Středa, T., Rožnovský, J. (eds): Monitorování přírodních procesů. Lednice 12. – 13. 9. 2018
ISBN 978-80-7509-570-1, 978-80-87361-86-3. MENDELU, VÚMOP, v.v.i. , 2018

Možnosti detekcie hydrometeorov pomocou zmien elektromagnetického signálu

Possibilities to detect hydrometeors based on the changes of the electromagnetic signal

Michal Kuba[1], Peter Fabo[1], Pavol Nejedlík[2], Dušan Podhorský[2]

[1]University of Žilina Research Centre, Žilina, SK, [2]Earth Science Institute of SAS, Bratislava, SK

Abstrakt:

Metódy detekcie atmosférických hydrometeorov pomocou zmien elekrtomagnetického poľa sú obyčajne založené na útlme signálu na frekvenciách rovných a vyšších ako 10GHz. Využitie nižších frekvencií vyžaduje odlišný mechanizmus, nakoľko vnútorný útlm signálu je v tomto frekvenčnom pásme malý. Zmena signálu v tomto frekvenčnom pásme je spôsobená interferenčným efektom zloženého signálu prichádzajúceho na antény rôznymi cestami (viac cestný únik, Fresnelova zóna). Interferencia samotná nie je korelovaná s prekážkami, ale zmena atribútov priestoru v línii priamej viditeľnosti už koreluje a vektor meraných údajov získaný detekciou z viacerých nezávislých zdrojov signálu už obsahuje korelovanú zložku. Predkladaná práca sa venuje skúmaniu pasívneho monitoring signálu BTS zo sietí mobilných operátorov GSM na frekvenciách 920-960 MHz. Merania poukazujú na závislosť zmeny interferovaného signálu na zmenách množstva a charakteru hydrometeorov v atmosfére.

Kľúčové slová: spodná vrstva troposféry, signál BTS, Fresnelva zóna

Abstract:

The methods of the detection of atmospheric hydrometeors based on the changes of electromagnetic field are usually based on the attenuation of the signal at frequencies 10GHz and more. The use of lower frequencies requests other mechanism because the internal attenuation is small in this band. The alteration of the signal in this band is evocated due to the interference effects of batching signals coming to antenna by different routes (multipath fading, Fresnel zone). The interference itself is not correlated with the obstacles but the change of the space attributes in the line of sight already correlates and vector of measured data acquired by measuring of several independent sources already involves correlated element. Passive monitoring of BTS signal of

mobile nets GSM 920-960 MHz was investigated in this work. The measurements showed the dependence of signal interference on the changes of the hydrometeors amount and their character in the atmosphere.
Key words: lower layer of troposphere, BTS signal, Fresnel zone

1. Introduction

The impact of the environment on electromagnetic waves propagation is known since their discovery and the effects of reflection and diffraction of these waves on the obstacle formed the point an evidence of their existence. Further research was focused on the phenomena connected to the various parameters of the atmosphere regarding the use of communication technologies and remote sensing of various objects.

Different forms of interaction between electromagnetic waves and atmospheric properties depend on the wavelength of the waves. Following are among the most important:

-oscillations of spherical resonator in long wave bend being created by conductible surface of the globe and ionosphere known as Schumann resonances. Electromagnetic waves of the frequency of 7.8Hz are activated mostly by flashes in thunderstorms in around equator [1]

-propagation of the long and short waves to the long distances is enabled by their reflectance from the ionosphere. The status of the ionosphere over a certain locality, namely its conductivity and the height of its layers depends on the solar activity and on the solar wind (a stream of charged particles entering the atmosphere) and on the location of the particular locality towards the sun [2]

-diffraction of the waves is typical for the short and ultra-short waves due to the changes in the density of atmospheric mass which changes with the air pressure, air moisture and temperature. Cumulatively are these phenomena described by a value called refractivity of the atmosphere which is and equivalent to the index of refraction [3]

-the effects of attenuation on the water vapor and the selective absorption on the molecules of atmospheric gases start to be dominant in the bend of microwaves. Intensive diffusion is observed for the wavelength comparable to the magnitude of the hydrometeors [4].

2. Reasons for applying new methods of hydrometeors detecting in lower troposphere

There are two general attitudes to detect hydrometeors applied in meteorological practice; it is remote sensing and ground based observation. Meteorological radars form the most important remote sensing tool regarding the hydrometeors monitoring. That is why we`ll take a look on this method as well as on the ground based observations.

Meteorological radars bring irreplaceable information for synoptics meteorology as they provide the information about the storms and accompanied phenomenon within the range of 150-250 km and about precipitation in the range of 100 km. Both meteorological radars and ground based stations are networked. We shall take an example of such networking in Slovakia.

First meteorological radar was set in operational use in Slovakia in 1972. The present network of meteorological radars in Slovakia is formed by four radars of III. generation *Meteor 735 CDP10* manufactured by Selex-Gematronik. They work on the wavelength of 5 cm (C band). They are equipped by Doppler mode to detect radial velocity and by polarimetric regime of measurements which is able to distinguish the type of hydrometeors and to perform more accurate measurement of precipitation. Due to the complex terrain of Slovakia radars are placed at the elevation from 584 m to 1240 m a.s.l. All radars are able to detect and to interpret following parameters:

- Z – radar echo
- V – Doppler radial velocity
- W – the length of velocity spectrum
- Z_{DR} – differential echo (the difference of radar echo at horizontal and vertical polarization)
- ρ_{hv} – coefficient of correlation of received signal with horizontal and vertical polarization
- Θ_{dp} – phase difference of received signal with horizontal and vertical polarization
- K_{dp} - specific phase difference of received signal with horizontal and vertical polarization.

Radars measure each 5 minutes. During this time they detect hydrometeors (cloud parts and precipitation) in the range of radar at multiply aerial tilts. The antenna rotates in azimuth 360° at each elevation. Emitted radiation (beam) is reflected when hitting any hydrometeor or any other object and the back scattered signal is received by the radar antenna and processed by the radar receiver. The intensity of radar echo is estimated from the amplitude of the received signal. It is interpreted in the units of radar echo - dBZ. Composite information of radar reflectivity is created from the products of all four radars each 5 minutes by the connected computer. Following maps interpreting the position of hydrometeors in lower troposphere are produced in operational mode:

Maximum – composite map of radar echo in vertical column. This product is focused to detect the development of thunderstorms. Nevertheless, it gives incomplete information about precipitation.

CAPPI 2km – composite map of radar echo at constant height (2km a.s.l.). This product gives better information about precipitation. However, it does not monitor the full space to the ground.

1h total – composite map of one hour precipitation. It is a floating cumulated precipitation total being updated each 5 minutes. It is derived out of the intensity of precipitation which is calculated from the measurements in the height of 0.5 km.

All this information are important in operational meteorology. Nevertheless, the detection of any hydrometeor by radar is restricted to the space about 700 m above ground which makes problems mostly in hilly areas.

Hydrometeors are of the most important meteorological variables for defining the climate dynamics, as well as the spatial patterns. The precipitation networks are built with respect to a geographical region in order to reflect spatial and temporal distribution of hydrometeors. Ground based measurements give us a perfect view on the development of particular meteorological phenomena but they are restricted to one point in space. Using the network data enables us to express the spatial distribution of different hydrometeors at macro-climatological scale by applying various interpolation methods. Nevertheless, the instant situation within the aerial scale of a few hundred of meters, but at first the temporal changes counting minutes to hours can`t be reflected. Considering different criteria it is not possible to apply any universal procedure do structure a precipitation network. There is no universally valid answer to the questions on the density of measurement stations required within a specific area. The Atmospheric Environment Service of Canada suggested [5] a general guidance recommending minimal gauge separations 24 kilometer in rural areas while higher density is desirable in heavily populated areas and in areas with marked orographic influences. Nevertheless, they stated “no limitations” for precipitation network density.

The density of precipitation networks reporting data on hydrometeors in Central Europe including the territory of Slovakia is quite dense in comparison to other regions. There are around 700 precipitation stations working in Slovakia which means one station per 70 square kilometers (a square of 8.4 km). This density fulfils the requirements being put on climatological spatial coverage of Slovak territory regarding long-term climatological averages and extremes. Spatial changes of short distance dimensions within a few hundred of meters as well as the temporal changes below one decade of days can`t be expressed, anyway. This includes both instant occurrence of different hydrometeors in particular space of interest (densely populated agglomerations, intensively farmed areas of a few tenth of square kilometers, traffic lines, etc.). They can`t be detected either by other means of remote sensing or by ground based point instrumental observations.

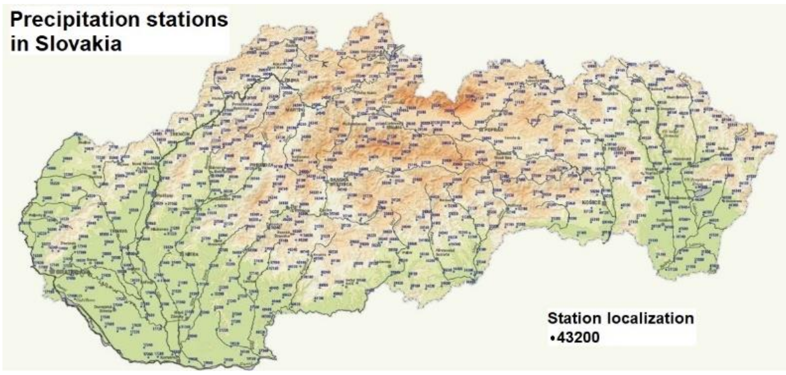

Fig. 1 Precipitation network in Slovakia

Some other methods of remote sensing like satellite data bring valuable information at regional level but either time or space resolution does not sufficiently reflect the instant local dimension of the occurrence of hydrometeors. Further methods should be employed to fulfill these demands.

2. Active and passive methods of hydrometeors detection by electromagnetic waves

Active methods require a broadcaster of electromagnetic energy of known parameters and the monitoring of the impact of the environment on above mentioned parameters (attenuation, selective absorption, polarization, frequency changes, time shifts). The typical applications of active methods are different types of radars, recently mostly Doppler meteorological radars, working on the frequencies 3.5 GHz and higher. One (standard radar) or multiply (bistatic radar) synchronized receivers are used.

Passive methods monitor different sources of electromagnetic waves and their interaction with atmospheric properties. One of these methods (still under the development) is trying to define the conditions in ionosphere and the vertical profile of water content in the atmosphere by investigating time delay of the signals from GPS satellites penetrating through the atmosphere [6]. The knowledge of the accurate time at the satellite and its location require the use of special GPS receiver.

Data link in microwave band used by GPS networks operators to switch their stations and for data transfer are used to estimate rainfall intensity. The method is based on the monitoring of power parameters of the broadcasters which directly depend on the attenuation caused by the rainfall. This method requires the use of such broadcasters which enable the monitoring of their capacity parameters with adequate accuracy and time resolution and a cooperation with the broadcasting operator. This is due to the commercial interests usually very difficult or not possible.

New method brings a specific attitude to passive monitoring of electromagnetic signals in the band of 920-960 MHz influenced by hydrometeors in low layers of troposphere within a height up to 100m from the ground. This band is used to connect the base telephone stations (BTS) of mobile operators with the users of mobile phones.

3. Properties of the atmosphere in high frequency bend of 1GHz.

Atmospheric properties in UHF bend (300MHz - 3GHz) make the point of investigation for longer time. This band frequently used for TV broadcasting in the past is s used for digital DVBT transfers and in mobile networks. The propagation of the signal is affected by absolute value as well as by vertical profile of the refractivity of the atmosphere being expressed in dimensionless unites N which are related to refractive index of the atmosphere n according to [7] as follows:

$$N = (n-1)\times 10^{6}$$

N depends from the air pressure p [mbar], absolute temperature T [K] a partial pressure of water vapor *e* [mbar]:

$$N = 77.6\,(p/T) + 3.73\times 10^{5}\,(e/T)$$

Because the refractivity is changing with the height the signal beam incurves according to Snell`s law. In case of linear gradient of refractivity the course of the signal is parabolic. Nevertheless, in reality the signal entering the antenna is created by the superposition of waves propagated through the atmosphere and the waves reflected by from the ground and from various obstacles, see Fig. 2.

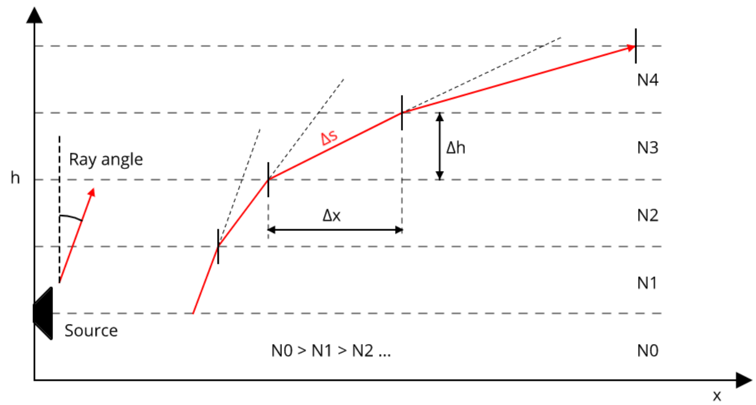

Fig. 2. The impact of the gradient of refractivity on the propagation of electromagnetic waves

There are a few examples of propagation of electromagnetic waves in the atmosphere being distinguished in the practice, see Fig. 3.

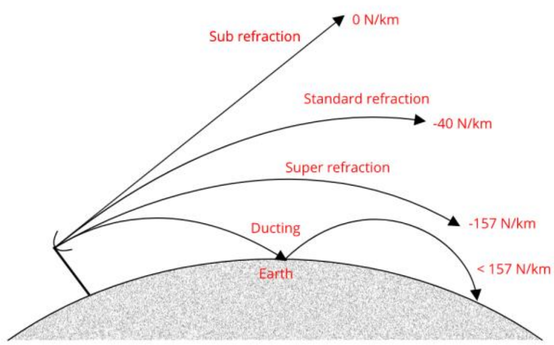

Fig 3. Examples of electromagnetic waves propagation in the atmosphere

Due to the changes of refractive index also the speed of the propagation of electromagnetic waves in the atmosphere changes. On top of that any environment can absorb and diffuse electromagnetic energy. As the measurement of the refractivity of the atmosphere is quite complicated numerical models were created to evaluate the impacts of the parameters of the environment on the electromagnetic waves propagation. An example of the output of MGM93 model for UHF band for different values of relative humidity is in Fig. 4.

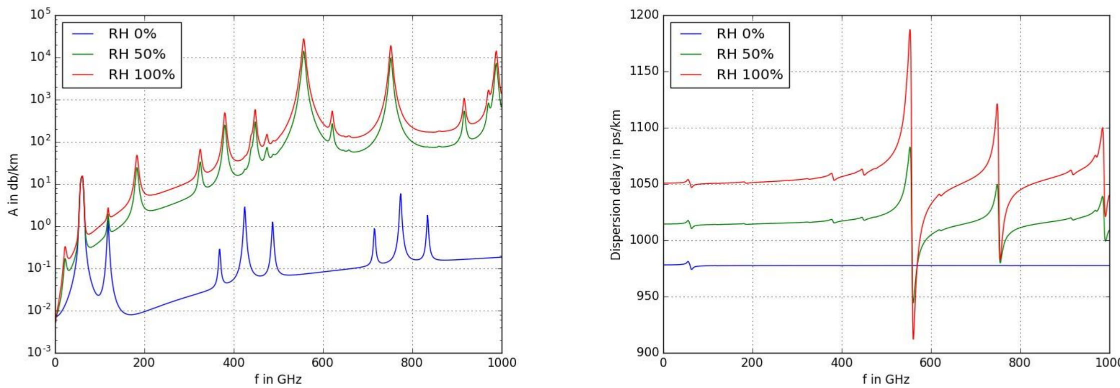

Fig. 4. Model MGM93 - attenuation and the delay of the signal for various values of relative humidity

The results show that the attenuation is neglectable at 1 GHZ frequency. The attenuation is more expressed only in higher frequencies. Accordingly, the impact of the hydrometeros like ground fog and rain is negligible, see Fig. 5. Simulation model also shows that neglectable changes in delay of the signal due to the changes in the speed of propagation and in UHF band do not depend on the frequency.

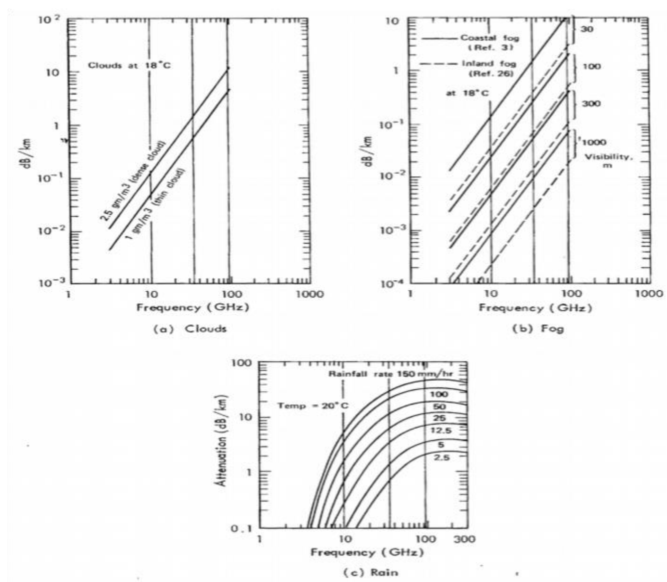

Fig. 5. Results of the experimental measurements of signal attenuation due to hydrometeors [8]

Vertical gradient of the refractivity is not equal in the atmosphere due to the unequal distribution of water vapor. It can change with the height depending on the occurrence of the hydrometeors in the atmosphere and on the thickness of the layers close to the ground saturated by water vapor. Vertical profile of the refractivity has a few breaking points where addition sign changes to minus sign and on the opposite. Such profiles are called bilinear or trilinear. Propagation of electromagnetic energy is in such cases complicated and interference among the beams traveling at different trajectories and being reflected from the ground can occur at the receiving antenna.

Further to that, as the atmosphere is not any static system incidental changes in refractivity are induced due to the convective motions in the atmosphere.

4. The use of UHF band up to 1GHz for the detection of hydrometeors in atmosphere

Dense network of BTS station and their massive active output in the band 920-960 MHz brings the idea to use this source covering basically all populated area to monitor lower levels of troposphere regarding the presence of hydrometeors and the water vapor close to the ground. BTS are usually placed on the roof of the buildings or on the masts up to 50 meters above the ground. One point on the ground is usually affected by the signal from number of BTS Fig. 5. Presently available instruments enable to get the BTS signal from relatively big area. A combination of the measurements from multiply points could enable to localize the position of hydrometeors presented in real time with adequate accuracy.

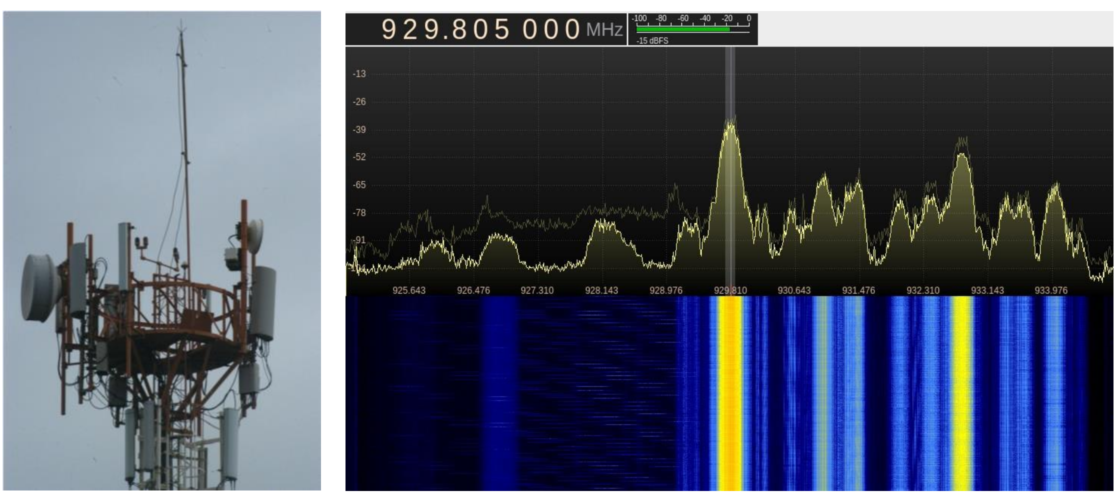

Fig. 6. BTS and power spectrum of a part of the band of mobile G2 network

Practical performance of such monitoring is complicated because of the fact that the standard methods of the detection of the hydrometeors in the atmosphere based on the attenuation are not usable in the bend of 1 GHz as the attenuation is neglectable in this band. The detection based on the time-lag used in the tomography of the atmosphere using the satellite signal is also not usable as reference time information is not available.

One of the possibilities is to use the diffraction of the signal trajectory due to the gradient of refractivity. Using the geometric patterns of signal propagation along different trajectories we can monitor the properties of the environment where the signal is propagated based on the time-lag between the signals on the antennas. It is obvious to use as the reference trajectory the shortest possible line in line of sight visibility (LOS). The second trajectory is created by the beam in the vertical arc. This is possible by using an appropriate beam antenna, see Fig. 7. As the Fresnel pattern of the antenna is not any vector and because the antenna receives also the signals from other directions (though of lower gain) the selection of the trajectory is limited to the first Fresnel zone. This is defined by the space with the signals with angular phase difference lower than the half of wave length.

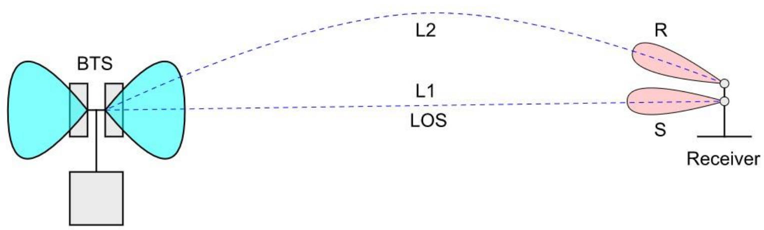

Fig. 7. Configuration and antennas alignment and their Fresnel patterns

As the changes in the environment in between the BTS and the receiver impact on both L1 and L2 trajectories along which the signal propagates the processing and the interpretation of the measured data is complicated in comparison to the signal attenuation or time-lag measurement. The outputs of both antennas (receiving the signal in LOS trajectory and the signal on the vertical arc beam) are channeled to the identical synchronized receivers. The block scheme is shown in Fig. 8. This enables us to connect mote antennas to input antenna switch (AS) and consequent processing by quadrature detector. After the filtration and analogue-digital transference of the antenna output we get complex values in data flow representing IQ data components of the signals from each antenna converted into basic band at the receiver output. Further processing is based on standard software and is computed by a PC where the measured data are modified and interpreted.

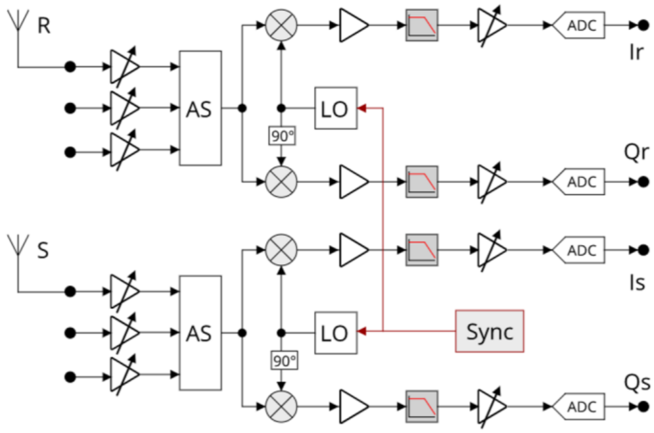

Fig. 8. Block scheme of the receiver

Time-lag of the signals caused by the wiring network antennas parameters and input amplifiers are included in the IQ components. This can be eliminated in the process of the calibration of the receivers in the beginning as well as in the regular intervals during the measurement. As the signal trajectory is included in the first Fresnel zone mutual phase displacement are within the interval $\langle -\pi/2, \pi/2 \rangle$ and are superposed to some constant value which depends on the relative positions of the antennas.

5. Data processing and data evaluation

IQ data on the receiver output include the information about all sources of the signal in selected band with sharply defined bandwith, see Fig. 9.

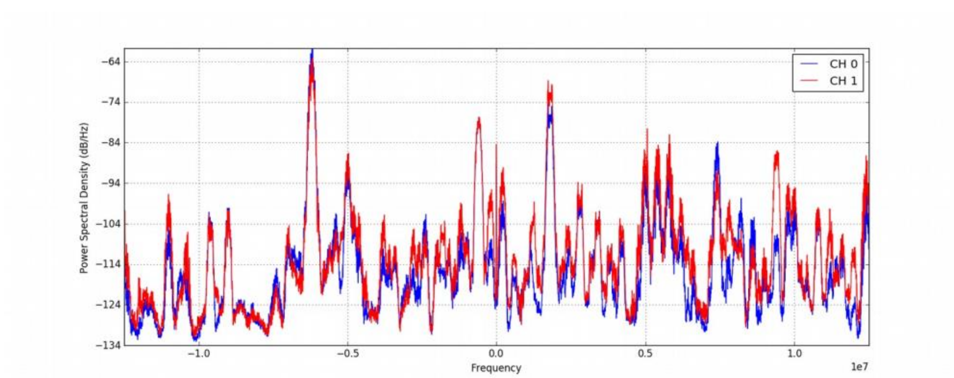

Fig. 9. Spectrum of the signals calculated from ID components,
mean frequency corresponds to 930 MHz

As e measure the signal of the concrete BTS, location of which is known, their signal has to be filtered from the broadband signal and their bandwith has to be restricted to the value in which they broadcast the maximum energy. Following proximate information with high time resolution can be obtained from filtered signals in real time:

-phase displacement between the signals of selected BTS at the entry into the receiver

-energy of the signals at the entry into the antennas

Values typically obtained during such measurements are shown in Fig. 10. These information are accessible in parallel for all BTS which make broadcasting in monitored band. Only those in LOS are only selected for evaluation.

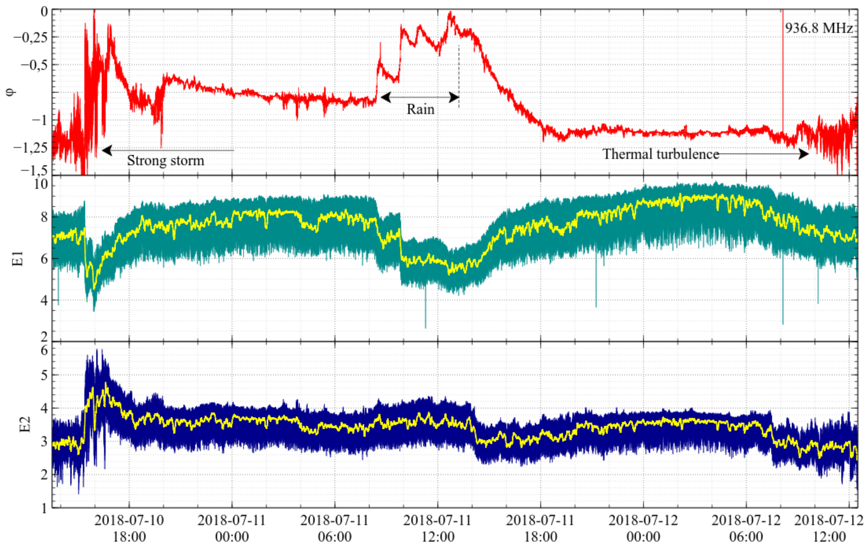

Fig. 10. Phase displacement and energy values measured during the cold front passage

6. Data analysis

Measured and processed data involve integral complex information about atmospheric conditions in the line between the BTS and the receiving antennas. As implied by refractivity formula the measured values are not single valued for air temperature, air humidity and air pressure. That is why the measured values will have to be related to the classical point measurements of hydrometeors within the distance in between the BTS and the antennas.

a. Process analysis

Some details can be clearly derived from the measured phase change which are directly proportional to the time-lags on trajectories L1 and L2. These can be directly related to the physical phenomena in the atmosphere:

-quick changes – precipitation

-slow changes – exponential decline of the air humidity which depends on the temperature changes and on the solar radiation changes

-noise –expressing the level of turbulence

b. Stochastic analysis

E1 and E2 values in Fig. 10 balance according to the level of interference of the signals on the antennas during the multipath propagation. As the variations of the energy caused by the turbulence are not correlated and on the opposite and the impact of the hydrometeors on the transmition channel shows the correlated component the level of correlation between the signals can be used to specify the background of the quick changes of the phase.

7. General results

One of the results of the measurement is shown in Fig. 11

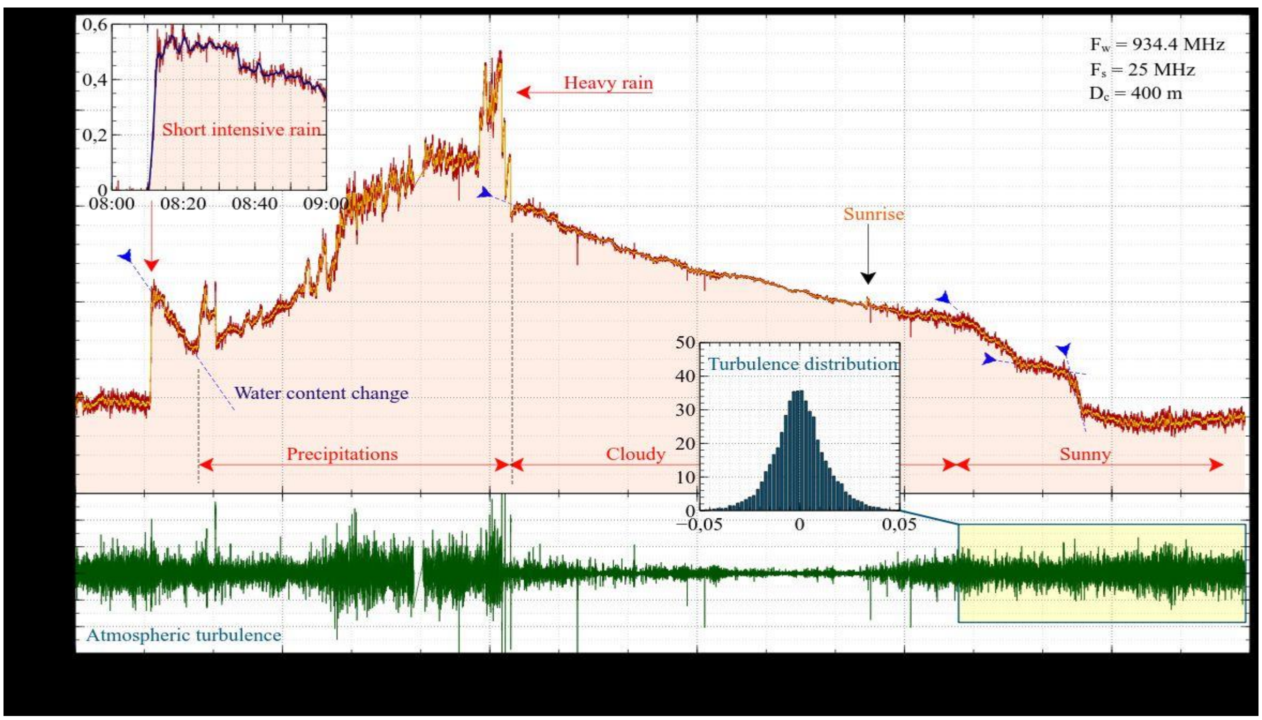

Fig. 11. Signal response to the hydrometeors occurrence within 50 m layer over the ground

Based on the measured values and their comparison with both independent ground based meteorological measurements and radar outputs, a good agreement can be stated at the qualitative level of the occurrence of the particular hydrometeors (course of air moisture, precipitation and fog) in lower troposphere. The measured values show high time resolution and their specific space location in the line of LOS. The measured data also involve atmospheric phenomena which are not directly related to hydrometeors and they appear as a noise (level of turbulence) but they can provide a supplementary information about the ongoing processes in the atmosphere at the particular moment. From the practical point of view, further development is necessary in design of antennas, in the reduction of data flow (it goes over 100 Mbyte/sec at the moment) but mostly, in the consolidation of the sensors together with the application of suitable models for reliable identification of meteorological phenomenon from the measured data.

8. Conclusions

Presented method of the monitoring of hydrometeors in lower troposphere based on the passive detection of relative phase difference is in experimental stage of development when basic physical principles are examined. Experimental measurements show the possibilities of the use of the sources of electromagnetic radiation in the band of 1 GHz for the detection of the hydrometeors in the lower troposphere. This band is suitable from the practical point of view, since in Slovakia only, there are more than 35000 DBs stations and DVTB TV broadcasters identified. The measurements do not require any authorization and do not involve any license limitations from the broadcasters as the method is fully passive and does not involve decoding of the transmitted information. It can use any sources of signal regardless of type and mode of modulation and Fresnel patterns of the antennas etc. The only necessary condition is the localization of the source of the signal and the direct line of sight between the broadcaster and the receiving antennas. The receiver is able to process the signal from number of sources from the selected direction in one point of time. The measurement is based on cheap SDR receivers at the moment and further processing depends only on the programming system. In case of the use of multiply receivers placed in the space in triangle or in a plygon when the LOS to the sources will cross each other gives the opportunity of space identification of the occurrence of particular hydrometeor. This can be of high interest especially in large city agglomerations and heavily overloaded traffic lines regarding the heavy rains, fogs etc. but also the applications in various warning systems.

References

[1] Schlegel, K., Füllekrug, M. (2002). 50 Years of Schumann Resonance. Physik in unserer Zeit, 33(6), 256-26.

[2] Barr, R.; Llanwyn Jones, David; Rodger, C.J. (2000). "ELF and VLF radio waves" (PDF). Journal of Atmospheric and Solar-Terrestrial Physics. 62 (17–18): 1689–1718. Bibcode: 2000JASTP..62.1689B. doi:10.1016/S1364-6826(00)00121-8.

[3] Mangum, J.,G. and .Wallace, P. (2015). Atmospheric Refractive Electromagnetic Wave Bending and Propagation Delay. Publications of the Astronomical Society of the Pacific, Volume 127, Number 947.

[4] Sogo O KAMURA, Tomohiro O GUCHI, Electromagnetic wave propagation in rain and polarization effects, Proc. Jpn. Acad., Ser. B 86 (2010), No. 6, p.539

[5] https://open.canada.ca/data/en/dataset/29e10789-68e2-57cd-88e0-652e6b3bfe28

[6] Benevides, P., Catalão , J., Miranda, P., Chinita, M., J. (2013). Analysis of the relation between GPS tropospheric delay and intense precipitation. Proc. SPIE 8890, Remote Sensing of Clouds and the Atmosphere XVIII; and Optics in Atmospheric Propagation and Adaptive Systems XVI, 88900Y (17 October 2013); doi: 10.1117/12.2028732; https://doi.org/10.1117/12.2028732.

[7] International Telecommunication Union, P.453: The radio refractive index: its formula and refractivity data, https://www.itu.int/rec/R-REC-P.453-13-201712-I/en

[8] C.C. Chen, Attenuation of Electromagnetic Radiation by Haze, Fog, Clouds and Rain, United States Air Force Project RAND, R-1694-PR, April 1975.

Acknowledgement: this work was done with the support of VEGA grant 2/0015/18, Meso- and micro-meteorological exploration of the occurrence of hydrometeors in boundary layer of troposphere based on passive evaluation of changes of electromagnetic radiation from anthropogenic sources.

Corresponding author: RNDr. Pavol Nejedlik, CSc

Earth Science Institute of Slovak Academy of Science

Dubravska cesta 9, 84005 Bratislava

+421 918806108, nejedlik@yahoo.com