Using a cubesat to improve irrigation: an innovative thermal imager

Victor Laborde\textsuperscript{1}, Profs. J. Loicq\textsuperscript{1,3}, S. Habraken\textsuperscript{1,2}, G. Kerschen\textsuperscript{3}

\textsuperscript{1}Centre Spatial de Liege, STAR institute, University of Liege, Belgium  
\textsuperscript{2}Hololab, Faculty of Sciences, University of Liege, Belgium  
\textsuperscript{3}Faculty of applied Sciences, University of Liege, Belgium
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

* 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 \( dn/d\lambda \): chromatic aberration

- Thermal problem
  - Materials have same thermal behaviour and strong \( dn/dT \)

<table>
<thead>
<tr>
<th>Optical material</th>
<th>n</th>
<th>( dn/dT \times 1e-6/K )</th>
<th>( dn/d\lambda \times 1e-3 ) (( \mu m^{-1} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>4,7( \mu m )</td>
</tr>
<tr>
<td>Ge</td>
<td>4,008</td>
<td>367,4</td>
<td>-10,2</td>
</tr>
<tr>
<td>ZnS</td>
<td>2,248</td>
<td>41,4</td>
<td>-5,6</td>
</tr>
<tr>
<td>ZnSe</td>
<td>2,431</td>
<td>90,9</td>
<td>-3,9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9,4( \mu m )</td>
</tr>
<tr>
<td>Ge</td>
<td>3,994</td>
<td>364,3</td>
<td>-0,9</td>
</tr>
<tr>
<td>ZnS</td>
<td>2,208</td>
<td>40,3</td>
<td>-13,0</td>
</tr>
<tr>
<td>ZnSe</td>
<td>2,410</td>
<td>64,3</td>
<td>-6,1</td>
</tr>
<tr>
<td>BK7</td>
<td>1,517</td>
<td>1,7</td>
<td>-41,0</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Optical material</th>
<th>n</th>
<th>dn/dT *1e-6/K</th>
<th>dn/dλ *1e-3 (μm-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>4,7μm</td>
<td></td>
</tr>
<tr>
<td>IRG22</td>
<td>2,511</td>
<td>68,6</td>
<td>-3,2</td>
</tr>
<tr>
<td>IRG24</td>
<td>2,620</td>
<td>21,2</td>
<td>-3,2</td>
</tr>
<tr>
<td>IRG25</td>
<td>2,620</td>
<td>62,1</td>
<td>-3,9</td>
</tr>
<tr>
<td>IRG26</td>
<td>2,792</td>
<td>33,6</td>
<td>-4,2</td>
</tr>
<tr>
<td>IRG27</td>
<td>2,414</td>
<td>-3,1</td>
<td>-4,0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9,4μm</td>
<td></td>
</tr>
<tr>
<td>IRG22</td>
<td>2,499</td>
<td>67,5</td>
<td>-3,4</td>
</tr>
<tr>
<td>IRG24</td>
<td>2,610</td>
<td>20,3</td>
<td>-2,3</td>
</tr>
<tr>
<td>IRG25</td>
<td>2,605</td>
<td>61,2</td>
<td>-3,7</td>
</tr>
<tr>
<td>IRG26</td>
<td>2,780</td>
<td>32,2</td>
<td>-2,8</td>
</tr>
<tr>
<td>IRG27</td>
<td>2,391</td>
<td>-3,6</td>
<td>-7,3</td>
</tr>
<tr>
<td>BK7</td>
<td>1,517</td>
<td>1,7</td>
<td>-41,0</td>
</tr>
</tbody>
</table>
 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: $f(T^\circ) = -2\alpha_{mat}$
  - Lighter design
  - Chalcogenide substrate ++

- Drawback
  - Loss of ‘transmission’ for large $\Delta\lambda$
  - 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 $\lambda_0$

For $\lambda = 2\lambda_0$:
  - Order 0 ($\infty$) is strong
  - Order 1 carries only 55% of the energy
  - Orders $>$1 visible
  - Stray light increases a lot
  - “focus” move at 170mm $<<$ 400mm

11th European CubeSat Symposium  Victor LABORDE  September 11, 2019
Multilayer diffractive optical elements (MLDOEs)

- 2 DOEs simultaneously designed
  - Each DOE optimized for $\lambda_1$ (MWIR), $\lambda_2$ (LWIR)
  - 2 profiles and 2 refractive index

- They act like a broad-band DOE!
  - Focus > 90% of irradiance for all $\lambda$ close to $\lambda_1$, $\lambda_2$
  - 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.
Fourier optics propagator

- Confirm high efficiency for all wavelength at focus (order 1)
- Compute LCA : chromatic power
- Compute $F(T^\circ)$ : thermal power
- Include refractive surfaces to make an achromatized hybrid
Thank you for your attention!

Acknowledgements

Contact

Victor LABORDE
Victor.laborde@uliege.be

Prof LOICQ Jérôme
j.loicq@uliege.be

Prof HABRAKEN Serge
shabraken@uliege.be

Centre spatial de Liège (CSL)
LIEGE Science Park
Avenue du pré-Aily
4031 Angleur
Belgium
+32 (0)4 382 46 00
csl@ulg.ac.be
Spectral radiance

MWIR

LWIR

Albedo Component
Ground Emissivity for T = 270
Ground Emissivity for T = 280
Ground Emissivity for T = 290
Ground Emissivity for T = 300
Backup thermal detector

- 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 $T^\circ$ resolution snapshot images
  - Cooling under 77$^\circ$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

![Graph showing albedo and ground emissivity against wavelength.](image-url)
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

Diffraction Encircled Energy
MWIR

Diffraction MTF
MWIR