Conceptualisation and Design of a "Mesoscale Radiometer"

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ABSTRACT

Where we describe the development and functionality of a new type of instrument, a mesoscale radiometer, designed to obtain crude but much needed measurements of fields of temperature and humidity over mesoscale areas around the instrument.

1. DECLARATION OF INTENT

Whereas the meteorological research community wishes to measure or at least constrain better fields of humidity and temperature for storm studies.

Whereas the operational weather community wishes to better predict storms, a task that requires improved constraints on the initial conditions of thermodynamic variables.

Whereas studies focusing on mesoscale events have shown that lack of knowledge of midlevel moisture limits the most the accuracy of weather forecasts [1] and that lack of knowledge of temperature fields limits the most convection initiation forecasts [2].

Whereas technology exists to measure winds and precipitation over large areas but is lagging behind for temperature and humidity, except for satellite-borne sensors that do not provide, *in fine*, data with the necessary temporal resolution in cloudy environments.

Whereas 3-D fields of thermodynamic parameters are required to advance mesoscale meteorology research, making simple ground-based profiling instruments insufficient for the task.

Whereas the operational and research communities have been looking for [3] and demanding [4] new approaches to obtain better humidity measurements at all scales for many years.

Whereas, *prima facie*, there did not appear to have been significant technological developments undertaken to fill this gap in our observing system capabilities at the time this project was instigated.

It was hereby resolved to develop of a new type of ground-based sensor that would attempt to measure the said humidity and temperature fields over mesoscale areas. This is its story.

2. APPROACH CONSIDERATIONS

If one decides to design an instrument to make thermodynamic measurements at the mesoscale, one is rapidly faced with a few physical and technical constraints:

1. Dwell time is limited. If one wants to measure fields of temperature and humidity at the mesoscale, the instrument must sample the region in an appropriately short time. A full volume scan of the atmosphere, say with several elevation angles, must therefore be completed in the order of 15 min or less, limiting the dwell time in any (azimuth, elevation) direction to much less than 1 s.
2. Active acoustic sensing is too slow for mesoscale distances, and passive sensing of acoustic waves and of electric, magnetic, and gravity fields did not seem to hold much potential for sensors on a ground-based platform. This leaves only EM waves. That being written, we may easily be wrong here; this issue should therefore be revisited before we completely abandon more unusual avenues.
3. If EM waves are used, they must include microwaves: since measurements must be taken by sampling the atmosphere over paths many tens of kilometres long, the wavelength(s) chosen must be in an electromagnetic region where the aerosol-loaded and occasionally cloudy atmosphere is relatively transparent. Yet, at the same time, the atmosphere must cause changes in one or more EM properties (velocity/delay, emission, or scattering) as temperature and/or humidity changes. These seemingly contradictory constraints made us focus our attention on the peak and both tails of the 22 GHz water vapour band.
4. With long sampling paths, the instrument's beam width must therefore be narrow and ideally similar at all wavelengths of operation. Given this and the previous constraints, the instrument should visually look like a radar, with a large antenna on a scanning pedestal.

Two different approaches met the constraints: a triple- or quadruple-frequency radar operating at K-band, making differential attenuation measurements where targets from insects to precipitation are available; and a narrow-beam multi-frequency radiometer operating also K-band. Budget considerations made us go for the second option because the first author could not add another zero to his request for funding. For reasons that should now be clear, we started calling this instrument a “mesoscale radiometer”.

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3. RADIOMETRY AT LOW ELEVATION ANGLES

Traditionally, microwave radiometry has been used to make satellite-borne or ground-based measurements of the vertical profiles of temperature and humidity. To achieve this, measurements must be made at high microwave frequencies that are unfortunately affected strongly by precipitation and often even ice clouds. Lower frequencies that would not suffer as much from this limitation cannot be used very well because the precipitation-free atmosphere is not opaque or thick enough to isolate the information coming from different distances from the sensor. For example, the peak of the 22 GHz water vapor band has an optical thickness τ of the order of 0.2. Hence, radiometers working at that frequency typically only measure vertically integrated quantities such as precipitable water and the integrated liquid water content. But what would happen if the same microwave radiometer would make measurements at very low elevation angles, such as 1° or 2°? Suddenly, the weak 22 GHz line becomes extremely bright and opaque; one can hence imagine that a multi-frequency "sounding" approach could be used to make measurements at different ranges. Such a radiometer might be able to obtain mesoscale measurements of humidity.

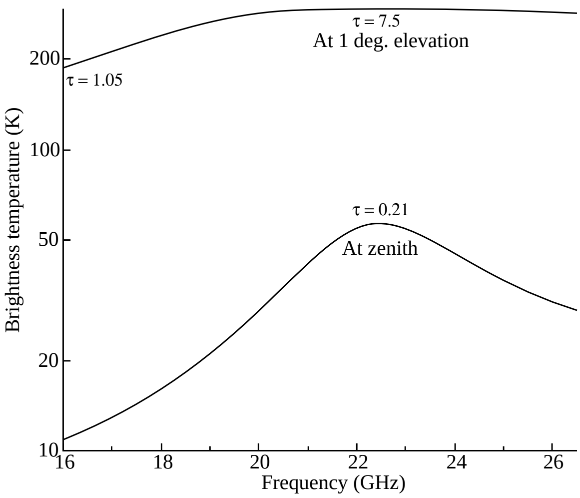

Fig. 1: Brightness temperature as a function of frequency for a cloud-free atmosphere typical of summer conditions (22°C surface temperature and 30 kg/m2 of precipitable water) for a ground-based radiometer pointing at zenith (lower curve) and 1° elevation (upper curve). The optical paths τ at the frequencies of minimum and maximum attenuation are also indicated.

Figure 1 shows simulated brightness temperature around the 22 GHz water vapour line for typical summer conditions. This quick test allows us to make a couple of interesting observations:

1. In the range between 16 and 27 GHz, where a single type of waveguide can be used, one can "see" a large range of optical thicknesses. This means that information from a variety of ranges can be isolated: For example, at 22.25 GHz, 80% of the signal comes from within 25 km (and below 0.5 km altitude), while at 16 GHz, it is 30%. In comparison, at vertical incidence, the fraction of the power originating from below 0.5 km accounts for 17% and 18% of the total signal at 22.25 and 16 GHz respectively.
2. The region of interest for measurement shifts towards the lower frequency half of the water vapour band, while vertically-pointing radiometers tend to focus on the higher frequency half because of its increased optical thickness. Indeed, at low elevation angles, we tend to have too high an optical thickness around 22 GHz instead of the opposite as is the case at vertical incidence. The search for τ of the order of 1, where the best constraints on humidity can be obtained, hence pushed us towards using lower frequencies, much more than is usually the case for K-band radiometers. Added benefits include greater availability of low cost components, and greater immunity to contamination by ice clouds and precipitation, at the expense of greater interference by other man-made transmitters. Mesoscale radiometers could be built with a reasonable budget.
3. At low elevations, the signal saturates at the peak of the water vapour band as the atmosphere becomes a near-blackbody. The brightness temperature hence tends towards the real temperature of the atmosphere. This in turn means that there is some temperature information that could be retrieved from such a system. The information may just be limited to a "mean boundary layer temperature" in the direction pointed by the antenna, but the possibility exists, and should be explored.
4. Finally, the large signal implies that, except near saturation, accurate estimates of the optical thickness can be made in short times. For example, if we collect data at one frequency over a period long enough to achieve 1°K error in brightness temperatures (of the order of 0.1 s, but strongly dependant on the hardware), we can estimate τ to better than 1%; similar accuracy would require at least 10 times longer at vertical incidence. This short dwell time opens the possibility for radiometers scanning at low elevations to scan the atmosphere in a manner and a sampling time comparable with that of research radars.

All that being said, there are shortcomings to making radiometric measurements so close to the horizon. These include the need for a very narrow and identical beam width at all wavelengths. Even then, contamination by the ground and by the very different signals coming from the top compared to the bottom of the beam cannot be ignored. In addition, such a large antenna makes the design and use of an external reference target extremely cumbersome. Nevertheless, this approach looked too promising to ignore, especially given the limited alternatives. Therefore, we undertook to build and test a prototype mesoscale radiometer and to evaluate its usefulness for weather research.

4. THE PROTOTYPE

Because of the need to make measurements at many pointing angles in a short time, data collection speed was an obsession in this project. The design chosen reflects that obsession as well as our experience that is much stronger on radar than on radiometry.

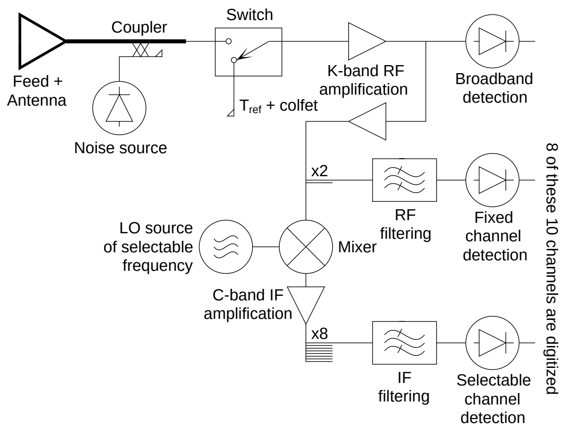

Fig. 2: Radiometer schematic diagram.

Figure 2 illustrates the microwave schematic diagram of the radiometer while Fig. 3 shows a picture of the unit in the field. On the microwave side, the mesoscale radiometer is similar to a traditional multi-channel radiometer. Differences include a 1-m diameter offset-fed parabolic reflector as the antenna, the lack of a true external blackbody reference target, the replacement of the passive “cold” reference with a colfet source [5] that acts as a cold reference when unpowered and an even colder reference when powered, and a fast-switching (1 µs) digititally tuned oscillator as the LO source. Microwave emission data are collected in nine parallel channels. There is some flexibility in the design for the selection of the frequency for each channel. There are three types of channels to choose from to make the up the nine data channels:

- Up to two fixed channels that can be chosen at any of three frequencies: 19.75, 22.5, 26.5 GHz;
- Up to eight dynamically selectable frequencies that can span from 16.2 to 26.2 GHz;
- One fixed broadband channel, covering the whole range from 16 to 27 GHz.

A commonly-used configuration consists of two fixed channels (22.5 and 26.5 GHz), six selectable frequencies (f_{IF}+4.2, f_{IF}+5, f_{IF}+5.8, f_{IF}+6.6, f_{IF}+7.4, and f_{IF}+8.2 GHz, with f_{IF} selectable from 12 to 18 GHz), and the broadband channel. Reconfiguration of the type of channels used can be made in a few hours by changing connections and microwave filters depending on the focus of the experiment or of the day (high-elevation profiling-like work, low-elevation mesoscale work, cloud studies, etc).

The temperature of most microwave components are monitored by thermistors and regulated by a thermoelectric cooler and heating resistors that are under computer control. The microwave components are enclosed in a box that also houses the electronics and the computer and whose air temperature is also regulated by a second thermoelectric cooler. The instrument is carried by a small radar pedestal.

Fig. 3: The prototype of the mesoscale radiometer.

Figure 3 shows the prototype of the mesoscale radiometer in June 2009.

5. SCANNING STRATEGIES

Two different types of scanning strategies must be considered: which sequence of frequencies and microwave sources must be used, and how to scan the antenna in elevation and azimuth. Both are related and depend on the meteorological conditions and on the type of measurements one is interested in obtaining.

5.1 Frequency selection strategies

Even though the novelty of the instrument resides in its ability to make measurements at low elevations, a fair bit of the time is spent making measurements at high (>10°) elevations, either for cloud work, as part of soundings in both low and high τ, or for calibration scans such as tipcals. Under such circumstances, emphasis should be put either on the higher frequencies for science measurements, or on all frequencies for calibration measurements. At very low elevations, measurements made on the high frequency tail of the water vapour band add little because of the near-saturation of the signal, and the emphasis should shift towards the low frequency tail of the water vapour band.

Until now though, we have chosen not to optimize the frequency scanning dynamically and have been collecting data at 26 frequencies spanning from 16.2 to 26.5 GHz, as well as from the broadband channel. We have found the broadband channel extremely useful as an overall data quality indicator, as it is extremely effective at picking up contaminations by interfering transmitters as well as serving as an indicator of data quality thanks to its extremely wide bandwidth. We are just beginning to investigate the science value of such a measurement. As for the 26 data channels, the 2 fixed channels at 22.5 and 26.5 GHz with a 800 MHz bandwidth and the 24 selectable channels chosen with a 200 MHz bandwidth, their large number is initially justified by the fact that we are exploring which frequencies provide the most information given the many elevation angles and weather situations the instrument may encounter and given the increasingly noisy environment at K-band due to other transmitters.

5.2 Angle scanning strategies

The scanning strategy in azimuth and elevation of a mesoscale radiometer is probably subject to more variations than the scanning strategy in frequency. One of the challenges is to be able to go as close to the horizon without being contaminated by ground emissions. At a new site, the best way to achieve this is by doing scans in elevation, which allow you to spot elevations contaminated by ground emissions. Once experience is garnered however, scans in azimuth remain a more efficient way to collect data. The lower the elevation angle is, the longer the path length over which measurements are taken. Measurements over these longer path lengths will both be of higher quality (smaller relative error in the estimate of τ at most frequencies at the optically thin K-band; Fig. 4) and constrain temperature and humidity over a larger area at the same time, making the collected data more valuable meteorologically. For weather surveillance at the mesoscale, a set of low elevation PPIs with occasional calibration scans may be the best approach. For other types of studies (clouds, boundary layer work), higher elevation scans may be more warranted, though the relative accuracy in τ is reduced.

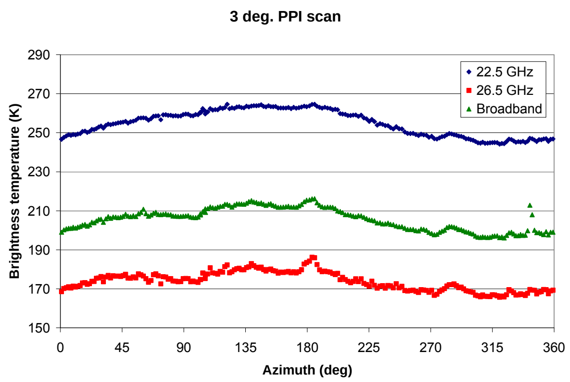

Fig. 4: Brightness temperature against azimuth for a 3° elevation PPI collected on 19 August 2009 south of Montreal in 2.5 minutes. The plot clearly suggests the presence of a north-south gradient in moisture. The peak in the broadband data at 345° azimuth is due to two towers transmitting around 23.5 GHz.

Given the limited range resolution afforded by the radiometric inversion process, the sampling region becomes very elongated in range. Data assimilation systems may be able to take advantage of such data. For human consumption however, it might be best to decrease the azimuthal resolution to something of the order of 5-10° without much loss. Here too, only experience will tell.

6. CONCLUSION

We have developed a variation on the radiometer that allows us to probe the mesoscale. It has been a bumpy ride, and we are just beginning to evaluate its capabilities. But the unique information such an instrument could provide makes it too interesting for us to ignore.

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