by Harald Czekala

CHANGING FREQUENCY

Providing atmospheric profiles in a minute

Passive microwave radiometers deliver upper-air data with unmatched temporal resolution and all-weather operations, 24 hours a day, 7 days a week

Upper-air measurements by radio soundings are 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 used in data assimilation schemes of the numerical weather prediction models, but also for localized scale forecasting and now-casting, aviation weather, and climatological records.

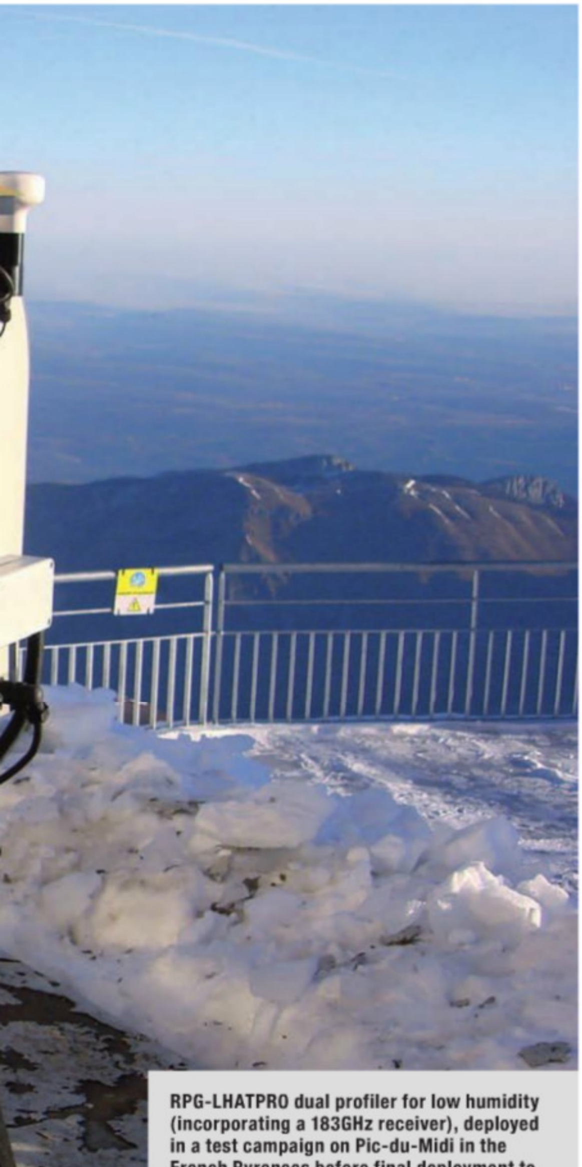
However, this method has some disadvantages. As well as the usual problems of drift in lateral directions and the long time that is needed for a full ascent to tropopause (and beyond), there is the time sampling (24:00 and 12:00 UTC at most stations), cost, and sensor accuracies. Humidity sensors are known to have bias problems and total blackouts 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 labor costs of the operator (or the automatic station, if present).

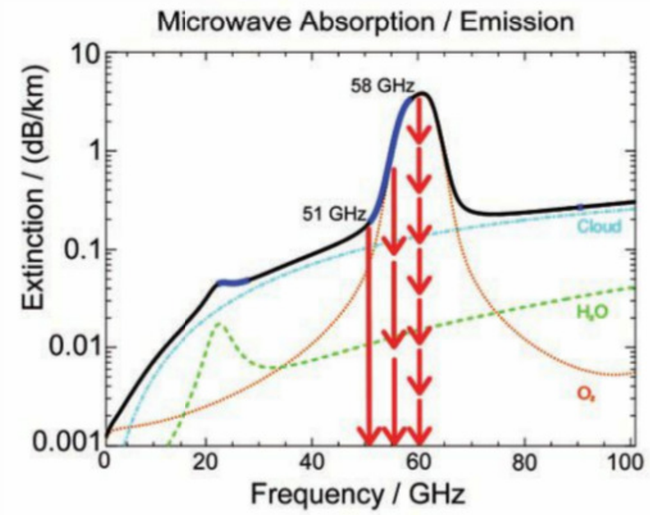
The most severe limitation, however, is the 12-hourly sampling rate. Frontal passages will most likely be missed, daily trends with sunrise and typical phenomena related to diurnal variations cannot be observed. Incorporating such trends into NWP models in a timely manner should be valuable information.

How do microwave sounding radiometers work?

Microwave radiometers (MWR) are passive receivers that measure the total power received in a number of channels. These channels usually have different (center) frequencies and bandwidth. The radiation

"Modern microwave radiometers offer a special approach to increase the temperature sounding even further"


RPG-LHATPRO dual profiler for low humidity (incorporating a 183GHz receiver), deployed in a test campaign on Pic-du-Midi in the French Pyrenees before final deployment to Dome C in Antarctica



Absorption spectrum in the microwave region with contribution from gases (emission in spectral lines, water vapor: green; oxygen: orange) and from liquid water drops (continuum emission with spectral dependence, blue line)

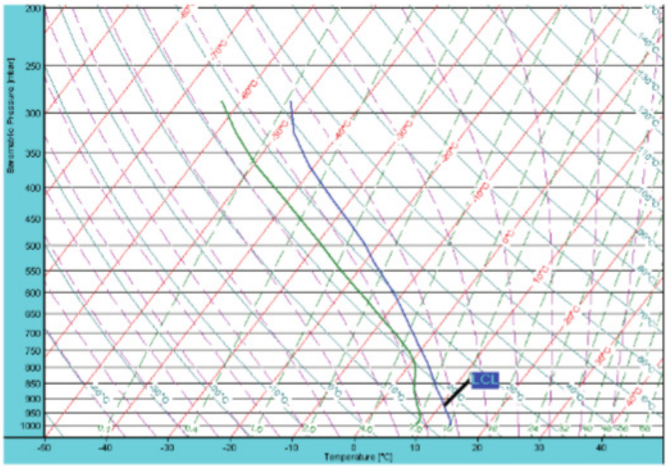
received is originating from the earth's atmosphere itself. It is thermal emission according to Planck's radiation law, just like infrared (IR) radiation. The notable difference is that the wavelength is not like IR (several µm), but in the centimeter range (14-5mm), belonging to frequencies of 22-60GHz.

The atmosphere emits in this microwave spectrum as shown in the figure above. The gaseous constituents (water vapor, oxygen, nitrogen) are capable of emissions only in discrete spectral lines at very specific frequencies, while liquid contributions (cloud water, rain) have an emission within all frequencies of the spectrum. Different atmospheric conditions (temperature profile, humidity profile, clouds) will lead to different contributions, which are all received together, but there is a type of 'fingerprint' of an atmospheric state in the way the multichannel signature is impacted.

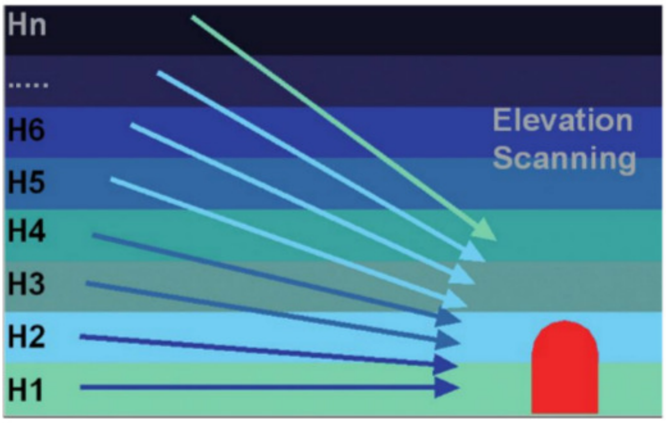
By a careful selection of channel frequencies, the microwave radiometers can gather information on the composition of the atmosphere. For temperature profiling, for example, a set of channels along the lower wing of the oxygen absorption line complex is used. At 51GHz, there is moderate absorption, which results in a total absorption of 2-3dB 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 its way up to the top of the atmosphere, meaning that half the signal would be absorbed.

In contrast, at 58GHz (which is in the center of the oxygen absorption line), the absorption is much higher (approx. 100dB). The same hypothetical signal emitted at the surface would now be absorbed much faster on its way up. At a height of 1km, there would be less than 10% of the signal left, and next to nothing would reach the tropopause.

Thinking now in terms of radiation that 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 51GHz, but not



Software-provided Skew-T thermodynamic diagram of the remotely sensed temperature and humidity profiles



Measurement concept for boundary-layer temperature profiling: an elevation-scan of the radiometer down to the horizon with optically thick frequency channels (having limited penetration depth) resolves lowest level inversion, but requires a narrow beam.

at 58GHz. 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. Because 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.

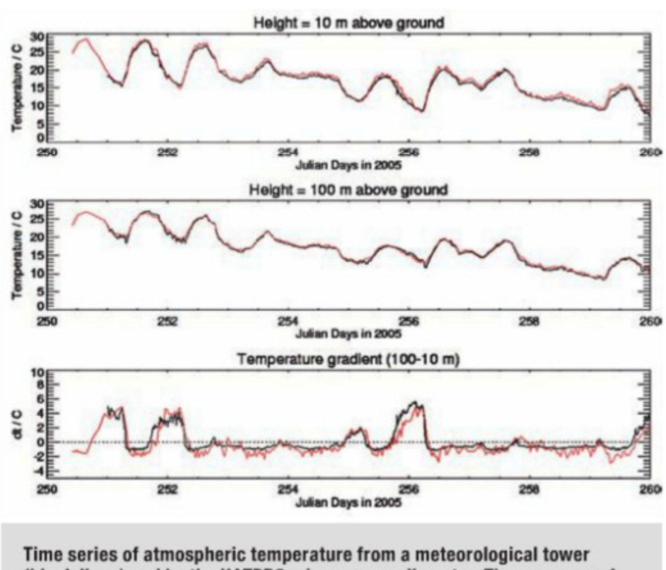
In a similar approach, the absorption line of the water vapor molecule at 22.235GHz can be used to assess the mixing ratio of the water vapor, giving a humidity profile. Cloud water is also detectable by inspecting frequencies that are either in or out of the water vapor line, therefore discriminating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

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

The true benefit

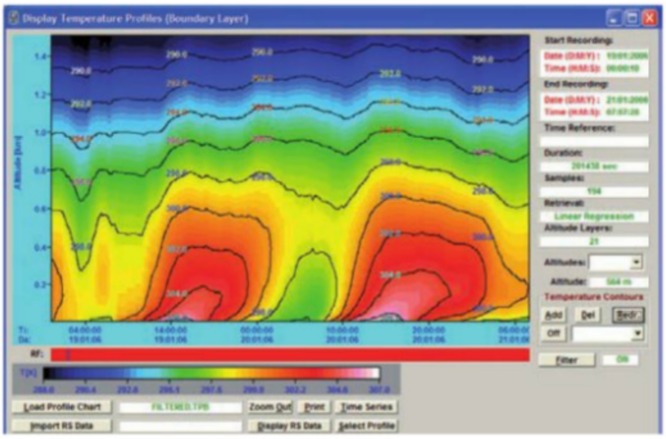
For the operational ground-based networks, the technology had to become cheaper, more robust, more mature. These points have been met in the past years, and today's instruments can deliver reliable information continuously minute-by-minute, all year round, in all weather conditions.

While radio soundings would miss the passage of a frontal system at 05:00 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.



Time series of atmospheric temperature from a meteorological tower (black lines) and by the HATPRO microwave radiometer. The upper panel shows the 10m layer temperature, the middle panel the 100m temperature, and the lowest panel gives the difference of both – the temperature gradient on a 90m layer. (courtesy of Prof. Crewell, University Cologne)

RPG- HATPRO-G2 microwave radiometer tested in Alfred Wegener Institute (AWI) Potsdam, Germany before final deployment to Nyalesund, Spitsbergen



Time series of vertical temperature profile as retrieved from a microwave dual profiler radiometer

RPG-HATPRO microwave radiometer deployed on German Arctic research vessel 'Polarstern', cruising the Atlantic Ocean. (c) 2007 Science Team Polarstern ANT.XXXIII-10

Rapid updates of the data sets are possible now, and trends and tendencies can be analyzed 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 as there is no chance to discriminate between radiation originating from the lowest atmospheric layers and radiation from the surface itself.

Microwave radiometers complement this view from above. The maximum information content is in the lowest layers, where most of the energy transfer into the atmosphere is taking place by solar heating.

Advanced technology

Modern microwave radiometers offer a special approach to increase the temperature sounding even further and beyond the standard multichannel observations. Using a channel of very high opacity (and very limited reach, or penetration depth) such as, for example 58GHz, the radiometer can perform elevation scans, 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 therefore gives only temperature information on this layer. Scanning to the next elevation, the beam intersects 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.

RPG-HATPRO-G2 microwave radiometer deployed at Lampedusa Island, Italy, south of Sicily

This iterative procedure enables high-precision and high-resolution temperature profiling. Validation experiments have shown that the remote-sensed temperature profile from the radiometers compares favorably with observations from meteorological towers 100m and 200m high. The vertical resolution is around 50m and capable of precisely resolving inversions on a scale of less than 100m.

During such an observation, the observed brightness temperature changes only in a range of 1% (e.g from 300-303K). The preconditions to do such high-precision boundary layer profiling are first a very sensitive system with low noise, and a narrow beam. The radiometers of RPG Radiometer Physics, for example, have a 1.6° beam width at the considered frequency, allowing scans down to 5° over the horizon. Smaller instruments have larger beams (optical law) and cannot scan quite 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. This enables individual band passes for all channels, giving a bandpass that is 10 times wider at 58GHz than at 51GHz (where very narrow channels are required), which then increases the received power and minimizes the noise. Increasing the integration time to 20 seconds on each angle and using four frequencies instead of only one, adds further precision and information content to the method, but also emphasizes the need to have parallel data acquisition in all radiometer channels.

Proven and mature

RPG radiometers are deployed worldwide in different climate conditions: the Arctic and tropical regions (-45°C to +50°C), high mountains (Atacama desert, 5.500m ASL), strong windspeeds (up to 250km/h on Zugspitze mountain, 2.600m ASL), snow, ice, rain, sea spray (Lampedusa island, Mediterranean), 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.

A decade of research and technology development has led to a mature technology that is ready to be deployed for worldwide operational networks. ▮

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