Atmospheric sounding in the 193 – 314 GHz frequency region

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Introduction

This document provides a basic review of the frequency bands between 193 and 314 GHz used for atmospheric sounding. The lower frequency limit of the review is set to the highest frequency covered by present operational microwave sensors, such as MHS and ATMS. The channels around the 183.31 GHz water vapour transition of future instruments (such as MWI and MWS) will also be limited to frequencies below 193 GHz. The upper limit is set to the lower end of the frequency range covered by the ICI channels around the 325.15 GHz transition. The frequency range will likely also be used by the Arctic Weather Satellite (AWS). That is, this review covers the range between 183.31 and 325.15 GHz regions, that both should be standard bands of future operational sensors and presumably already have high priority for frequency protection.

Limb sounding

Already the UARS Microwave Limb Sounder (MLS) had a band around 205 GHz, performing early measurements of the ClO enhancement associated with ozone hole above Antarctica (Waters et al., 1995). The ClO transitions targeted are found at 204.35 GHz. Aura MLS continued, and are still performing, these measurements, but are also measuring a number of other gases (Table 1). Other microwave limb sounding missions (SMILES and Odin/SMR) do not have channels in this frequency range. On the other hand, a mission in development in China, TALIS, is planned to have several receivers operating in the frequency range of concern.

Down-looking satellite observations

Table 2 covers planned operational missions and some cubesat missions. The operational missions having channels in the considered frequency range are MicroWave Sounder (MWS) and Ice Cloud Imager (ICI), both instruments in development for the next generation of European polar orbiting weather satellites. The listed cubesat missions should be the most mature ones of relevance. TROPICS and TWICE have similarities with MWS, while the objective of SWIRP is closer to the one of ICI (but SWIRP will also cover infrared observations).

Air-borne measurements

Some air-borne radiometers have a band around 220 or 243 GHz to measure hydrometeors or surface properties (Table 3), i.e. for the same reason as downward-looking instruments have bands in this frequency range. ISMAR and MIRAC-P are flown on a regular basis. The exact status of the two remaining air-borne sensors is not known, but at least CoSSIR is considered for future campaigns.

Acronym or name	Frequency range [GHz]	Target quantities	Reference and URL
Aura MLS	200-207	ClO, N_2O, O_3	
	230-236	CO, $O^{18}O$, O_3	
	243-250	O_3	Waters et al. (2006)
			ieeexplore.ieee.org/abstract/document/1624589/
TALIS	195.2-197.2	O_3	
	199.3-201.3	N_2O, O_3	
	202.7-204.7	ClO, N_2O, O_3	
	229.7-236.7	CO, ^{18}OO, O_3	
	242.7-249.7	O_3	Wang et al. (2020)
			www.atmos-meas-tech.net/13/13/2020/

Table 1: Frequency bands between 193 – 314 GHz of active (Aura MLS) and planned limb sounding missions (TALIS). Aura MLS has not complete coverage of the stated frequency ranges. A figure showing the placement of the individual frequency bands is found at mls.jpl.nasa.gov/images/unfolded-big.png.

Acronym or name	Frequency range [GHz]	Target quantities	Reference and URL
MWS	228.0-230.0	Hydrometeors, surface properties	MWS science plan
			www.eumetsat.int/website/home/Data/ScienceActivities/ ScienceStudies/SciencePlansforfuturemissions/index.html
ICI	239.2-247.2	Hydrometeors, surface properties	Eriksson et al. (2020)
			www.atmos-meas-tech.net/13/53/2020
SWIRP	215.5-225.5	Hydrometeors, surface properties	Wu et al. (2019)
			ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190001731.pdf
TROPICS	203.8-205.8	Hydrometeors, surface properties	Blackwell et al. (2018)
			rmets.onlinelibrary.wiley.com/doi/full/10.1002/qj.3290
TWICE	239.2-247.2	Hydrometeors, surface properties	Jiang et al. (2019)
			agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019EA000580

Table 2: Frequency bands between 193 – 314 GHz of planned operational sensors (first part) and some missions of cubesat character (in various stage of maturity, second part). The MicroMAS and MiRaTA cubesat missions are not included as they can be considered as pathfinders for TROPICS.

Ground-based measurements

Ground-based radiometry above 200 GHz is limited to high latitudes sites, such as Kiruna (Sweden) and research stations on Antarctica (Table 4). The table is not necessarily totally complete, e.g. measurements have also been performed from Thule (Greenland, Fiorucci et al. (2013)) but it is not clear if this instrument is still in operation. Some instruments perform continuous measurements of a specific frequency region, while others are tunable and observe various transitions in a time-share basis.

Acronym or name	Frequency range [GHz]	Target quantities	Reference and URL
ISMAR	239.2-247.2	Hydrometeors, surface properties	Fox et al. (2017)
		old.faam.ac.uk/index.php/science-instruments/remote-sensing/564-ismar-international-sub-millimetre-airborne-radiometer	
MIRAC-P	241-245	Hydrometeors, surface properties	Mech et al. (2019)
		www.atmos-meas-tech.net/12/5019/2019/amt-12-5019-2019.pdf	
CoSSIR	216-224	Hydrometeors, surface properties	Evans et al. (2005)
		airbornescience.nasa.gov/instrument/CoSSIR/	
MIR	216-224	Hydrometeors, surface properties	Racette et al. (1996)
		airbornescience.nasa.gov/instrument/MIR	

Table 3: Frequency bands between 193 – 314 GHz used by air-borne instruments of down-looking character.

Location	Frequency range [GHz]	Target quantities	Reference and URL
Mauna Kea	278.4-278.8	ClO	Nedoluha et al. (2011)
			doi.org/10.1029/2010JD014732
Scott Base	278.4-278.8	ClO	Nedoluha et al. (2016)
			www.atmos-chem-phys.net/16/10725/2016/
Troll station	230.6+249.7-250.9	CO, NO, O_3	Daae et al. (2014)
			www.earth-syst-sci-data.net/6/105/2014/
Kiruna	195-235	ClO, CO, O_3	Raffalski et al. (2005)
			www.atmos-chem-phys.net/5/1399/2005/
Kiruna	268-281	ClO, HNO_3, N_2O O_3	Kopp et al. (2002)
			doi.org/10.1029/2001JD001064

Table 4: Ongoing and recent ground-based observations above 200 GHz.

The frequency region of concern is basically the only one where ClO can be observed from ground. Two clusters of transitions have been used, at 204.4 and 278.6 GHz. The first one of these is also used by the MLS and TALIS limb sounders.

Some other transitions in the region, that have been observed and have unique characteristics to enable ground-based measurements of the corresponding species, are CO at 230.5 GHz (Straub et al., 2013), $O^{18}O$ at 233.9 GHz (Pardo et al., 1995) and NO at 250.8 GHz (Newnham et al., 2011). A review of optimal transitions to observe for some other species by Turner et al. (2016) identified 235.5 GHz for HOBr, 269.5 GHz for HO_2 and 301.4 GHz for N_2O as important frequency ranges.

It should be noted that emission signatures detected by ground-based measurements are in general weak, down to a few 0.01 K. This means that the observations can easily be ruined by interfering signals despite an upward-looking geometry.

Discussion

Gases in the middle atmosphere

The ground-based and limb sounding measurements found in the tables above mainly target gases between about 10 to 100 km. Considering the central importance of ClO in the depletion of the ozone layer, both clusters of ClO transitions in the frequency region shall be protected. The one at 204.4 GHz is favoured by limb sounders, at it gives possibility for combined measurements of the 183.31 GHz water vapour transition (by a lower sideband). The 278.6 GHz cluster is more commonly observed by ground-based instruments. In both cases, a surrounding frequency range should also be protected to allow simultaneous observations of other gases. For example, the region 268 - 279 GHz includes suitable transitions to observe ClO, O_3, HNO_3 and N_2O (see e.g. Crewell et al. (1995) and accompanying papers, or Berg (2000). Aura MLS has bands giving an almost complete coverage of 200 to 207 GHz, covering together transitions of ClO, O_3, and N_2O.

Protection for observation of other gases should also be considered. Several important transitions are found between 230 and 236 GHz. Also NO at 250.8 GHz should have high priority. See the ground-based section above for details.

Hydrometeors in the troposphere

The region around 230 GHz has an unique position for downward looking observations. It is the highest frequency range that gives coverage down to the surface even in the presence of clouds. Observations at optical and thermal infrared wavelengths are disturbed even by very thin clouds. At far-infrared wavelengths water vapour is strongly absorbing and the surface is invisible also in the absence of clouds. This is the case up to wavelengths matching about 400 GHz. Around 340 GHz the surface can be observed at dry conditions, but not in general. That is, the first real "window range" on the low frequency side of the far infrared is the one around 230 GHz.

Accordingly, without doubt, a frequency range around 230 GHz. must be preserved for passive satellite and air-borne measurements. To ensure high-quality data (i.e. low noise) a continuous band of about 8 GHz is required.

This 230 GHz window is not used by present operational sensors (i.e. ones used for weather forecasting) but that is due to the status of microwave technology at the time these sensors were designed. On other hand, both the next generation of European polar orbiting weather satellites and most of the US cubesats aiming at weather observations have channels between 200 and 250 GHz.

There exist several possibilities to place a channel in the 230 GHz region, as can be understood by Table 2. For MWS, the 229 GHz channel complements the 183 GHz suite, with more sensitivity to the ice scattering to possibly account for some ice contribution in the 183 GHz channels. For ICI, the 243 GHz channel is a key channel to estimate the cloud ice content, centrally placed between 183 and 325 GHz water vapour transitions, and providing an optimal range of sensitivity to the ice phase in this frequency domain.

Three copies of the ICI instrument will be launched and the ICI mission will continue to at least 2045. Considering that the primary goal of the ICI instrument is the characterisation of the ice phase in the clouds, with the 243 GHz as a key channel to meet this goal, the protection of the frequency range selected for ICI should be the main candidate for frequency protection.

Conclusion

The ranges 200 - 207 GHz and 268 - 279 GHz shall be protected to ensure measurements of ClO and several other species highly important for the chemistry in the strato- and mesosphere. For the same application, the range 230 - 236 GHz and 250.8 GHz should also be given priority. It can be noted that by protecting 230 - 251 GHz, both the measurement of several gases and the need for weather forecasting are covered simultaneously (see below).

Microwave humidity channels have a growing impact on global weather predictions (Geer et al., 2017), and considering the already high importance of accurate weather forecasts for societal services (Bauer et al., 2015), it is crucial that also frequencies above 200 GHz can be used for this purpose without interference. MWS and ICI represent huge investments in themselves, but the critical risk is to loose the possibility to improve weather forecasts even further and then saving the society costs that are considerably larger than the initial investment.

Accordingly, a sufficient wide frequency range around 230 GHz must be saved for undisturbed weather observations. As mentioned, to ensure high-quality data a continuous band of about 8 GHz is required. We argue strongly for that the primary candidate band to protect is the one selected for the ICI mission, i.e. 239.2 - 247.2 GHz.

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