ	Gasses	Center λ	Gasses
4.07997	H_2O	4.23729	H_2O	4.38596	H_2O	4.54545	H_2O	4.71698	H_2O
4.90196	H_2O	5.02513	H_2O	5.07614	H_2O	5.12820	H_2O	5.18135	H_2O
5.23560	H_2O	5.29101	H_2O	5.34759	H_2O	5.40541	H_2O	5.46448	H_2O
5.52486	H_2O	5.58659	H_2O	5.64972	H_2O	5.71429	H_2O	5.78035	H_2O
5.84795	H_2O	5.91716	H_2O	5.98802	H_2O	6.06061	H_2O	6.13497	H_2O
6.21118	H_2O	6.28931	H_2O	6.36943	H_2O	6.45161	H_2O	6.53595	H_2O
6.62252	H_2O	6.71141	H_2O	6.80272	H_2O	6.89655	H_2O	6.99301	H_2O
7.09220	H_2O	7.19424	H_2O	7.29927	H_2O	7.40741	H_2O	7.51880	H_2O
7.63359	H_2O	7.75194	H_2O	7.87402	H_2O O_3	8.00000	H_2O O_3	8.13008	H_2O O_3
8.26446	H_2O O_3	8.40336	H_2O O_3	8.54701	H_2O O_3	8.69565	H_2O O_3	8.84956	H_2O O_3
9.00901	H_2O O_3	9.17431	H_2O O_3	9.34579	H_2O O_3	9.52381	H_2O O_3	9.70874	H_2O O_3
9.90099	H_2O O_3	10.1010	H_2O O_3	10.3093	H_2O O_3	10.5263	H_2O O_3	10.7527	H_2O O_3
10.9890	H_2O O_3	11.2360	H_2O	11.4943	H_2O	11.7647	H_2O	12.0482	H_2O CO_2
12.3457	H_2O CO_2	12.6582	H_2O CO_2	12.9870	H_2O CO_2	13.3333	H_2O CO_2	13.6986	H_2O CO_2
14.0845	H_2O CO_2	14.4928	H_2O CO_2	14.9254	H_2O CO_2	15.3846	H_2O CO_2	15.8730	H_2O CO_2
16.3934	H_2O CO_2	16.9492	H_2O CO_2	17.5439	H_2O CO_2	18.1818	H_2O CO_2	18.8679	H_2O CO_2
19.6078	H_2O CO_2	20.4082	H_2O	21.2766	H_2O	22.2222	H_2O	23.2558	H_2O
24.3902	H_2O	25.6410	H_2O	27.0270	H_2O	28.5714	H_2O	30.3030	H_2O
32.2581	H_2O	34.4828	H_2O	37.0370	H_2O	40.0000	H_2O	43.4783	H_2O
47.6190	H_2O	52.6316	H_2O	58.8235	H_2O	66.6667	H_2O	76.9231	H_2O
90.9091	H_2O	111.111	H_2O	142.857	H_2O	200.000	H_2O	333.333	H_2O

Table 10: *Center wavelengths used for broad-band long-wave calculations and relevant gasses.*

Default Scattering types

Name	r_{min} [microns]	r_{max}	No. of sizes
Cloud Water	1.0	50.0	50
Drizzle	10.0	500.0	10
H_2SO_4 25%	0.01	10.0	30
H_2SO_4 50%	0.01	10.0	30
H_2SO_4 75%	0.01	10.0	30
Soot	0.01	10.0	30
Sea Salt	0.01	10.0	30
Dust	0.01	10.0	30
Columns (perfect)	1.75	650.0	8
Columns (rough)	1.75	650.0	8
Plates (perfect)	15.0	650.0	6
Plates (rough)	15.0	650.0	6
Ice	0.5	50.0	50
Snow (large ice)	25.0	2500.0	50

Table 2: Default scattering types.

Model:
For each z_i where $Mask(z_i) = 1$

$$N_{is}(R) = \frac{N_{s,is}}{R_{ms,is}} \frac{1}{\Gamma(\gamma_{s,is})} \left(\frac{R}{Rm_{s,is}} \right)^{(\gamma_{s,is}-1)} exp[-R/Rm_{s,is}]$$
$$+ \frac{N_{l,is}}{R_{ml,is}} \frac{1}{\Gamma(\gamma_{l,is})} \left(\frac{R}{Rm_{l,is}} \right)^{(\gamma_{l,is}-1)} exp[-R/Rm_{l,is}]$$

where is is the scattering type (water,plates,columns etc..)
(**water and ice are assigned before hand via masks.**)

Free Parameters:
For each z_i where $Mask(z_i) = 1$

1. $\alpha_{is,l}, \alpha_{is,s}$, ($is = 0$ for water, $is = 1$ for ice)
2. $Rm_{s,is}, Rm_{l,is}$
3. γ's are fixed

Should target thinner ice clouds to check MS effects for CALIPSO

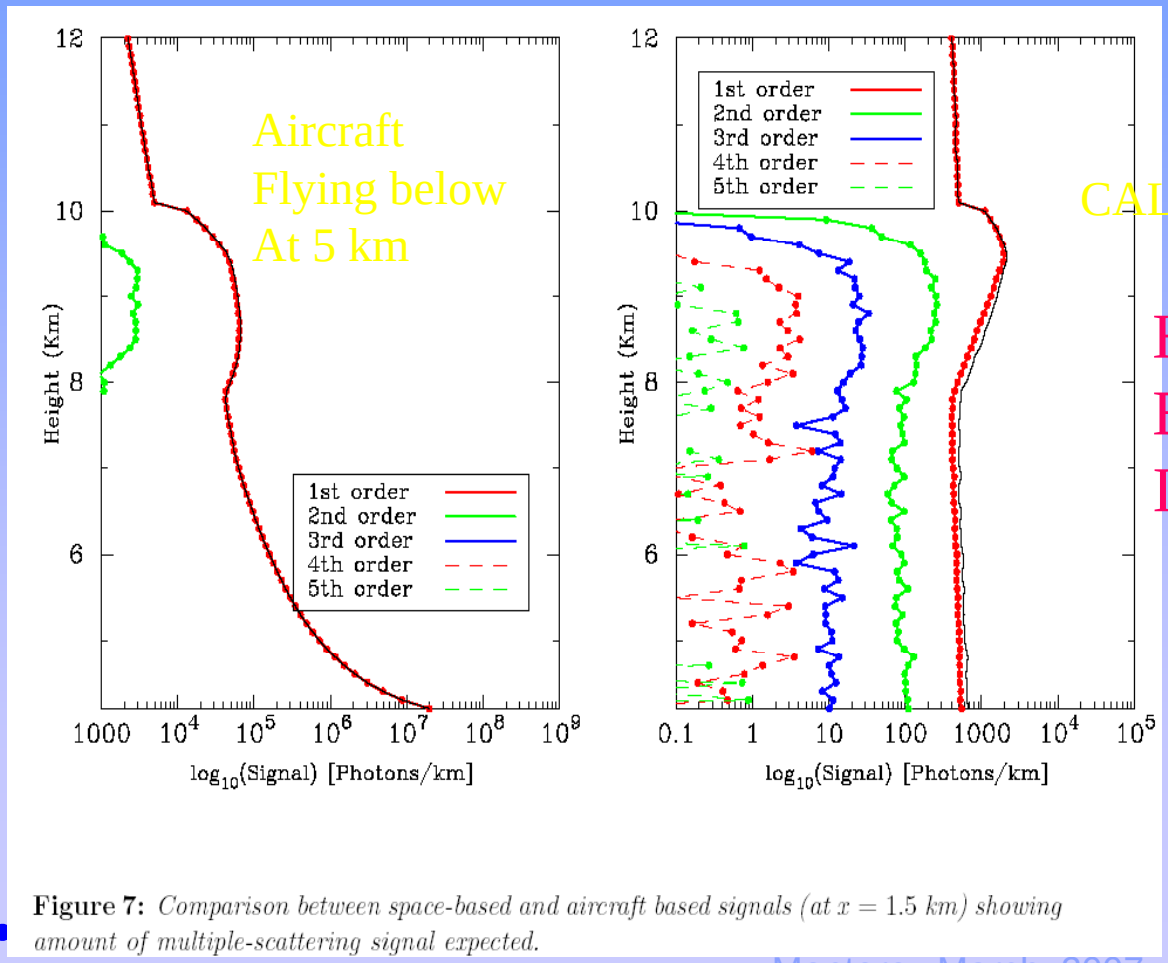
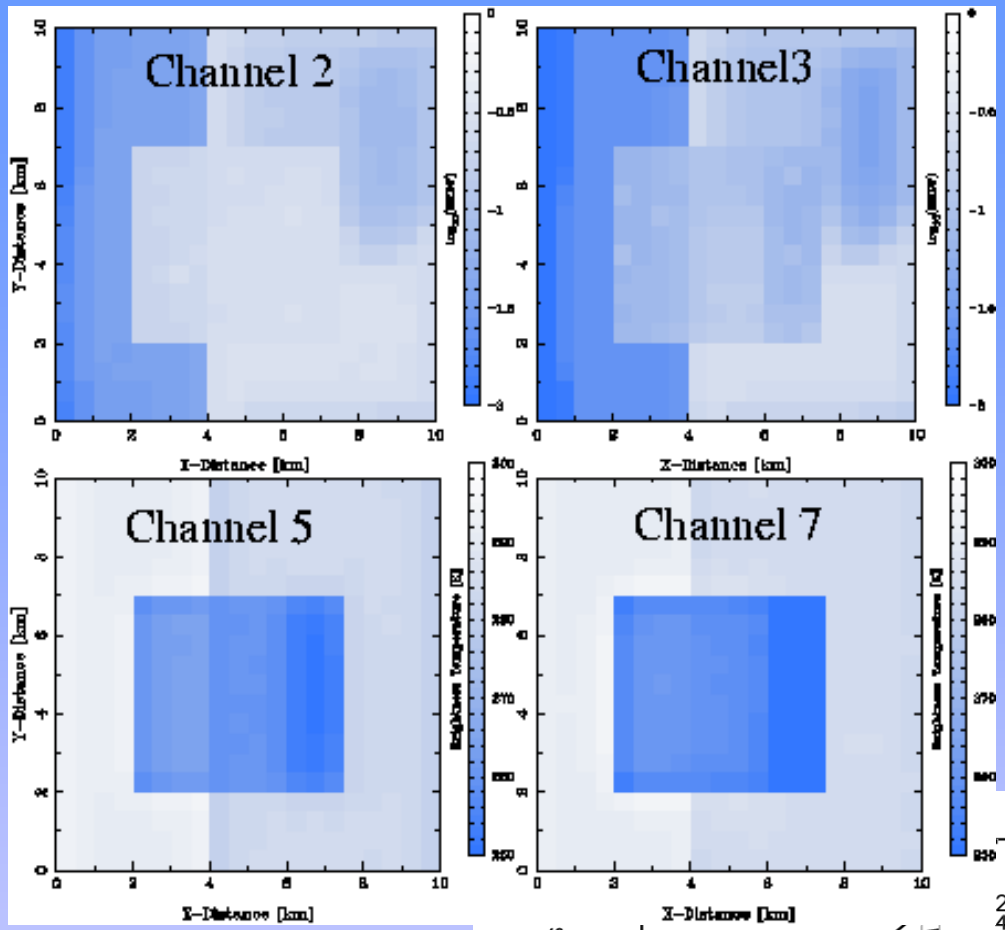
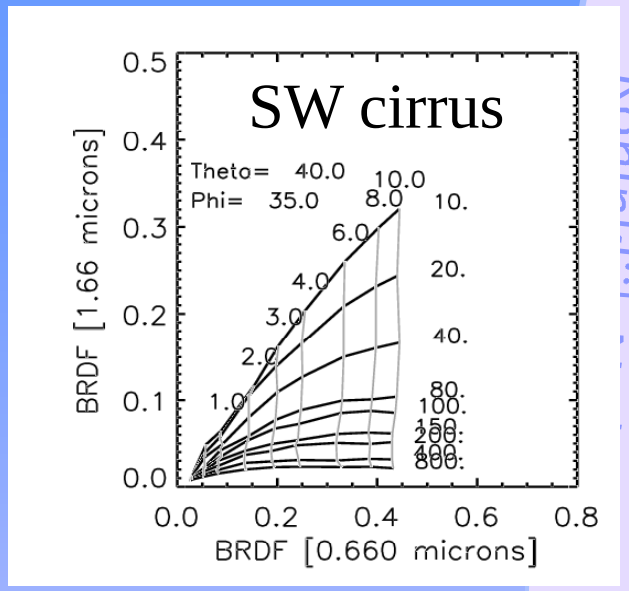
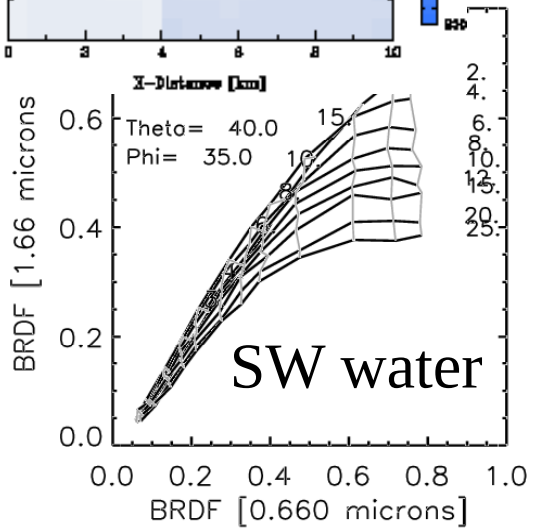


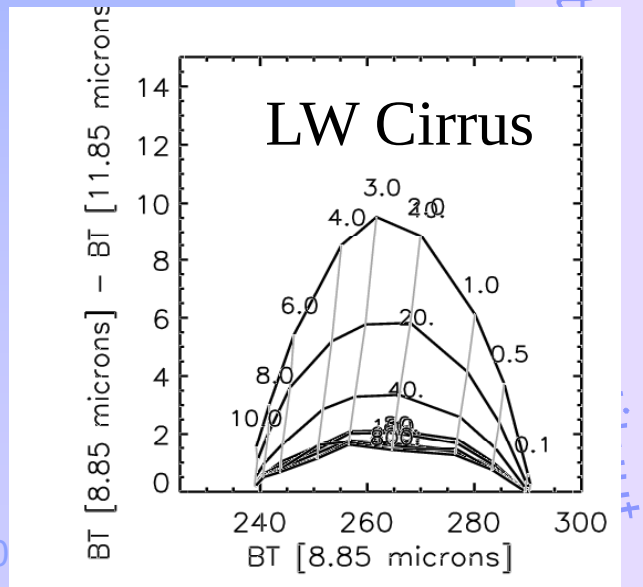
Figure 7: *Comparison between space-based and aircraft based signals (at $x = 1.5$ km) showing amount of multiple-scattering signal expected.*

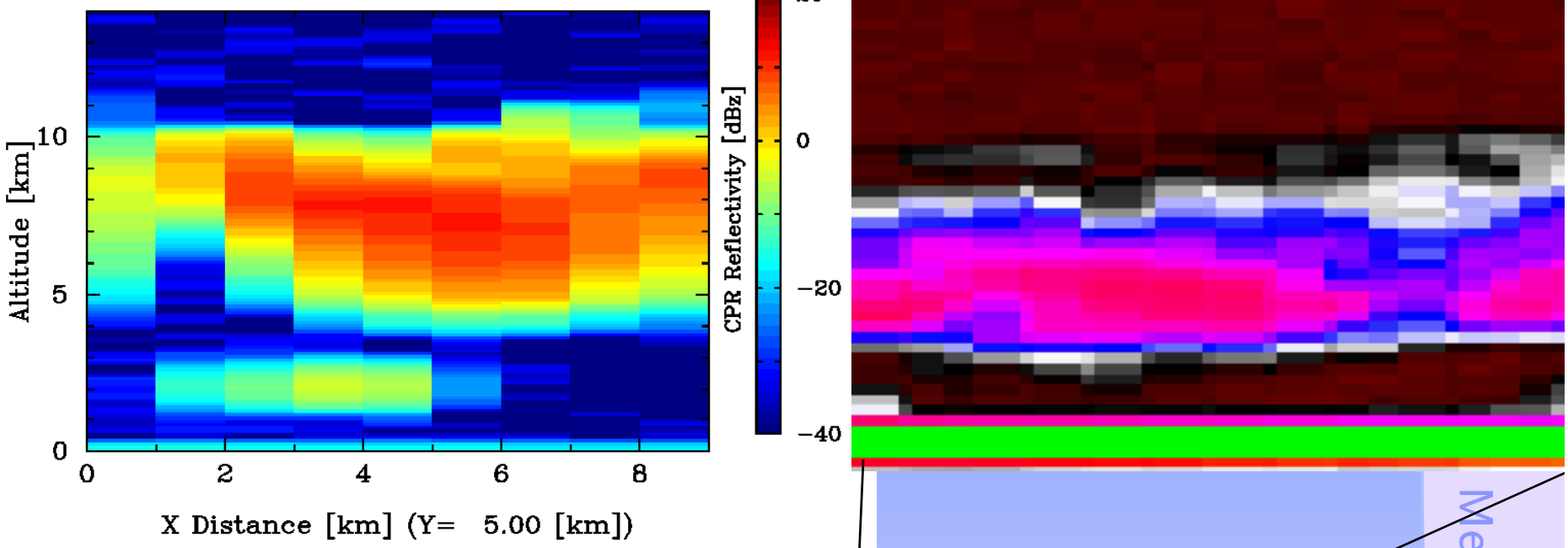
Here tau underestimated
By 50% if MS not taken
Into account

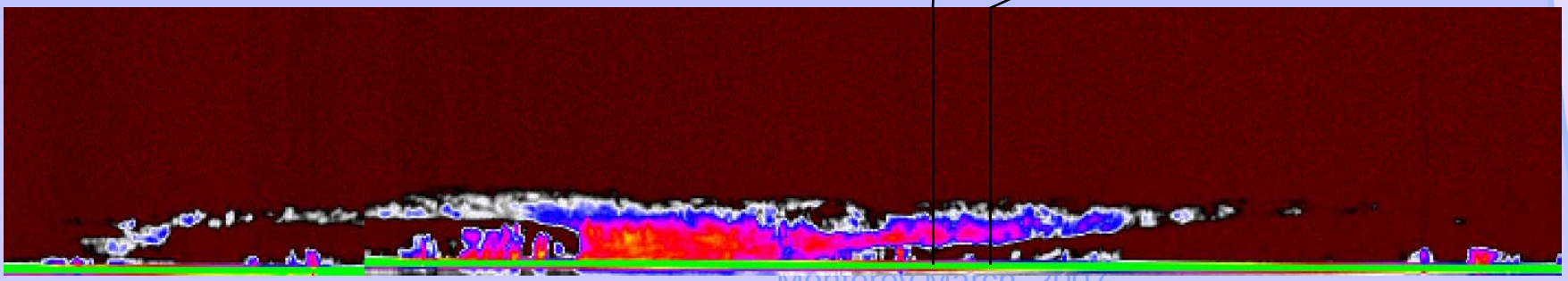

Channel 2
Channel3
Channel 5
Channel 7
X-Distance [km]
Y-Distance [km]


SW cirrus
Theta= 40.0
Phi= 35.0
BRDF [1.66 microns]
BRDF [0.660 microns]


SW water
Theta= 40.0
Phi= 35.0
BRDF [1.66 microns]
BRDF [0.660 microns]


LW Cirrus
BT [8.85 microns] – BT [11.85 microns]
BT [8.85 microns]





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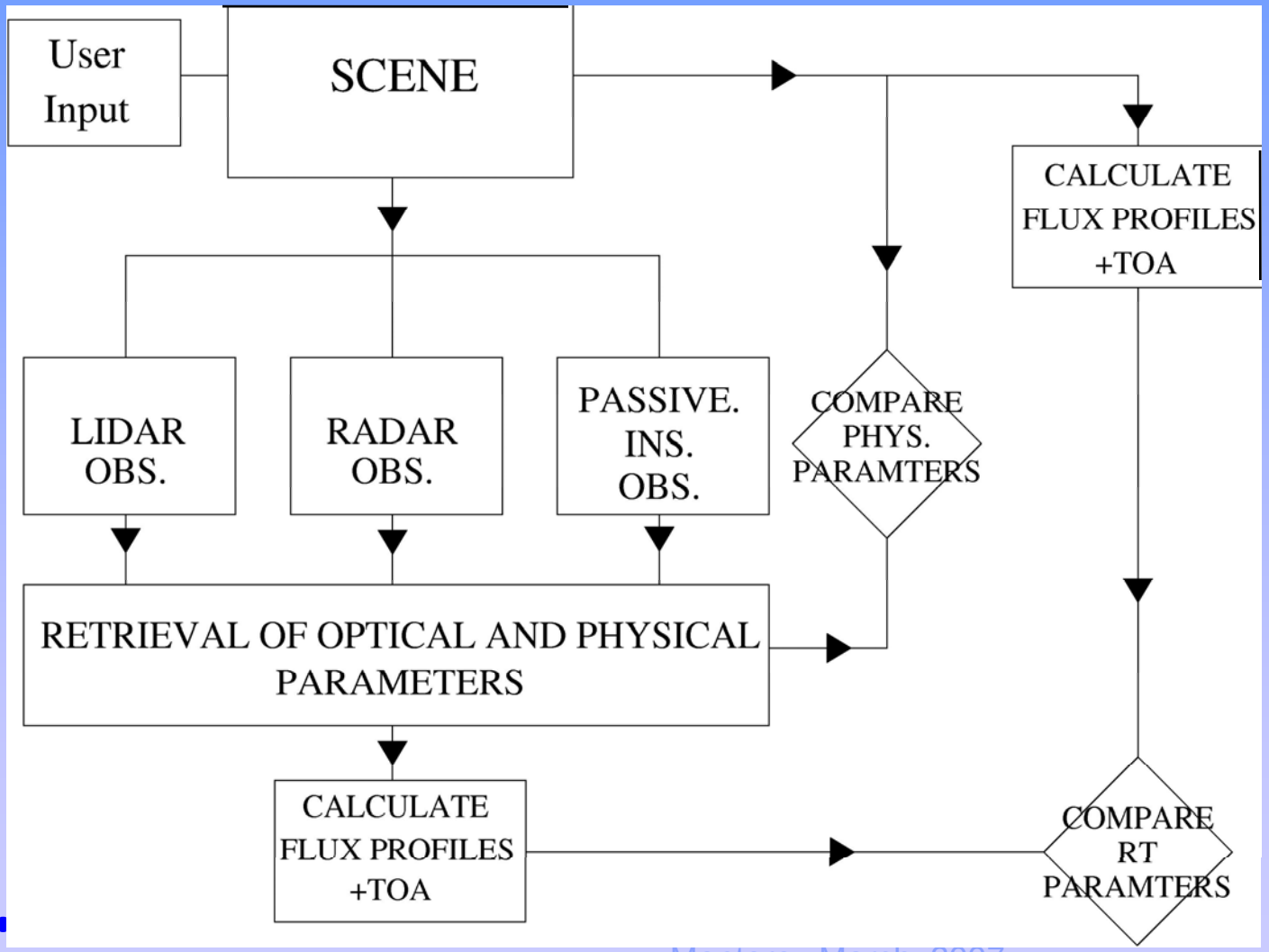
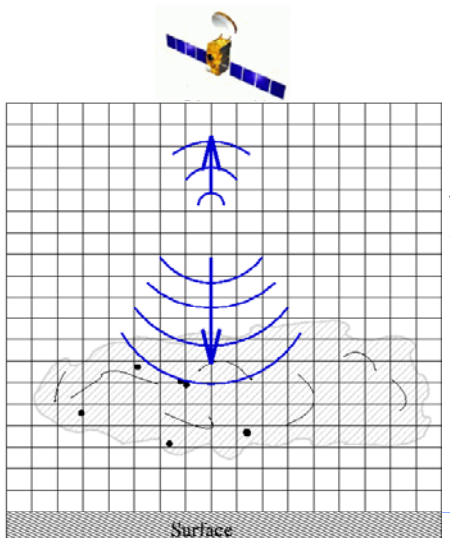
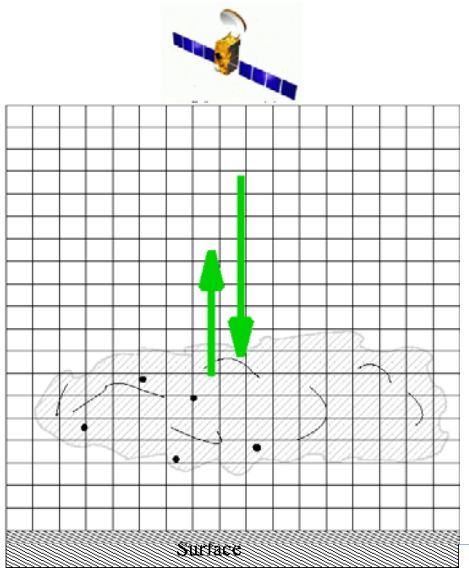
Monterey March, 2007

End-to-End collection of tools

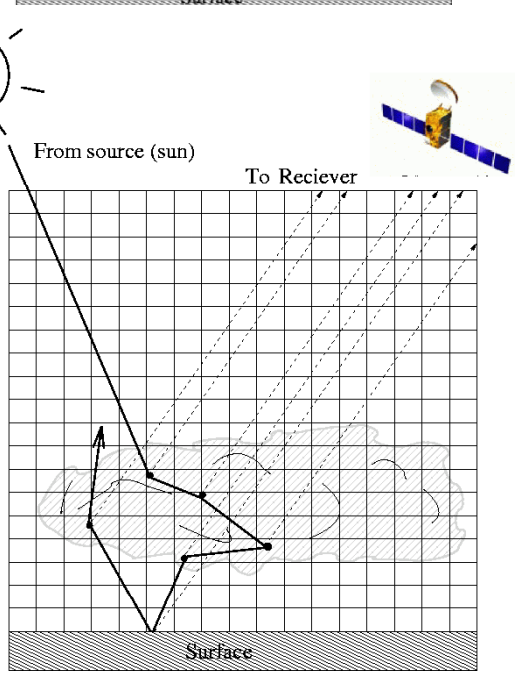




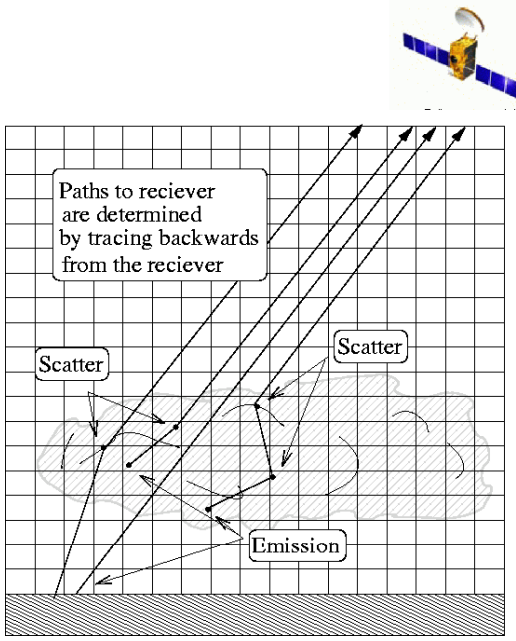
Radar
simulator



Lidar
MC code



SW
MC code



LW
MC code

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