The reply to the anonymous referee #1 (RC1)

We are thankful to the referee for the very detailed analysis of our study. We appreciate the criticism and accept this criticism as very useful for deeper understanding of the combination of a large number of problems relevant to the considered scientific task (the LWP gradient detection by microwave observations). However, we do not agree with several comments and suggestions made by the esteemed referee and below we present our argumentation for that. At the same time we definitely agree with one of the most important statements of the referee relevant to the general conclusion which was made in our study: there was indeed a discrepancy between our too optimistic declaration: "*…the results confirmed the presence of the horizontal land-sea LWP gradient in the vicinity of the radiometer*" and the results which were presented in Fig. 12. When preparing the revised version of our manuscript we chose another scenario (greatly improved) for training of the regression algorithm and we got new results which are now in full agreement with our previous declaration (please see our answers below).

Despite the fact that we argue with several comments and suggestions of the referee, we took all of them into account while preparing the revised version of our manuscript. We agree that we might have described the corresponding issues in the original version of the article not clearly enough. One of the main critical comments of the referee is related to methodology. We hope that the explanations given in the revised version clarify the logic of our research activities and show why we keep the structure of the article and the approach unchanged in the revised version.

Below, the actual comments of the referee are given in **`bold courier font and blue colour`**. The text added to the revised version of the manuscript is marked by red colour.

Notice: Since both anonymous referees made several similar remarks, our answers to these remarks which are given in both replies are identical.

`In this paper, the authors want to analyze liquid water path (LWP) gradients in a coastal area based on microwave radiometer (MWR) measurements. While the topic in general is of interest, I have substantial concerns about the paper in its present form.`

To the extent of our knowledge the studies devoted to the detection of horizontal inhomogeneities of atmospheric parameters from ground-based passive microwave measurements are not numerous and ours is the first attempt to solve the specific problem relevant to the LWP gradient detection by microwave method in the coastal area. Therefore, we decided that it would be interesting for the scientific community to see the step-by-step analysis of the problem from the very beginning, i.e. starting with the consideration of the forward problem. The task that faces us appeared to be much more complicated than expected when the study had been conceived. We revealed that there are many possible directions of further research both in simulating measurements numerically and in conducting the experiment with modified setup. However, we still have the feeling that the very first results which we obtained will be interesting and useful for the remote sensing scientific community. So, it was the background for our decision to present in the article all our first results along with the identification of problems and possible ways of further development of this research. We do not claim that we obtained the final solution. We demonstrate the complexity of the problem. We partly understand the criticism of the referee towards our paper, but we would like to stress, that the experimental setup of the HATPRO radiometer at our measurements site was initially developed for improving temperature retrievals in the lower layers rather than for solving the problem of the LWP gradient detection. However, we managed to apply these measurements to the task under consideration and got promising results. In order to clarify the logic of our research, we added the following text at the end of the introduction section in the revised version:

> To the extent of our knowledge, the studies devoted to the detection of horizontal inhomogeneities of atmospheric parameters from ground-based passive microwave measurements are not numerous and ours is the first attempt to solve the specific problem relevant to the investigation of the LWP gradient in the coastline area. Therefore, we decided that it would be reasonable to present the step-by-step analysis of the problem starting from the consideration of the forward problem and to demonstrate the complexity of the task that faces us. We used the classical approach to the solution of inverse problem of atmospheric optics: analysis of the forward problem on the basis of simulations, analysis of measured quantities for several test cases, tuning the retrieval algorithm, processing the experimental data with the help of this algorithm, and the comparison of the results to the independent data. Although the concept of using angular measurements to characterize water vapor and liquid water path gradients is feasible, its practical applications are very difficult due to the high variability of the liquid water in the clouds, the inhomogeneity of water vapor, etc.. In addition, we would like to emphasize that the experimental setup of the HATPRO radiometer at our observational site was initially developed for improving temperature retrievals in the lower layers rather than for solving the problem of the LWP gradient detection. However, we managed to apply these measurements to the task under consideration and got promising results.

A large part of the paper is dedicated to the analysis of measured off-zenith brightness temperatures (BTs) in comparison to calculated off-zenith BTs based on the retrieved atmospheric profiles from zenith MWR measurements. The authors state correctly that the BT difference (DTB) which they then derive is related to the gradient in LWP, gradients in T and q as well as further errors and uncertainties. The latter point is really crucial.

To our opinion, we can not distinguish any single point as crucial. In the discussion section of the article, we have indicated a large number of other factors which could provide an impact on the considered problem including the sampling scenario, observational geometry, observational condition control, etc..

Large uncertainties are related to the forward calculations they performed using the retrieved T and q profiles (highly smoothed!) and the retrieved LWP. Even if the retrieved LWP is quite accurate, it is still unclear where to place the liquid water vertically. This is not discussed at all and will lead to large uncertainties in the calculated brightness temperatures and brightness temperature differences. This has large implications for the results shown in Figs. 6-10, but the authors merely discuss them.

We would like to argue with the esteemed referee against this notion. Indeed, the considered microwave remote sensing method provides highly smoothed T and q profiles and this fact is known and it was quantified in a number of studies with the help of DOFS calculation (Degrees Of Freedom for Signal). This essential nature of the radiative transfer of the downwelling radiation in the considered microwave range exhibits itself both in the forward and inverse problems. The brightness temperature calculations for the zenith and off-zenith geometry are equally insensitive to small scale variations of the parameter distributions along the line of sight. Therefore this smoothing feature does not affect our calculations and relevant conclusions. So, we argue that "**This has large implications for the results shown in Figs. 6-10**". The referee pays attention to the important issue which concerns the placement of the cloud vertically. This issue is closely related to the problem of the profile smoothing and poor spatial resolution of the method. The value of DOFS shows the number of independent pieces of information that can be extracted from microwave observations. For liquid water profile, DOFS is less than 2 that means the small influence of the liquid water distribution on the results of the brightness temperature calculations. This fact indicates implicitly that the placement of the cloud vertically does not play a crucial role in forward calculations and in the solution of the inverse problem. A kind of proof for that is a wide use of regression algorithms for joint IWV (integrated water vapour) and LWP retrieval from 2-channel observations under the conditions of large uncertainty in the temperature profile and without any information on the cloud placement. However following the comment of the referee that we merely discuss this problem in the article we added the following text in the section "Case study" just before the analysis of Figs. 6-10:

> Prior to analysing the cases, we would like to make a note concerning the accuracy of calculations of the brightness temperature difference. These calculations use the temperature, humidity and cloud liquid water profiles retrieved from zenith observations as an input. It is well known that the ground-based microwave method has rather poor spatial resolution which yields smoothed profiles and the very large uncertainty of the vertical placement of a cloud. This fact is known and it was quantified in a number of studies with the help of DOFS calculation (Degrees Of Freedom for Signal which show the number of independent pieces of information that can be extracted from observations). This essential feature of the transfer of the downwelling microwave radiation in the considered spectral region exhibits itself both in the forward and inverse problems. The brightness temperature calculations for the zenith and off-zenith geometry are equally insensitive to small scale variations of the parameter distributions along the line of sight. Therefore this smoothing feature does not affect our calculations and relevant conclusions. The current version of the retrieval setup assumes the placement of a cloud inside the 0.5-5.5 km altitude range (low and medium clouds). Outside this range, the cloud liquid water profile is constrained to zero values. The workability of this retrieval setup has been confirmed in the study devoted to cross-validation of different methods of the LWP retrieval (Kostsov et al., 2018a). For liquid water profile, DOFS is less than 2 that means the small influence of the liquid water distribution on the results of the brightness temperature calculations. This fact indicates implicitly that the placement of the cloud does not play a crucial role in forward calculations and in the solution of the inverse problem. Also, a kind of proof for that is a wide use of regression algorithms for joint IWV (integrated water vapour) and LWP retrieval from 2-channel observations under the conditions of large uncertainty of the temperature profile and without any information on the cloud vertical location. Based on the above mentioned reasons, we consider the applied radiative transfer model accurate enough for making comparisons between measured and calculated brightness temperature values. Also, it is important to note that most of the cases which were selected for analysis are characterized by clear sky conditions over the water area, therefore the cloud placement error is absent for the off-zenith calculations.

As far as the issue of the cloud placement is concerned, we note that this placement (not only vertical, but also horizontal) becomes very important for scattered clouds with horizontal size smaller than the size of the water body under investigation. This is due to the specific off-zenith observational geometry. In the revised version of the article we discuss this circumstance in the new subsection 2.2 on the basis of extensive modelling of scattered clouds and corresponding radiative transfer calculations:

> ### 2.2 Modelling of measurements in the atmosphere with scattered clouds
>
> Fig. 5b refers to an overcast atmospheric situation which is the simplest but idealised case for estimation of the magnitude of the LWP gradient effect in the measurement domain. In order to be closer to reality, we simulated the scattered clouds over land and sea in the vicinity of the radiometer using a Monte Carlo method. The observational plane (see Fig. 2) was extended and divided into cells (two rows, each row contained 4 cells of the 12x3.25 km size) located over the Gulf of Finland and two opposite shores. In each cell, the random number generator produced the values of the following cloud parameters: the vertical extent (0.3-2 km, uniform distribution); horizontal size (0.5-5 km, uniform distribution); the cloud placement within a cell (uniform distribution); LWP (lognormal distribution). It should be emphasized that the average horizontal size of generated clouds was much smaller than the size of the water body under investigation. While modelling the LWP values, we considered two situations: one with the existing LWP land-sea gradient and another without such a gradient. The mean LWP values for the first situation were the same as taken previously for overcast conditions: (0.08 and 0.04 kg m^{-2} for land and sea correspondingly). For the second situation, the mean LWP value was taken as 0.08 kg m^{-2} everywhere. The number of generated cases was about 165000. Every

instantaneous cloud spatial distribution was combined with one set of the meteoparameter profiles (temperature, pressure, and humidity). For these meteoparameters, the assumption of horizontal homogeneity was used. The sets of profiles were obtained in the course of 2 years of observations by the HATPRO radiometer (2013-2014) with the sampling interval of 2 min. As a result, we obtained a statistical ensemble which characterised all seasons.

The important issue which should be discussed with special attention is the influence of the instrument field-of-view (FOV) on the interpretation of the off-zenith measurements. The 22 and 31 GHz channels are optically transparent even for small elevation angles. If the vertical distributions of atmospheric parameters within FOV at a certain distance from the radiometer can be approximated by linear functions, the effect of FOV will be negligible. The situation can change crucially in case of scattered clouds, especially small size clouds and small elevation angles. With a 3-degree FOV, the HATPRO radiometer will be sampling an air portion of about 1 km vertical size at 20 km distance from the radiometer. Possible configurations of the observational geometry in case of scattered clouds are illustrated in Fig. A. One can see that small clouds may appear entirely within FOV of the radiometer (as shown in Fig. A for the cloud over the opposite shore). Some clouds may be missed by observations due to their location in between the lines-of-sight (LOS) corresponding to different elevation angles. Two or more scattered clouds may fall into FOV. Moreover, one cloud may be detected both in zenith and off-zenith observations.

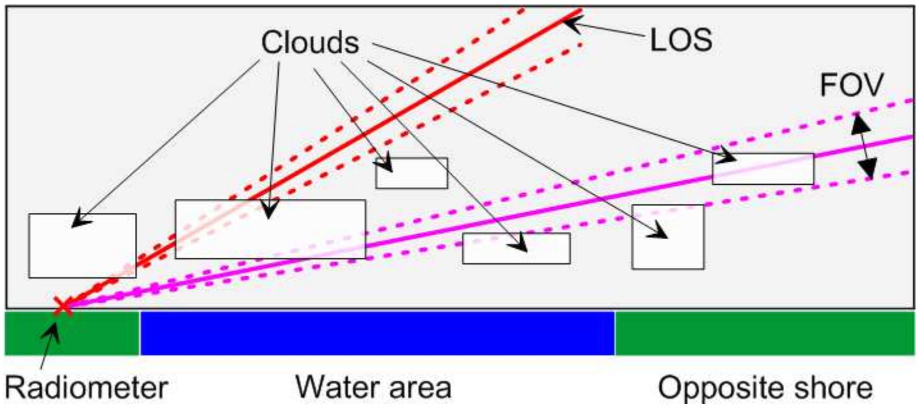

Fig. A: Possible configurations of the observational geometry in case of scattered clouds (a schematic illustration). Solid lines designate the line-of-sight (LOS) of the observations at various elevation angles. Dashed lines show the field-of-view (FOV) of the radiometer.

Fig. A demonstrates the large variety of atmospheric situations. Obviously, for scattered clouds it makes no sense to compare single zenith and off-zenith observations since the LWP gradient signal is a random value under such conditions. It is evident that taking into account not only the spatial variability of clouds but also their temporal variability, we can speak about the LWP gradient component in measurements only in terms of mean values obtained by averaging over large amount of data. Fig. B presents the statistical distributions of simulated brightness temperatures at 31.4 GHz for four elevation angles. For each angle two situations are considered: one with existing LWP land-sea gradient and another without such gradient. The input data for radiative transfer calculations were the Monte Carlo simulations of scattered clouds described above. One can see from Fig. B that for all angles the distribution "with gradient" is shifted towards smaller brightness temperature values if compared to the distribution "without gradient"; however this effect is less pronounced for the elevation angle 11.4° due to the influence of the clouds over the opposite shore of the water body.

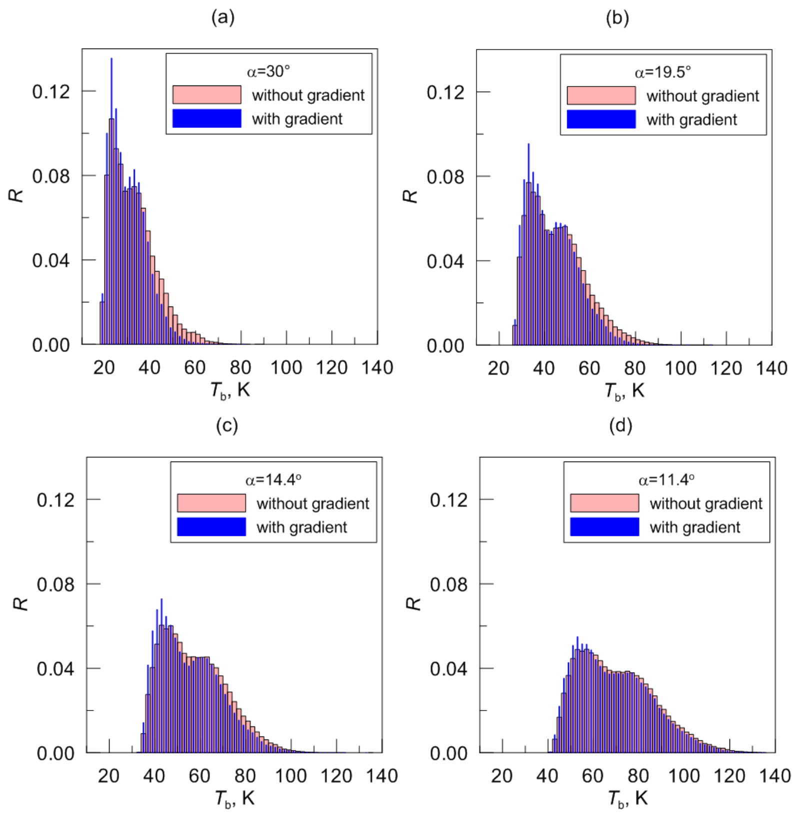

Fig. B: Statistical distributions (in terms of relative frequency of occurrence *R*) of brightness temperatures at 31.4 GHz simulated for four elevation angles and for two situations: one with existing LWP land-sea gradient and another without such gradient. Input data: the Monte Carlo model of scattered clouds.

In order to estimate the component in measured quantity, which is related to the LWP land-sea gradient effect, we analyse the difference between the mean values of T_b datasets which were calculated for situations without and with the gradient. This difference is equivalent to the D_{grad} values shown in Fig. 5b and presents a measure of the “useful signal” relevant to the LWP gradient contribution. Therefore, we use the same designation of this difference and show it in Fig. C as a function of the elevation angle. One can see the dramatic contrast to the overcast case (see Fig. 5b). For scattered clouds, there is no increase of the useful signal for smaller elevation angles. Contrariwise, the D_{grad} values for elevation angles 11.4° and 14.4° are lower than for the angles 19.5° and 30°. The sharp decrease of D_{grad} at 11.4° is explained by the influence of high LWP of the clouds over the opposite shore of the water body.

In order to assess if the instrument FOV affects the magnitude of the useful signal, we present in Fig. C the D_{grad} values which were calculated for infinitely narrow beam width, i.e. neglecting FOV. The results show that there are no considerable differences between the cases “accounting for FOV” and “neglecting FOV”. One should keep in mind that we compare the results which were obtained by averaging of a very large number of individual measurements.

However the effect of FOV exists and it is illustrated by Fig. D which shows the statistical distribution of the difference between the brightness temperature obtained neglecting FOV and the brightness temperature obtained accounting for FOV. We suggest that this difference is a measure which characterises in the best way the FOV influence on the results of the interpretation of the off-zenith measurements. The effect of FOV exhibits itself in the form of additional measurements noise which has a systematic and a random component. The absolute value of the systematic component (characterised by the mean value of the distribution) is less than 0.5 K for all four considered elevation angles and this value can be considered as negligible. No specific dependence of the systematic component on the elevation angle can be seen. In contrast, the random component, which is characterised by the standard deviation, increases for smaller elevation angles. The obtained values of the random component can be used for the estimation of a minimal number of individual measurements which should be sampled in order to suppress considerably the influence of FOV. For example, for a set consisting of about 600 individual measurements, the random component of the error due to neglecting FOV at the elevation angle 11.4° will be reduced to the value about 0.1 K. It means that for the current experimental setup averaging over the 10 day time period is enough for suppressing the random error due to FOV.

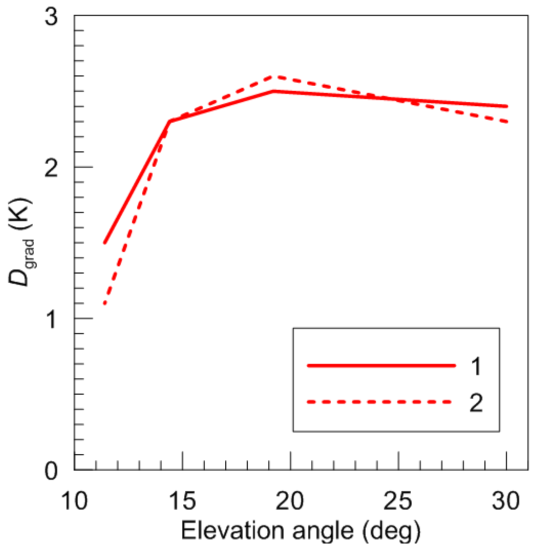

Fig. C: The LWP gradient signal D_{grad} as a function of the elevation angle at 31.4 GHz. Input data: the Monte Carlo model of scattered clouds. Solid line (1) corresponds to the results obtained with account for FOV; dashed line corresponds to the results obtained when FOV is neglected.

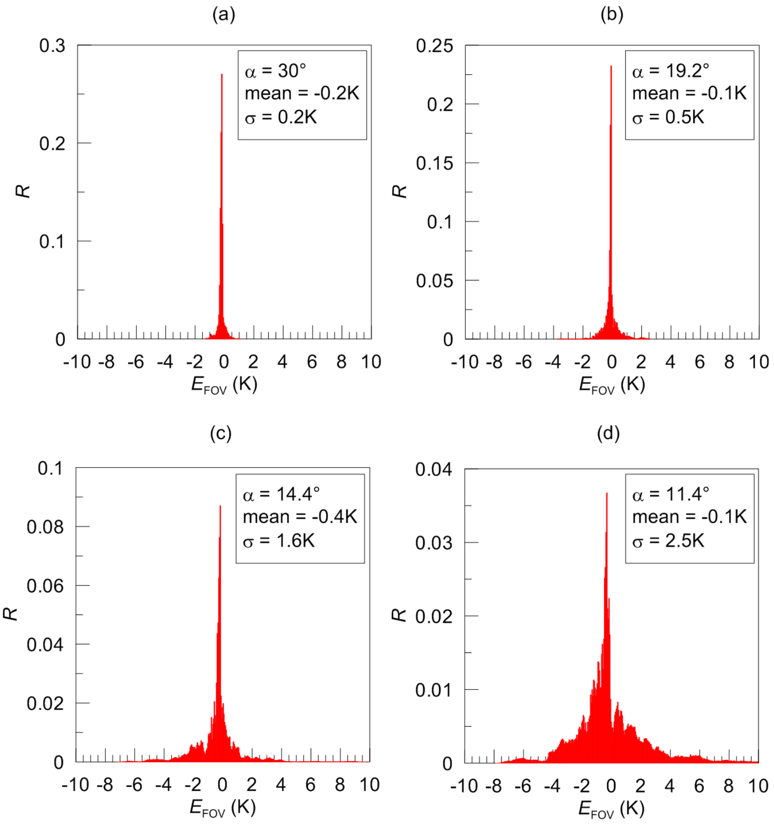

Fig. D: Statistical distributions (in terms of relative frequency of occurrence R) of brightness temperature difference E_{FOV} "T_B neglecting FOV minus T_B accounting for FOV" at 31.4 GHz simulated for four elevation angles. Input data: the Monte Carlo model of scattered clouds.

So, the described Monte Carlo simulations of clouds and the brightness temperature calculations lead to several important conclusions. First, we reiterate that for scattered clouds it makes no sense to compare single zenith and off-zenith observations since the LWP gradient signal is a random value under such conditions. Second, for averaged quantities, the magnitude

> of the component of measured signal determined by the LWP land-sea gradient (useful signal) in case of scattered clouds is rather small and therefore one can expect difficulties in detecting it, especially taking into account the presence of a large number of interfering factors. Third, the instrument FOV affects the results of the off-zenith measurements in case of scattered clouds by introducing additional noise. Its systematic component is small and averaging over several hundred cases can minimise its random component. So the assumption of infinitely small beam width can be used for processing measurements if the analysis is done for averaged quantities.

The authors see the problem of disentangling the BT signal of the LWP gradient and that is why the analysis is very qualitative. However, this discussion does not provide a new insight. The conclusions which are drawn could be made without having these measurements: e.g. a liquid cloud located over the instrument with a clear-sky scene around will cause positive DTB values. In my opinion, the whole section on the BT comparison does not provide new insights but rather leaves the reader with many more open questions.

If we understand the referee's opinion correctly, it refers to the section "Case study". We can not agree with this opinion and our reasons are the following:

1) Forward calculations and their comparisons with measurements (analysis in the measurement domain) are very important and in many studies they are a first and an essential step before solving an inverse problem. They are especially useful when considering the multi-parameter inverse problems which physically are formulated as ill-posed. The solution of such problems implies the application of a priori information which can affect the result to a great extent. Besides, in case multiple parameters are retrieved simultaneously, their retrieval errors are coupled in a complex way. These two factors can make the analysis in the domain of sought parameters difficult and ambiguous. Therefore, we start with the analysis in the measurement domain for better understanding of the useful and interfering signals.
2) We guess that the referee refers to our conclusion #1 in the end of section 3 when stating that "**The conclusions which are drawn could be made without having these measurements**". This statement of the esteemed referee does not seem so obvious since: (a) clouds are atmospheric objects, which are characterised by extremely large spatial and temporal variability; (b) probably, the position of the radiometer with respect to the coastline and the experimental setup and geometry are not optimal for the considered task. Therefore, the model simulations should be verified by comparison with experimental data. Besides the theoretical prediction of the value of useful signals should be compared to the experimental data.
3) The referee makes the remark about very qualitative character of our analysis. This is correct to a certain extent since the true state of the atmosphere over the water body (the Neva bay) was unknown: the SEVIRI instrument provides averaged data on LWP, and there was no information on pressure, temperature and humidity profiles. Obviously, quantitative analysis is problematic under such circumstances, but this is not our fault. We managed however to make estimations of the useful and interfering signals.

However, following the referee's comment we added a paragraph in the beginning of section 3:

> Forward calculations and their comparisons with measurements are the preliminary and essential steps before solving inverse problems in many studies. Analysis in the measurement domain can be especially useful when considering the multi-parameter inverse problems which physically are ill-posed. The solution of such problems implies the application of a priori information which can affect the result to a great extent. Besides, in case multiple parameters are retrieved simultaneously, their retrieval errors are coupled in a complex way. These two factors can make the analysis in the domain of sought parameters difficult and ambiguous. Therefore we start with the analysis in the measurement domain for better understanding of the useful and interfering signals. Since clouds are atmospheric objects which are characterised by extremely large spatial and temporal variability and since the experimental setup and geometry

> were not optimised for considered task, the model simulations should be verified by comparison with experimental data. In addition, the theoretical prediction of the value of useful signal should be compared to the experimental data.

Additionally, we modified the conclusion #1 in section 3:

> Concluding this section, we can formulate the following statements:
>
> 1) As predicted, the LWP land-sea gradient (higher LWP over land, lower LWP over water) is detectable and shows up as positive values of the difference between modelled and measured brightness temperatures of the MW radiation. These positive values can be seen in the whole considered range of elevation angles (4.8°-30°). The experiment revealed that the magnitude of the useful signal (D_{grad}) can vary from 2 K to 24 K depending on elevation angle and LWP land-sea difference (as it is provided by the SEVIRI satellite instrument). Obviously, thorough quantitative analysis is problematic due to the fact that the true state of the atmosphere over the water body (the Gulf of Finland) was unknown: the SEVIRI instrument provided averaged data on LWP, and there was no information on corresponding pressure, temperature, humidity profiles and type of cloudiness.

The authors recognize that the best way to proceed is to develop and apply LWP retrieval algorithms and compare LWP directly for the different elevation angles. I agree that this is the way to go, however, again the methodology that they follow to derive the retrieval coefficients is not sound: the authors take the retrieved T and q profiles together with the retrieved LWP again to simulate the BTs for the various elevation angles. Also, here it is not reasonable to use the retrieved profiles for the forward calculations due to the very smoothed T and q profiles (which are thus not representing the realistic atmospheric state). It is again not clear how LWP is vertically distributed. A proper way to generate retrieval coefficients is to use a representative, realistic set of atmospheric profiles from radiosonde or NWP model data.

We do not agree with this statement. Above, we have already presented our opinion about the problem of profile smoothing and the cloud vertical placement in general and about their influence on the results of the forward calculations in particular. As we have already noticed, the more important problem is the cloud horizontal size and placement in case of scattered clouds. In the revised version of the manuscript, we applied our Monte Carlo model of scattered clouds for the derivation of regression coefficients. We used these new regression coefficients and added the retrieval results to the plots which show monthly means of the LWP gradient, please see our answers below.

The MWR measurements/simulations are also set into context to a SEVIRI LWP product. In order to be able to set the results in context to SEVIRI, which views a different scene than HATPRO, a more thorough analysis of the representatively is needed.

We strongly disagree with this remark of the referee. First of all, thorough comparison of the HATPRO and SEVIRI data on LWP has already been done in two previous papers by the authors' team published in AMT. The references to these papers are given in the present article in the proper context. We do not think that it is necessary to reproduce already published results. However, addressing this remark of the referee, in the middle of section 4 after the formulae (6, 7, 8) we added a short note in order to emphasize the agreement between the HATPRO and SEVIRI data which had been demonstrated previously:

> We would like to emphasize that the extensive and thorough comparison of the HATPRO and SEVIRI data on LWP for pixel 243 has already been made and the results have been published (Kostsov et al., 2018b, 2019). Good agreement for daily mean LWP of the ground-based and satellite data has been revealed. Moreover, the cross-comparison of the HATPRO LWP data with the data from two space-borne instruments SEVIRI and AVHRR confirmed the agreement not only for averaged values, but also for single measurements (Kostsov et al.,

> 2019). To date, there were no attempts to compare the satellite and ground-based data on LWP over water surfaces. However, the validity of the satellite data over large water bodies was confirmed implicitly by the comparison of the SEVIRI and AVHRR results over the Gulf of Finland and the Lake Ladoga (Kostsov et al., 2019).

I am not sure how much can be concluded from the comparison provided in Figs. 11-12. Yes, on the one hand, SEVIRI and the MWR reveal similar signatures to some extent, on the other hand there are also quite differences. It is totally unclear if this is due to sampling issues, viewing geometry or methodology. Even if uncertainties are discussed I do not see a robust result that can be provided from this comparison.

We agree with this remark of the referee. The approach to training the regression algorithm which we had applied previously appeared to be ineffectual (we trained the algorithm separately for each of the considered seasons and years and considered the overcast case only neglecting scattered clouds with varying horizontal and vertical extent). When preparing the revised version of the manuscript, we made thorough forward modelling of scattered clouds and on the basis of this modelling we trained the regression algorithm. The proper training yielded new retrieval results which are robust and clearly show the presence of the LWP land-sea gradient and its seasonal features. We added the comparison with the reanalysis data which showed good agreement between the microwave data and reanalysis data. A large part of section 4 has been changed. The new text and figures are presented here:

> In the course of developing the retrieval algorithm, we used two variants of training data sets. At first, we trained the algorithm separately for each of the seasons and years and considered only the overcast case with limited range of variations of the cloud base and the cloud vertical extension. This approach appeared to be ineffectual and did not produce robust results. It was found that extensive forward modelling of scattered clouds with highly variable parameters was necessary. Therefore, finally, training of the regression algorithms was performed on the basis of the Monte Carlo modelling of the atmosphere with scattered clouds described in subsection 2.2. The complete training dataset included the values of LWP calculated along the line-of-sight and converted to the LWP in the vertical column. In case of crossing several clouds by the line-of-sight the LWPs from all these clouds were taken into account. The brightness temperatures at 22.24 GHz and 31.40 GHz were calculated accounting for the instrument FOV. This training dataset was used to derive the regression coefficients. As a result, for each of the regression algorithms (linear or quadratic) of the LWP retrieval we had at our disposal 8 sets of regression coefficients corresponding to 8 elevation angles. Testing of the regression algorithms in the numerical experiments conducted for simulated overcast conditions and scattered clouds has shown that the algorithms overestimate the true LWP for off-zenith observations with the bias in the range 0.003-0.006 kg m^{-2} (for elevation angle 60°). The bias slightly increases for smaller elevation angles. For zenith observations, the bias is negligibly small. So, we can make the conclusion that the algorithms can not overestimate the LWP gradient, if it is detected while processing field measurements.
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> …………….
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> We would like to emphasize that the extensive and thorough comparison of the HATPRO and SEVIRI data on LWP for pixel 243 has already been made and the results have been published (Kostsov et al., 2018b, 2019). Good agreement for daily mean LWP of the ground-based and satellite data has been revealed. Moreover, the cross-comparison of the HATPRO LWP data with the data from two space-borne instruments SEVIRI and AVHRR confirmed the agreement not only for averaged values, but also for single measurements (Kostsov et al., 2019). To date, there were no attempts to compare the satellite and ground-based data on LWP over water surfaces. However, the validity of the satellite data over large water bodies was confirmed implicitly by the comparison of the SEVIRI and AVHRR results over the Gulf of Finland and the Lake Ladoga (Kostsov et al., 2019).
>
> Taking into account the remarks made above, we can analyse Fig. 12. First of all, we pay attention to the fact that after removing the LWP values greater than 0.4 kg m^{-2} from the SEVIRI datasets the D_{LWP} derived from satellite observations became much smaller than shown in Fig. 11 for the complete datasets. However the temporal behaviour remains the same as in Fig. 11 for all seasons if we look at D_{S1}. If we look at D_{S2} and D_{S3} we can notice the increase of values from February to March 2013 instead of decrease as shown in Fig. 11. The most important result shown in Fig. 12 is that the ground-based microwave measurements definitely detect the LWP land-sea gradient during all seasons and this

gradient is positive as in case of the satellite measurements (larger LWP values over land and smaller over sea). The gradient is negative only for March 2013 but its corresponding absolute value is small. Comparing the gradients obtained by the ground-based measurements during warm and cold seasons we may conclude that in general the gradients during cold season are smaller than during warm season and not as variable as during warm season. For warm season, the gradient derived from microwave measurements at the 60° elevation angle is smaller than the gradients obtained from measurements at other elevation angles. It is interesting to note that there are no noticeable differences between the values corresponding to elevation angles 11.4°, 14.4° and 19.2° during warm season and between the values corresponding to all considered angles during cold season. This fact leads to the conclusion that the clouds over the opposite shore do not produce a noticeable influence on the results. Therefore hereafter when comparing the SEVIRI and HATPRO data we shall consider only the D_{S1} values.

For the warm seasons of 2013 and 2014, temporal behaviour of the LWP gradient revealed by the satellite measurements completely differs from that obtained by the ground-based measurements. The satellite measurements show two local maxima in June-July and in October while the ground-based measurements demonstrate maxima in May and August-September. The maximal values of the gradient derived from satellite observations are much larger than the maximal values of the gradient derived from ground-based observations. In contrast to the warm season, during the cold season the temporal behaviour of the gradient is the same for the SEVIRI and the HATPRO results. In order to find any explanations for the agreement of the results in terms of temporal behaviour during cold season and the disagreement during warm season, additional investigations are necessary involving thorough assessment of the error budget of the results – not only ground-based but also derived from satellite observations. It should be noticed that the analysis of the quantities in the measurements domain demonstrated several similar patterns in temporal behaviour of D_{TB} and D_{LWP} during warm season of 2014 and cold season of 2013.

It is interesting to compare the obtained values of the LWP land-sea gradient with the data which are provided by reanalysis, namely ERA-Interim from ECMWF (Dee et al., 2011). The main shortcoming of such comparison is the coarse spatial resolution of the reanalysis data. The internal resolution of the ECMWF data is 0.75 deg, i.e. about 80 km which is too poor to describe the scene of our experiment. For higher resolutions of the reanalysis data, the interpolation procedure is applied, but the highest recommended resolution is 0.25 deg (28 km). So we have chosen the 28 km resolution but even in this case we could not apply the reanalysis data to the scene of our experiment. Therefore we selected two areas 0.25×0.25 deg which are the nearest to the HATPRO radiometer and which represent the land surface and the water body. The location of these areas on a map is shown in Fig. E. The ECMWF data for land surface refers to the territory located about 30 km to the south from the HATPRO radiometer. The ECMWF data for the water surface refers to the territory located about 120 km to the west and 30 km to the north from the measurement site. The ECMWF data on LWP for 6 and 12 UTC were collected and averaged over a period of one month.

The comparison of the LWP gradient from SEVIRI, HATPRO and the ECMWF reanalysis is presented in Fig. F. Due to large displacement of the reanalysis data we can not expect the agreement in temporal behaviour but we can compare the average magnitude of the LWP gradient. For a warm season, one can see a very good coincidence of the magnitude of the LWP gradient derived from the ground-based observations and provided by reanalysis. The best agreement can be seen for the period May-July/August. The discrepancies increase during the period August-October 2014. For the cold season in contrast to SEVIRI and HATPRO, the reanalysis provides negative LWP land-sea gradients. However, the absolute values of these gradients are not large. The HATPRO results display positive gradients and the temporal patterns are similar to the patterns shown by the SEVIRI data. In general, we can make three main conclusions from this comparison. First, the SEVIRI and the HATPRO instruments detect positive LWP land-sea gradients during all seasons but the magnitude of the gradient detected by the ground-based instrument is considerably smaller than detected by the satellite instrument. Second, the LWP gradients provided by HATPRO and reanalysis during the warm season are in a very good agreement. Third, the reanalysis data demonstrate negative LWP gradient during cold season in contrast to the SEVIRI and the HATPRO data. The mean values of the LWP land-sea gradient for all considered time periods are given in Table T1. One can see that there are no noticeable seasonal differences in the SEVIRI data while the HATPRO results demonstrate lower values during cold season. The analysis of physical reasons for the seasonal differences in the LWP land-sea gradient is beyond the scope of the present study. To our opinion, such analysis requires much more data including the satellite data sampled over various water bodies.

Also, Fig. F demonstrates how some factors affect the obtained results. We present D_{LWP} obtained by the HATPRO instrument at the elevation angle 14.4° for three scenarios of training the regression algorithm. The main scenario describes scattered clouds, existing LWP land-sea gradient, and the microwave measurements with the account for FOV. The second scenario neglects FOV and the third one describes the conditions without LWP land-sea gradient. One can see both factors produce negligibly small effect on the obtained results. The conclusion was expected since neglecting FOV is equivalent to the presence of additional random noise which is suppressed by averaging. Also, it is important to mention that the presence of the LWP land-sea gradient in the training data set does not automatically provide its detection when processing the field campaign data. The training was performed with respect to LWP values rather than the gradient values. Besides, the training was performed for each elevation angle separately.

Table T1. Mean values of the LWP land-sea gradient (kg m^{-2}) for different time periods derived from the SEVIRI and the HATPRO observations and provided by the ECMW reanalysis.

Season	SEVIRI	HATPRO	ECMWF
2013WH	0.022	0.011	0.009
2014WH	0.025	0.013	0.006
2013CD	0.018	0.003	-0.005
2014CD	0.022	0.005	-0.003

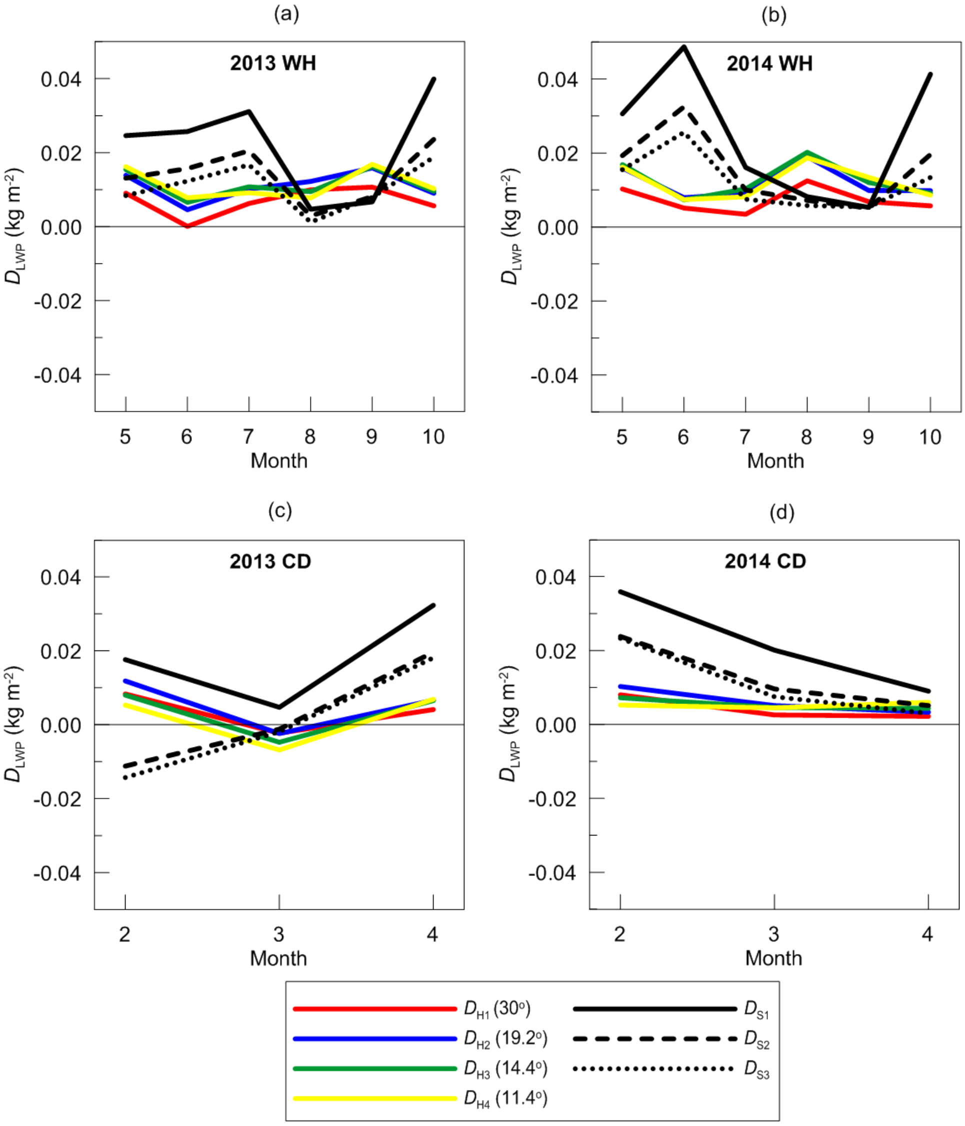

Figure 12: Monthly mean land-sea LWP difference D_{LWP} as a function of time for various time periods obtained from the satellite and the ground-based observations. D_{Hj} (j=1,…,4) denote D_{LWP} obtained by the HATPRO instrument at four

elevation angles (colour lines, see the legend). D_{Sj} (j=1,2,3) denote D_{LWP} obtained by the SEVIRI instrument and calculated by three different formulae, see the text.

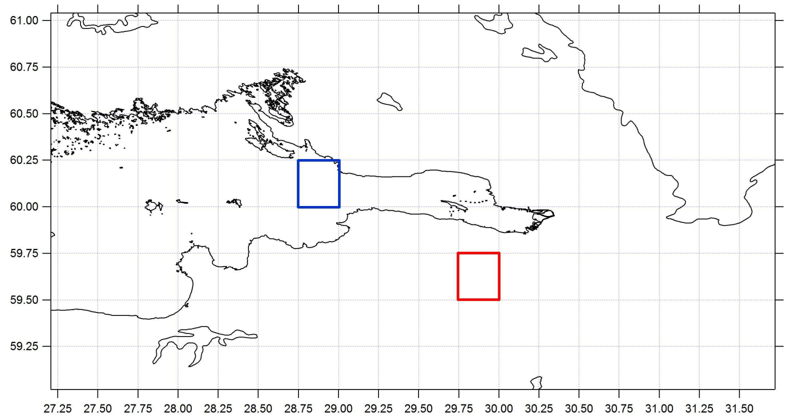

Fig. E: The map showing the geographical location of the reanalysis data on LWP for the land surface (red) and for the water body (blue).

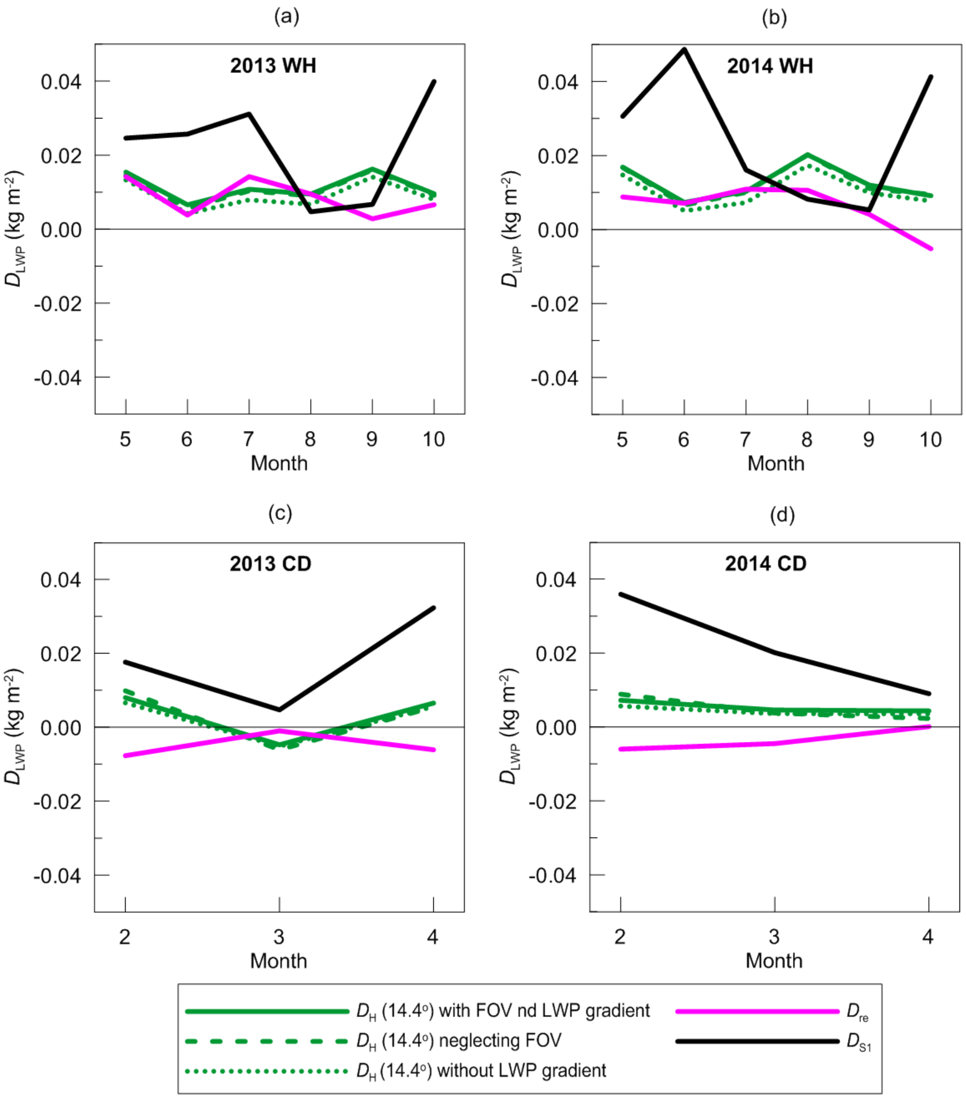

Figure F: Monthly mean land-sea LWP difference D_{LWP} as a function of time for various time periods obtained from the satellite and the ground-based observations. D_H denotes D_{LWP} obtained by the HATPRO instrument at the elevation angle 14.4° for three scenarios of training the regression algorithm (green lines, see the legend). D_{S1} denotes D_{LWP} obtained by the SEVIRI instrument and calculated by formula (6). D_{re} is the LWP land-sea gradient provided by the ECMWF reanalysis.

In the end, the authors state that: “The main conclusion of the study is the following: the approach to detection of the land-sea LWP gradient from microwave measurements by the HATPRO radiometer operating at the observational site of St.Petersburg State University has been successfully tested and the results confirmed the presence of the horizontal land-sea LWP gradient in the vicinity of the radiometer”. When looking at Fig.12, D_LWP for HATPRO reveals various kinds of differences for LWP in zenith and offzenith directions. These differences are sometimes positive, sometimes negative but there is not a scientific conclusion which can be drawn in my opinion; at least from the results which are presented and considering all the uncertainties which are prevailing in the methodology. Thus, the paper does not provide substantial new insight in this topic in its current form.

We agree in general with this remark but we partly disagree with the conclusion of the esteemed referee that “**the paper does not provide substantial new insight in this topic in its current form**”. Our study tackles not one single topic of a kind “does the LWP land-sea gradient exist or not?” but a variety of problems and aspects relevant to passive microwave remote sensing using off-zenith geometry. Our study is pioneering in solving the specific task of the LWP land-sea gradient detection and therefore it is natural that some questions are left open. We would like to draw the attention of the esteemed referee to the title of our paper: “feasibility study”. Our study is self-consistent in this respect and new insights which are present in the paper refer to the experimental results and their all-round analysis. As far as our conclusion is concerned, we have already mentioned in the beginning of our reply that we definitely agree with one of the most important statements of the referee relevant to the general conclusion which was made in our study: there was indeed a discrepancy between our too optimistic declaration: “…*the results confirmed the presence of the horizontal land-sea LWP gradient in the vicinity of the radiometer*” and the results which were presented in Fig. 12. When preparing the revised version of our manuscript we chose another scenario (greatly improved) for training of the regression algorithm and we got new results (described above) which are now in full agreement with our previous declaration. However we have rearranged the conclusion section accounting for the new retrieval results:

6 Summary and conclusions

Previously, the measurements of the cloud liquid water path (LWP) by the SEVIRI and AVHRR satellite instruments provided the evidences of the systematic differences between LWP values over land and water areas in Northern Europe. In the present study an attempt is made to detect such differences by means of ground-based microwave observations performed near the coastline of the Gulf of Finland in the vicinity of St.Petersburg, Russia. The microwave radiometer RPG-HATPRO located 2.5 km from the coastline is functioning in the angular scanning mode and is probing the air portions over land (at elevation angle 90°) and over water area (at 7 elevation angles in the range 4.8°-30°). The data obtained within the time period December 2012 – November 2014 were taken for analysis.

In this study we used the classical approach to the solution of inverse problem of atmospheric optics: analysis of the forward problem on the basis of simulations, analysis of measured quantities for several test cases, tuning the retrieval algorithm, processing the experimental data with the help of this algorithm, and the comparison of the results to the independent data. The decision to make such step-by-step analysis was stipulated by the fact that although the concept of using angular measurements to characterize water vapor and liquid water path gradients is feasible, its practical applications are very difficult due to the high variability of the liquid water in the clouds, the inhomogeneity of water vapor, etc.. The high temporal and spatial variability of cloud parameters (vertical and horizontal placement, horizontal size, LWP, vertical extension) are the reason for solving the problem of detection of the LWP land-sea gradients only on the basis of averaging of a large number of measurements.

At the first stage on the basis of simulations including the Monte Carlo simulations of the atmosphere with scattered clouds, the assessment was done of the magnitude of the LWP land-sea gradient signal in the brightness temperature measurements. The estimations show that the mean value of this signal at 31.4 GHz can vary in a wide range from 2.5 K for scattered clouds up to 4-14 K for overcast conditions. The instrument field-of-view (FOV) affects the results of the off-zenith measurements in case of scattered clouds by introducing additional noise. The systematic component of this noise is small and averaging over several hundred cases can minimise its random component. So the assumption of infinitely small beam width can be used for processing measurements if the analysis is done for averaged quantities.

At the second stage of investigations the problem of the LWP gradient detection is examined in the measurement domain in the special case study. The brightness temperatures of the microwave radiation measured at different elevation angles in the 31.4 GHz and 22.24 GHz spectral channels are analysed and compared with the corresponding values which were calculated under the assumption of horizontal homogeneity of the atmosphere. The difference between measured and calculated brightness temperatures D_{TB} is taken as a main quantity for analysis. Several specific cases, selected on the basis of the satellite observations by the SEVIRI instrument were considered in detail including: clear-sky conditions, the presence of clouds over the radiometer and at the same time the absence of clouds over the Gulf of Finland, and the overcast conditions over the radiometer and over the opposite shore of the Gulf of Finland. As predicted, the LWP land-sea gradient (higher LWP over land, lower LWP over water) shows up as positive values of the difference between modelled and measured brightness temperatures of the MW radiation. The analysis of the test cases revealed that the magnitude of the LWP gradient signal in brightness temperature measurements can vary from 2 K to 24 K depending on elevation angle and LWP land-sea difference (as it is provided by the SEVIRI satellite instrument). These positive values can be detected in the whole considered range of elevation angles (4.8°-30°). The effect of LWP land-sea gradient at small elevation angles can be masked by the signal from clouds over the opposite shore of the Gulf of Finland. Besides, there is a systematic negative component of the brightness temperature difference which is clearly revealed under cloud-free conditions and can reach in the warm and humid season 20K by its absolute value at small elevation angles. So far, we do not have enough information for accurate identification of the origin of this negative component.

The analysis of monthly mean values of D_{TB} at 31.4 GHz (the LWP gradient signal in the measurement domain) does not lead to unambiguous conclusion about the existence of the LWP land-sea gradient since the sign of these values is alternating. However, several similar patterns were detected in the temporal behaviour of D_{TB} and the LWP gradient derived from the satellite observations by the SEVIRI instrument (in particular for May-August of 2013 and 2014 and for February-April 2013). The presence of these similar patterns confirmed the conclusion that the systematic component in measurements makes the analysis in the brightness temperature domain (i.e. measurement domain) complicated. The suggestion has been made that this systematic component is caused by water vapour inhomogeneity. In order to perform a separation of variables in our problem, we abandoned the analysis of the quantities in the measurement domain and started the analysis in the domain of sought parameters. Linear and quadratic regressions have been selected as suitable retrieval algorithms for the LWP retrievals.

Training of the regression algorithms was performed on the basis of the Monte Carlo modelling of the atmosphere with scattered clouds which was used for extensive simulations of the microwave measurements when the forward problem was analysed. In the present study, we used for retrievals only two of seven spectral channels in the K-band: 22.24 GHz and 31.40 GHz. Testing of the regression algorithms in the numerical experiments conducted for simulated overcast conditions and scattered clouds has shown that the algorithms overestimate the true LWP for off-zenith observations with the bias in the range 0.003-0.006 kg m^{-2} (for elevation angle 60°). The bias slightly increases for smaller elevation angles. For zenith observations, the bias is negligibly small. So, we can make the conclusion that the algorithms can not overestimate the LWP gradient, if it is detected while processing field measurements. The linear and quadratic regression algorithms produced similar results, therefore the results obtained by the linear regression algorithm only are presented in the article.

The most important result is that the LWP retrievals definitely demonstrate the existence of the LWP land-sea gradient during all seasons and this gradient is positive as in case of the satellite measurements (larger LWP values over land and smaller over sea). The gradient is negative only for March 2013 but its corresponding absolute value is small. Comparing the gradients obtained by the ground-based microwave measurements during warm and cold seasons we may conclude that in general the gradients during the cold season are smaller than during the warm season and not as variable as during the warm season.

The intercomparison of the LWP land-sea gradient data from the HATPRO and SEVIRI measurements and the ECMWF reanalysis has been carried out. The SEVIRI and the HATPRO instruments detect positive LWP land-sea gradients during all seasons but the magnitude of the gradient detected by the ground-based instrument is considerably smaller than detected by the satellite instrument. For the warm seasons of 2013 and 2014, temporal behaviour of the LWP gradient revealed by the satellite measurements completely differ from that obtained by the ground-based measurements. In contrast to warm season, during cold season the temporal behaviour of the gradient is the same for the SEVIRI and the HATPRO results. The LWP gradients provided by HATPRO and reanalysis during warm season are in a very good agreement. During cold season in contrast to the SEVIRI and the HATPRO data, the reanalysis data demonstrate negative LWP gradient.

The main conclusion of the study is the following: the approach to detection of the land-sea LWP gradient from microwave measurements by the HATPRO radiometer operating at the observational site of St.Petersburg State University has been successfully tested and the results confirmed the presence of the horizontal land-sea LWP gradient in the vicinity of the radiometer. Further research is needed in order to increase the accuracy of the retrieval method and to find the explanations for the revealed differences in the magnitude and temporal behaviour of the LWP gradient obtained from the ground-based, satellite and reanalysis data. The study has identified several problems: sparse data sampling in angular scanning mode, not optimal azimuthal orientation of the instrument, the necessity to improve the data processing algorithm and the need to find the origin of the systematic component in signal measured in angular scanning mode.

Accordingly, we made some changes in the Abstract:

Preliminary results of the retrieval of LWP over water by statistical regression method applied to the microwave measurements by HATPRO in the 31.4 GHz and 22.24 GHz channels are presented. The monthly averaged results are compared to the corresponding values derived from the satellite observations by the SEVIRI instrument and from the reanalysis data. The SEVIRI and the HATPRO instruments detect positive LWP land-sea gradients during all seasons but the magnitude of the gradient detected by the ground-based instrument is considerably smaller than detected by the satellite instrument. The LWP gradients provided by HATPRO and reanalysis during warm season are in a very good agreement. During cold season in contrast to the SEVIRI and the HATPRO data, the reanalysis data demonstrate negative LWP gradient.

In my opinion, the paper needs substantial revision which is beyond major revisions. For this reason, I recommend to decline the manuscript. I suggest to extensively revise the study and encourage the authors to submit a paper at a later stage.

The referee suggests to extensively revise the study beyond major revision and to resubmit it. First of all we would like to stress that the study is based on the experimental data obtained during several years – brightness temperatures measured from ground at different frequencies. The results relevant to zenith observational mode have been successfully verified, checked, validated and compared with independent data previously. There are no reasons to have doubts in the quality of brightness temperature values obtained in the off-zenith mode. These results can not be revised and, if we understand correctly, the referee means the revision of the data interpretation. We insist that it is a matter of authors choice what approaches and methods to apply for the interpretation and what sequence of activities to select. We have chosen the analysis of the forward problem first and the solution of the inverse problem next. This is a classical sequence. The esteemed referee does not qualify any our approaches and results as "erroneous". The critical remarks refer mainly to the fact that the results are not convincing enough. We do not think that it is the serious reason for declining the paper, especially taking into account the fact that our work is pioneering for the specific task of LWP land-sea gradient detecting by ground-based passive microwave radiometry. As we have shown in the section 5, there are a large number of various factors which affect the results. In the revised version of our manuscript we present the retrieval results which were obtained by the newly trained regression algorithm. We got promising results. We think that there are still many possibilities for further improvements, but nevertheless the existing results are interesting and useful.

I suggest to concentrate on the analysis of the LWP variability in LWP space and not in BT space and to proper set up multivariate regression-based retrievals for zenith and off-zenith LWP. A physical motivation and discussion for the LWP gradients is currently missing. Why should LWP be enhanced over land than over water? Do you always expect this feature? If the SEVIRI LWP product is used, it needs to be properly introduced and uncertainties discussed (SEVIRI is not the truth!) as well as the representativity of SEVIRI for the HATPRO site and vice versa. Are the LWP pdfs similar for SEVIRI and HATPRO? If case studies with LWP gradients are presented, the physics behind including the role of the meteorological/synoptic situation could shed more light on why certain gradients exist or not.

In this comment, the referee puts out many suggestions for the revision of the paper. Several of these issues have already been mentioned in the original version of the manuscript and discussed briefly. The extent analysis of the topics suggested by the referee is beyond the scope of the present study which does not have the goal to embrace and analyse in detail the whole variety of primary and secondary problems which arise (relevant both to the experimental part and to the interpretation part). Our short comments to the referee's suggestions are the following:

1) We insist that it is the matter of the authors' choice to make analysis booth in the BT space and LWP space.
2) Now, the regression algorithm trained in different way has been applied and the results are included in the revised version.
3) Physical motivation for LWP gradient is given in the Introduction with proper references to literature.
4) Extended analysis of the LWP gradient as observed from satellites is beyond the scope of our study.
5) The quality of the SEVIRI data and the comparisons of the ground-based and space-borne data are discussed in the revised version (see our respective answer above).
6) We agree that in the case studies the analysis of synoptic situations would be interesting but it is not so important as the cloud size and horizontal and vertical location which is studied in the revised version.

A qualitative analysis is nice but quantifying the LWP version gradient would even add more value to the paper.

We are thankful to the referee for the high estimate given to the section 5 (we guess that this comment refers to this section).

Concluding our reply we would like to thank the referee once again for the comments which indeed helped to improve our manuscript. We edited the acknowledgement section accordingly:

> The authors are grateful to two anonymous referees for making very insightful remarks and for introducing several useful ideas which helped greatly to improve the manuscript.

Vladimir Kostsov
on behalf of all co-authors

Note: For convenience, in the revised version of the manuscript the new figures have their own numeration (by letters) and are placed at the end of the manuscript.