Filterbank spectrometers for Hyperspectral Microwave Atmospheric Sounding (HYMAS)

Peter Hargrave, Ben Flatman, Prateek Dongre – Cardiff University
Stafford Withington – University of Cambridge
Stefan Buehler, Lukas Kluft – University of Hamburg
Bill Bell, Fiona Smith – UK Met Office

hargravepc@cardiff.ac.uk

Application areas

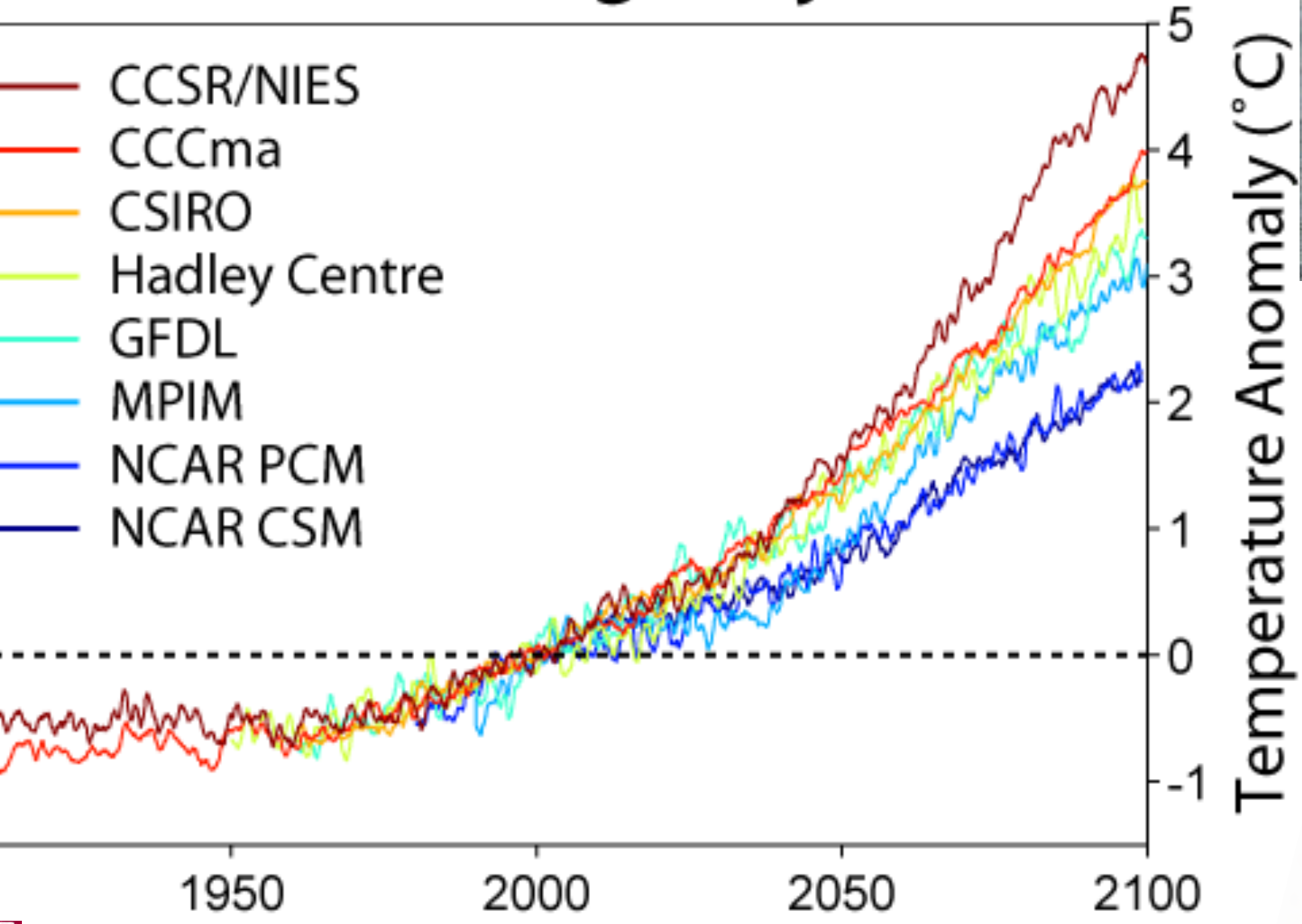
- Climatology – the role of cloud feedbacks in the Global climate system
- Meteorology – *Full Global coverage* - measurements of temperature & humidity profiles with high (3-D) spatial resolution and accuracy

UNIVERSITY OF CAMBRIDGE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Met Office
UK SPACE AGENCY
CEDI-ST
hargravepc@cardiff.ac.uk

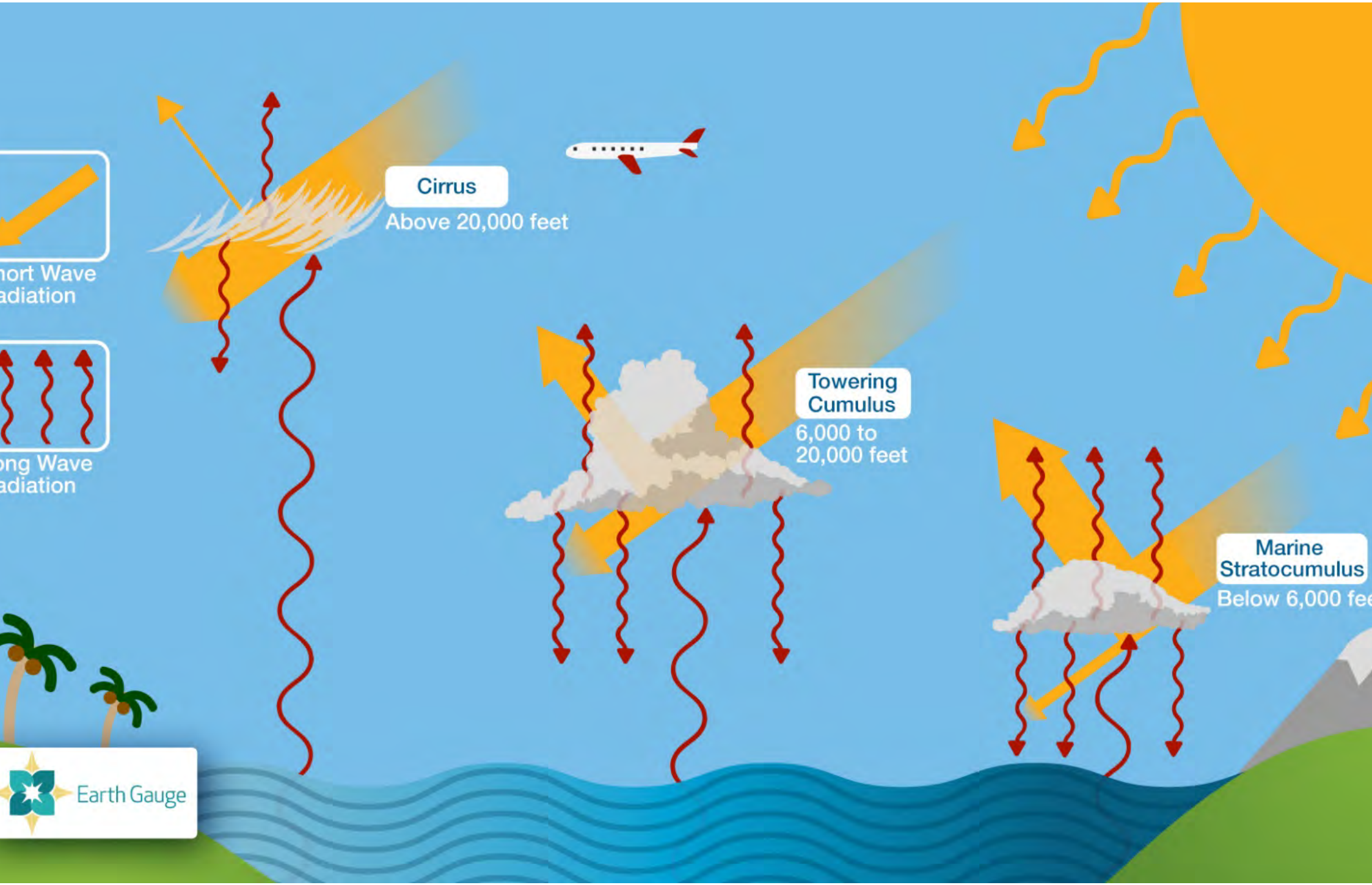
Climatology

UNIVERSITY OF CAMBRIDGE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Met Office
UK SPACE AGENCY
CEDI-ST
hargravepc@cardiff.ac.uk

Global Warming Projections



UNIVERSITY OF CAMBRIDGE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Met Office
UK SPACE AGENCY
CEDI-ST
hargravepc@cardiff.ac.u


hort Wave
adiation
ong Wave
adiation
Cirrus
Above 20,000 feet
Towering
Cumulus
6,000 to
20,000 feet
Marine
Stratocumulus
Below 6,000 fe
Earth Gauge

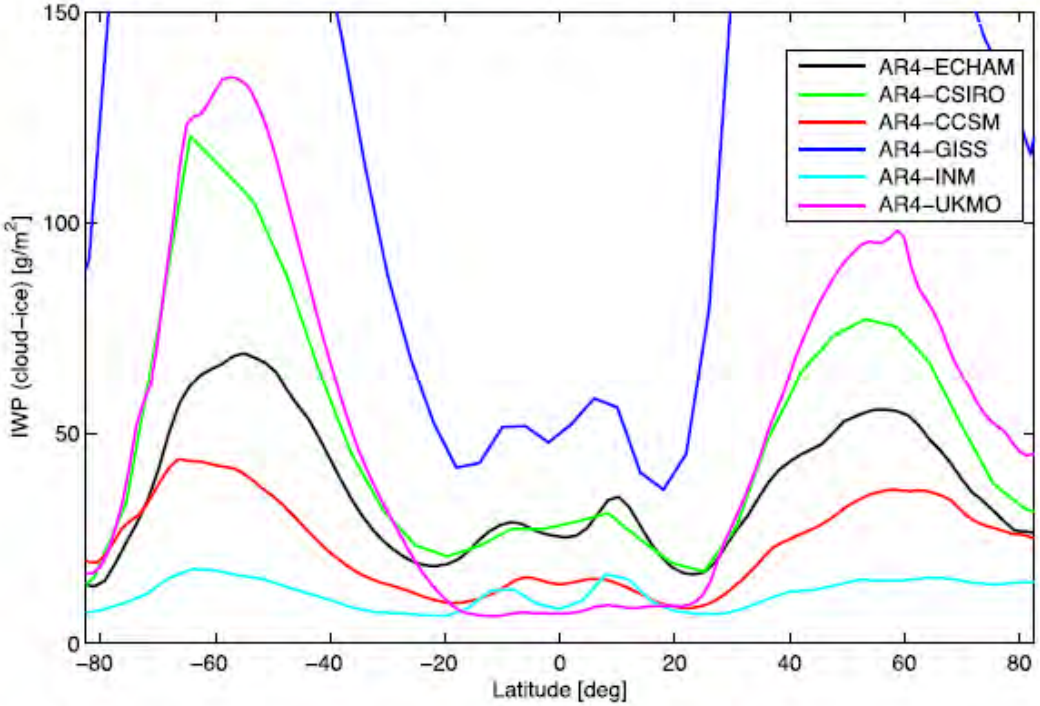
Clouds in climate models

IPCC, 4th Assessment:

'In many climate models, details in the representation of clouds can substantially affect the model estimates of cloud feedback and climate sensitivity [...]. Moreover, the spread of climate sensitivity estimates among current models arises primarily from inter-model differences in cloud feedbacks [...]. Therefore, cloud feedbacks remain the largest source of uncertainty in climate sensitivity estimates.'

Review article:
Stephens [JC, 2005]

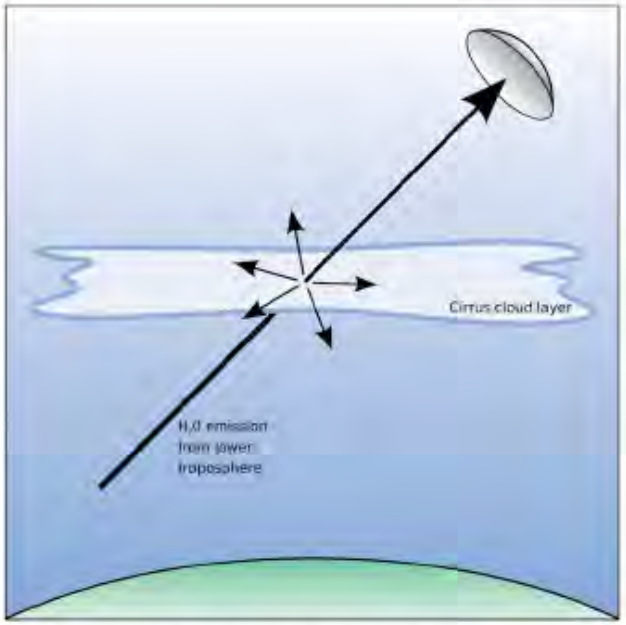
Comparison of different AR4 climate models



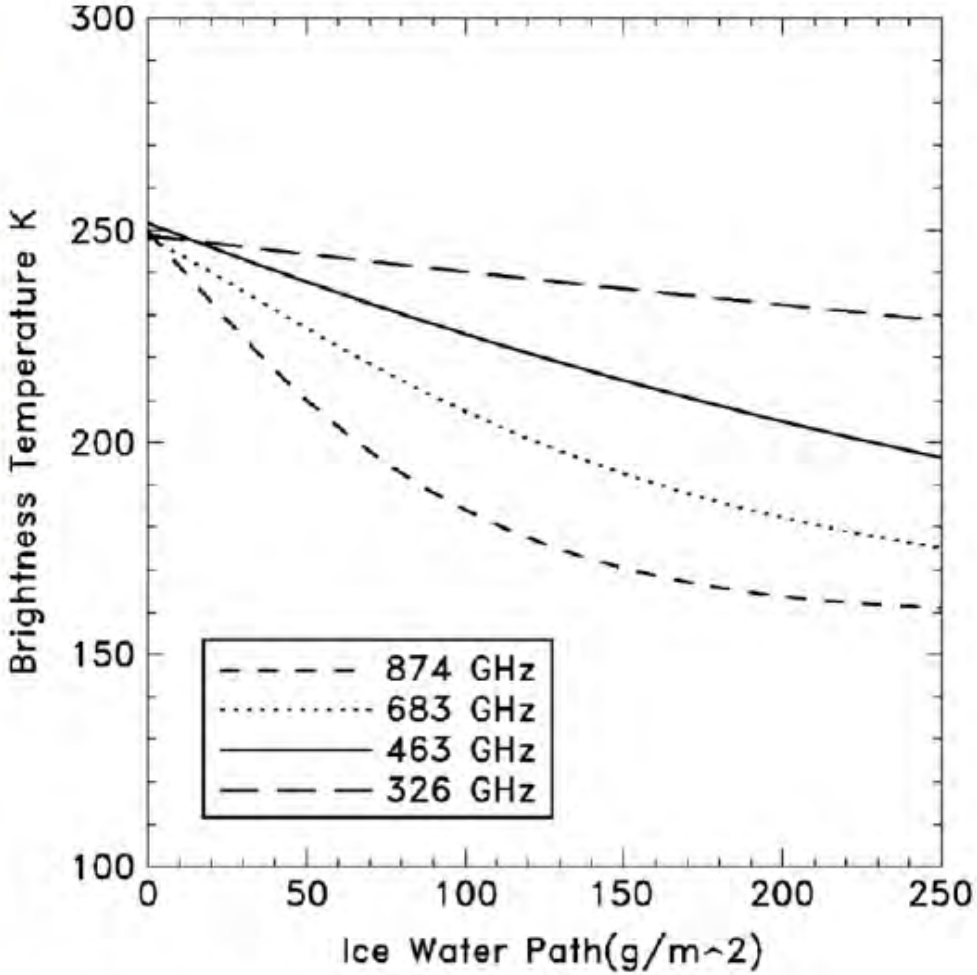
- **IWP [g/m2]** = vertically integrated „Ice Water Content" (IWC).
- Zonal mean over 100 years.
- AR4-GISS*0.5 to bring to same scale.

Eliasson, S., S. A. Buehler, M. Milz, P. Eriksson, and V. O. John (2011), **Assessing observed and modelled spatial distributions of ice water path using satellite data, *Atmos. Chem. Phys., 11, 375–391, doi:10.5194/acp-11-375-2011.***

“Traditional” Sub-mm observation concepts – ICI on MetOp-SG



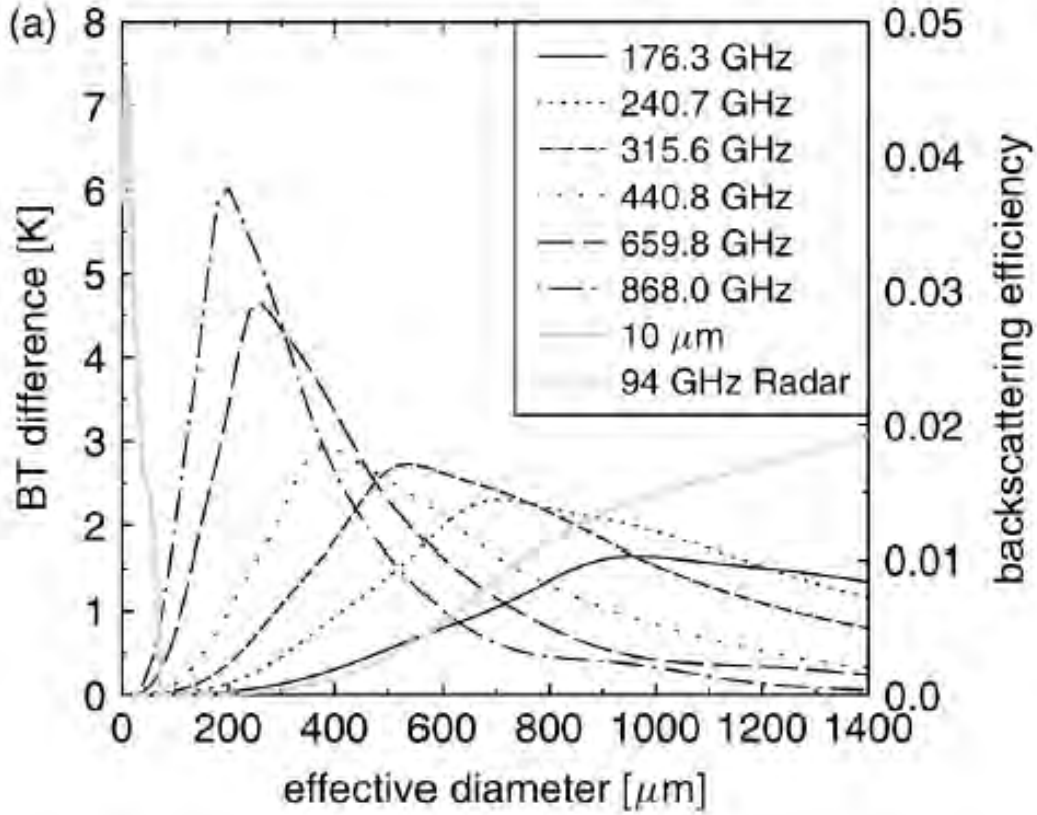
Observation geometry.

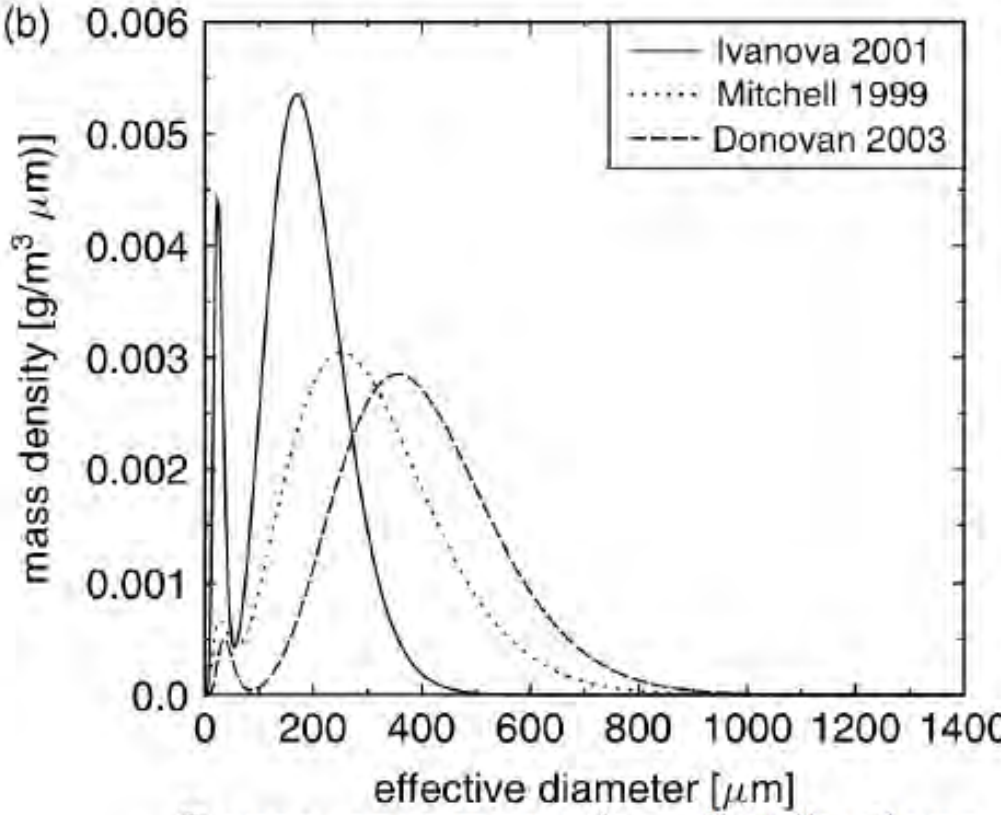


ARTS simulation.
Cloud ice signal at different frequencies.
Midlatitude-winter, spherical ice particles with D=200 µm.
Figure from *Buehler et al.* [QJRMS 2007].

UNIVERSITY OF CAMBRIDGE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Met Office
CEDI-ST
hargravepc@cardiff.ac.uk

Particle size vs. wavelength





Some common size distributions (from *Buehler et al.* [QJRMS 2007]).

Sub-millimeter measurements can sample the size distribution.

Meteorology

UNIVERSITY OF CAMBRIDGE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Met Office
UK SPACE AGENCY
CEDI-ST
hargravepc@cardiff.ac.uk

Meterology – state of the art

IR sounders

- IASI
  - 8534 channels
  - 19-83 THz
  - NEDT 0.1 - 0.2 K
- Good performance, but limited to *clear sky conditions* only

MW sounders

- AMSU-A/B
- MWS, MWI on MetOp-SG
  - 13 channels
  - 18.7 - 229 GHz
  - NEDT 0.4 – 1.4 K
- Poor vertical resolution
- *BUT* can see down into cloud

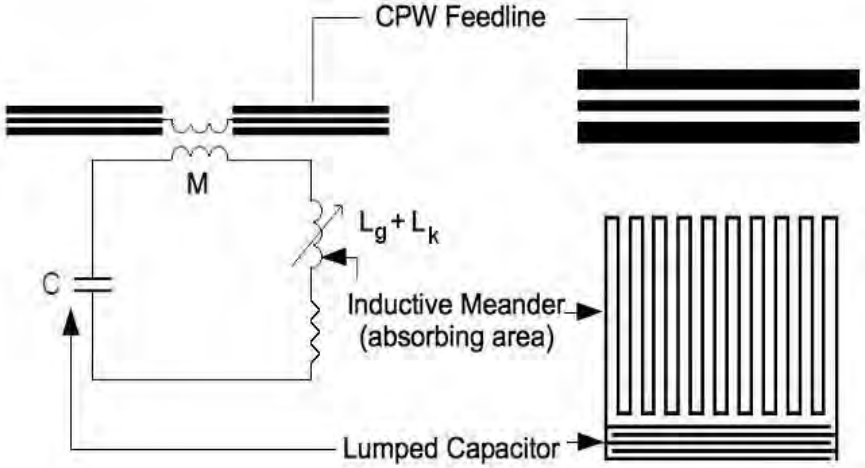
h spatial resolution (3-D), low noise measurements of temperature and humidity are great demand for improving predictions from numerical weather prediction models

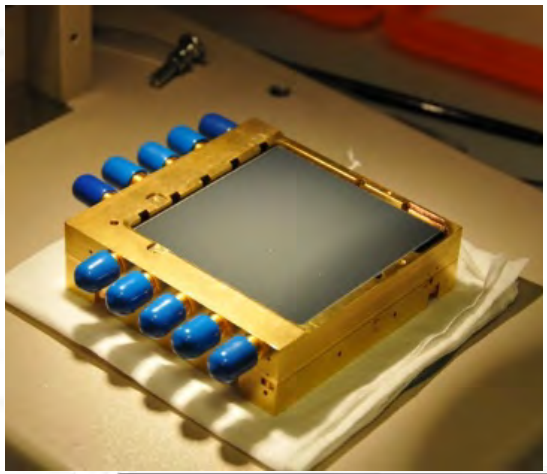
UNIVERSITY OF CAMBRIDGE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Met Office
UK SPACE AGENCY
CEDI-ST
hargravepc@cardiff.ac.uk

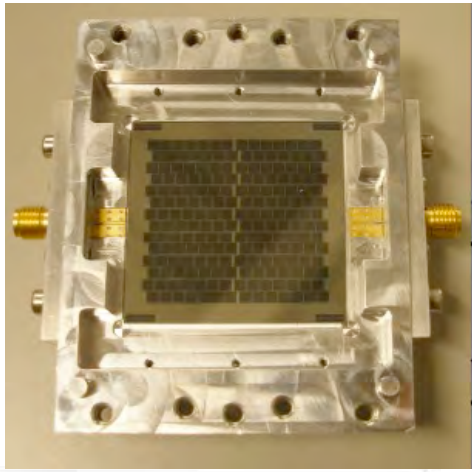
Technology

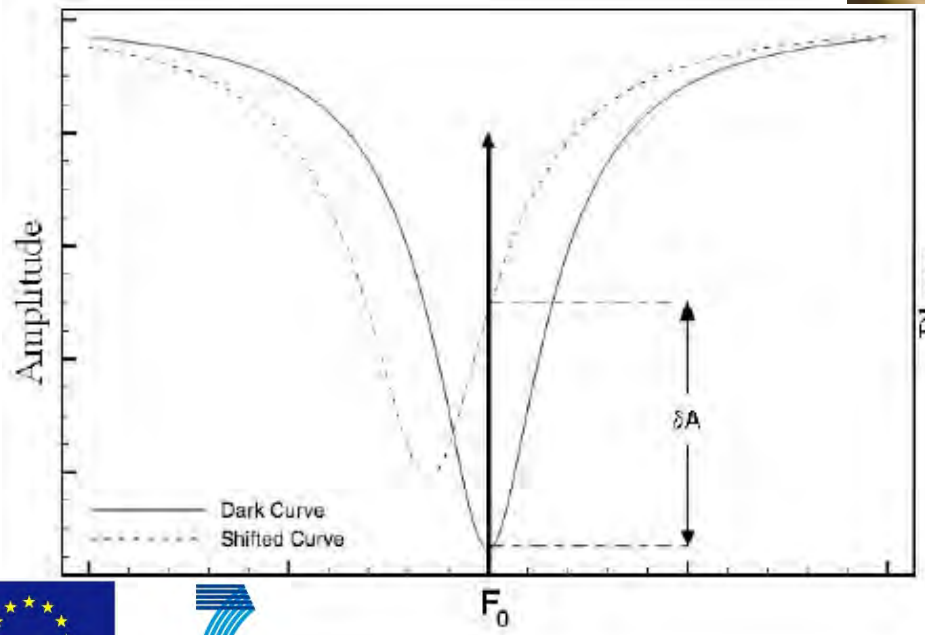
UNIVERSITY OF CAMBRIDGE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Met Office
UK SPACE AGENCY
CEDI-ST
hargravepc@cardiff.ac.uk

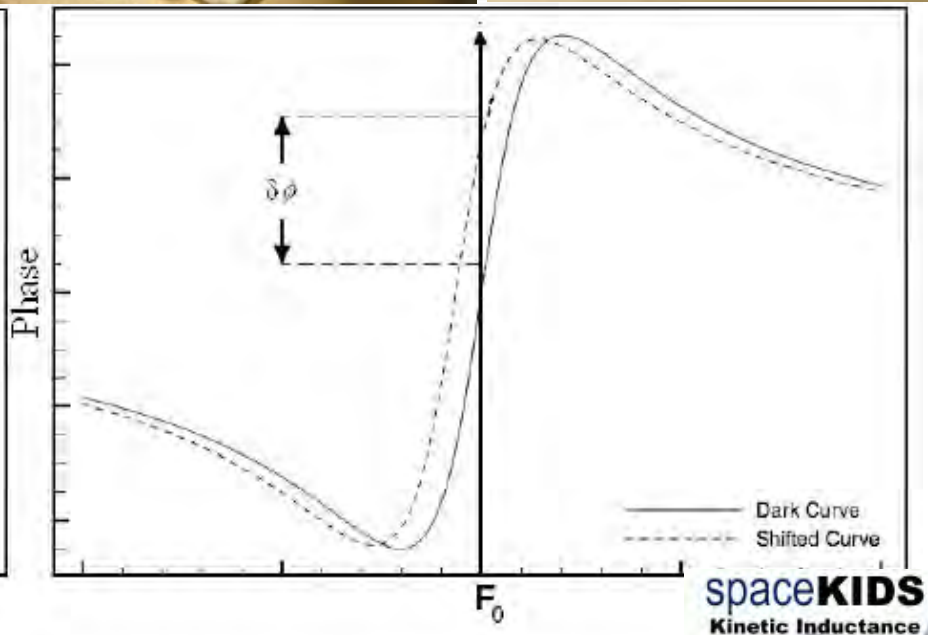
Kinetic Inductance Detectors









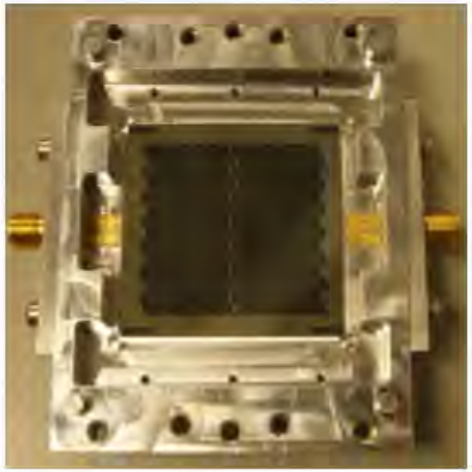


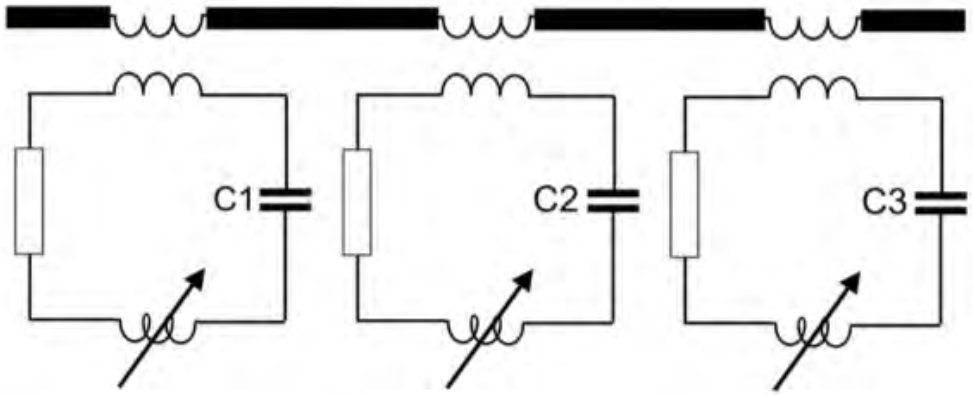
SEVENTH FRAMEWORK PROGRAMME

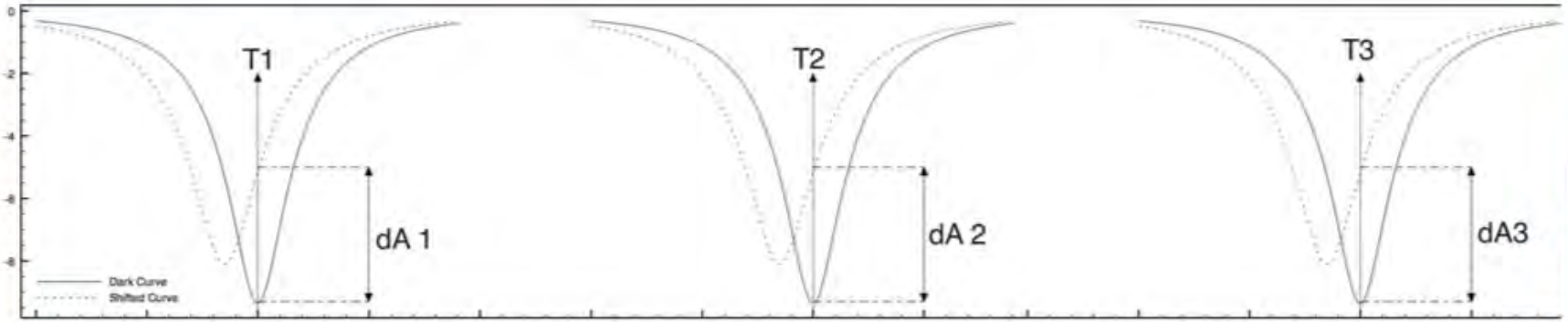
spaceKIDS
Kinetic Inductance Detectors for Space

Natural multiplexing in KID devices

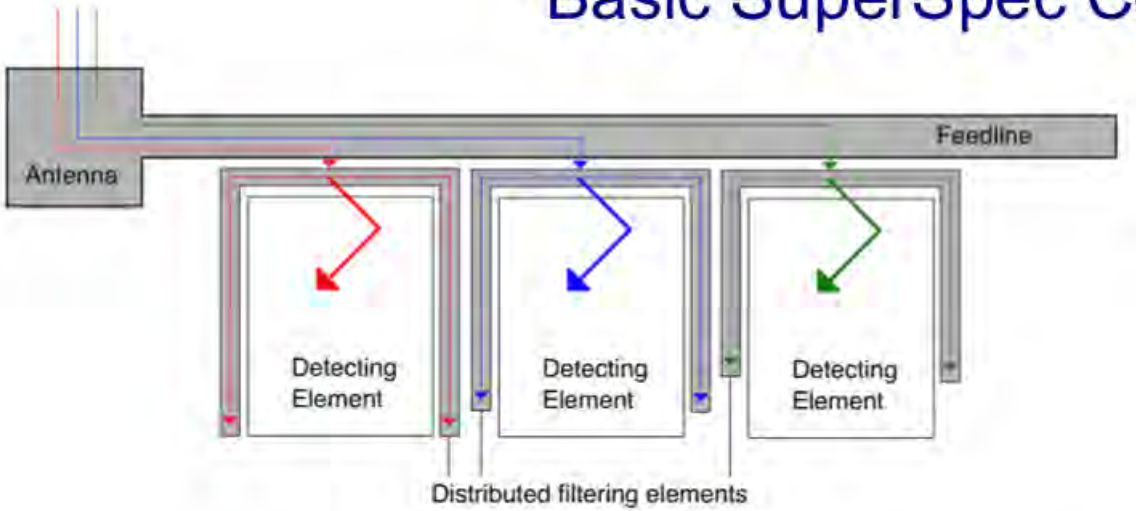
- Each LEKID is a high Q micro-resonator with a tunable f0
- We can therefore multiplex many LEKIDs onto a single CPW feed-line

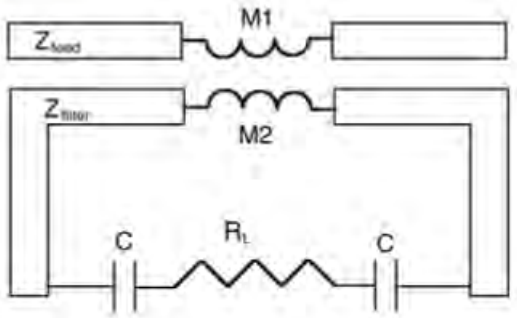






Basic SuperSpec Concept





- Large number of ultra sensitive detectors ≈ 600 detectors per pixel for R=700 to cover 195-305 GHz atmospheric window – Kinetic Inductance Detectors.
- Low loss high frequency transmission lines and antenna structures – Niobium ($\nu_g \approx 700$ GHz) on low loss substrates such as Si_2N_x or Diamond
- Modern micro-fabrication techniques – Deep UV / e-beam lithography

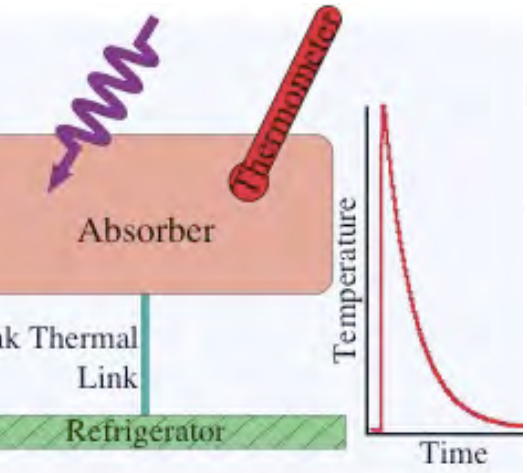
KID-based filterbank spectrometers

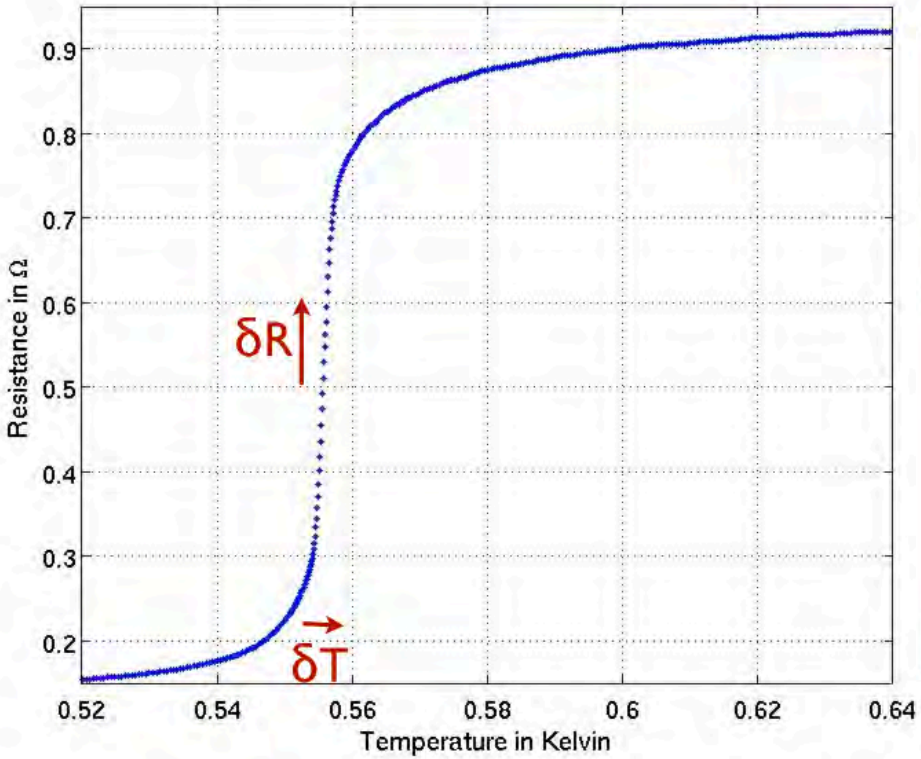
- Superspec (Caltech) – 600 channels, 195-305 GHz, R~800
  - Shirokoff, E., et al. "Design and performance of superspec: An on-chip, KID-based, mm-wavelength spectrometer." *Journal of Low Temperature Physics* 176.5-6 (2014): 657-662.
- DESHIMA (SRON, Netherlands) – 5000-10000 channels, 320-950 GHz, R~1000
  - Endo, A., et al. "Design of an integrated filterbank for DESHIMA: On-chip submillimeter imaging spectrograph based on superconducting resonators." *Journal of Low Temperature Physics* 167.3-4 (2012): 341-346.

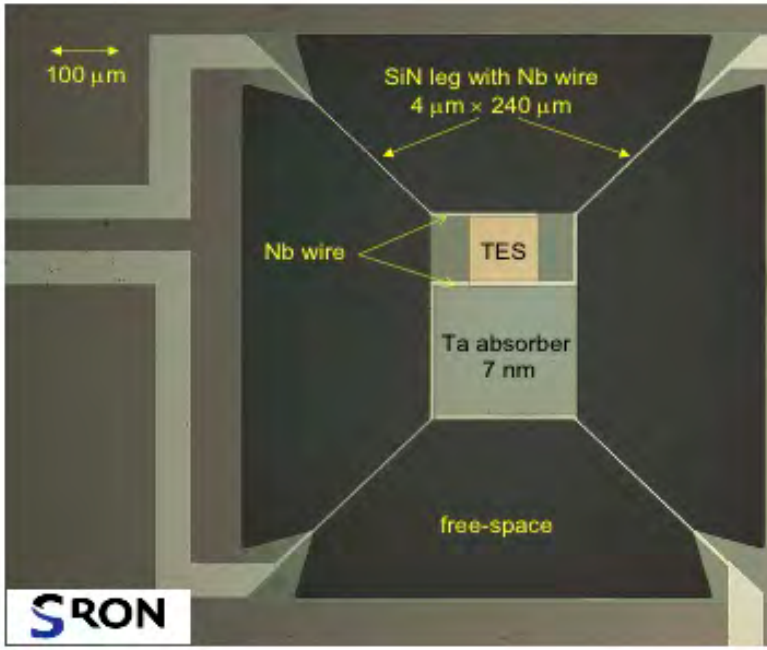
UNIVERSITY OF CAMBRIDGE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Met Office
UK SPACE AGENCY
CEDI-ST
hargravepc@cardiff.ac.uk

TES-based filterbank spectrometers

- HYMAS concept – Cardiff University / University of Cambridge







UNIVERSITY OF CAMBRIDGE

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Met Office

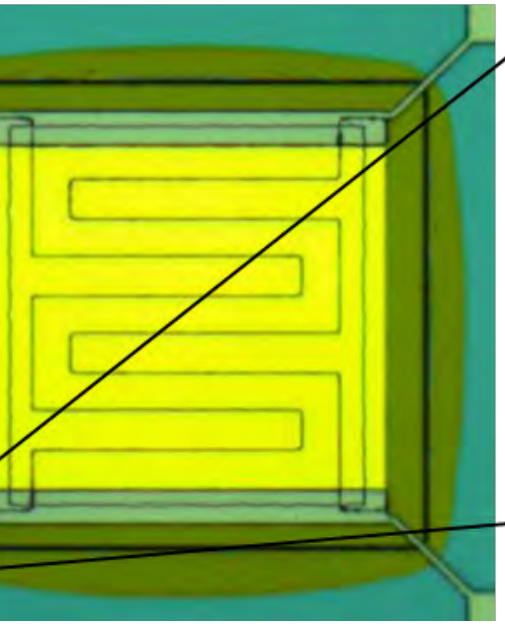
UK SPACE AGENCY

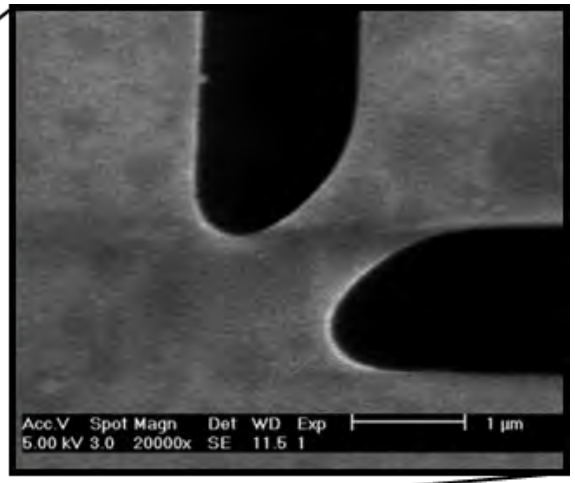
CEOI-ST

hargravepc@cardiff.ac.uk

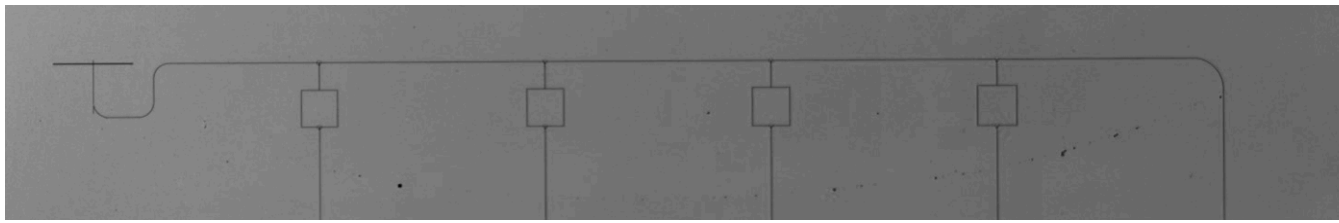
TES-based filterbank spectrometers

- HYMAS concept – Cardiff University / University of Cambridge





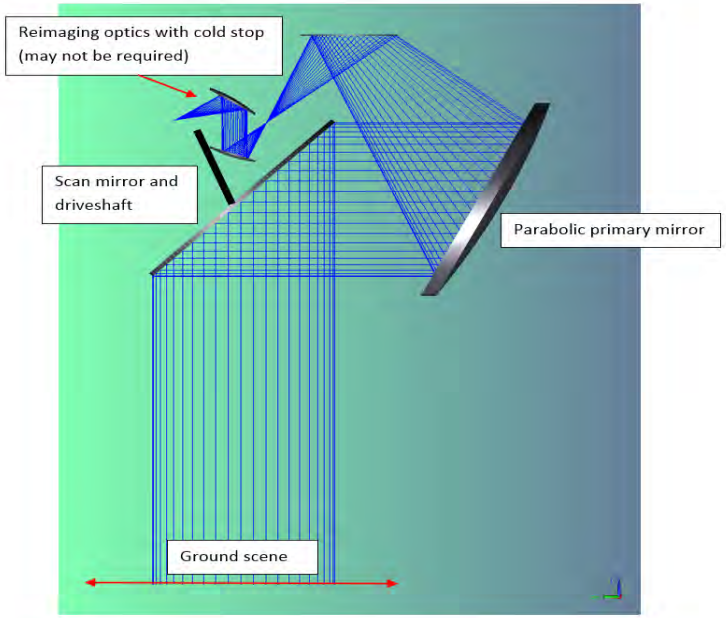
- Key advantages
  - Ultra-high sensitivity
  - Access to important 50-60 GHz O_2 lines

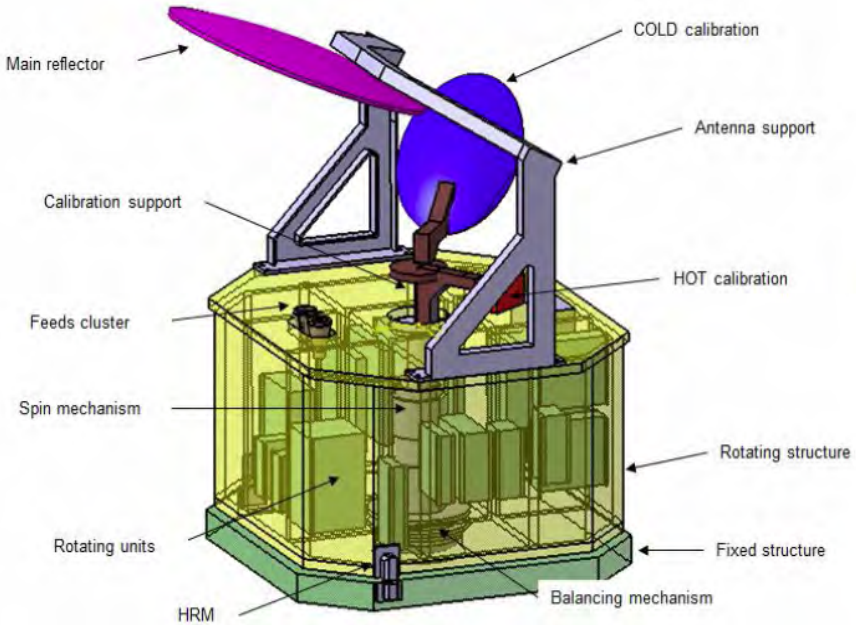


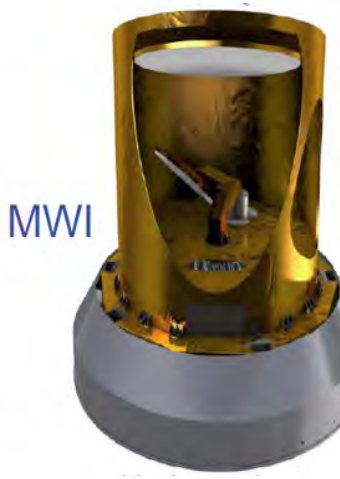
UNIVERSITY OF CAMBRIDGE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Met Office
UK SPACE AGENCY
CEOI-ST
hargravepc@cardiff.ac.uk

Instrument concept

- Continuous coverage 50-850 GHz, R~1000 possible
- Channel optimisation study in progress
- Conical scanning, ~50° cone angle
- 75 cm primary aperture





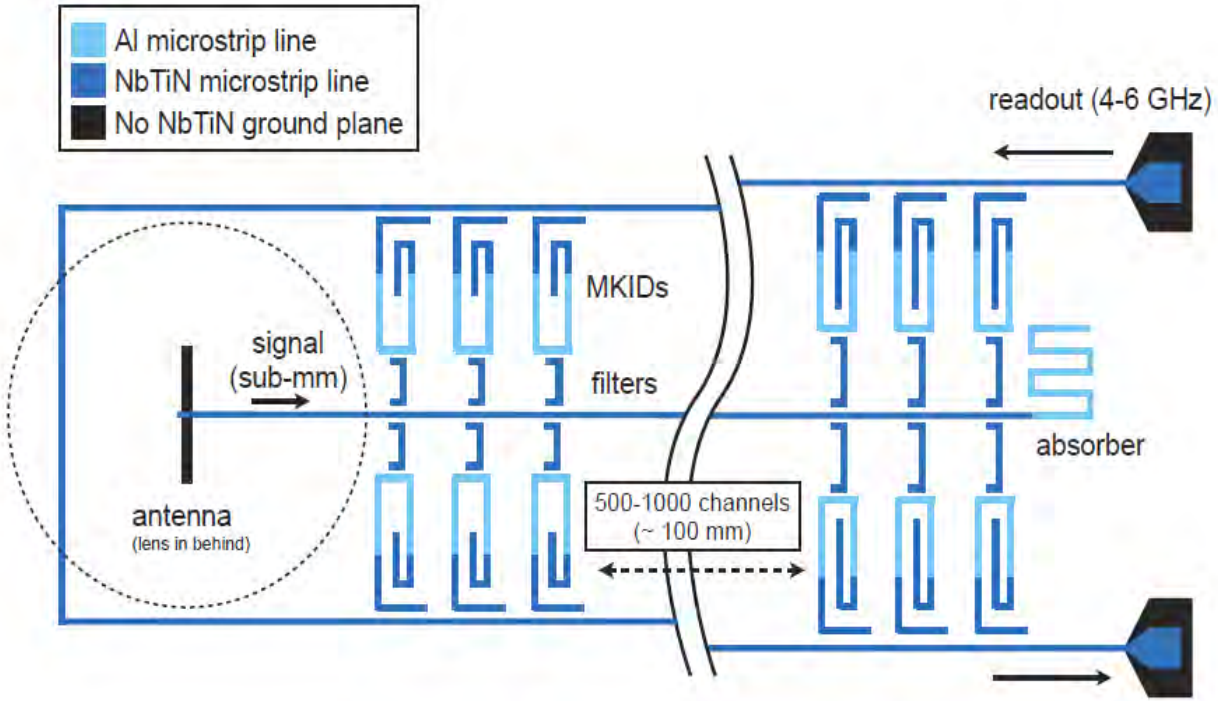


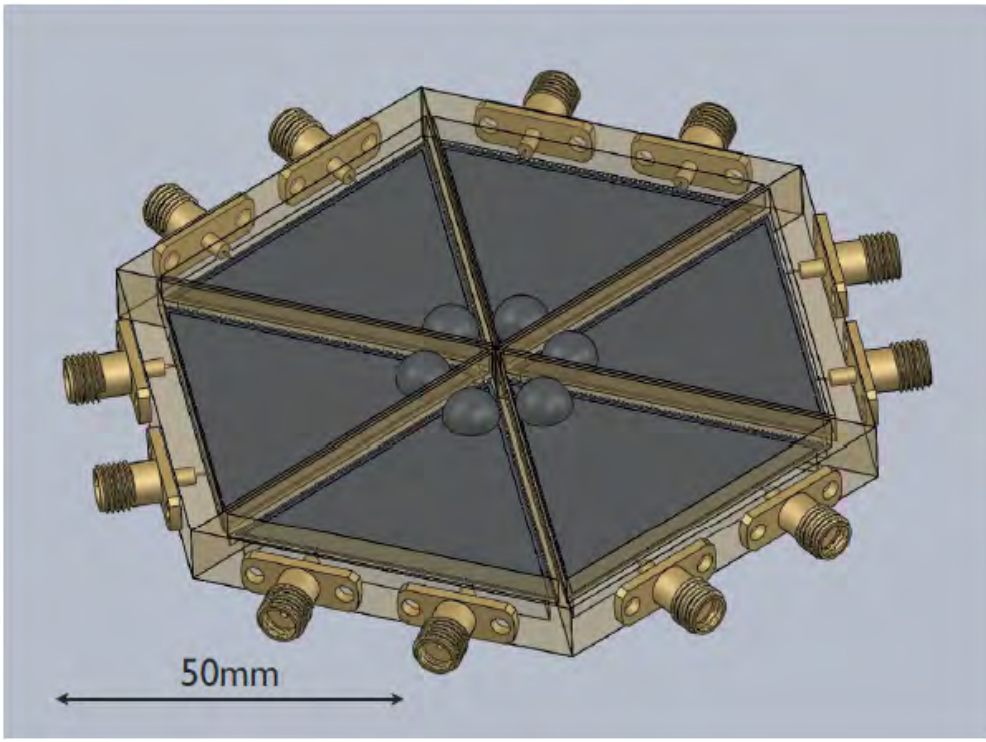
UNI CAMBRIDGE

Universität Hambu
DER FORSCHUNG | DER LEHRE | DER BILDUNG

MetOffice CEDI-ST

Receiver system





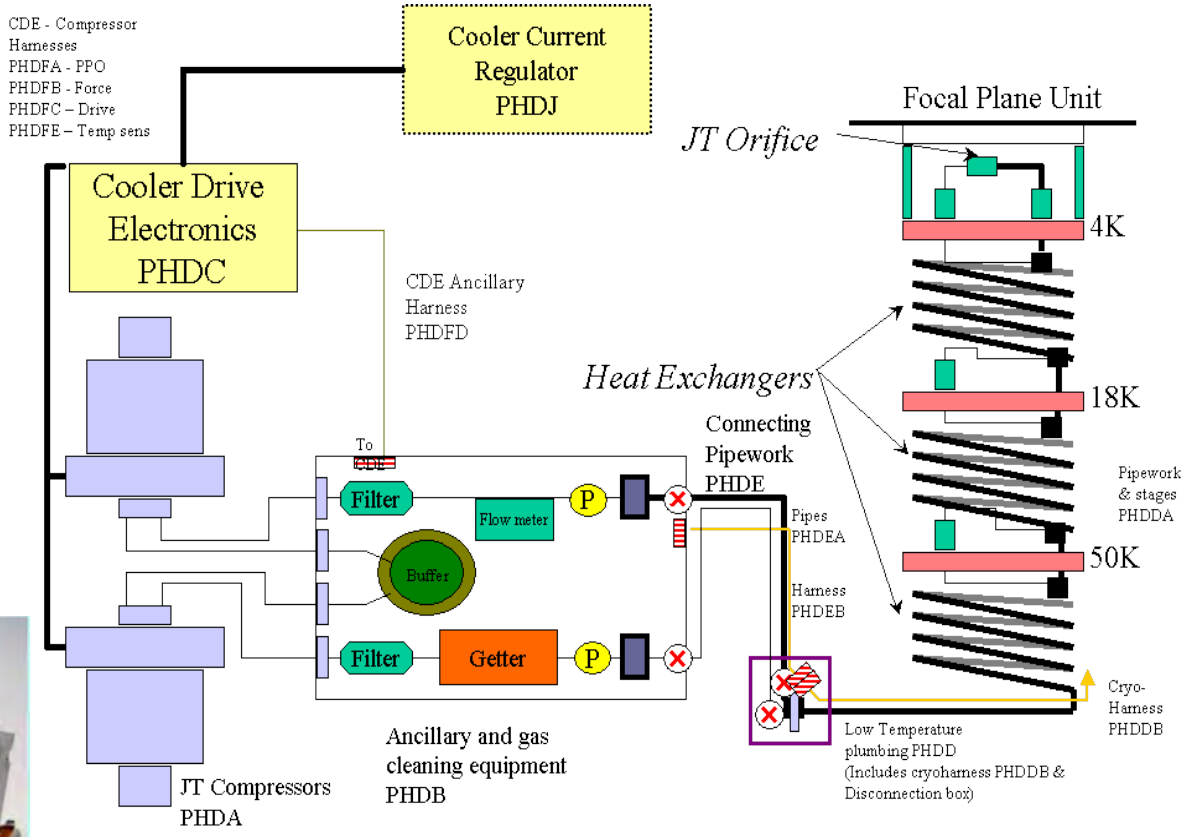
3-4 filterbanks – 50-100 GHz, 100-200 GHz, 200-400 GHz, 400-800 GHz
Prime & redundant channels

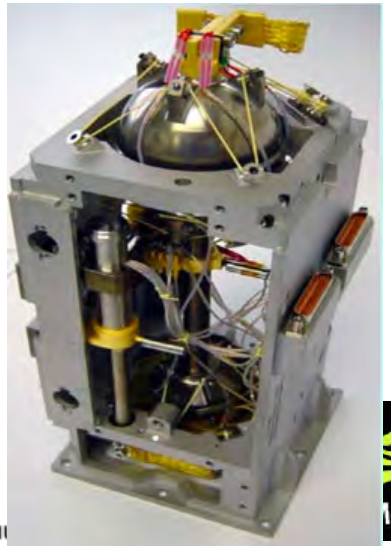
UNIVERSITY OF CAMBRIDGE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Met Office
UK SPACE AGENCY
CEOI-ST

hargravepc@cardiff.ac.uk

Cooling system

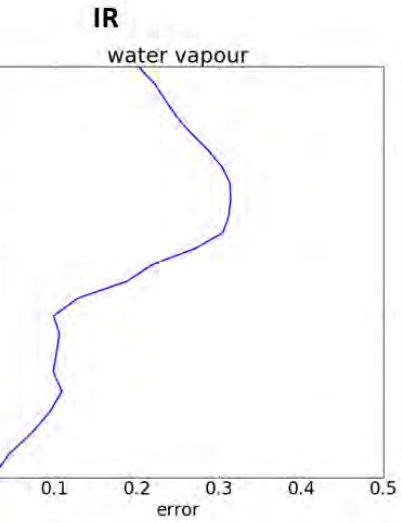
- Space heritage
  - Planck 4 K cooler
  - Herschel 300 mK sorption coolers
- Radiator design is a big focus area

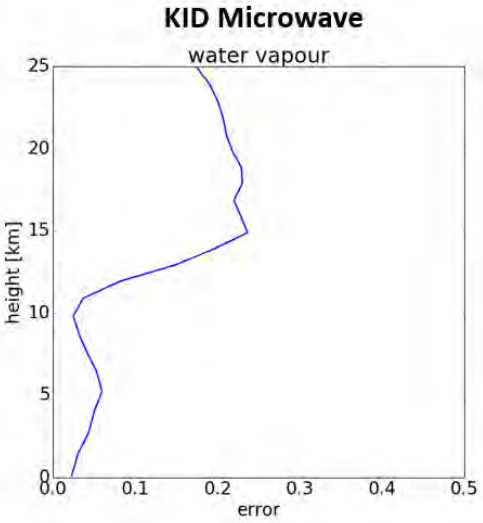


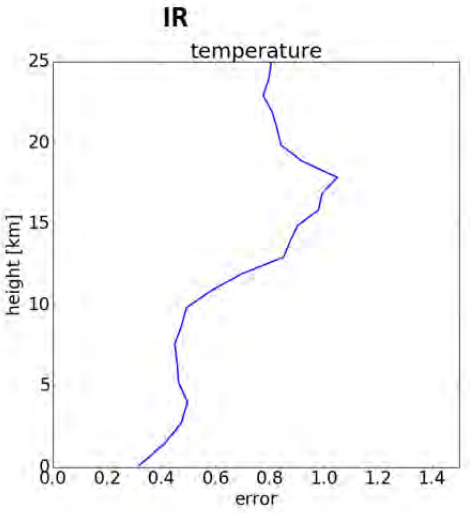


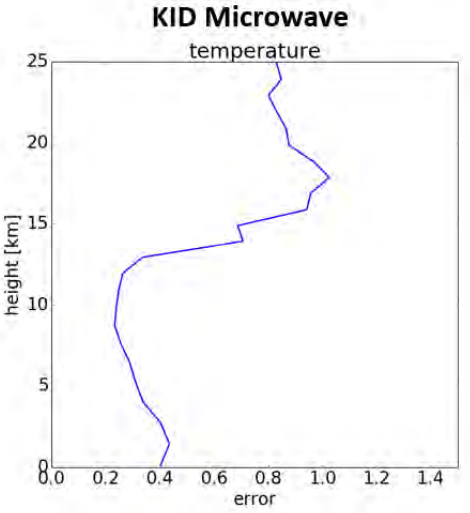
hargravepc@cardiff.ac.uk

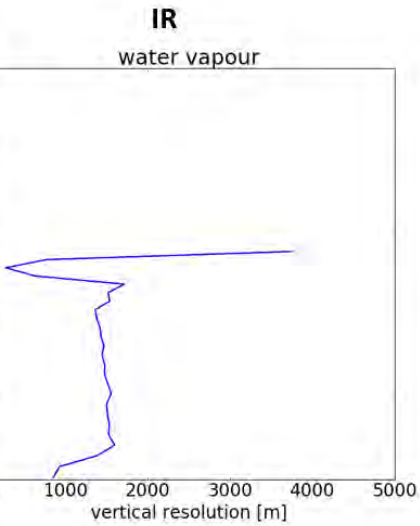
rformance predictions

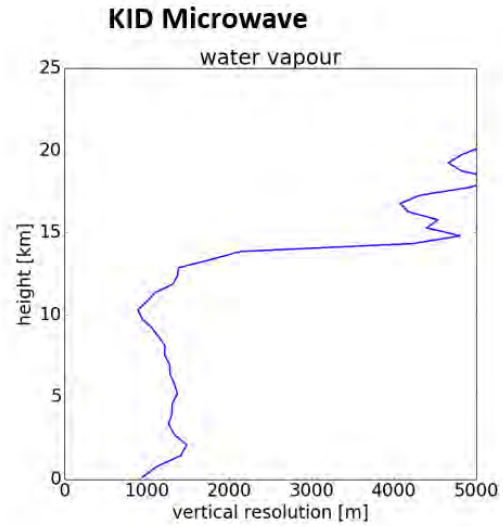












- All benefits of both IR and MW sounders in 1 instrument
- Covers all channels of the 3 MetOp-SG instruments with much greater sensitivity and resolution (spatial and spectral)

UNIVERSITY OF CAMBRIDGE

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Met Office

UK SPACE AGENCY

CEDI-ST

hargravepc@cardiff.ac.uk

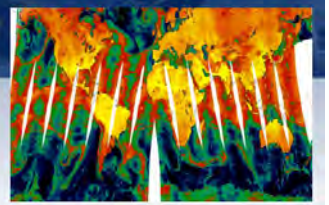
rformance predictions

- Full Globe coverage in 24 Hrs
- Continuous spectral coverage 100-850 GHz possible - ~1000 channels at R~500

Channel (GHz)	Bandwidth (GHz)	Ground Resolution (km)	Background power (W)	Background limited NEP ($WHz^{-1/2}$)	Detector NEP ($WHz^{-1/2}$)	NEΔT (K)
116.75	0.234	4265	1.25E-13	6.23E-18	2.00E-17	0.006
117.15	0.234	4251	1.26E-13	6.25E-18	2.00E-17	0.006
117.35	0.235	4244	1.26E-13	6.26E-18	2.00E-17	0.006
117.55	0.235	4236	1.26E-13	6.27E-18	2.00E-17	0.006
118.75	0.238	4194	1.27E-13	6.33E-18	2.00E-17	0.006
119.95	0.24	4152	1.29E-13	6.39E-18	2.00E-17	0.006
120.15	0.24	4145	1.29E-13	6.41E-18	2.00E-17	0.006
120.35	0.241	4138	1.29E-13	6.42E-18	2.00E-17	0.006
120.75	0.242	4124	1.30E-13	6.44E-18	2.00E-17	0.006
166.9	0.334	2984	1.78E-13	8.88E-18	2.00E-17	0.004
172.31	0.345	2890	1.84E-13	9.16E-18	2.00E-17	0.004
176.31	0.353	2824	1.88E-13	9.37E-18	2.00E-17	0.004
178.31	0.357	2793	1.90E-13	9.48E-18	2.00E-17	0.004
180.31	0.361	2762	1.92E-13	9.58E-18	2.00E-17	0.004
182.31	0.365	2731	1.94E-13	9.69E-18	2.00E-17	0.004
183.11	0.366	2719	1.95E-13	9.73E-18	2.00E-17	0.004
183.31	0.367	2716	1.95E-13	9.74E-18	2.00E-17	0.004
183.51	0.367	2713	1.96E-13	9.75E-18	2.00E-17	0.004
184.31	0.369	2702	1.96E-13	9.80E-18	2.00E-17	0.004
186.31	0.373	2673	1.99E-13	9.90E-18	2.00E-17	0.004
188.31	0.377	2644	2.01E-13	1.00E-17	2.00E-17	0.004
190.31	0.381	2616	2.03E-13	1.01E-17	2.00E-17	0.004
194.31	0.389	2563	2.07E-13	1.03E-17	2.00E-17	0.004
240.7	0.481	2069	2.55E-13	1.28E-17	2.00E-17	0.003
243.2	0.486	2047	2.58E-13	1.29E-17	2.00E-17	0.003
245.7	0.491	2027	2.60E-13	1.30E-17	2.00E-17	0.003
315.65	0.631	1577	3.32E-13	1.67E-17	2.00E-17	0.002
321.65	0.643	1548	3.38E-13	1.70E-17	2.00E-17	0.002
323.65	0.647	1538	3.40E-13	1.71E-17	2.00E-17	0.002

Metop-SG

MWS
Microwave Sounding



Objectives
- Temperature/humidity profiles in clear and cloudy air
- Cloud liquid water total column
- Imagery: precipitation

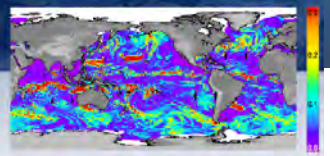
Heritage
AMSU-A, MHS

Baseline performance
- as AMSU/A, MHS
- horizontal resolution as ATMS

Implementation
- NOAA ATMS as baseline
- ESA development in Phase A as option

EUM/PEPS/VWG/11/0184
Issue 1
08/09/2011

MWI
Microwave Imaging



Objectives of a new mission
- precipitation and cloud products
- water vapour profiles and imagery
- sea-ice, snow, sea surface wind

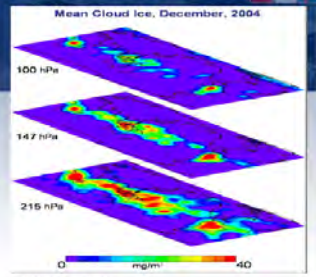
Heritage
SSM/I(S), AMSR-E

Baseline performance
4 spectral channels as SSM/I (18.7 – 89 GHz)

Implementation
ESA development

EUM/PEPS/VWG/11/0184
Issue 1
08/09/2011

ICI: Ice Cloud Imaging



NASA: Aura/MLS

Objectives of a new mission
- Cloud products, in particular ice clouds
- Snowfall detection and quantification
- Water-vapour profiles and imagery

Heritage
Aura-MLS, Odin-SMR (both limb viewing)

Baseline performance
- Conically scanning
- Nadir-viewing geometry
- 11 spectral channels
  - 183 – 664 GHz

Implementation
ESA development

Breakthrough: 11 channels
- **Establishes operational ice-cloud imaging mission**
- **Support of weather forecast, hydrology, and climate monitoring**

EUM/PEPS/VWG/11/0184
Issue 1
08/09/2011

Met Office CEOI-ST

Slide: 11 EUMETSAT

Implementation ~2020

UNIVERSITY OF CAMBRIDGE

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Summary and Conclusions

- A TES/KID based hyperspectral microwave instrument will have temperature and humidity retrieval performance equivalent or better than current & future hyperspectral IR instruments
- *Not limited to clear sky conditions*
- Would provide information on hydrometeor content, much better than ICI on Metop-SG – excellent constraint of essential climate variables

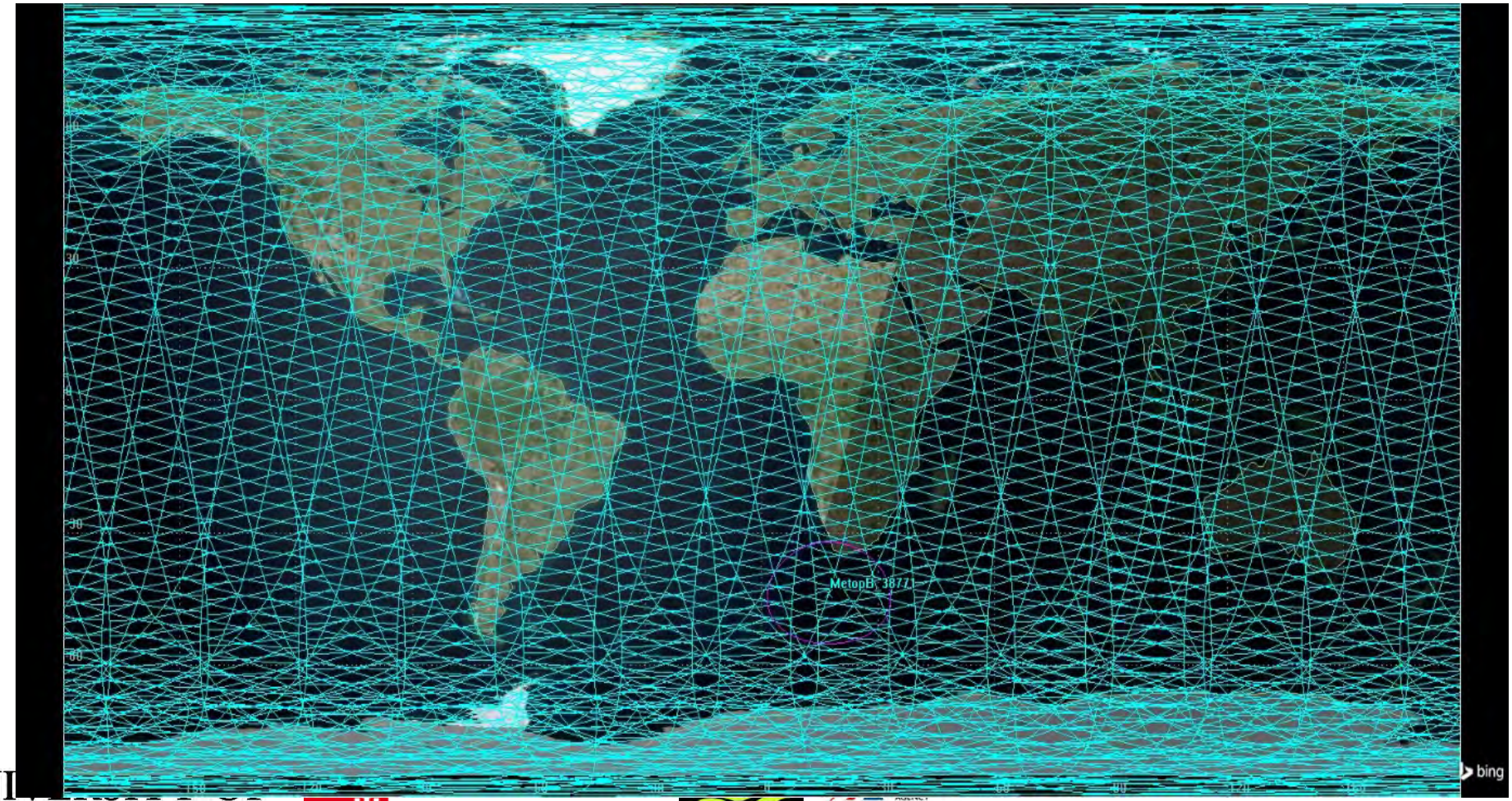
hargravepc@cardiff.ac.uk

Thank you!

hargravepc@cardiff.ac.uk

Satellite instrument concept - Orbit

817 km, SSO, near polar, 09.30 ascending node



UNIVERSITY OF CAMBRIDGE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Met Office
CEDI-ST
hargravepc@cardiff.ac.uk