Using a cubesat to improve irrigation: an innovative thermal imager

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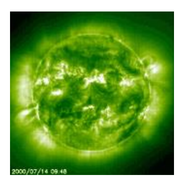

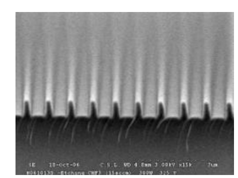

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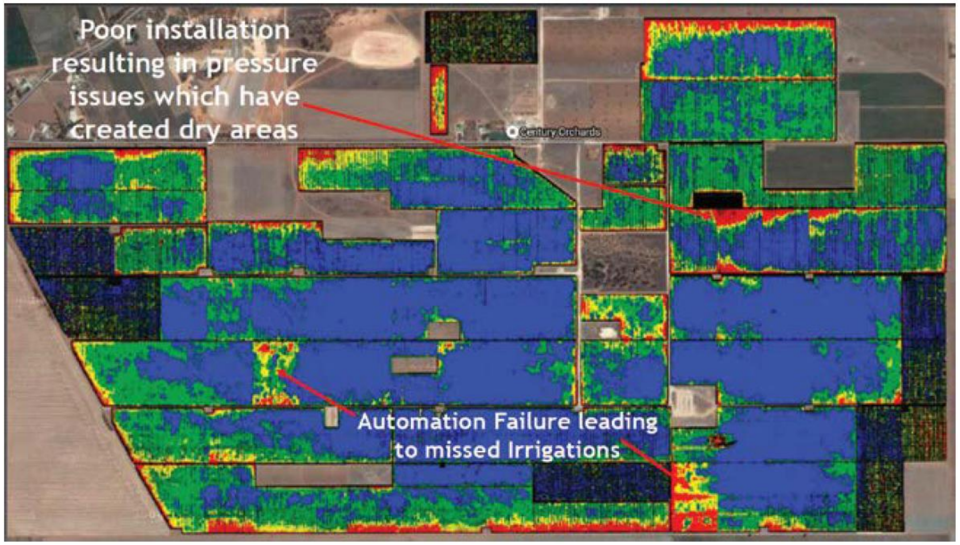
Infrared remote sensing applications

- **Hot target detection :**
  - **Exhausts leaks**
  - **Volcanic activity**
  - **Forest fires**
- **Atmosphere monitoring**
  - **Composition**
  - **Urban pollution**
- **Vegetation care and mapping**
- **Agriculture : irrigation monitoring**
  - **70% of Earth fresh water**
  - **Hydric stress linked to evapo-transpiration**
  - **Daily comparison between ground and leaves temperature**



Hydric stress seen in thermal infrared*

* Credit: *Century Orchards, Water stress thermal image. Red = water deficit stress, Blue = low water stress*

CubeSat payload

- **R&D study of a dual band IR camera on board a CubeSat**

- **Final requirements**
  - **1°K resolution**
  - **50m spatial resolution (MWIR band)**
  - **Daily coverage between 12h-14h local time**
  - **Payload fits in 3U**

- **Current phase : demonstrator design**
  - **Feasibility of small IR camera**
  - **Image quality/resolution is sufficient**
  - **LEO radiations effects on IR optics and detector**

- **Next step : flight a constellation**
  - **Complementary of Sentinel 8 (multi spectral IR)**
  - **Daily coverage for agriculture application**

Advantage of dual band

- **3-5µm : MWIR**
  - **High spatial resolution**
  - **Very sensitive to hot targets (600°K)**
  - **Clear weather / high humidity**
  - **Albedo < 3,9µm**

- **8-12µm : LWIR**
  - **Low spatial resolution**
  - **High T° resolution for ambient targets (300°K)**
  - **Turbulences, fog, dust, …**

- **Image combination**
  - **Details + accurate temperature mapping**
  - **Imaging conditions can be bad**
  - **Enhanced details by subtracting both images**

Example of combining IR images

Dual-band IR images of the city of Freiburg (Germany). Contrast and details are enhanced by overlaying both MWIR and LWIR images with complementary colors.

Streets exhibit higher intensity in the MWIR, and appear clearly when both images are substracted

Credit: Dual-band camera system with advanced image processing capability (Oliver Schreer, Mónica López Sáenz et al. Proc. of SPIE Vol. 6542 65421C-1)

IR materials

- **Classic materials for dual band IR**
  - ZnS, ZnSe, Ge
  - Very expensive : one inch diameter Ge costs 500$ (BK7 5$!)
  - High index : strong AR coating needed but fewer lenses

- **Dispersion problem**
  - IR materials are not very dispersive but the bandwidth is very large
  - Negative dn/dλ: chromatic aberration
- **Thermal problem**
  - Materials have same thermal behaviour and strong dn/dT

Optical material	n	dn/dT *1e-6/K	dn/dλ *1e-3 (µm-1)
	4,7µm		
Ge	4,008	367,4	-10,2
ZnS	2,248	41,4	-5,6
ZnSe	2,431	90,9	-3,9
	9,4µm		
Ge	3,994	364,3	-0,9
ZnS	2,208	40,3	-13,0
ZnSe	2,410	64,3	-6,1
BK7	1,517	1,7	-41,0

Chalcogenide materials (SCHOTT)

- **UMICORE, SCHOTT: IR materials of Chalcogenide family**

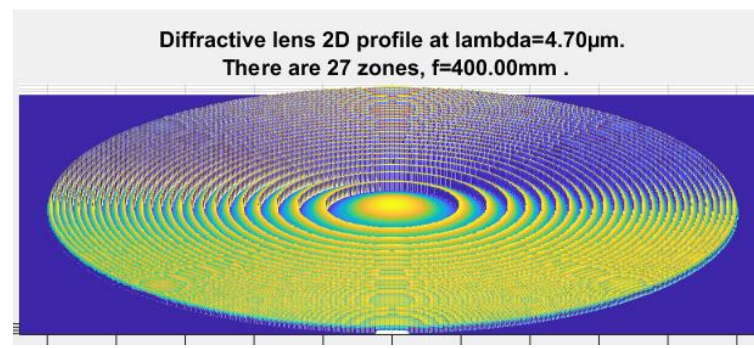
- **SCHOTT family is IRG22-27 made of Ge, As, Se**
  - **Mouldable materials : production cost reduction (constellation)**
  - **Lower index and thermal power**

Optical material	n	dn/dT *1e-6/K	dn/dλ *1e-3 (µm-1)
	4,7µm		
IRG22	2,511	68,6	-3,2
IRG24	2,620	21,2	-3,2
IRG25	2,620	62,1	-3,9
IRG26	2,792	33,6	-4,2
IRG27	2,414	-3,1	-4,0
	9,4µm		
IRG22	2,499	67,5	-3,4
IRG24	2,610	20,3	-2,3
IRG25	2,605	61,2	-3,7
IRG26	2,780	32,2	-2,8
IRG27	2,391	-3,6	-7,3
BK7	1,517	1,7	-41,0

Hybrid design : refractive-diffractive

- **Diffractive surfaces play as additive or subtractive power**
  - **Etched/diamond turned on refractive surface**
  - **Saw tooth profile**

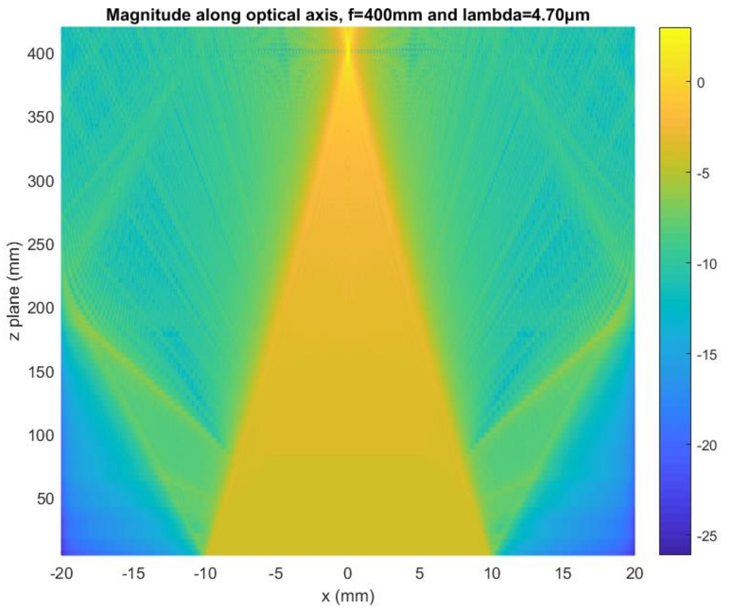
- **Diffractive optics properties**
  - **Opposite dispersion:** $V = -\frac{\lambda_0}{\Delta\lambda}$
  - **Opposite thermal behaviour:** $f(T°) = -2\alpha_{mat}$
  - **Lighter design**
  - **Chalcogenide substrate ++**

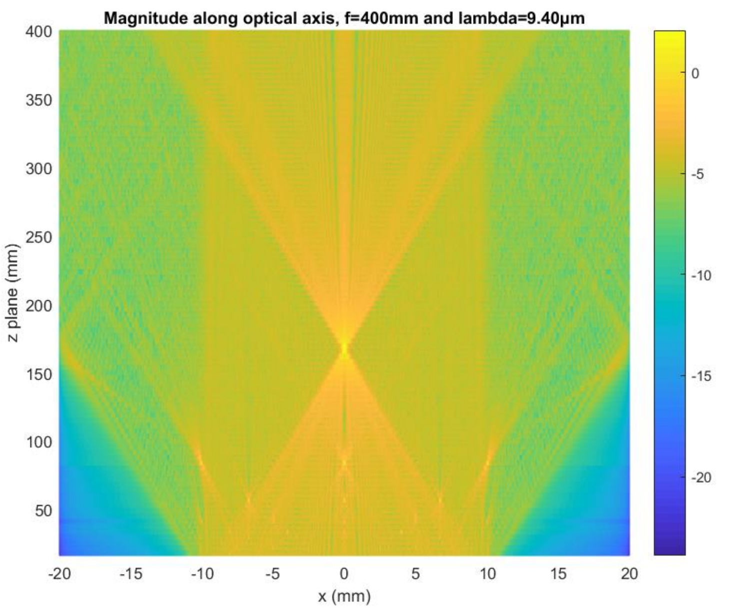


- **Drawback**
  - **Loss of ‘transmission’ for large Δλ**
  - **Not suitable if the bandwidth is too wide …**

Diffractive optics behaviour

- **Fourier optics propagator**
  - **By design, the focus (order 1) has 99% of the total irradiance when illuminated at λ0**





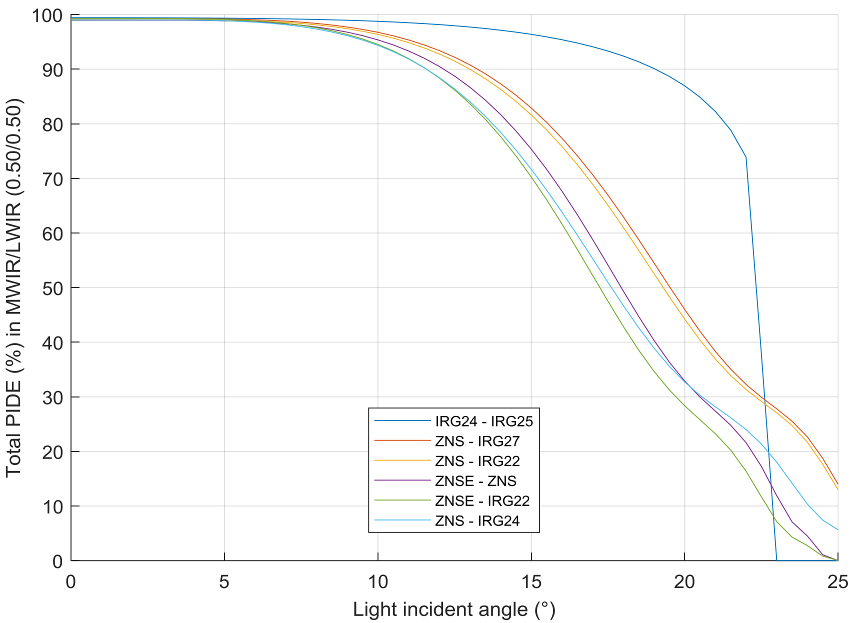
For λ = 2*λ0:

- **Order 0 (∞) is strong**
- **Order 1 carries only 55% of the energy**
- **Orders >1 visible**
- **Stray light increases a lot**
- **“focus” move at 170mm<<400mm**

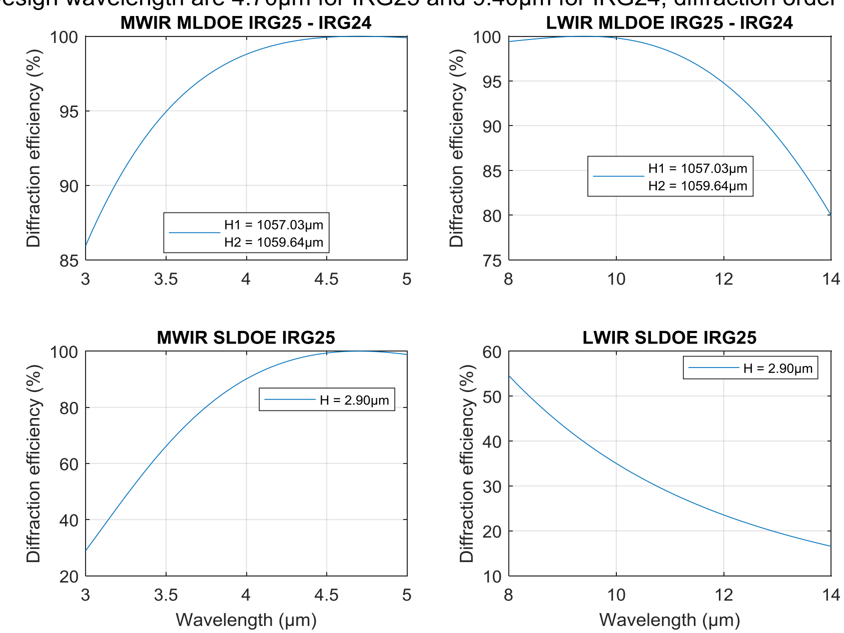
Multilayer diffractive optical elements (MLDOEs)

- **2 DOEs simultaneously designed**
  - **Each DOE optimized for λ1 (MWIR), λ2 (LWIR)**
  - **2 profiles and 2 refractive index**
- **They act like a broad-band DOE !**
  - **Focus > 90% of irradiance for all λ close to λ1, λ2**
  - **Materials selected with optimization process**
  - **Incident angles are taken into account**

PIDE for best MLDOE combinations versus incident angles at diffraction order m= 1
Design incident angle is 0.00° and relief design wavelength are 4.70µm (1) and 9.40µm (2)

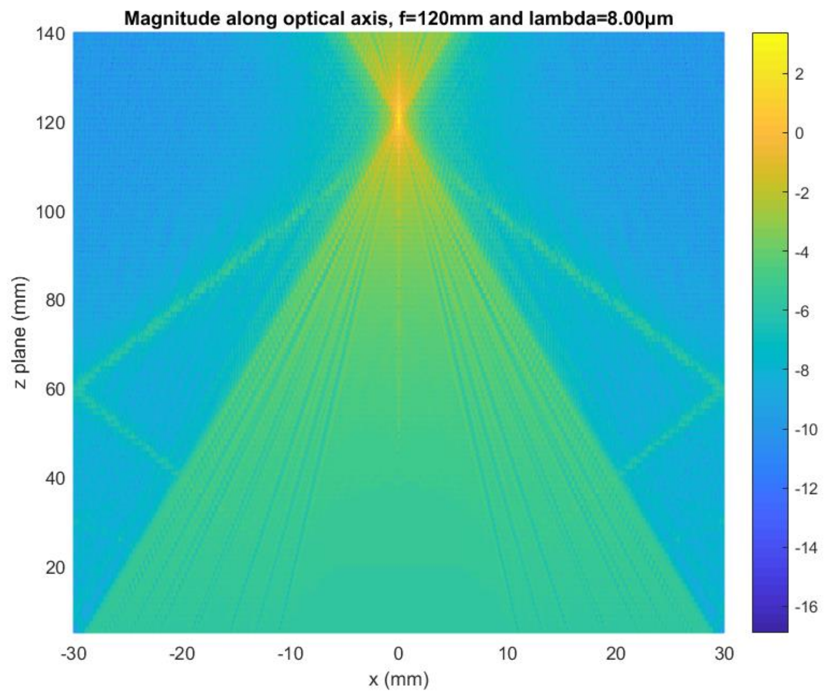


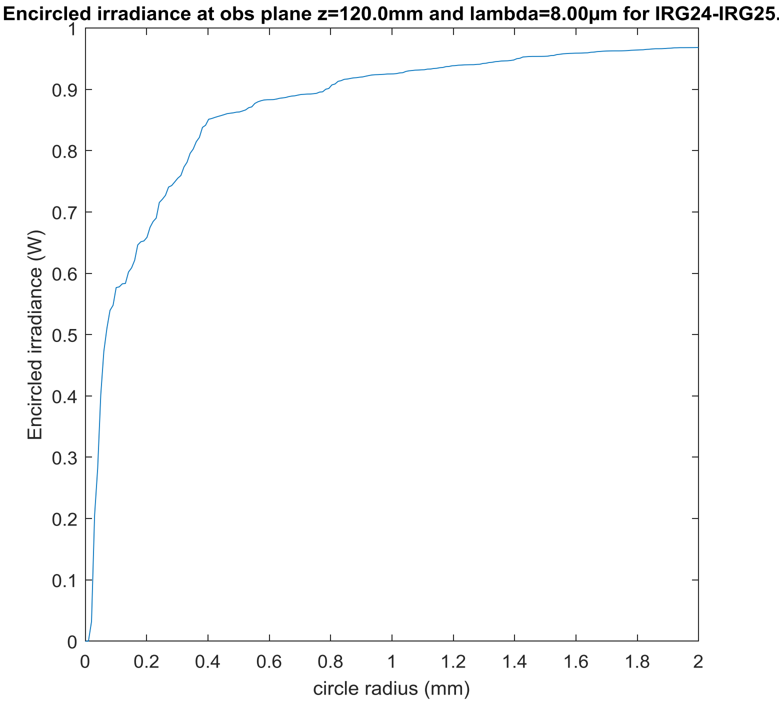
Diffraction efficiency in MWIR/LWIR with both types of DOE at normal incidence.
Design wavelength are 4.70µm for IRG25 and 9.40µm for IRG24, diffraction order m= 1.



Test of MLDOE

- **Fourier optics propagator**
  - **Confirm high efficiency for all wavelength at focus (order 1)**





  - **Compute LCA : chromatic power**
  - **Compute F(T°) : thermal power**
  - **Include refractive surfaces to make an achromatized hybrid**

Thank you for your attention !

Acknowledgements

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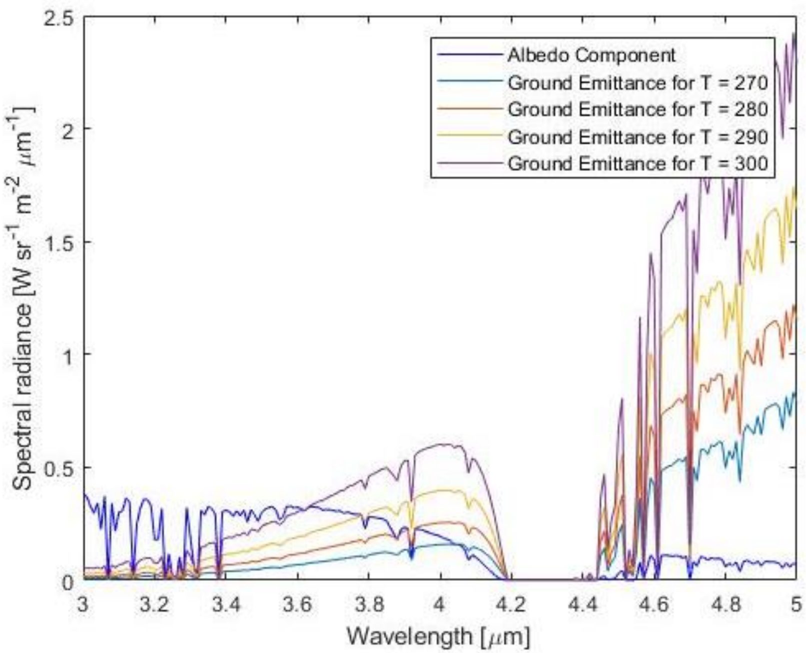
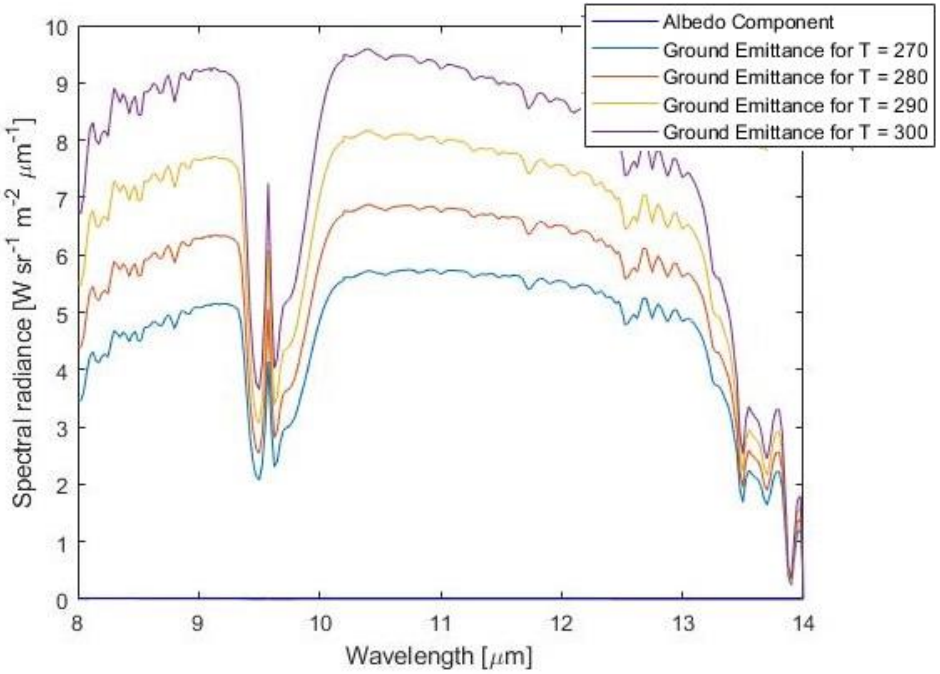
Spectral radiance

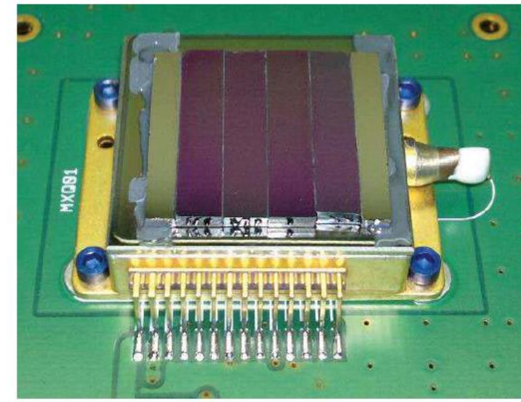
MWIR



LWIR



Backup thermal detector



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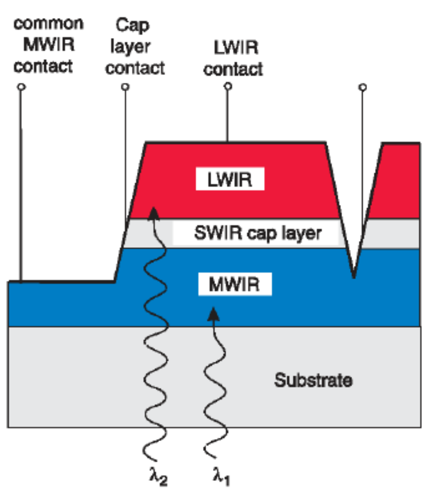
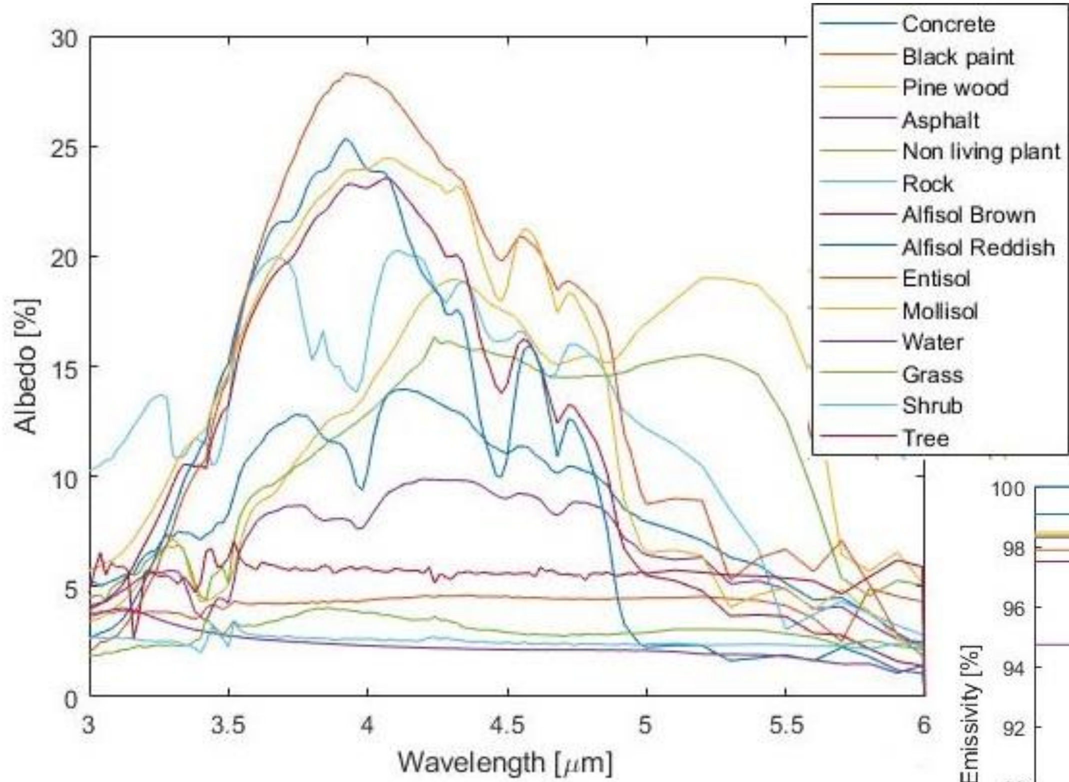
- **For compactness, a dual band detector is chosen:**
- **Dual band Microbolometer**
  - **Cheap and small, uncooled**
  - **Slow response time : need for scanning system or even TDI to improve NEDT**
  - **Wavelength insensitive : application of band pass filters to select the bands**
  - **SCD Bird 640 is a good candidate**

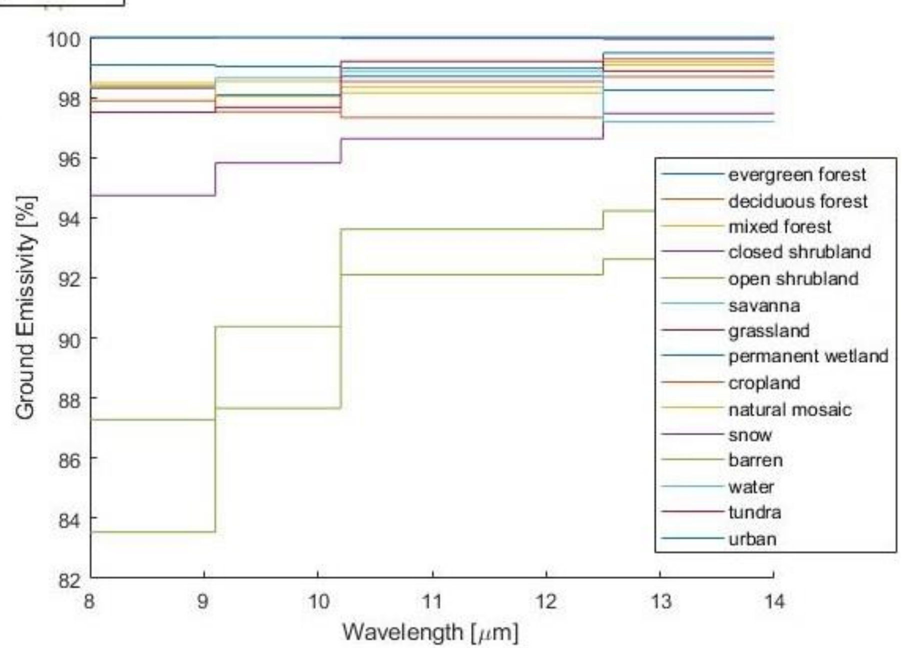


- **Dual band photodetector/QWIP**
  - **Fast and high T° resolution snapshot images**
  - **Cooling under 77°K : bulky Stirling cooler**
  - **No « HOT » techno for dual band like in MWIR**
  - **Expensive**
  - **Leonardo UK/Italy, Sofradir, Raytheon, AIM…**

* Credit: *Technological development of multispectral filter assemblies for micro bolometer, Roland LE GOFF1, François TANGUY1 et al*

Backup radio





Backup what next ?

- **f/1.5 CODEV Design have been made in MWIR with one diffractive surface**
  - **Use MLDOE instead to extend to LWIR also**
  - **CODE V analysis tools (PSF, MTF,…)**
  - **Vigneting is very bad if TDI**
- **Athermalization algorithm is used to optimize materials and focal length**
  - **Include MLDOE powers to athermalize for LWIR**
- **Check fabrication and tolerances of MLDOE**
  - **Number of teeth, spacing and materials ductility (chalco ok)**
  - **Apply specific tolerances (teeth depth)**
  - **Run Finite Differences tolerances to check sensitivity of these tolerances**
  - **Run Monte Carlo analysis to validate the tolerances**
- **Run ASAP for stray light analysis**
  - **Find infrared AR coatings for dual bands**
  - **Checks for reflexions and ghosts**
  - **Check cold stop efficiency (stray rays)**

Backup design MWIR