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Study of characteristic properties of electromagnetic radiation in the presence of earth's atmosphere

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Abstract
This study focuses on investigating the characteristic properties of electromagnetic radiation interaction in the presence of Earth's atmosphere. Electromagnetic radiation is an essential component of modern technology and has multiple applications in various fields. However, its transmission and reception are largely affected by the Earth's atmosphere, which introduces various types of distortions and absorptions. In this study, we aim to understand the fundamental properties of electromagnetic radiation interaction with the Earth's atmosphere, including atmospheric absorption, scattering, refraction, and reflection. We will also explore the effects of different atmospheric conditions, such as temperature, pressure, and humidity, on the propagation of electromagnetic radiation. The results of this study will provide insights into the limitations and challenges associated with the use of electromagnetic radiation in different atmospheric conditions and aid in the optimization of electromagnetic communication and sensing technologies.

Keywords: Earth’s atmosphere, applied temperature, density of atmosphere, applied frequency

Introductions

Electromagnetic radiation is an essential part of modern technology and has numerous applications in various fields, including communication, medicine, and remote sensing [1-9, 10-13]. However, the propagation of electromagnetic radiation is affected by the Earth's atmosphere, which introduces various types of distortions and attenuations [9-14]. As a result, it is important to understand the properties of electromagnetic radiation interaction in the presence of the Earth's atmosphere to mitigate these effects and optimize the performance of electromagnetic systems and devices [12-25].

In this study, we aim to investigate the characteristic properties of electromagnetic radiation interaction in the presence of the Earth's atmosphere. Specifically, we will explore atmospheric absorption, scattering, refraction, and reflection, and how these properties change under different atmospheric conditions. We will also investigate how these effects manifest in different parts of the electromagnetic spectrum, including radio waves, microwaves, and infrared, among others.

Understanding the fundamental properties of electromagnetic radiation interaction with the Earth's atmosphere is critical to the development of optimized communication, sensing, and imaging technologies. The results of this study will benefit multiple fields, including aerospace, climate research, and remote sensing. By investigating the theoritical foundation and empirical observation related to electromagnetic radiation in atmosphere [12-28]. This study seeks to contribute to the broader knowledge base, offering insight that could enhance both scientific understanding and practical applications [13-30].

1. **Radiation:** Energy that moves in the form of waves or particle.
2. **Electromagnetic radiation:** A fundamental form of energy that can be described as waves or particles called photons.
3. **Distortion:** Phenomenon that occurs when light passing through a planet's upper atmosphere is refracted or bent.
4. **Attenuation:** The reduction in the intensity of light, sound, or electromagnetic signal as they pass through the earth's atmosphere.
5. **Absorption:** Process by which the earth's atmosphere absorbs most of the sun's X-rays, ultraviolet, infrared radiation, but not visible light.

6. **Scattering:** Occurs when a particle or a gas molecules interact with electromagnetic radiation causing it to redirect from its original path.

Theoretical description

1. Composition and structure of the gaseous atmosphere

At sea level, the principal constituent of the dry atmosphere are molecule of Nitrogen (about 78% by volume), Oxygen (21%) and the inert gas Argon (1%). There is also significant but variable (typically 0.1% to 3%) amount of water vapors, often specified by the relative humidity H. This is defined by this equation [6-15]:

$$H = \frac{P_{water}}{P_{sat}(T)} \quad (1)$$

As a fraction between zero 1, where $P_{water}$is the *Partial pressure* of water vapor, which can be defined as the total product of the total atmospheric pressure with the volume fraction of water vapor, and $P_{sat}(T)$ is the saturated vapor pressure of water at temperature T [9-14, 16-22].

Atmospheric pressure and density diminish with the height above the Earth`s surface [22-25]. This is because the molecule, acted upon by gravity, tend to sink to the surface but are prevented from doing so fully by thermal excitation. The distribution of density with the height is thus governed by the Boltzmann distribution and is approximately exponential [23-29]. There are however, significant variation from this approximation dependence and it in conventional to divide the atmospheric into several layers [2-6]. The height range just specified are for typical condition at temperature latitude: there is considerable seasonal and latitude variation [22-30].

The absolute temperature *T*, pressure *P* and the density *ρ* of the atmosphere can be assume to be related to one another by [2-6].

$$\frac{\rho T}{P} = \frac{Mm}{R} \quad (2)$$

Where $M_m$is the mass of one mole atmospheric gas and*R*is the gas constant. This equation is based on the assumption that the atmospheric behave as an ideal gas [17-21].

The atmospheric pressure *P* at a height *x* at a measure of the mass of air, and hence the number of molecules, above *x*. this follow the earth`s gravitation field strength *g* may be assumed to be constant over the range of height for which *P* is significant, so that.

$$P(x) = Mmg \int_x^{\infty} N(x')dx' \quad (3)$$

Where *N(x`)* is the molar concentration (number of per unit volume) at height *x'*. The variation of pressure with height can be modeled rather crudely as an exponential [22-30],

$$p(z) = p_0 \, exp\left(-\frac{z}{z_0}\right) \quad (4)$$

For the troposphere, a value of z_0 of roughly 7.5km is appropriate [30].

2. Molecular Absorption and Scattering

A detailed understanding of process by which molecules absorb and scatter electromagnetic radiation requires considerable knowledge of quantum mechanics [3-19]. We may state, however that the energy of an individual energy of an individual molecule cannot be varied continuously, but must be one of a number, in principle infinite, of discrete value called energy level [22-28]. If molecules absorb electromagnetic radiation, it must be promoted from one energy level to another, and hence only certain value of the energy increase ΔE are allowed [2-11]. Plank`s law states that the frequency *F* of the electromagnetic radiation is given by,

$$\Delta E = hF \quad (5)$$

Where *h* is Plank`s constant, although it is often more convenient to write this equation in term of angular frequency ω:

$$\Delta E = \frac{h}{2\pi}\,\omega = \hbar\omega \quad (6)$$

Thus, we expect molecules will absorb "selectively", at particular frequencies, which are usually called absorption lines [2-6].

3. Mechanism of Molecular absorption

There are three main mechanism by which molecules can absorb electromagnetic radiation. The first of these, requiring the largest amount of energy, involves the promotion of electron to higher energy levels [5-7]. These are termed as electronic transition [8]. So we will illustrate the idea with reference to the hydrogen atom. In this case, the electronic energy level are given by,

$$E_n = -\frac{me^4}{32\pi^2\varepsilon_0\hbar^2}\frac{1}{n^2} \quad (6)$$

Where *m* is electron mass and *n* is a quantum number that can take only positive integer values. So that we expect to find the absorption line due to the electronic transition in the ultraviolet and visible regions of the electromagnetic spectrum [9-17].

The second mechanism of molecular absorption that we shall consider is vibration. The molecular bond between atoms behave more or less like a spring [12-19]. To model this, we consider a diatomic molecule constituting of two atoms, with masses $m_1$and m_2, connected by spring with force constant *k*, as shown in figure 1. Classically give the natural angular frequency of this system,

$$\omega_0 = \sqrt{\frac{k(m_1+m_2)}{m_1 m_2}} \quad (7)$$

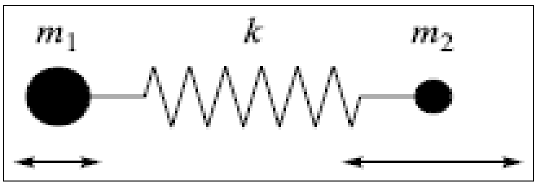

Fig 1: Classical model of molecular vibration and quantum mechanics gives the energy level as

$$E_v = \left(v + \frac{1}{2}\right)\hbar\omega_0 \quad (8)$$

Where v is a quantum number that can take any non-negative value [22], this quantum number can change only by ±1, so in fact only possible amount of energy that can be absorbed is $\Delta E=\hbar\omega_0$, giving an absorption line at the resonant frequency

$$f=\frac{\omega_0}{2\pi}.$$

The last absorption mechanism we shall discuss in rotation [12-19]. We will consider a simple diatomic molecule consisting of two atoms, with masses m_1 and m_2, separated by a fixed distanced [22-29]. classically, this system can rotate about the centre of mass of the two atoms. The moment of inertia of the system is given by,

$$I=\frac{m_1 m_2}{m_1+m_2}d^2 \quad (9)$$

And according to a quantum mechanics, the energy of such a state is given by

$$E_J=\frac{J(J+1)\hbar^2}{2I} \quad (10)$$

Where J is a quantum number that can take any non-negative integer value, when electromagnetic radiation absorbed, J must increases by 1. We find that the frequency of a rotation absorption line is given by,

$$F=\frac{(J+1)h}{4\pi^2 I} \quad (11)$$

Where F is a frequency, J is a quantum number, I is a moment of inertia [21-30].

We have simplicity suggested that a molecular transition occurs at a single frequency, so that the absorption line in the spectrum has a width of zero. In fact all lines are broadening to some extent [1, 6-16]. In portion to the frequency of the line, the effect is largest for electronic transition [22-28]. Much more significant is the effect of thermal motion of the gas. The line width Δf due to this effect, which is usually called Doppler Broadening, is given by:

$$\frac{\Delta f}{f}=\sqrt{\frac{RT}{M_m c^2}} \quad (12)$$

Where f is the frequency of the line, R is the gas constant, T is the absolute temperature, $M_m$is the mass of one mole of the gas, and c is the speed of light.

Another important mechanism is pressure Broadening, also called Collision broadening [22-29]. The molecules of gas collide with one another and with other molecules in the atmosphere, and these collisions disturb the state of the molecule. The pressure broadening can be written as:

$$\Delta f\approx\frac{\sigma N_A p}{\sqrt{M_m RT}} \quad (13)$$

Where p is the gas pressure, σ is related to the collision cross-section for the molecules, $N_A$is Avogadro number [12-17].

4. Molecular Scattering

If we model a molecule very simply as an electrically conducting sphere of radius a, much smaller than the wavelength λ of the radiation, it will have a polarisability:

$$\alpha=4\pi\varepsilon_0 a^3 \quad (14)$$

This crude model describes Rayleigh scattering by individual molecules. We can estimate the region of the electromagnetic spectrum in which it is important as follows [12-18]. From equation (3) we know that the molar concentration of the molecules in the atmosphere, integrated through the whole atmosphere, is given by:

$$\frac{p_0}{M_m g}$$

Where p_0 is the sea level pressure, M_m is the molar mass of the molecules and g is the gravitational field strength [3-9]. Thus we can estimate the optical thickness of the atmosphere due to molecular Rayleigh scattering as,

$$\tau_s\approx\frac{N_a p_0}{M_m g}\frac{128\pi^5 a^6}{3\lambda^4}$$

Where $N_A$is Avogadro`s number. M_m is the mass of molecules.

We can derive a very simple model of this phenomenon by assuming that the earth is flat, and considering a ray that makes an angel θ to the horizontal [9-11]. The optical thickness is given by:

$$\tau=\int_0^\infty \gamma(x)dx \quad (15)$$

Where $\gamma(x)$ is the attenuation coefficient at distance s along the ray. We know that x is related to the height h in the atmosphere by:

$$\chi=\frac{h}{\sin\theta}$$

So we can rewrite our expression for the optical thickness as;

$$\tau=\frac{1}{\sin\theta}\int_0^\infty \gamma(x)dx \quad (16)$$

In other words, the optical thickness is increased by a factor of 1/sin(θ) with respect to its value for a vertical ray [3-7].

5. Larger particles: fog, cloud, rain and snow

At any one time, about half of the earth`s surface will be covered by Cloud. Precipitation can also have a significant effect on the propagation of electromagnetic radiation [7-15]. In the case of rainfall, the rain rate is the dominant factor since this largely controls both the size distribution of the droplets and their density. Fog and low-altitude cloud consist of water droplets, but these are very much larger than the droplet in aerosols [8-17]. If the number density of the droplets is N, the scattering coefficient is therefore given by;

$\gamma_s \approx \pi a^2 N$

The mass density of liquid water in the fog or cloud is given by;

$$\rho = \frac{4}{3}\pi a^3 N \rho_w \quad (17)$$

Where ρ_w is the density of water, and we have assume that the droplets are spherical, so we see that we can write the scattering coefficient as;

$$\gamma_s \approx \frac{3p}{4a\rho_w}$$

Since the droplet radius is not strongly dependent on the mass density ρ, this equation implies that the scattering coefficient is roughly proportional to the mass density of liquid water in the cloud [22-28].
The water droplets in rain are roughly 100 times larger than those in clouds, being of the order of 1 mm in radius [8-14].
We can define a droplet size distribution $N(a)$, such that $N(a)da$is the number of droplets per unit volume having radii between a and $a + da$, so assuming that the scattering cross-section of an individual drop is given by πa^2, the scattering coefficient is then,

$$\gamma_s = \int_0^\infty \pi a^2 N(a) da \quad (18)$$

And the mass density of liquid water in the rain is

$$\rho = \int_0^\infty \frac{4}{3}\pi a^3 \rho_w N(a) da \quad (19)$$

Where ρ_w is the density of water. The drop size distribution is mainly governed by the rain rate, usually specified in millimeters per hour [6-11].

6. The Ionosphere

The ionosphere is an ionized layer above the Earth`s atmosphere, extending from about 70km to a few 100km above the surface [7, 9].
The ionization is produced by extreme ultraviolet and X-radiation from the sun, and it can have significant effect on the propagation of radio-frequency electromagnetic radiation.
We know the dielectric constant of plasma is given by;

$$\varepsilon_r = 1 - \frac{Ne^2}{\varepsilon_0 m_e \omega^2} \quad (20)$$

Where N is the number density of the electrons, e is the charge and me the mass of an electron, and ω is the angular frequency of the radiation. The plasma frequency is,

$$\omega_p = \sqrt{\frac{Ne^2}{\varepsilon_0 m_e}} \quad (21)$$

and the dielectric constant is positive and negative according as ω is greater or less than ω_p. We may write the dispersion relation for radiation propagation in a plasma at a frequency very much higher than the plasma frequency as;

$$\omega = \frac{ck}{1 - \frac{Ne}{2\varepsilon_0 m_e \omega^2}} \quad (22)$$

So we can evaluate the group velocity from equation,

$$v_g = \frac{d\omega}{dk} = \frac{c}{1 + \frac{Ne}{2\varepsilon_0 m_e \omega^2}} \quad (23)$$

This is clearly less than *c*, as expected. Further-more we can calculate the time *T* Taken for a pulse of radiation to travel through a finite region of the ionosphere [9-19]. Since,

$$T = \int \frac{dz}{Vg}$$

Where *z* measure propagation distance, we obtain,

$$T = \frac{z}{c} + \frac{e^2}{2\varepsilon_0 m_e \omega^2 c} \int Ndz \quad (24)$$

Here the first term is just the time taken for light to travel the distance *z*, and the second term consists of a frequency-dependent constant multiplied by the integrated number-density of electron along the path through the ionosphere [9-13].

ResultS and Discussion

Variation of intensity with distance for different values of absorption coefficient

The graph has been plotted between final intensity (I) with distance (x) for different values of absorption coefficient (a). Fig:-1), from this figure it is clearly seen that the intensity decrease exponentially as the distance increases, with steeper decrease for high absorption coefficient.
This graph shows how the intensity (I) of electromagnetic radiation decreases as it travels through the Earth's atmosphere over a distance (x). The absorption coefficient (a) varies, representing different atmospheric conditions (e.g., clear sky vs. foggy conditions). As (x) increases (moving further through the atmosphere), the intensity (I) decreases. The decrease is more rapid for higher values of (a), indicating stronger absorption (more attenuation of radiation). The curve is steeper for larger (a), meaning the radiation is absorbed more quickly in the atmosphere.

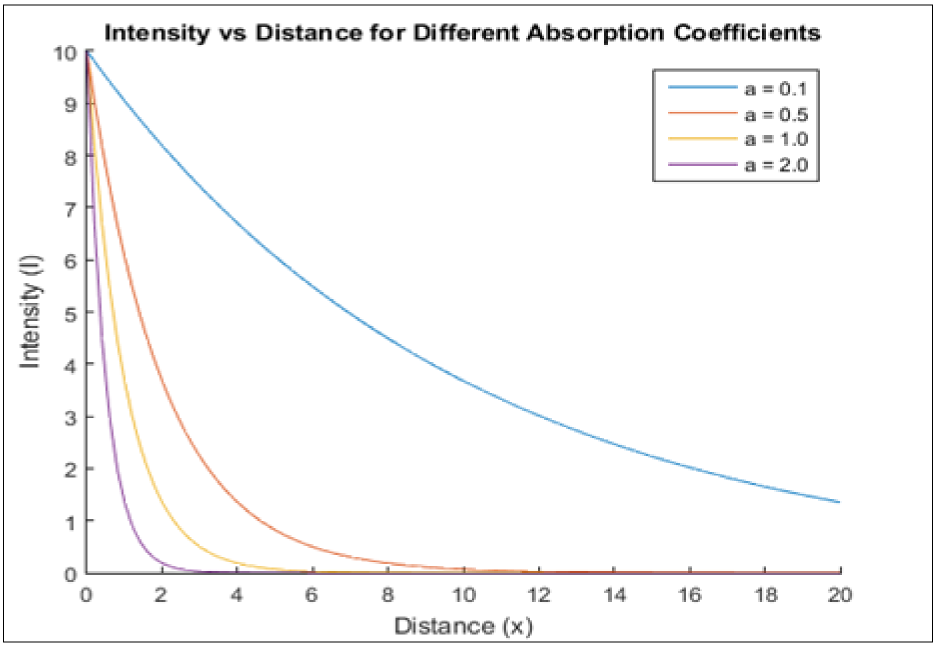

Fig 2: Intensity vs distance for different absorption coefficients

Effect of intensity for different values of absorption coefficient

The graph has been plotted between intensity (I) with absorption coefficient (a). Shown in fig (2) it is clearly seen by the curve shows how the intensity decrease as the absorption coefficient increase which reflects the exponential attenuation of electromagnetic radiation as passes through the atmosphere.

This graph shows how the intensity (I) changes as a function of the atmospheric absorption coefficient (a) for a fixed distance (x). It represents how different levels of atmospheric absorption affect the remaining intensity of electromagnetic radiation. As the absorption coefficient (a) increases, the intensity (I) decreases exponentially. For small values of (a), the intensity remains relatively high, indicating low atmospheric absorption. For larger values of (a), the intensity drops rapidly, indicating that the atmosphere is absorbing a significant portion of the radiation. The graph emphasizes how sensitive the intensity is to changes in the absorption coefficient, particularly when (a) is large.

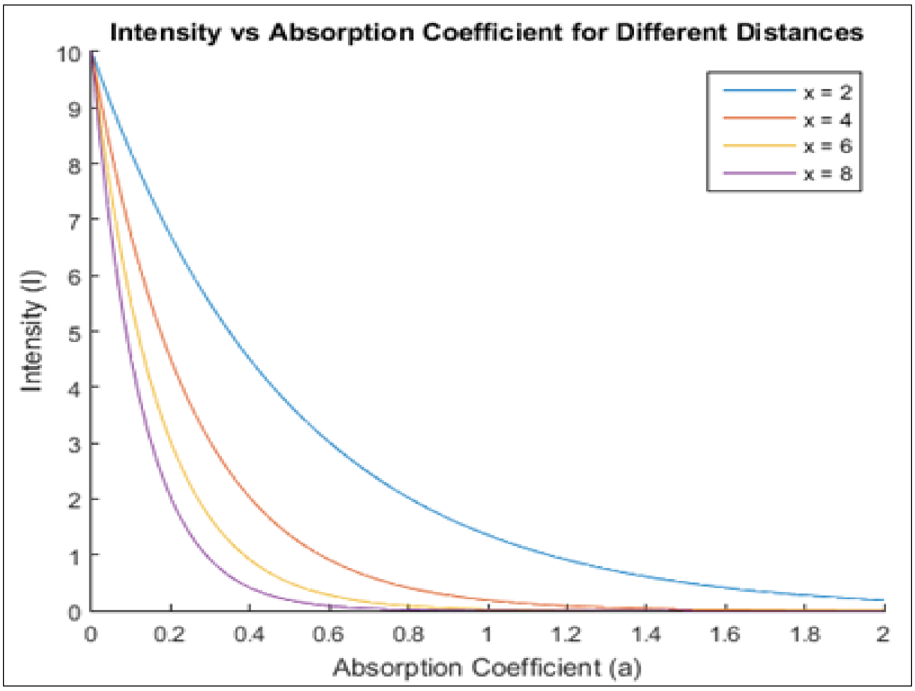

Fig 3: Intensity vs distance for different absorption coefficients

Effect of line width with frequency for different temperature (t)

The graph has been plotted between line width (Δf) with applied frequency (f) for different values of temperature (T). From this figure it is clearly seen that the line width increases with increase in value of temperature with respect to applied frequency. It means line width increases when the value of temperature increases. The line width is maximum when temperature T (T= 500 Kelvin) and the line width is minimum at temperature T (T = 10 Kelvin). For different values of temperature the line width increases with respect to applied frequency. The relative line width increases linearly with frequency. This linearity indicates that as the frequency of electromagnetic radiation, the line width broadens proportionally. This behavior is constant across all temperature, showing that higher frequencies are inherently associated with broader spectral lines.

To achieve a higher line width, both the applied frequency and temperature must be increased, as line width is directly proportional to these two factors.

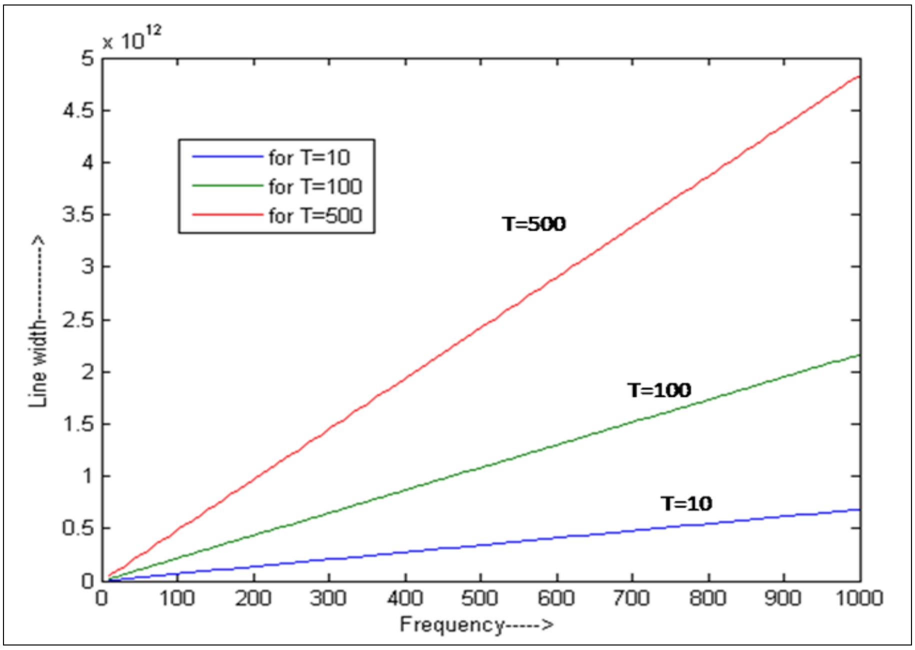

Fig 4: Effect of line width with frequency for different temperature (t)

Effect of line width with applied frequency for different values of gas masses

The graph illustrate the relationship between line width and applied frequency for various gas masses. it clearly show that line width increases as the mass of atmospheric gas decreases, with respect to applied frequency. specifically, the line width is highest when the atmospheric gas mass is lowest and the line width is lowest when atmospheric gas mass is highest. Across different gas masses, the line width constantly increase with applied frequency. This indicates that selecting a combination of higher applied frequency and lower atmospheric gas mass will result in greater line width is directly proportional to both applied frequency and the inverse of atmospheric gas mass.

To achieve a higher line width, it is necessary to increase the applied frequency while simultaneously deceasing the atmospheric gas mass, as line width is directly proportional to the frequency and inversely proportional to the gas mass.

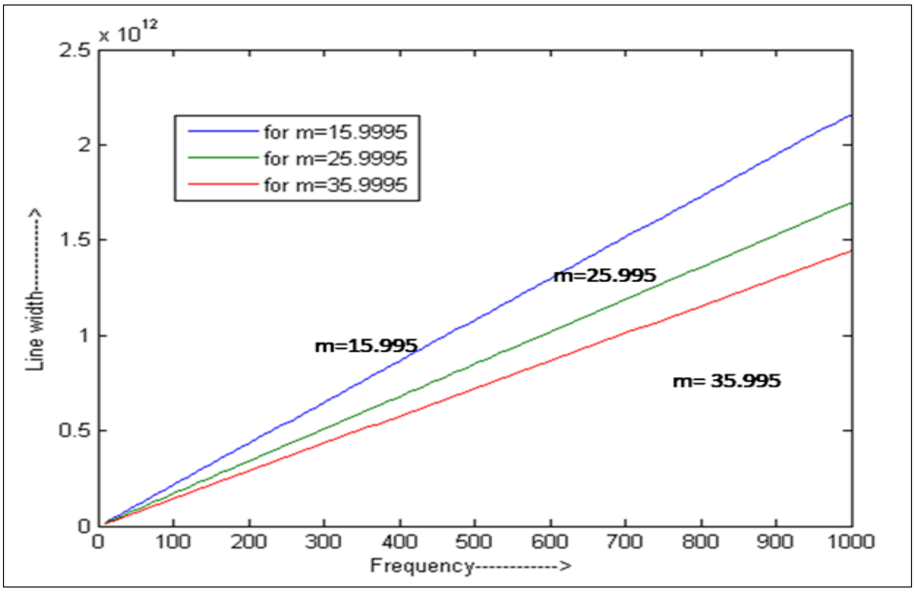

Fig 5: Effect of line width with applied frequency for different values of gas masses

Effect of density of atmosphere with temperature for different mass of atmospheric gas: Let's first discuss the effect of atmospheric density in relation to different values of atmospheric gas mass. The graph shows the relation between atmospheric density and temperature for various atmospheric gas masses. From the graph it is evident that density increase with higher values of atmospheric gas mass as temperature rises. Specifically, the atmospheric density is higher when the gas mass is maximum and lowest when gas mass is minimum. Across different atmospheric gas masses, density consistently increase with temperature. This suggest that to achieve a higher atmospheric density, one should select condition with both a higher applied temperature and greater atmospheric gas mass.

As atmospheric density is directly proportional to both the applied temperature and mass of atmospheric gas. Therefore, to increase atmospheric density, one must increase both temperature and mass of atmospheric gas.

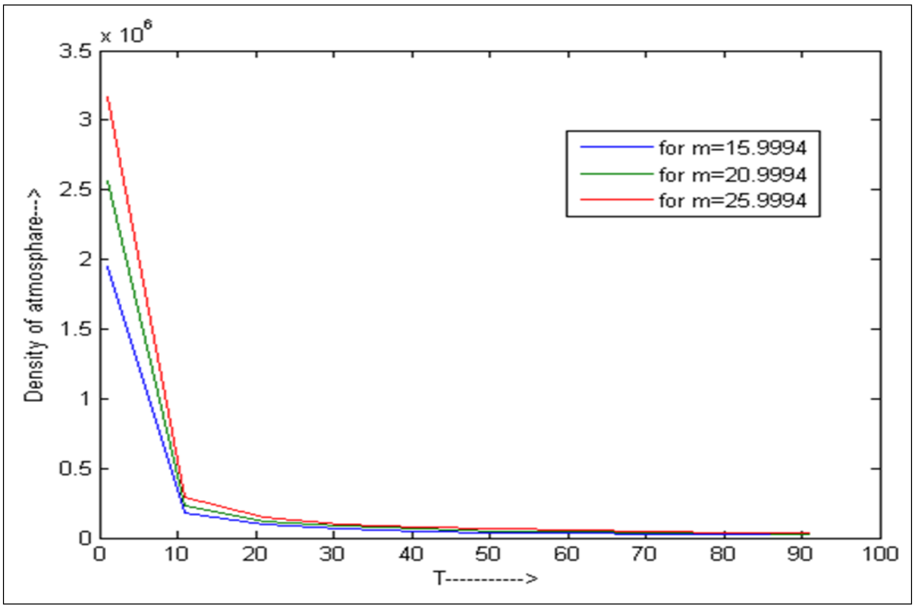

Fig 6: Effect of density of atmosphere with temperature for different mass of atmospheric gas

Effect on density of atmosphere with applied temperature for different values of atmospheric pressure

Let's first examine the effect of atmospheric density in relation to different value of atmospheric pressure. The graph shows the relationship between atmospheric density and temperature for various atmospheric pressures. The graph clearly demonstrate that atmospheric density increases as atmospheric pressure rises with increase in temperature. Specifically, atmospheric density is highest at the maximum pressure (P=2000.25\ times 10^3) and lowest at the minimum pressure (P=1013.25\times 10^3). Across different values of atmospheric pressure, density consistently increase with temperature. This indicates that achieving higher atmospheric density requires selecting conditions with both higher applied temperature and higher atmospheric pressure. As atmospheric density is directly proportional to both applied temperature and atmospheric pressure. Therefore, to increase atmospheric density, one must increase both the temperature and the atmospheric pressure.

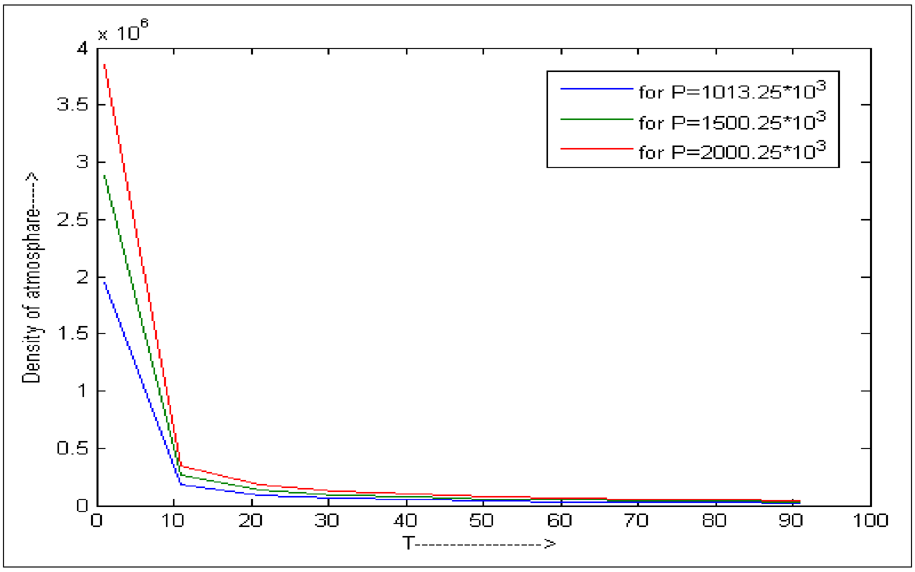

Fig 7: Effect on density of atmosphere with applied temperature for different values of atmospheric pressure

Conclusion

In conclusion, the study of characteristic properties of electromagnetic radiation in the presence of earth's atmosphere provides valuable insight into the complex interaction between radiation and atmospheric constituents. By analyzing how electromagnetic waves behave as they pass through the atmosphere, particularly in terms of absorption, scattering, and reflection, we gain deeper understanding of the processes that govern energy transfer and wave propagation. It is crucial for various applications such as communication, remote sensing, and weather forecasting. The atmosphere affects the transmission, absorption, and scattering of electromagnetic radiation, leading to changes in their spectral properties, polarization, and intensity. The understanding of atmospheric effects on electromagnetic radiation has led to the development of sophisticated models and tools to correct for atmospheric distortions in satellite, radar, and optical measurements. While the study of atmospheric effects on electromagnetic radiation is still an active research area, advances in technology and modeling have significantly improved our ability to accurately measure and predict electromagnetic radiation in the presence of earth's atmosphere.

It has been found that our study reinforces the importance of considering atmospheric effect when analyzing electromagnetic radiation, offering a foundational understanding that can be applied to improve technologies and scientific model related to earth's atmosphere and beyond.

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