Response to reviewer 1

First, we thank the reviewer for reading our paper and for his/her comments.

General comments

Firstly, I’d like to thank the authors for their work. I have marked for major revision as I think more is needed to address the benefits arising from having the CIMR channels on one platform. I did not feel the paper addressed this, despite saying it was very important. The paper updates a popular figure that has been used for many years to illustrate the sensitivity of low frequency microwave observations to a range of geophysical products. The major change is that the new plot takes account of the atmosphere and adds SIC and additional plots show difference between tropics, middle latitudes and polar latitudes and details for the arctic. The updated plot and new plots will be of interest butt he paper does not give any particular new OS insights. It’s a short paper to revisit the plot and look at sensitivity in the context of CIMR. It feels to me to be a first useful step in a wider study that will give a deeper understanding, but more progress is needed to justify publication.

The CIMR mission has been described with more details in a previous publication (Kilic et al., JGR, 2018) and other papers describe some potential applications of CIMR (see for instance a list of publication at https://cimr.eu). The famous Wilheit figures has been used widely by the community, for CIMR and other missions. It was felt necessary to’officially’ update this figure and to provide a reference for this update. This is the goal of this technical note. We are aware that this is not a full detailed study and this is the reason why we chose the technical note format.

Scientific significance: Fair

The paper does not reveal any substantial new understanding of ocean science.

Scientific quality: Good

The paper addresses the value of CIMR by examining the sensitivity of microwave frequencies to a range of geophysical parameters. Scientifically this is fine and the calculations are state of the art. However, it could perhaps have addressed more the linkage between frequencies. The paper says this is important, but then does not address this aspect.

Presentation quality: Good

The results are clear, but presenting only normalised sensitivities can give a misleading impression of the relative importance of sensitivities at a particular frequency, it only shows well the point of maximum sensitivity for each geophysical parameter. This is discussed further below.

Specific points requested by OS

1. Does the paper address relevant scientific questions within the scope of OS? CIMR is an important mission for OS, so the question is relevant.

2. Does the paper present novel concepts, ideas, tools, or data? The paper updates the work of Wilheit, but is not novel.

3. Are substantial conclusions reached? The variability with region is shown to be significant, but I think this is well known since papers such as Phalippou (1996) and of course earlier work by Dr Prigent amongst others.

4. Are the scientific methods and assumptions valid and clearly outlined? Yes, though I would have liked to see more to address linkage between the frequencies, as this is a key aspect of CIMR, having 1 to 40 GHz on the same platform.

5. Are the results sufficient to support the interpretations and conclusions? Yes

6. Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? Yes

7. Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Yes, given the limited ambition of the paper, though a more complete analysis of the MIMR, AMSR-E and AMSR2 literature is relevant, as CIMR only adds the L-band channel to the capability of these sensors.

8. Does the title clearly reflect the contents of the paper? It is not obvious to me why the authors choose to imply their paper is about the arctic. Fig. 2 is middle latitude,Fig. 3 compares arctic, middle latitude and tropics. Fig. 4 is arctic with a couple of paragraphs of discussion. Yes, SIC has been added compared to Wilheit. But overall there does not seem to be a particular emphasis on the arctic in the analysis. It’s a global study.

The initial Wilheit figure was about open ocean at mid latitude. We added arctic simulations and sensitivity to sea ice.

9. Does the abstract provide a concise and complete summary? Yes

10. Is the overall presentation well structured and clear? Yes

11. Is the language fluent and precise? Yes

12. Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Yes

13. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced,combined, or eliminated? No

14. Are the number and quality of references appropriate? Yes – but more on MIMR etc literature would be appropriate, as noted above.

A reference to MIMR has been added.

15. Is the amount and quality of supplementary material appropriate? No supplementary material needed

Specific comments

P2 L28 “No gap in coverage at the pole” What the authors mean is every orbit will see the pole, so there will be an observation every c.100 minutes. No gap may mislead some readers who are not familiar with polar orbiting satellites.

The sentence has been clarified. It has been replaced by “CIMR … will fully cover the poles”.

P2 L31 Not sure why you use the word harsh. It will observe all aspects of the arctic environment. This seems poetic language for a scientific paper.

“harsh” has been deleted

P2 L33 Could you be more specific on the range of terrestrial products that CIMR will improve analysis of, that are additional to those you have just listed. Its not clear what you are talking about.

Some precisions have been added "(e.g. soil moisture, vegetation dynamics, snow water equivalent) »

Equation 1: You have assumed a specular reflection. How realistic is this for some of the snow and ice surfaces you are concerned with? Suggest to clarify.

As demonstrated in Matzler (2005), the distinction between specular and lambertian scattering is not an issue for conically scanning instruments such as CIMR with incidence angles close to 55°. The problem arises for incidence angle close to nadir as can be the case for cross-track sounders such as AMSU or MHS.

Matzler, C. (2005). On the determination of surface emissivity from satellite observations. IEEE Geoscience and remote sensing letters, 2(2), 160-163.

Equation 2: Why do you use finite difference rather than differentiating the code and how have you ensured that your dx is appropriate to get a robust estimate of the local gradient?

In the microwave windows between 1 and 40 GHz, the variations of Tb as a function of the different parameters are quasi-linear, therefore we can use the finite difference to compute the sensitivity and the choice of dx is not very critical (contrarily to what happens in the calculation of the gradients in spectral lines).

Equation 3: Whilst normalising like this maintains consistency with the Wilheit figureit may give a misleading impression of relative sensitivity to different parameters at agiven frequency. It would be useful also to show the unnormalized figures.

Figure 4 is unnormalized with sensitivities that are plotted with logarithmic scale.

Figure 4: I do not understand this figure. What is the cause of the sharp spectralfeature in the SST sensitivity around 15 GHz? This makes no physical sense to me.Please explain.

This is because the results are presented with a logarithmic scale, because the sensitivities are very different depending on the parameters. Around 15 GHz the sensitivity to SST becomes zero, this is why we have this shape.

P8 L145-155 I am struggling to see the point in this analysis. You have a multi-channel instrument, you have already stated that the multi-channel aspect is important, its clear that single channel frequency retrievals are useless (even ignoring sensitivity to other parameters). I am not sure how this analysis gives new insights? It seems far less useful than a multi-channel information content study.

The multi-channel analysis has been done in Kilic et al., 2018. In this study, our goal is to present, in a convenient way for the users, the CIMR channels individually and their advantages in terms of sensitivity.

P9 L164-166 This does not seem to be a new finding, yet it reads like it is.

It is a confirmation and it summarizes to the community why these channels have been selected for CIMR.

P9 L169-171 I agree the major aspect of CIMR is to use these frequencies together but this is really not explored in this short paper. The paper only repeats rather well known aspects of the sensitivity of individual frequencies. It is not difficult with the calculated gradients to explore the multi-channel aspects using linear information content theory. Its not new, but it would give more insight into the use of these channels together.

As mentionned above, this multi-channel analysis has been presented in Kilic et al., 2018.

Kilic, L., Prigent, C., Aires, F., Boutin, J., Heygster, G., Tonboe, R. T., ... & Donlon, C. (2018). Expected performances of the Copernicus Imaging Microwave Radiometer (CIMR) for an all-weather and high spatial resolution estimation of ocean and sea ice parameters. Journal of Geophysical Research: Oceans, 123(10), 7564-7580.

Response to reviewer 2

First, we thank the reviewer for reading our paper and for his/her comments.

This technical note deals with the sensitivity of the future CIMR microwave mission to various ocean and ice parameters. It is an update of the Wilheit figure that has been widely used with a focus on the incidence angle of CIMR (55 ◦) and using a more recent modelling. I have no doubt that this information will be useful to the CIMR community, but I find the novelty of the paper quite modest with respect to other studies. I think with some changes (see below) the paper could represent a more important contribution to the community. It is nicely written and easy to read.

We are aware that this paper does not present fondamental novel results. It is a practical update of the Wilheit figure that has been widely used by the community. This is why we chose to submit this result as a technical note and not as a regular paper.

A first concern is about the atmospheric contribution : to which extent is the Rosenkranz (2017) model valid at L-Band ? The Rosenkranz citation corresponds to a code and I did not find easily the corresponding references in the litterature but I am not sure at all it considers the contribution of the molecular Oxygen which is the dominant contribution at low frequency. Even though this contribution is much less than at higher frequency, given the low sensitivity of the brightness temperature to the salinity at L-Band, it cannot be ignored. This model is not used in salinity retrieval processors today.

The Rosenkranz gas absorption coefficients have been widely used in the microwave community, even for the retrieval of water vapor and temperature in the assimilation of microwave satellite data in operational weather centers. It includes all the physics required for an accurate evaluation of the atmospheric absorption by water vapor and oxygen in the atmosphere. It is valid from 1 GHz up to 1000 GHz. The provided citation includes many more citations to different works from Rosenkranz and colleagues. The reviewer may refer to the MPM model from Liebe that is also widely used. Note that Liebe and Rosenkranz worked a lot together, with Rosenkranz still active, with the model we used including the latest updates.

Another concern is with Figure 2 : the title of the paper makes a focus on the Arctic Ocean but this figure is for the middle latitudes, I suggest you change the title of the paper or do this Figure for Arctic conditions. The conditions described in Table 2 are very restrictive and do not represent the true variation of the parameters. I suggest you consider more representative variations and report the corresponding sensitivity as a shadowing around median conditions on Figure 2. The normalisation of Figure 2 does not allow to get quantitative estimates. I suggest you add several Y axis with scales corresponding to the non normalized sensitivity for each parameter.

Figure 4 provides the information the reviewer suggests, without normalization.

Detailed remarks :
Abstract Line 7-8 ’state of the art’: Levine and Dinnat (2020) recently published a similar study with a discussion of the sensitivity given by various state of the art ocean RTMs. The originality here is not to reproduce the figure of Wilheit with a recent model, but to update it at 55 ◦ which was not specifically studied by Levine and Dinnat. In addition, to my knowledge, the Rosenkranz atmospheric model is not considered as a state of the art model at L-Band.
Le Vine, D.M.; Dinnat, E.P. The Multifrequency Future for Remote Sensing of Sea Surface Salinity from Space. Remote Sens. 2020, 12, 1381.

Thank you for the reference to the LeVine and Dinnat paper, we added it to our paper.

The atmospheric model that is presented in LeVine and Dinnat is the MPM92 model from Liebe et al (1985, 1992) (reference 37 and 38 in there paper) with Rosenkranz improvements (reference 39 of the same paper). It is the same model that we use, but with a more recent reference.

Line 29-30 : what are the main parameters of interest on METOP-SG for CIMR ? Maybe add a reference for METOP-SG. What do the acronyms MWI/ICI and SCA mean ?

There are two instruments of interest on MetOp-SG, for synergy with CIMR. First the scatterometer ASCAT that can provide the ocean wind speed with accuracy, and second the two microwave imagers MicroWave Imager (MWI) and the Ice Cloud Imager (ICI) that extent the frequency range of CIMR up to 654 GHz, for atmospheric retrievals. Products from ASCAT (ocean wind speed) and from MWI/ICI (water vapor and liquid water content) could be used as first guess in the retrievals of CIMR.

The meanings of the acronyms have been added : "MetOp MicroWave Imager (MWI)/Ice Cloud Imager (ICI) and SCAtterometer (SCA) measurements »

Line 40 : I guess it is meant : state of the art of the various components of Radiative Transfer Model. In fact only one model is considered for each contribution whereas several are in use in the community and none of them have been absolutely ruled out given present uncertainties. I suggest to refer to the recent study of Levine and Dinnat who showed the sensitivities obtained with various widely used components of radiative transfer models.

We agree that the paper from Levine and Dinnat presents an interesting comparison of the different radiative transfer models for the ocean. Our model selection is based on Kilic et al., 2019 that also compared different models (including the ones used in Levine and Dinnat), including comparisons with satellite observations. Kilic et al 2019 showed that the model that fits the observations better over the full frequency range and environment ranges is the model from RSS.

Table 2 : how do realistic variations in the surface and atmospheric conditions modify the results ? I would suggest putting a shadow around the curves on Figure 2 to reflect the variations due to surface and atmospheric conditions as well as uncertainties coming from uncertainties on RTM.

The variations due to the surface and atmospheric parameters are shown in Figure 3 for 3 typical cases. The uncertainties of the RTM is a problem that is partly treated in Kilic et al., 2019. We would like to keep Figure 2 easy to understand and close to Figure of Wilheit.

Lines 68-75 : Molecular Oxygen is the main contributor at L-Band and is a significant contributor at low frequency (see Levine and Dinnat, appendix C), it should be considered. How does the Rosenkranz model compare with the MPM92 model more widely used at L-Band ?
Strictly speaking, equation 1 should be vertically integrated ; I guess neglecting the vertical integration might have some impact on the result, especially at high frequency, this should be discussed.

We are fully aware that O2 is the main contributor to the atmospheric absorption at L-band. See our response above. It is actually Rosenkranz who derived the oxygen parameter for the Liebe models. Liebe was mainly working on the water vapor attenuation. Liebe passed away several years ago and a new reference for the model is the one that is given in the paper.

Line 91 and Figure 2: I guess you mean : maximum value of the sensitivity. I don’t like much this normalisation because it does not allow a quantitative reading (I also have this problem when reading the Wilheit figure). You might envisage to add several Y axis with scales corresponding to the non normalized sensitivity for each parameter.

We would like to keep Figure 2 close to the Wilheit one. But in Figure 4 the sensitivities are shown unnormalized with a logarithmic scale.

Line 111 : Partly redundant with the introduction

Yes the sentence “CIMR has a 55 ◦ incidence angle and a large swath (>1900 km) to provide full coverage of the poles (i.e., with no gap at the pole itself), for the first time with a conical scanner” has been deleted.
We modified the following sentence by: “The choice of an incidence angle of 55° for CIMR has been constrained by the swath width (to fully cover the poles), and the spatial resolution.»

Legend of Figure 4 : unclear what does ‘units’ mean

The units are the units of measurements for the sensitivities to the different parameters. It is explained in the text e.g., “The TCWV and TCLW show respectively a sensitivity of 1.0 K per 1 kg/m2 at 18.7 GHz, and 1.05 K per 20 g/m2 at 36.5 GHz”.

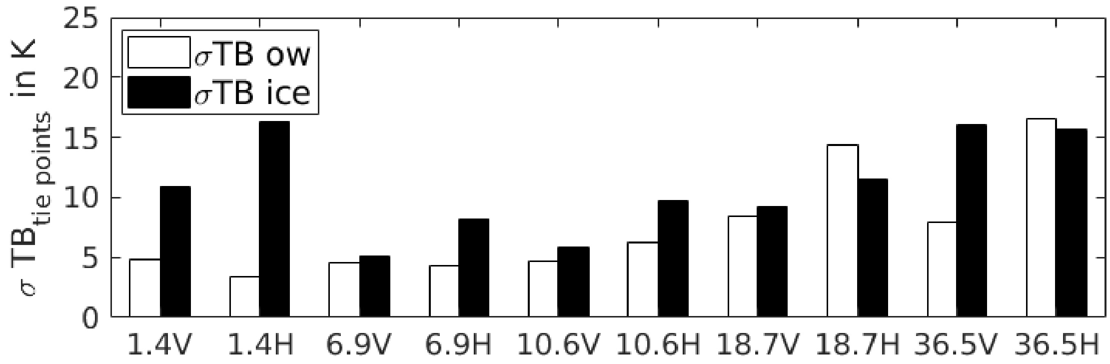
Response to reviewer 3

First, we thank the reviewer for reading our paper and for his/her comments.

This technical note presents a sensitivity analysis of geophysical parameters relevant to the frequencies and viewing geometry anticipated for the arctic-focused CIMR mission. The focus of the work is a more quantitative reproduction of the classic Wilheit 1979 figure using more up-to-date information including RTM and inclusion of the atmospheric contribution. The note finishes with anticipated single channel TB sensitivity to the CIMR precision range for desired retrievables. The paper is well written and the results reasonably well presented. The information is highly useful for the CIMR team and future users of the data. The paper is lacking in scientific novelty for a publication. Suggestions are given below for some possible expansions that could add to the contribution of this work.

We are aware that this paper does not present fondamental novel results. It is a practical update of the Wilheit figure that has been widely used by the community. This is why we chose to submit this result as a technical note and not as a regular paper.

Specific Comments: Line 65: What are some of the uncertainties and sources of error associated with this?



The sea ice emissivity varies upon different parameters the main one are the ice type, the ice thickness, and the snow depth. In the figure above you can see the standard deviation of the ice brightness temperature (black rectangle) derived from the round robin data package that is cited in the paper.

Line 96: I understand the desire to present a single case here with explanation before diving in to the comparisons, but using the midlatitude case seems an odd choice here. I suggest reorganizing this section and either presenting 3 versions of Figure 2 (one for each of midlatitude/arctic/tropical) or (perhaps more in line with the original idea) leave the first section as "a general case" but average all areas together, making it truly general for this discussion, then next presenting Figure 3 teasing them all apart and discussing the latitudinal differences.

We would like to keep Figure 2 close to the Wilheit initial figure for an easier comparison, before changing the geophysical condition.

Lines 106-109: Is this the best place for this discussion? May be better placed in the introduction?
Yes, it has been moved to the introduction.

Section 3 - General: Please add a sense of the variability in these parameters, and how this variability differs for each of tropical/mid-lat/arctic. This is an important piece that is missing to make this more robust.

Yes we added sentences to explain the variation of the parameters : « The TCWV and the SST vary globally between roughly 5 to 60 kg/m2 and 273 to 305K, respectively, with mean values that strongly depend upon the latitude. The OWS and SSS vary globally between roughly 0 to 20 m/s and 32 to 38 psu with mode values around 7 m/s and 34 psu, respectively. »

Section 3 - General: More discussion of differences from the Wilheit figure and how the changes are related to the updated technique and inclusion of the atmospheric contribution (more than the quick mention at line 101) would be a nice addition to this work.

Yes, we added the following sentence: « Note that with this updated version of the Figure of Wilheit1979 taking into account the sensitivity to the atmosphere, we can see that the sensitivities to the other parameters, such as SST or OWS, are decreased at higher frequencies (>18 GHz), and especially near the water vapor absorption line at 22 GHz. »

Technical note: A sensitivity analysis from 1 to 40 GHz for observing the Arctic Ocean with the Copernicus Imaging Microwave Radiometer

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Abstract. The Copernicus Imaging Microwave Radiometer (CIMR) is one of the high priority missions for the expansion of the Copernicus program within the European Space Agency (ESA). It is designed to respond to the European Union Arctic policy. Its channels, incidence angle, precisions, and spatial resolutions have been selected to observe the Arctic Ocean with the recommendations expressed by the user communities. In this note, we present the sensitivity analysis that has led to the choice of the CIMR channels. The famous figure from Wilheit (1979), describing the frequency sensitivity of passive microwave satellite observations to ocean parameters, has been extensively used for channel selection of microwave radiometer frequencies on board oceanic satellite missions. Here, we propose to update this sensitivity analysis, using state-of-the-art radiative transfer simulations for different geophysical conditions (Arctic, mid-latitude, Tropics). We used the Radiative Transfer Model (RTM) from Meissner and Wentz (2012) for the ocean surface, the Round Robin Data Package of the ESA Climate Change Initiative (Pedersen et al., 2019) for the sea ice, and the RTM from Rosenkranz (2017) for the atmosphere. The sensitivities of the brightness temperatures (TBs) observed by CIMR as a function of Sea Surface Temperature (SST), Sea Surface Salinity (SSS), Sea Ice Concentration (SIC), Ocean Wind Speed (OWS), Total Column Water Vapor (TCWV), and Total Column Liquid Water (TCLW) are presented as a function of frequency between 1 to 40 GHz. The analysis underlines the difficulty to reach the user requirements with single channel retrieval, especially under cold ocean conditions. With simultaneous measurements between 1.4 and 36 GHz onboard CIMR, applying multi-channel algorithms will be facilitated, to provide the user community with the required ocean and ice information under arctic environments.

1 Introduction

The Copernicus Imaging Microwave Radiometer (CIMR) is currently being implemented by the European Space Agency (ESA) as a High Priority Copernicus Mission (HPCM). It partly follows previous studies conducted at ESA for the Multifrequency Imaging Microwave Radiometer (MIMR) (Bernard et al., 1990). CIMR will deploy a wide-swath (>1900 km) conically scanning multi-frequency microwave radiometer with a 55° incidence angle with the Earth surface. CIMR measurements will be made using a forward scan arc followed ∼260 seconds later by a second measurement of the same location using a backward

Table 1. CIMR characteristics as expressed in Donlon and CIMR Mission Advisory Group (2020).

Frequency (GHz)	Spatial resolution (km)	Incidence angle (°)	NeΔT (K)
1.414	<60	55	0.3
6.925	≤15	55	0.2
10.65	≤15	55	0.3
18.7	≤5	55	0.3
36.5	≤5	55	0.7

scan arc. Polarised (H and V) channels centred at 1.414, 6.925, 10.65, 18.7 and 36.5 GHz are included in the mission design under study. The frequency selection for a satellite mission has to account for the International Telecommunication Union (ITU) frequency regulation, and to ensure continuity with past and current missions. Therefore, the flexibility to choose the channel frequencies and their bandwidths is limited. The real-aperture resolution of the 6.9/10.65 GHz channels is <15 km, and 5 and 4 km for the 18.7/36.5 GHz channels respectively. The 1.4 GHz channel will have a real-aperture resolution of <60 km (fundamentally limited by the size of the ∼8 m deployable mesh reflector) (see Table 1). However, most channels will be oversampled by ∼20% allowing gridded products to be generated at better spatial resolution. Channel NeΔTs are within 0.2-0.8 K with an absolute radiometric accuracy goal of ≤0.5 K. CIMR will fly in a dawn-dusk orbit providing, with one satellite, ∼95% global coverage every day, better than daily coverage poleward of 55° N and S, and ~~no gap in coverage at the pole itself~~will fully cover the poles (no gap). CIMR will operate in synergy with the EUMETSAT MetOp-SG(B) mission so that in the polar regions (>65°N and 65°S) collocated and contemporaneous measurements between CIMR and MetOp ~~MWI~~MicroWave Imager (MWI)/~~ICI and SCA~~ Ice Cloud Imager (ICI) and SCAtterometer (SCA) measurements will be available within +/− 10 minutes.

CIMR is primarily designed to observe the ~~harsh~~ Arctic environment. Among other parameters, it will provide estimates of the Sea Ice Concentration (SIC), the Sea Surface Temperature (SST), thin Sea Ice thickness (tSIT), Sea Ice Drift (SID), Sea Ice Type, Sea Surface Salinity (SSS), and a range of terrestrial products under clear and cloudy conditions (e.g. soil moisture, permafrost, vegetation dynamics, snow water equivalent). An initial CIMR retrieval capability has been evaluated in Kilic et al. (2018).

One of the key issues to obtain the best precisions on the retrieved parameters is the sensitivity to the parameters to be retrieved. In 1979, Wilheit illustrated the relative sensitivity of the passive microwaves to the ocean parameters for the Scanning Multi-channel Microwave Radiometer (SMMR) (see Figure 1). This figure is certainly the most famous illustration in the ocean passive microwave remote sensing community: it has been reused at many occasions to justify the frequency selection for a large range of missions (e.g., Imaoka et al. (2010); Gabarro et al. (2017)). However, this figure has not been recalculated for a quantitative exploitation of the results. Here, we update the original figure using state of the art Radiative Transfer Models (RTMs). We perform a sensitivity analysis of the passive microwaves to the sea and ice parameters to produce a new figure. This is used to confirm the selection of centre frequencies used by the CIMR radiometer for different geophysical conditions.

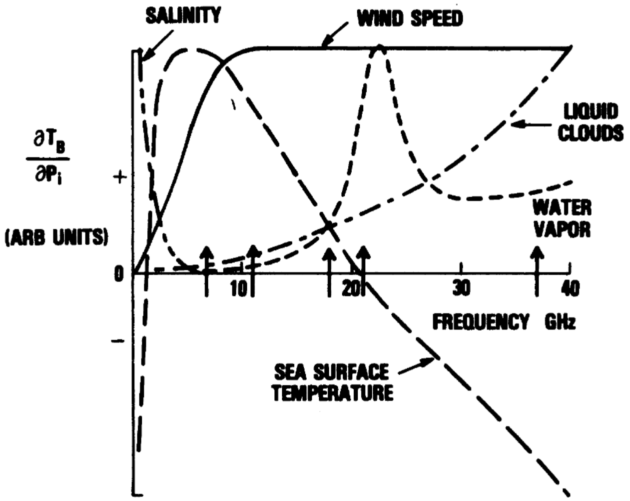

Figure 1. Figure 3 in Wilheit (1979). Schematic superposition of the spectra of various geophysical parameters, P_i. The arrows indicate SMMR frequencies. The signs have been chosen to be positive in the frequency range of primary importance to the given parameter.

In Section 2, the methodology and the RTMs used to perform the simulations will be described. The results will be presented in Section 3. The sensitivities for a general case corresponding to mid-latitude conditions will be presented, then we will focus on the case of the challenging Arctic conditions. Finally, Section 4 will conclude this study.

2 Materials and Method

2.1 Description of the Radiative Transfer Model

To simulate the sensitivity of the passive microwave satellite observations to the geophysical parameters as a function of frequency over the ocean, a RTM is required. It has to include the simulation of the ocean and ice emissivity, as well as the contribution from the atmosphere, clear and cloudy.

The ocean emissivity varies primarily with the SST, the Ocean Wind Speed (OWS), and the SSS. The emissivity of a flat ocean surface can be simulated from the Fresnel equations, with the sea water permittivity calculated as a function of SST and SSS. When the OWS strengthens, waves appear, the surface gets rougher, and foam can be generated. To calculate the ice-free ocean emissivity, the Remote Sensing Systems RTM (Meissner and Wentz, 2012) is adopted. A comparison of ocean RTMs by Kilic et al. (2019) showed that this model is appropriate for frequencies between 1 and 40 GHz. This model is essentially fitted to satellite observations, with the Special Sensor Microwave/Imager (SSM/I) and WindSat observations between 6-89 GHz (Meissner and Wentz, 2004, 2012), and with Aquarius observations at 1.4 GHz (Meissner et al., 2014, 2018).

Sea ice is a very complex medium composed of different layers of ice, possibly covered by snow. Physically-based emissivity models require a large range of ancillary information that are hardly accessible and they encounter strong difficulties to simulate observations consistently over a large spectral range. The ESA Sea Ice Climate Change Initiative (CCI) Round Robin Data Package (RRDP, Pedersen et al. (2019), https://figshare.com/articles/Reference_dataset_for_sea_ice_concentration/6626549) is a large dataset of co-located brightness temperatures from the Soil Moisture and Ocean Salinity (SMOS) satellite and the Advanced Microwave Scanning Radiometer 2 (AMSR2) over sea ice with relevant meteorological data. Here, the RRDP is used to provide a realistic sea ice emissivity value. The stored brightness and sea ice surface temperatures for the Arctic conditions are extracted and used to derive a representative emissivity estimate. The emissivities are first computed at the observation frequencies, which are close to the CIMR observing channels, followed by a smooth interpolation to provide emissivity values at the frequencies between the currently observed channels.

The sensitivities to atmospheric parameters, including Total Column Water Vapor (TCWV) and Total Column Liquid Water (TCLW), are also evaluated. In previous similar studies (Wilheit, 1979; Imaoka et al., 2010), the sensitivities of the signal to the TCWV and the TCLW were estimated, but the atmosphere was not accounted for in the analysis of the sensitivity to the surface parameters. Here, the clear-sky atmospheric contribution is systematically included, leading to more realistic results at the top of the atmosphere, especially above 15 GHz. The widely used RTM of Rosenkranz (2017) for the atmospheric absorption is applied, with the latest improvements in atmospheric gas absorption as well as a formulation for the cloud liquid water non-scattering contribution. Note that below 40 GHz, hydrometeor scattering is usually negligible.

2.2 Sensitivity computation

The brightness temperatures at the Top-Of-Atmosphere TB_{TOA}, at frequency f, polarization p, and incidence angle θ, is computed as follows:

$$TB_{TOA}(f,p,\theta) = T_s \cdot e(f,p,\theta) \cdot \tau(f,p,\theta) + TB_{down}(f,p,\theta) \cdot \tau(f,p,\theta) \cdot (1 - e(f,p,\theta)) + TB_{up}(f,p,\theta) \tag{1}$$

with e the surface emissivity, τ the atmospheric transmission, TB_{down} (resp. TB_{up}) the atmospheric downwelling (resp. upwelling) brightness temperature. T_s is the surface skin temperature, here a SST or an ice surface temperature (T_{ice}).

For simplicity, we assume that the extra-terrestrial contributions to the signal (cosmic background, Galaxy, Sun, Moon) as well as the Faraday rotation, have already been removed from the satellite measurements. However, we note that these contributions are especially critical at 1.4 GHz.

Different surface-atmospheric conditions will be considered: mid-latitudes, arctic, and tropical. The TCWV and the SST vary globally between 5 to 70 kg/m^2, and 273 to 305 K, respectively, with mean values that strongly depend upon the latitude. The OWS and the SSS vary globally between 0 to 20 m/s, and 32 to 38 psu with mode values around 7 m/s and 34 psu, respectively. For each latitude range / environment, the surface and atmospheric parameters can undergo significant variabilities, here some mean values are chosen for these parameters for illustration purposes. Table 2 summarizes the value of the surface and atmospheric parameters used for each of these environments.

Table 2. Surface and atmospheric conditions for the three considered environments

Environment	TCWV (kg/m^2)	SST (°C)	SSS (psu)	OWS (m/s)	T$_{ice}$ (°C)
Arctic	5	0	34	6	0
Mid-latitudes	20	10	34	6	-
Tropical	40	24	34	6	-

The sensitivity represents the variation of the TB_{TOA} for a given variation of a given parameter. The sensitivities to SST, SSS, OWS, SIC, TCWV, and TCLW are computed using finite differences:

$$K_x = \frac{\Delta TB_{TOA}}{\Delta x} = \frac{TB_{TOA}(x_2) - TB_{TOA}(x_1)}{x_2 - x_1} \tag{2}$$

where x represents the geophysical parameter (SST, SSS, OWS, SIC, TCWV, or TCLW) and K_x the sensitivity to this parameter. In the following, to help interpreting the results, the sensitivity of each parameter from 1 to 40 GHz is normalized by its maximum value:

$$K_{x,norm} = \frac{K_x}{max(K_x)} \tag{3}$$

In addition, for each parameter, the most sensitive polarization is selected. It is systematically the vertical polarization for SST and SSS, and the horizontal polarization for the other variables (SIC, OWS, TCWV, and TCLW).

3 Results

3.1 Sensitivity for a general case

Figure 2 shows the normalized sensitivities of the ocean (SST, SSS, OWS), and atmospheric parameters (TCWV, TCLW), as a function of frequency between 1 and 40 GHz, at 55° incidence angle. The sensitivities are shown for the mid-latitude environment. The CIMR channels are indicated on the top. For each parameter, the sensitivity curve has been normalized as indicated in Eq. 3.

The maximum sensitivity to the SST is obtained at C-band (4-8 GHz) with a value of 0.6 K/K. A large negative sensitivity has been observed on previous similar figures (Wilheit, 1979; Imaoka et al., 2010) at frequencies above $\sim$ 20 GHz: that was due to the lack of atmospheric contribution in the analysis. For SSS, the sensitivity drastically decreases with frequencies, above 1 GHz. In the studied range of frequency~~studied~~, the maximum sensitivity for SSS is of 0.7 K/psu at 1 GHz. The sensitivity to OWS is larger at higher frequencies (>18 GHz) with a maximum sensitivity of 0.9 K/(m/s).

~~The frequency selection for a satellite mission has to account for the International Telecommunication Union (ITU) frequency regulation. Therefore,~~ Note that with this updated version of the Figure of Wilheit (1979) taking into account the ~~flexibility to~~

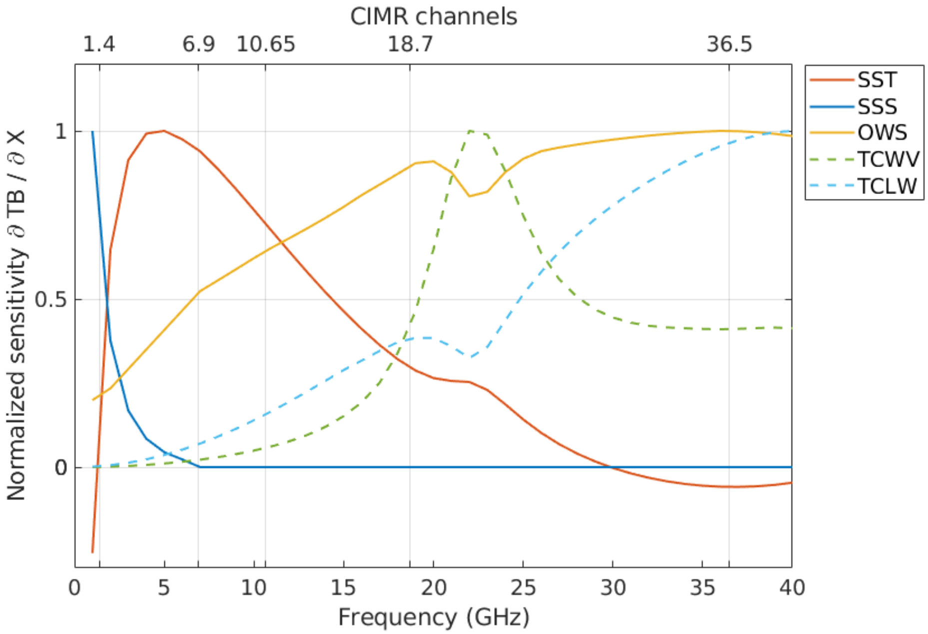

Figure 2. Normalized sensitivities of the satellite measurements to surface parameters (solid lines) and atmospheric parameters (dashed lines) as a function of frequency at 55° incidence angle. For the ocean and atmospheric parameters, the mid-latitude conditions are used. The selected central frequencies for CIMR are indicated (vertical bars).

~~choose the channel frequencies and their bandwidths is limited.~~ sensitivity to the atmosphere, we can see that the sensitivities to the other parameters, such as SST or OWS, are decreased at higher frequencies (>18 GHz), and especially near the water vapor absorption line at 22 GHz.

The CIMR frequencies have been chosen to maximize the measurement sensitivity to the surface parameters, to ensure the continuity of the satellite measurements with current missions (SMOS, SMAP, AMSR2), and to avoid Radio Frequency Interferences (RFI) as much as possible.

~~CIMR has a 55° incidence angle and a large swath (>1900 km) to provide full coverage of the poles (i.e., with no gap at the pole itself), for the first time with a conical scanner.~~ The choice of ~~incidence angle~~ an incidence angle of 55° for CIMR has been constrained by the swath width (to fully cover the poles), and the spatial resolution. By increasing the incidence angle, we increase the swath width, but we degrade the spatial resolution of the measurements for a given satellite altitude (noting that the satellite altitude is fixed to be the same as that of MetOp-SG(B)). This choice of incidence angle has also been tested in terms of sensitivity. The same sensitivity calculations have been performed with smaller incidence angles (not shown): the sensitivities to the ocean surface parameters systematically increase when increasing the incidence angle.

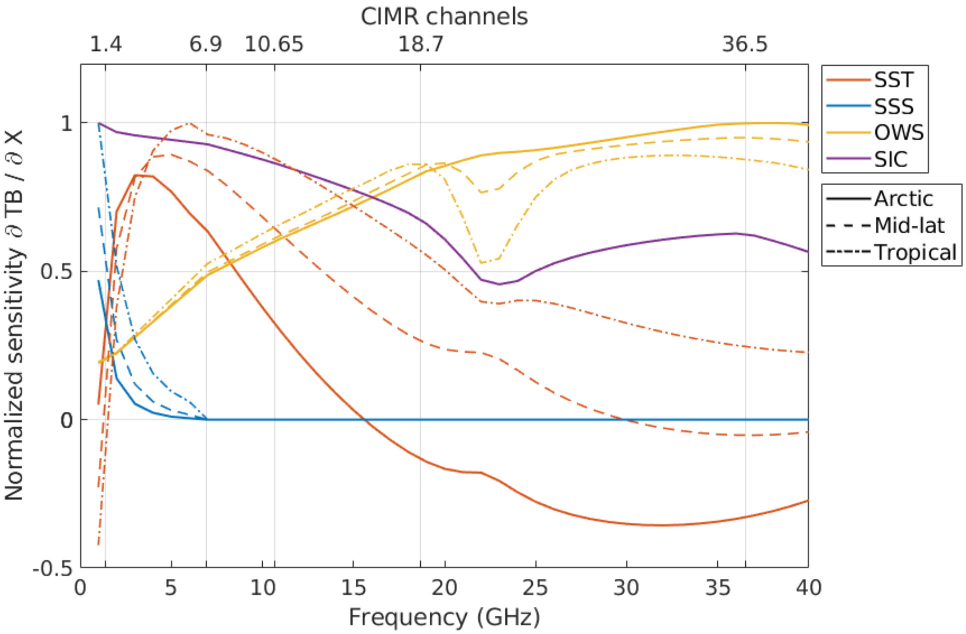

Figure 3. Normalized sensitivities of the satellite measurements to the surface parameters as a function of frequency for the different environments at 55° incidence angle, under clear sky conditions. Solid lines: Arctic. Dashed lines: Mid-latitudes. Dotted lines: Tropical.

3.2 The Arctic case

While CIMR will provide measurements over the global domain on a daily basis, it is primarily designed to observe the arctic environment. This is an extreme environment, with drier atmosphere and colder surface conditions that impact the sensitivity of the satellite observations to the ocean and ice geophysical parameters. This places high demands on the sensitivity of the CIMR radiometer design requirements (Donlon and CIMR Mission Advisory Group, 2020).

Figure 3 shows the sensitivities of the satellite measurements to SST, SSS, OWS, as a function of frequency for arctic, mid-latitude, and tropical environments (the SIC sensitivity is only shown for the arctic conditions). For each ice-free ocean variable, the curves are normalized by the maximum value for the three considered environments.

The maximum sensitivity to the SIC is provided by the frequencies below 10 GHz with a maximum sensitivity of 1.7 K/1%SIC. Note nevertheless that the SIC retrieval also requires high spatial resolution, with the smaller frequencies suffering from a coarser spatial resolution. Under arctic conditions, the sensitivities are clearly reduced for SST and the SSS, as compared to warmer conditions. This will make the retrieval of these variables more challenging (leading to larger uncertainties) under cold environments. This is due to intrinsic physical changes in the dielectric properties of the ocean waters, from cold to warm temperatures. In addition, under arctic conditions, the frequency of the maximum sensitivity to SST and SSS significantly decreases. The maximum sensitivity to SST is between 2 and 4 GHz in the Arctic, and between 5 and 7 GHz in the Tropics. For the SSS, using a flat ocean surface, Dinnat et al. (2018) and Le Vine and Dinnat (2020) observed a maximum SSS sensitivity at

$\sim$400 MHz (resp. 800 MHz) at SST of 0° C (resp. 30° C). For the OWS, the sensitivity decreases with increasing atmospheric opacity, from the Arctic to the Tropics.

3.3 Sensitivities relative to the user requirement precisions

For the CIMR mission, the primary user requirements, as expressed in Donlon and CIMR Mission Advisory Group (2020) in terms of standard total uncertainty, are $\leq$0.3 K for SST in polar regions (55° N or S and above), and $\leq$0.2 K for global coverage, 5% for SIC (averaged over all seasons). For SSS, the requirement is $\leq$0.3 psu over monthly time-scales~~, although this is a secondary geophysical parameter~~. Here, we calculate the change in measured TB_{TOA} corresponding to the required parameter precision. In order to estimate the parameter with the required precision using a single channel retrieval, the instrument noise for that channel will have to be below that level. Note in addition that in these sensitivity calculations, the other parameters are fixed, i.e., there is no uncertainty related to them. For parameters that are not driving the CIMR design, the following precisions are considered: 1 m/s for OWS, 1 kg/m^2 for TCWV, and 20 g/m^2 for TCLW.

Figure 4 shows the results for each parameter in an arctic environment. It highlights the challenge to reach the geophysical precision expected to comply with the mission requirements. For the SST and SSS, the change in measured TB_{TOA} is respectively of 0.08 K per 0.2 K at 6.9 GHz, and 0.06 K per 0.2 psu at 1.4 GHz, meaning that an instrument noise lower than these values is required on the CIMR measurement at those frequencies to retrieve the parameters with the target precision in the arctic conditions, with single channel algorithms. For the OWS, the sensitivity is around 1 K per 1 m/s, and for the SIC, the sensitivity is strong with respect to the target precision, with 8 to 4 K per 5%. The TCWV and TCLW show respectively a sensitivity of 1.0 K per 1 kg/m^2 at 18.7 GHz, and 1.05 K per 20 g/m^2 at 36.5 GHz. Retrieval methods have been developed to benefit from observations in multiple channels with CIMR (Kilic et al., 2018; Jimenez et al., submitted). By using these multi-channels algorithms, it is possible to improve the retrieval precision compared to a single channel algorithm. However, this analysis still provide an indication of the challenges to reach the required retrieval precisions.

4 Conclusions

In this study, we computed the sensitivities to SST, SSS, SIC, OWS, TCVW, and TCLW as a function of frequency between 1 to 40 GHz, using the RTMs from Meissner and Wentz (2012) and Rosenkranz (2017) for the ocean and the atmosphere, and the RRDP for the sea ice. We reproduced the well-kown figure from Wilheit (1979) with state-of -the-art radiative transfer models, taking into account the atmosphere, and considering different geophysical conditions (arctic, mid-latitude, and tropical).

CIMR channels have been selected to provide the best compromise for ocean and sea ice products in terms of precision and spatial resolution considering the other constraints such as the full coverage of the poles, same orbit altitude as MetOp-SG, ITT frequency regulation, and possible RFI contaminations. It also ensures the continuity of the measurements from previous satellite microwave radiometers.

Our sensitivity analysis confirms the channel selection of CIMR: 1.4 GHz is the key frequency to estimate SSS, 6.9 GHz to estimate SST, and the channels between 6.9 and 36.5 GHz to estimate SIC. The frequencies from 18.7 to 36.5 GHz can provide

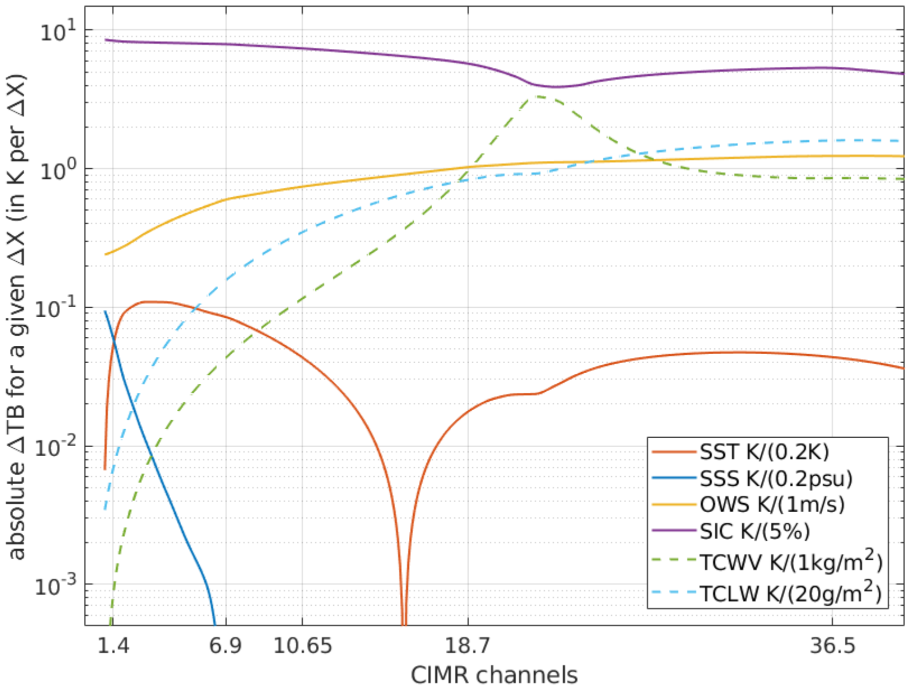

Figure 4. Changes in measured TB_{TOA} corresponding to the required precision of the CIMR parameters. Calculations are performed as a function of frequency, at 55° incidence angle, in the Arctic (SST=0° C, OWS=6 m/s, SSS=34 psu, TCWV=5 kg/m^2). The *units* are indicated in the legend for each ~~parameters~~parameter.

information on OWS, TCWV, and TCLW. In polar regions, the sensitivity to SST and SSS is smaller, and the maximum sensitivity is shifted toward the lower frequencies.

CIMR will provide simultaneous polarized measurements at 1.4, 6.9, 10.65, 18.7, and 36.5 GHz ~~, in both vertical and horizontal polarizations,~~ for the first time on a single satellite. The use of these multiple channels in coincidence to retrieve the ocean and sea ice surface parameters will be a major advantage to reach the target precision required by the user communities, especially in the polar regions. Algorithms are currently under developments to fully exploit the CIMR channels and reach the best performances for the estimation of the ocean and sea ice parameters (Kilic et al., 2018; Scarlat et al., 2020; Kilic et al., 2020; Prigent et al., 2020; Jimenez et al., submitted).

Author contributions. This study was conducted by L.K., and C.P.. C.J., and C.D. have contributed to the writting of the paper.

Competing interests. The authors declare no conflict of interest.

Acknowledgements. We are very grateful to Thomas Wilheit for his comments on his original figure. We thank Remote Sensing Systems for providing their ocean Radiative Transfer Model. We also acknowledge all the members of the CIMR Mission Advisory Group for their discussions and developments on the CIMR mission. This work is in part funded by the European Space Agency CIMR-APE study ESA Contract 40000125255.

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