EarthCARE
- Cloud radar and lidar in space by 2015

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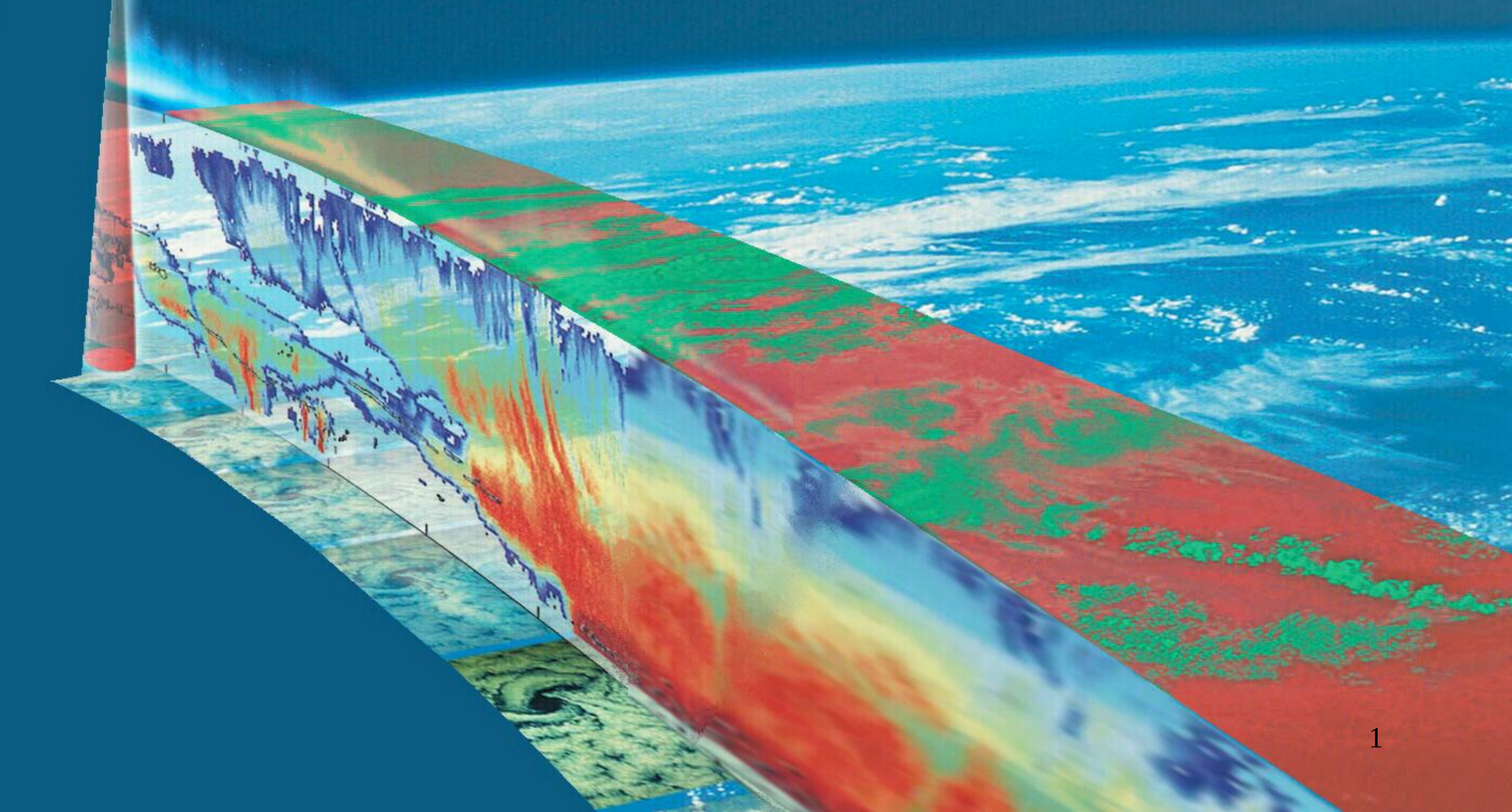
(EUROPEAN CHAIR OF EARTHCARE JMAG)



•EarthCARE has been defined with the specific scientific objectives of quantifying aerosol-cloud-radiation interactions so they may be included correctly in climate and numerical weather forecasting models to provide:

- Observations of the vertical profiles of natural and anthropogenic aerosols on a global scale, their radiative properties and interaction with clouds.
- Observations of the vertical distribution of atmospheric liquid water and ice on a global scale, their transport by clouds and their radiative impact.
- Observation of cloud distribution (‘‘overlap’), cloud-precipitation interactions and the characteristics of vertical motion within clouds.
- The retrieval of profiles of atmospheric radiative heating and cooling through the combination of retrieved aerosol and cloud properties.

The climate and weather forecasting problem

A) Future global warming 1 or 5K?

Cloud feedbacks dominate the sensitivity of climate to external forcing but existing models do not agree.

- more low clouds reflecting sunlight → cooling
- more high (cold) clouds, less IR to space → warming

Do current models have the correct cloud vertical structure, overlap, amount of condensate, sedimentation rate of ice (i.e. cirrus lifetime) ?

b) aerosols and clouds

- aerosols act as cloud condensation nuclei
- more aerosol → more reflective cloud → less precipitation → longer lifetime?
- more aerosol → smaller droplets, → faster evaporation → shorter lifetime?

Can we quantify these indirect aerosol effects ?

The climate and weather forecasting problem

DURING THE PAST DECADE SCHEMES HAVE BEEN DEVELOPED TO REPRESENT CLOUDS AND AEROSOLS EXPLICITLY IN NUMERICAL WEATHER PREDICTION (NWP) MODELS.

- **The water/ice content of clouds then produces precipitation.**
- **The schemes need evaluation and improvement so as to provide better forecasts of hazardous events such as flash flooding and air pollution episodes.**

CLIMATE MODELS USE THE SAME PARAMETERISATION SCHEMES AS THOSE IN WEATHER FORECASTING.

- **If we can get observed clouds and rainfall right in climate and weather forecasting models, then we have more confidence in predictions of future climate.**

ONLY RADAR AND LIDAR CAN PROVIDE GLOBAL OBSERVATIONS OF VERTICAL PROFILES OF CLOUDS AND AEROSOLS.

EARTHCARE – FOUR INSTRUMENTS (platform- Astrium UK)

RADAR (Japan) – to detect clouds and precipitation.

1. 2.5m dish, 94GHz (3mm). Footprint 750m.
2. Nadir pointing Pulse length 3.3µsec (500m resolution)
3. PRF 6100-7500 Hz. Horizontal resolution 1km. Doppler.

LIDAR AT 355nm. (Astrium SAS) – aerosols and thin clouds.

1. 34mJ at 51hz. Every 140m (horiz); Vert resolution 100m.
2. Cross polar return – shape of particles.
3. High spectral resolution: directly determines optical depth.

MULTI-SPECTRAL IMAGER (SSTL, UK)

1. To provide context for narrow band active instruments.
2. Swath 150km, each pixel 500m resolution.
3. Seven wavelengths 0.7, 0.86, 1.6, 2.2, 8.8, 10.8, 12 µm

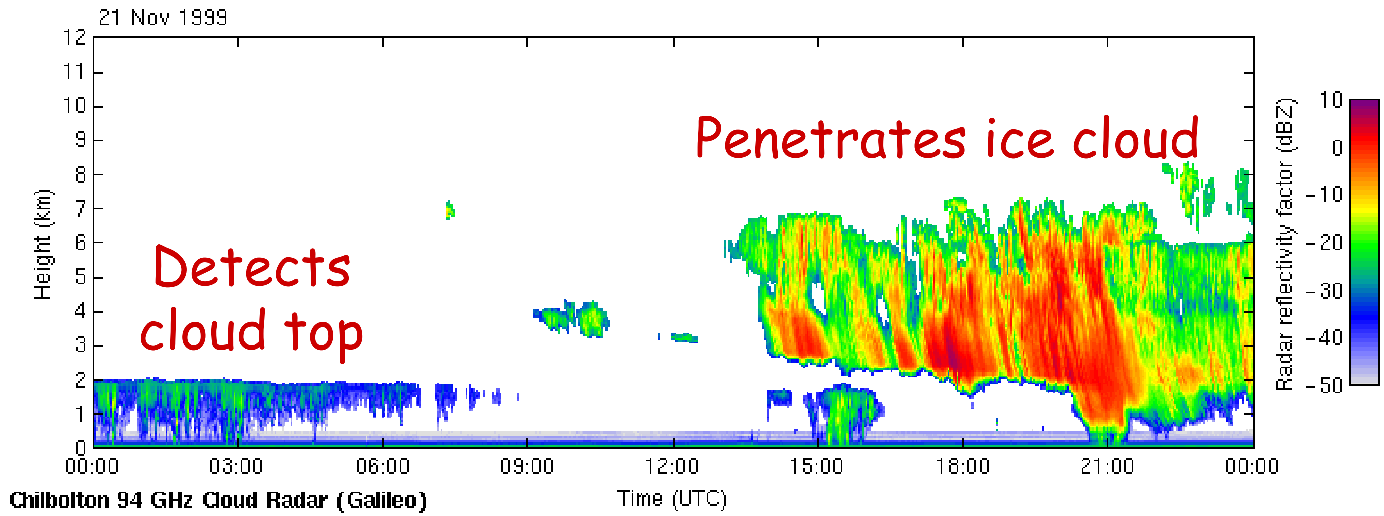
BROAD-BAND RADIOMETER - SEA(UK) – RAL provides the optics.

1. Upwelling visible and IR fluxes – for radiation closure.
2. 10km resolution, nadir pointing and 55° fwd and aft.

Basics of radar and lidar

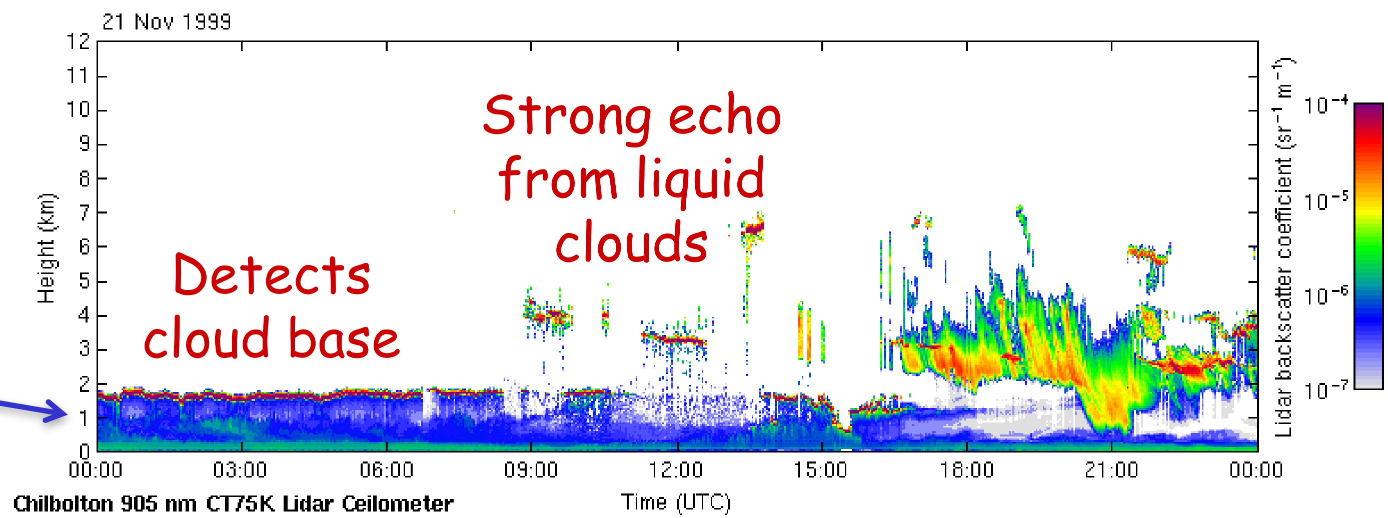
Radar: $Z \sim D^6$

Sensitive to large particles (ice, drizzle)



Lidar: $\beta \sim D^2$

Sensitive to small particles (droplets, aerosol)



Radar/lidar ratio provides information on particle size

ESA's Living Planet Programme
Earth Explorer Missions

1. **GOCE - Gravity Field and Steady-State Ocean Circulation Explorer - Gradiometer - launched March 2009**
2. **SMOS - Soil Moisture and Ocean Salinity satellite**
   L-band radiometer - launched November 2009
3. **CryoSat - to measure Earth's ice cover**
   SAR interference radar - launched April 2010
4. **Swarm - trio of satellites to measure Earth's magnetism**
   launch 2012.
5. **Aeolus - Atmospheric Dynamic Mission**
   355nm lidar. Dwell 45 °off-nadir. Wind every 100km.
   Detect shift of 1m/s in molecular return. Launch 2013

6. EarthCARE - Earth Clouds Aerosol Radiation Explorer

Four instruments: 94Ghz cloud radar; 355nm HSRL lidar; imager; radiometer. - Launch Nov 2015.

Joint Japanese-European (JAXA-ESA) Mission

EARTHCARE – TECHNICAL CHALLENGES

RADAR

1. Large dish at 94GHz (3mm)
2. Doppler – Measure phase shift from successive returns,

Need short separation targets rapidly decorrelate because of finite beamwidth and satellite motion.

Need long separation only one pulse in the atmosphere.

3. Satellite motion 7km/s – pointing knowledge to 25μrad, for an error of 0.17m/s. Difficult.

LIDAR AT 355nm.

1. Laser induced contamination – lessons from AEOLUS
2. Laser lifetime (10^9 shots). To reduce risk recent change: 30mJ (UV) at 74Hz $\rightarrow$ 34 mJ at 51Hz

so horizontal resolution per pulse is 140m (was 100m) {Still much lower power than AEOLUS, and less stringent frequency stability requirement}

THE EARTHCARE SAGA - part 1

- 1991 - FIRST MEETING IN PASSADENA.
- …….

1999 - EARTH RADIATION MISSION – joint JAXA-ESA

proposed to Explorer Selection meeting (Granada)

Atmospheric Dynamic Mission selected. - clear air winds

(355nm lidar: 45deg off nadir - Doppler shift of molecular return)

- **2004 – Frascati Meeting - EARTHCARE SELECTED!!**

Dopplerised 94GHz cloud radar

High Spectral Resolution 355nm Lidar

- **2010 (Dec) - 2011 (Feb)**

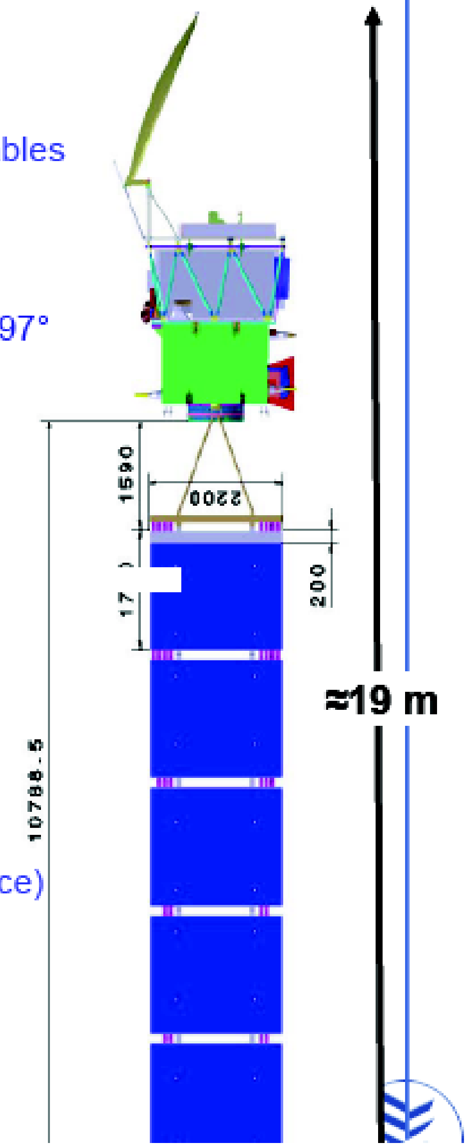
INDEPENDENT EARTHCARE ASSESSMENT

Conclusion – if essential to decrease risk then lower prf of lidar.

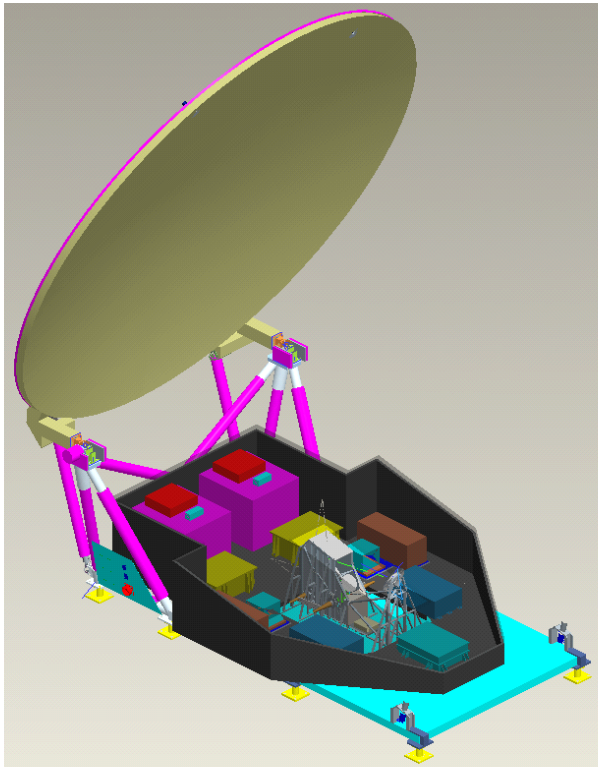
Aerosols products at 20km along track resolution not at 10km.

EarthCARE Satellite (1)

- Mission Duration: 3 years (including 6-month commissioning) + 1 year consumables
- Mission Orbit
  - Orbit type: LEO – Frozen Orbit – SSO
  - MLST DSN **14:00**
  - Mean spherical altitude: 393 km (nominal) / 394.4 km (Cal/Val) Inclination: 97°
  - Repeat cycle (nominal/Cal/Val): 25 / 9 days
  - Attitude control: 3-axis stabilised, yaw-steering control
- Dry Launch Mass: (excl. **313 Kg** propellant): 1859 Kg
- Payload
  - 2 active instruments: ATLID & CPR
  - 2 passive instruments: BBR & MSI
- Power Sub-system
  - Deployable solar array, GaAs triple junction cells, 21 m2
  - Li-ion battery (nom. capacity): 324 Ah
  - Average Power consumption: 1645 W
- Communication Links
  - Generated data rate average: <15 kbps (housekeeping) & <2.5 Mbps (science)
  - S-Band (control & monitoring, 2 passes / day):
    - Uplink: 64kbps (max 10 TCs/s)
    - Downlink (with/without ranging): 128 kbps/2 Mbps
  - X-Band downlink (for science data & stored HKTM): 150 Mbps



CPR overview – Major Specifications —



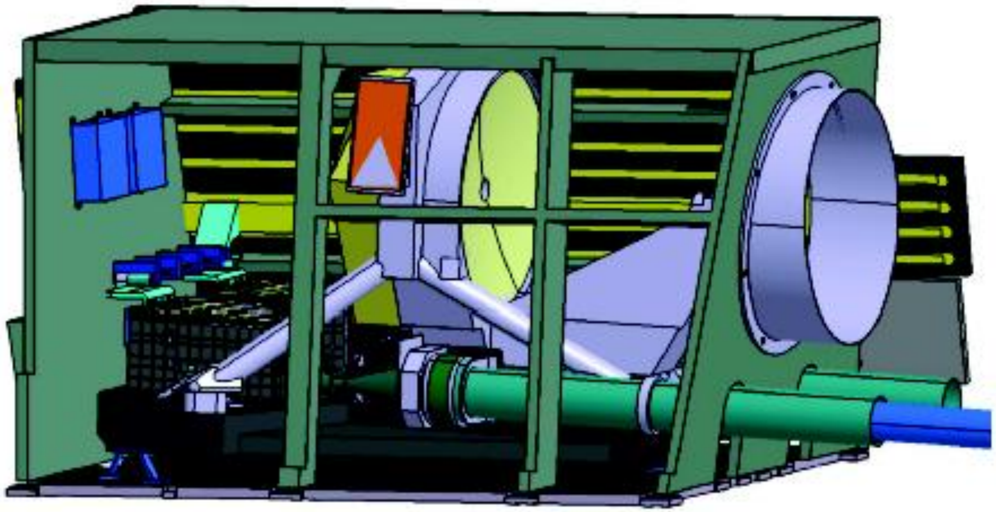
•Top cover is transparent to show inside

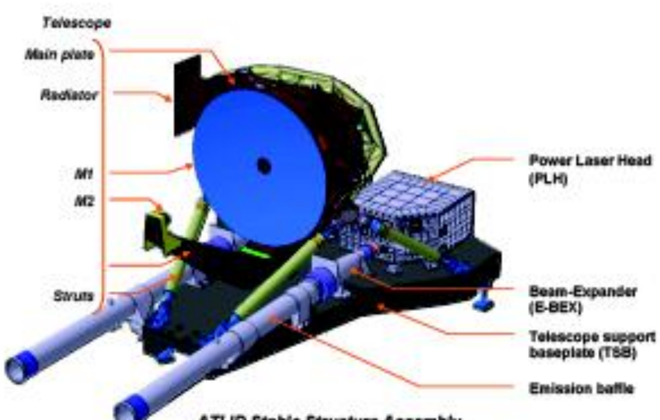
•Physical charastristics
- –size 2500x2700x1300 [mm] (stow),
- • 2500x2700x3550 [mm] (deploy)
- –Main reflector diameter: 2.5m
- –Mass: 270kg (TBD)
- –Power: 330W (TBD)
- –Max data rate: 270kbps

Radar type	94 GHz Doppler Radar
Center frequency	94.05 GHz
Pulse width	3.3 micro second (equivalent to 500m vertical resolution)
Beam width	0.095 deg
Polarization	Circular
Transmit power	> 1.5 kW (Klystron spec.)
Height range	-0.5 ~ 20 km
Resolution	500 m (100 m sample); Vertical, 500m integration; Horizontal
Sensitivity*	-35 ~ +21 dBZ
Radiometric accuracy*	< 2.7 dB
Doppler measurement	Pulse Pair Method
Doppler range*	-10 ~ +10 m/s
Doppler accuracy*	< 1 m/s
Pulse repetition frequency	Variable; 6100~7500 Hz
Pointing accuracy	< 0.015 degree

•*; at 10 km integration and 387 km orbit height

ATLID overview (2/2)





ATLID Stable Structure Assembly (SSA) and equipments

Mass : 483kg

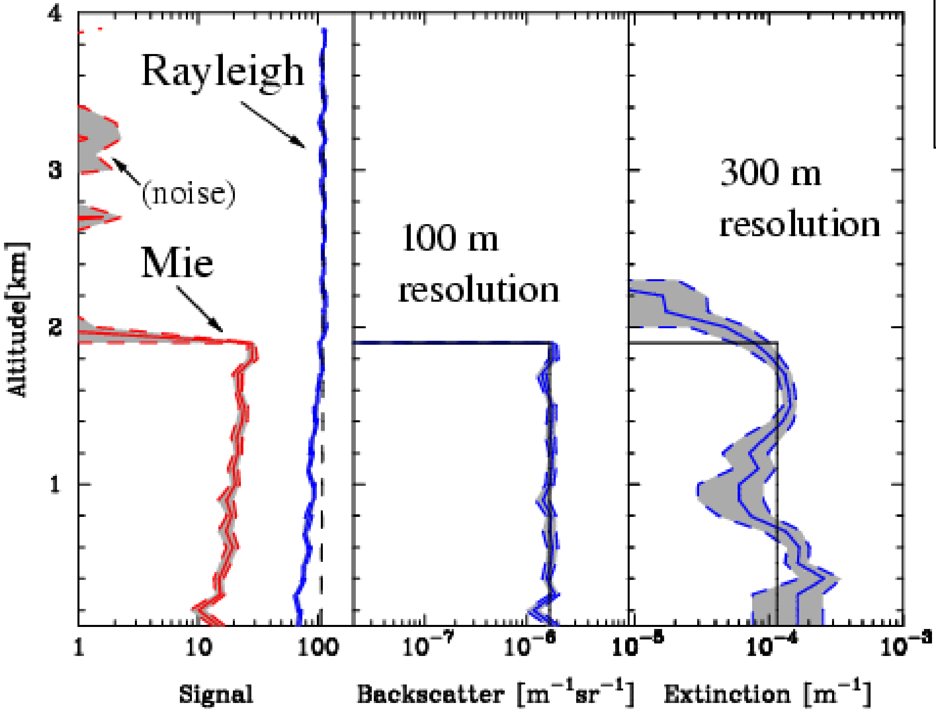
Power : 585W

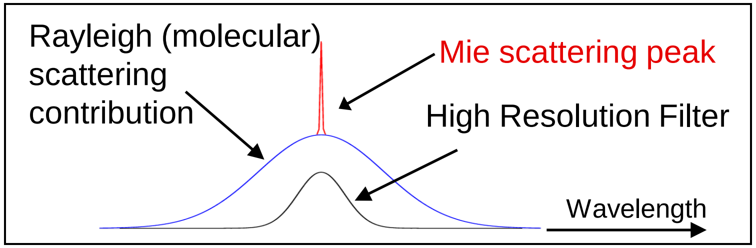
Data rate < 660kb/s

Observation Technique
High Spectral Resolution 355 nm Lidar

Uniform Aerosol in lowest 2km

Raw signals True backscatter Extinction





1. **Compare observed molecular return with expected non-attenuated value**
   ⇨ True extinction coefficient and optical depth

2. **Use extinction to correct the attenuated backscatter to give true backscatter**

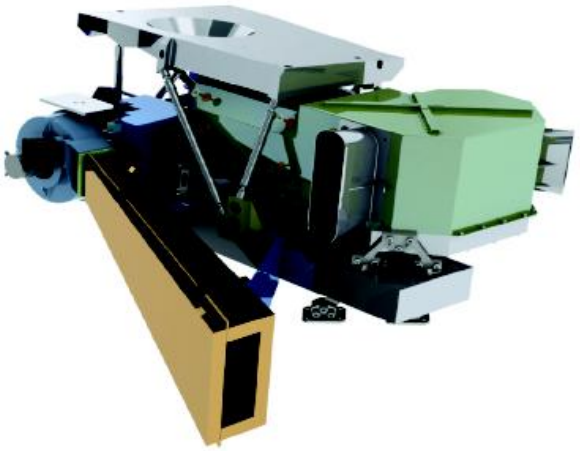
3. **Derive the true lidar ratio**
   = extinction/backscatter

Additional information:

- Direct measurement of extinction (optical depth) of aerosol and clouds.
- Shape of ice particles and aerosols: from cross-polarisation channel
- Distinguish different aerosols and ice crystal habit : from cross-polarisation ratio and lidar ratio (extinction/backscatter).

MULTI-SPECTRAL IMAGER

- Power: 52 W
- Mass: 56 Kg
- Data Rate: 561 kbps



BROAD BAND RADIOMETER

Power	**45w**
Mass	**48kg**
Data rate	**139kbps**

Combine all instruments:"Best Estimate" algorithm

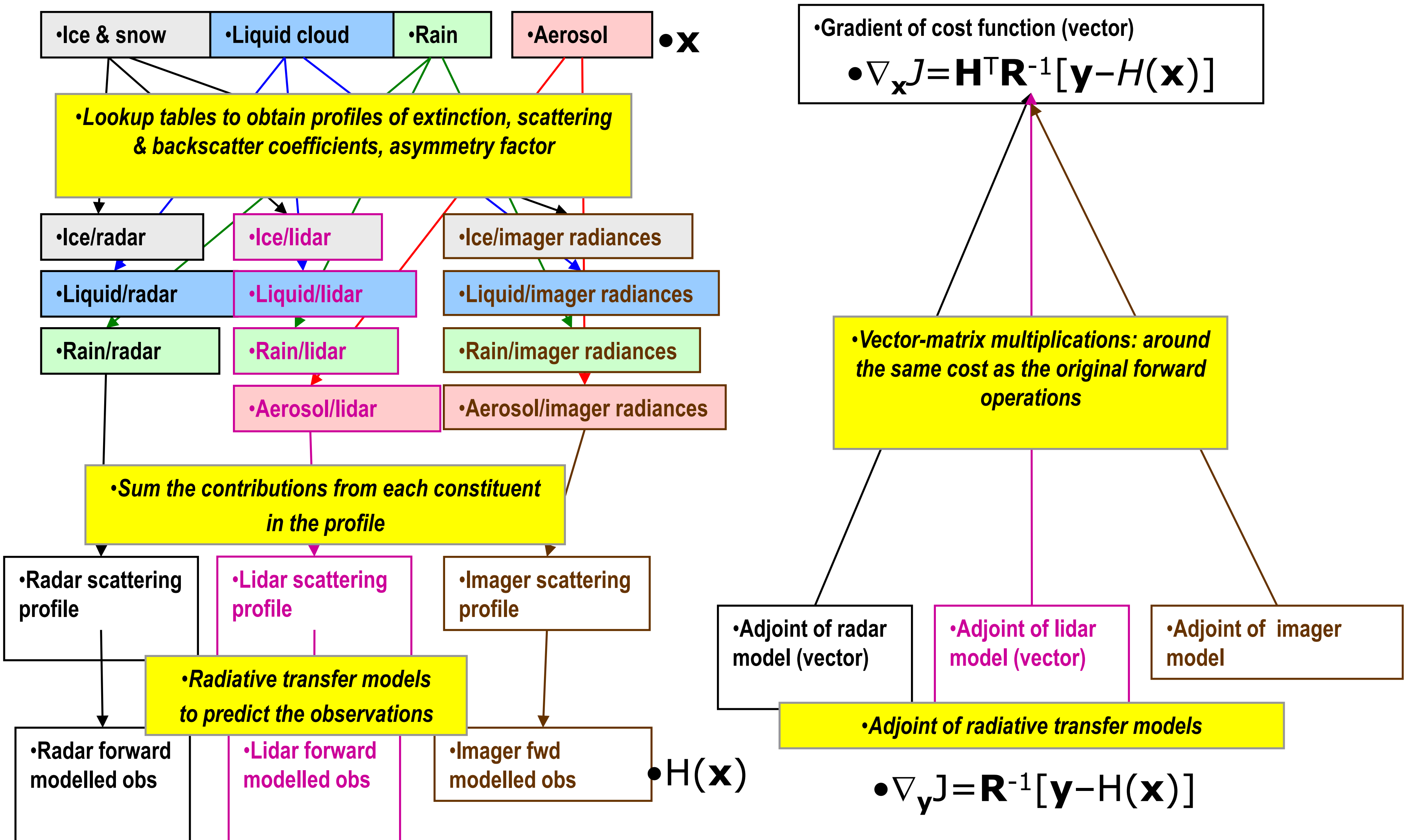
Robin Hogan – U of Reading

- Combine all measurements available (radar and lidar profiles, imager radiances. (vector **y**)
- Retrieve profile of cloud, precipitation and aerosol properties simultaneously
  - Ensures integral measurements can be used when affected by more than one species (e.g. radiances affected by ice and liquid clouds)
  - Forms the state vector **x**

    e.g. Profile of ice particle mean size and concentration.
- Variational approach (also known as optimal estimation theory)
  - Rigorous way to do a retrieval with proper weighting of errors in observations and prior assumptions by minimizing a *cost function*
  - Rigorous estimate of retrieval errors

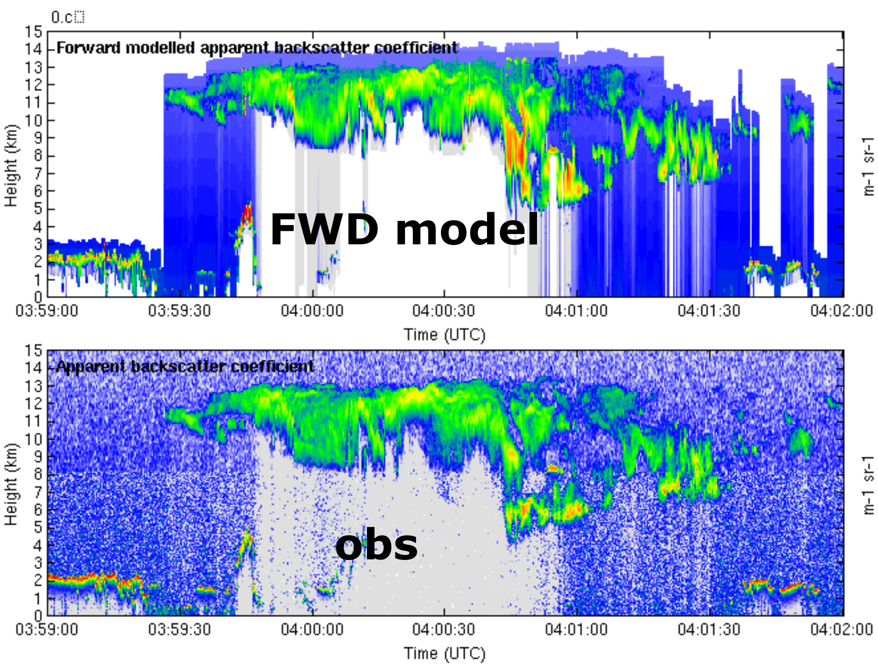
Unified retrieval: Forward model

- From state vector **x** to forward model the observations $H(\mathbf{x})$...

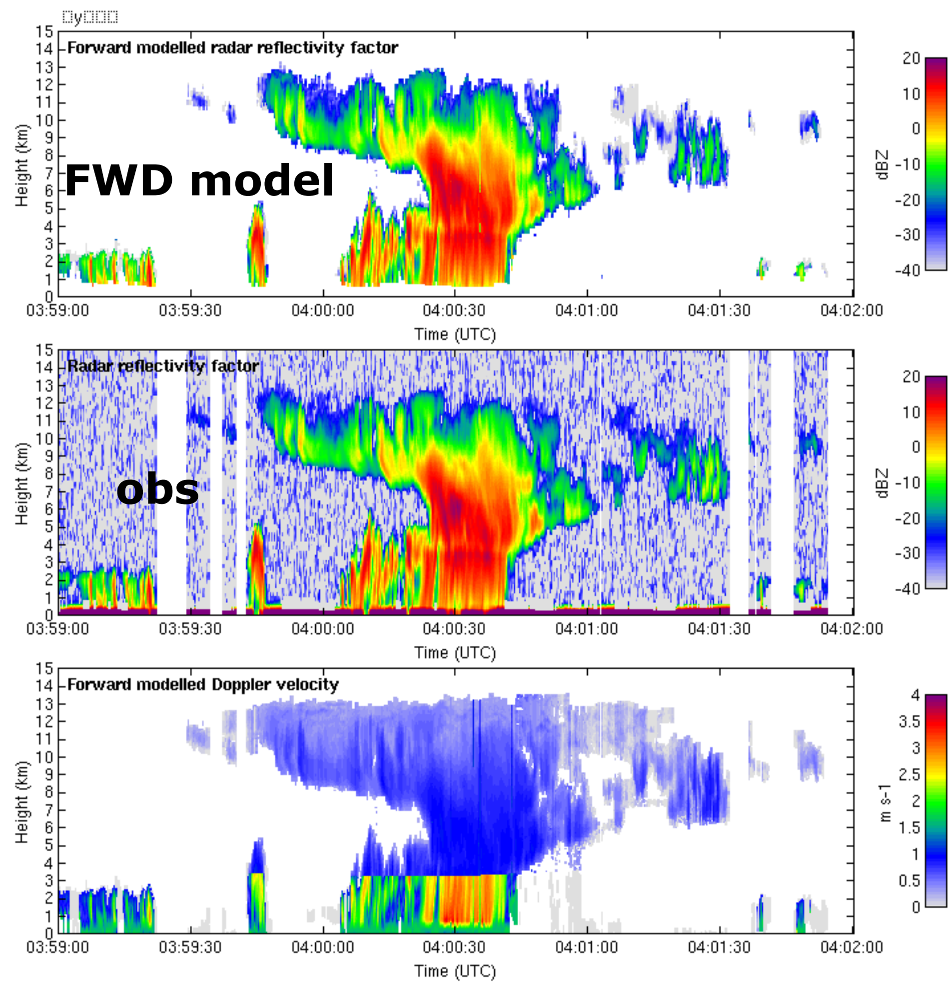


Observations vs forward models

- **Lidar backscatter**



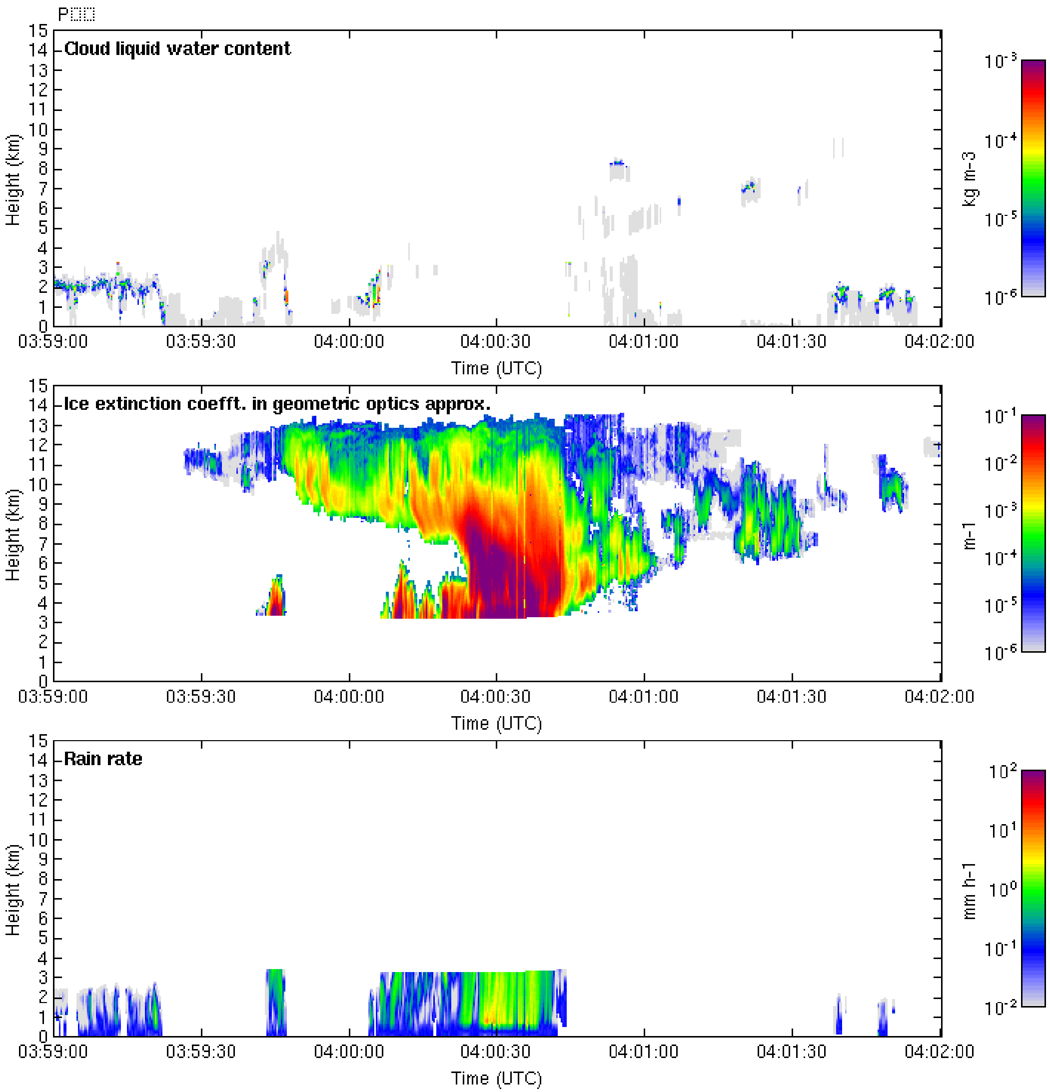
- **Radar reflectivity factor**



- Radar and lidar backscatter are successfully forward modelled (at final iteration) in most situations

Can also forward model Doppler velocity

Example of three retrieved components - with errors – 'level two products' NWP/climate modellers can use them .



- Liquid water content
- Ice extinction coefficient (could derive ice water content)
- Rain rate

SCIENCE ADVANCES FROM EARTHCARE (1)

– Improved aerosol products

a) First space based direct measurement of aerosol extinction profiles to an accuracy of 10% rather than a factor of two.

b) More reliable identification of aerosol type using the lidar ratio and depolarisation ratio.

c) Improved daylight performance of lidar – aerosol in the boundary layer available both day and night.

-Improved cloud products (extra 7dB radar sensitivity)

a) More accurate retrieval of high ice clouds detecting 80% rather than 40%, and ice water content with 20% accuracy rather than 60%

b) Better sampling of liquid water clouds; 60% rather than 40%.

and the Doppler provides:

c) First global measurements of convective motions

d) First global measurements of ice fall speed.

e) First global measurements of droplet fall speed in precipitation.

SCIENCE ADVANCES FROM EARTHCARE (2)

– Improved radiation products

a) Direct measurements of the optical depth of clouds and aerosol rather than having to derive a value from the backscatter.

b) Radar detection of more high ice clouds, so that their optical depth, ice water content & ice particle size are better determined.

c) Better observations of low level stratocumulus by the radar.

d) Co-located broad band radiometer for radiation closure.

- Evaluation of climate and forecasting models.

a) Improved aerosol identification and optical depth day and night.

b) More accurate measurements of high ice clouds and low water clouds.

c) Improved radiation products including the important downwelling IR.

d) The first observations of the sedimentation velocity of ice particles

e) The first global estimates of the convective motions within clouds

f) The first estimates of terminal velocities of precipitation.

Finally we note that national weather centres are now developing schemes to assimilate radar and lidar observations of clouds and aerosols in real time to provide a better initial state of the atmosphere for their forecasts.

THE EARTHCARE SAGA - part 2

- **1991**

- LEVEL ONE SATELLITE DATA FOR REGISTERED USERS

- **2011**

- SATELLITE DATA AVAILABLE FREELY ON THE WEB.

- MOST CLIMATE MODELLERS AND NATIONAL WEATHER SERVICES CAN'T/WON'T USE LEVEL ONE DATA.

- TO JUSTIFY THE INVESTMENT IN THE SATELLITE AND ENSURE THE DATA IS FULLY EXPLOITED IT IS ESSENTIAL TO SUPPORT THE DEVELOPMENT OF LEVEL TWO PRODUCTS.

- EXTRA slides

EarthCARE – 'Follow on' to Cloudsat,Calipso.

Radar and lidar on the same satellite.

RADAR 8dB more sensitive - larger dish /lower orbit.

will see thin cirrus and many more stratocumulus clouds

+ Doppler capability.

(provide pdfs of motions to evaluate convective paramterisations).

LIDAR – has high spectral resolution - separates the more slowly moving returns from the cloud/aerosols from the rapidly moving molecular returns.

Avoids problem of trying to correct for lidar attenuation – use molecular channel to measure extinction independently.

– characterise ice crystals and aerosols from:

extinction/backscatter ratio + depolarisation ratio.

RADAR – Rayleigh scattering: Cloud particles and precipitation

RADAR RETURN varies as ND^6/λ^4

Where N is cloud particle concentration, D is size.

RAIN – cm wavelength radar (D ≈ mm)

λ =3.4mm (94GHZ) for more sensitivity

Small λ: sees all ice clouds (D ≈ 100μm)

but still miss some water clouds (D ≈ 10μm)

2.5m ANTENNA in 400km orbit - 700m footprint

LIDAR see what we see – 355nm. HIGH SPECTRAL RESOLUTION – SEPARATES THE RETURNS FROM:

Mie scattering – SLOW VELOCITY: Backscatter from aerosols.

See clouds - penetrate ice clouds, but water clouds rapidly extinguish the lidar signal.

Molecular return – HIGH VELOCITY - proportional to air density, any reduction of molecular return → aerosol/cloud optical depth.

Cloud Parameterisation

- Operational models currently in each grid box typically two prognostic cloud variables:
  - Prognostic liquid water/vapour content
  - Prognostic ice water content (IWC) OR diagnose from T
  - Prognostic cloud fraction OR diagnosed from total water PDF
- Particle size is prescribed:
  - Cloud droplets - different for marine/continental
  - Ice particles – size decreases with temperature
  - Terminal velocity is a function of ice water content
- Sub-grid scale effects:
  - Overlap is assumed to be maximum-random
  - What about cloud inhomogeneity?

How can we evaluate & hence improve model clouds?

CLOUDNET – JUST A FEW SITES, NEED SATELLITES FOR GLOBAL COVERAGE

THE ‘A’ TRAIN’

CloudSat and Calipso

Launch April 2006.

CloudSat 94Ghz radar

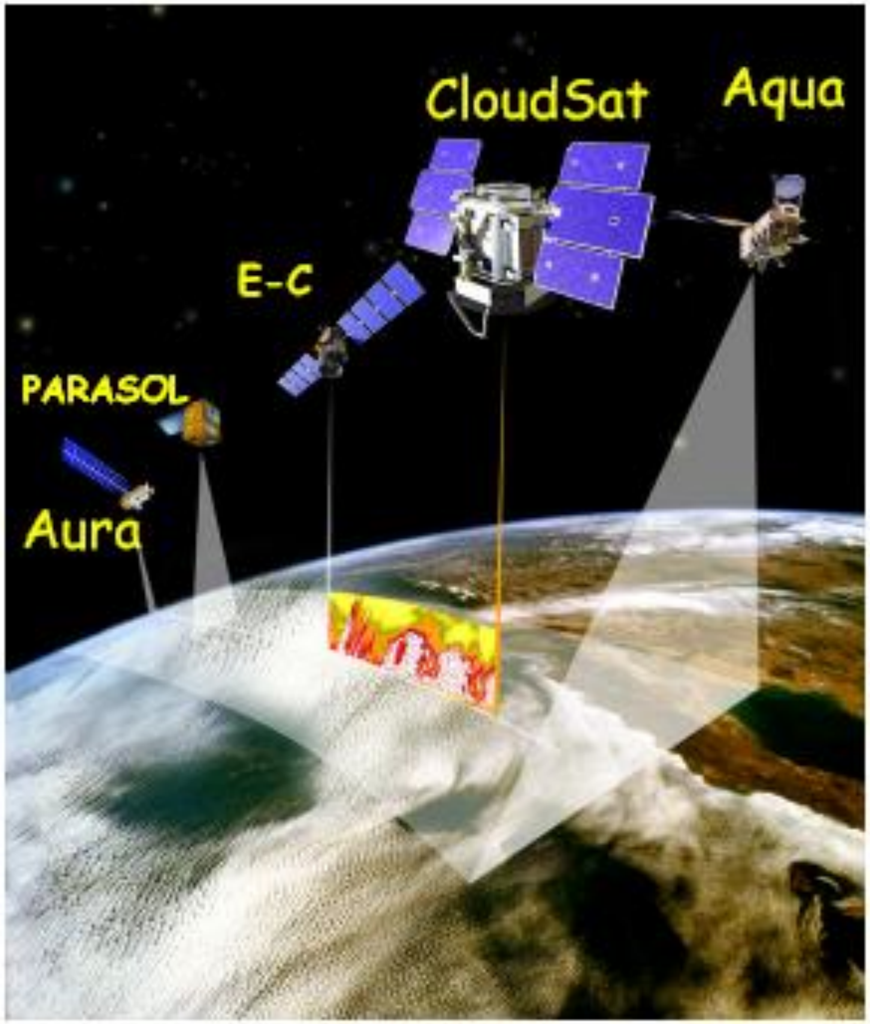
-26dBZ sensitivity

60secs behind MODIS on Aqua.

Calipso 532nm lidar:

Clouds, aerosol, molecular+ cross polar.

15 secs behind cloudsat

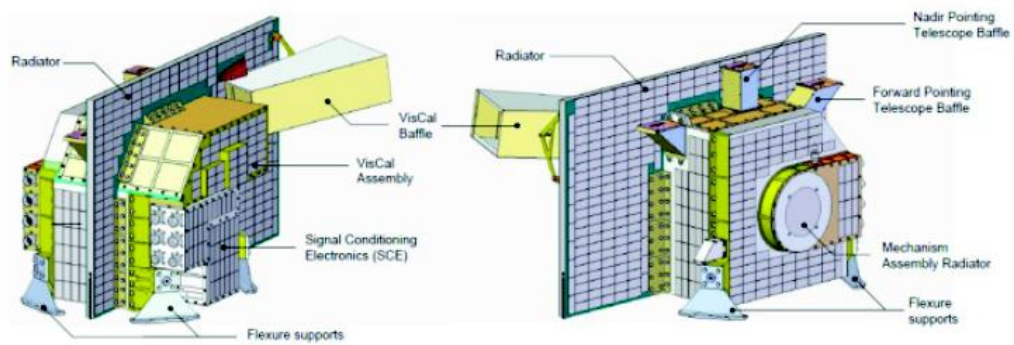


esa

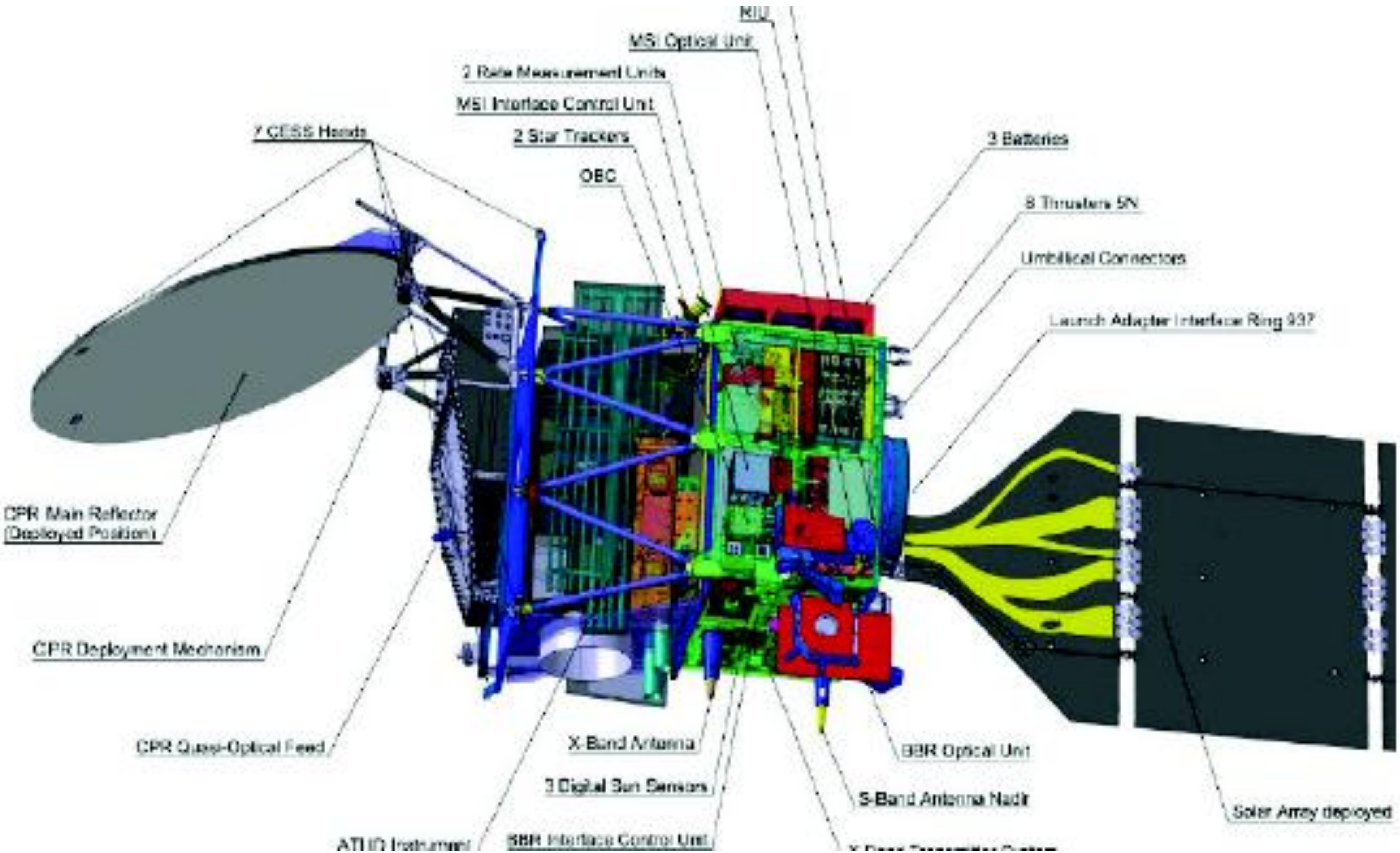
JAXA

BBR

Instrument Overview



Mass (incl. margin)	48kg
Power	45W
Data rate	139 kbps


MSI Optical Unit
2 Rate Measurement Units
MSI Interface Control Unit
7 CESS Heads
2 Star Trackers
OBC
3 Batteries
8 Thrusters 5N
Umbilical Connectors
Launch Adapter Interface Ring 937
CPR Main Reflector
(Deployed Position)
CPR Deployment Mechanism
CPR Quasi-Optical Feed
X-Band Antenna
3 Digital Sun Sensors
ATLID Instrument
BBR Interface Control Unit
BBR Optical Unit
S-Band Antenna Nadir
Solar Array deployed