WSN: Compact 680 GHz Imaging Radar

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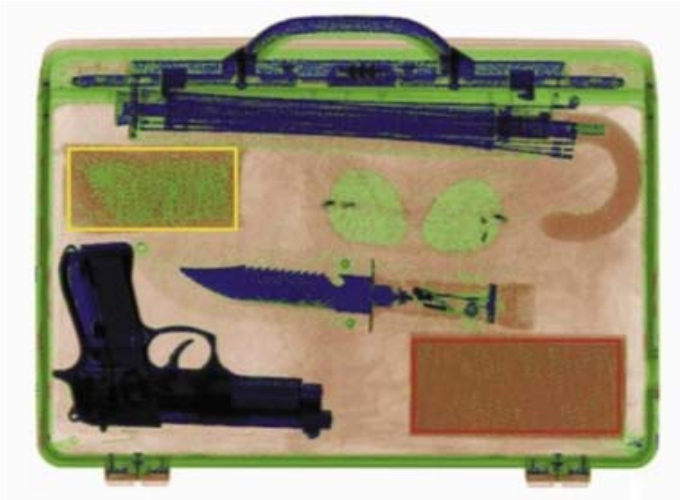
Introduction

- **THz Imaging Overview**
  - -X-Ray, IR, and Active THz Imaging
  - - Why Radar?
  - - Basics of FMCW ranging
- **Compact Radar Implementation and Architectures**
  - - System Architecture
  - - Front-End and Optics
  - - Back-end and Digital Signal Processing and Calibration
- **Physical Limitations of Imaging Radar**
  - - Cross-Resolution Limitations
  - - Penetration Limitations
- **THz Radar Multiplexing**
  - - Automatic focusing

X-Ray Transmission



X-Ray Capture

- X-ray imagery has an 8 order of magnitude wavelength advantage over THz radiation and is not diffraction limited.
- Excellent penetration properties. Even through metal containers.
- Ionizing - Limited potential for standoff systems.

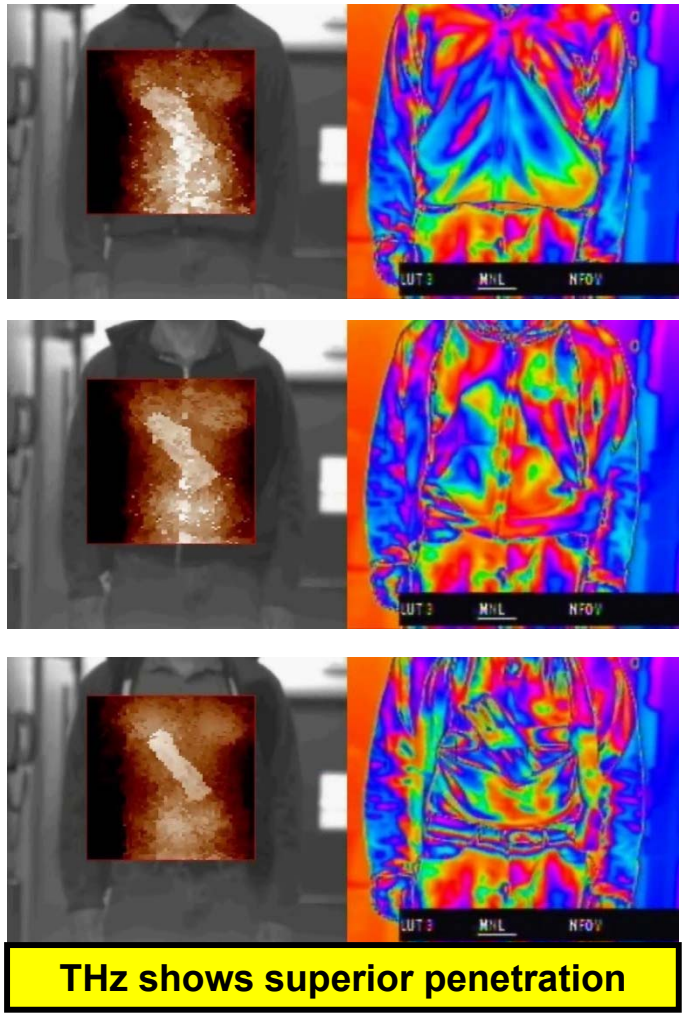
Infrared Imaging and THz

THz IR

cotton sweatshirt + fleece jacket

just cotton sweatshirt

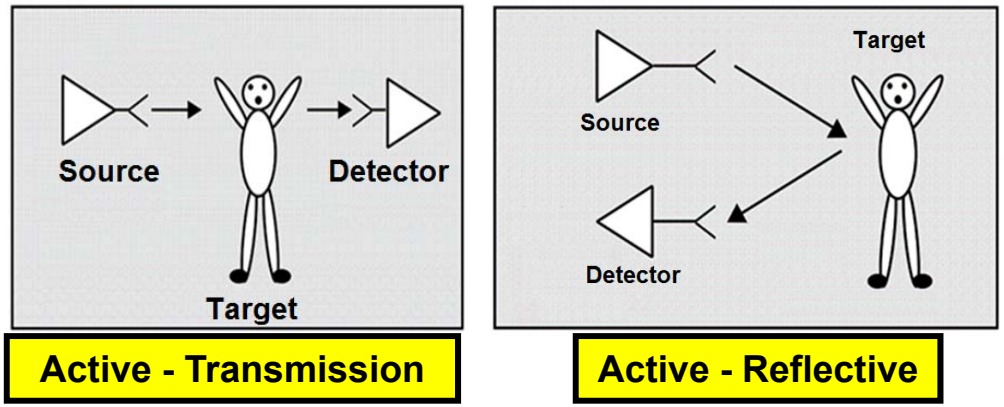
no concealing layers



Mock Pipe-bomb

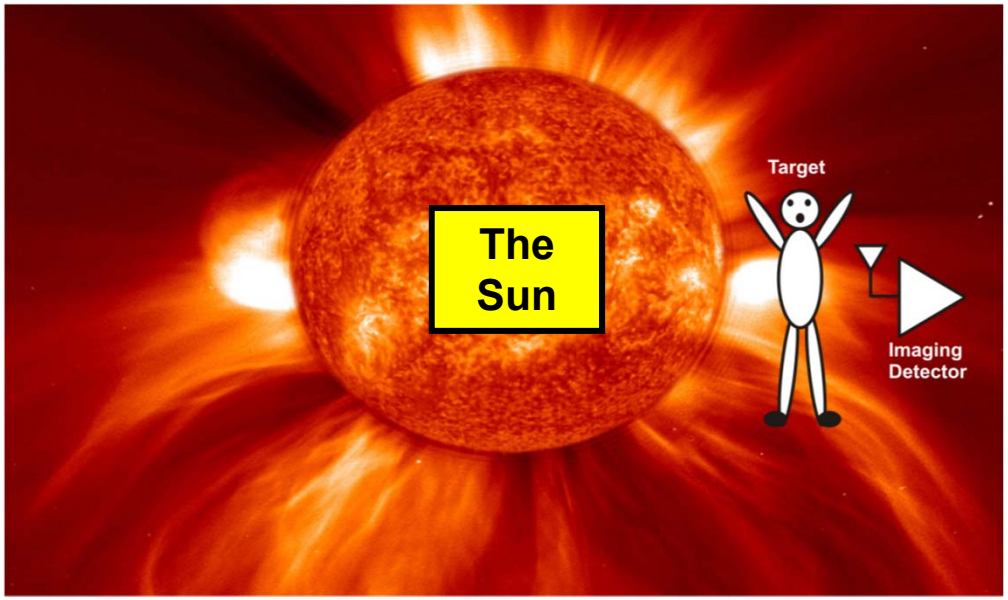
THz shows superior penetration

Active THz Imaging Systems



- Active THz imaging systems can be grouped into 2 basic categories based on orientation of target, source, and detector.

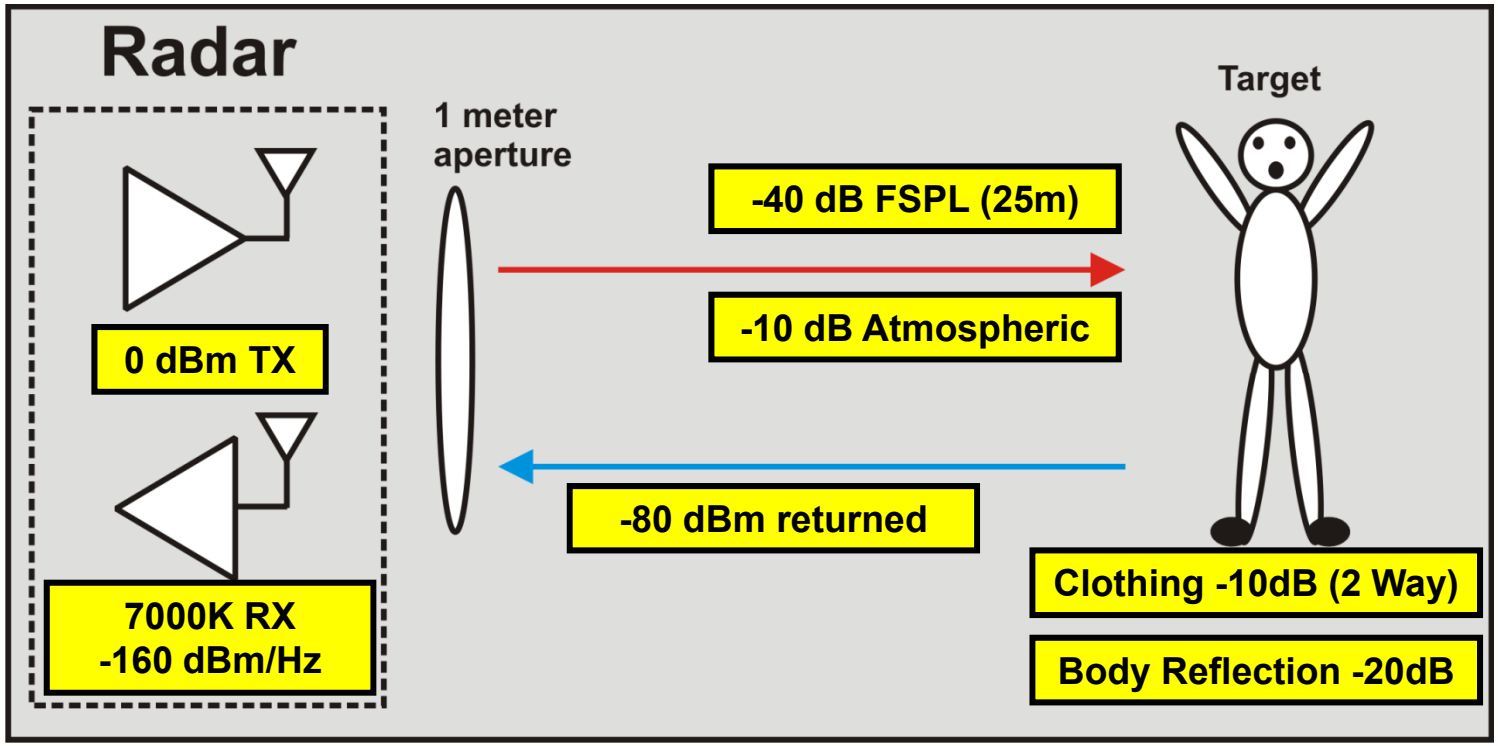
Transmission Imaging



- The human body presents too much loss for transmission (through-target) imaging at THz frequencies.
- Source power equivalent to earth's sun would be needed as well as very long integration times.
- The target would be damaged.

Reflective Imaging

- Very high SNR is possible with reasonable source powers and receiver noise performance.



SNR > 30 dB possible with only 10 µs integration time!

Power (SNR) Imaging

- Contrast (SNR) from the THz or millimeter-wave beam is completely dominated by the beam-target angle.

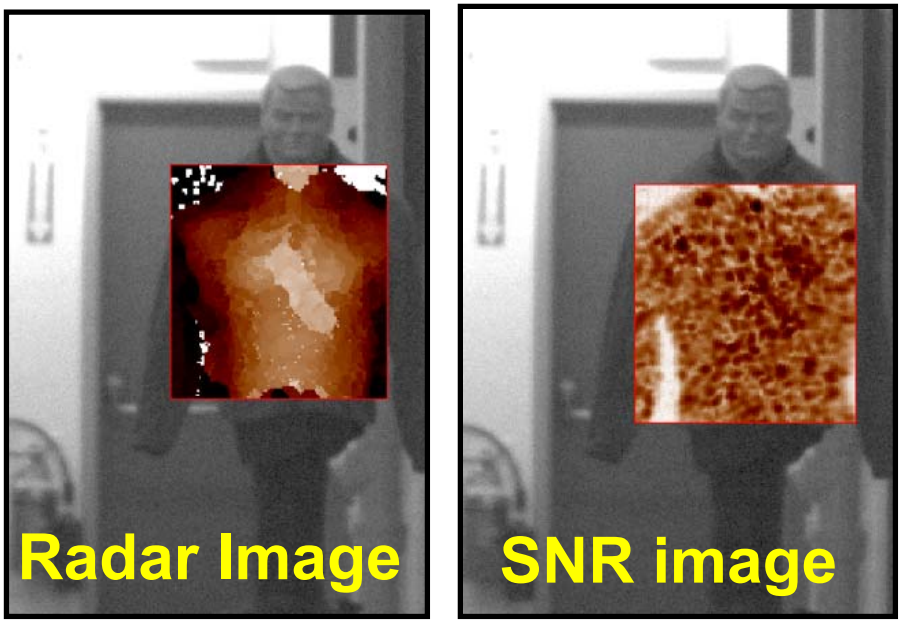


Image contrast based on material differences is totally swamped by speckle effect from clothing layers.
Continuous-wave imaging is ineffective for security screening!

Imaging Radar

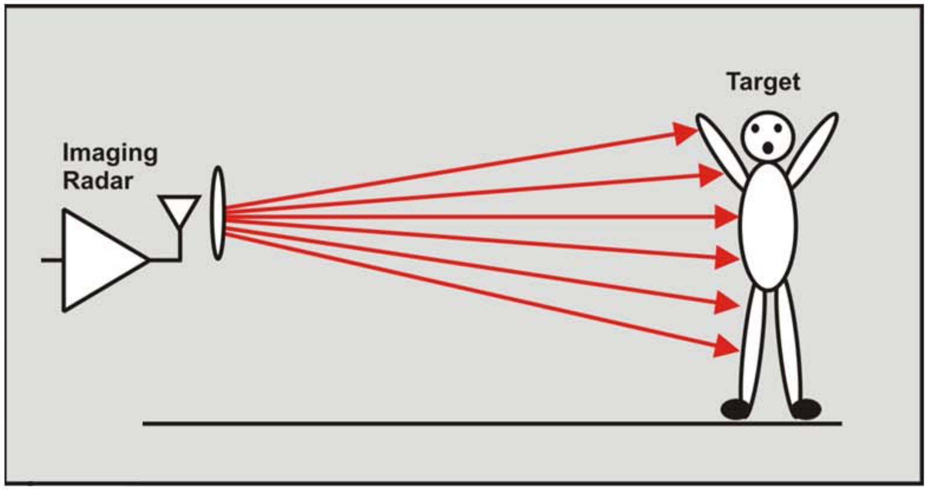
RFIC 2013

- Imaging radar couples an imaging operation with a radar that measures target range.

- By constructing images with range data instead of SNR the problems associated with angle dependence of the clothing are avoided.

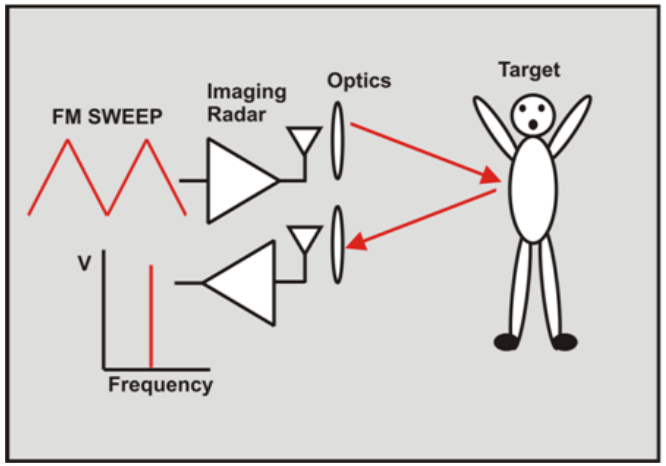
X-Position (columns) / Y-Position (rows)

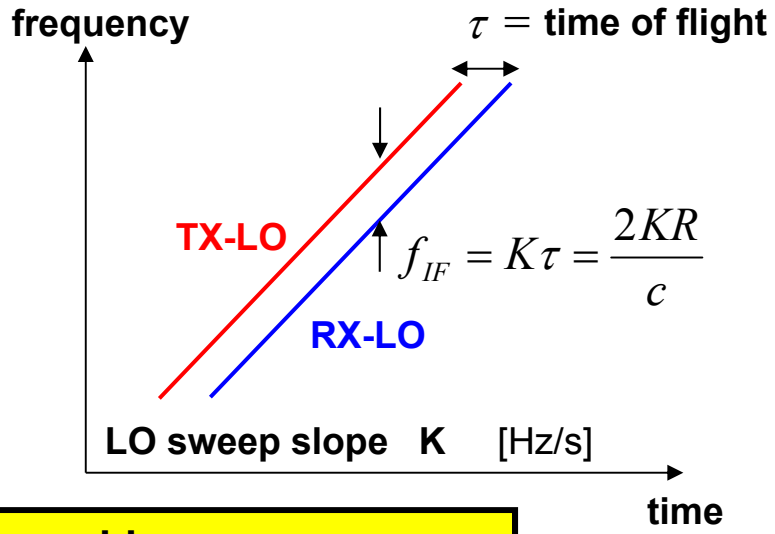
3.1cm	3.0cm	2.9cm	2.1cm	3.1cm	3.0cm	2.9cm	2.1cm
2.8cm	3.4cm	2.3cm	2.4cm	2.8cm	3.4cm	2.3cm	2.4cm
3.1cm	3.0cm	2.9cm	2.1cm	3.1cm	3.0cm	2.9cm	2.1cm
2.8cm	3.4cm	2.3cm	2.4cm	2.8cm	3.4cm	2.3cm	2.4cm
3.1cm	3.0cm	2.9cm	2.1cm	3.1cm	3.0cm	2.9cm	2.1cm
2.8cm	3.4cm	2.3cm	2.4cm	2.8cm	3.4cm	2.3cm	2.4cm
3.1cm	3.0cm	2.9cm	2.1cm	3.1cm	3.0cm	2.9cm	2.1cm
2.8cm	3.4cm	2.3cm	2.4cm	2.8cm	3.4cm	2.3cm	2.4cm



FMCW THz Radar

- Frequency-modulated CW radar uses a swept transmitter and receiver LO to measure the time of flight.
- Although FMCW is older than pulsed (switched T/R) radar it offers the advantage of higher SNR with lower source power as the illumination duty cycle is 100%.



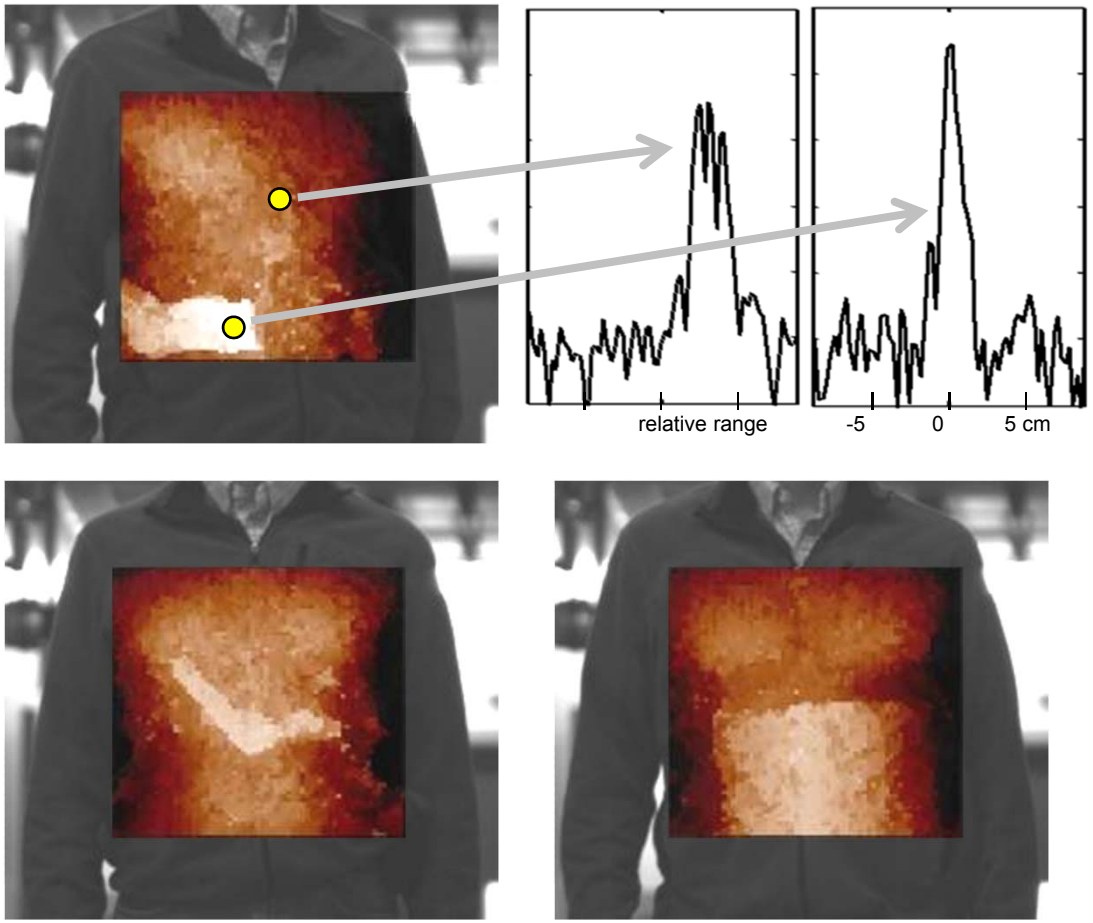


$$\delta r = \frac{c}{2\Delta F}$$

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

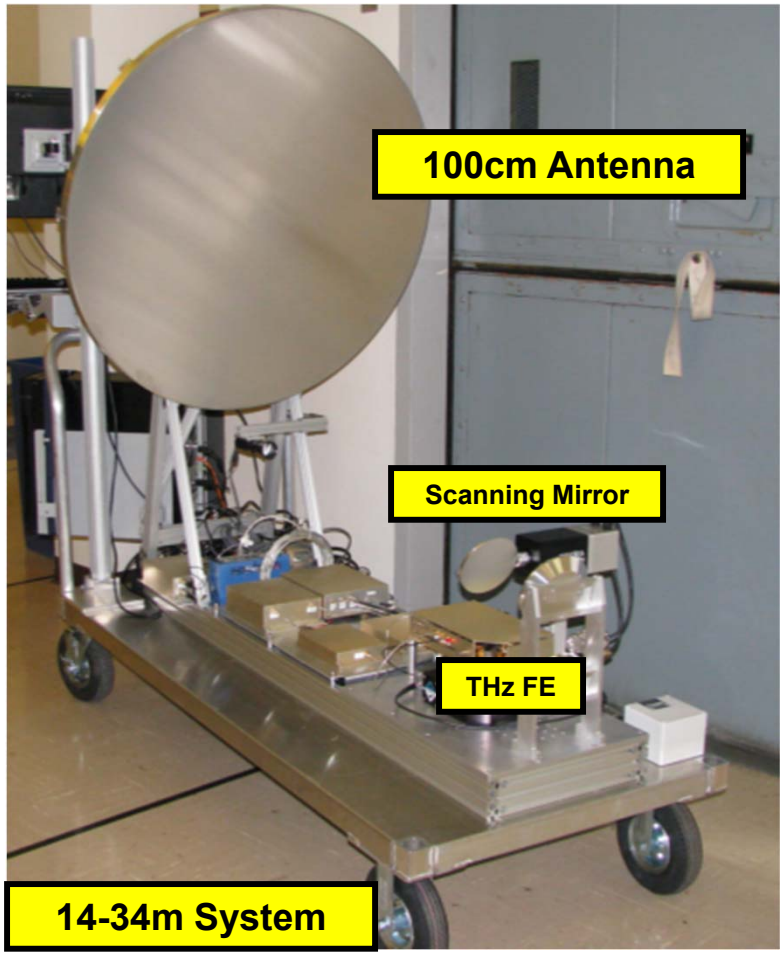
Imaging Radar Concept

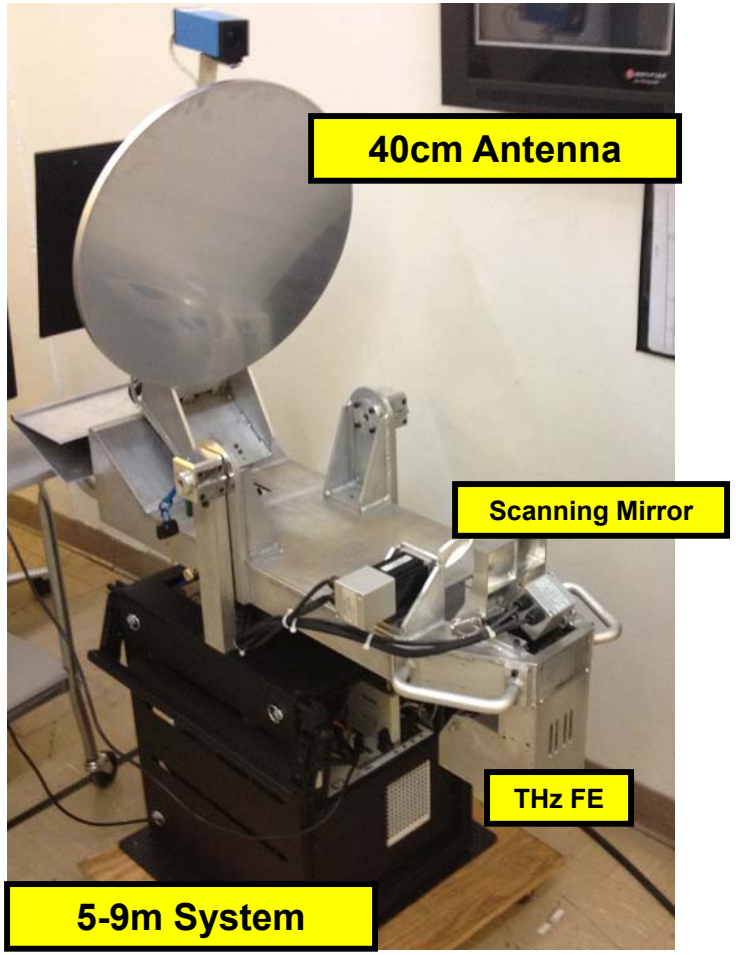
- Use THz imaging radar to reveal potential threats by capturing other surfaces under the clothing.



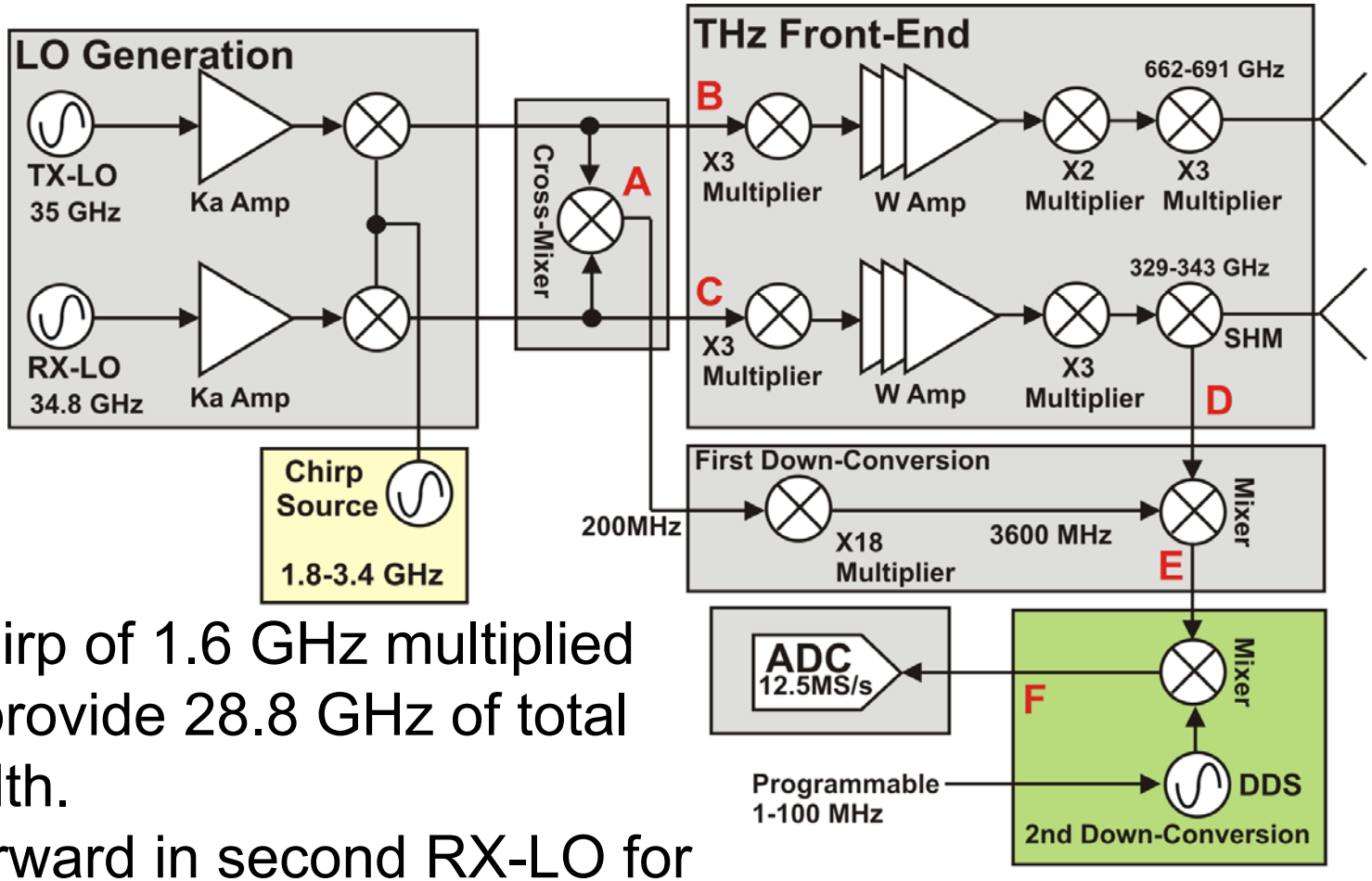
THz Radar Implementation and Architecture

Compact THz Imaging Radar





THz Radar Architecture

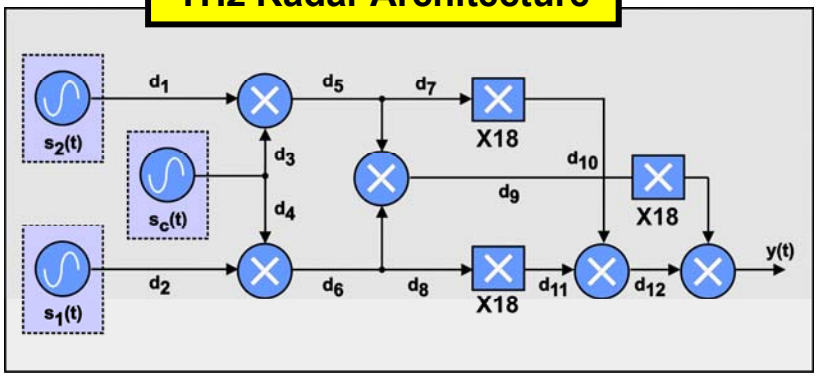


- Initial chirp of 1.6 GHz multiplied 18X to provide 28.8 GHz of total bandwidth.
- Feed-forward in second RX-LO for phase noise reduction via range correlation.

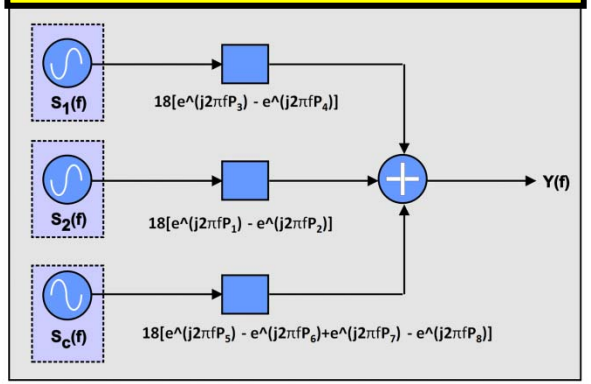
Range Correlation

- Tx & Rx LO are correlated. This effect is called “Range Correlation” in radar terminology. We exploit this to suppress low offset phase noise by feeding forward the receiver LO. (High frequency phase noise not cancelled)

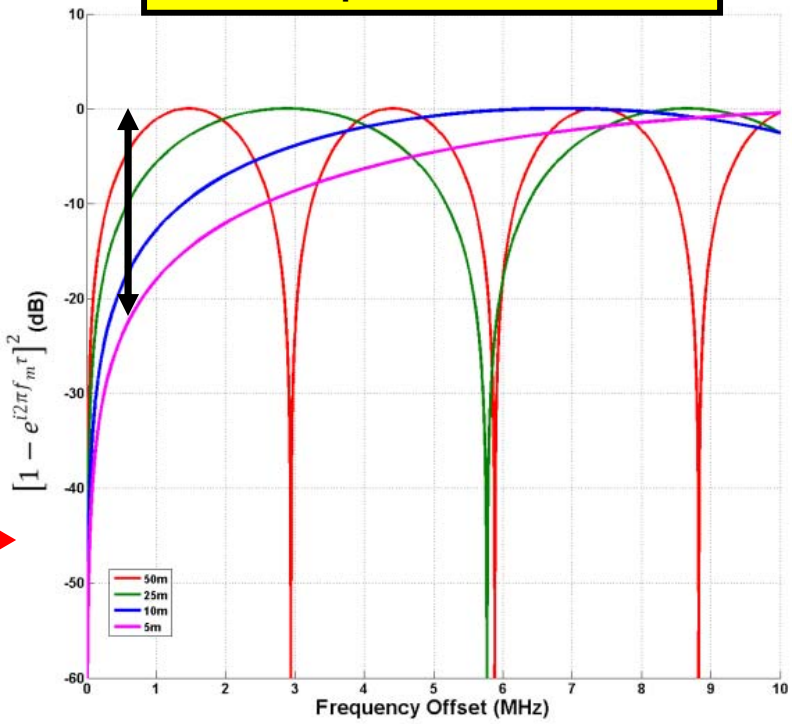
THz Radar Architecture



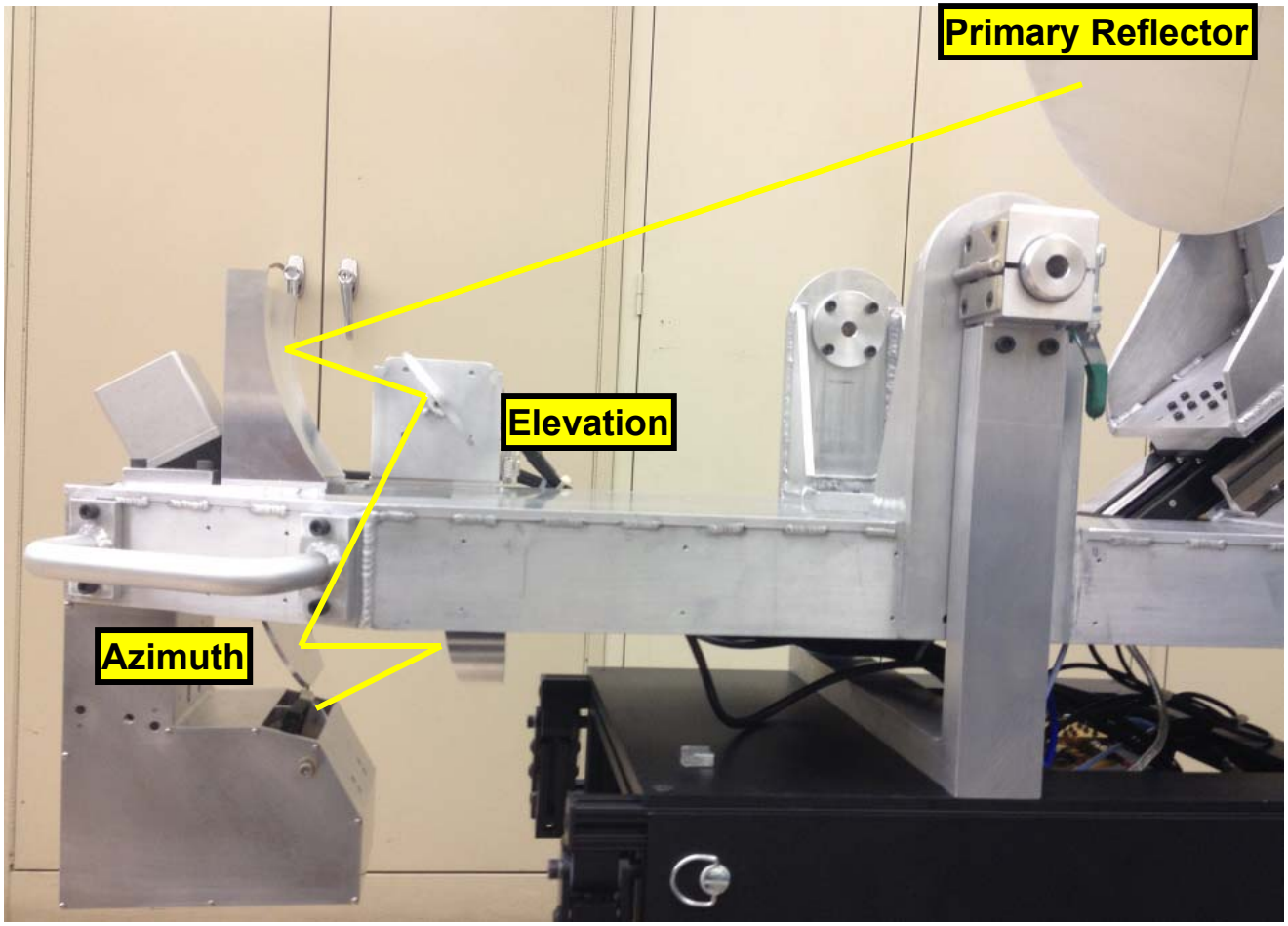
Equivalent P-Noise Model



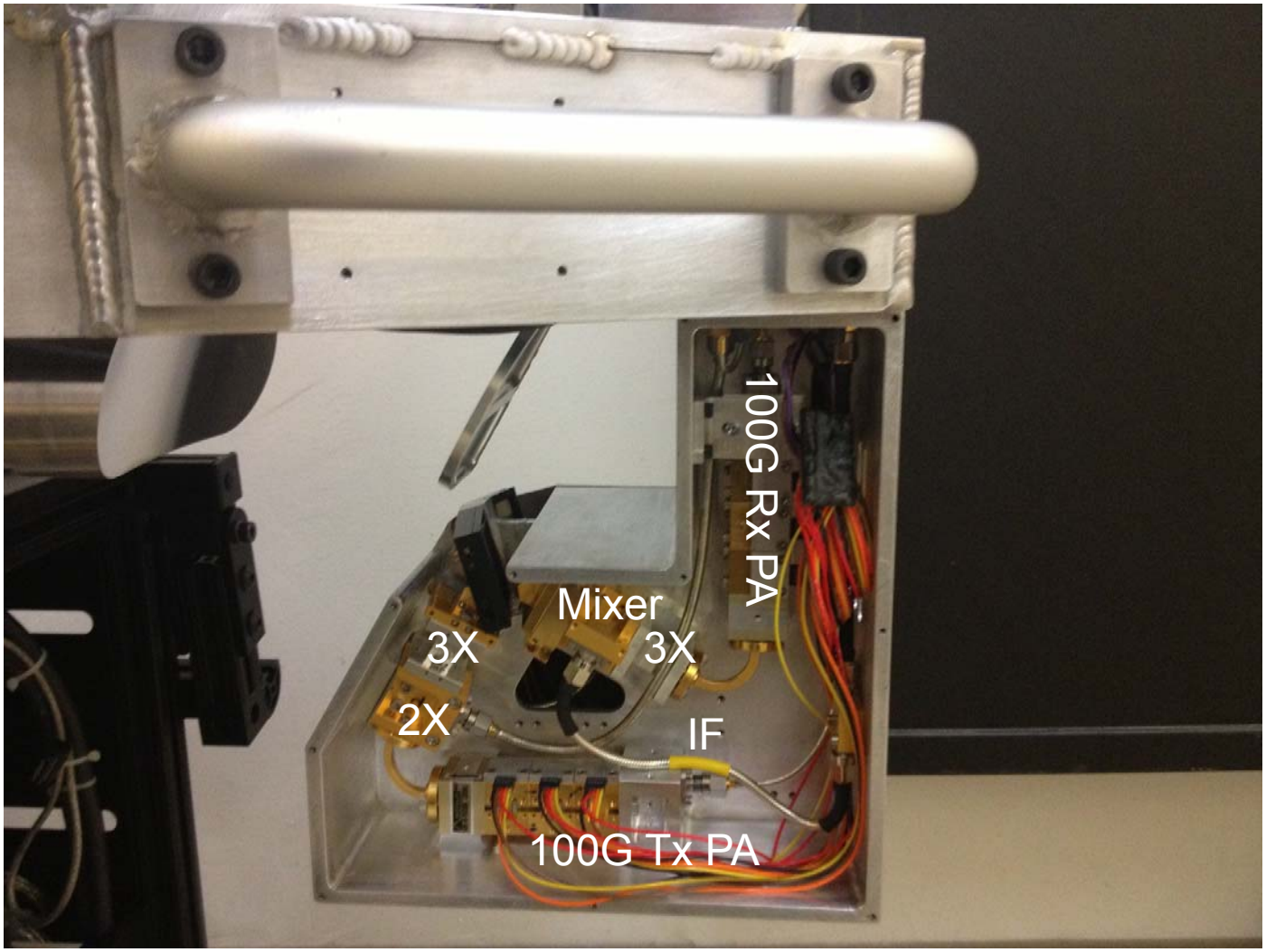
Low Freq noise is cancelled



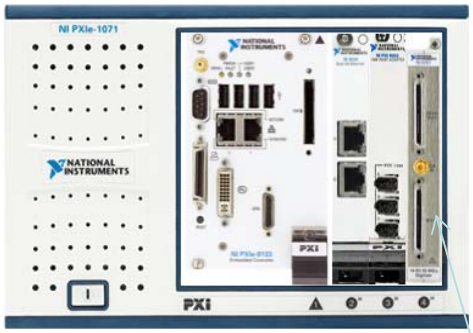
Scanning Optics



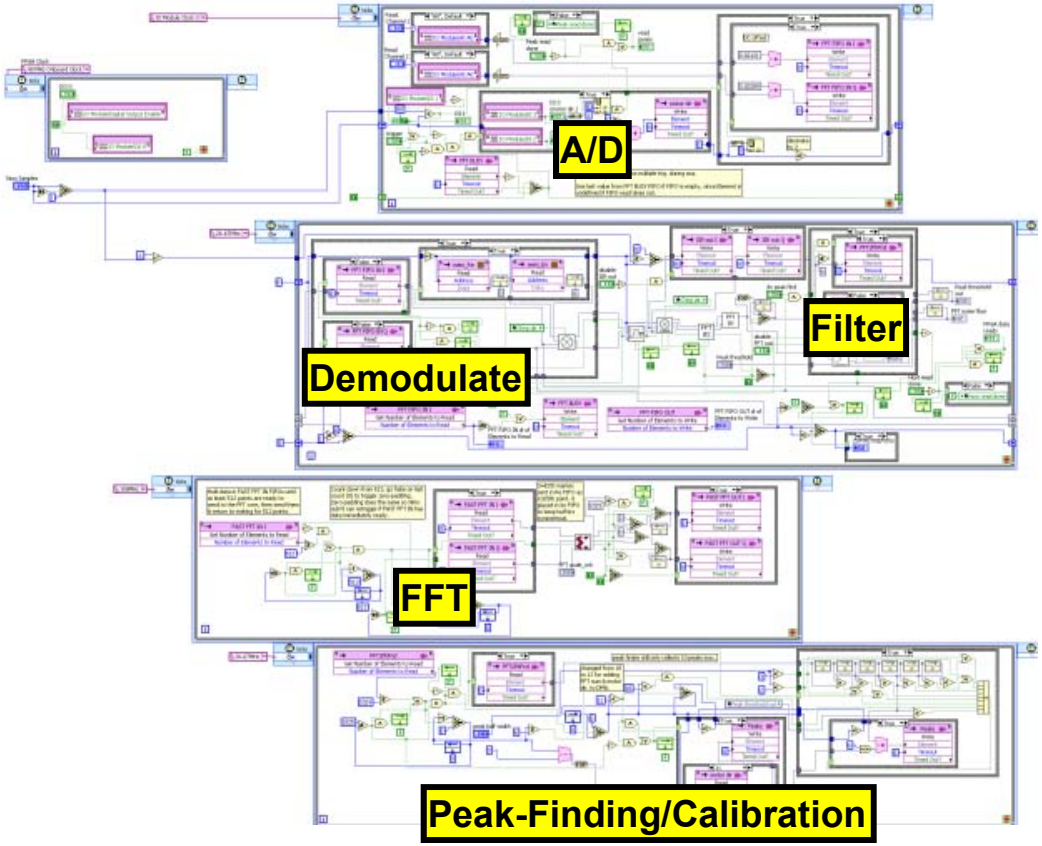
Front-End Electronics



Back-End Processing

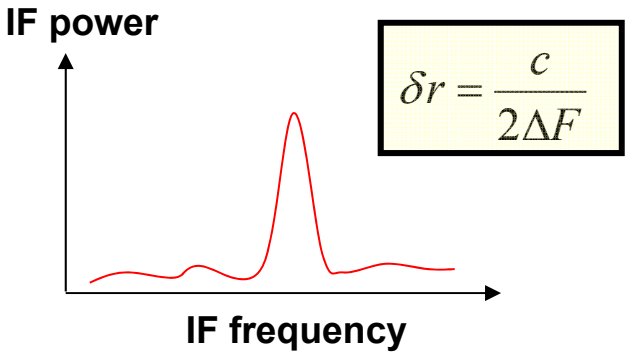


FPGA & A/D



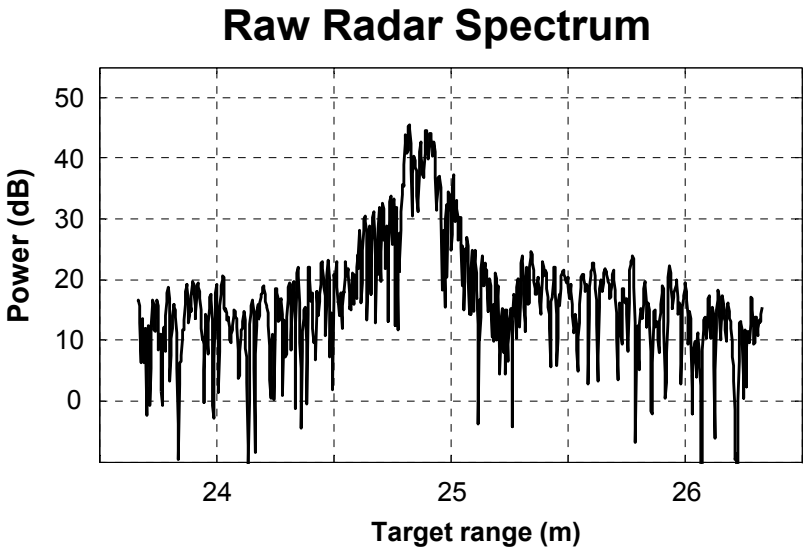
- Back-end is implemented on an FPGA with integrated A/D to allow more system flexibility during development.

Chirp Non-Linearity



$$\delta r = \frac{c}{2\Delta F}$$

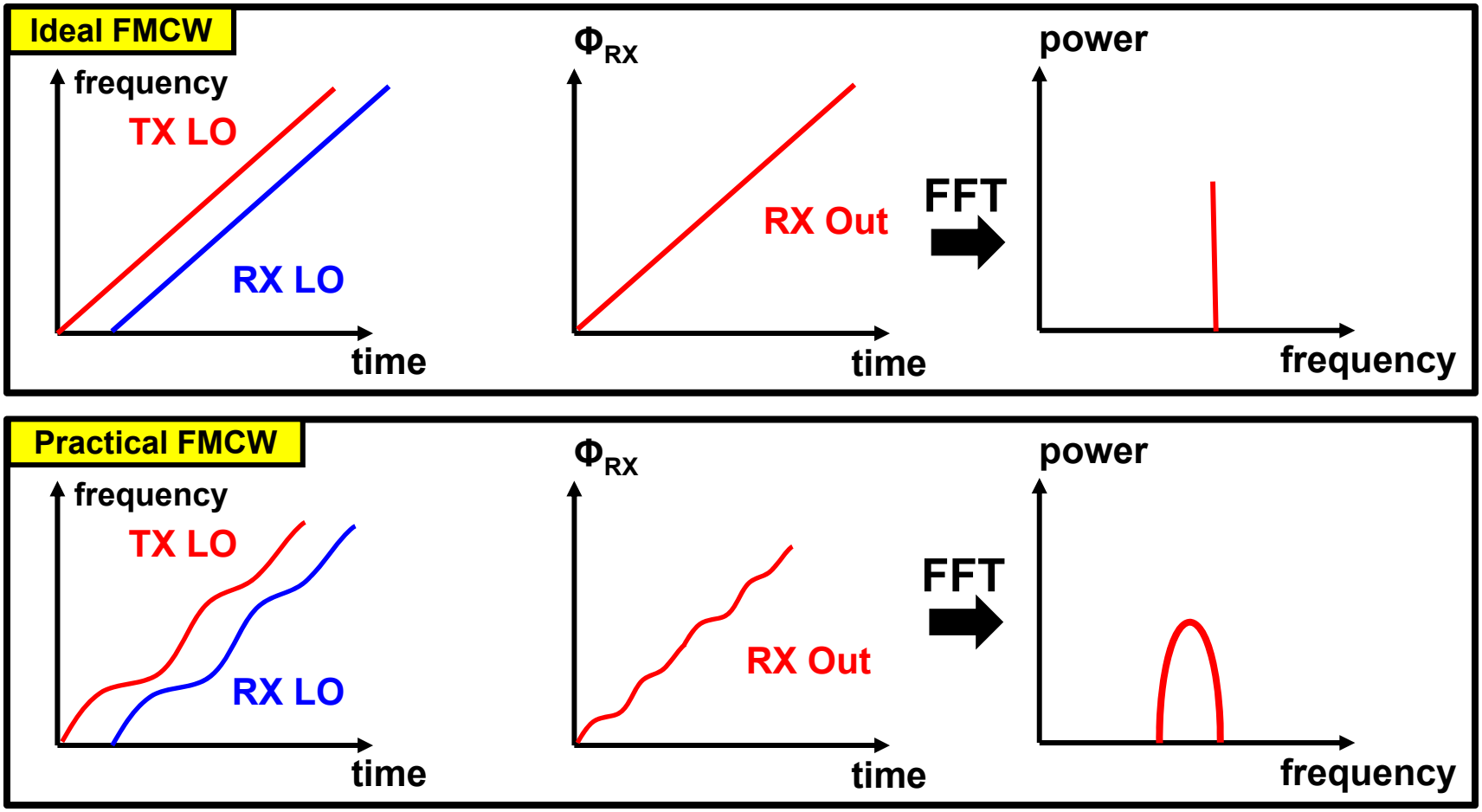
Theoretical Res: 1 cm



Measured Res: 25 cm

- With our 28.8 GHz chirp bandwidth we expected to obtain a range resolution of approximately 1.0 cm but obtained only 25 cm of range resolution due to chirp non-linearity.

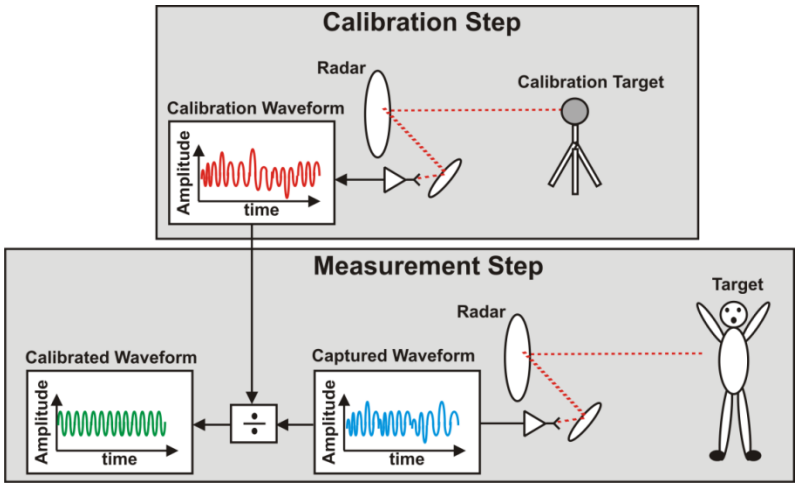
Chirp Non-Linearity

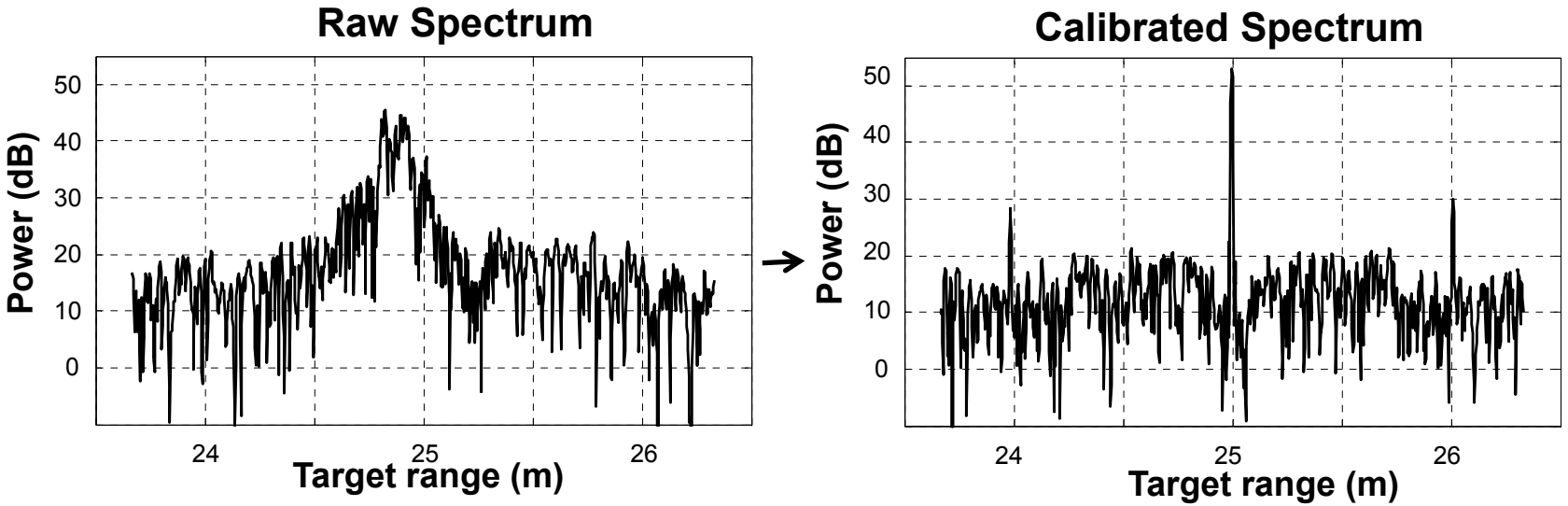


- Non-linearity originates in both the sweep generation and front-end of the radar.

Chirp Equalization

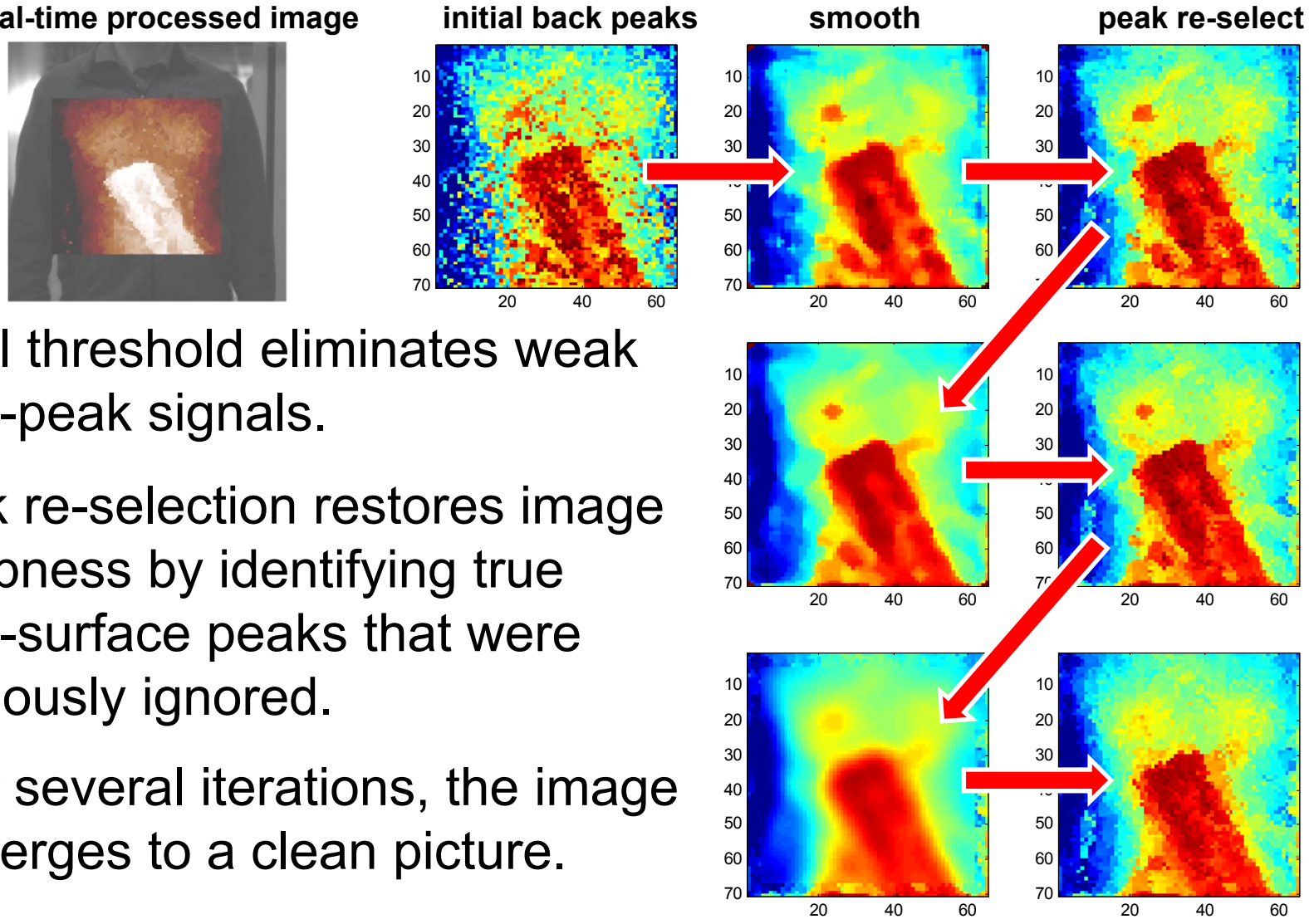
- First measure time domain return of a point target to capture the radar non-linearity.
- Divide subsequent targets by the time domain waveform produces DC (an ideal tone) for each reflection.





Equalization is a must for Hi-Res Radar

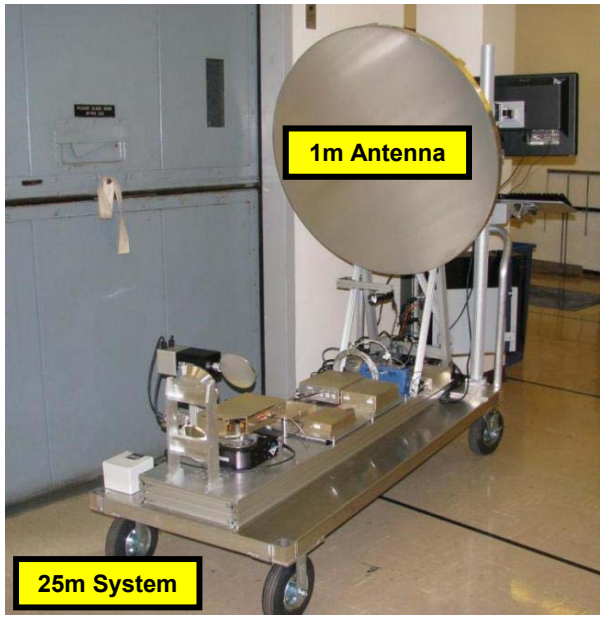
Image Processing



- Initial threshold eliminates weak back-peak signals.
- Peak re-selection restores image sharpness by identifying true back-surface peaks that were previously ignored.
- After several iterations, the image converges to a clean picture.

Physical Limitations of THz Imaging Radar

Cross Resolution



- Radar cross-resolution is limited by diffraction.

$$\text{Res} = \frac{1.22\,(\text{target range})\,\lambda}{(\text{antenna size})}$$

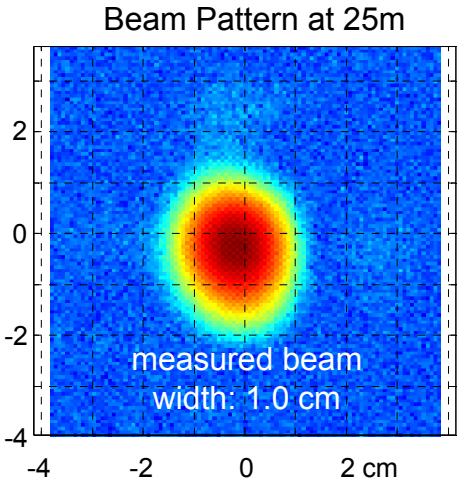
- To improve:
  1. Frequency can increase.
  2. Range can decrease.
  3. Antenna size can increase.

No other options…

- Our long range antenna is pretty large already (70 lbs!). Any larger would be impractical.
- Beyond 700 GHz penetration of clothing becomes more difficult as attenuation per pass quickly increases.

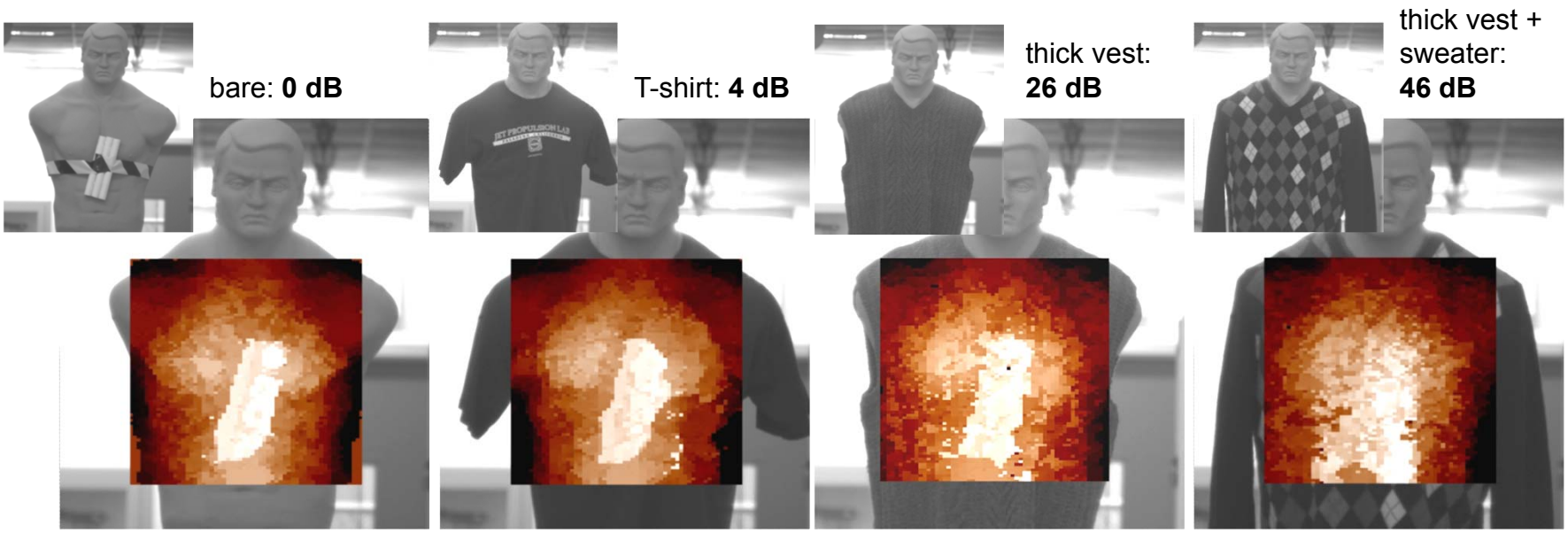
Bringing the target closer to the radar seems the only way to improve imaging cross resolution*

***but this may limit applications**

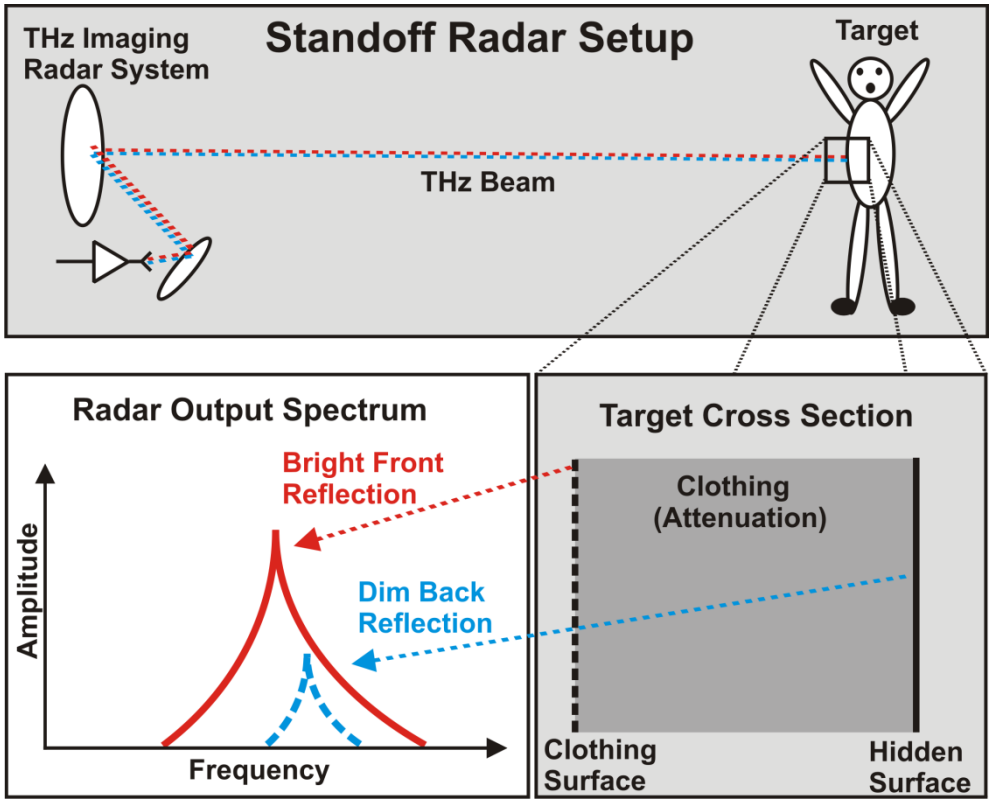


Penetration Limits

garment	mass density (mg/cm^2)	average one-way (dB)	min. (dB)	max. (dB)	standard dev. (dB)
Cotton T-shirt	42	2.02	1.73	2.26	0.19
Thin lambswool sweater	35	10.05	9.29	10.71	0.61
Thick wool vest	84	13.43	12.14	14.79	0.97



Will More Power Help?

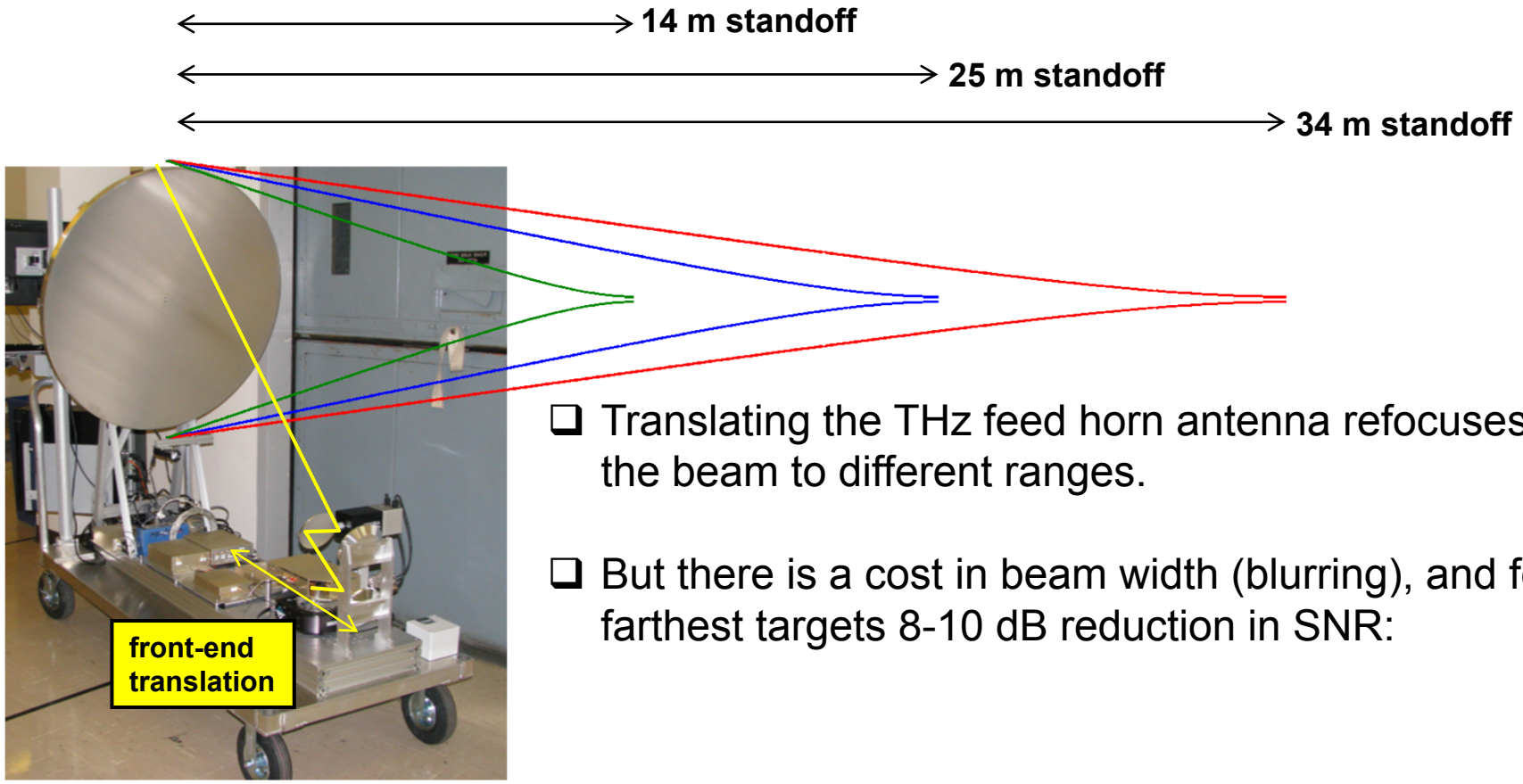


- Large phase noise skirt from the bright front-surface reflection will mask the dim radar signal from the back surface.
- Noise is carried from the TX so improving the receiver noise figure will not help!
- Increasing the transmit power will not help either! Both peaks will increase together.
- Lowering the frequency would help penetration at the cost of cross resolution or standoff.

Reducing phase noise is the only path to improved penetration of thick clothing without sacrificing cross-resolution or standoff.

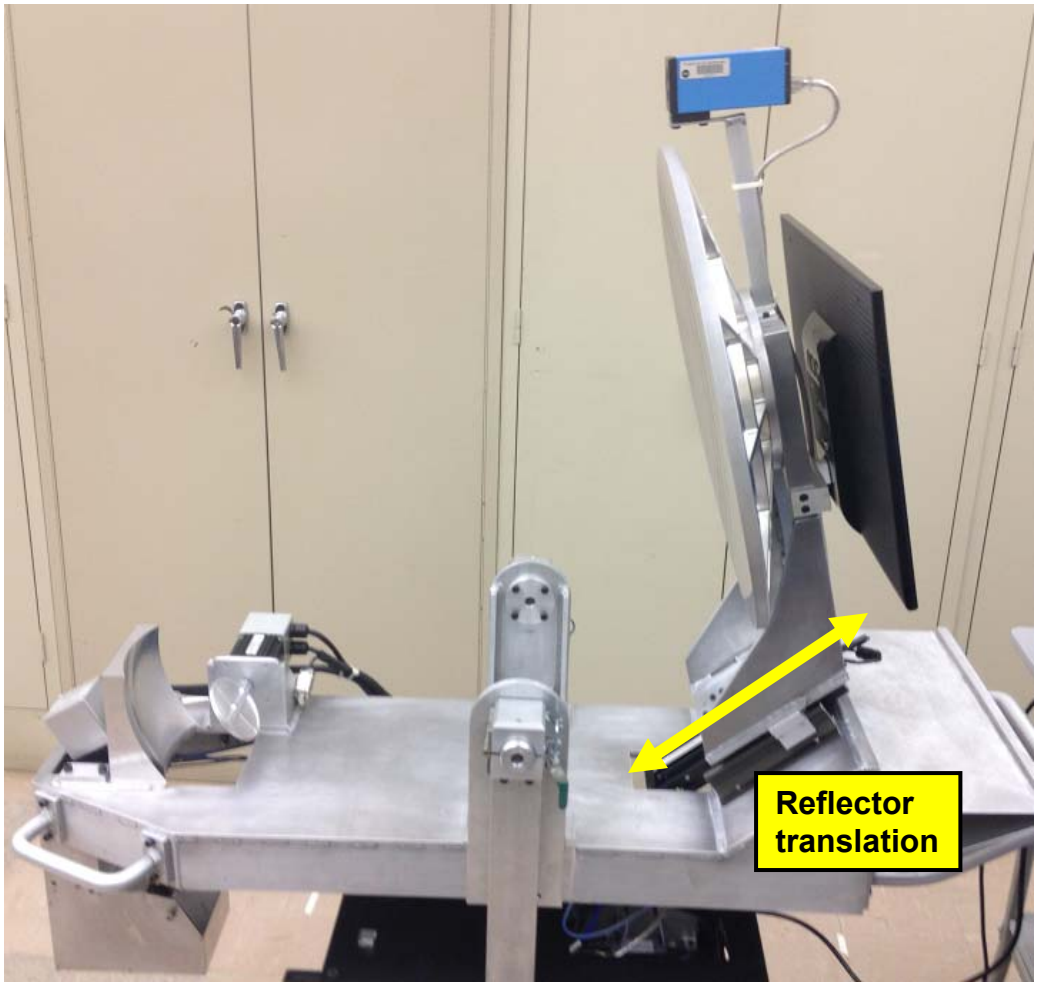
Automatic Focusing

Original Refocusing Concept

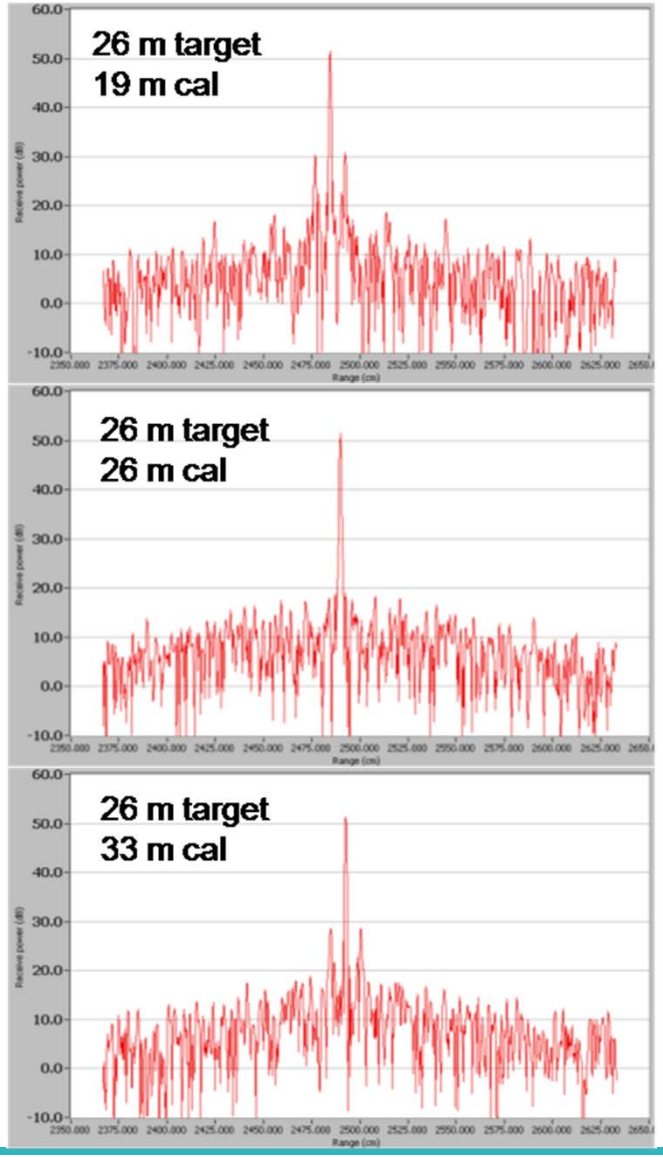


- Translating the THz feed horn antenna refocuses the beam to different ranges.
- But there is a cost in beam width (blurring), and for farthest targets 8-10 dB reduction in SNR:

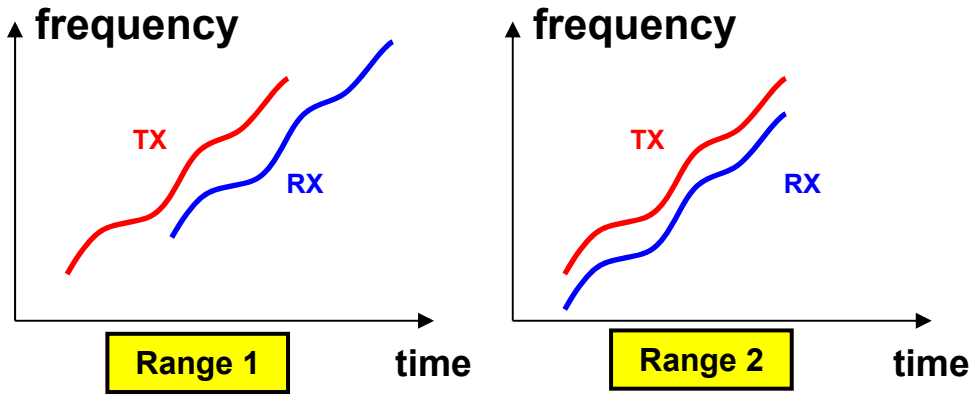
Compact Refocusing



Equalization and Standoff



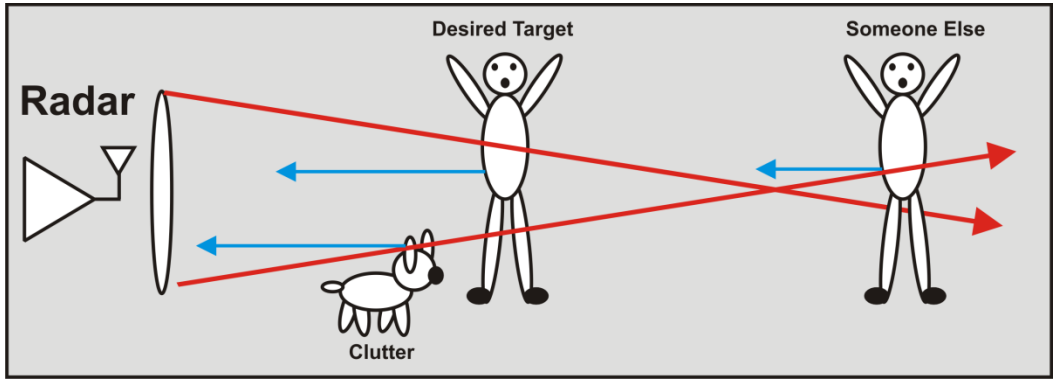
- If the radar is equalized at one range, then this compensation doesn't work as well at other ranges.
- The relative chirp non-linearity between the Tx and Rx chains is de-correlating over short time/range scales.



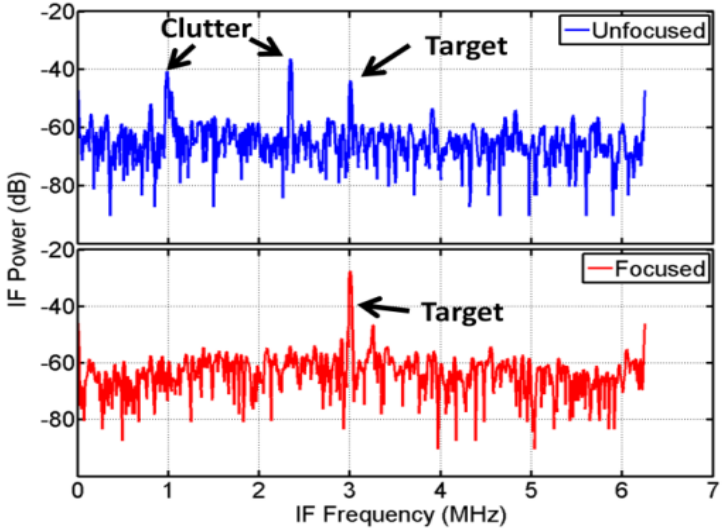
- Multiple compensations can be easily stored and recalled as needed depending on the target range.

Finding the Target

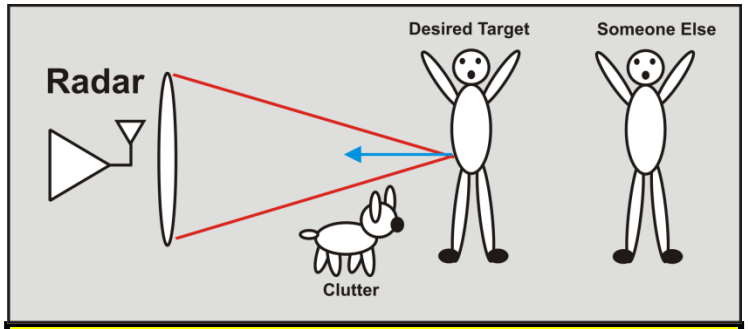
- Cluttered environments make it difficult to tell where the radar is pointed.
- Although a large beam will hit a target, it may also go past a person and reflect brightly from farther-away objects.
- Close in objects at the edge of the FOV may also be a problem.



SNR based criteria are not effective for radar focusing.



Focusing Algorithm

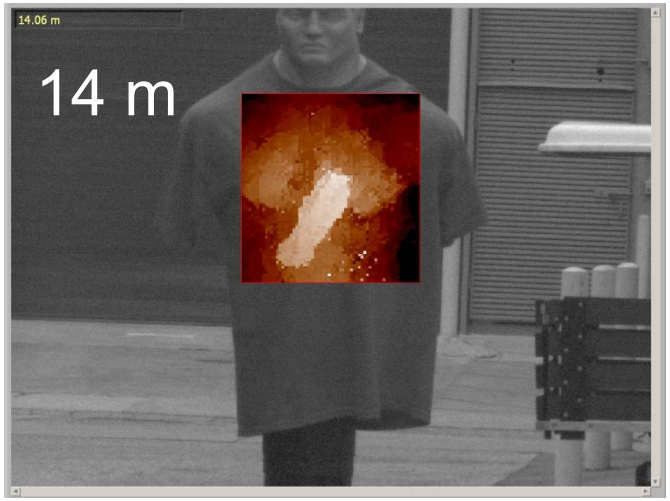


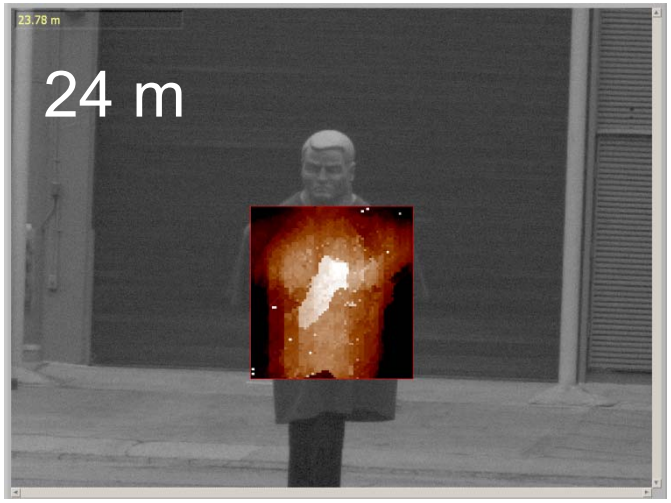
When a well-focused beam hits a person, there is no clutter problem.

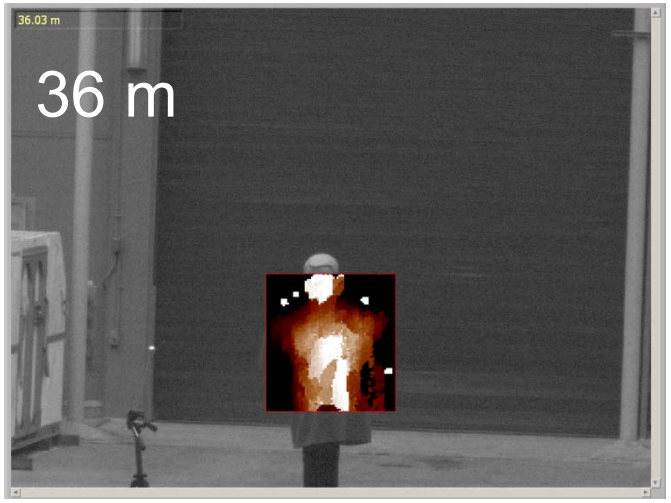
Auto-focusing Algorithm:

1. The user aims the radar to a target using the optical camera.
2. The feed translation stage is swept in position, looking for signal returns with exactly one range detected.
3. The translation stage is positioned to optimum point for this range.
4. The range-appropriate chirp nonlinearity compensation file is loaded.

Auto-focusing Results

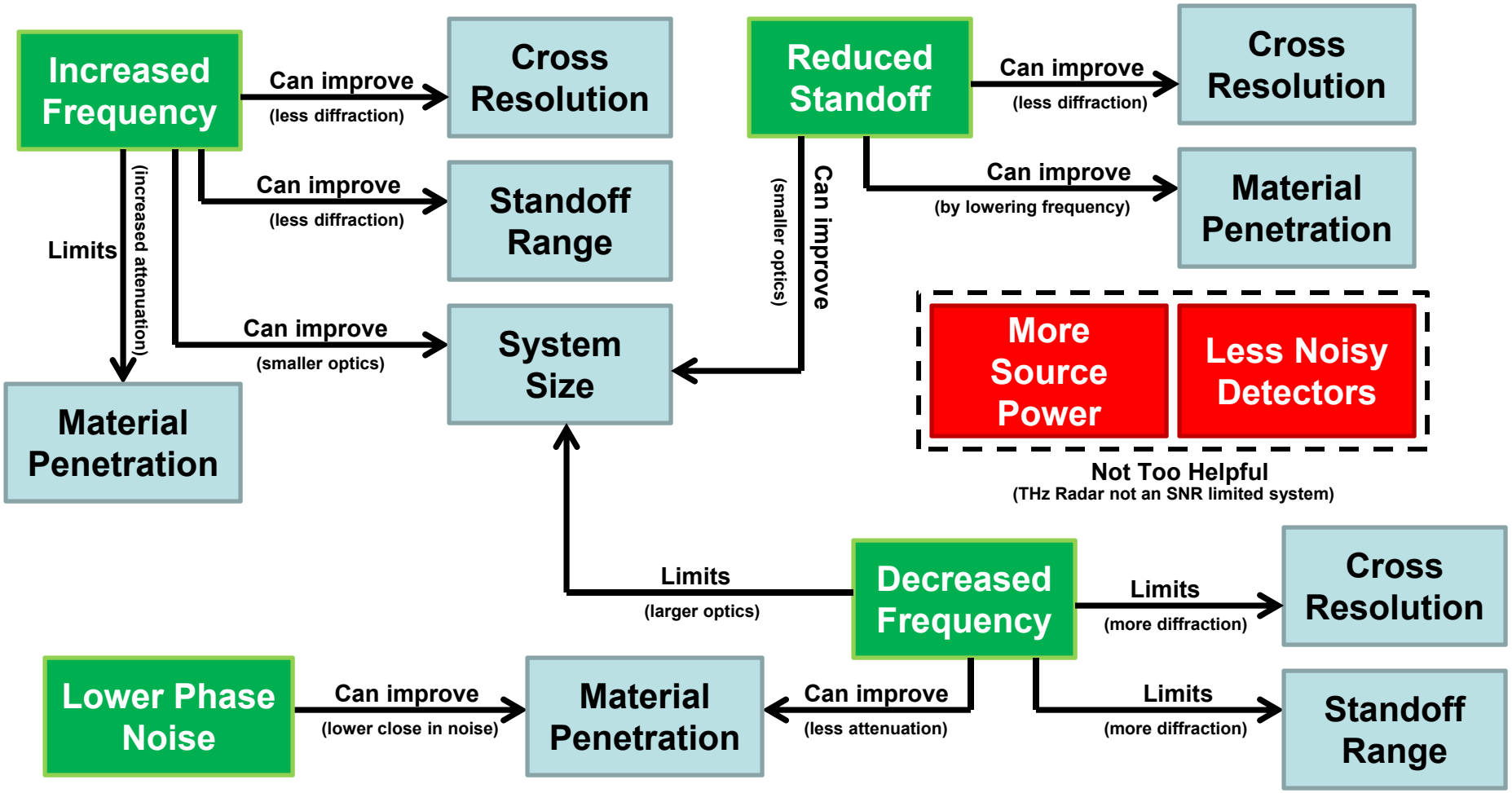






Summary of Radar Limitations

- Our THz Radar performance is fundamentally limited by physical relations of the imaging tradeoff space and phase noise of our LO:



Future Directions

Beyond improving the attainable imaging performance several other important directions need to be addressed:

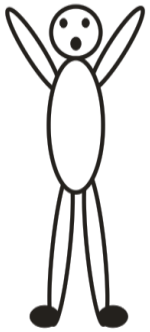
Improved Scanning Speed – Critical for real world applications where screening subject may not be stationary.

System Power – Becomes important for applications where portable systems are desirable

$COST$ – THz imaging radar has to be affordable for the applications that can benefit from the technology otherwise it will not become practical.

($10^{6}-Army Base $10^{5}-Airports $10^{4}-Stadiums $10^{3}-Mass Transit)

Thank You!



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Fernando Aguirre & Jason Carlton