Response to reviewer 2

The reviewer's comments are in black and our answers are in red.
Modifications of the manuscript are reported in bold and italic.
The pages and lines reported here correspond to the original pdf.
New references can be found at the end of the document.

This paper describes a new far-infrared radiometer that has been built and preliminarily eployed in support of the TICFIRE satellite project of the Canadian Space Agency. This discussion paper is generally well-written and has a considerable amount of detail, including demonstration measurements that are very nice to have. It will therefore serve as a very useful resource for future development of far-infrared radiometry. However, this discussion paper would benefit from a number of relatively minor, but still necessary, changes that should be incorporated prior to publication in AMT. These changes are listed below:

We are grateful to this reviewer for the encouraging comments, and tried to add the pieces of information needed to clarify the points raised. These modifications are detailed below.

1. The spectral transmittance of the 9 filters needs to be discussed in considerably more detail. What materials were used? Was the choice of spectral response for each filter driven largely by the limitations in the materials, or were they chosen specifically for science value? If it is the former, does more work need to be done to develop exotic (or mundane) materials that can be used for these filters? Can the spectral response for each filter be modified in future versions of this radiometer? Are the spectral responses stable, or will they degrade in unknown ways either on the ground, on an aircraft, or in a space environment? I am confused by the choice of the 10-12 µm band, as this appears to be partially contaminated by O3. Also, a figure is needed for atmospheric transmission to TOA vs height per band as a function of column water vapor.

According to the reviewer, additional technical details about the filters are given below. Many details are provided here but all those details are not added to the manuscript.

Initially the instrument was supposed to host 6 filters (1, 2, 3, 6, 8, 9 of Table 1). The 6 spectral bands were chosen for their scientific value, with the intent to cover as much as possible the whole spectrum from 8 to 50 µm (excluding the CO_2 band). The width of the bands was chosen so that a sufficient and relatively constant amount of radiation lies in each band. Later on the budget of the project was increased, allowing us to buy 3 new filters. It was decided to split the band 6 in 3 different bands (4, 5 7) because it corresponds to the spectral region where the atmospheric cooling rates greatly vary with altitude (see Plate 6 of Clough et al., 1992). Increasing the spectral resolution of the FIRR in this region should provide a better vertical resolution of the retrievals.

Based on these scientific requirements the 9 filters were ordered to 4 different commercial companies (Reynard Corporation, University of Reading, Infrared Filters Solutions, QMC Instruments) used to providing filters for spatial applications (note that only few companies are able to design bandpass filters in the far-infrared, which limited our choice). The final spectral response of each filter is the result of a trade between the science value (requirement) and technological limitation. For instance, the leak at 31 µm for the band 17 – 18.5 µm (which was erroneously missing on the dicussion paper) is a limitation of the material used for the coating (Fig. 1). Getting rid of this leak would have implied a reduction of the overall transmittance of the filter, which would have been even more critical.

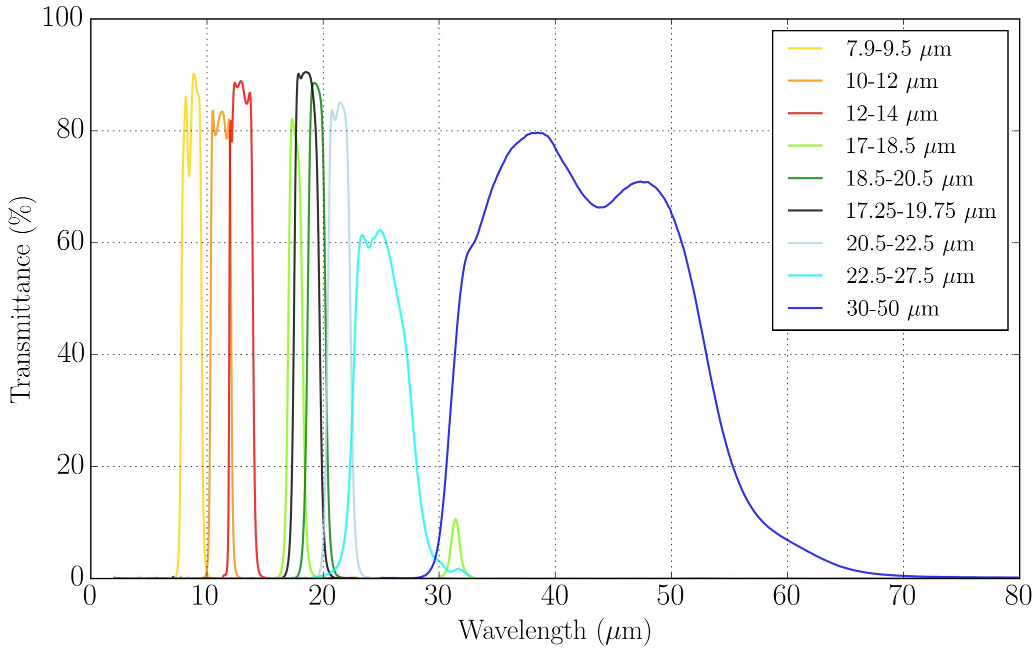

Figure 1: Spectral transmittances of FIRR filters updated with the leak at 31 µm.

The substrate for filters 1 and 2 is Zinc Sulfide.
The substrate for filters 3 is Zinc Selenide.
The substrate for filters 4, 5, 6, 7, 8 is Cadmium Telluride.
We do not know the material of the mesh filter 9, neither the coatings used for the interference filters.

The details regarding the filters suppliers and materials have been added to Table 1.

So far the Canadian Space Agency does not intend to invest much into improving the filters and prefers using existing technology. Similar filters were already used for the Mars Climate Sounder on the Mars Reconnaissance Orbiter (McCleese et al., 2007). The effort is rather put on the microbolometers sensors developed at INO, which constitute the originality of the FIRR instrument. Nevertheless, it remains possible to change the filters for the future versions of the radiometer (including that on the TICFIRE satellite) according to the results of the ongoing experiments.

The filters were delivered around December 2014 and their transmittances were measured at this time. Since then they are in the instrument and have not been characterized again. However, the measurements taken in the last year do not show any indication of filters degradation and the companies mentioned above have worked in the past on satellite projects so that we are confident about the robustness of the filters. We intend to measure the filters transmittance in the course of the summer 2016, which will provide information about their degradation.

Regarding the overlap of the FIRR bands with the 9.6 µm absorption band of ozone, we first point out that it is rather the band 7.9 – 9.5 µm that is impacted as shown in Figure 2. This overlap was initally not considered as a problem and when we actually realized that it could be one, the filter was already delivered and it was too late to order a new one. This filter will be modified for the future versions of the radiometer to avoid this overlap.

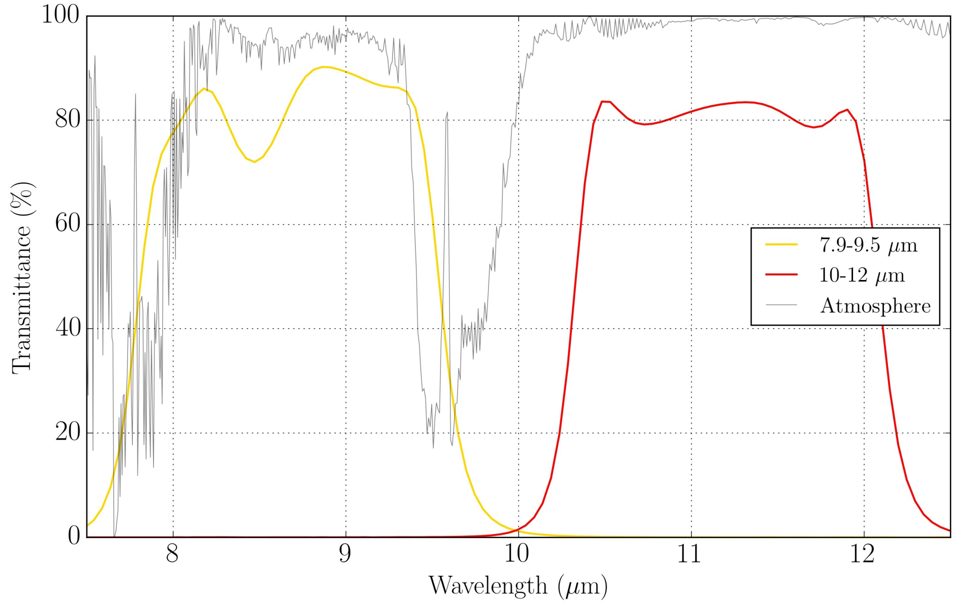

Figure 2: Transmittances of the FIRR filters 1 and 2, and atmospheric transmittance, highlighting the ozone absorption band.

As suggested, a figure showing the transmittance of the atmosphere in the FIRR bands as a function of column water vapor was added (Fig. 3).

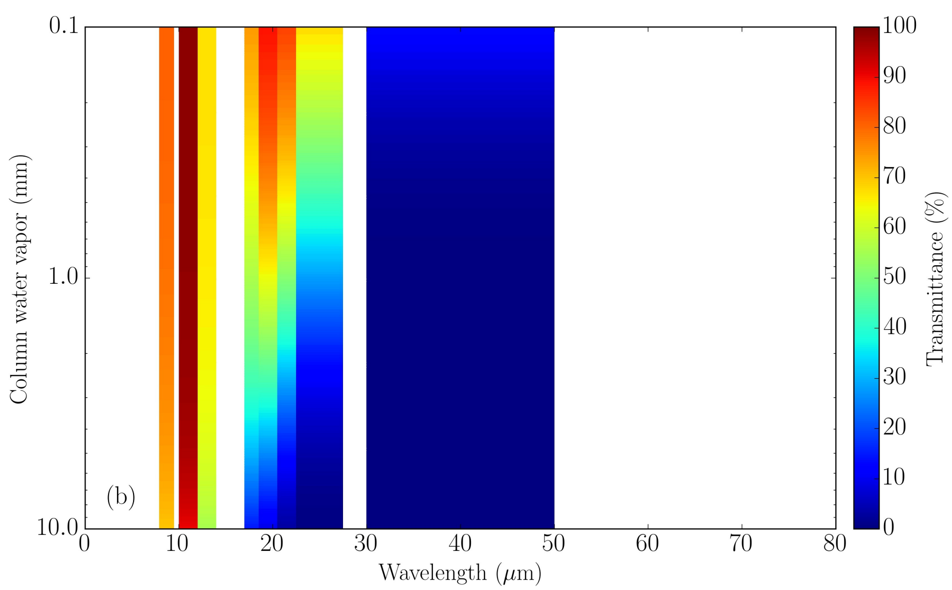

Figure 3: Atmospheric transmittance in FIRR bands as a function of column water vapor. The transmittances were computed with MODTRAN for the standard Subarctic Winter atmosphere.

According to the answers given above, the paragraph of the manuscript dedicated to the description of the filters was modified as follows (p.4, l.99):

“The motorized filter wheel is used to select the spectral channel to be measured. It currently hosts 9 1.25-inch diameter filters, as well as an opaque position and an open position, ***the last two positions being essentially used to investigate the thermal behavior of the filters and calibration enclosure***. Six more positions are available on the wheel but currently unused. All filters are interference filters except for the 30-50 μm filter that is a mesh filter. ***These filters were custom made by four different companies experienced in satellite applications (e.g. McCleese et al., 2007)***. ***Their spectral characteristics is the result of a trade between the user's requirements and technological limitations. The objective was to cover as much as possible the spectral range from 8 to 50 μm, while ensuring that a sufficient amount of radiation lies in each band.*** The transmittances of all filters were measured in the laboratory and are shown in Fig. 2a. Their spectral characteristics***, the materials used for the substrate of the interference filters and the suppliers references*** are summarized in Table~\ref{filters_table}. The narrow field of view of the FIRR ensures near-normal incidence on the filters which is beneficial to the angular uniformity of the transmittance. ***In order to illustrate the sensitivity of FIRR spectral bands to water wapor, Fig. 2b shows the transmittance of the atmosphere in those bands as a function of column water vapor.***”

2. It was not made clear to this reviewer if the plan is for the instrument, as described here, to be flown in TICFIRE, or if this is just a stepping-stone to the instrument that will be flown in TICFIRE. Is the idea to demonstrate this capability on a breadboard and then build something identical that is space-qualified? Are the components of the radiometer described here space-qualified, or is additional technology demonstration required?

The FIRR represents only a first step towards the TICFIRE mission. It was developed for ground and airborne measurements, and designed according to the constraints imposed by such kind of operation. The primary objective of the FIRR is to demonstrate the capability of the technology (filters + gold black coating + microbolometers) to sense far infrared radiation with a resolution sufficient to extract physical information about the state of the atmosphere. In itself it already provides new radaition measurements in the far-infrared, a largely underexplored region of the Earth spectrum. However, there is still much development required to meet the satellite requirements. This is currently discussed at the Canadian Space Agency with the industrial partners.

Many hints have been added along the text to insist that FIRR and TICFIRE instruments are different:

p.1, l.1:
“A far infrared radiometer (FIRR) dedicated to measure radiation emitted by clear and cloudy atmospheres was developed ~~as a breadboard for~~ ***in the framework of*** the Thin Ice Clouds in Far InfraRed Experiment (TICFIRE) ***technology demonstration*** satellite project.”

p3. l.69:
“Here we present the far infrared radiometer (FIRR) prototype designed to measure radiation in 9 spectral bands ranging from 8 to 50 μm. ***The FIRR is aimed at demonstrating the capability of a microbolometer-based radiometer to accurately measure F-IR radiation***. The design and data acquisition procedure [...]”

p.8, l.237:
“***Contrary to TICFIRE that will have a much larger field of view and significantly different optics***, the FIRR is not intended to be used as an imager. ***Hence*** the calibrated radiances are averaged [...]”

p.15, l.482:
“As the TICFIRE is meant to be an imager, spatial averaging will be limited. ***In addition, since the optics and detectors of TICFIRE will be different than those of the FIRR, it is hazardous to apply FIRR radiometric characteristics to TICFIRE. However, it has been shown that spatial averaging over a reduced number of pixels, as well as temporal averaging, could improve TICFIRE radiometric performances.*** All in all, a ***trade*** will have to be made [...]”.

p.16, l.515:
“These preliminary results nevertheless represent a substantial step toward the TICFIRE mission, ***whose design is currently discussed with industrial partners at the Canadian Space Agency.”***

3. Can the change in emissivity of the blackbodies over time be estimated? Can this change be estimated on orbit? Is it important, or are there a large number of internal reflections so it doesn’t really matter?

First, the details about the cavity effect of the blackbodies can be found at https://www.ssec.wisc.edu/gifts/blackbody/posters/calcon2003/calcon2003-best-aeri-traceability.pdf. Due to multiple internal reflections, a change of emissivity of the BB internal surface results in a change of emissivity of the BB approximately 13 times less, so that siginificant changes in BB emissivity are not expected unless excessive surface emissivity changes are experienced.

Regarding the FIRR, it is planned to check the emissivity stability after one year of operation in laboratory, once the instrument is brought back from Eureka (NU) where it is currently installed. The temperature sensors should also be validated after one year of operation, because they are as important as the emissivity for the calibration procedure.

Concerning the on orbit calibration, it has so far not be considered in details for the satellite project. Procedures have been proposed in the past for other satellite projects (e.g. Latvakoski et al., 2010 for CLARREO) and could be further investigated. However, as a Tech Demo satellite, TICFIRE is not intended to acquire data for decades, but rather for a couple of years. The easiest solution is probably to account for a potential change in blackbodies calibration in the overall uncertainty budget. It would still be possible to estimate a posteriori the actual change in emissivity and sensitivity of the temperature sensors. The on orbit calibration of the blackbodies is thus beyond the scope of this paper and only that of the FIRR is now detailed:

p.4, l.97:
“It can not be set at a temperature below the ambient temperature, though, because the BBs can only be heated. ***Potential deterioration of the calibration unit will be investigated based on a yearly check up of the BBs emissivity and temperature sensors.”***

4. What is meant by scene temperature for Figure 6? For an observation where each filter is giving a different brightness temperature reading, should the reader expect to use Figure 6 as an estimate of each filter’s NETD based on that filter’s brightness temperature?

The caption was actually misleading. The scene temperature is in fact the actual temperature of the blackbody. So yes, Figure 6 gives an estimate of the filter's NETD based on that filter's brightness temperature. It was specified in the caption so that it is now consistent with the main body of the text:
“Noise equivalent temperature difference (NETD) corresponding to a noise equivalent radiance (NER) of 0.01 W m^{-2} sr^{-1}, as a function of ***blackbody*** temperature for all spectral bands of the FIRR.”

5. The authors should comment on whether TICFIRE will be able to see the effects of surface processes on dehydrated conditions? Recent publications (e.g., Chen et al, GRL, 2014 and Feldman et al, PNAS, 2014) have highlighted the large differences in far-IR surface emissivity between frozen and unfrozen surfaces, with large scientific implications for polar feedbacks. Would any of the filters be able to reliably detect a signal arising from a difference in far-IR surface emissivity of 0.1? of 0.2?

In very dry conditions (PWV < 1 mm), the atmospheric transmittance reaches 50% in most bands of the FIRR (Fig. 3 of this comment). This means that the radiation measurements are very sensitive to the surface temperature and emissivity.

More quantitatively, a change of 0.1 in surface emissivity at a temperature of -30°C results in a change of emitted radiation in single FIRR bands of 0.3 - 0.7 W m^{-2} sr^{-1} depending on the band. Assuming a transmittance of 50%, this means a signal variation larger than 0.1 W m^{-2} sr^{-1} which is definitely detectable by the FIRR (accuracy ~ 0.02 W m^{-2} sr^{-1}). The other way, we estimate that the FIRR should be able to detect a change in surface emissivity of 0.02, all other things being equal. However, for FIRR data to be useful to detect changes in surface emissivity, the surface temperature should be well constrained. In view of comparisons, at -30°C a change of emissivity of 0.02 is roughtly equivalent to a change of surface temperature of 1K.

A short paragraph has been added to the discussion of the paper to detail this point.

p.16, l.509:
"***In an airborne or satellite configuration, downward looking FIRR measurements would also be very sensitive to the surface emissivity and temperature, especially in dry regions where atmospheric transmittance exceeds 50% in most spectral bands (Fig.2b). FIRR measurements could help filling a gap in the spectral characterization of Earth surfaces emissivities, which are so far poorly constrained by observations in the F-IR (Feldman et al., 2014). This could also improve climate simulations in the polar regions, which are known to be sensitive to snow surface emissivity (Chen et al., 2014). Practically, for a snow surface at -30°C, a change of emissivity of 0.02 would result in a change of radiance at the top of atmosphere larger than the FIRR radiometric resolution for most FIRR bands, highlighting the potential of the instrument for such an application.***"

Additional changes:

As mentioined above, a small leak in the 17 – 18.5 µm band had not been accounted for in the discussion paper. Figure 2 showing the transmittances has been updated and all figures including measurements in this band have been redrawn. This did not imply any modification of the manuscript except some minor changes in the quantitative analysis of Section 3.2.

References

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