Atmospheric Profiles in a Minute – Passive Microwave Radiometers Deliver Upper Air Data with un-matched temporal resolution and 24/7 all-weather operations.

1 Introduction: The old ways…

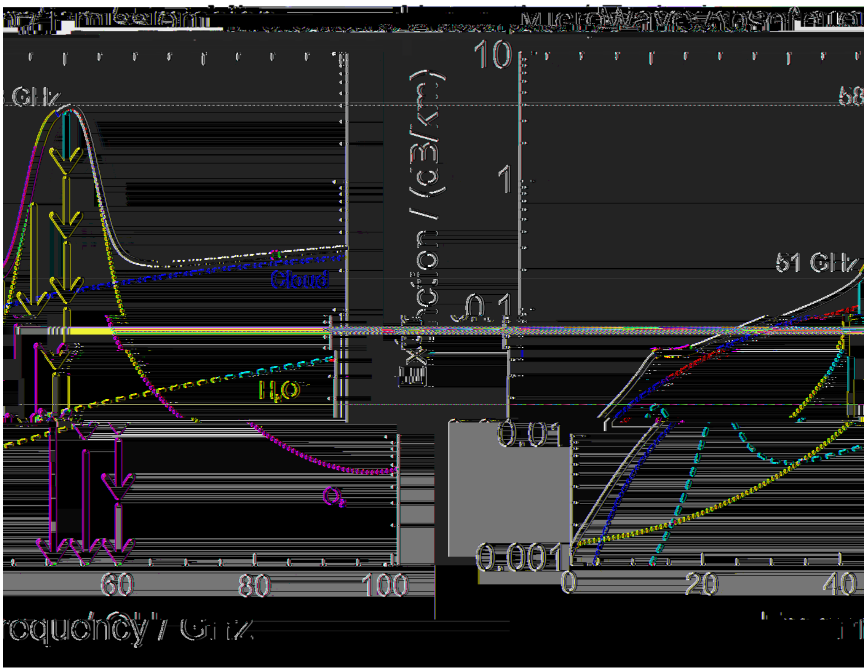
Upper-air measurements by radio soundings is a standard procedure at most weather services around the world. Important information on the troposphere's vertical profiles of temperature and humidity is obtained (usually) twice a day, serving a variety of purposes. The input is uses in data assimilation schemes of the numerical weather prediction models, but also for localized scale forecasting and now-casting, aviation weather, and climatological records.

However, this method bears some disadvantages. Apart from the usual problems of drift in lateral directions and the long time that is need for a full ascent to tropopause (and beyond), there is the time sampling (00 and 12 UTC at most stations), cost, and sensor accuracies: Humidity sensor are known to have bias problems, and total black-outs due to sensor-icing while passing through a cloud. Such profiles will most likely never make it into any data processing chain because they will be rejected as grossly inconsistent, and as such are done in vain. The cost of the sounding stations is not only driven by the balloons, gas filling, and the sonde itself, but also by the labour costs of the operator (or the automatic station, if present).

The most severe limitation, however, is the 12-hourly sampling rate. Frontal passages will most likely be missed, daily trends with sun rise and typical phenomena related to diurnal variations cannot be observed. Incorporating such trends into NWP models in a timely manner should be valuable information.

2 How do Microwave Sounding Radiometers work?

Microwave radiometers (MWR) are passive receivers which measure the total power received in a number of channels. These channels usually have different (center) frequencies and bandwidth. The radiation received is originating from the earth's atmosphere itself. It is thermal emission according to Planck's radiation law, just like infrared (IR) radiation. The notable difference is that the wavelength is not like IR (several µm), but in the cm range (14mm to 5mm), which belongs to frequencies of 22 GHz to 60 GHz.



The atmosphere is emitting in this microwave spectrum according **to Figure 1**. The gaseous constituents (water vapour, oxygen, nitrogen) is only capable of emission in discrete spectral lines at very specific frequencies, while liquid contributions (cloud water, rain) is having an emission at all frequencies of the spectrum. Different atmospheric conditions (temperature profile, humidity profile, clouds) will lead to different contributions, which are all received together. Still, there is a kind of "fingerprint" of an atmospheric state in the way the multi-channel signature would be impacted.

By a careful selection of channel frequencies, the microwave radiometers can gather information on the composition of the atmosphere. For temperature profiling, for example, as set of channels along the lower wing of the Oxygen absorption line complex is used. At 51 GHz, there is moderate absorption, which results in a total absorption of 2 to 3 dB for a full path through the atmosphere, from bottom to top. A (hypothetical) signal that would be emitted at the surface would be attenuated by 3dB on it's way up to the top of the atmosphere, meaning that half the signal would be absorbed.
In contrast, at 58 GHz (which is in the center of the oxygen absorption line, the absorption is much higher (in the order of a hundred dB). The same hypothetical signal emitted at the surface would now be absorbed much faster on it's way up. At 1km height, there would be less than 10% of the signal left, and next to nothing would reach the tropopause.

Thinking now in terms of radiation which is emitted from oxygen molecules in the atmosphere, it is obvious that the emission from higher levels of the atmosphere can still be received by the microwave radiometer at 51 GHz, but not at 58 GHz. Given the high opacity in this channel, the instrument receives radiation only from low layers.

With several channels of varying opacity in between, there is a staggered depth of looking into the atmosphere. Since the concentration of oxygen is well known and quite constant, this information can now be used to find out about the vertical distribution of temperature.

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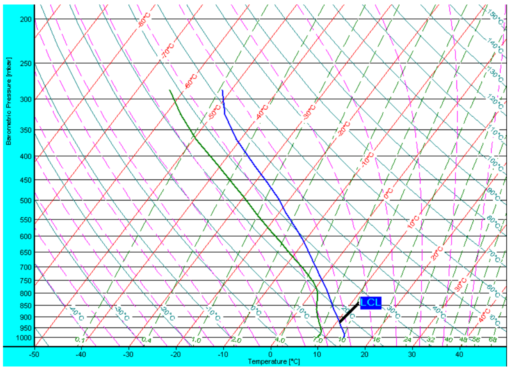
In a similar approach, the absorption line of the water vapour molecule at 22.235 GHz can be used to asses the mixing ratio of the water vapour, giving a humidity profile. Cloud water is also detectable by inspecting frequencies which are either in or out of the water vapour line, this discriminating the influence on such channels by either liquid water or the gaseous form of water vapour. Mathematical retrieval procedure are used to invert this (usually ill-posed) information problem.

The technology is not exactly new now, and has been used since more than 30 years. In fact, most of the polar orbiter satellites that can be seen as the back-bone of information supply to NWP models, have microwave sounding instruments (for temperature and humidity) as well as microwave imaging instruments (cloud water and rain).

3 Benefit

For the operational groundbased networks, the technology had to become cheaper, more robust, more mature. These points have been met in the past years, and today's instruments can deliver reliable information in a minute by minute fashion, continuously, all around the year, in all weather conditions

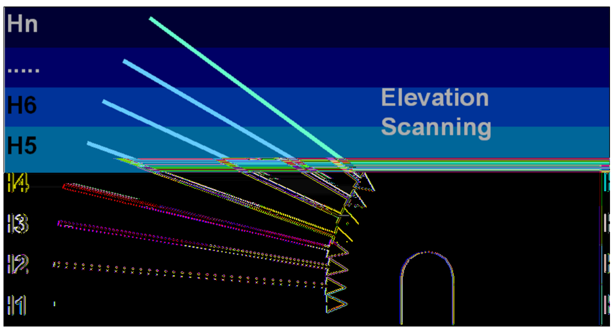


While radio soundings would miss the passage of a frontal system at 5 UTC, for example, the radiometer would give detailed and timely accurate data that shows the changes that happen to the temperature profile. Data assimilation schemes could fill the gap in between radio sonde launches. Rapid updates of the data sets are possible now, trends and tendencies can be analysed for nowcasting purposes.

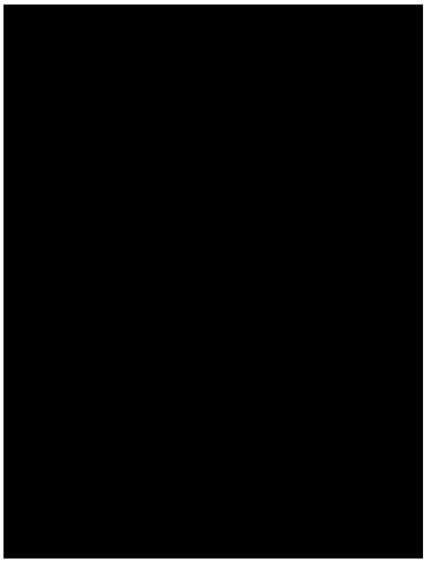
The strongest gain when using microwave radiometers is in the lowest levels of the atmosphere, especially the boundary layer. In the mid-level and upper atmosphere, there is data from satellite sounding instruments, but these instruments have their limits: Close to the surface, the satellite sounders go blind since there is no chance to discriminate between radiation originating from the lowest atmospheric layers and radiation from the surface itself. Microwave radiometers are complementing this view from above in a perfect way: The maximum information content is in the lowest layers, where also most of the energy transfer into the atmosphere is taking place by solar heating.

4 Advanced Technology

Modern microwave radiometers offer a special approach to increase the temperature sounding even further and beyond the standard multi-channel observations. Using a channel of very high opacity (and this very limited "reach", or penetration depth) like, for example 58 GHz, the radiometer can perform elevation scans **(Figure 3)**, ranging from close to horizontal views up to vertical (zenith) pointing. At the smallest elevation angles, the radiation is only originating from the lowest level of the atmosphere and thus giving a temperature information of only this layer. Scanning to the next elevation, the beam is intersection more layers (but still has a limited reach), so the temperature is a mixture of two layer temperatures. With the first temperature

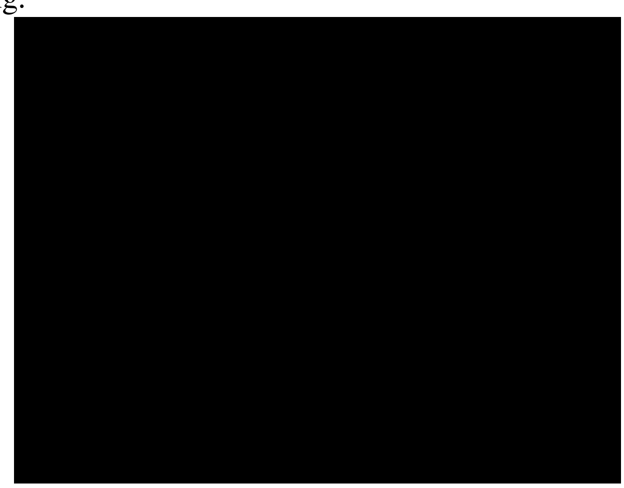


known from the previous scan, the mixture can be decomposed and the temperature of the second layer can be estimated.



This iterative procedure allows for high-precision and high resolution temperature profiling. Validation experiments have shown that the remote sensed temperature profile from the radiometers compares better to observations of meteorological towers (100m and 200m high) than radio soundings launched directly at the tower. The vertical resolution is around 50 meters and capable of precisely resolving inversions on a scale of less than 100 meters.

During such an observation, the observed brightness temperature changes only in a range of 1 % (e.g., from 300K to 303 K). The preconditions to do such high-precision boundary layer profiling therefore are (1) a very sensitive system with low noise, and (b) a narrow beam. The radiometers of RPG radiometer Physics, for example, have two-degree beam width at the considered frequency, allowing scans down to 5° over the horizon. Smaller instruments have larger beams (optical laws!) and cannot scans as low, rendering the whole scanning procedure less useful in the beginning.



In addition, RPG radiometers use parallel direct detection of all channels in the system, thus allowing individual band-passes for all channels, which enables a 10-times wider bandpass at 58 GHz than at 51 GHz (where very narrow channels are required), thus increasing the received power and minimizing the noise. Increasing the integration time then to 20s on each angle and using 4 instead of only one frequency, adds further precision and information content to the method, but also emphasize the need to have parallel data acquisition in all radiometer channels in order to utilize this approach.

5 Proven and mature

The RPG radiometers are deployed world wide in different climate conditions: Arctic and tropical regions (-45°C to +50°C), high mountains (Atacama desert, 5.500m asl), strong wind speeds (up to 250 km/h on Zugspitze mountain, 2.600m asl), snow, ice, rain, sea spray (Lampedusa island, Mediterranean sea) and even on Oceanic research vessel Polarstern, cruising the Atlantic Ocean.

In addition to environmental hardening, the software has also been adapted to meet today's user needs in terms of quality flagging, data black/white-listing and status information of instrument hardware-sanity.

As a bottom line, a decade of research and technology development has lead to a mature technology that is ready to be deployed for worldwide operational networks.