

# International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

*Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas*



## *Wideband response of a terahertz-millimeter imager based on a 384x288 pixel uncooled bolometric detector*

*Marc Terroux*

*Linda Marchese*

*Martin Bolduc*

*Luc Mercier*

*et al.*



## WIDEBAND RESPONSE OF A TERAHERTZ-MILLIMETER IMAGER BASED ON A 384X288 PIXEL UNCOOLED BOLOMETRIC DETECTOR

Marc Terroux, Linda Marchese, Martin Bolduc, Luc Mercier, Claude Chevalier, Lucie Gagnon, Bruno Tremblay, Francis Généreux, Jacques-Edmond Paultre, Francis Provençal, Patrick Beaupré, Yan Desroches, François Châteauneuf, Alain Bergeron

*INO, 2740 Einstein, Québec, Québec, Canada, G1P 4S4*

### I INTRODUCTION

In the past, bolometer-based imagers have been used for earth observation. Uncooled-bolometer based imagers are especially well suited for this due to their low power consumption. NIRST (New Infra-Red Sensor Technology), an example of an imager based on uncooled bolometers,[1] monitors high temperature events on the ground related to fires and volcanic events, and will measure their physical parameters and takes measurements of sea surface temperatures mainly off the coast of South America as well as other targeted opportunities. NIRST has one band in the mid-wave infrared centered at 3.8  $\mu\text{m}$  with a bandwidth of 0.8  $\mu\text{m}$ , and two bands in the thermal infrared, centered respectively at 10.85 and 11.85  $\mu\text{m}$  with a bandwidth of 0.9  $\mu\text{m}$ .

From their principle of operations, bolometers can exhibit sensitivity over a very wide spectral band. In this paper the wideband response of a bolometer-based imager in the THz to millimeter wavebands is presented. The detector is based on the same technology as the one use for the NIRST mission, packaged in a 384x288 pixel two-dimensional array format and further tuned to the THz-millimeter regime. The detector integrated into a camera core is further equipped with a rapid optics specifically designed for the THz-millimeter band.

Terahertz and millimeter wavebands are characterized by long wavelengths compared to the traditional infrared and visible spectra. INO has developed a terahertz camera core based on a 384 x 288 pixel 35  $\mu\text{m}$  pixel pitch uncooled bolometric terahertz detector. The camera core provides full 16-bit output at video rates at 50 frames/sec. The introduction of this new camera core with a small pixel pitch array paves the way to the use of smaller THz optics and the design of more compact systems which should yield to a wider acceptance of the technology. Moreover testing of this camera, initially designed for the THz sub-millimeter regime, has shown good sensitivity response in the longer millimeter wavelengths. Recent tests have shown that the camera was responsive over at least the range of 70  $\mu\text{m}$  to 3.1 mm, measurements being limited only by the availability of the testing sources.

This paper reviews the various characteristics of the camera as well as its performances. It begins with overview of the detector and camera core, the basis for the 384 x 288 pixel THz camera. The properties of the custom designed optics are also presented. Results showing the performances of the camera in terms of noise-equivalent power and imaging capabilities are also presented.

### I THZ FOR SPACE AND CAMERA OVERVIEW

THz wavebands have been only used sparsely in space imaging, nevertheless the few instruments realized showed that millimetre and submillimetre wavelengths could be useful for some space applications. For instance studies have shown that these waveband can penetrate dark clouds. This would allow reveal dust at the origin of stars and planets. Other space applications stand in the field of atmospheric sciences for the limb study and in meteorology to understand the relationship between atmospheric chemistry and climate [2].

#### A. Camera overview

INO has recently developed a real-time (video rate) 384x288 THz camera, shown in Fig. 1. The core of the THz imager is a 35  $\mu\text{m}$  pitch detector array that is based on INO's uncooled VOx microbolometer technology 0. The THz detectors are fabricated in INO's clean room. A standard ceramic package is used for final packaging. The detector FPA is sealed with a high resistivity float zone silicon (HRFZ-Si) window having an anti-reflective coating consisting of a layer of Parylene, the thickness of which depends on the required optimization wavelength. The FPA is mounted on an INO IRXCAM core giving an uncooled THz camera assembly. The additional THz objective consists of a refractive 44 mm focal length F/1 THz lens.

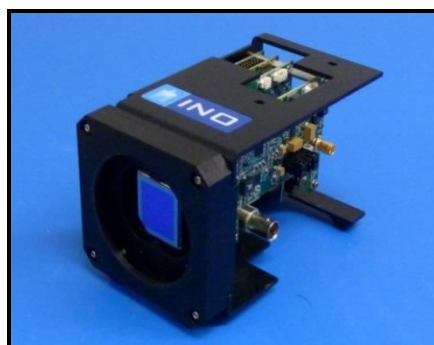


Fig. 1 IRXCAM-THz-384 terahertz camera core

Table 1. Infrared and Terahertz camera comparison

	IRXCAM-THz-384	IRXCAM-1024
Wavelength	40 $\mu\text{m}$ – 3 mm	8-12 $\mu\text{m}$
Array Size (pixels)	384 x 288	1024 x 768
Pixel pitch	35 $\mu\text{m}$	17 $\mu\text{m}$

Table 1 presents a comparison between an infrared camera, the IRXCAM-1024 and the terahertz camera, the IRXCAM-THz-384. As is listed in the table, the wavelength ranges are different, where the infrared, or thermal camera is most sensitive to the 8 – 12  $\mu\text{m}$  wavelength band and the terahertz camera is optimized for the longer wavelengths, from 40  $\mu\text{m}$  out to 3 mm. The pixel dimensions and array sizes also differ for the two cameras, where the THz version is based on an array of 384 x 288 35  $\mu\text{m}$  sized microbolometer pixels and the infrared is based on an array of 1024 x 768 17  $\mu\text{m}$  sized microbolometer pixels. It is important to note that in the case of the THz camera, the pixel size is may be up to almost 100 times smaller than the imaging wavelength (that may go up to 3 mm), whereas in the case of the IR camera the pixel dimension is only approaching the imaging wavelength. Previous imaging results have demonstrated that the subwavelength imaging in the THz band is not only possible, but that the camera produces high quality images. These results, also confirmed with the latest high-quality images as shown in the following section, aside from being important results for the advancement of THz imaging, are important for the field of IR imaging, as they provide predictions of subwavelength imaging at these wavelengths.

### B. Optics

In addition to the camera core, INO has also developed two THz objectives, one refractive and the other catadioptric. The specifications of the two objectives are listed in Table 2, and images of each are shown in Fig. 2. The refractive lens barrel is made of high-resistivity float-zone silicon (HRFZ-Si) lenses coated for anti-reflection with a Parylene layer whose thickness depends on the optimized imaging wavelength. The catadioptric lens barrel is a combination of two mirrors and one lens. The mirrors are aluminum and the lens is also HRFZ-Si coated with parylene. The 44 mm, F-0.95 refractive barrel has a focusing distance from 30 cm out to infinity, whereas for the 51 mm, F-1.07 catadioptric lens barrel, this distance ranges from 2 m to infinity. Both have been characterized and the refractive barrel has been extensively used for imaging experiments.

Table 2. Specifications of the custom refractive and catadioptric THz objectives

	Refractive	Catadioptric
Number of elements	2	3: 1 lens, 2 mirrors
Lens material	HRFZ-Si	HRFZ-Si
AR coating	Parylene	Parylene
Focal length	44 mm	51 mm
F-number	0.95	1.07
Object distance	30 cm to infinity	2 m to infinity
Dimensions	80 mm diam; 60 mm length	78 mm diam; 114 mm length



**Fig. 2.** Refractive (left) and catadioptric (right) THz objectives

*C. Sensitivity*

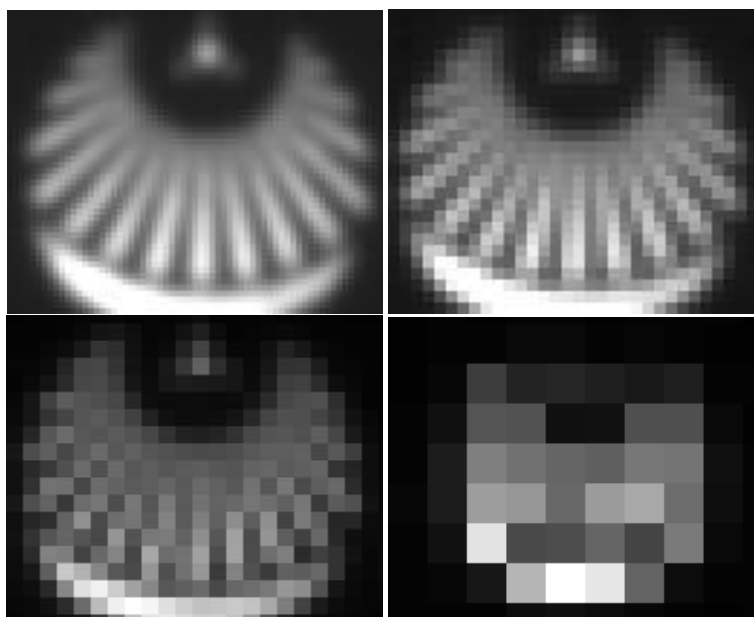
The sensitivity of the detectors was measured, using the noise equivalent power (NEP) as the figure of merit. Table 3 lists the NEP values for wavelengths 287.7  $\mu\text{m}$  and 662.82  $\mu\text{m}$  (2.54 THz, 1.04 THz and 0.45 THz, respectively). These values clearly show the high sensitivity and broadband nature of the terahertz camera.

**Table 3.** NEP values as a function of wavelength.

Wavelength [ $\mu\text{m}$ ] (Frequency [THz])	NEP [pW]
287.7 (1.04)	50
662.82 (0.45)	190

*D. Resolution*

An experimental investigation of subwavelength imaging was previously performed demonstrating that smaller pixels, even those much smaller than the imaging wavelength are advantageous [8]. Fig. 3 presents a sample of the results. The image on the top left was taken using the IRXCAM-THz-384 camera core, thus having a pixel size of 35  $\mu\text{m}$ . The three other images were created by meaning over pixels of real THz images; the top right image was created by meaning over 2 x 2 pixels of the 35  $\mu\text{m}$  pixel image to achieve a pitch of 70  $\mu\text{m}$ . The image in the bottom left was created by meaning over 2 x 2 pixels of a 52  $\mu\text{m}$  pixel image to achieve a pitch of 104  $\mu\text{m}$  and the image in the bottom right was created by meaning over 6 x 6 pixels of the 52  $\mu\text{m}$  pixel image to achieve a pitch of 312  $\mu\text{m}$ . A degradation of image interpretability with increasing pixel size is evident. As well, the larger the pixel dimension, the lower the spatial frequency cut-off with a loss of almost all object details at pixel size of 312  $\mu\text{m}$ . It is important to point out that at even at 104  $\mu\text{m}$  that is close to the imaging wavelength, that the resolution is clearly degraded.



**Fig. 3.** Image comparisons at 118  $\mu\text{m}$  of a metal chopper with the 35- $\mu\text{m}$  pixel pitch IRXCAM-THz-384 (top left) with constructed images with pixel dimensions 70  $\mu\text{m}$  (top right), 104  $\mu\text{m}$  (bottom left) and 312  $\mu\text{m}$  (bottom right).

## II REMOTE NON-DESTRUCTIVE INSPECTION

One of the advantages of imaging in the terahertz band over the infrared or visible bands is the ability to see through certain barrier materials. This important capability opens the door for a wide range of terrestrial and space applications. One important application is parcel inspection. Most of the packages sent through the mail go uninspected due to time and cost constraints. A non-invasive video-rate system could perform inspections on a conveyer belt and would not delay the mailing process.

Fig. 4 presents an example of THz see-through imaging, of a cardboard mailing envelope with a knife hidden inside. The top image is a mosaiced image taken from a video taken with the IRXCAM-THz-384 camera at 60 Hz frame rate, using a THz laser at 432  $\mu\text{m}$  wavelength. The bottom two images are visible photos showing a top view of the envelope (left) and an inside view showing the knife that is taped within the envelope (right). Note that in the THz image not only is the knife well defined with high contrast, but the pieces of tape are also clearly well resolved.

Fig. 5 presents a second example of seeing through parcels, where in this case the knife is hidden inside a bubble wrap padded envelope. In this case, the details of the bubble wrap as well as the outline of the knife are clearly defined.



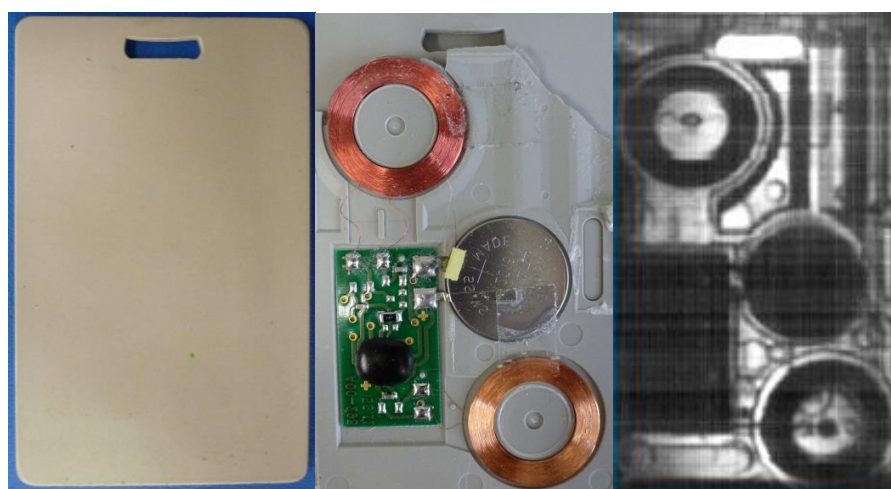
**Fig. 4.** THz mosaiced image taken at 432  $\mu\text{m}$  of a knife seen through a cardboard mailing envelope (top) and visible images showing the knife hidden inside the envelope (bottom).



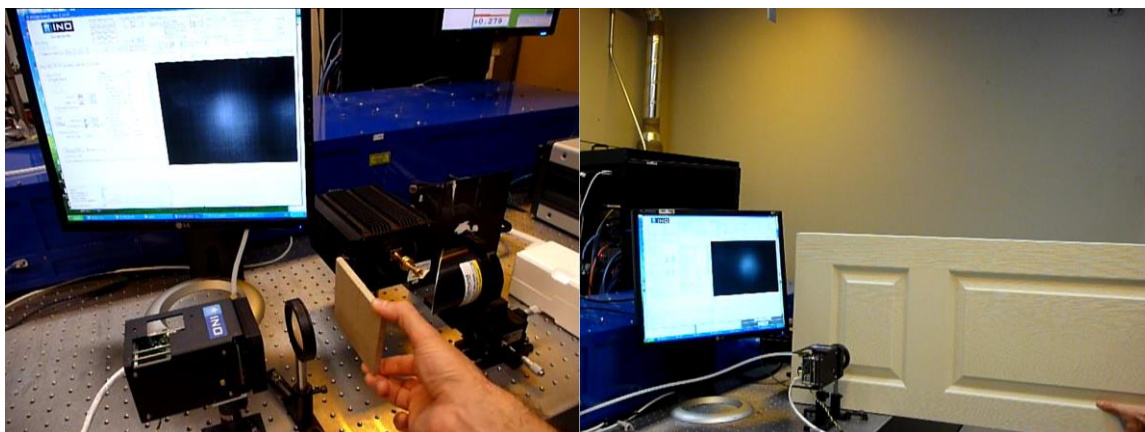
**Fig. 5.** THz mosaiced image taken at 432  $\mu\text{m}$  of a knife seen through a padded (with bubble wrap) mailing envelope (top) visible image showing the knife hidden inside the padded envelope (bottom).

Various material can be inspected with THz. Depending of the material to be inspected the choice of the wavelength will vary. For instance wavelengths around  $100\mu\text{m}$  allows to see most of the plastic made components. Inspection of parts can be thus performed with THz. This inspection will provide clues about the components composing the parts which are not seeable in the visible image. Furthermore, the thickness of the material will be related to the transmission (or opacity) of the image. Figure 6 illustrates such an example where a component made of plastic is inspected with a  $118\mu\text{m}$  wavelength source. The parts composing the card are clearly identifiable and more over the variation of the thickness of the plastic inside the card are reflected by the variation of the opacity of the image. As such important clue concerning an assembled object can be retrieved as long as the wavelength used is transmitted by the material to be inspected. Once again, on Figure 6, the resolution of the fine details is extremely good considering that the wavelength used,  $118\mu\text{m}$ , is about 3 times larger than the pixel pitch,  $35\mu\text{m}$ .

Another illustration of the sensitivity of the camera at  $2.6\text{mm}$  is provided in Figure 7. Both a ceramic tile and an empty wood door are shows transmission windows at  $2.6\text{mm}$ . This illustrate both the transmission capabilities of these materials at  $2.6\text{mm}$  but also the sensitivity of the camera. Further tests have shown sensitivity at  $3.1\text{mm}$ .



**Fig. 6.** Inspection of plastic components with the THz: the visible image (left), the interior of the component (center), the THz image of the left components. .



**Fig. 7.** Transmission experiments with various materials at a wavelength of 2.6 mm: ceramic tile (left) and wood door (right). The white spot on the computer screen corresponds to the transmitted beam captured by the camera.

### III CONCLUSIONS

The THz waveband can be useful for various space applications including dust and limb sounding. INO has developed and uncooled THz camera showing high sensitivity and resolution. Moreover, experimental imaging tests have shown the very good quality of the image, despite the size of the pixel which is much smaller than the THz wavelength. The very wideband response (up to 3.1 mm) of the detector makes it a highly interesting tool for space applications.

### IV REFERENCES

- [1] Jonny Gauvin, François Châteauneuf, Linda Marchese, Patrice Côté, Mélanie Leclerc, Claude Chevalier, Hugo Marraco, and Linh Ngo Phong, "Design of the SAC-D/NIRST Camera Module," Proc. SPIE 6678, Infrared Spaceborne Remote Sensing and Instrumentation XV, 667814, 2007.
- [2] P. de Maagt, "Terahertz Technology for Space and Earth Applications," Antennas and Propagation, EuCAP 2006, page 1-4, 2006..
- [3] Chevalier, C., Mercier, Duchesne, F., L., Gagnon, L., Tremblay, B., Terroux, M., Genereux, F., Paultre, J.-E., Provençal, F., Desroches, Y., Marchese, L., Jerominek, H., Alain, C., Bergeron, A., "Introducing a 384x288 pixel terahertz camera core," Proc. SPIE 8624, 86240F (2013).
- [4] Bergeron, A., Marchese, L., Savard, É., LeNoc, L., Bolduc, M., Terroux, M., Dufour, D., Châteauneuf, F., Jerominek, H., "Resolution capability comparison of infrared and terahertz imagers," Proc. SPIE 8188, 81880I (2011).
- [5] Bolduc, M., Terroux, M., Marchese, L., Tremblay, B., Savard, É., Doucet, M., Oulachgar, H., Alain, C., Jerominek, H., Bergeron, A., "THz imaging and radiometric measurements using a microbolometer-based camera," IEEE 6105155, 1-2 (2011).
- [6] Pope, T., Doucet, M., Dupont, F., Marchese, L., Tremblay, B., Baldenberger, G., Verreault, S., Lamontagne, F., "Uncooled detector, optics, and camera development for THz imaging," Proc. SPIE 7311, 73110L (2009)
- [7] Blanchard, N., Marchese L., Martel A., Terroux M., Savard É., Chevalier C., Mercier L., Gagnon L., Lambert J. Bolduc M. and Bergeron A., "Catadioptric optics for high-resolution terahertz imager," Proc. SPIE 8363, 83630B (2012).
- [8] A. Bergeron ; L. Marchese ; M. Bolduc ; M. Terroux ; D. Dufour ; E. Savard ; B. Tremblay ; H. Oulachgar ; M. Doucet ; L. Le Noc ; C. Alain ; H. Jerominek, " Introducing sub-wavelength pixel THz camera for the understanding of close pixel-to-wavelength imaging challenges," Proc. SPIE 8373, Micro- and Nanotechnology Sensors, Systems, and Applications IV, 83732A (May 1, 2012).