Terahertz radar imaging for standoff personnel screening

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[Logos and icons]
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Potential benefits of active, narrowband THz imaging:

- Very high SNR is possible because of high-power sources and low-noise detectors
- Video-rate imaging feasible with small number of transceivers

1 m diameter aperture

7,000 K noise = 0.1 pW/μs

1 mW @ 670 GHz

1 mW x 10^{-8} = 10 pW

25 m standoff: x10^{-4} geometric loss (beam-spreading)

x10^{-1} atmospheric loss (worst case)

clothing: x10^{-1} two-way loss

body: x10^{-2} reflection
Potential benefits of active, narrowband THz imaging:

- Very high SNR is possible because of **high-power sources and low-noise detectors**
- Video-rate imaging feasible with small number of transceivers

\[
\text{SNR} = 1000 \text{ with only 10 } \mu\text{s integration time!}
\]

100x100 pixels in 100 ms possible with a **single beam**
JPL’s THz Imaging System, 2011

• Requirements for detection: solid object, ~1 inch in size (in 3 dimensions)
• Material of concealed object is irrelevant to detection

small mock bomb belt (2.3 cm thick)
replica hand gun (2.5 cm thick)
large mock bomb belt (2.5 cm thick)
Frequency-modulated continuous wave (FMCW) radar: appropriate when available power is limited.

\[ f_{IF} = K\tau = \frac{2KR}{c} \]

Range resolution: inversely proportional to chirp bandwidth

THz systems can achieve enormous bandwidths, and hence range resolution.
FMCW Waveform Nonlinearity

raw point-target range spectrum

Range resolution from 28.8 GHz bandwidth
- expected: <1 cm
- achieved: ~25 cm

Broadening from modulation in amplitude and chirp profile causes modulation in IF signal. But if deterministic, then this can be "subtracted out"!

\[
s_T(t) = A_T(t) \cdot \exp[i\omega(t) + i\delta\phi_T(t)]
\]

\[
s_{LO}(t) = A_{LO}(t) \cdot \exp[i\omega(t) + i\delta\phi_{LO}(t)]
\]

\[
s_{IF}(t) = \exp(i\omega_R t) \cdot A_{IF}(t, R) \exp[2\pi i \cdot \delta\phi_{IF}(t, R)]
\]
1. Acquire calibration waveform on point target:

\[ s_0(t) = \exp(i\omega_{R0} t) \cdot A_0(t, R) \exp[2\pi i \cdot \delta \varphi_0(t, R)] \]

2. Divide subsequent IF signals by (complex) calibration: bandwidth-limited resolution achieved

\[ s_{IF}(t) \rightarrow s_{IF}(t) \div s_0(t) \]

\[ \delta \varphi_{IF}(t, R) \rightarrow \delta \varphi_{IF}(t, R) - \delta \varphi_0(t, R_0) \]

\[ A_{IF}(t, R) \rightarrow \frac{A_{IF}(t, R)}{A_0(t, R_0)} \]
JPL built and designed chirper
• 1.6-3.2 GHz up/down chirp in <0.1 ms
• Very low phase noise
• Digital synthesis stability
• Careful digital/analog ground isolation
High range resolution at cm-scale is critical for being able to digitally ‘peel away’ layers of clothing and reveal potential threats.
Phase Noise Limitations

Idealized phase noise model:

- Phase noise is multiplied in frequency multipliers.
- For simple heterodyne measurement, transmit and LO phase noise is uncorrelated.
- Expected phase-noise floor: \(-97 \text{ dBc/Hz} + 3 \text{ dB} \times 20 \log(18) \text{ dB} + 10 \log(10\text{kHz}) \text{ dB} = -29 \text{ dB}\)
- We get -44 dBc above; *why so good? Can we do even better?*

measured SNR: 34-44 dB (phase noise floor)

“potential” SNR: 67 dB (thermal noise floor)

thermal noise floor at -13 dB on this scale

K.B. Cooper, European Microwave Conf., Oct 2011
Phase Noise Cancellation via Homodyne

\[ \delta \varphi = \mathbb{C} \cos(2\pi f mt) \]

\[ \delta \varphi_{IF} \approx N\alpha(2\pi f m\tau) \sin(2\pi f mt) \]

This makes the heterodyne effectively homodyne!

- Phase noise in IF will vanish if the electrical path delays are balanced
- One source of imbalance is the time-of-flight of \( \tau \approx 170 \text{ ns} = 6 \text{ MHz}^{-1} \)
- At 100 kHz offset, expect cancellation of \((2\pi \cdot 100\text{kHz} \cdot 170 \text{ ns})^2 = -19 \text{ dB}\)
- Expect -29 dBc -19 dB = -48 dBc phase noise floor; close agreement w/ msmt

Confirmation:

- -29 dBc noise floor restored without “homodyne” circuit in place.
- Complicated by chirp source common to Tx and LO chains, and by dispersion in submm electronics
- Can tunable cancellation be improved?
• Higher frame rates wanted: rapid crowd scanning, subjects in motion, wider field of view

• Better THz components will not help: bottleneck from mechanical scanning

• Path to video rates: scanning multiple beams simultaneously

Goal: Near-Video Rate THz Radar Imaging

Concept: 3D stacks of precision micromachined silicon waveguide: 
extremely compact integration

N beams = N x speed-up

But it’s not practical to duplicate the front-end module 8 times!

~5 inches
670 GHz imaging radar is effective at detecting concealed threats

Good penetration allows for covert operation and “seeing through” even thick clothing

Chirp stability and calibration is critical for achieving high range resolution and hence high contrast imagery

Careful circuit architecture can improve noise floor and dynamic range

Transceiver array development is underway to reach near-video frame rates