ICEMuSIC – A new instrument concept for mm-wave observations of ice clouds, temperature and humidity sounding

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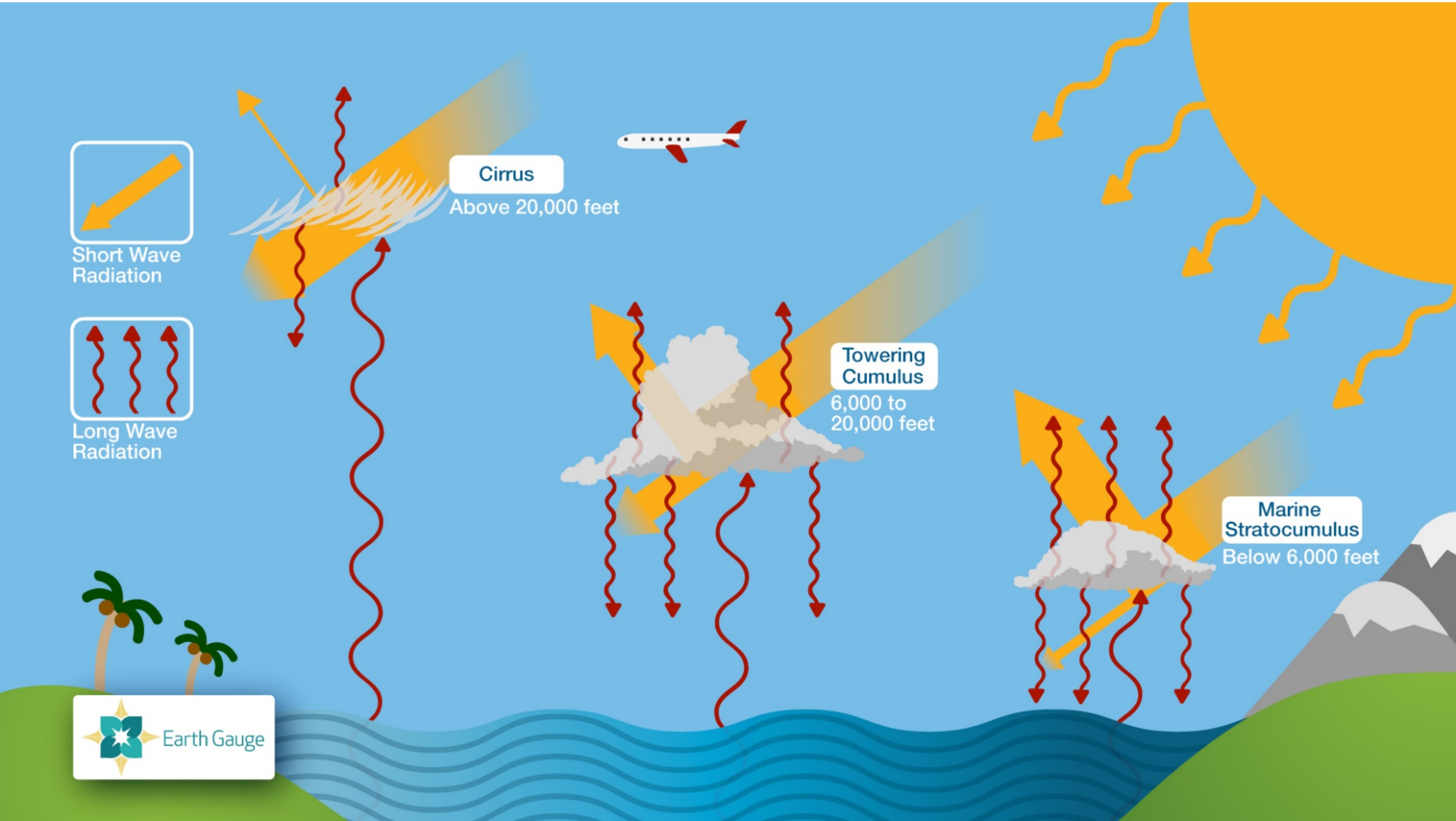
Outline

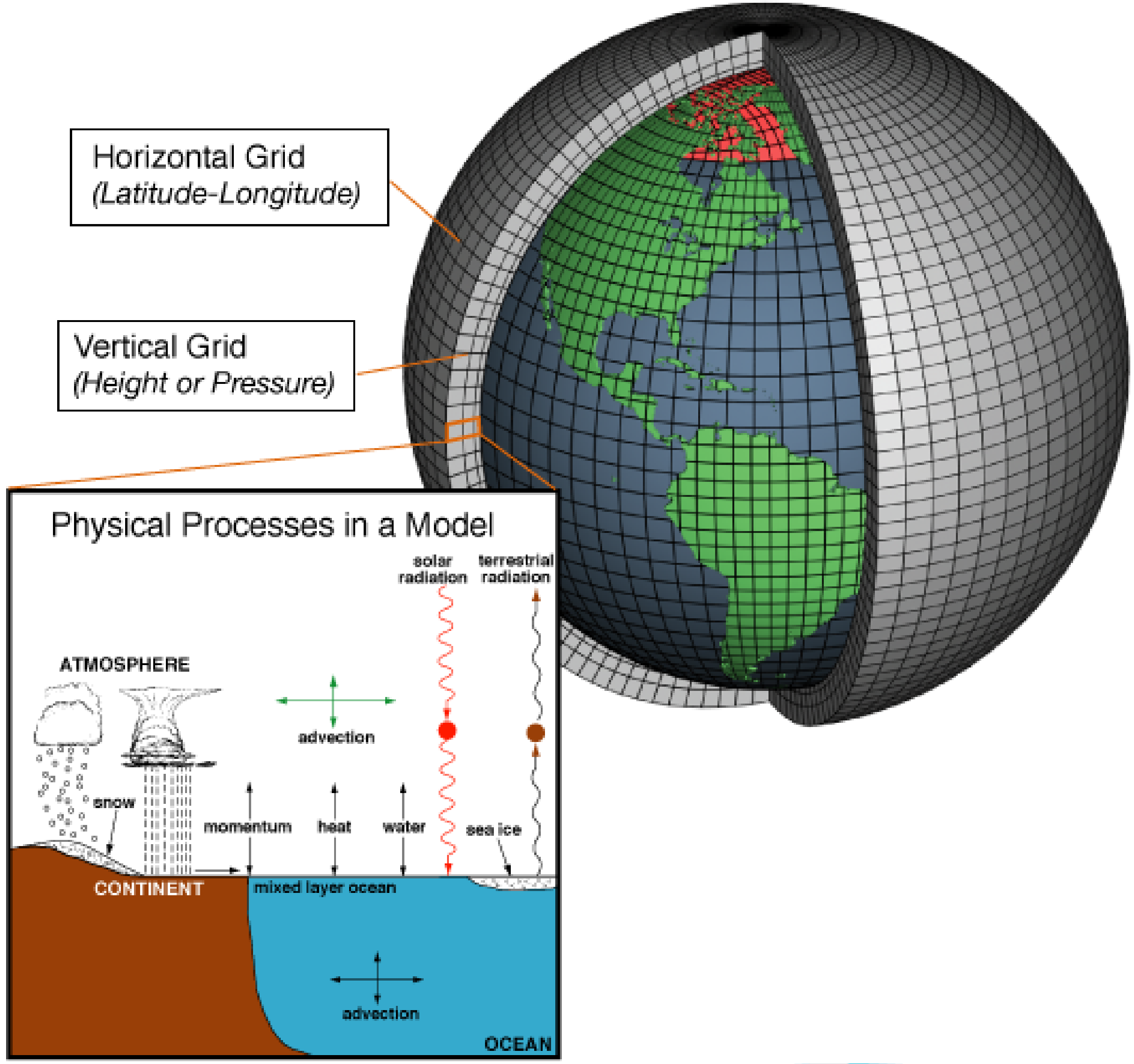
- Science background – climatology and meteorology
- Instrument baseline concept
- Enabling technologies
- Instrument / mission options and status

- Ice clouds play a crucial role in the global climate system & energy budget of the atmosphere
  - Reflect NIR radiation back to space (cooling)
  - Reflect upwelling TIR radiation back to Earth (warming)



General circulation climate models

- Atmospheric – assumes sea surface temperatures
- Oceanic only
- Coupled models – combine atmospheric & oceanic circulation



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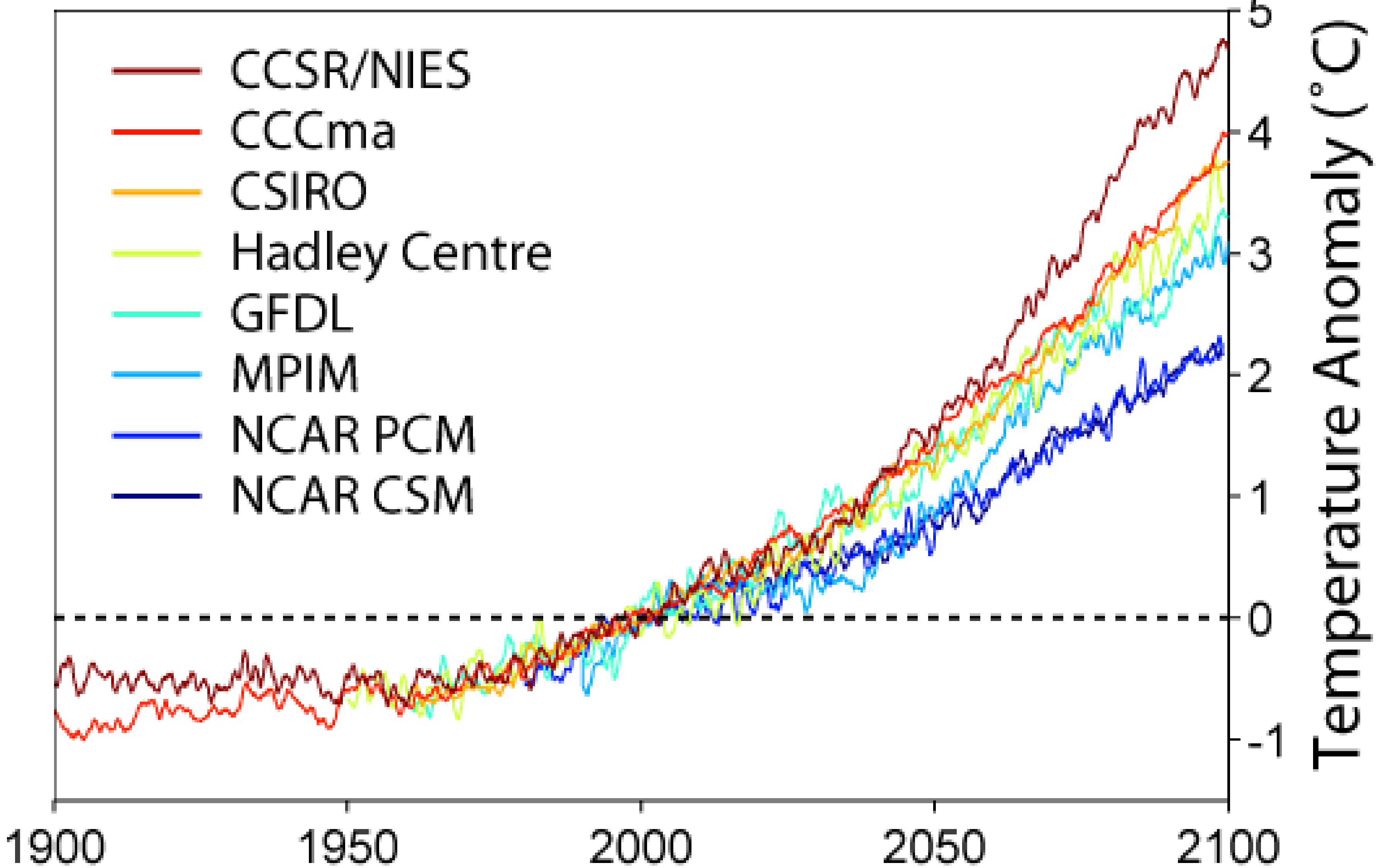
Global Warming Projections



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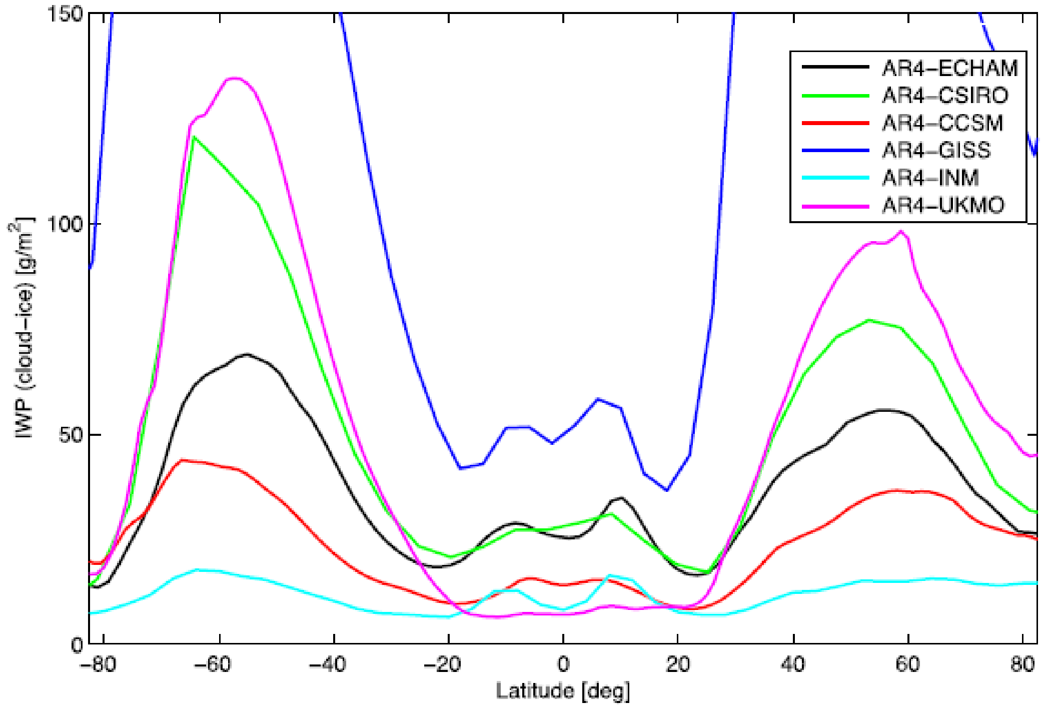
Clouds in climate models

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



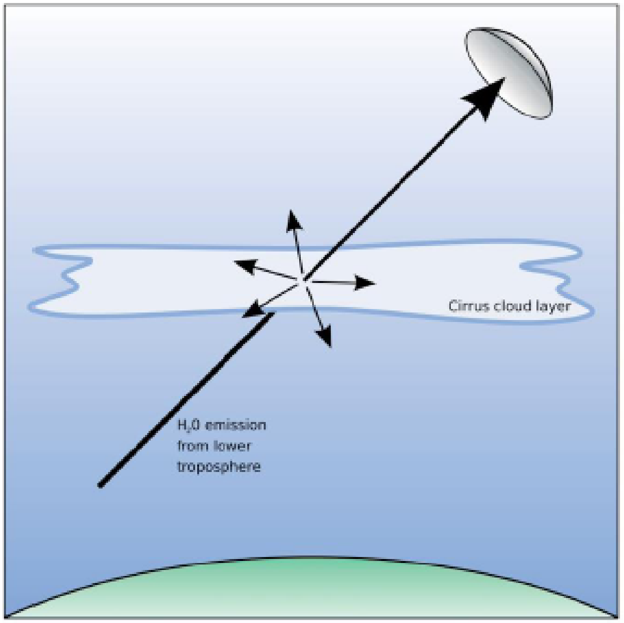
- **IWP [g/m2]** = vertically integrated „Ice Water Content“ (IWC).
- Zonal mean over 100 years.
- AR4-GISS*0.5 to bring to same scale.

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.***

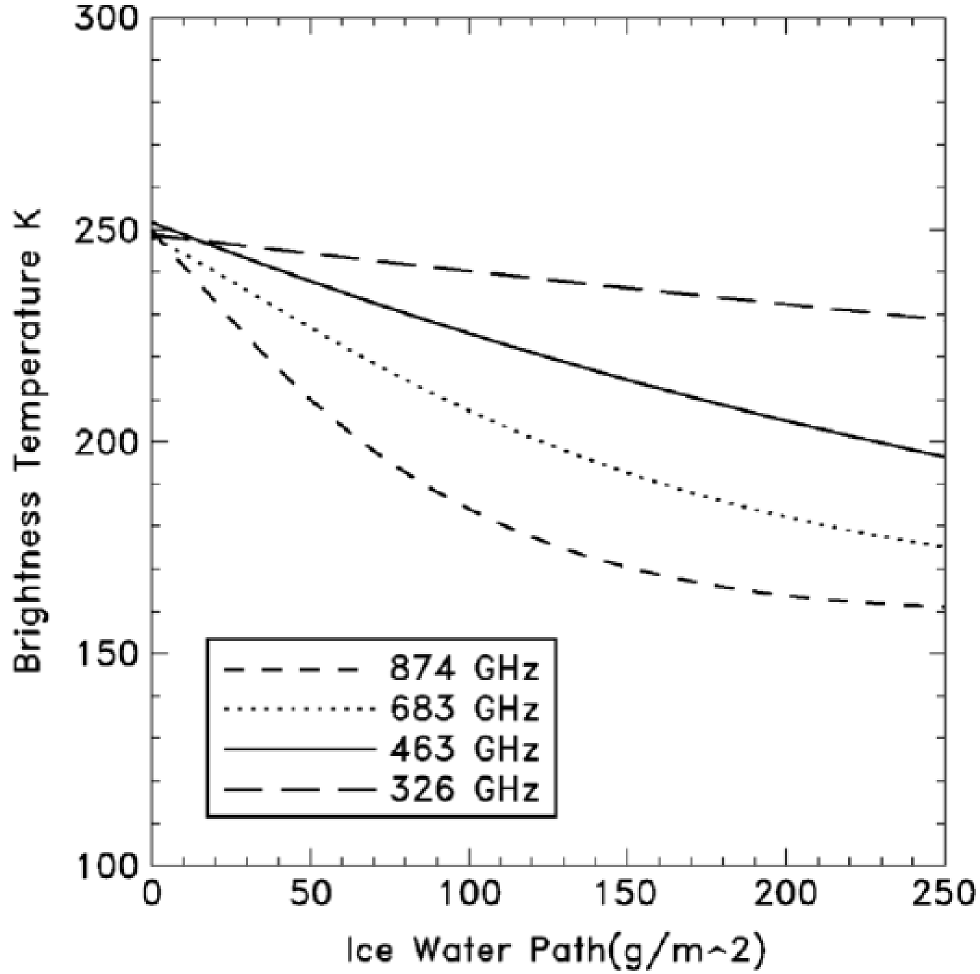
Critical need to constrain essential climate variables (ECVs)

- Ice Water Path – total column integrated ice mass
- Mean particle size and size distribution
- Secondary benefits:
  - Cloud altitude
  - Humidity profile
  - Hydrometeor profile
  - Precipitation rate
  - Total column water vapour

"Traditional" Sub-mm observation concepts



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].

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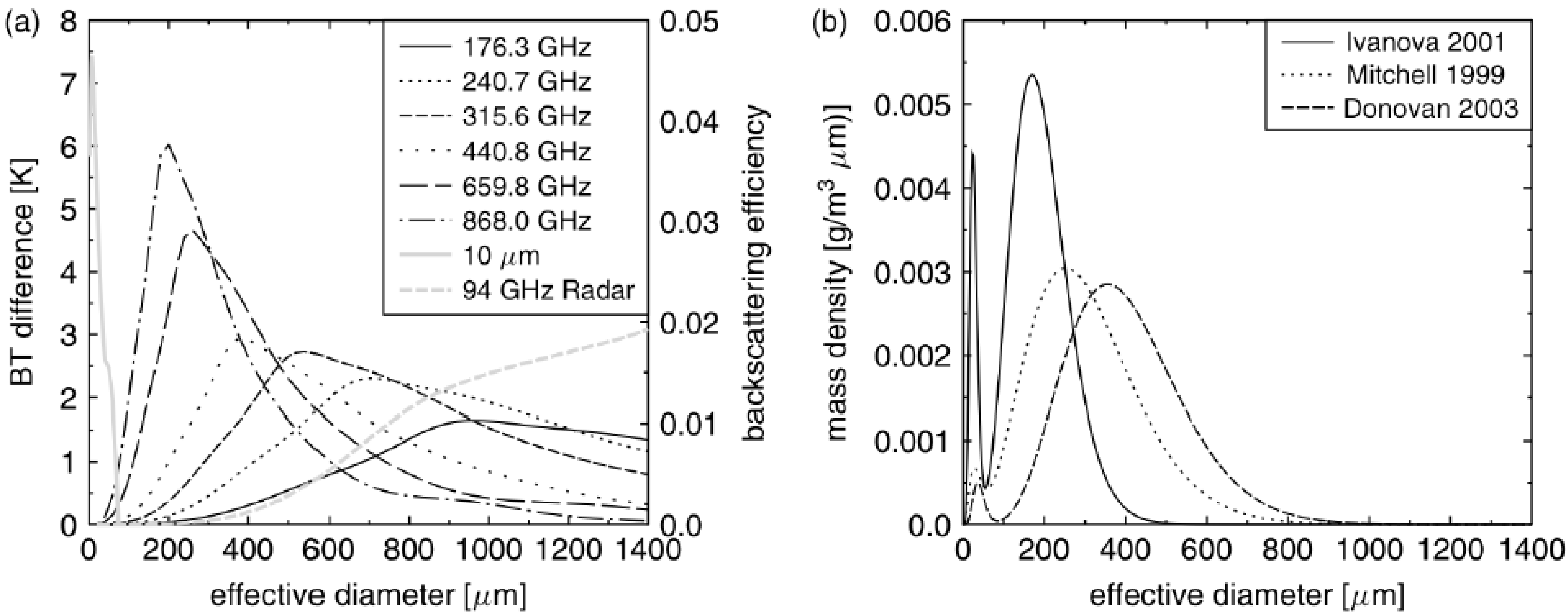
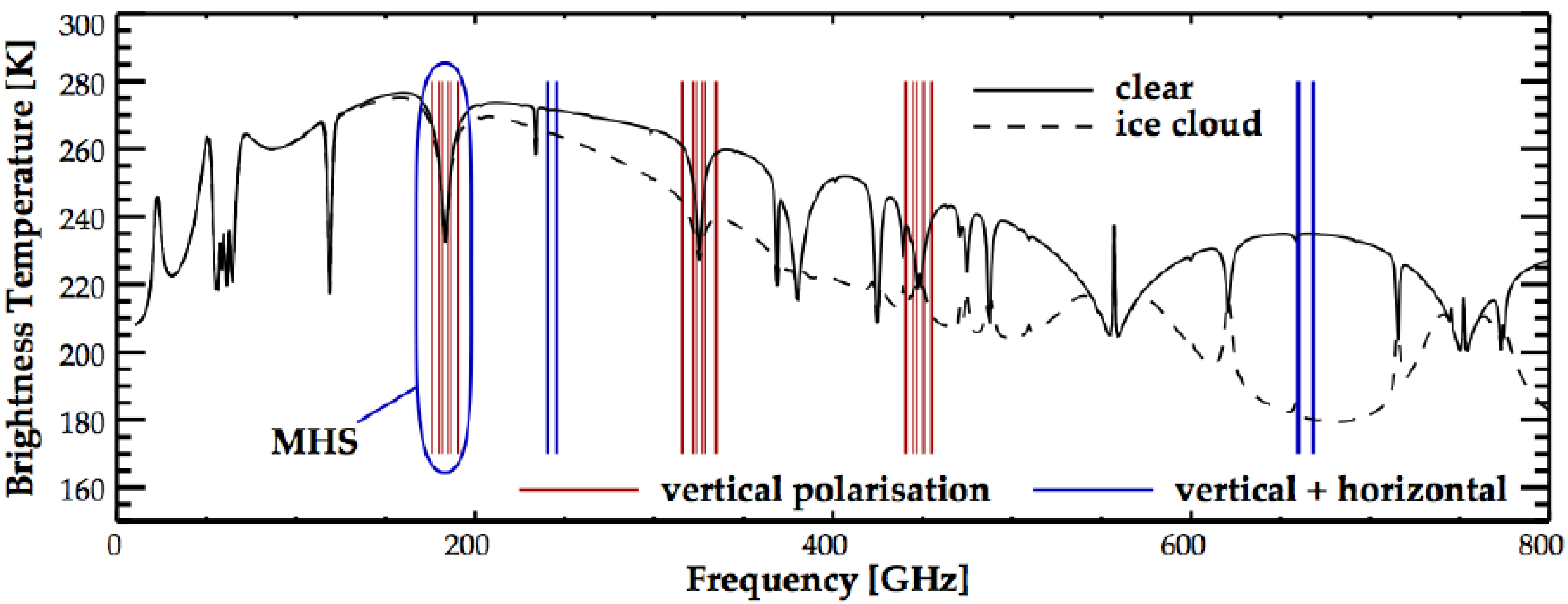
Particle size vs. wavelength



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

Sub-millimeter measurements can sample the size distribution.

CloudICE / ICI mission channels



- Buehler, S. A., E. Defer, F. Evans, S. Eliasson, J. Mendrok, P. Eriksson, C. Lee, C. Jimenéz, C. Prigent, S. Crewell, Y. Kasai, R. Bennartz, and A. J. Gasiewski (2012), **Observing Ice Clouds in the Submillimeter Spectral Range: The CloudIce Mission Proposal for ESA's Earth Explorer 8**, *Atmos. Meas. Tech.*, ***5***, 1529–1549, doi:10.5194/amt-5-1529-2012.
- Buehler, S. A., C. Jiménez, K. F. Evans, P. Eriksson, B. Rydberg, A. J. Heymsfield, C. Stubenrauch, U. Lohmann, C. Emde, V. O. John, T. R. Sreerekha, and C. P. Davis (2007), **A concept for a satellite mission to measure cloud ice water path and ice particle size**, *Q. J. R. Meteorol. Soc.*, ***133***(S2), 109–128, doi:10.1002/qj.143.
- Jiménez, C., S. A. Buehler, B. Rydberg, P. Eriksson, and K. F. Evans (2007), **Performance simulations for a submillimetre wave cloud ice satellite instrument**, *Q. J. R. Meteorol. Soc.*, ***133***(S2), 129–149, doi:10.1002/qj.134.

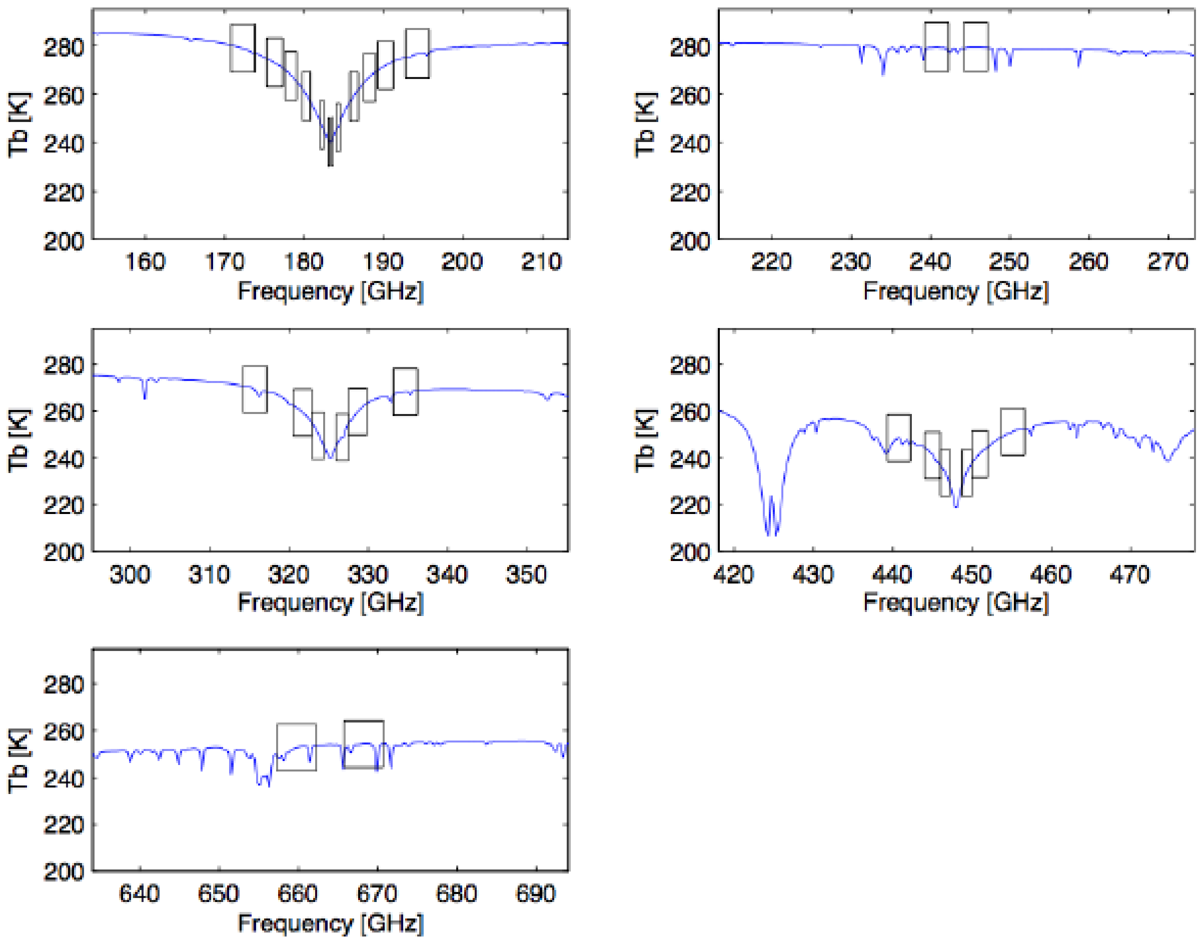


Fig. 3. A detailed view of the CloudIce channel positions. The spectrum shown is the simulated clear-sky radiance (in Planck brightness temperature units) for a tropical model atmosphere. Each channel consists of two sidebands, located on either side of a central frequency. The heterodyne technique used implies that only a single measurement value is recorded for the integrated radiance in both sidebands. The atmospheric scenario is from Anderson et al. (1986).

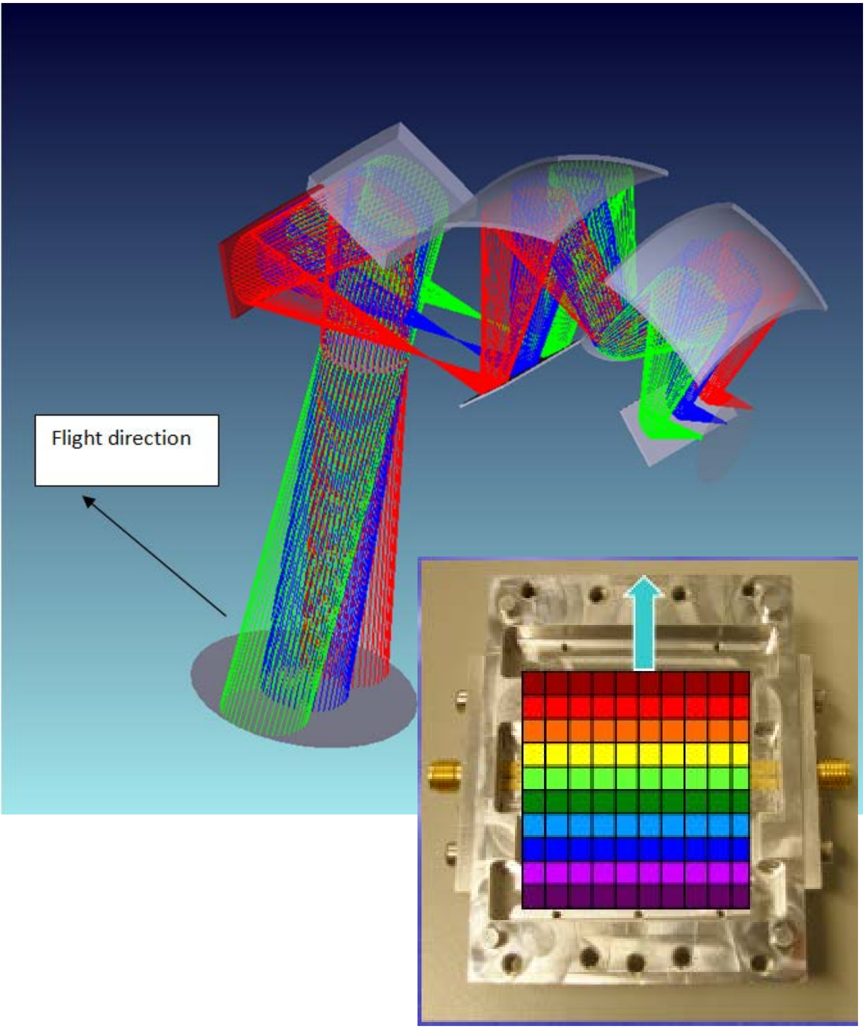
Buehler, S. A., E. Defer, F. Evans, S. Eliasson, J. Mendrok, P. Eriksson, C. Lee, C. Jimenéz, C. Prigent, S. Crewell, Y. Kasai, R. Bennartz, and A. J. Gasiewski (2012), **Observing Ice Clouds in the Submillimeter Spectral Range: The CloudIce Mission Proposal for ESA's Earth Explorer 8**, *Atmos. Meas. Tech.*, **5**, 1529–1549, doi:10.5194/amt-5-1529-2012.

Table 3. CloudIce channel specifications and radiometric requirements. NeΔT is the random error in the measurement, due to radiometric noise. Abs. ΔT is the absolute error in the measurement.

#	Center freq. GHz	Freq. offset GHz	Bandwidth MHz	Pol.	NeΔT K	Abs. ΔT K
1	183.31	0.20	200	V	2.0	1
2		1.00	500	V	1.5	1
3		3.00	1000	V	1.0	1
4		5.00	1500	V	1.0	1
5		7.00	2000	V	1.0	1
6		11.00	3000	V	1.0	1
7	243.20	2.50	3000	V	1.5	1
8				H		1
9	325.15	1.50	1600	V	1.5	1
10		3.50	2400	V	1.0	1
11		9.50	3000	V	1.0	1
12	448.00	1.40	1200	V	2.0	1
13		3.00	2000	V	1.5	1
14		7.20	3000	V	1.5	1
15	664.00	4.20	5000	V	1.5	1
16				H		1

The ICEMuSIC concept

- Ice Cloud Explorer Multi-Spectral Imaging Camera



- Instrument study funded by UK space agency & CEOI-ST
- Pushbroom multispectral imager based on submm superconducting detector arrays – operation from 300 mK
- Wide field optics – no mechanical scanning – 3-4 x 25° modules
  - Could integrate flat lenses
- Huge sensitivity improvement c.w. ICI / IASI / AMSU etc

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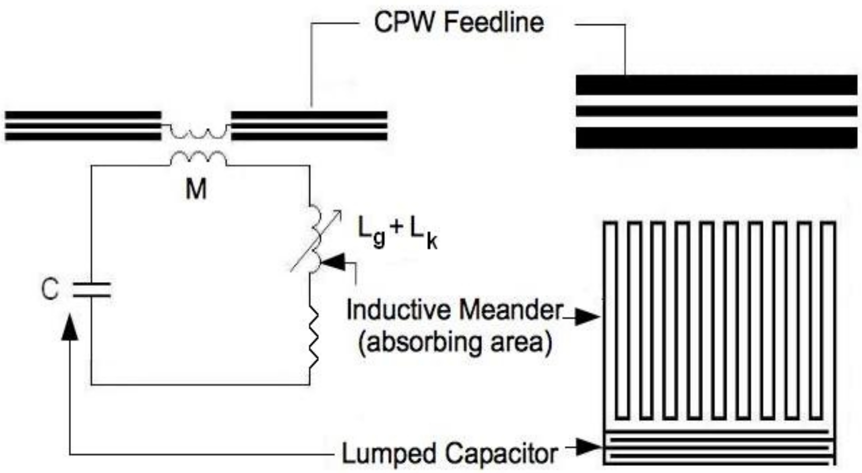
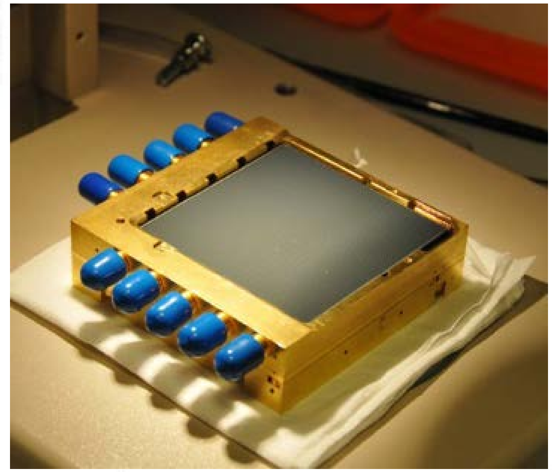
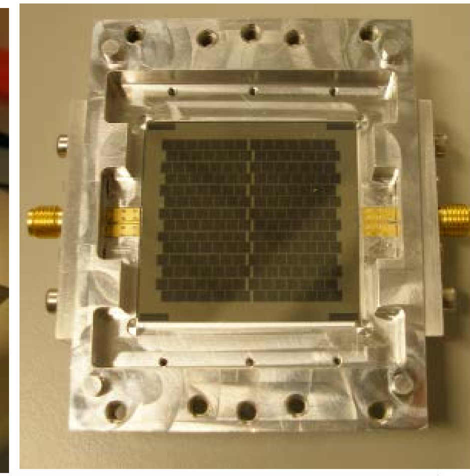
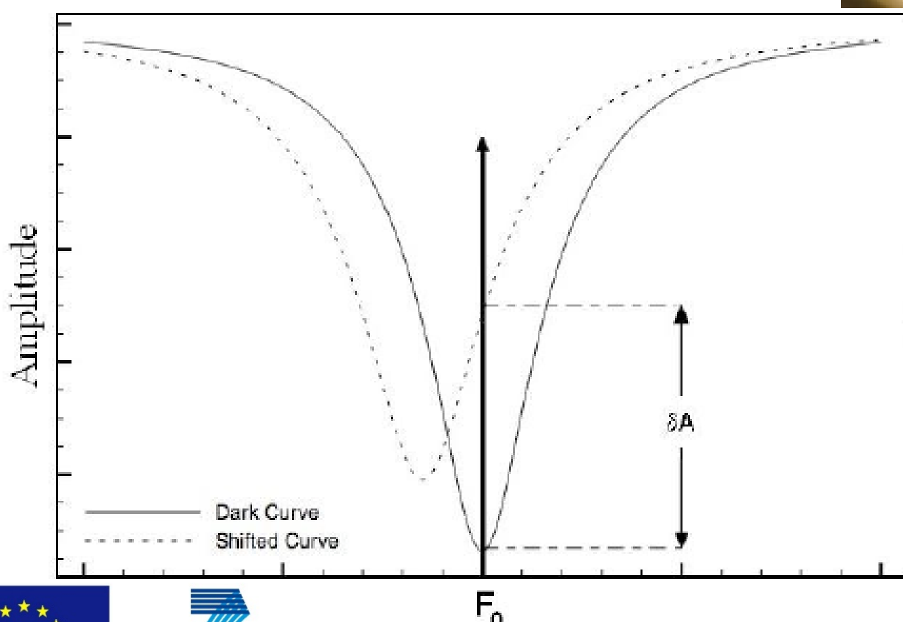
ICEMuSIC technologies

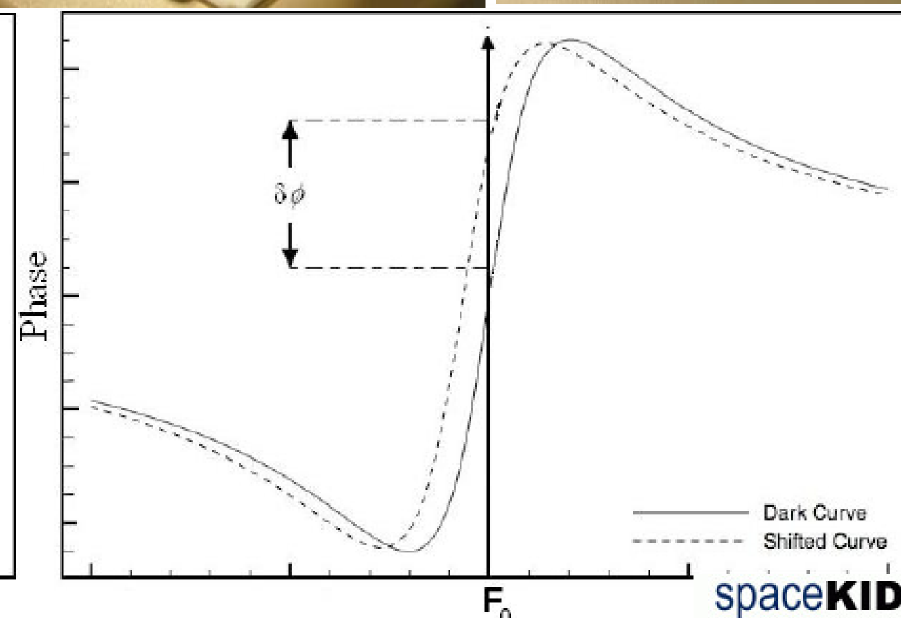
- Kinetic Inductance Detectors









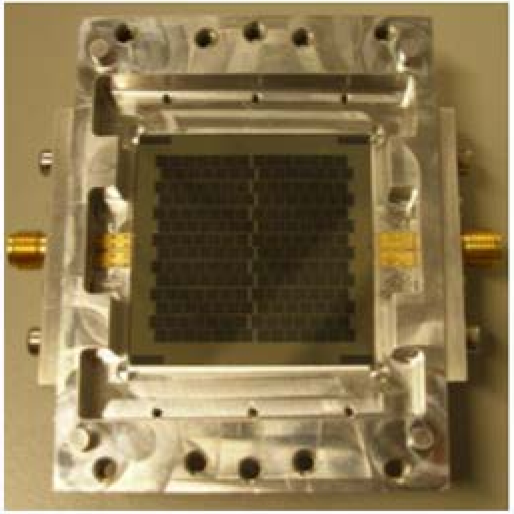


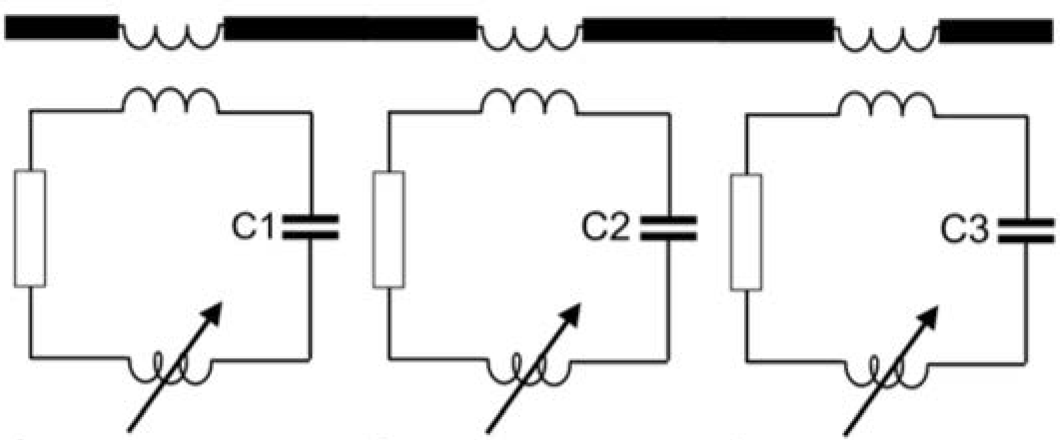
SEVENTH FRAMEWORK PROGRAMME

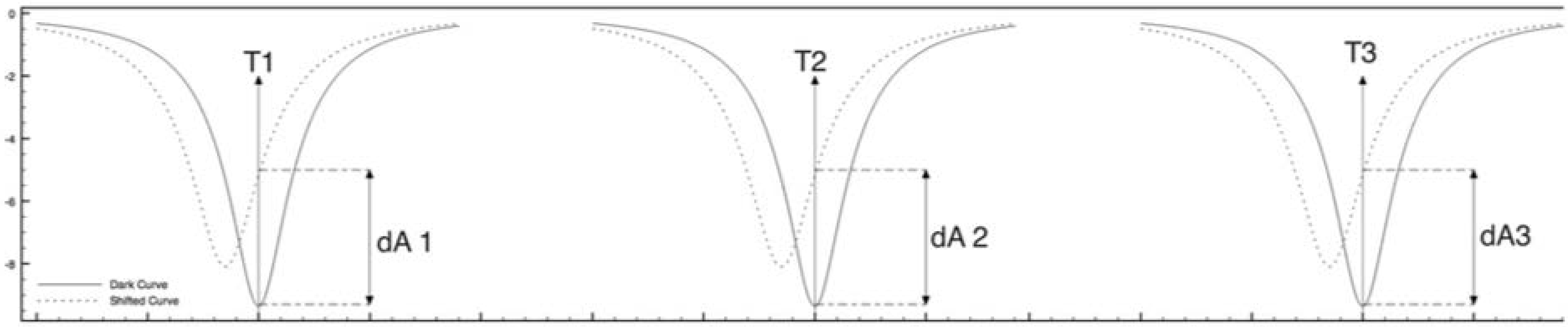
spaceKIDS
Kinetic Inductance Detectors for Space

ICEMuSIC technologies

- Detectors – Kinetic Inductance Detectors



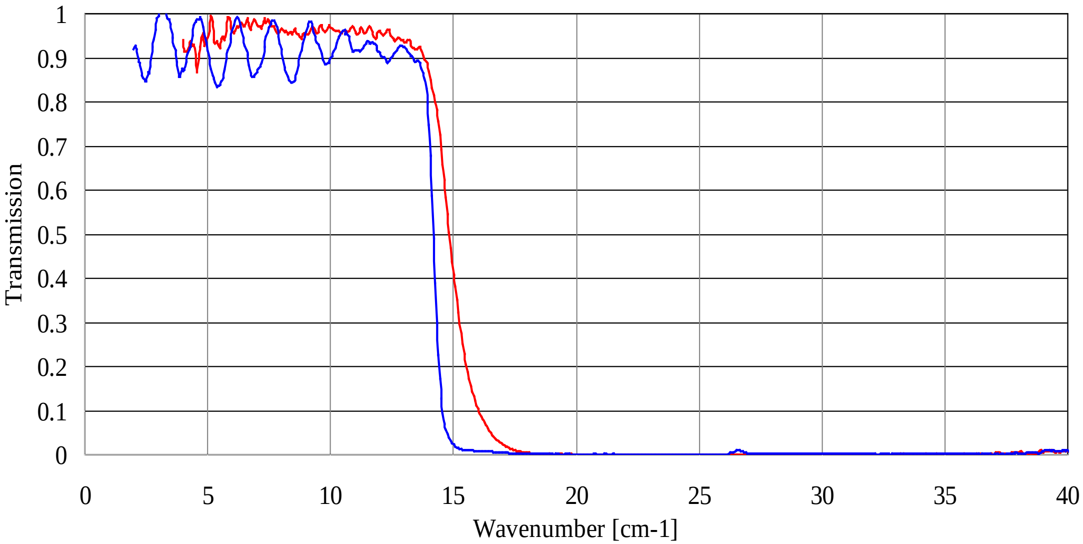


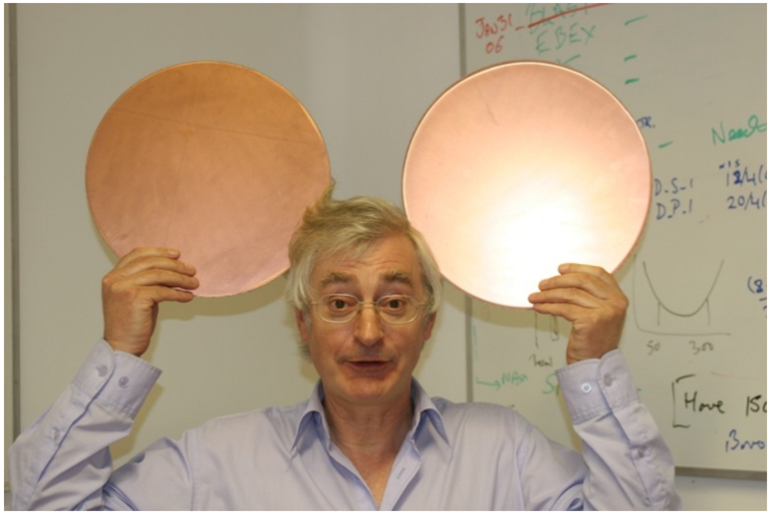


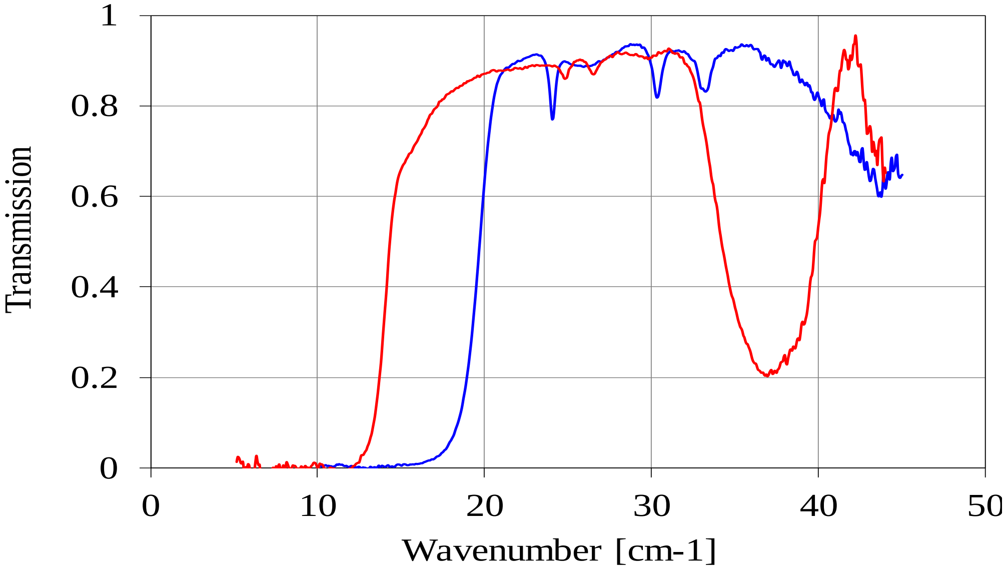
SEVENTH FRAMEWORK PROGRAMME

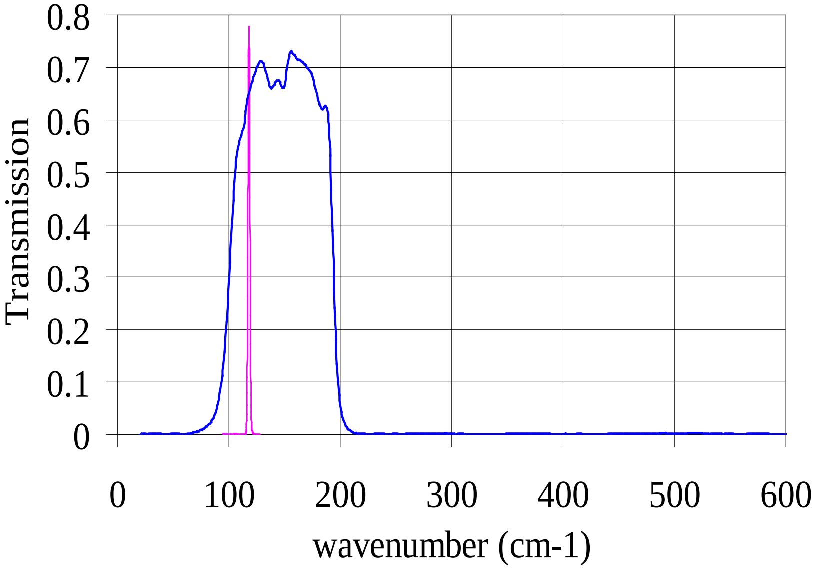
spaceKIDS Kinetic Inductance Detectors for Space

Filters – HP, LP, BP

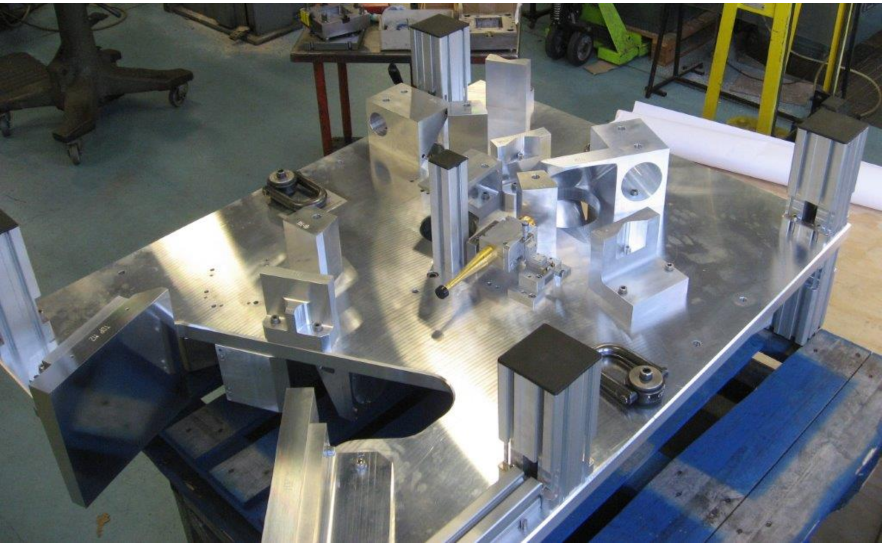


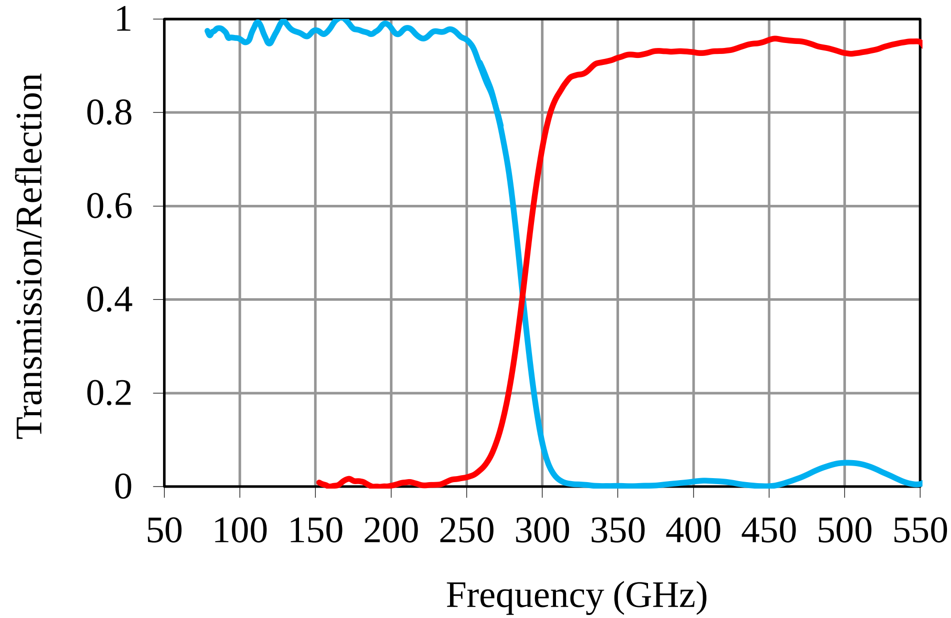


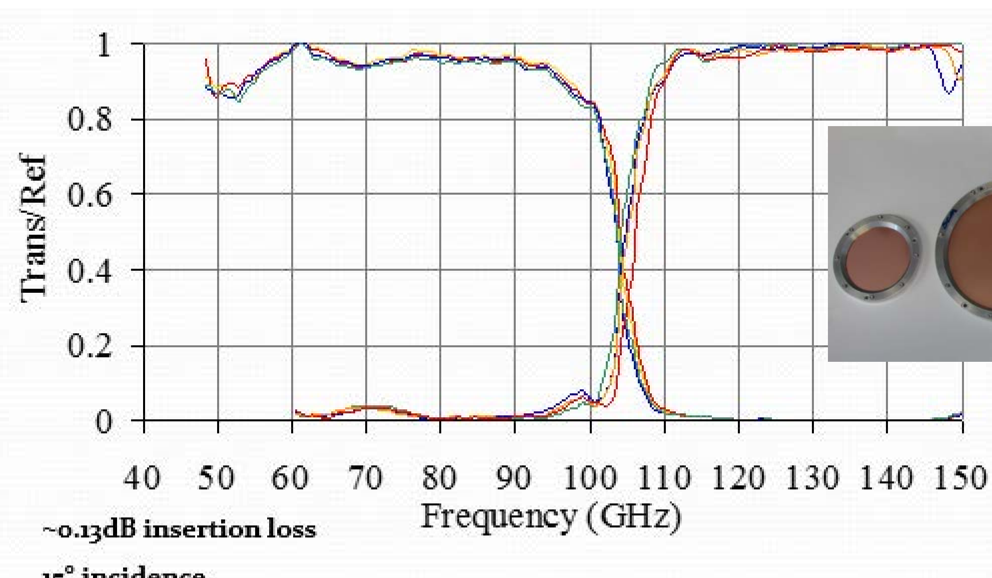




Dichroics



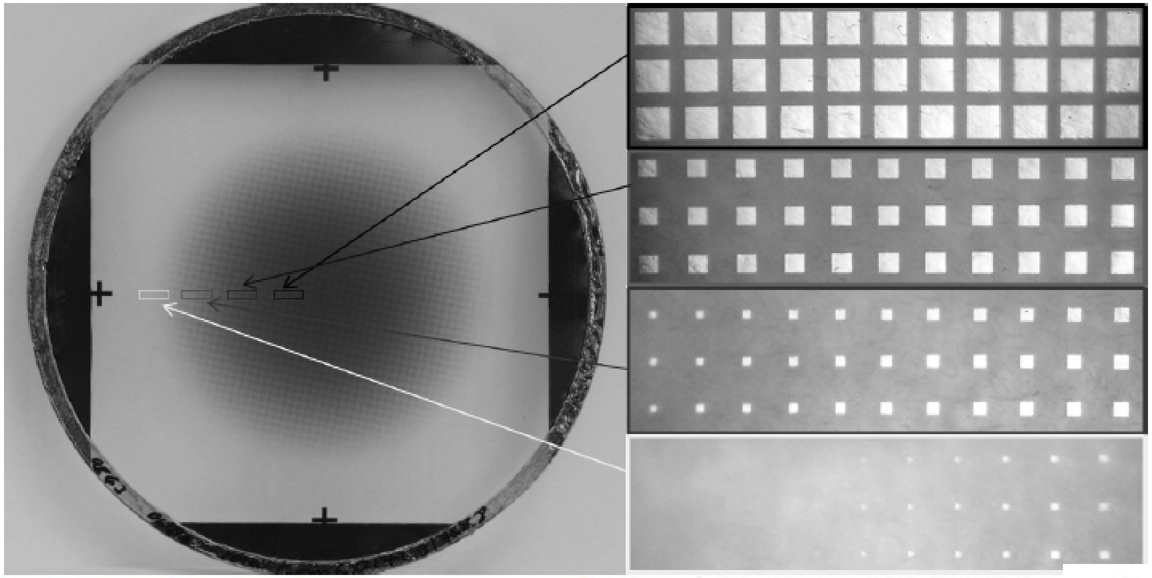

Transmission/Reflection
1
0.8
0.6
0.4
0.2
0
50 100 150 200 250 300 350 400 450 500 550
Frequency (GHz)

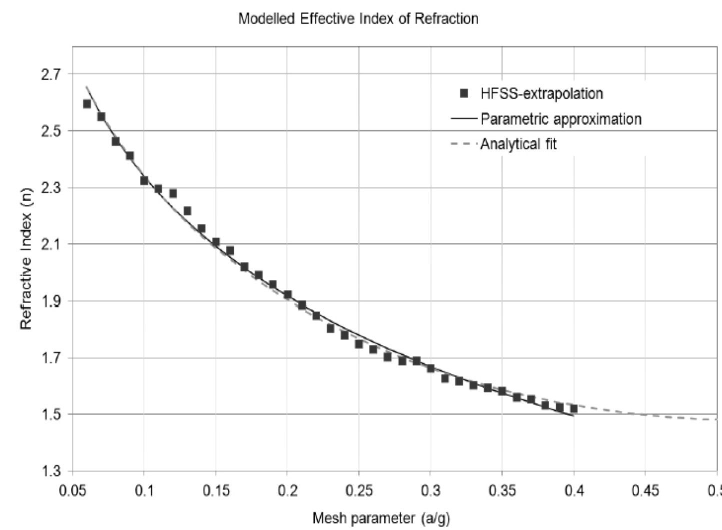

Trans/Ref
1
0.8
0.6
0.4
0.2
0
40 50 60 70 80 90 100 110 120 130 140 150
Frequency (GHz)
~0.13dB insertion loss

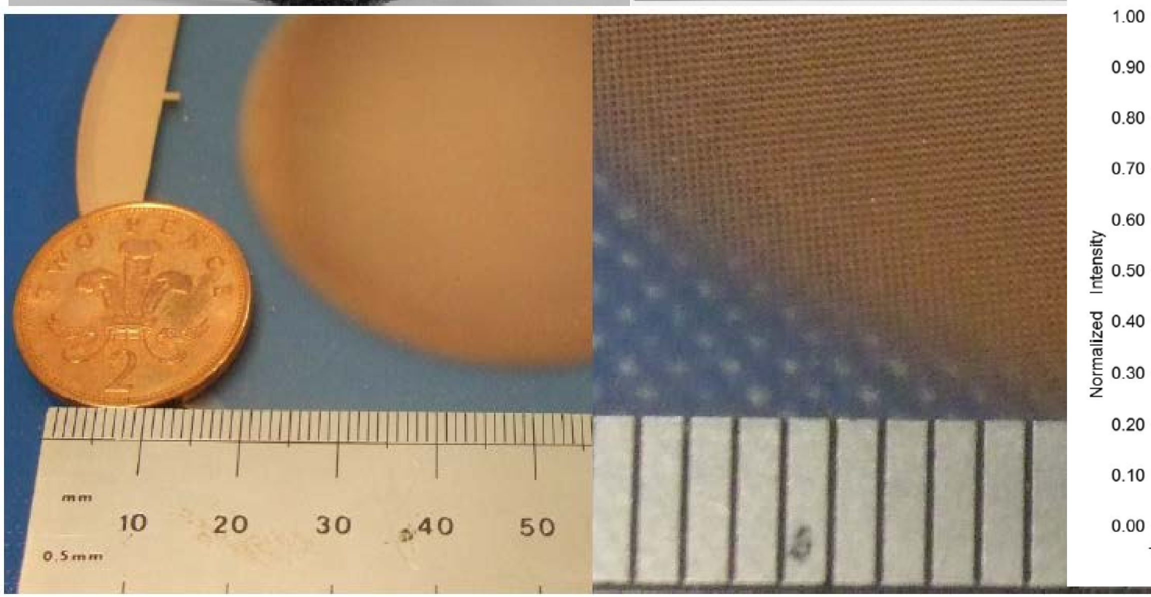
Flat lenses

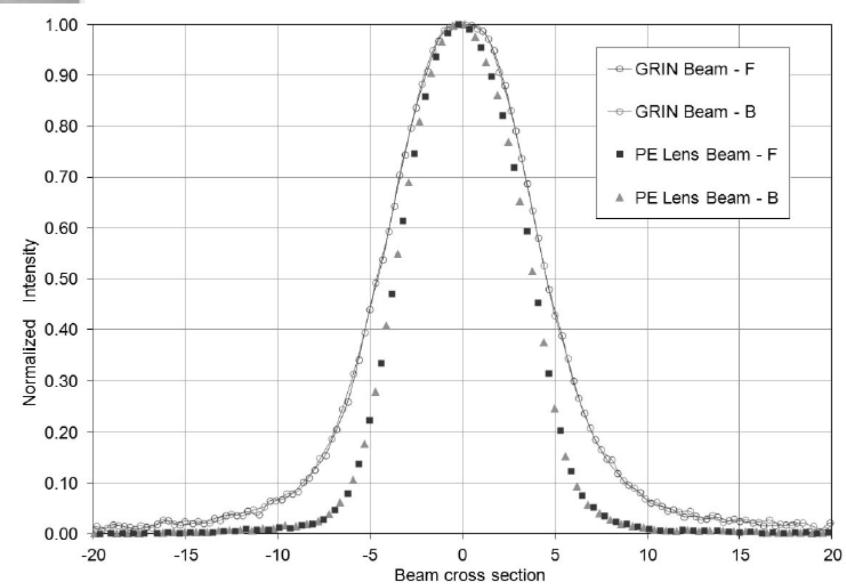
G. Savini, P. Ade, and J. Zhang, "A new artificial material approach for flat THz frequency lenses,"

Opt. Express 20, 25766-25773 (2012).







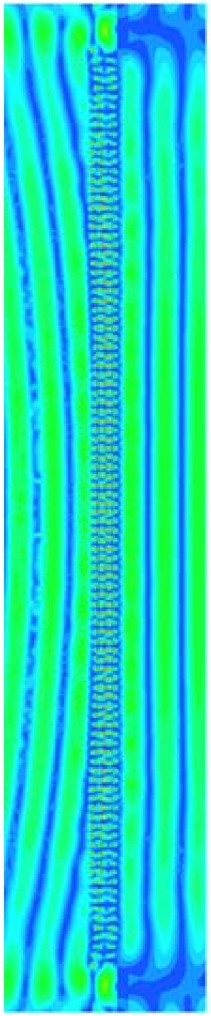


Flat Mesh Lens: Finite-element modelling check

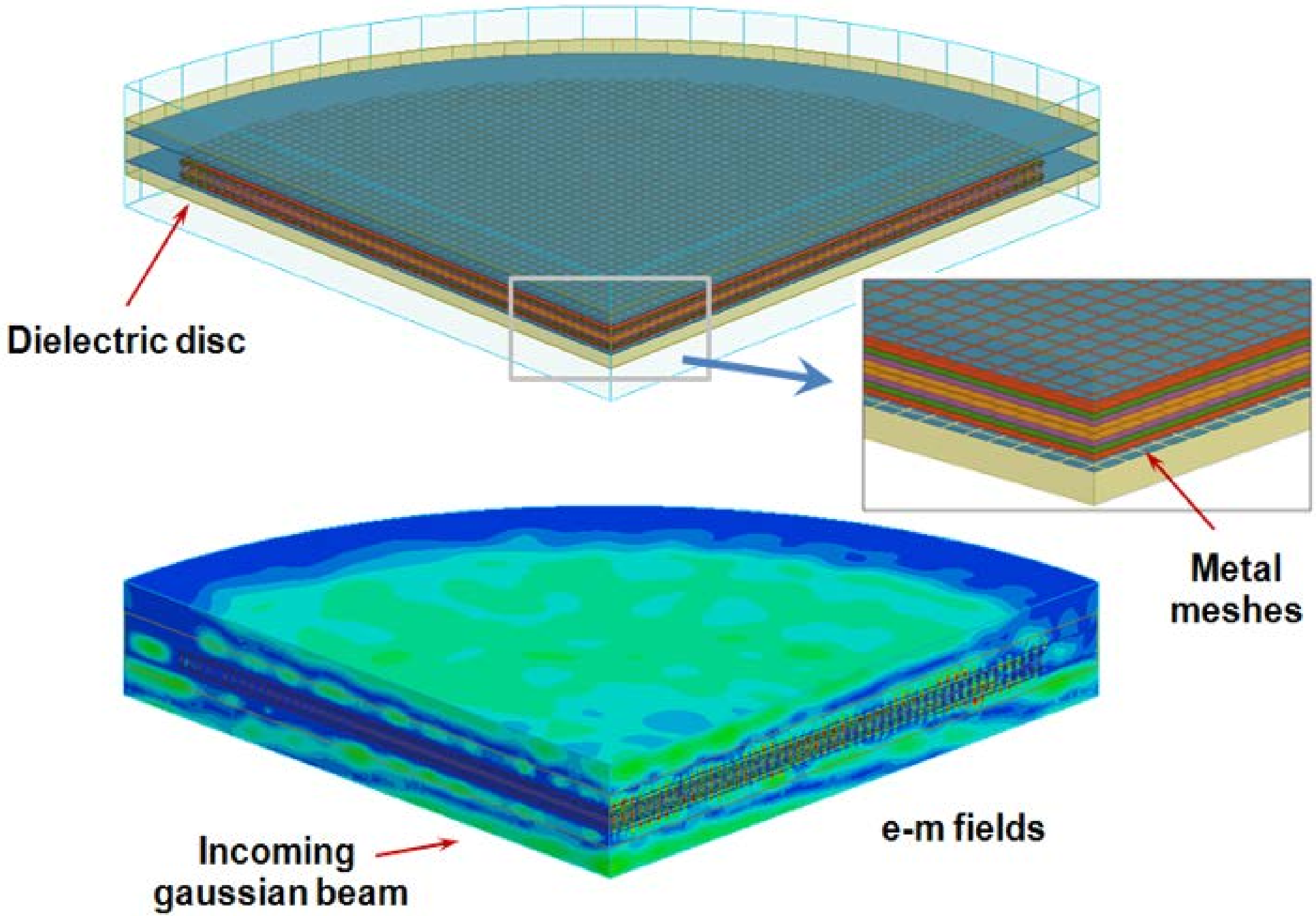
G. Pisano et al.
Applied Optics **52**,n.11, (2013)

2D model (cylindrical)

Central TL array



3D full model



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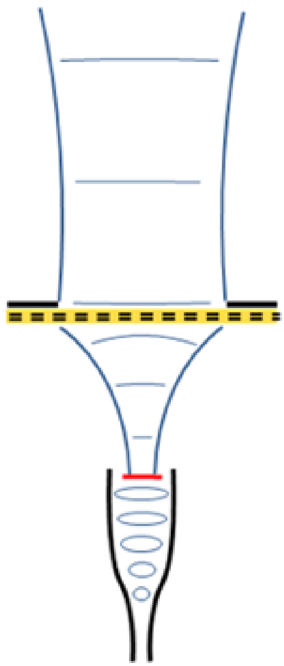
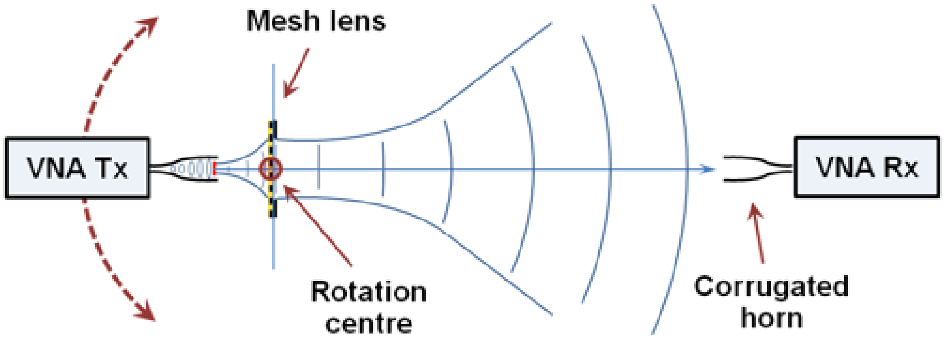
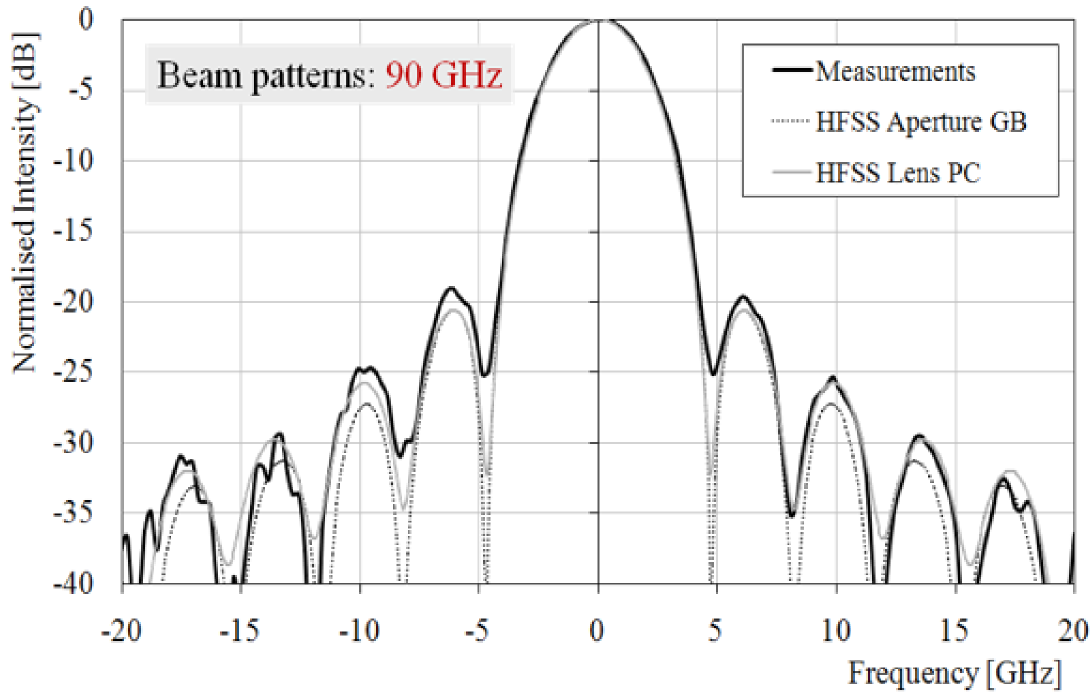
Flat Mesh Lens: VNA beam tests

G. Pisano et al.
Applied Optics **52**,n.11, (2013)



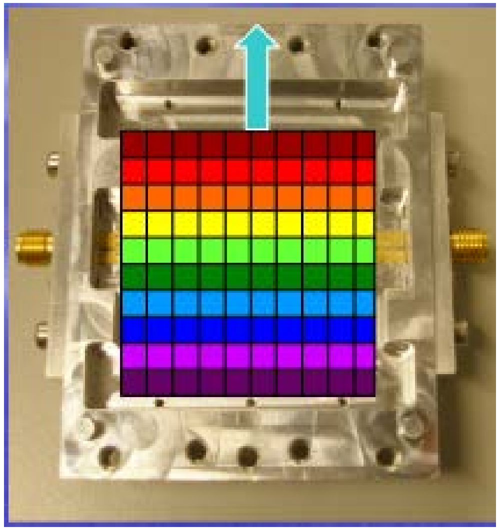




→ Experimental agreement down to the 4th side lobes

ICEMuSIC

- Simple instrument – spectral bands defined by strip filters - ~1% spectral bandwidth
  - Ice cloud parameter retrieval accuracy comparable to ICI on Metop-SG
  - NETD 0.3 mK – 3.0 mK, but retrieval limited by sky noise from wide bands
- Baseline instrument – spectral bands defined on chip
  - Antenna-coupled KIDS or tuned-backshort LEKIDS
  - Potentially 0.1% frequency bandwidth
  - Target 1km spatial resolution @ 186 GHz (0.8 m diameter aperture for LEO)
  - NETD in range 6-22 mK, depending on band
  - Scene power 5-10 pW
  - Detector NEP requirement 3-20 x 10^{-17} $WHz^{-1/2}$

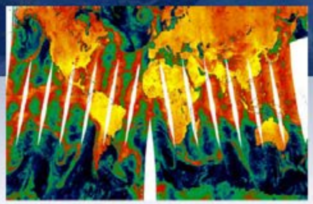


ICEMuSIC

Priority	Frequency (GHz)	Bandwidth (MHz)	# pixels	Angular resolution (mrad)	Spatial resolution (m)	Integration time (ms)	Average scene power, P_{det} (W x 10^{-14})	Photon noise limited NEP ($WHz^{-1/2}$ x 10^{-17})	MRTD (mK)
2	89	89	104	5	2106	114	4.5	0.3	6
2	150	150	175	3	1250	68	8.3	0.6	8
1	183.31	183.31	213	2	1023	55	10.2	0.7	8
1	186.31	186.31	217	2	1006	54	10.3	0.7	8
1	190.31	190.31	222	2	985	53	10.5	0.7	9
1	205	205	239	2	914	49	11.3	0.8	9
1	312.5	312.5	364	1	600	32	17.1	1.2	11
1	321.5	321.5	374	1	583	32	17.6	1.2	11
1	505	505	588	0.9	371	20	27.2	1.9	14
1	530	530	617	0.9	354	19	28.5	2.0	14
1	875	875	1018	0.5	214	12	45.5	3.3	18
1	1500	1500	1746	0.3	125	7	73.4	5.4	22

Metop-SG

MWS
Microwave Sounding



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

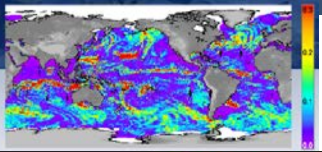
Heritage
AMSU-A, MHS

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



RSS (2011)

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 G

Implementation
ESA development

EUM/PEPS/VWG/11/0184
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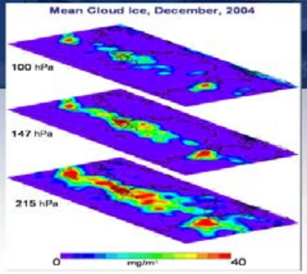
ICI: Ice Cloud Imaging



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

 EUMETSAT

Implementation ~2020

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All Metop-SG microwave & sub-mm channels >89 GHz could be covered by one instrument!

#	F (GHz)	Offset (GHz)	Bandw (MHz)	NED T (K)	Abs. ΔT (K)	Utilisation	MWS	MWI	ICI
1	89			0.2		Window on MWS. Precipitation & snowfall (0.8K) on MWI			
2 (x2)	118.75	1.2		1.2		Precipitation over sea and land including light precipitation and snowfall, height and depth of the melting layer (MWI)			
3 (x2)		1.4		1.2					
4 (x2)		2.1		1.2					
5 (x2)		3.2		1.2					
6 (x2)	165.5	0.725				Quasi-window, water-vapour profile, precipitation over land, snowfall			
7 (x2)	183.31	0.2	200	2.0	1	Water vapour profile and snowfall. NEDT requirements taken from most challenging cases of combination of MWS, MWI and ICI requirements.			
8(x2)		1.0	500	0.7	1				
9(x2)		2.0	700	0.5	1				
10(x2)		3.0	1000	0.5	1				
11(x2)		5.0	1500	0.35	1				
12(x2)		7.0	2000	0.35	1				
13(x2)		11.0	3000	1.0	1				
8	229			0.5		Quasi-window – MWS Water-vapour profile			
9(x2)	243.2	2.5		0.6		Quasi-window, cloud ice retrieval, cirrus clouds			
10(x2)	325.15	1.5		1.4		Cloud ice effective radius			
11(x2)		3.5		1.2					
12(x2)		9.5		1.1					
13(x2)	448	1.4		1.9		Cloud ice water path and cirrus			
14(x2)		3.0		1.5					
15(x2)		7.2		1.3					
16(x2)	664	4.2		1.5		Cirrus clouds, cloud ice water path			

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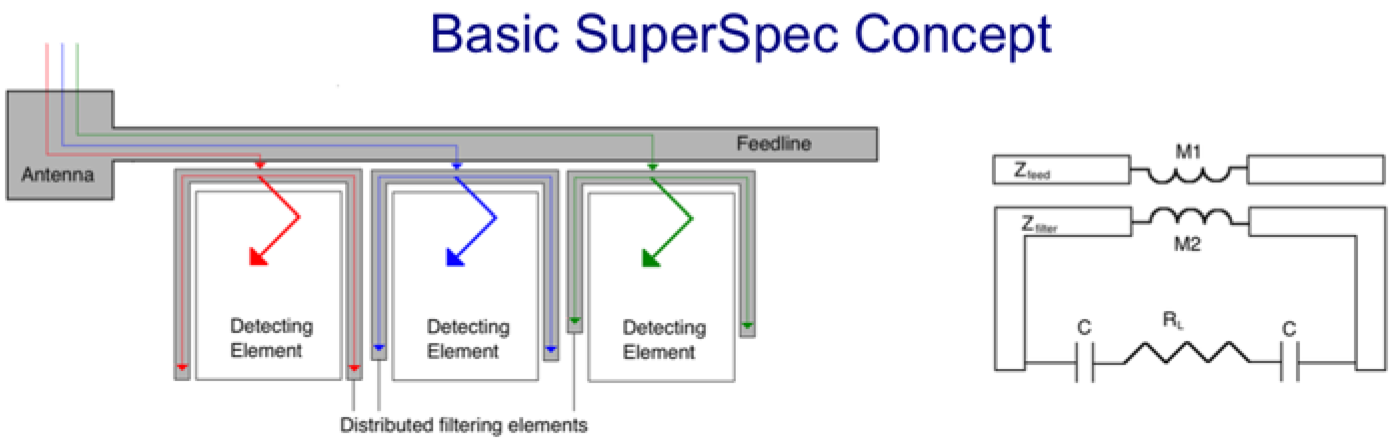
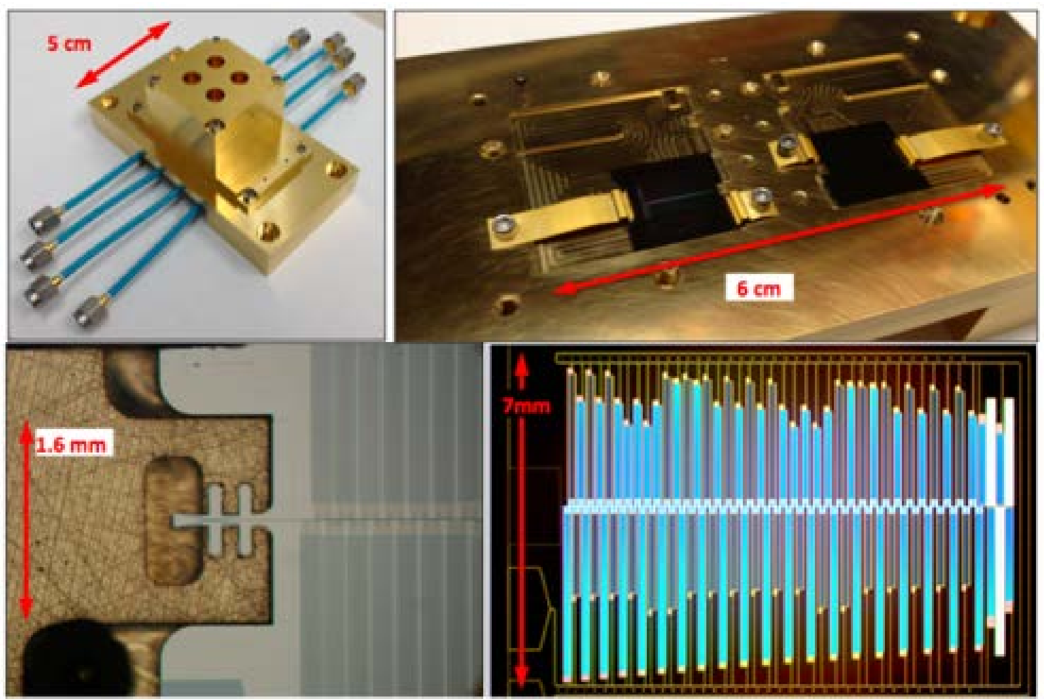
ICEMuSIC vs. scanning radiometers

	ICEMuSIC	Scanning radiometer
Primary mirror scanning?	No – fixed optics	Yes
Spatial resolution	High - ~1 km @ 186 GHz	Limited – typically ~15 km
Spectral resolution	~ 0.1%	
Sensitivity (NEDT)	~ few mK	~ few K
Field of view	~25° (instantaneous)	~100° (scanned)
Cooling requirements	Active - < 4 K	Passive
Frequency range	90 – 1500 GHz baseline	40 – 660 GHz typical

Superspec

- ~600 spectral elements per spatial pixel
- R~800





DESHIMA

- 5000-10000 sensors
- 320-950 GHz
- f/Δf ~1000

Development of DESHIMA: A Redshift Machine Based on a Superconducting On-Chip Filterbank

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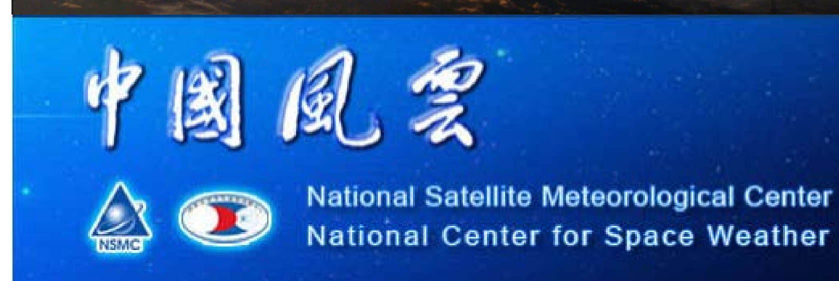
ICEMuSIC channels

- Number of spectral channels limited only by readout capabilities
  - Trade-off spectral vs. spatial coverage
- Possible for up to 1000 spectral channels in range 90-1500 GHz, 0.1% bandwidth per channel
- Preliminary atmospheric radiative transfer simulations have been run for ~650 channel instrument (150-800GHz) – VERY significant improvement (c.w. e.g. IASI) in temperature and water vapour retrieval – v. accurate and v. high resolution T & w.v. profiles

Future opportunities

- EE-9?
- H2020 – airborne demo.
- Dedicated satellite
  - Could join “A-train”? – complementary sensor data
  - Polar, sun-synchronous
  - Daily global coverage
- ISS
  - Diurnal variations
  - Less constraints on resources
- Bilateral opportunities – Significant interest from China - in talks with FY-4 team and NSMC / NSSC / CAS.



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Thank you!