ABSTRACT

A simplified millimeter wave outdoor test set-up for the analysis of both wave propagation and radar target characteristics has been assembled. Due to the special lay-out, both the forward and return path attenuation and the observed atmospheric clutter cross section can be simultaneously evaluated. The system is intended for the testing of a highly mobile Ka-band battlefield surveillance and target tracking radar. Recordings can utilize either a monostatic or bistatic operational mode and rely on pulsewidths typically shorter than 100 ns or use the pure continuous wave principle. In order to get a statistically valid sample of the propagation path, the current test range distance is 1000 meters. Depending on the selected antennas, the 3 dB beamwidth can be varied down to 0.2O. The physical size of the test target is near 1 m². At distances of operational interest, rain clutter RCS is estimated to exceed 100 m² even if 100 ns pulses are used.

INTRODUCTION

Although approaching its 70th birthday, radar is still one of the key sensors for national defense and anti-terrorist actions. In order to provide smaller ground-based or navy units a reliable means to monitor their tactical environment, transportable small-scale radar devices are needed. Besides this, the operation of short-range anti-aircraft guns and missiles should be supported in bad visibility with suitably scaled autonomous sensor systems, which match their typical kill radius of 2-3 km. The requirement for mobility pushes the design effort towards a reduced physical size and thus towards millimeter waves due to favourable antenna apertures, despite e.g. [1] does not encourage such constructions. For a lightweight jeep trailer or a patrol boat, the system mass should be kept below 500 kg and the antenna diameter smaller than 1.25 meters. Operation on battery power is highly desirable as is the capability to withstand shocks and vibration. One of the fundamental questions is if operationally sufficient transmitter power level and receiver noise figures are technically feasible and if so, how to select the frequency.

The well-known radar equation from [2] can be combined with target RCS information in order to find a rough estimate for the needed power or to judge the range characteristics under free space conditions as a function of operating frequency. If we assume a rectangular planar target having dimensions much larger than the wavelength and a parabolic radar antenna, we obtain through elementary manipulation the received power as

\[ P_{in} = \frac{P_T \pi^2 d^4 a^2}{64 r^4 \lambda^2} \]  

(1)

where \( r \) is the range to the target and \( a \) its size (as a square) and \( d \) is the radar antenna’s aperture diameter. The additional attenuation can be approximated as

\[ L_{atm} = \left[ 0.1 + \frac{(f - 30)}{30} \frac{0.15}{dB} \right] \frac{dB}{km} \]  

(2)

where \( f \) is to be given in gigahertz. Combining the characteristics from (1) and (2) we find out that for planar targets an increase in radar frequency might be justified but for cylindrical cases (an aircraft hull, a cruise missile) there’s not much benefit - partly because of the additional term of (2). Besides this it is noteworthy that e.g. [3] reports the attenuation of one single fir tree at 60 GHz to be 20-25 dB. Thus the choice of operating frequency can be based on other parameters, e.g. the performance of commercially available components, which are described for example in [4], [5], [6], [7] and [8].
or on the clutter characteristics of a typical operating environment about which very little unclassified data is at hand for millimeter wave frequencies.

PUBLISHED MILLIMETER WAVE RADAR SYSTEM CHARACTERISTICS

The first known mobile millimeter radar to enter large-scale military service is possibly the Long Bow system for the Apache AH-64 moving-wing platform. The device operates in the Ka-band in a look-down fashion and is intended e.g. against tanks. No real performance data is available. Several civilian 60-90 GHz systems for vehicular monitoring have been developed. Both pulse-doppler and FMCW set-ups based on laboratory equipment or integrated components are shown in [9], [10] and [11]. Output power varies from 2 to 13 dBm, noise figure is typically 4-7 dB and processing bandwidth around 150 MHz. Electronic tuning through 1 GHz has been achieved at 94 GHz. A range resolution of 0.75 m and a measuring range above 150 m have been obtained. The angular resolution was 1.5° and the processing of the whole field of view in [11] took 13 ms (10 000 cells). The work in [12] describes an add-on to an existing C-band radar. Here at 36 GHz the output power is 2 W, the receiver noise figure below 4 dB and the parabolic antenna main beam covers 60°x120°.

A PRELIMINARY SCHEME FOR A PROPAGATION TEST RANGE

Taking (1) and (2) and by combining linear and power curve models of component behavior we can construct a modified equation for the signal to noise ratio after IF filtering as a function of relative wavelength which yields

\[
\frac{P_{\text{in}}}{P_N} = K \frac{\lambda^3}{r^4} \left[ 10^{-5} - 3 \cdot 10^{-5} \frac{\lambda_0}{\lambda} \right] r
\]

where K is a scaling constant and \( \lambda_0 \) is the reference wavelength. The relative effects of (3) are shown in Fig.1.

Assuming a shaped parabolic antenna of 1 meter diameter for mobility and mostly MMIC-based electronics similar to those documented above, we can estimate at Ka-band a detection distance up to 8 km for planar targets and above 2.5 km if e.g. cylindrical shapes are encountered. These figures will be drastically reduced against stealth targets (like the F-117) for which [13] gives an RCS of 0.025 m² although no frequency is indicated. Modern adaptive processing algorithms are assumed to give a gain of 15 – 20 dB which enables a S/N near 0 dB for the raw IF port. The detection bandwidth should be above 150 MHz and for some frequency agility also millimeter wave tuning is expected. Fig. 2. indicates the effects of selected front-end configurations on the obtainable system temperature.

![Fig.1. A performance comparison of millimeter wave radar electronics. The C/N for a fixed - yet arbitrary - detection distance as a function of wavelength is shown here based on available LNA noise figures and PA output power.](image-url)
Fig. 2. The effects of radar front-end configurations on the overall system temperature. Examples are A (LNA 300 K / 20 dB, MIX 500 K / 3.5 dB, IF 100 K), B (LNA 200 K / 20 dB, MIX 1000 K / 5 dB, IF 100 K), C (LNA 200 K / 20 dB, MIX 500 K / 3.5 dB, IF 100 K) and D (LNA 100 K / 20 dB, MIX 500 K / 3.5 dB, IF 100 K).

However, even (3) does not take into account e.g. the secondary targets caused by clutter inside the main beam and being most prominent in heavy rain or snowfall. For example [1] and [2] show some empirical equations for the estimation of rain-based clutter but both have been obviously created much before the era of millimeter wave chips. On the other hand the more recent [9], [10] and [14] are all focused at such short propagation distances where rain can not be a serious practical problem.

In order to be able to create a suitable database, which contains both attenuation and rain clutter data at interesting millimeter wave frequencies, a two-way test system has been constructed. The target is typically a conducting rectangle or sphere (physical size about 1 m²) and it contains a flush-mounted millimeter wave waveguide antenna together with a bandpass-filtered diode detector. This simple receiver gives a straightforward way of estimating the one-way path loss. The transmitting site has also a coherent receiver, which detects the returning signal, but because of pulsed operation, can distinguish between target and clutter echoes. Naturally, the pulse width is very short (50 - 100 ns) to enable an unambiguous separation of the spatial clutter elements. The dynamic range of the system exceeds 100 dB and the sensitivity of the diode receiver is about - 30 dBm. A simplified block diagram of the test transmitter is illustrated in Fig.3.

One of the interesting features is the use of variable beamwidths (from 1.4 down to 0.2 degrees) together with different pulse lengths (50 ns to 300 ns) whereby we are able to adjust the apparent three dimensional clutter volume [15]. Additionally, the hardware supports a pulsed or continuous frequency modulated scheme for a doppler measurement of particle velocities. A simultaneous recording of relevant weather data supports the test sessions. Some preliminary expected results are indicated in Fig. 4 for the typical light anti-aircraft gun radar measuring a target at 5000 m maximum distance with 100 ns pulses. It is evident that antenna beamwidths below 1° should be used to ensure sufficient processing possibilities in severe weather conditions.

Fig. 3. The test radar transmitter utilizes one intermediate frequency and a combination of FM and pulse modulation.
Fig. 4. Already a modest rain of 15 mm/h will cause clutter RCS values that are far above typical targets (1 - 10 m² for non-stealth technologies) at millimeter wavelengths if the antenna beamwidth and pulse duration can not be reduced. Comprehensive rain attenuation data can be found e.g. in [16].

REFERENCES