A Method for Analyzing Active SMMW Imaging System Performance

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***Abstract*—This paper will describe the development of a technique for comparing the performance of Sub-MMW Imagers used for detecting objects concealed under clothing. The analysis is separated into 4 independent elements that can be calculated separately so that tradeoffs in transmitter and receiver characteristics can be performed. The derivation of the analysis and various examples of tradeoffs will be presented.**

I. Introduction

Significant efforts are underway to use either passive or active MMW and Sub-MMW imaging systems to detect objects concealed under clothing[1]. Some have reached the point of commercial availability[2] and have proved useful for contraband detection under controlled conditions. Studies[1] have shown that when the conditions are uncontrolled, passive techniques become less desirable for contraband detection at standoff ranges which give the operators a margin of safety[1]. In recent years, several programs have been funded to investigate using active techniques in the range of 100 to 1000 GHz for standoff detection out to ranges of 100m, a range which has been cited by some to be a desirable operating range.

Active imaging involves the detection of an object that is typically covered by a semi-transparent media (clothing) which also scatters energy back toward the imaging receiver. So the process of detecting a concealed weapon is more than receiving a reduced signal from an object; it is the process of distinguishing a concealed object from a background which is also scattering energy into an imager. This process is very similar to the process of detecting camouflaged targets on a battlefield with a synthetic aperture radar; a process which has had significant investment for the last 40 years..

Spatial resolution requirements for good detection are dependent on the physical size of the object and are independent of range as long as signal-to-noise ratio (SNR) is adequate. A typical SNR requirement for imaging systems is 6:1, which coincidentally is the same as the tangential sensitivity measurement of noise for video detectors. Since obscured objects must be detected and identified against the cluttered background, the imager must have sufficient sensitivity to image the clutter (clothing over skin) with adequate SNR. The clutter (clothing over skin) behaves like a rough surface scatterer[3] and can be characterized by a normalized backscatter (as in SAR).

This analysis will demonstrate how performance calculations can be separated into four independent effects: 1) integrated receiver noise power vs. different receiver scan techniques, 2) transmitter power per pixel vs. different transmitter scan techniques, 3) antenna performance, and 4) phenomenology which includes clothing/skin backscatter and atmospheric attenuation.

II. Analysis

Starting with the radar range equations and using the assumptions defined above, we have derived an equation that defines a quantity we call the signal-to-noise ratio zero (SNR0) which must be exceeded in order for the imaging sensor to have a defined performance level. SNR0 is equivalent to the signal to noise ratio received if the transmitter is connected directly to the receiver. SNR0 is defined in one of two ways depending on whether the system uses (1) bolometers as receivers where the sensitivity is defined by the NEP and integration bandwidth or (2) heterodyne receivers where the sensitivity is determined the noise figure, and integrated bandwidth. SNR0 thus is a measure of the RF sensor component performance.

If we use the radar range equation defined as:

$$SNR = \frac{P * G^2 * \lambda^2 * \sigma * Int * L_{ant}{}^2 * L_{atm}{}^2}{(4\pi)^3 * R^4 * k * T * B * N} \qquad 1)$$

We can rearrange it to be:

$$SNR = P * \left(\frac{Int}{k * T * B * N} \right) * \frac{G^2 * \lambda^2 * \sigma * L_{ant}{}^2 * L_{atm}{}^2}{(4\pi)^3 * R^4} \qquad 2)$$

for receivers with LNAs or mixers or

$$SNR = P * \left(\frac{1}{NEP * \sqrt{\tau}} \right) * \frac{G^2 * \lambda^2 * \sigma * L_{ant}{}^2 * L_{atm}{}^2}{(4\pi)^3 * R^4} \qquad 3)$$

for receivers using detectors. If we use the relationship between the antenna gain and range to the resolution size on a area of interest we have:

$$CNR = SNR0 * \left((1.22)^4 * \lambda^2 * L_{ant}{}^2 \right) * \frac{\pi^2 * \sigma_0 * L_{atm}{}^2}{4^4 * \Delta^2} \qquad 4)$$

where Δ is the resolution size, σ_0 is the normalized backscatter coefficient of the surface we are imaging, CNR is the Clutter-to-Noise Ratio that is required for good image quality and SNR0 is defined as:

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$$SNR0 = P * \left(\frac{1}{NEP * \sqrt{\tau}} \right) \quad 5)$$

or

$$SNR0 = P * \left(\frac{Int}{k * T * B * N} \right) \quad 6)$$

again depending on the type of receiver.

The target detection phenomenology can then be incorporated into a term (TGT) which can be defined through examination of equation 4 to be

$$TGT = \frac{4^4 * \Delta^2}{\pi^2 * \sigma_0} * CNR \quad 7)$$

Examining equation 4, we can also separate out the loss and resolution effects of the antenna as:

$$ANT = (1.22)^4 * \lambda^2 * L_{ant}^{\ 2} \quad 8)$$

where the factor of 1.22 comes from the definition chosen for the resolution of a uniformly illuminated aperture. Depending on the specific design of the antenna, this constant can be changed.

If we then rearrange terms we reach the conclusion that:

$$SNR0 \geq TGT * ANT * L_{atm}^{\ -2} \quad 8)$$

in order for the system to meet the performance requirement defined by the minimally acceptable CNR. Most importantly, the only point where range enters into this equation is in the determination of atmospheric loss. We have thus obtained an equation where ANT and SNR0 can be evaluated for fixed values of TGT and L_{atm}. For this analysis, by fixing ANT we can calculate requirements for SNR0 vs. range under a fixed condition of TGT and ANT. For atmospheric effects in the sub-MMW region, the dominant atmospheric attenuator is water vapor. For these studies we use three levels, a winter condition (Buffalo) where the absolute attenuation is 0.7 gm/m^3, a US Standard condition (Boulder) of 7.5 gm/m^3, and a very humid condition (Bangkok) of 35 gm/m^3 representing conditions like Southwest Asia.

Using this formulation we can compare the performance of different transmitter and receiver technologies against an operational scenario defined by $TGT*L_{atm}^{-2}$.

III. An Example and Tradeoffs

Table I describes a conceptual system and set of requirements that we will use to assess the relative performance of a variety of receivers. Note that because the resolution is defined; the antenna size is not and will be determined once a receiver technology is selected for the operational range required

System Characteristics		
Frequency	650	GHz
Height scanned	2	meter
Width scanned	1	meter
Resolution required	0.0375	meter
CNR required	6	
Output Frame rate	30	Hz
CW Transmitter Power	0.1	W
Bandwidth	15	GHz
Diffraction Limited Resolution	$1.22D^2/\lambda$	
One-way Antenna Loss	-6	dB
Phenomenology		
Normalized Backscatter	-10	dB
Atmospheric Attenuation		
Buffalo -0.7 gm/m^3	9	dB/km
Boulder - 7.5 gm/m^3	60	dB/km
Bangkok - 35 gm/m^3	290	dB/km
Derived Characteristics		
Height of Image	64	pixels
Width of Image	32	pixels
Dwell Time per pixel		
Spot Scanner	1.6276E-05	sec
32 pixel Line Scanner	0.0010416	sec
2D FPA	0.0333333	sec

Table I – Postulated system and performance characteristics for this study.

To assess receiver technologies, we will look a several different component options; a state-of-the-art detector as defined by the TIFT[4] program, a conceptual LNA built using devices produced for the SWIFT[5] program, heterodyne systems of differing IF bandwidths, and the highest performance, the heterodyne receiver with the conceptual LNA in front of it. Table II lists the salient characteristics of these receivers.

We will then look at CW source having an average power of 100 mW, which while not currently available represents a useful round number for these calculations. Table III then lists the instantaneous powers available per pixel for three types of illumination strategies, scanning spot illumination, scanning line illumination, and area illumination. Spillover of the illuminator outside the imaging area is represented by a 3 dB loss in the antenna loss value.

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Receiver	NEP or NF W/sqrt(Hz) or dB	Noise	RF Band-width GHz
Room Temperature detector	1E-12	-120 dBW + dBHz/2	60
LNA/Detector	12	-204 dBW/Hz	60
Heterodyne /detector wide	12	-204 dBW/Hz	15
Heterodyne /detector narrow	12	-204 dBW/Hz	.001
Heterodyne coherent	12	-204 dBW/Hz	.001

Table II – Receiver architectures and performance characteristics assessed in this study.

	Units	Instantaneous Power
Total Power	dBW	-10.00
Spot illumination	dBW	-10.00
Line illumination	dBW	-28.06
Area illumination	dBW	-43.11

Table III – Transmitter instantaneous power per pixel for a 100mW source and three scanning geometries.

Putting these values together in various combinations we get values for SNR0 that are represented in Table IV. We can than plot required SNR0 vs. range for the defined value of TGT and the three atmospheric loss values and compare the calculated values of SNR0.

Figure 1 is a plot of the required SNR0 vs. range under different atmospheric conditions and for the specific requirements for resolution, detection SNR, backscatter, and frequency used in this study. The different points plotted along the line representing the worst case atmosphere represent the different sensor concepts analyzed. The minimum requirement for SNR0 under the conditions specified is approximately 79 dB which exceeds the capability of the defined detector based systems under all atmospheric conditions. This does not mean that a detector based system will not work under all conditions as a spot scanning system can be shown to have sufficient SNR0 but requires a rapid electromechanical scanning system.

IV. Conclusions

A simple method for evaluating differing receiver architectures for sub-MMW imaging systems has been presented. The method is based on recognizing the need to have sufficient sensitivity to image the clothing in a weapon detection scenario in order to have sufficient sensitivity to detect an obscured weapon. The results show that for maximum performance, a coherent receiver can provide significant advantages over other approaches.

Configurations to Plot		
	Name	SNR0
Area illumination and 2D FPA using detector	DetT2R2	69.50
Line illumination and 1D FPA using detector	DetT1R1	77.03
Area illumination and 2D FPA using LNA /detector	LNADetT2R2	87.61
Area illumination and 2D FPA using Heterodyne and narrowband detector	HetDetNT2R2	111.50
Line Illumination and Line Scanning Receiver using Heterodyne/Coherent	HetCohT1R1	134.12
Area illumination and Line Scanning Receiver using Heterodyne and narrowband detector	HetDetNT2R1	103.98
Area illumination and Line Scanning Receiver using Heterodyne/Coherent	HetCohT2R1	119.06

Table IV – calculated SNR0 for various imaging system architectures.

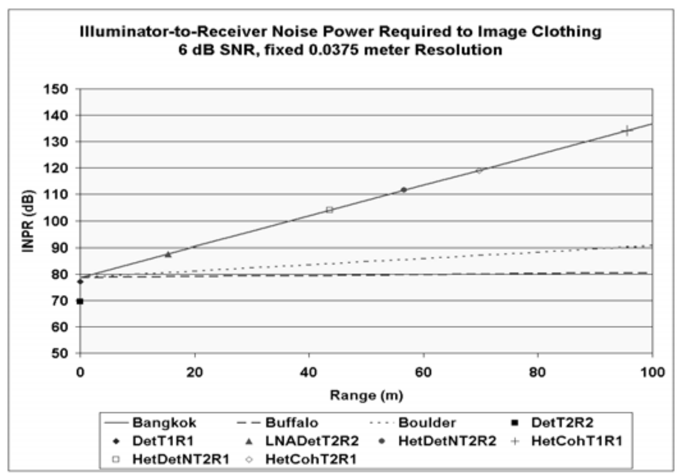

Figure 1 Required SNR0 vs. range for three different atmospheric conditions.

V. References

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