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Terahertz Technology for Space and Earth Applications

P. de Maagt



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Outline

- Introduction
- Space Applications (some examples):
 - Large Reflectors for Space Astronomy
 - Other Traditional Drivers
- Terrestrial Applications (some examples):
 - Concealed objects detection
 - Medical
 - Pharmaceutical/NDT
- Future Trends in Antenna Technology
- “Classical” and “Non-Classical” Feed Technology

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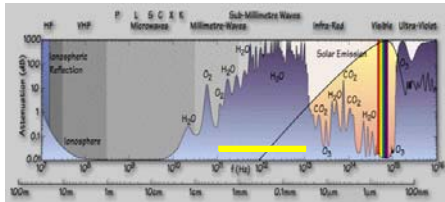
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The THz Frequency Range

CLAIM: the most scientifically rich, yet most underutilized region of the electromagnetic spectrum



THz radiation is the electromagnetic radiation between infrared optics and microwaves, loosely defined between $f = 0.1 - 10 \text{ THz}$ (3 mm - 30 μm)

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The THz “gap”

THz is at the transition from microwaves to optics

$$\nabla \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}$$

current density \vec{j} dominates at low “microwave” frequencies, using the motion of electronic charges to generate radiation.

At optical and infrared wavelengths, sources of radiation are associated with dipolar transitions, specifically electronic transitions, occurring within atoms or molecules and are related to the electric displacement $\partial \vec{D}$

<p>in comparison to microwaves:</p> <ul style="list-style-type: none"> <input type="checkbox"/> higher bandwidth (data trans.) <input type="checkbox"/> higher resolution (imaging) <input type="checkbox"/> integration (small) 	<p>in comparison to optics:</p> <ul style="list-style-type: none"> <input type="checkbox"/> less scattering (dust) <input type="checkbox"/> material selectivity (gases, semicond., biomolecules, ...) <input type="checkbox"/> transparency
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“THz” photons

Optical photons are emitted when electrons change energy states during relaxation (e.g. from a conduction band to a valence band)

THz photons are emitted when a molecule changes its **thermal, rotational or bending state** \Rightarrow energies involved are much smaller

optical spectroscopy \Rightarrow information on atomic composition


THz spectroscopy \Rightarrow information regarding the **molecular concentration** as well as its **physical condition** (heat, pressure, speed etc.)

THz radiation emitted or absorbed by a gaseous region allows to investigate chemical and physical processes **in places where instrumentation cannot (easily) be sent**


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Herschel/Planck









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Herschel/Planck

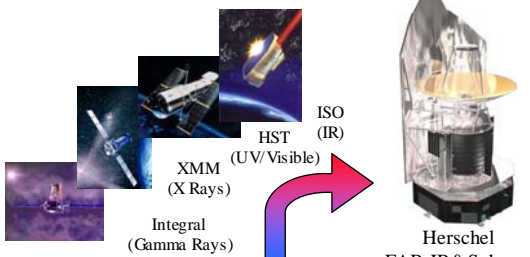





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Spectral Coverage







COMPLETING THE SPECTRUM COVERAGE

Herschel is the **only space facility** covering the far infrared to submillimetre range (no atmospheric absorption, no atmospheric emission)

“Discovery potential” is large

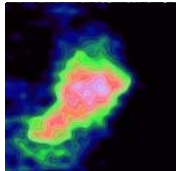

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Sub-mm Wave Observation

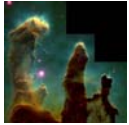
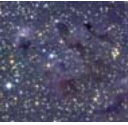
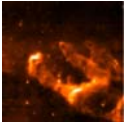
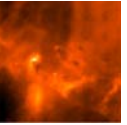


- Things look “different” at “different” frequencies.


Millimetre and sub-millimetre wavelengths can penetrate dark clouds.




M16 – the ‘Eagle Nebula’

HST 0.5 μm
NIR 1-2 μm
ISOCAM LW2 7 μm
ISOCAM LW3 15 μm


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Orion nebula






Using 3 different parts of the electromagnetic spectrum allows us to peer through the obscuring matter to see objects hidden within.

- 1) visible light: Nebula is opaque
- 2) Near IR: will remove the reflected light, the Stars are revealed inside it.
- 3) THz: dust is revealed from which new stars and planets are born.


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Herschel (FIRST) Antenna Configuration

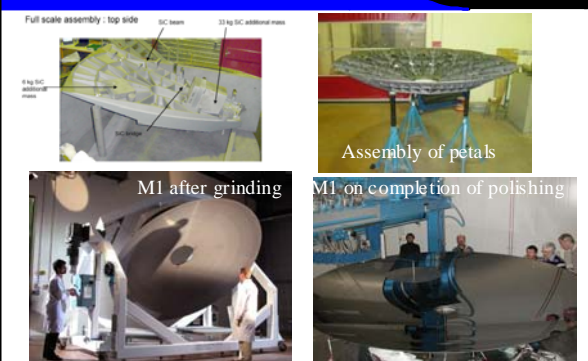


HERSCHEL (previously named FIRST)

- Frequency coverage 450 GHz to above 4 THz
- Cassegrain Antenna (3.5 m)
- System focal length 28.5 m
- Wave Front Error < 10 μm (goal is 6 μm)
- High accuracy and in-orbit thermal stability required
- Passively cooled to below 80 K
- Total mass (reflectors, support, interfaces, Thermal hardware) 320 kg.

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Herschel Reflectors



Full scale assembly: top side

Assembly of petals

M1 after grinding

M1 on completion of polishing

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Herschel Antenna

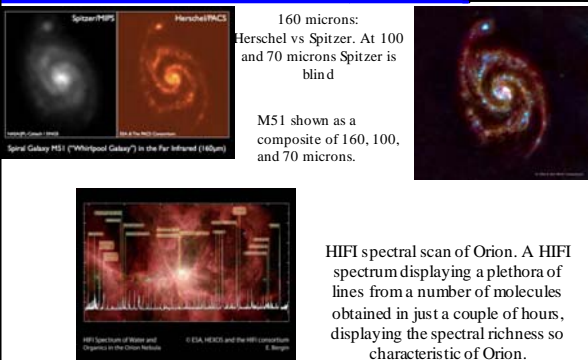


M2 after polishing. Note scatter cone in the centre

M1 cleaned and prepared for coating

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Herschel First Light




160 microns: Herschel vs Spitzer. At 100 and 70 microns Spitzer is blind

M51 shown as a composite of 160, 100, and 70 microns.

HIFI spectral scan of Orion. A HIFI spectrum displaying a plethora of lines from a number of molecules obtained in just a couple of hours, displaying the spectral richness so characteristic of Orion.

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Planck Antenna Configuration

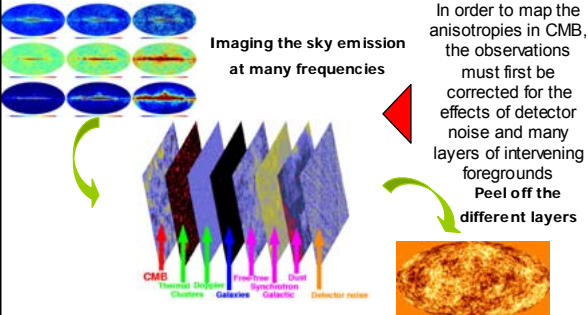


Planck: Features a modified Gregorian Reflector design with

- An aplanatic main antenna (dimension 1.5 m)
- Extremely low sidelobes
- System focal length 1.8 m
- Main reflector surface accuracy is about 10 μm
- Very important to have strict control of stray light (micro-cracking, dust, etc.)
- Total mass (reflectors (30/14kg)+ support) 175 kg.

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Distinctive features



Imaging the sky emission at many frequencies

In order to map the anisotropies in CMB, the observations must first be corrected for the effects of detector noise and many layers of intervening foregrounds

Peel off the different layers

Therefore, as a "by-product", Planck's observations will provide a wealth of information about our own Milky Way and other galaxies.

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Planck Mapping of Sky

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Cosmic Microwave Background

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Planck reflectors

Honeycomb structure

Placement on front sheet

Polished

Coated

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Planck Instrument

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Planck Instruments

Low Frequency Instrument	High Frequency Instrument
Freq.: 30, 44, 70 GHz	100, 143, 217, 353, 545, 857 GHz
Techn: HEMT correlation receivers	Polarized sensitive and spider-web bolometers
Temp: 20K (Front end), 300K (back end)	0.1K
Ang. Res: 10' (100 GHz) to 33' (30 GHz)	10.7' (100 GHz) to 5' (850 GHz)
Goal Temp. sens.: 12 μ K (70GHz)	4.5 μ K (100 GHz)

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Planck First Light

A map of the sky at optical wavelengths shows a prominent horizontal band which is the light shining from our own Milky Way. The superimposed strip shows the area of the sky mapped by Planck during the First Light Survey.

Filamentary structures are apparent on large scales (Planck, right) and small scales (Herschel, left) in the Milky Way. The Planck image, was obtained by the HFI @ 857 GHz. The dark horizontal band is our Galaxy. The colours represent the intensity of heat radiation by dust.

a region in the Aquila constellation covering a portion of the sky about 55°.

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Other Traditional Drivers

- Planetary/ Cometary Science
- Atmospheric Sciences
- Meteorology

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Outline

- Space Applications
 - Planetary/Cometary Science
 - Astronomy Science
 - Meteorology
 - Atmospheric Science
- Terrestrial Applications

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Atmospheric Science

Key topics

a) To measure and to understand the human impact on the chemistry and composition of the lower and middle atmosphere.

b) investigate the interactions between atmospheric chemistry, atmospheric composition and climate.

- limb-viewing observations at millimetre and submillimetre wavelengths in addressing the scientific objectives identified has a lot of potential.

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Limb sounding

$X+O_3 \Rightarrow XO + O_2$
 $XO+O \Rightarrow X+O_2$
 $O+O_3 \Rightarrow 2O_2$

Freq: 100GHz to 3.5 THz

CIO Chemistry

e.g.: $O_3, N_2O, H_2O, O_3, BrO, HCl, HBr, OH, NO, N_2O, CO, ClO$

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People screening

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Security and Defence Applications





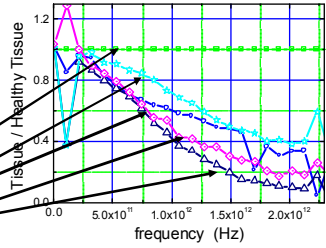
- Checkpoint people screening for hidden weapons & Explosives
- Stand-off detection of explosives-suicide bomber
- Baggage screening for explosives
- Postal screening for explosives, biological & chemical agents
- Chem/Bio detection
- Mine detection
- Communications
- Non-destructive evaluation

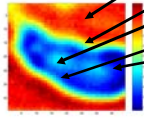



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Melanoma Characteristic Spectra








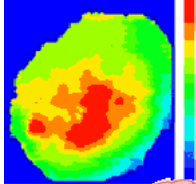

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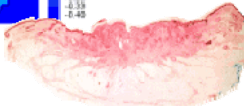
Image Analysis





THz image







Histology confirms diagnosis

Clinical photograph showing suspected basal cell carcinoma on patients forehead

<http://www.teraview.co.uk>


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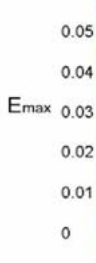
3-D-Imaging

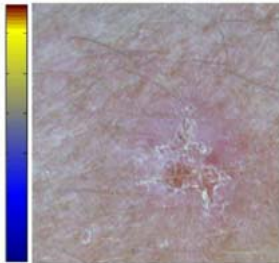



visual and terahertz images of a patient with a basal cell carcinoma, one of the common forms of skin cancer.

- The visual image shows the skin surface.
- Terahertz image of the surface, which shows similar information.
- Terahertz image at a depth of a few hundred microns showing how the tumour (invisible from the surface) has spread underneath the top layer of the skin.


Surface Features



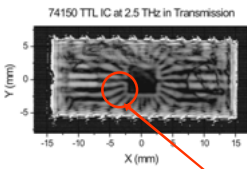



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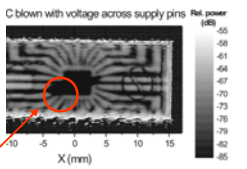
Imaging of semiconductors




74150 TTL IC at 2.5 THz in Transmission




C blown with voltage across supply pins






2.5 THz Images of an Integrated Circuit before and after over voltage applied on supply terminals


THz image of an integrated circuit penetrates the plastic package to reveal circuit features, metal contacts, and connection integrity.


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Terahertz Interferometry

	Instrument Mass (kg)	Instrument Power Consumption (W)
Basic nowcasting system SI, 183	214	161
Extended nowcasting system SI, 118, 153	235	210
Advanced nowcasting system SI, 118, 153, 380	253	261

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Terahertz Interferometry

F (GHz)	N	IF-H	IF-V
53	140		
118	105		
183	105		
380	105		

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CNF/CNT CFRP material

- The incorporation of nanotechnology in the field of composites has opened new horizons towards the development of advanced materials with unique functional properties.
- Carbon Nanofiber (CNF) and Carbon Nanotubes (CNT) are very promising filler materials due to high axial Young modulus and thermal and electrical properties. (Increased fracture resistance for 0.5% and 1% CNTs content)

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CAD and Integration

- Following advances in CAD, fixed tuned diode mixers and multipliers can now be accurately designed using commercial non-linear software and EM structure simulators which describe the circuit arrangement.
- Design and fabrication methodology is validated for frequencies up to 1THz
- There are potential advantages in integrating several functional components (e.g., mixer LO, IF amplifier) within a single waveguide cavity:
 - Smaller, lower mass, potential performance improvements, simpler interfaces...

380GHz Schottky diode mixer

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2.5 THz - Corrugated Feedhorn

Example of 2.5 THz feedhorn mandrel, feedhorn and beam pattern

Waveguide 100 x 25 microns
Corrugation spacing ~26 microns

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“Non-Classical” Technology

Conventional Technology exists, but keep an eye on:

- Integrated Antenna Technology
- Micromachined antenna Technology
- Metamaterial Technology

Objective:
to obtain equal or improved performance as compared to classical technologies with higher reliability.

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Dipole measurements

Radiation patterns

Beamwidth E plane => 44 deg
Beamwidth H plane => 64 deg

The high directivity values are due to an increase in the effective radiating area

Effective area dipole
 $A_{eff} = \frac{\lambda^2}{4\pi} D_0 \approx 0.13\lambda^2$

Dipole+woodpile
 $A_e \approx 1.1\lambda^2$

E-plane => $1-1.3\lambda$
H-plane => $0.58-0.78\lambda$

Agrees well with predictions

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EBG Heterodyne Mixer

Silicon Machined Waveguide
UMS Diode Pair
IF output
EBG backed double dipole

Diodes soldered into circuit

Complete EBG Mixer Circuit

Noise Temperature at 250 GHz $\approx 3500K$

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Imaging Array

Manufactured Heterodyne Imaging Array for 500 GHz

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40.000 Pixel Array at 1 THz

Monolithic Heterodyne Array Receiver Wafer

Schottky Diode Mixer
MMC Power Amplifier
Frequency Multiplier
Local Oscillator input port
Via hole to Intermediate Frequency Output Circuit
Integrated Calibration Load
Waveguide Horn Antenna Array (rectangular, diagonal, or conical)

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250-300GHz Twin Array

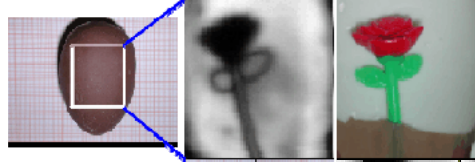
Assembled 8x250GHz mixers
RF input and LO transition

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Conclusions

- Traditional heartland of THz technology (remote sensing and radio astronomy) continues to represent a strong technology push and pull.
- Key to success is top-performance combined with low-power and mass.
- Arguably this has paved the technological path towards broadly usable THz systems for everyday applications

The future?



Questions ??