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Estimation Propagation Delays Induced in GPS Signals by Some Atmospheric Constituents

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***Abstract**: When radio waves propagate through the earth's neutral atmosphere, the radio signals are affected significantly by the variability of its refractive index, which causes primarily in the delay of the arrival, usually referred to as the tropospheric delay. The Global Positioning System (GPS) is space-based radio navigation. The GPS system receiver provides exact location and time information for an unlimited number of users in all weather, day and night, anywhere in the world. The GPS used three frequencies that are (L1 = 1.57542 GHz, L2 = 1.22760 GHz and L3 = 1.38105 GHz). The work part mainly focuses on how to illustrate and model the effects of the atmospheric constituents such as, water vapor, clouds, rain and snow on the GPS frequencies.The differential phase shift (∆Ø) in case of rain is caused by the oblate rain drop that is has two different axes, and because of the difference of the concentration of rain drops, also (∆Ø) doesn't depend on the temperature but increase with the increase of the frequency where the values of (∆Ø) are 6 deg/km for L1, 5 deg/km for L2 and 5.4 deg/km for L3. The differential attenuation (∆A) in case of rain in addition to depend on the shape of rain drop and the concentration of drops, it depends on the temperature and the frequency. The (∆Ø) in case of snow caused by the irregular shape of snow particle and depends on the temperatures and the frequency. The (∆A) in case of snow has very low values in different temperatures and frequencies.*
***Keywords:** propagation delays,GPS signals, radio waves.*

I. Introduction

Attenuation of the radio waves is the major cause to weaken the signal of GPS and make it to delay through its path from satellite to receiver by tropospheric consequents such as rain, cloud, fog, water vapor and oxygen.

Tropospheric delay is produced when the signal received from a GPS satellite is refracted by the troposphere as it travels to the receiver on the ground. The delay is due to the larger refractive index n of atmospheric gases (n > 1) than of vacuum (n = 1). This larger refractive index causes the decrease of speed of light (group velocity) in medium below its vacuum value c. The cause of this effect is that the signal path has a slight curvature with respect to the geometric straight line path.[1-3]

A Number of investigations have presented models to compute GPS signals attenuation through atmosphere. Westwater [4] suggested descriptive equation to calculate the absorption coefficientsof oxygen and water vapor and this equation depended on classic models of VanVleck and Weisskopf [5] .Demin et al [6], studied the effectsof dual molecules of water vapor and suggested descriptive equation to calculate the effect of these molecules in absorption of microwaves. Sudhir Man Shrestha [7] studied the estimation of tropospheric delay and wet refractivity using GPS measurements,Results indicated that slant wet delays may be derived from the estimated wet refractivity fields with accuracies of 2-3 cm. Karen Cove [8] examined methods for improving tropospheric delay estimation by using meteorological data. This includes the use of surface meteorological parameters in global prediction models and numerical weather prediction model data the estimation of the delay.

S.Katsougiannopoulos et al [9], estimated the tropospheric delay using 3 days of GPS pseudorange observations (days 157, 158, 159 in 2005), and the total zenith delay derived from the analysis centre. they compared the estimated delay from the permanent GPS data with that measured from radiosonde measurements which carried out at Thessaloniki airport, located near to GPS station . Mohd Hafiz Yahya and Md. Nor Kamarudin [10] studied the impact of tropospheric delay towards the accuracy of GPS height determination; they showed that the tropospheric delay is a distance-dependent error that will increase when the baseline length between two stations increases. Furthermore, it also varies with changes in meteorological condition of daily observation. Based on another test using simulated data, it is proved that the amount of tropospheric delay will decrease when the antenna height increases.

Daniel Alvaro Seron [11] used three different scenarios are studied through simulations with time-series of rain attenuation at 20 GHz in order to evaluate the effectiveness in terms of propagation of multiple-site diversity from a small-scale to large-scale .
Tareq A. Alawadi [12] investigated the effects of cloud attenuation on satellite communication systems at 20 GHZ and 50 GHZ, he concluded that one major obstacle in the design of EHF earth-space communication systems is the large and variable signal attenuation in the lower atmosphere, due to a range of mechanisms

including attenuation (and scattering) due to clouds and rain, tropospheric scintillation caused by atmospheric turbulence and variable attenuation by atmospheric gasses. In particular, cloud attenuation becomes very significant at EHF. S. J. Malinga1 et al [13] , Computed rain attenuation through scattering at microwave and millimeter bands in South Africa , the results are further applied to the terrestrial radio links and satellite links at a chosen rain rate and specified frequencies .

II. Methodology

There are three frequencies used in the global positioning system (GPS) L1 = 1.57542 MHz, L2 = 1.22760 GHz and L3 = 1.38105 GHz, these frequencies are affected the atmosphere specially by the tropospheric constituents like water , ice , snow etc. , therefore they tend and refract from its path by the refractivity . The refractivity can be determined by the refractive index. The complex refractive index consists of two parts, the imaginary part and the real part. The imaginary part (k) of the complex refractive index represents the absorption amount and it has three values , if $k > 0$ (the wave will be absorbed) , if $k = 0$ (the wave will be transmitted without absorption losses) , and if $k < 0$ (the wave will be amplitude) . The real part (n) of the complex refractive index represents the refractive index.

The differential phase shift ($\Delta\emptyset$) has three values, horizontally oriented targets ($\emptyset_h$) (horizontal axis > vertical axis) will produce an increasing, positive differential phase shift with range. Vertically oriented targets ($\emptyset_v$) (vertical axis > horizontal axis) will produce a decreasing, negative differential phase shift with range. And, spherical targets (horizontal axis = vertical axis) will produce near zero differential phase shift with range.

1.2 Differential Phase and Differential attenuation for Rain and Snow

The horizontal and vertical complex propagation constants of the medium $k_{H,V}$ (m^{-1}) can be expressed by [14]:

$$k_{H,V} = k_z + \frac{\pi\, k_z}{12}\ N \int_{D\,min}^{D\,max} Q_{H,V}\ (e_x, M)\ D^3\ N\ (D)\ dD \quad \mathbf{1}$$

where:

D is the diameter of a sphere with volume equal to that of spheroid ,N (D) is the particle size distribution (m^{-4}) , D_{max} and D_{min} are the maximum and minimum diameter of particle , and k_z is the free propagation constant (m^{-1}) [$k_z = 2\pi / \lambda$, λ is the wavelength (m)] . $Q_{H,V}$ are function of the eccentricity e_x and refractivity M of the particle as follows :

$$Q_{H,V} = M^2 - 1 / 1 + P_{H,V}\ (M^2 - 1) \quad \mathbf{2}$$

Where:

$$P_V = \frac{1}{e_x^2}\,[1 - (1 - e_x^2 / e_x^2)^{1/2} \sin^{-1} e_x \quad \mathbf{3}$$

$$P_H = (1 - P_V)^{1/2} \quad \mathbf{4}$$

The eccentricity e_x is a function of the semi – minor and semi – major axes (a and b) $e_x{}^2 = 1 - a^2 / b^2$ The refractivity M is related to the complex dielectric constant ε by $M^2 = \varepsilon$ [98] .

III. Results And Discussion

1-3 Differential Attenuation versus Rainfall Rate

Figures (1),(2) and (3) state that the values of differential attenuation (ΔA) of each frequency tend to be an inverse exponential increase with the increase of the (R) . We used five different temperatures (0, 5, 10, 15, and 20) ° C for each frequency that is used in GPS and we found that the three frequencies (L1 , L2 and L3) are affected the increase of temperatures with the increase in rainfall rate , where the value of (ΔA) decreases with the increase of temperatures as rainfall rate increases , in other words , the value of differential attenuation for each frequency will be the highest when the temperature is 0° C with the increase of rainfall rate , but this difference in the values is low . The value of (ΔA) increases with the increase of (R) , that means its value is positive because of the horizontally polarized pulse is affected more than the vertical polarized pulse because the rain drop is oblate and its horizontal axis is longer than its vertical axis since the concentration of water drops are more in the horizontal axis and this difference in (ΔA) will lead to the delay of GPS signal from and to satellite. Also , we notice that the value of (ΔA) differs with the difference in the frequency where it increases with the increase in the frequency , so the frequency (L1) has the highest value of (ΔA) from the other two frequencies (L2 and L3) , by another meaning , the value of (ΔA) depends on the frequency where if the frequency increases , the value of (ΔA) increases .

From figures (4),(5) and (6) we can notice that there is a comparison between the values of (ΔA) of the three frequencies that are used in GPS (L1 , L2 and L3) and for different temperatures (0 , 5 and 10)°C that are drown versus the (R) , where that the relationship between (ΔA) and (R) is an inverse exponential relationship where the values of (ΔA) of the three frequencies increase with the decrease of the temperature as (R) increases and this increase in the values of (ΔA) is obvious with the difference of the temperatures and with the increase of the rainfall rate , this means that the temperature play an important role for the values of differential attenuation , also the rainfall rate has a strong and effective role for the values of (ΔA) and this because of the shapes of rain drops and its concentration . The values of (ΔA) change according to the used frequency, where they increase with the increase of the frequency, the frequency (L1) has the highest value of (ΔA) than the other two frequencies (L2 and L3).

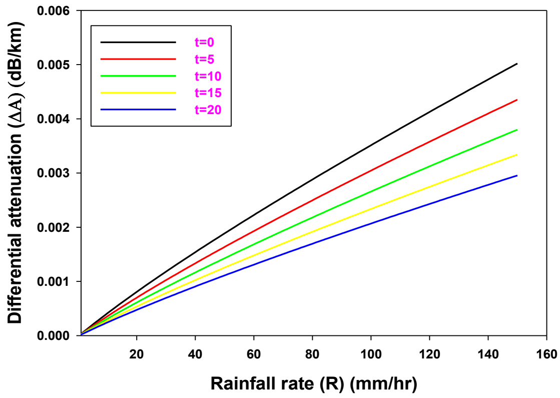

Figure 1. Differential attenuation (ΔA) versus rainfall rate (R) of the frequency (L1) for different temperatures.

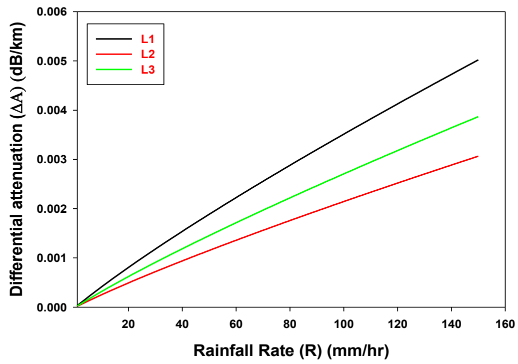

Figure .4 Differential attenuation (ΔA) versus rainfall rate (R) of the three frequencies (L1,L2 and L3) at t = 0° C.

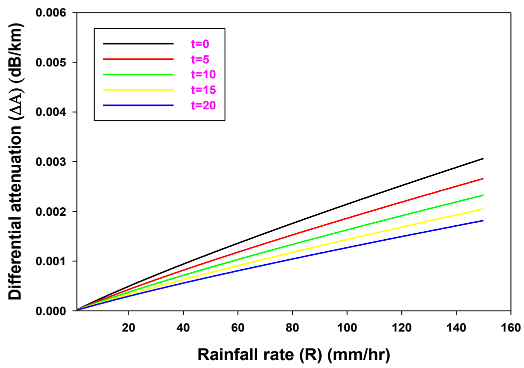

Figure 2.Differential attenuation (ΔA) versus rainfall rate (R) of the frequency (L2) for different temperatures.

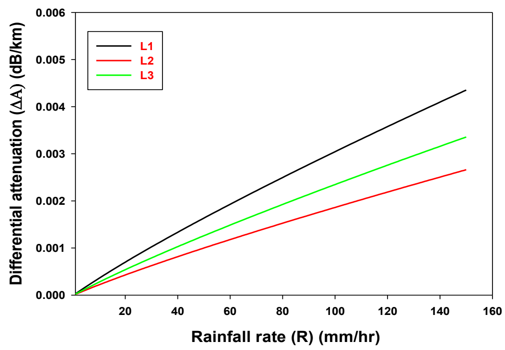

Figure 5. Differential attenuation (ΔA) versus rainfall rate (R) of the three frequencies (L1,L2 and L3) at t = 5° C

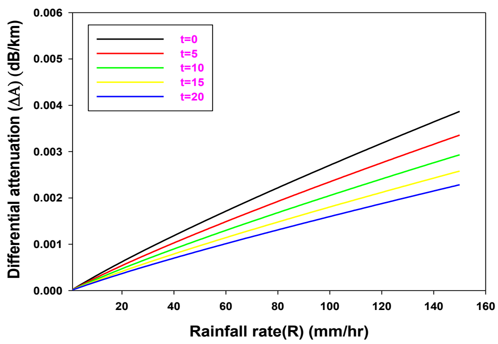

Figure 4. Differential attenuation (ΔA) versus rainfall rate (R) of the frequency (L3) for different temperatures

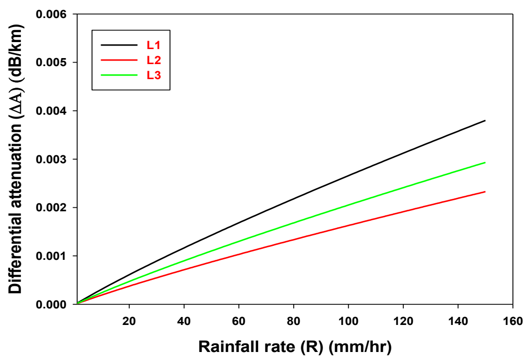

Figure 6. Differential attenuation (ΔA) versus rainfall rate (R) of the three frequencies (L1,L2 and L3) at t = 10° C

2-3Differential Phase Shift versus Precipitation Rate of Melted Snow

Figures (7), (8) and (41) show that the (ΔØ) for each frequency tend to be an inverse exponential increase with the increase of the precipitation rate of melted snow (PRMS). We used five different temperatures (0 , -5 , -10 , -15 , -20)° C for each frequency from the frequencies (L1 , L2 and L3) that are used in GPS , where we can notice that the values of (ΔØ) are different with the difference of temperatures for each frequency with the increase of the (PRMS) where they (values of ΔØ) increase and have the highest value when t = 0° C (nearly 0.84 deg/km) for (L1) , (0.66 deg/km) for (L2) and (0.74 deg/km) for (L3) , then the values start to decrease with the decrease of temperatures where (ΔØ) values as t = -5° C are (0.72 deg/km) for (L1) , (0.58

deg/km) for (L2) and (0.65 deg/km) for (L3) , and when t = -10° C thevalues of (Δ∅) will be very close to its values when t = -15° C , but they start to increase by very low increase as t = -20° C where its values are higher than its values as t = -10° C by very low values , this means that the values of (Δ∅) decrease at temperatures (0 , -5 , -10 , -15)° C then (Δ∅) increase when temperature decreases to (-20° C) , this is because of the shape of the snow particle is irregular and depending on temperature and humidity therefore the refractive index of snow will be low compared to the refractive index of water , and as result , its impact will be small on microwaves , and this means that the values of (Δ∅) depend on the shape of the snow particle and temperature . Also , we can notice from these figures that the values of (Δ∅) change with the frequency change , where they increase with the increase of the used frequency , the highest frequency (L1) has the highest value of (Δ∅) from the other two frequencies (L2 and L3) with the increase of (PRMS) .

Figures (9) , (10) and (44) illustrate a comparison between the values of (Δ∅) for the three frequencies (L1 , L2 and L3) that are used in GPS and are drown with the increase of (PRMS) for different temperatures (0 , -5 , -10)° C , where we notice that there is an inverse exponential relationship between (Δ∅) and (PRMS) where the values of (Δ∅) of the three frequencies at the given temperatures will be increased with the increase of (PRMS) an inverse exponentially , where the temperatures have an obvious effect on the values of (Δ∅) with the increase of the precipitation rate of melted snow , where the (Δ∅) values decrease with the decrease of temperature and the increase of (PRMS) , and this decrease in the (Δ∅) values is varying because of the shape of snow is irregular depending on the temperature and the humidity which make the refractive index of snow is low compared to the refractive index of water . Also , we can notice that the value of (Δ∅) depends on the frequency where it will be high as the frequency is high and decreases with the decrease of the frequency , the frequency (L1) has the highest value of (Δ∅) than the other two frequencies (L2 and L3) for all temperatures that are used in this study .

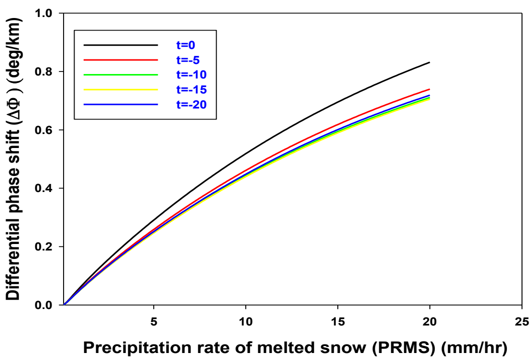

Figure 7. Differential phase shift (Δ∅) versus precipitation rate of melted snow (PRMS) of the frequency (L1) for different temperatures

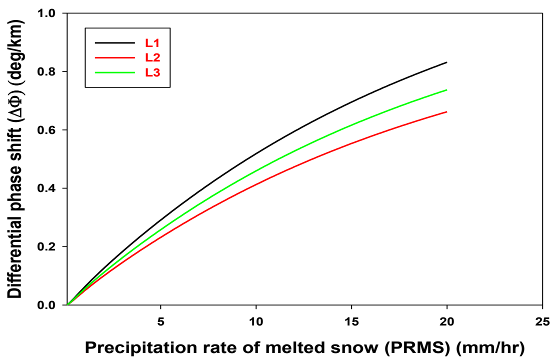

Figure 10. Differential phase shift (Δ∅) versus precipitation melted snow (PRMS) of the three frequencies (L1,L2 and L3) at t = 0° C

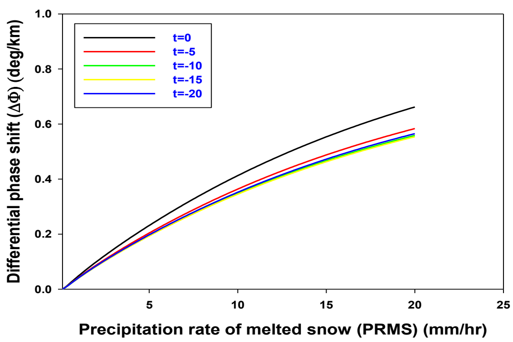

Figure 8. Differential phase shift (Δ∅) versus precipitation rate of melted snow (PRMS) of the frequency (L2) for different temperatures.

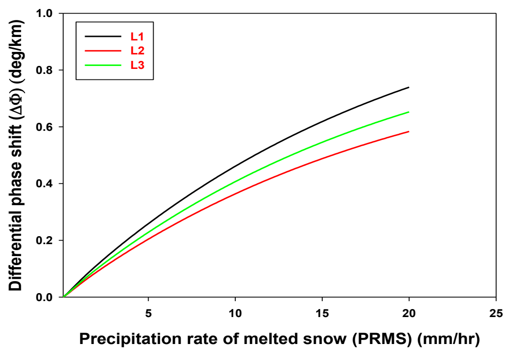

Figure11. Differential phase shift (Δ∅) versus precipitation melted snow (PRMS) of the three frequencies (L1,L2 and L3) at t = -5° C

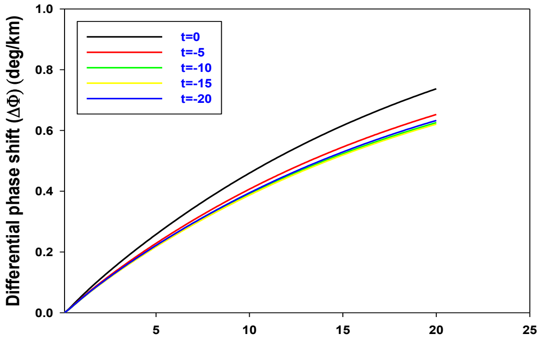

Figure 8. Differential phase shift (ΔØ) versus precipitation rate of melted snow (PRMS) of the frequency (L3) for different temperatures

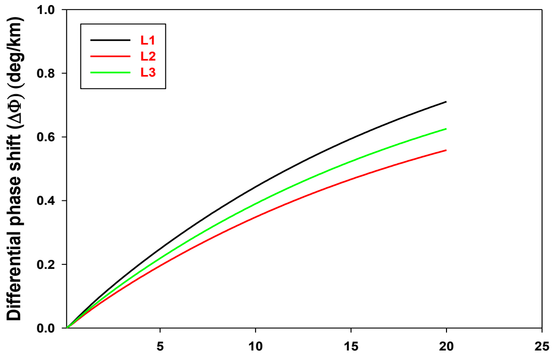

Figure 12. Differential phase shift (ΔØ) versus precipitation melted snow (PRMS) of the three frequencies (L1,L2 and L3) at t = -10° C

3-3Differential Attenuation versus Precipitation Rate of Melted Snow

From figures (11) , (12) and (13) we can notice that the values of (ΔA) for each frequency tend to be an inverse exponential increase with the increase of (PRMS) . We used five different temperatures (0 , -5 , -10 , -15 , -20)° C for each frequency from the three frequencies (L1 , L2 and L3) that are used in GPS , where we find that the values of (ΔA) depend on the temperature and there is a weak impact of temperature on the values of (ΔA), where they increase with the decrease of temperature , but this increase is varying , in addition , the values of (ΔA) generally are very low where they are (0.0077 dB/km) at 0° C while at -20° C will be (0.0018 dB/km) for (L1) , its values are (0.0075 dB/km) at 0° C and (0.0018 dB/km) at -20° C for (L2) , while its values are (0.0076 dB/km) at 0° C and (0.0018 dB/km) at -20° C for (L3) , that means if the temperature decreases , the values of (ΔA) may be equal for the three frequencies (L1 , L2 and L3) .

Also, we can notice that the values of (ΔA) are different with the difference of the frequency, but this difference is low, where the values of (ΔA) are equal for the three frequencies at low temperatures.

Figures (14) , (15) and (16) show a comparison between the values of (ΔA) for the three frequencies (L1 , L2 and L3) that are used in GPS and for different temperatures (0 , -5 , -10)° C that are drawn versus (PRMS) , where the relationship between (ΔA) and (PRMS) is an inverse exponential relationship , where the difference of the temperatures has an obvious effect on the value of (ΔA) of the three frequencies with the increase of (PRMS) , but this effect is a weak , also there is small difference in the values of (ΔA) of the three frequencies at the same temperature .Generally , the values of (ΔA) of the frequencies (L1 , L2 and L3) will be a very low , the causes of this as it is known are the irregular shape of the snow particle and the low refractive index of snow . Also, the values of (ΔA) differ with the difference of the frequency, where they will be the highest when the frequency is the highest that means they increase with the increase of the frequency.

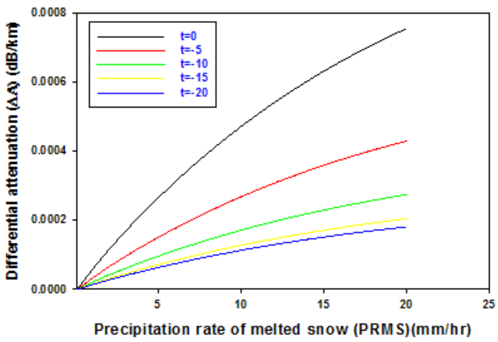

Figure 13. Differential attenuation (ΔA) versus precipitation melted snow (PRMS) of the frequency (L1) for different temperatures.

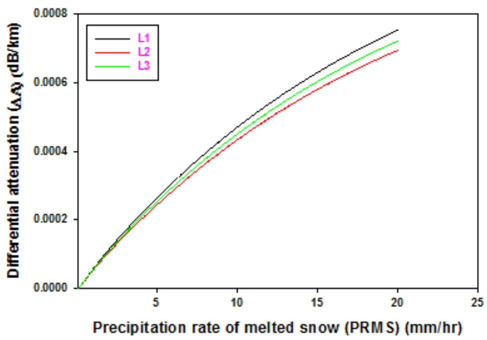

Figure 16. Differential attenuation (ΔA) versus precipitation melted snow (PRMS) of the three frequencies (L1,L2 and L3) at t = 0° C

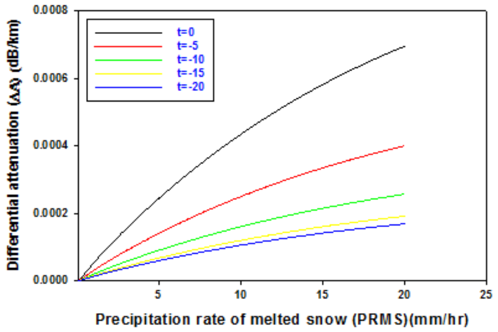

Figure 14. Differential attenuation (ΔA) versus precipitation melted snow (PRMS) of the frequency (L2) for different temperatures

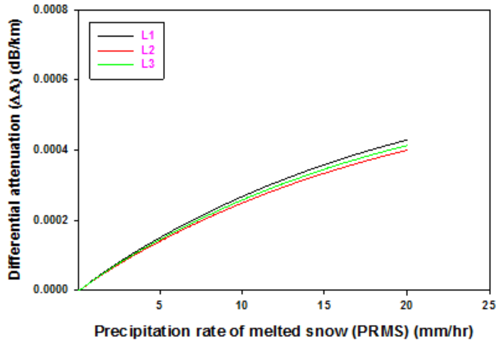

Figure 17. Differential attenuation (ΔA) versus precipitation melted snow (PRMS) of the three frequencies (L1,L2 and L3) at t = -5° C

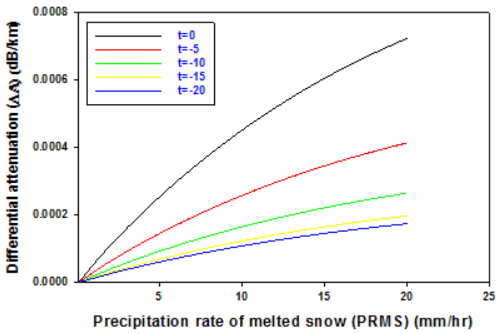

Figure 15. Differential attenuation (ΔA) versus precipitation melted snow (PRMS) of the frequency (L3) for different temperatures.

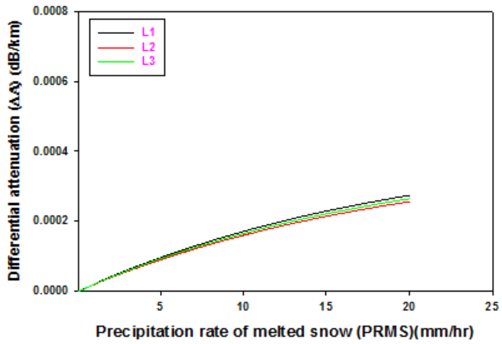

Figure 18. Differential attenuation (ΔA) versus precipitation melted snow (PRMS) of the three frequencies (L1,L2 and L3) at t = -10° C

IV. Conclusion

The complex refractive index is the main cause of delay of the GPS signals through the atmosphere by ice, water, clouds and snow because of the difference of density, temperature shape and dielectric constant. The differential phase shift (ΔØ) depends on the shape and the concentration of rain drops and its values are positive because of the oblate shape of drops (horizontal axis > vertical axis).

The values of the differential phase shift will be irregular in low temperatures because of the irregular shape of snow , the values of (ΔØ) in the case of rain are higher than its values in the case of snow because of the refractive index of snow is small compared with water . The (ΔA) is related the (ΔØ) in the cases of rain and snow and depends on the temperature, the (ΔA) in the case of rain is higher than its values in the case of snow.

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