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Laser Radar with Improved Software Reliability Factor

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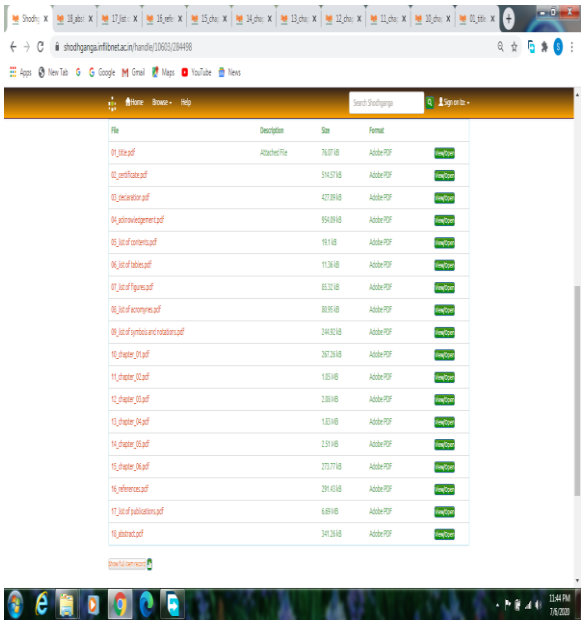
Abstract :

INTRODUCTION TO RADAR SYSTEMS

94 GHz by about 5 dB (on average) than horizontal polarization, which is the opposite to the experience at microwaves. (It should be cautioned that the few measurements available were taken at low grazing angle and over a limited range of wind speeds.) As with 'trees and grass, the value of (To for snow increases with frequency and grazing angle.77.78.102 Crusted snow (that which has melted and refrozen), produces higher values of (To at 35 GHz and 94 GHz than wet snow, grass, or trees. At microwaves the backscatter from rain can be explained according to the Rayleigh scattering model with the reflectivity varying as the fourth power of the frequency.



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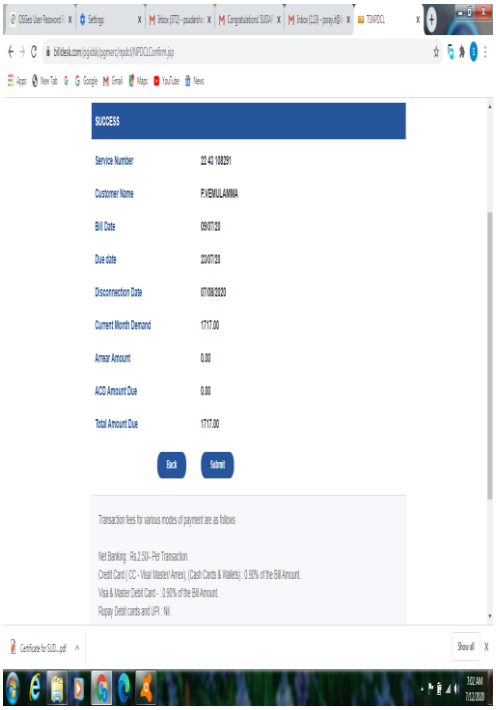

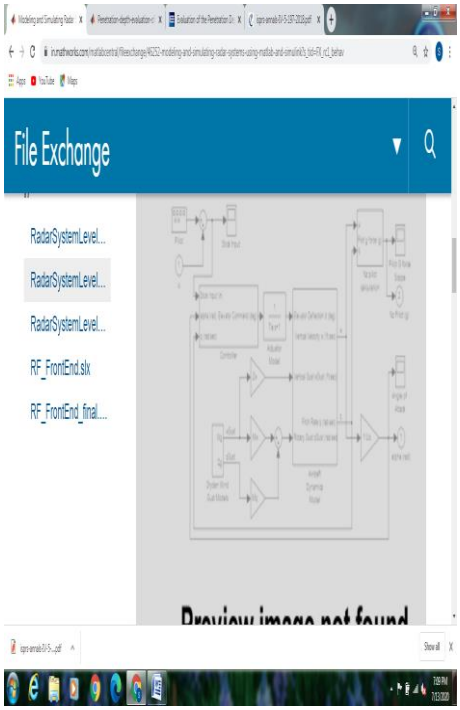

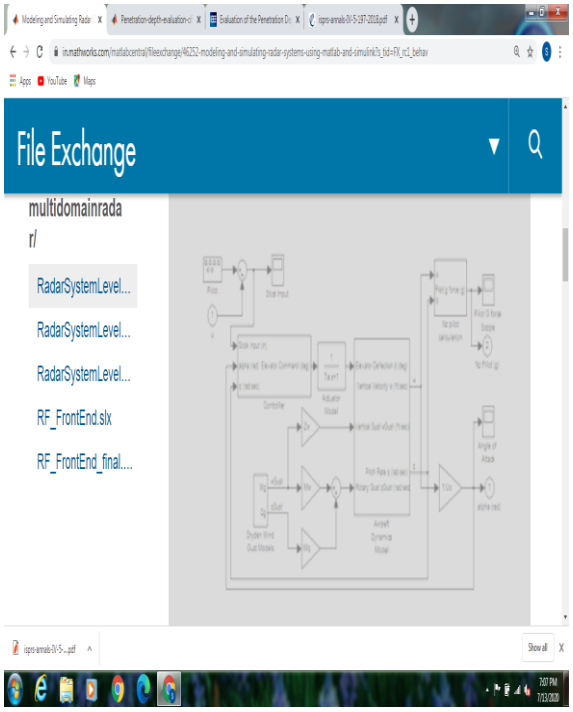

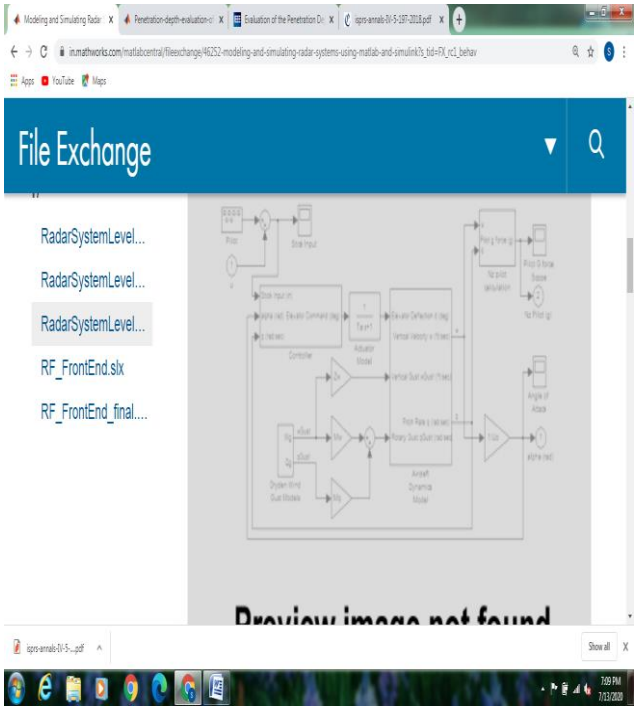

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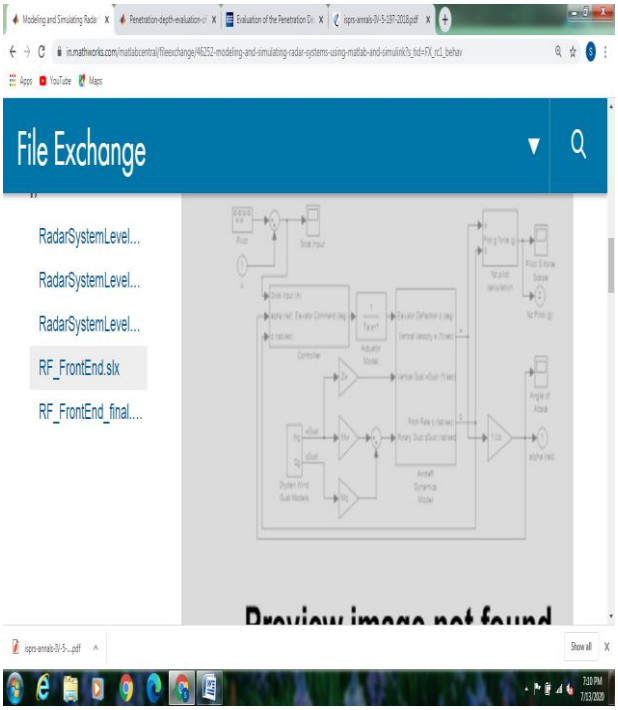

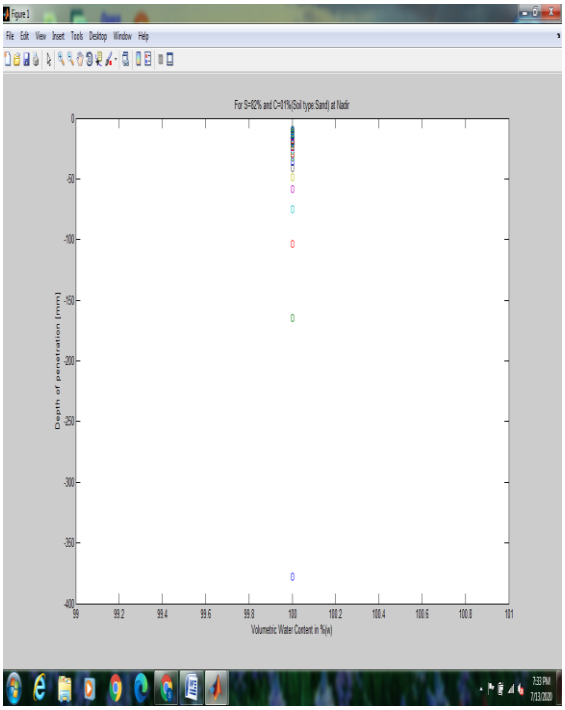

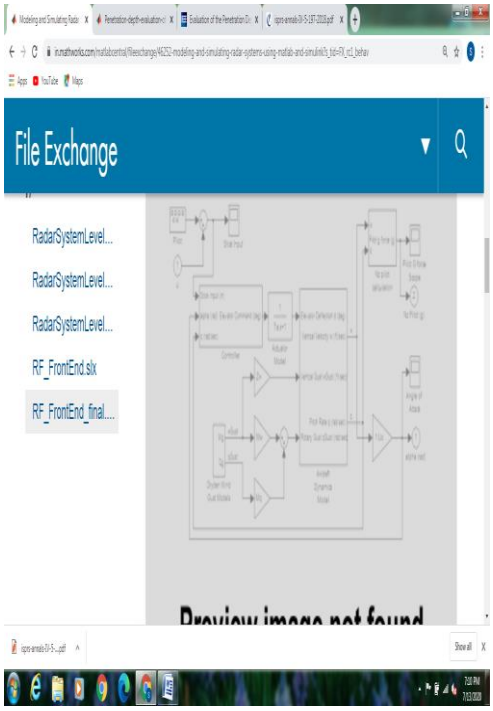

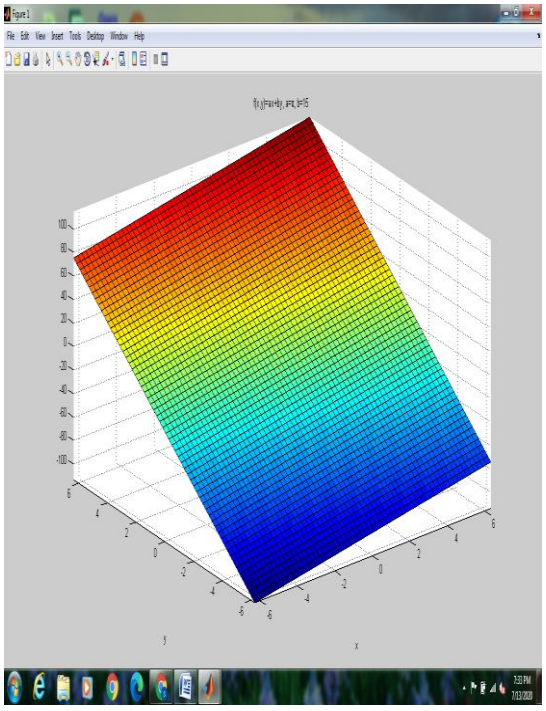

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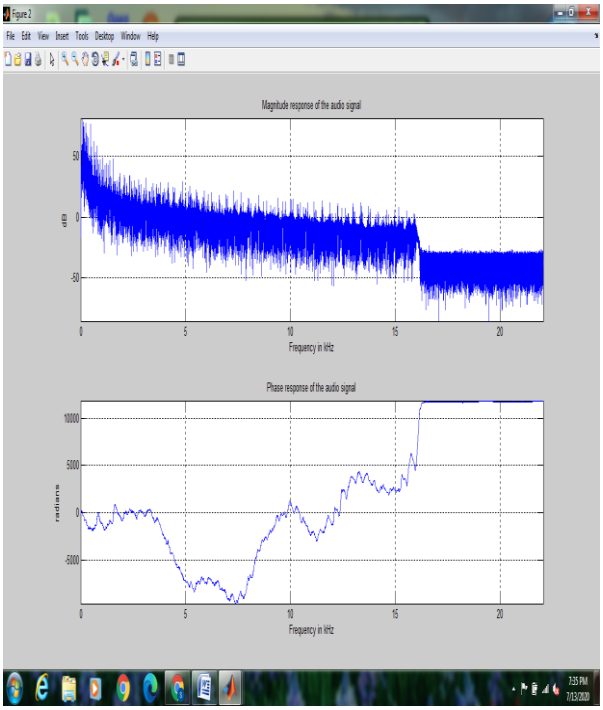

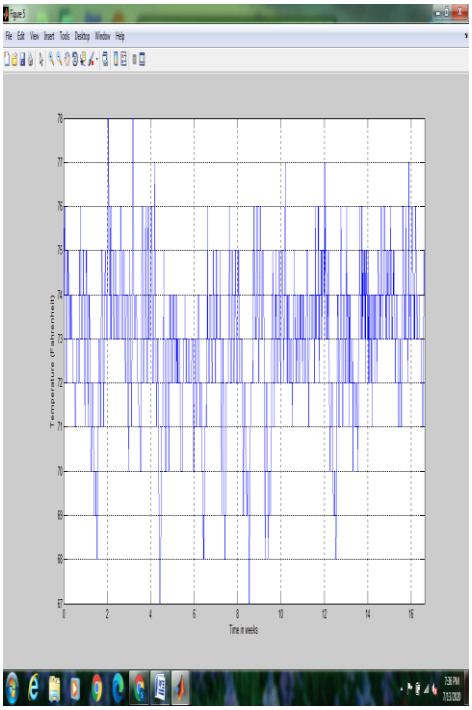

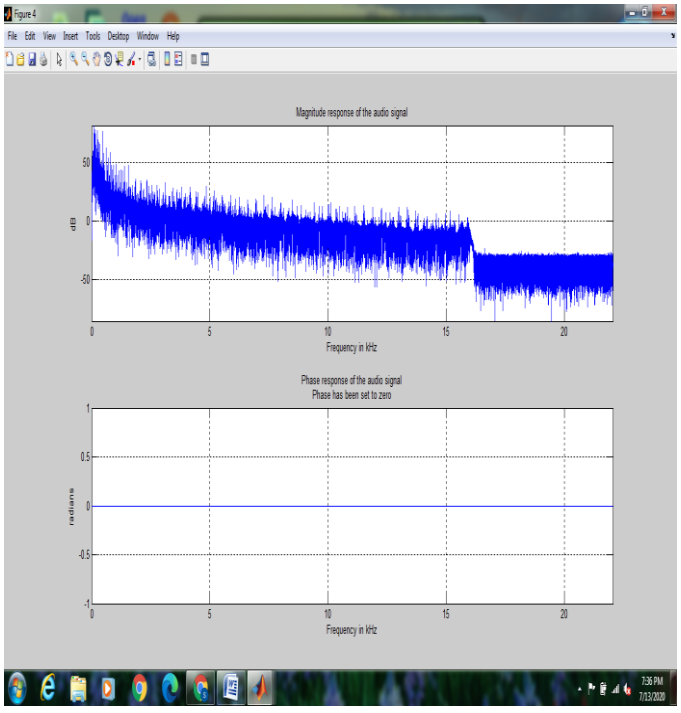

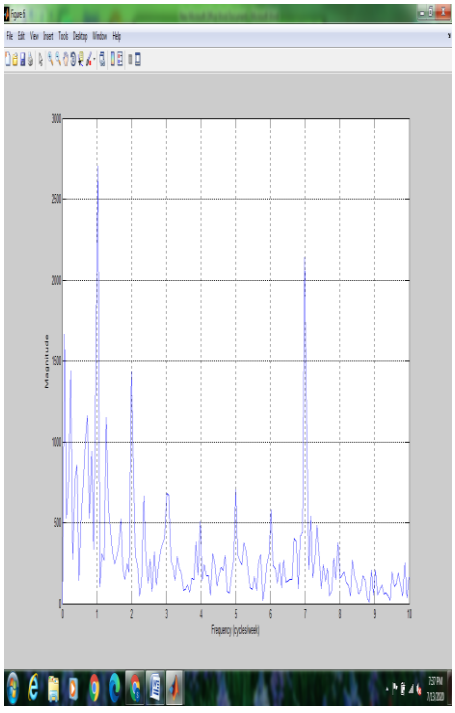

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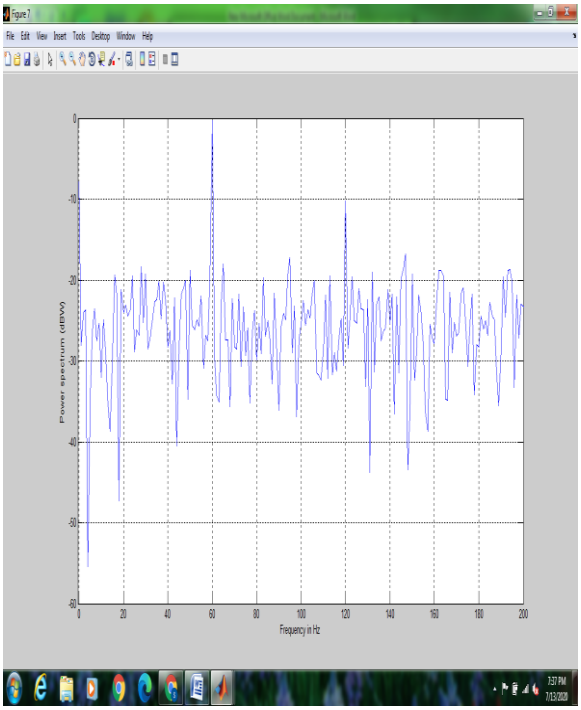

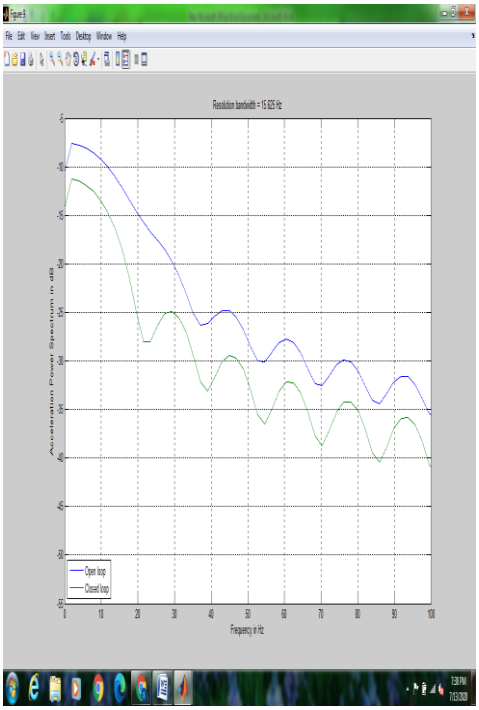

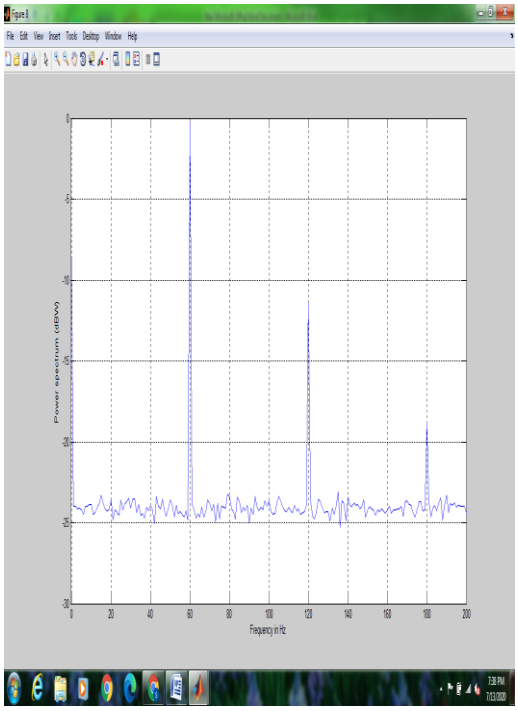

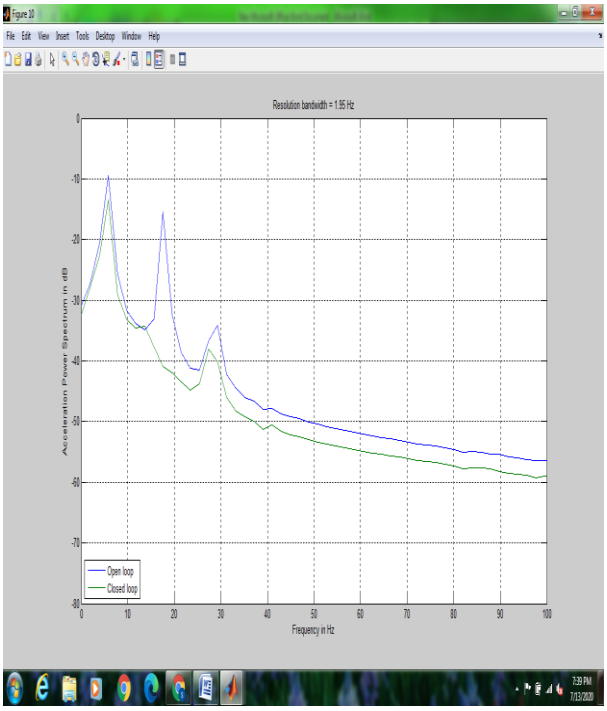

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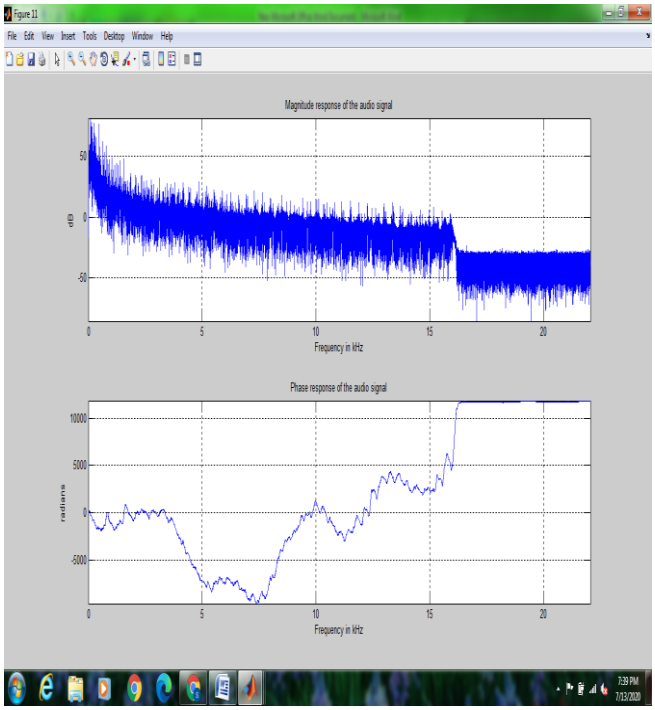

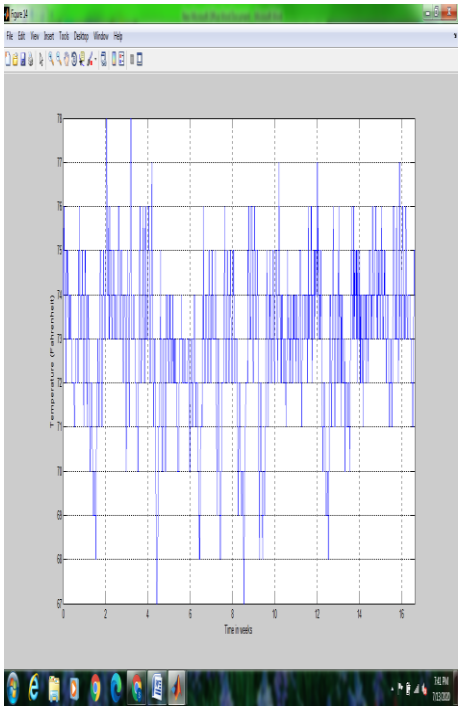

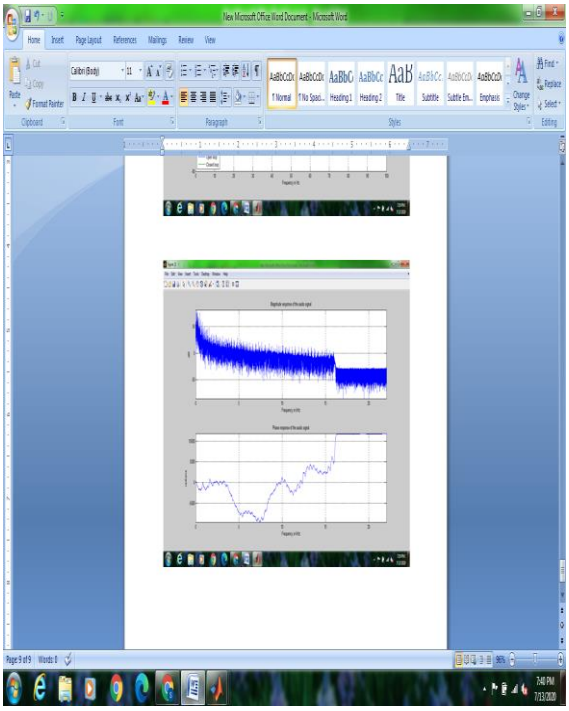

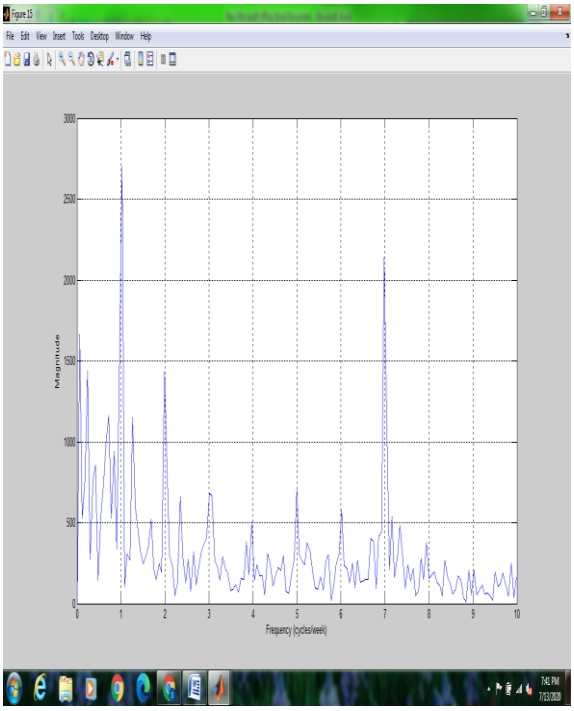

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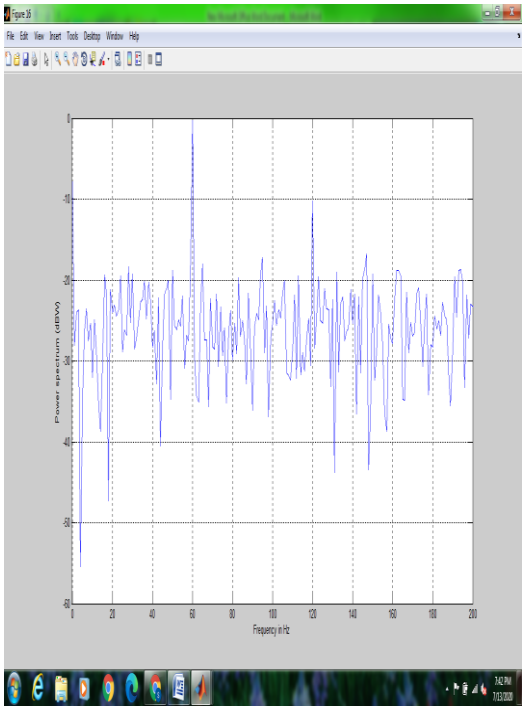

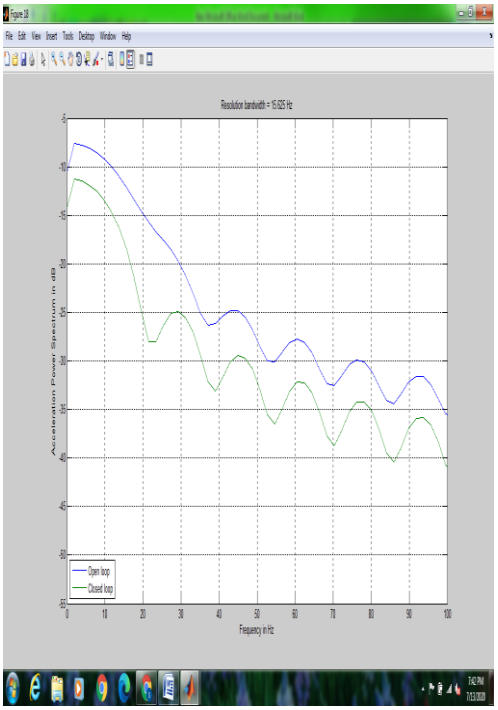

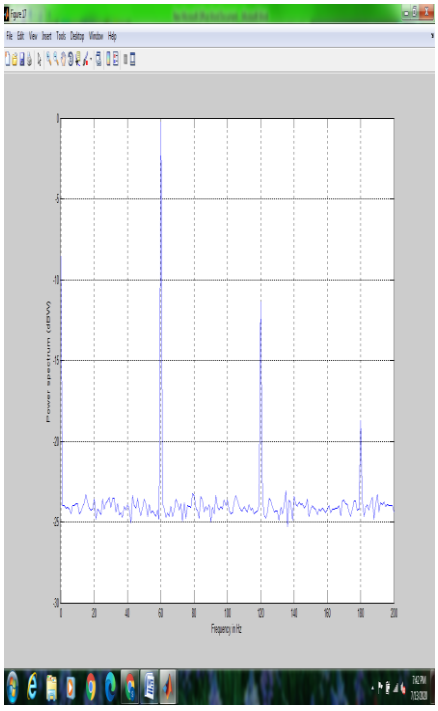

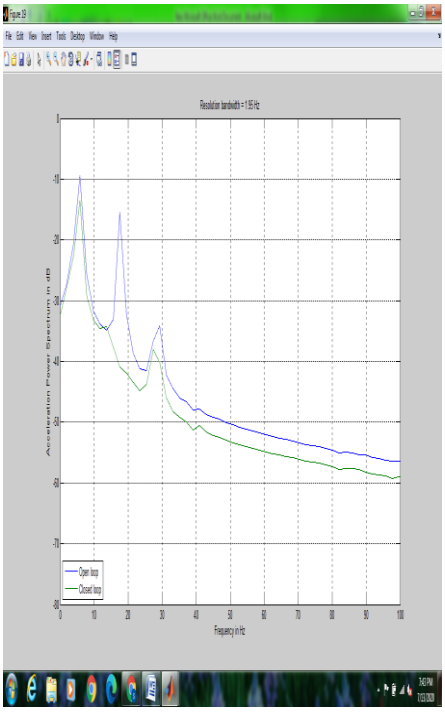

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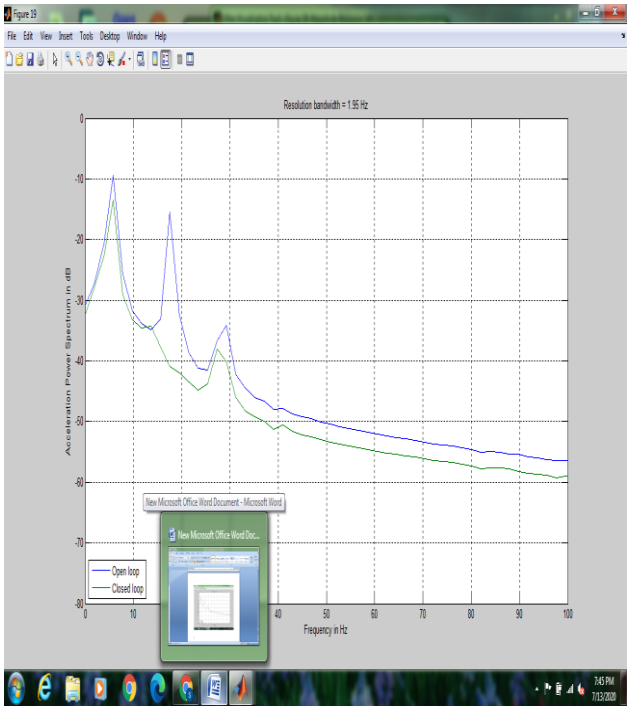

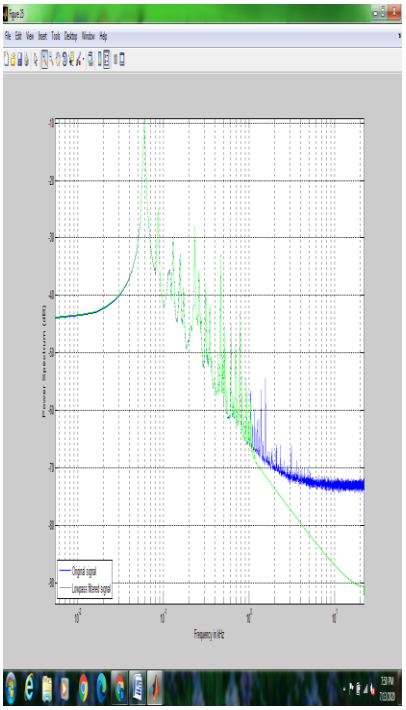

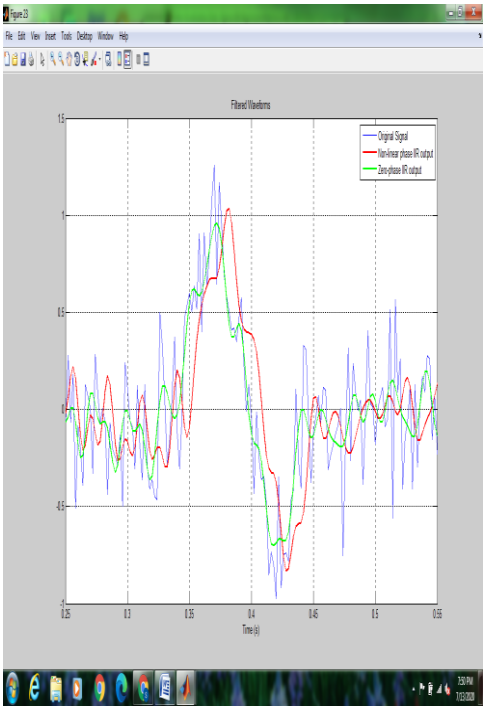

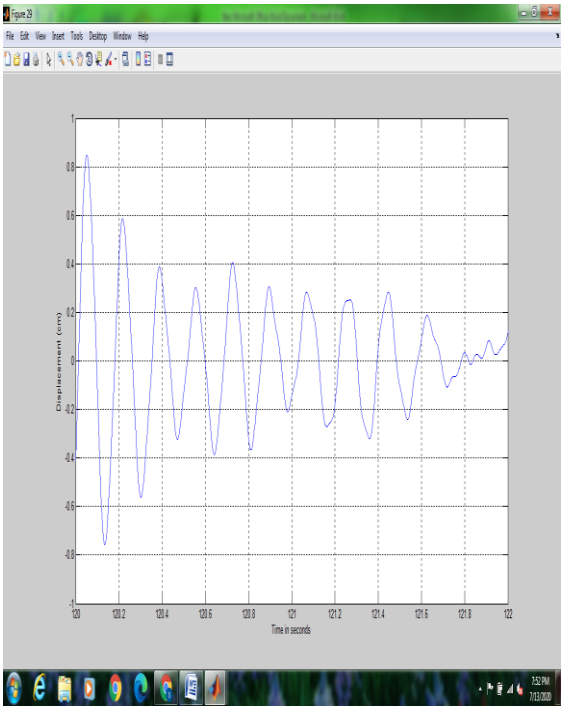

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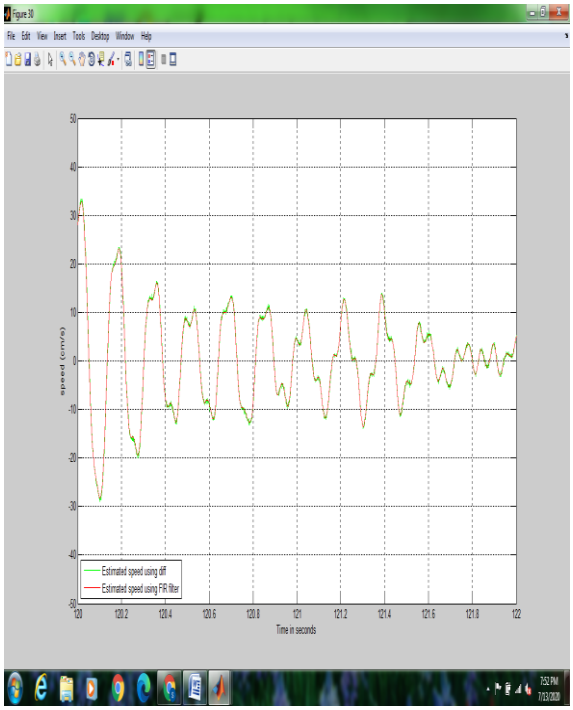

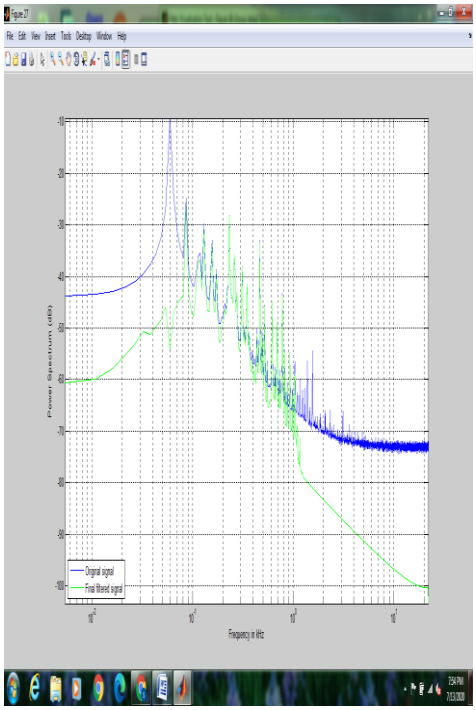

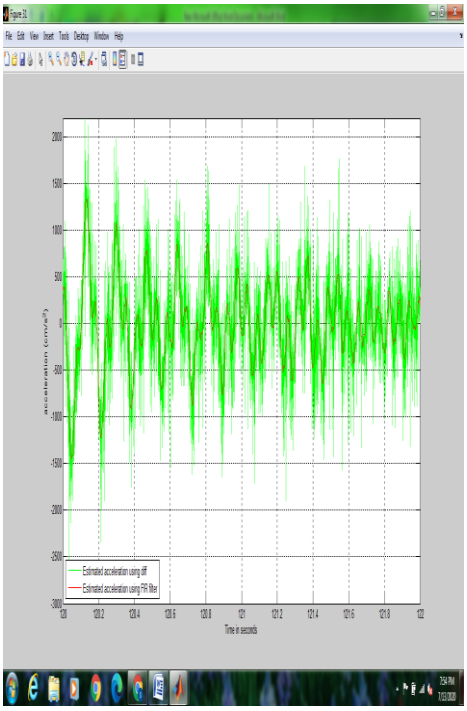

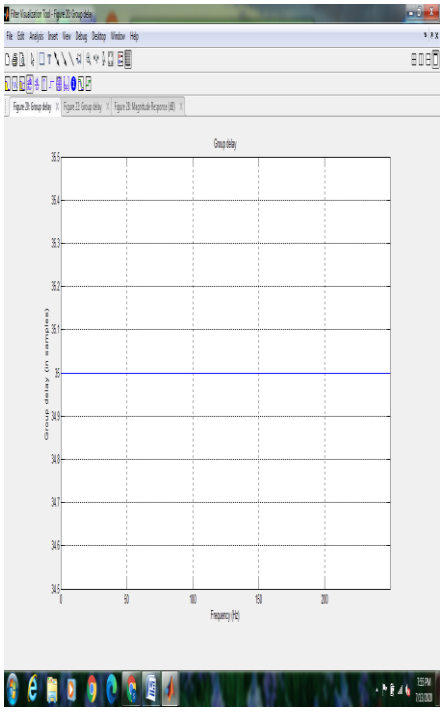

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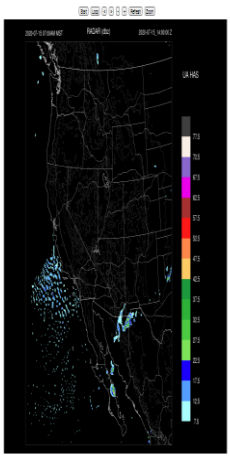

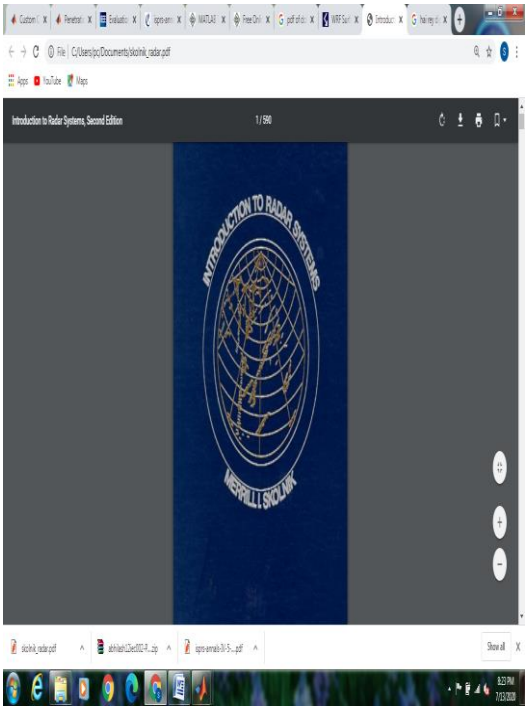

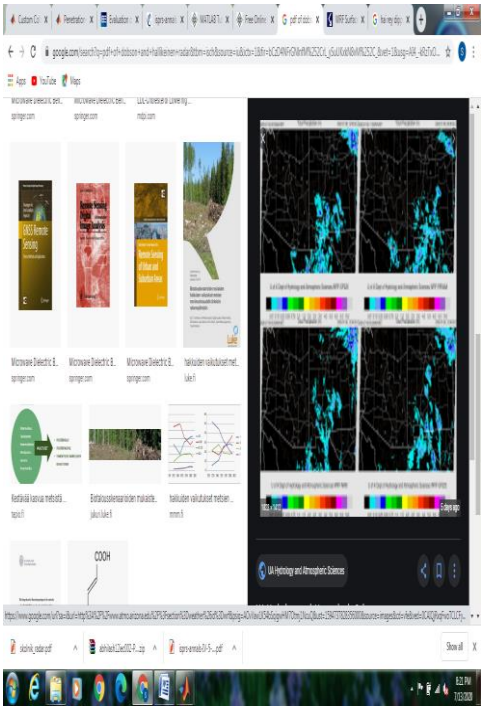

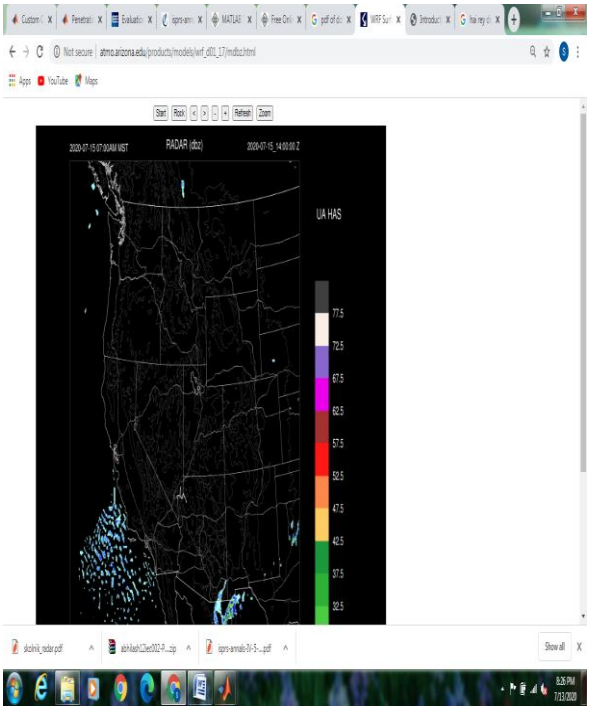

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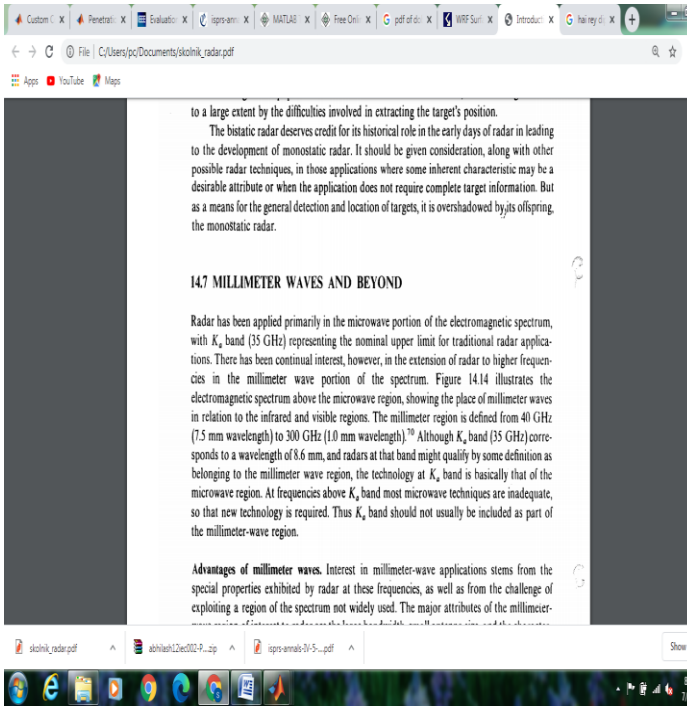


to a large extent by the difficulties involved in extracting the target's position.

The bistatic radar deserves credit for its historical role in the early days of radar in leading to the development of monostatic radar. It should be given consideration, along with other possible radar techniques, in those applications where some inherent characteristic may be a desirable attribute or when the application does not require complete target information. But as a means for the general detection and location of targets, it is overshadowed by its offspring, the monostatic radar.

14.7 MILLIMETER WAVES AND BEYOND

Radar has been applied primarily in the microwave portion of the electromagnetic spectrum, with K_u band (35 GHz) representing the nominal upper limit for traditional radar applications. There has been continual interest, however, in the extension of radar to higher frequencies in the millimeter wave portion of the spectrum. Figure 14.14 illustrates the electromagnetic spectrum above the microwave region, showing the place of millimeter waves in relation to the infrared and visible regions. The millimeter region is defined from 40 GHz (7.5 mm wavelength) to 300 GHz (1.0 mm wavelength).[70] Although K_a band (35 GHz) corresponds to a wavelength of 8.6 mm, and radars at that band might qualify by some definition as belonging to the millimeter wave region, the technology at K_a band is basically that of the microwave region. At frequencies above K_a band most microwave techniques are inadequate, so that new technology is required. Thus K_a band should not usually be included as part of the millimeter-wave region.

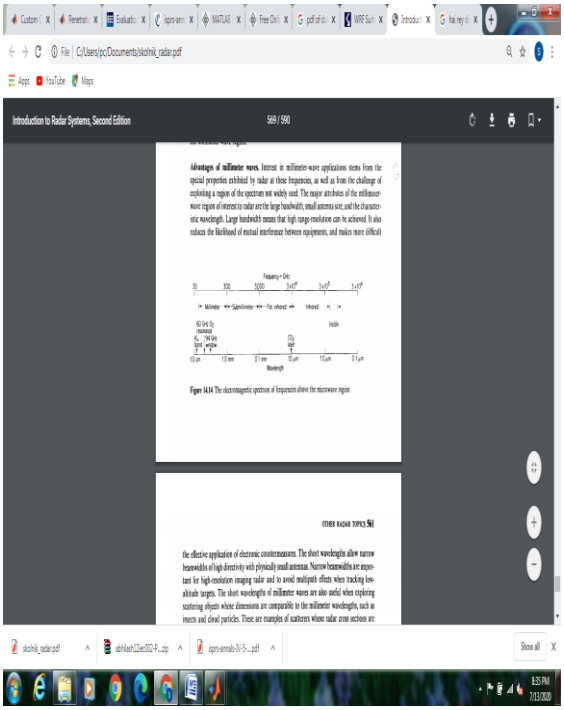
Advantages of millimeter waves. Interest in millimeter-wave applications stems from the special properties exhibited by radar at these frequencies, as well as from the challenge of exploiting a region of the spectrum not widely used. The major attributes of the millimeter-

Introduction to Radar Systems, Second Edition 570 / 590

OTHER RADAR TOPICS 561

the effective application of electronic countermeasures. The short wavelengths allow narrow beamwidths of high directivity with physically small antennas. Narrow beamwidths are important for high-resolution imaging radar and to avoid multipath effects when tracking low-altitude targets. The short wavelengths of millimeter waves are also useful when exploring scattering objects whose dimensions are comparable to the millimeter wavelengths, such as insects and cloud particles. These are examples of scatterers whose radar cross sections are greater at millimeter wavelengths than at microwaves since they are generally in the resonance region (Fig. 2.9) at millimeter wavelengths, but in the Rayleigh region at microwaves (where the cross section varies as the fourth power of the frequency). Another advantage of the short wavelengths is that a doppler-frequency measurement of fixed accuracy gives a more accurate velocity measurement than at lower frequencies. The large attenuation of millimeter waves propagating in the clear atmosphere sometimes can be employed to advantage in those special cases where it is desired to reduce mutual interference or to minimize the probability of the radar being intercepted by a hostile intercept (elint) receiver at long range.

The above attributes of the millimeter-wave region suggest as potential applications low-angle tracking, interference-free radar, ECCM, cloud-physics radar, high-resolution radar, fuzes, and missile guidance. These, as well as other applications, have not been widely employed because of the concomitant limitations that occur with operation at millimeter waves.



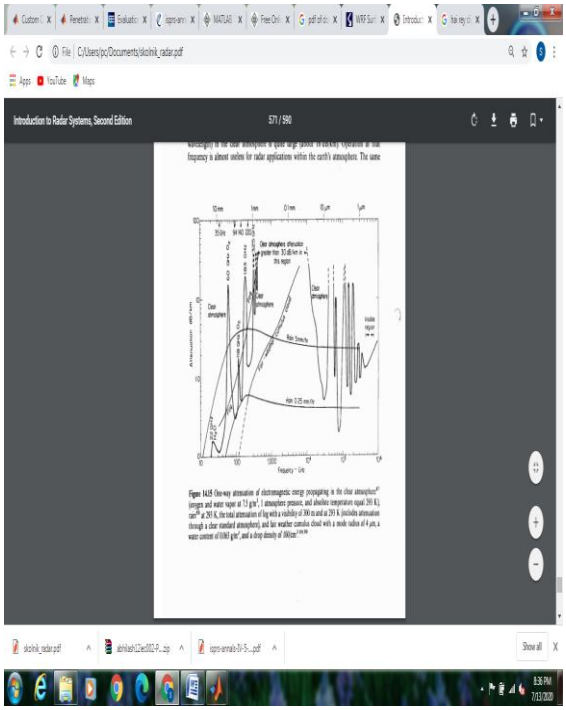
Introduction to Radar Systems, Second Edition 569 / 590

Advantages of millimeter waves. Interest in millimeter-wave applications stems from the special properties exhibited by radar at these frequencies, as well as from the challenge of exploiting a region of the spectrum not widely used. The major attributes of the millimeter-wave region of interest to radar are the large bandwidth, small antenna size, and the characteristic wavelength. Large bandwidth means that high range-resolution can be achieved. It also reduces the likelihood of mutual interference between equipments, and makes more difficult

Figure 14.14 The electromagnetic spectrum of frequencies above the microwave region.

OTHER RADAR TOPICS 561

the effective application of electronic countermeasures. The short wavelengths allow narrow beamwidths of high directivity with physically small antennas. Narrow beamwidths are important for high-resolution imaging radar and to avoid multipath effects when tracking low-altitude targets. The short wavelengths of millimeter waves are also useful when exploring scattering objects whose dimensions are comparable to the millimeter wavelengths, such as insects and cloud particles. These are examples of scatterers whose radar cross sections are



Introduction to Radar Systems, Second Edition 571 / 590

Figure 14.15 One-way attenuation of electromagnetic energy propagating in the clear atmosphere[69] (oxygen and water vapor at 7.5 g/m^3, 1 atmosphere pressure, and absolute temperature equal 293 K), rain[70] at 293 K, fire total attenuation of fog with a visibility of 300 m and at 293 K (includes attenuation through a clear standard atmosphere), and fair weather cumulus cloud with a mode radius of 4 μm, a water content of 0.065 g/m^3, and a drop density of 300/cm^3.[71,72]

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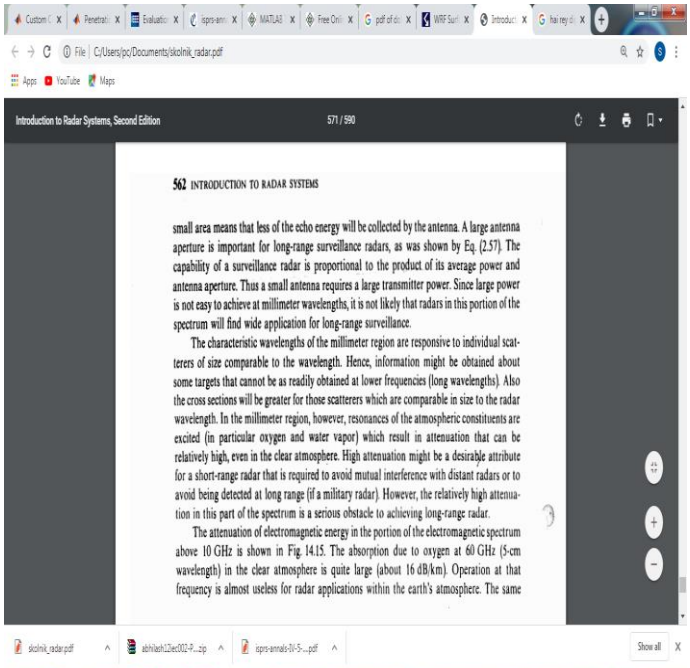
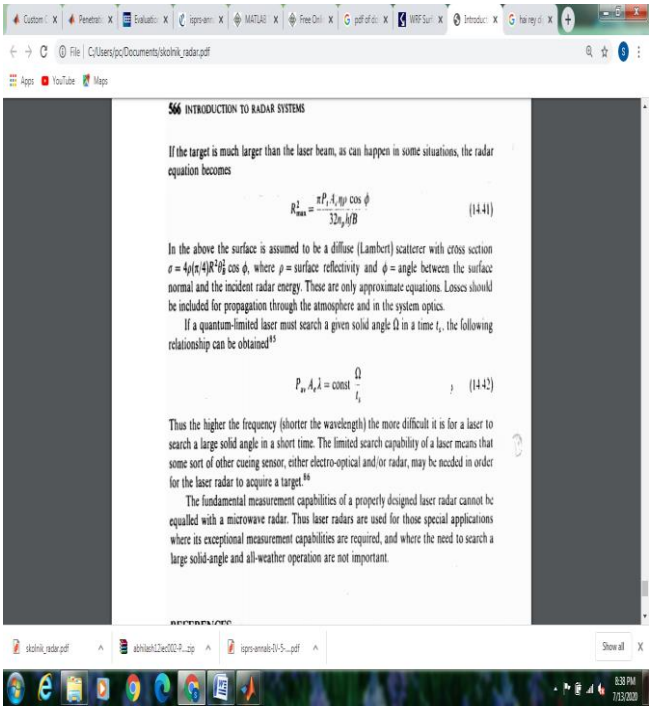


562 INTRODUCTION TO RADAR SYSTEMS

small area means that less of the echo energy will be collected by the antenna. A large antenna aperture is important for long-range surveillance radars, as was shown by Eq. (2.57). The capability of a surveillance radar is proportional to the product of its average power and antenna aperture. Thus a small antenna requires a large transmitter power. Since large power is not easy to achieve at millimeter wavelengths, it is not likely that radars in this portion of the spectrum will find wide application for long-range surveillance.

The characteristic wavelengths of the millimeter region are responsive to individual scatterers of size comparable to the wavelength. Hence, information might be obtained about some targets that cannot be as readily obtained at lower frequencies (long wavelengths). Also the cross sections will be greater for those scatterers which are comparable in size to the radar wavelength. In the millimeter region, however, resonances of the atmospheric constituents are excited (in particular oxygen and water vapor) which result in attenuation that can be relatively high, even in the clear atmosphere. High attenuation might be a desirable attribute for a short-range radar that is required to avoid mutual interference with distant radars or to avoid being detected at long range (if a military radar). However, the relatively high attenuation in this part of the spectrum is a serious obstacle to achieving long-range radar.

The attenuation of electromagnetic energy in the portion of the electromagnetic spectrum above 10 GHz is shown in Fig. 14.15. The absorption due to oxygen at 60 GHz (5-cm wavelength) in the clear atmosphere is quite large (about 16 dB/km). Operation at that frequency is almost useless for radar applications within the earth's atmosphere. The same



566 INTRODUCTION TO RADAR SYSTEMS

If the target is much larger than the laser beam, as can happen in some situations, the radar equation becomes

$$R^2_{\max} = \frac{\pi P_t A_r \eta \rho \cos\phi}{32 \pi_s h \beta} \qquad (14.41)$$

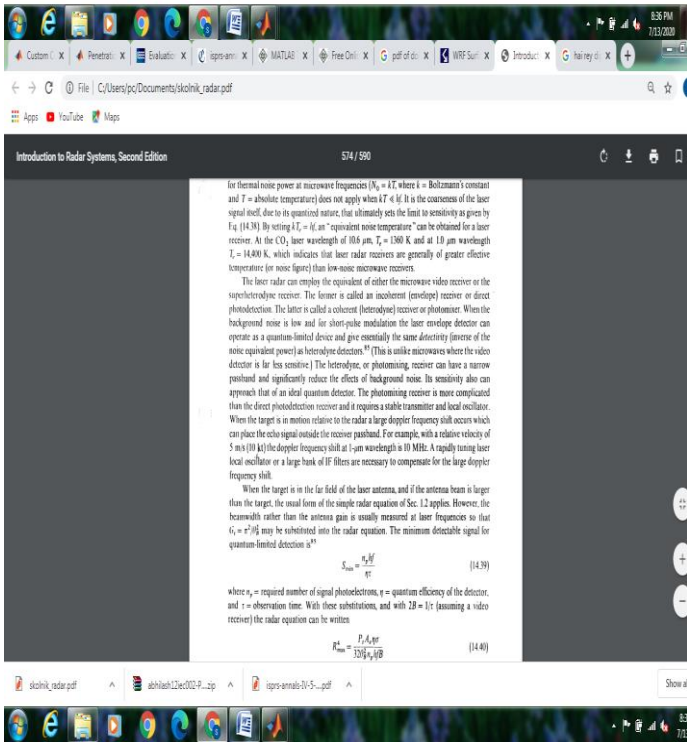
In the above the surface is assumed to be a diffuse (Lambert) scatterer with cross section $\sigma = 4\rho(\pi/4)R^2\theta^2_b \cos\phi$, where ρ = surface reflectivity and ϕ = angle between the surface normal and the incident radar energy. These are only approximate equations. Losses should be included for propagation through the atmosphere and in the system optics.

If a quantum-limited laser must search a given solid angle Ω in a time t_s, the following relationship can be obtained[85]

$$P_{av} A_r \lambda = \text{const} \frac{\Omega}{t_s} \qquad (14.42)$$

Thus the higher the frequency (shorter the wavelength) the more difficult it is for a laser to search a large solid angle in a short time. The limited search capability of a laser means that some sort of other cueing sensor, either electro-optical and/or radar, may be needed in order for the laser radar to acquire a target.[86]

The fundamental measurement capabilities of a properly designed laser radar cannot be equalled with a microwave radar. Thus laser radars are used for those special applications where its exceptional measurement capabilities are required, and where the need to search a large solid-angle and all-weather operation are not important.



for thermal noise power at microwave frequencies ($N_0 = kT$, where k = Boltzmann's constant and T = absolute temperature) does not apply when $kT \ll hf$. It is the coarseness of the laser signal itself, due to its quantized nature, that ultimately sets the limit to sensitivity as given by Eq. (14.38). By setting $kT_e = hf$, an "equivalent noise temperature" can be obtained for a laser receiver. At the CO_2 laser wavelength of 10.6 μm, T_e = 1360 K and at 1.0 μm wavelength T_e = 14,400 K, which indicates that laser radar receivers are generally of greater effective temperature (or noise figure) than low-noise microwave receivers.

The laser radar can employ the equivalent of either the microwave video receiver or the superheterodyne receiver. The former is called an incoherent (envelope) receiver or direct photodetection. The latter is called a coherent (heterodyne) receiver or photomixer. When the background noise is low and for short-pulse modulation the laser envelope detector can operate as a quantum-limited device and give essentially the same detectivity (inverse of the noise equivalent power) as heterodyne detectors.[83] (This is unlike microwaves where the video detector is far less sensitive.) The heterodyne, or photomixing, receiver can have a narrow passband and significantly reduce the effects of background noise. Its sensitivity also can approach that of an ideal quantum detector. The photomixing receiver is more complicated than the direct photodetection receiver and it requires a stable transmitter and local oscillator. When the target is in motion relative to the radar a large doppler frequency shift occurs which can place the echo signal outside the receiver passband. For example, with a relative velocity of 5 m/s (10 kt) the doppler frequency shift at 1-μm wavelength is 10 MHz. A rapidly tuning laser local oscillator or a large bank of IF filters are necessary to compensate for the large doppler frequency shift.

When the target is in the far field of the laser antenna, and if the antenna beam is larger than the target, the usual form of the simple radar equation of Sec. 2.2 applies. However, the beamwidth rather than the antenna gain is usually measured at laser frequencies so that $G_t = \pi^2/\theta^2_b$ may be substituted into the radar equation. The minimum detectable signal for quantum-limited detection is[83]

$$S_{\min} = \frac{n_s hf}{\eta \tau} \qquad (14.39)$$

where n_s = required number of signal photoelectrons, η = quantum efficiency of the detector, and τ = observation time. With these substitutions, and with $2B = 1/\tau$ (assuming a video receiver) the radar equation can be written

$$R^4_{\max} = \frac{P_t A_r \eta \pi}{32 \theta^2_b n_s h \beta} \qquad (14.40)$$

waves.

Limitations of millimeter waves. The application of millimeter wavelengths has been limited by the availability of suitable components. Transmitter powers are low, receiver noise figures are high, transmission lines lossy, and equipment generally costly and unreliable. There is reason to believe, however, that this is not fundamental and that equipment shortcomings eventually can be overcome with sufficient effort. There exists adequate technology to either side of the millimeter wave spectrum: at the longer wavelengths (microwaves) and at the shorter wavelengths (IR and visual). Also, there are component developments at millimeter wavelengths which indicate that technology is not basically limited. For example, high power has been demonstrated with the gyrotron, or electron cyclotron maser, comparable to that achieved with microwave devices. Kilowatts of CW power can be obtained in the vicinity of 1-mm wavelength and several tens of kilowatts at 3-mm wavelength.[72] Over a megawatt of pulse power is claimed at 3-mm wavelength. Millimeter-wave gyrotrons require extremely high voltages (the electrons travel at relativistic velocities) and superconducting magnets. Receivers with mixer front-ends using Schottky-barrier diodes at room temperature have demonstrated respectable noise figures. Double-sideband noise figures of 6.5 dB can be obtained at 94 GHz, 8.5 dB at 140 GHz, and 11 dB at 325 GHz. (It has been suggested that a 7-dB single-sideband noise figure is achievable over these wavelengths.)[73] Even lower noise figures are possible with superconded Josephson junctions operating at liquid-helium temperatures. There has also been significant development of high-gain antennas at millimeter wavelengths, especially for radio astronomy.[74] Unconventional transmission lines have also been developed.[95, 97]

Thus the advances in components made in the past as well as technology evident to either side of the millimeter region give reason to believe that Nature has not ruled out attainment of adequate capabilities at millimeter wavelengths.

Unfortunately, the limited availability of suitable millimeter wave components is not the

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 01, January-2021

the clear-air attenuation. A fair-weather cumulus cloud has low attenuation at millimeter wavelengths. A one-way attenuation of 0.3 dB/km at 94 GHz might not be significant for short-range radar, but it can be overwhelming for long-range radar. For example, a 5-km radar will experience a two-way attenuation of 3 dB, which is tolerable in most situations. A 50-km radar, however, will have 30-dB attenuation, which is usually intolerable. Thus long-range radar is not likely at millimeter wavelengths under normal circumstances. Although the attenuation at ~nillirnetcr wavelengths is far greater than that at microwave wavelengths, the losses iticurred in propagating ~~lillimeter wavelengths through fog, haze, and smoke is less than at infrared or visible wavelengths. Anotlier example where a particular property of millimeter-wave radar has both favorable and unfavorable aspects is that of the doppler frequency shift. It was shown in Sec. 3.1 that tlic doppler frequeticy shift was proportional to the carrier (rf) frequency. This rest~lts in more accurate relative-velocity measurements with millimeter wavelengths than at lower frequencies. The large doppler shifts at millimeter wavelengths, however, can sometimes result in the echo signal being outside the receiver bandwidth, which complicates the receiver design. Also, the large doppler frequencies at millimeter wavelengths cause the blind speeds of MTI radars to appear at lower velocities than at microwaves, an undesirable property. Thus, a frustrating paradox of the millimeter-wavelength region is that some of its claimed good points are also its weaknesses. Clutter at millimeter wavelengths. In chap. 13 it was implied that knowledge of radar clutter characteristics at microwaves was less than desired. There is even less information on clutter at frequencies above 10 GHz. Details will not be given here, but the general trends will be summarized for the several types of clutter that have been measured. The a&rage clutter cross section per unit area for one set of measurements of trees and vegetation at millimeter wavelengths is given by75.102

aO(dB) = - 20 + 10 log (0125) - 15 log R (14.37) wlicrc 0 is tl~e grazing angle in degrees and R is in centimeters. Thus, a0 increases with increasing frequency. Vertical polarization produced echoes 3 to 4 dB greater than horizontal polarization. These measurements were made in Georgia during the summer and fall months and included deciduous trees and pine trees. The grazing angles were from 2 to 25". The pulse

These measurements were made in Georgia during the summer and fall months and included deciduous trees and pine trees. The grazing angles were from 2 to 25°. The pulse width was. 100 ns and the antenna beam width was in the vicinity of one degree. The value of 0-0 for sea clutter at low grazing angle and low winds has been reported 76 to .. but not increase with frequency much above X band," but also 77 the trend of increasing reflectivity with decreasing wavelength also holds for sea clutter although the effect is not nearly as pronounced as for land clutter." However, both references state that for higher sea states (the maximum wind speed was 14 knots) the value of 0-0 at 94 GHz is less than that at X hand. Another observation is that vertical polarization seems to produce lower values of 0-0 at 94 GHz by about 5 dB (on average) than horizontal polarization, which is the opposite to the experience at microwaves. (It should be cautioned that the few meas~lrements available were taken at low grazing angle and over a limited range of wind speeds.) As with trees and grass, the value of a0 for snow increases with frequency and grazing angle.77-78,102 Crusted snow (that which has melted and refrozen), produces higher valt~es of o0 at 35 GHz and 94 GHz than wet snow, grass, or trees. At microwaves the backscatter from rain can be explained according to the Rayleigh scattering model with the reflectivity varying as the fourth power of the frequency (Sec. 13.7). In the millimeter-wave region, the drop sizes of the raindrops span both the Rayleigh and the Mie scattering regions so that a difference in behavior can be expected. Experimental measurements indicated that, on the average, the radar backscatter at 9.4 and 35 GHz far appeared to follow the Rayleigh scattering Deviations from Rayleigh were found at 70 and 95 GHz, and the backscatter at 95 GHz was observed to be less than at 70 GHz. The back scatter at. millimeter waves was found to depend on the drop signal distribution of the pricipitation.102 Even though the rain rates were the same, the backscatter from rain containing drops 2 to 6 mm in diameter was approximately 10 dB greater than rain containing drops 1 mm in diameter or less. The amplitude fluctuations of the rain backscatter were approximated by a log-normal probability distribution over the range from 9.4 to 94 GHz and at rain rates from 1 mm/h to 60 mm/h. The variance (and standard deviation) of the log-normal distribution was independent of rain rate and decreased with increasing frequency. The de correlation times at 95 GHz varied from about 3.4 ms at 5 mm/h rain rate to 1.4 ms at 100 mm/h. At X band the de correlation times were longer and varied from 14 ms at 5 mm/h to 5.4 ms at 100 mm/h. Utility of millimeter waves. Experimentation with millimeter wavelength radiation and microwave radiation both date back to the end of the nineteenth century. The first microwave experiments were those of Hertz in 1886. Experiments at 6-mm wavelength occurred in 1895.80 In the early 1920s, millimeter-wave research was reported in the United States, Germany, and Russia, with wavelengths as short as 0.22 mm.81 Although many important applications of the microwave region have been developed, there has been almost no comparable activity in the millimeter-wave region. There are many possible reasons for this lack of activity, including lack of adequate millimeter-wave components, small antenna sizes, and difficult MTI. Rut the most restricting of all has been the relatively large attenuations experienced when propagating through the clear atmosphere, as well as the added attenuation during rain. The large attenuations are likely to limit millimeter radar to short-range applications where the total attenuations are tolerable or to applications where the atmosphere is absent, such as in space or at very high altitudes. Millimeter wavelengths might also find application when the propagation path does not traverse a large part of the earth's atmosphere, as when a ground-based radar directs its energy at or near the zenith. (At 94 GHz the two-way loss In transiting the entire atmosphere is

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International Journal of Engineering Research & Technology (IJERT)
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Vol. 10 Issue 01, January-2021

about 1.7 dB at zenith, 3.5 dB at 60" from the zenith, and 10 dB at 80" from the zenith.)82 Sub millimeter wavelengths.83s84 The advantages of high resolution, wide bandwidth, and small antenna aperture are even more prevalent in the sub millimeter proportion of the electromagnetic spectrum than at millimeters. The attenuation in the clear atmosphere, however, is far worse than at millimeters and varies from about 10 dB/km at l-mm wavelength to more than 100 dB/km at 0.1-mm wavelength.

Laser radar with improved reliability

The large attenuations experienced in clear air in the millimeter (60 GHz) and submillimeter regions are not present in the infrared and visible regions of the spectrum

564 INTRODUCTION TO RADAR SYSTEMS
94 GHz by about 5 dB (on average) than horizontal polarization, which is the opposite to the experience at microwaves. (It should be cautioned that the few measurements available were taken at low grazing angle and over a limited range of wind speeds.) As with 'trees and grass, the value of (To for snow increases with frequency and grazing angle.77.78.102 Crusted snow (that which has melted and refrozen), produces higher values of (To at 35 GHz and 94 GHz than wet snow, grass, or trees. At microwaves the backscatter from rain can be explained according to the Rayleigh scattering model with the reflectivity varying as the fourth power of the frequency (Sec. 13.7).

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The amplitude fluctuations of the rain backscatter were approximated by a log-normal probability distribution over the range from 9.4 to 94 G Hz and at rain rates from 1 mm/h to 60 mm/h. The variance (and standard deviation) of the log-normal distribution was independent of rain rate and decreased with increasing frequency. The de correlation times at 95 GHz varied from about 3.4 ms at 5 mm/h rain rate to 1.4 ms at 100 mm/h. At X band the de correlation times were longer and varied from 14 ms at 5 mm/h to 5.4 ms at 100 mm/h. Utility of millimeter waves. Experimentation with millimeter wavelength radiation and microwave radiation both date back to the end of the nineteenth century. The first microwave experiments were those of Hertz in 1886. Experiments at 6-mm wavelength occurred in 1895.80 In the early 1920s, millimeter-wave research was reported in the United States. Germany, and Russia, with wavelengths as short as 0.22 mm. 81 Although many important applications of the microwave region have been developed, there has been almost no comparable activity in the millimeter-wave region. There are many possible reasons for this lack of activity, including lack of adequate millimeter-wave components, small antenna sizes, and difficult MTI. But the most restricting of all has been the relatively large attenuations experienced when propagating through the clear atmosphere, as well as the added attenuation during rain. The large attenuations are likely to limit millimeter radar to short-range applications where the total attenuations are tolerable or to applications where the atmosphere is absent, such as in space or at very high altitudes. Millimeter wavelengths might also find application when the propagation path does not traverse a large part of the earth's atmosphere, as when a ground-based radar directs its energy at or near the zenith. (At 94 GHz the two-way loss in transiting the entire atmosphere is about 1.7 dB at zenith, 3.5 dB at 60° from the zenith, and 10 dB at 80° from the zenith.)82 Sub millimeter wavelengths.83 . 84 The advantages of high resolution, wide bandwidth, and small antenna aperture are even more prevalent in the sub millimeter proportion of the electromagnetic spectrum than at millimeters. The attenuation in the clear atmosphere, however, is far worse than at millimeters and varies from about 10 dB/km at I-mm wavelength to more than 1000 dB/km at OJ-mm wavelength. Laser radar. The large attenuations experienced in clear air in the millimeter (60 G Hz) and sub millimeter regions are not present in the infrared and visible regions of the spectrum (Fig. 14.15). (The atttenuato in rain. Iiowcver. is still large.) Thus laser radars operating in the infrared and visible rcgiolis achieve the ;advantages of high angular resolution, wide bandwidth, and doppler frequency sensitivity without the accompanying disadvantage of high attenuation as experienced ill the sub millimeter region. because of its snr is all physical aperture a laser radar is riot suited for most surveillance apl~lications. It is, however, well suited for precision rneasureriletit and target iniaging. The rfesigri of a laser radar follows the same general principles as otlier radars. but witli some exceptions. R5.93.94.105 111 ndcfition to using a trnnsriiitter unlike those found at niicrowave frequencies, the laser radar cxl~ihits otlicr difScrcr~ccs that n~irst be accounted for wlicn considering radar desigli. For cxnmidc. tile receiver sensitivity is riot determined by thermal noise as at microwaves, hut by qili~~itt~~ii eISect~. 'T'lic tio~sc I)OWCI. per iltiit batidwidtli at most laser frequencies is given by \vlicrc /I = Planck's colistant = 6.626 x 10-" J .s, and./'= frequency. The familiar expression for thermal noise power at rtiicrowave frequencies (No = kT, where k = Boltzmann's constant arid 7' = absolute temperature) does not apply when kT Q It is the coarseness of the laser signal itself, due to its quantized nature, tliat ultimately sets tlie limit to sensitivity as given by I:q. (14.3X). 13y settirig k7;, = lrfl an "eqi~ivaletit noise temperature" can be obtained for a laser receiver. At the CO, laser wavelength of 10.6 pm, T,

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Tlie minimum detectable signal for quarituni-lirnitcd detcctiorl isR5 where 11, = required nuniber of signal photoelectrons, q = quantum efficiency of the detector, and r = observation time. Witli tliese substitutions, and with 2B = l/r (assuming a video receiver) the radar equation can be written OTHER RADAR TOPICS 565 (Fig. 14.15). (Thc attcnuation in rain. however. is still large.) Thus laser radars operating in the infrarcd and visihlc regions achicvc-thc advalltagcs ofhigh angular resolution, wide bandwidth, . and doppler frequency sensitivity without the accompanying disadvantage of high attenuation as expericnccd in the submillimcter rcgion. Bccausc of its small physical apcrture a laser radar is not suited for most surveillance applications. It is, however, well suited for precision measurement and target imaging..The design of a laser radar follows the same general principles as other radars. hut with some cxceptions.RS.93.94.I05 In addition to using a transmitter unlike those found at microwave frequencies, the laser rada I' exlJi bits ot her d irlercnces that Illust be accounted for when considering radar design. For example. the receiver sensitivity is not determined by thermal noise as at microwaves, but by quant um effects. The noise power per unit bandwidth at most laser frequencies is given by No = hI' (14.3R) (14.39) \vhere II = Planck's constant = 6.626 x 10- J-l J .s, and f = frequency. The familiar expression for thermal noise power at microwave frequencies (No = kT, where k = Boltzmann's constant and T = absolute temperature) does not apply when kT hI It is the coarseness of the laser signal itself. due to its quantized nature, that ultimately sets the limit to sensitivity as given by Fq. (14.3R). By settling kJ:. = Ill: an "equivalent noise temperature" can be obtained for a laser receiver. At the CO 2 laser wavelength of 10.6 11m, I;. = 1360 K and at 1.0 11m wavelength 7;. = 14.400 K. which indicates that laser radar receivers are generally of greater effective temperature (or noise figure) than low-noise microwave receivers. The laser radar can employ the equivalent of either the microwave video receiver or the super heterodyne receiver. The former is called an incoherent (envelope) receiver or direct photo detection. The latter is called a coherent (heterodyne) receiver or photomixer. When the back ground noise is low and for short-pulse modulation the laser envelope detector can operate as a quantum-limited device and give essentially the same detect ability (inverse of the noise equivalent power) as heterodyne detectors. 8s (This is unlike microwaves where the video detector is far less sensitive.) The heterodyne, or photomixing, receiver can have a narrow passband and significantly reduce the effects of background noise. Its sensitivity also can approach that of an ideal quantum detector. The photomixing receiver is more complicated than the direct photodetection receiver and it requires a stable transmitter and local oscillator. When the target is in motion relative to the radar a large doppler frequency shift occurs which can place the echo signal outside the receiver passband. For example, with a relative velocity of 5 mls (10 kHz) the doppler frequency shift at I-Jim wavelength is 10 MHz. A rapidly tuning laser local oscillator or a large hank of IF filters are necessary to compensate for the farge doppler frequency shift.

Conclusions :

When the target is in the far field of the laser antenna, and if the antenna beam is larger than the target. the usual form of the simple radar equation of Sec. 1.2 applies. However. the beam width rather than the antenna gain is usually measured at laser frequencies so that advanced radar InSAR can also be developed.

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