Passive Millimeter-Wave Imaging and Potential Applications in Homeland Security and Aeronautics

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Objectives and Scope of Research

- Explore the potential applications of passive millimeter-wave imaging technology in aviation safety and homeland security

- To discuss some systems engineering aspects of the design of passive millimeter-wave imagine cameras

- To design and implement a passive millimeter-wave imagine camera at 94 GHz using opto-mechanical scanning
Atmospheric Effects on Attenuation of the Electromagnetic Spectrum
Why Passive Millimeter-Wave Imaging?

- All Natural objects whose temperatures are above absolute zero emit passive millimeter-wave radiation.

- Millimeter-waves are much more effective (Lower attenuation) than infrared in poor weather conditions such as fog, clouds, snow, millimeter-waves have natural appearances.

- The amount of radiation emitted in the millimeter-wave range is $10^8$ times smaller than the amount emitted in the infrared range.
However, current millimeter-wave receivers have at least $10^5$ times better noise performance than infrared detectors and the temperature contrast recovers the remaining $10^3$.

This makes millimeter-wave imagine comparable in performance with current infrared systems.

Electromagnetic radiation windows occur at 35 GHz, 94 GHz, 140 GHz, and 220 GHz.

Choice of frequency depends on specific application.
Potential Applications

1. **Homeland Security:**
   1. Detection of concealed weapons
   2. Airport security
   3. Corporate Security

2. **Aeronautics:**
   1. Airport safety in landing and taxiing operations in bad weather conditions

3. **Diagnostics:**
   1. Medical diagnostics
   2. Plasma

4. **General Applications**
   1. Defense
   2. Environmental
Passive Millimeter-Wave Imager Concept

Antenna Scanning System

COLLECTOR ANTENNA

ELECTRONICS

COMPUTER

SUPER-RESOLUTION Software
Some Systems Engineering Aspects in the Design of Passive Millimeter-Wave Imagine Cameras

- **Emission of Radiation:**
  - All Objects whose temperatures are above absolute zero emit millimeter-wave radiation
  - In practice, natural objects behave as grey-body emitters and their actual emission is the black-body value multiplied by a wavelength-dependent emissivity which is specific to that material.
  - Atmospheric windows exit at 35, 94, 140 and 220 GHz
  - In the millimeter-wave region the sky temperature is about 100 K
Methods of Detection of Millimeter-Wave

- Traditional methods, using doped germanium bolometers cooled to liquid helium temperatures to improve noise performance over a large bandwidth.

- Using tuned amplifiers before the detector in superheterodyne receivers. Bandwidth of 3 GHz and a typical gain of 60 dB.

- Direct detection receivers.
**System Performance**

- **Special Resolution:**
  - In a diffraction limited system, the angle $\alpha$, subtended by the smallest resolvable object in the scene is given by

  $$\alpha = \frac{\lambda}{D}$$

  (1)

- $\lambda$: The wavelength of the incident radiation
- $D$: The diameter of the collection optics
For $N$ picture points across the horizontal FOV = $\theta$

$$\alpha = \frac{\theta}{N} \quad (2)$$

That is,

$$N = \frac{D\theta}{\lambda} \quad (3)$$

In optically immersed systems,

$$N = \frac{nD\theta}{\lambda} \quad (4)$$

Where $n$ is the refractive index of the medium.

The quality $D\theta$ is called the lagrange invariant and it remains a constant throughout an imaging system.
- A typical thermal imager operating at 10 $\mu$m having an objective diameter of 100 mm and FOV of 6° has a performance value of $N = 10^3$. In practice, the value is less due to aberrations introduced by the detector array and a value closer to 500 would be appropriate.

- In millimeter-wave imaging, an aperture of 1 meter operating at wavelength of 3 mm would have a performance of $N=330$, which is comparable with that above.

- An aperture of 1 meter is too large for most applications. Super-resolution techniques are used to decreased the physical size.
Thermal Sensitivity

- The thermal sensitivity of an imager is the lowest temperature, $\Delta T$, in the scene that is detectable by the imager. It is given by

$$\Delta T = \frac{N_T}{\sqrt{B \tau}}$$  \hspace{1cm} (5)

- where $N_T$ is the noise temperature of the imager, $B$ the RF bandwidth and $\tau$ is the post detector integration time.

- For the highest thermal sensitivity, $N_T$ must be low and $B$ and $\tau$ must be as high as possible. For a typical system, $N_T$ may be 3000K, $B$ may be 3GHz and $\tau$ 10msec. This gives a $\Delta T$ of 0.5K.
Real-Time Operation

- To operate in real time the integration time of the whole imager should not be greater than about 10-25 msec. This can be achieved in a number of different ways. For example there could be a focal plane array of receivers each having this integration time. Or else much higher performance receivers having shorter integration times could be scanned across the scene to still give the same overall thermal sensitivity and frame rate.

- If the total number of picture points in the image is \( m \) and if this is achieved by scanning \( n \) detectors across the scene, then the integration time, \( \tau \), of each receiver is given by

\[
\tau = \frac{tn}{m}
\]

Where \( t \) is the required integration time of the whole imager and is slightly shorter than the frame rate.
We then have that

$$\Delta T = \frac{N_T}{Bm}$$

(7)

This equation may be rearranged to give

$$n = \left(\frac{N_T}{\Delta T}\right)^2 \frac{m}{Bt}$$

(8)

3.4. Cost Effective Solutions

- In the equation above, $n$ represents the total number of receiver channels and can be used to calculate the overall cost of the receiver electronics.

- the total cost = \(c \left(\frac{N_T}{\Delta T}\right)^2 \frac{m}{Bt}\)

- Where $c$ is the cost of one receiver.
Cost-effective Solutions

- The cost of a receiver in a large focal plane array of cheap receivers would have to be as low as $4 to compete with the cost of a smaller number of more expensive, higher-performance, scanned receivers having a noise temperature of 500 K, a bandwidth of 5 GHz and a cost of $3000, operating at half the TV rate.
This cost comparison assume that the scanned system is optimized to make full use of the small number of receivers required. Otherwise the costs would be higher than necessary.

- Clearly some form of scanning is the preferred option at present. It will require highly integrated mass production for the cost of a focal plane array to become lower than, or comparable with, the price of the scanned solution.
General Description of the Passive Millimeter-Wave Imaging Camera

- Opto-Mechanical Scanner
The RF Front End

A block diagram of the downconverter is illustrated:
System Specification

Specifications

- **RF Frequency Range**: 87 - 99GHz
- **LNA**: Model FLNA-10-18-6
- **Gain**: 18dB min. 86 – 100GHz
- **Noise Figure**: 6dB max, 4.5dB typical at 94GHz
- **LO Frequency**: 94.0 GHz within +/-100MHz
- **LO Drive**: +13dBm typical
- **LO Source**: Gunn oscillator, GN-10 type, free running, 10MHz/deg.C typical
- **Mixer IF Frequency Range**: Dc – 8GHz minimum
- **Mixer Conversion Loss**: 8dB max, <7.0dB typical
- **IF Amplifier Gain**: 35dB minimum per module, overall 70dB min.
- **IF Noise Figure**: <1.5dB first module
- **Detector**: 10MHz to 12.4GHz 0.5mV/microW zero biased Schottky Diode
- **Overall System Noise Figure**: <6.20dB
- **Overall Gain**: >50dB
Thank You

I would be glad to answer all of your questions...