INSPIRE

INSPECTING AND PRESERVING INFRASTRUCTURE THROUGH ROBOTIC EXPLORATION

3D Microwave Camera for Concrete Delamination Detection

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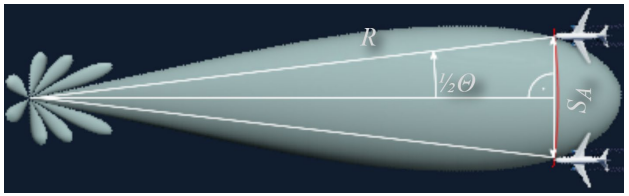
Outline

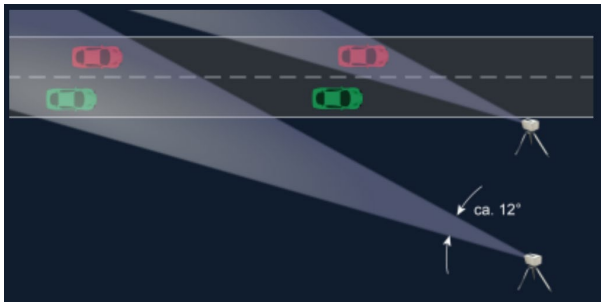
- Microwave SAR imaging
- Concrete delamination imaging
- Antennas for NDE
- Antenna pattern effect on SAR resolution
- Antenna pattern effect on SAR sidelobe level

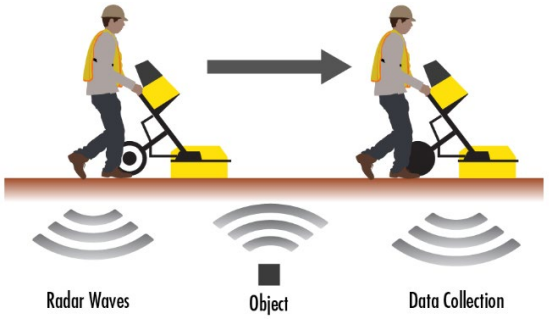
Microwave Imaging

- **Microwave imaging techniques, have demonstrated great potential for NDE of polymers and composites.**
- **Microwave and Millimeter Wave imaging technique provide:**
  - **one-sided 3D imaging**
  - **multi-view technique**
  - **improved SNR**
- **These imaging techniques can be implemented using imaging arrays that yield imaging results in *real-time.***

Traditional Radar







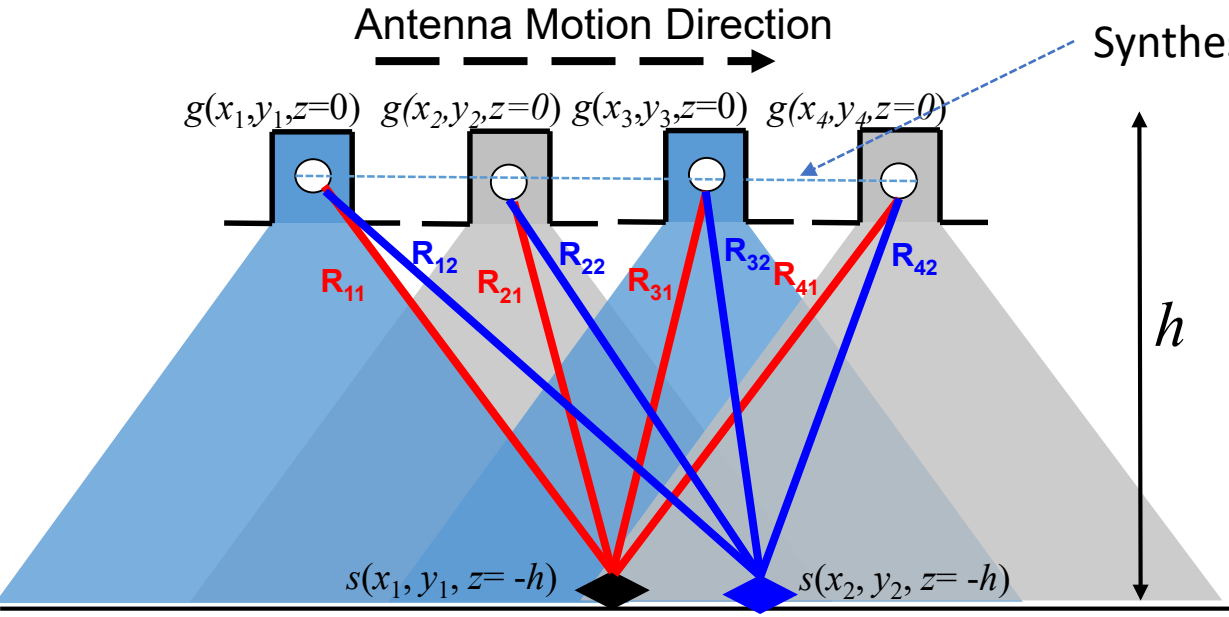
$$S_A \geq 2R \cdot sin\frac{\Theta}{2}$$

(a) Traditional radar sensing technique[1][2]

(b) Ground penetrating radar[3]

- The angular resolution is dependent on the distance and antenna half-power beamwidth (HPBW).
- When the target-to-antenna distance is large or the dimension of target is very small, the resolution is bad.

Synthetic Aperture Radar (SAR)



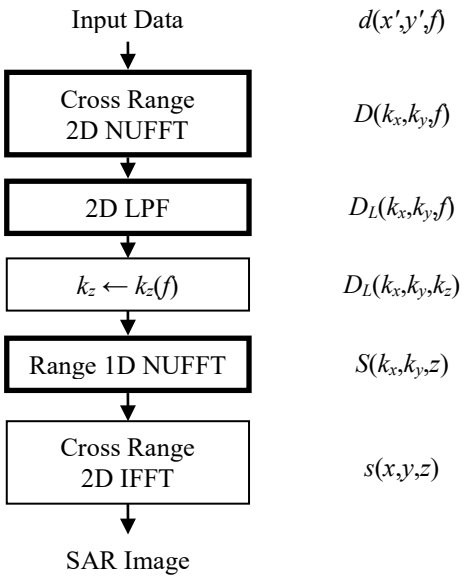
Synthesized antenna (Synthetic aperture)

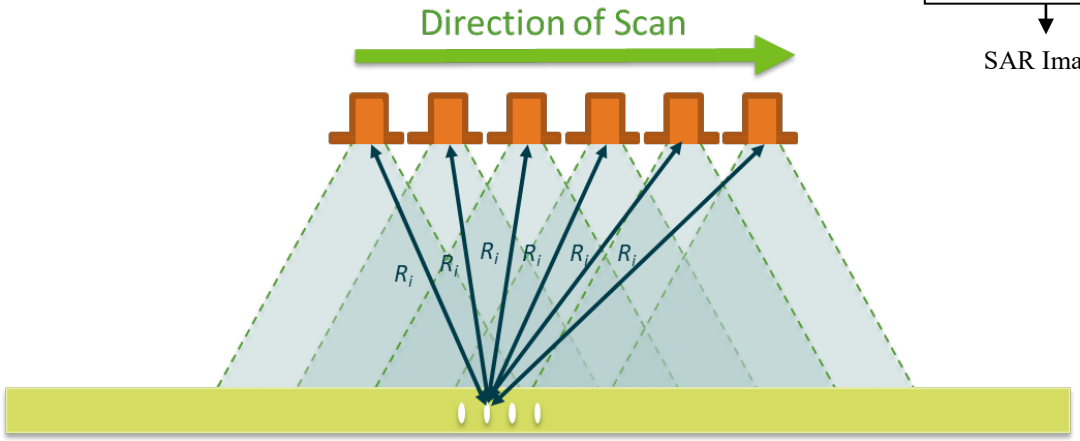
⟹ Higher resolution
3D imaging

[1] https://www.britannica.com/technology/radar
[2] https://www.radartutorial.eu/01.basics/Angular%20Resolution.en.html
[3] https://www.kci.com/resources-insights/innovator/ground-penetrating-radar-as-part-of-sue-and-damage-prevention/

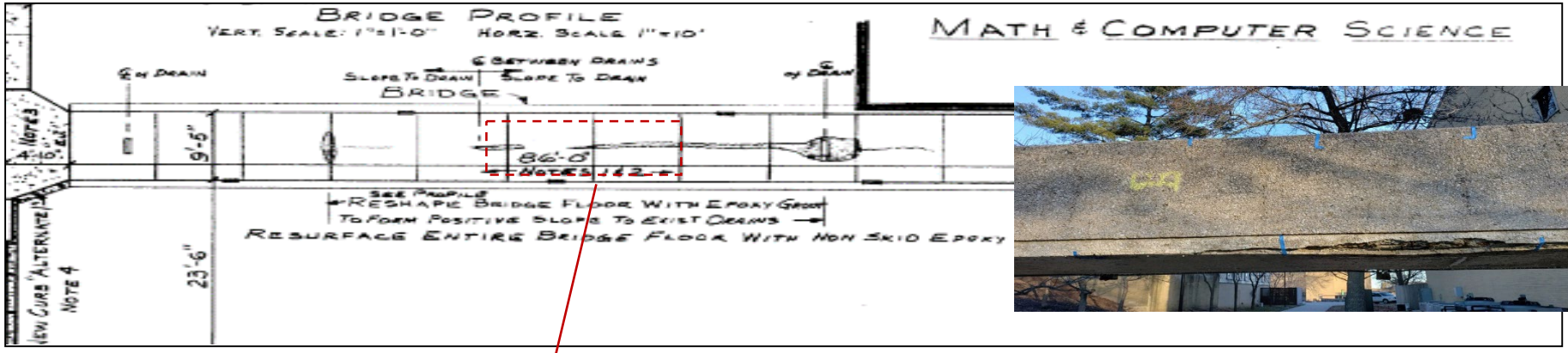
Microwave SAR Imaging

- **Cross-range resolution: [$\frac{\lambda}{4}$, S.A. beam width]**
- **Range resolution: $\frac{v}{2B}$ or better**
- **SAR is FFT based and fast**
- **Large bandwidth is desired.**
- **Coherence over Space/Freq. provides high SNR.**

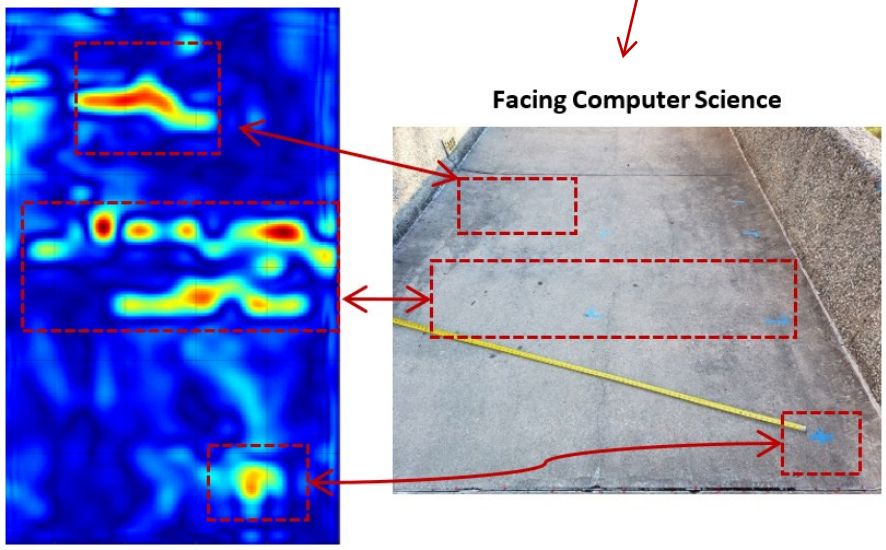


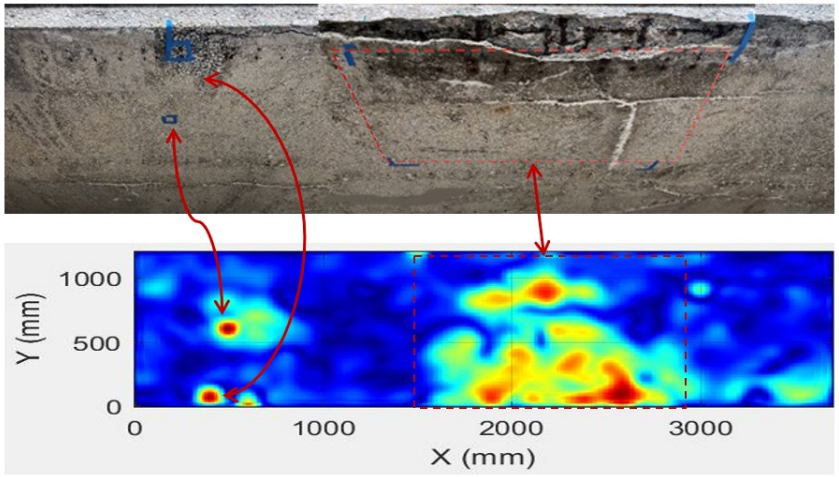


Bridge Inspection[1]



- Synthetic aperture radar (SAR) has been used in bridge delamination detection. High-resolution images have been obtained.

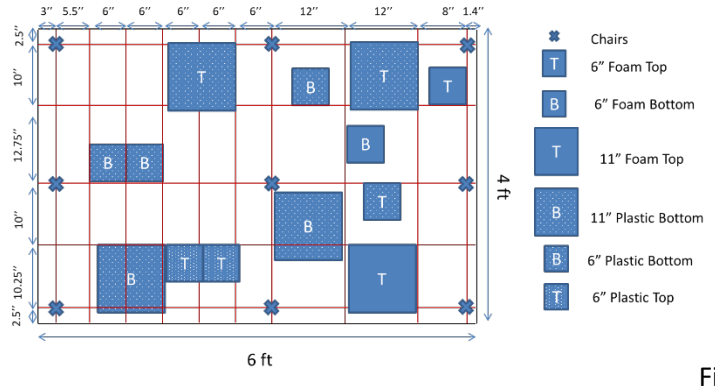




[1] Mohammad Tayeb Ahmad Ghasr, Stephona Barker, Chao Liu, Genda Chen, and Reza Zoughi. " Detection of Delamination and Effect of Rebar Corrosion in a Pedestrian Bridge Deck Using Microwave SAR Imaging Approach" *Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure* (2019: Aug. 4-7, St. Louis, MO) (2019)

Simulated Concrete Delamination

Aim is to confirm the validation of the SAR imaging technique in concrete delamination detection



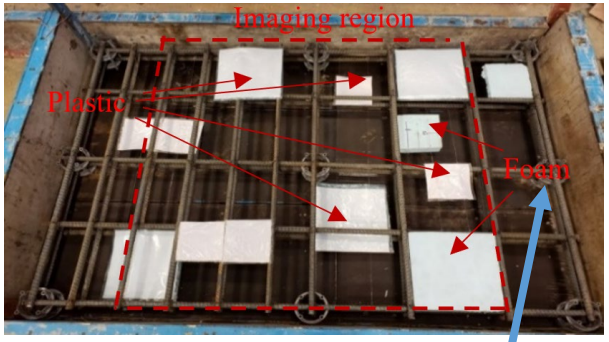
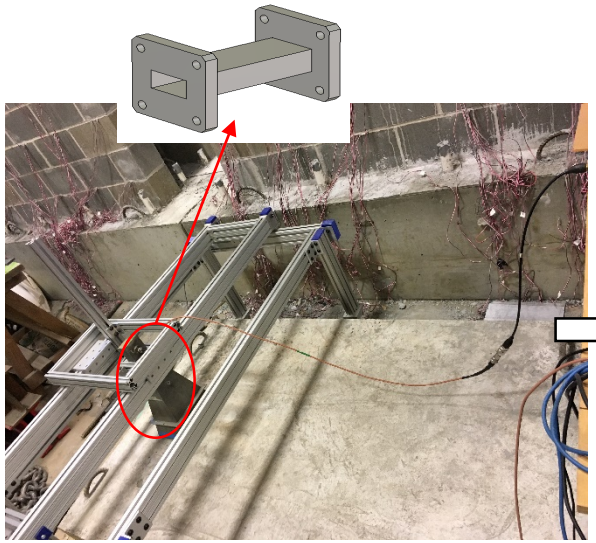
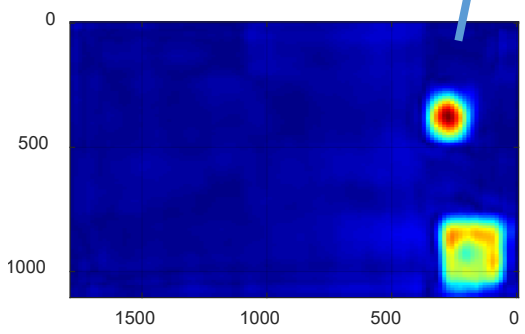


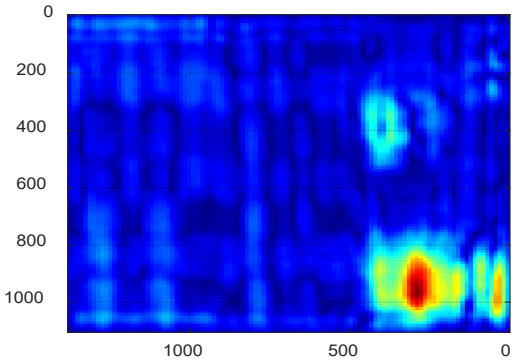
Figure : Concrete with simulated delamination

Imaging



(a) Measurement setup



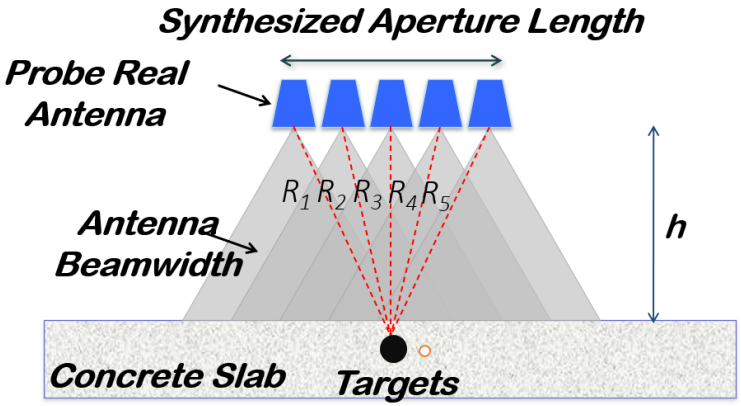


(b) Image produced by S-band waveguide, left: depth around 60 mm, right: depth at 100 mm.

- Frequency range of S-band waveguide: 2.6-3.95 GHz.
- Penetration depth is not enough due to high frequency.

Antennas for NDE SAR

Requirements on the scanning antenna



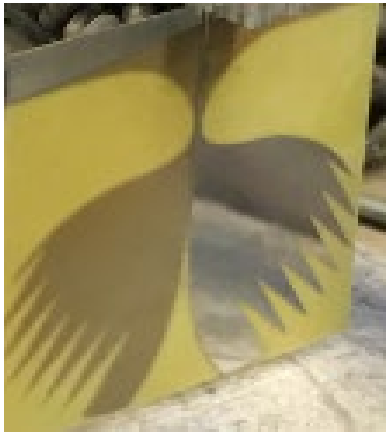
- Cross-range resolution: higher frequency and wide beamwidth
- Range resolution: wide bandwidth
- Penetration depth: lower frequency
- Signal-to-noise ratio: higher gain

⇩

- Scanning antenna: low starting frequency, wide bandwidth, wide beamwidth and high gain.

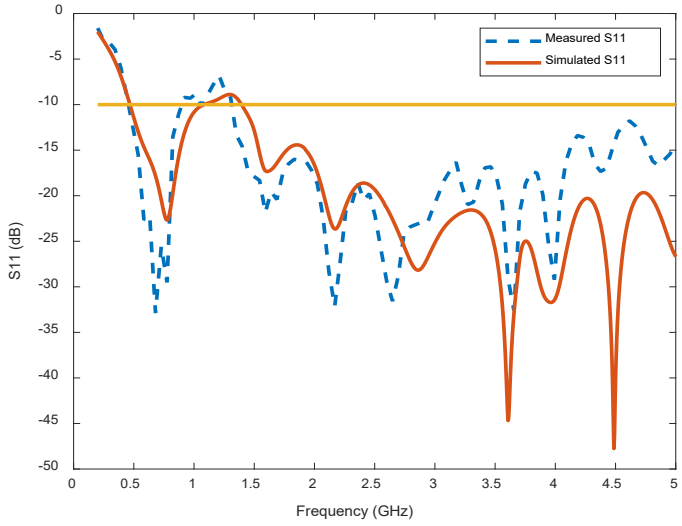
- To get higher resolution, the beamwidth of the antenna used should be increased.

Vivaldi antenna

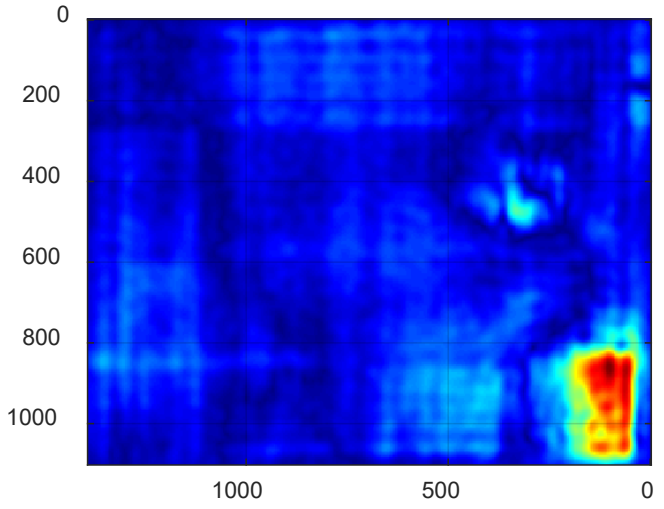


(a) Fabricated antenna

(b) S-parameter measurement setup

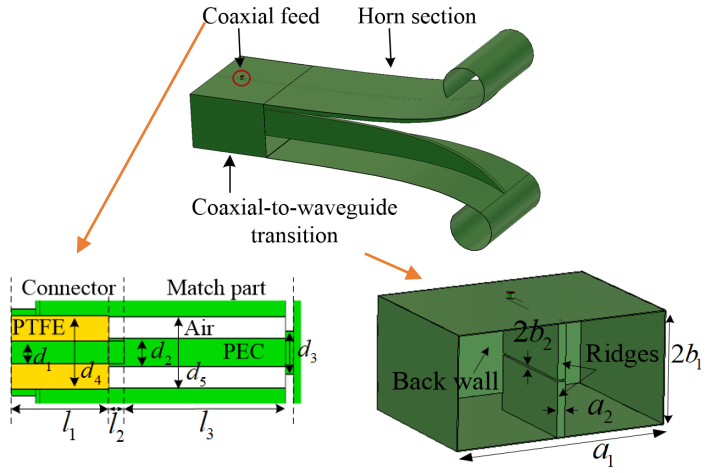


(c) S-parameter simulation and measurement results

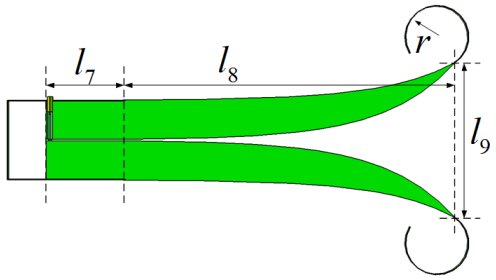


(d) Image from Vivaldi at 100 mm depth

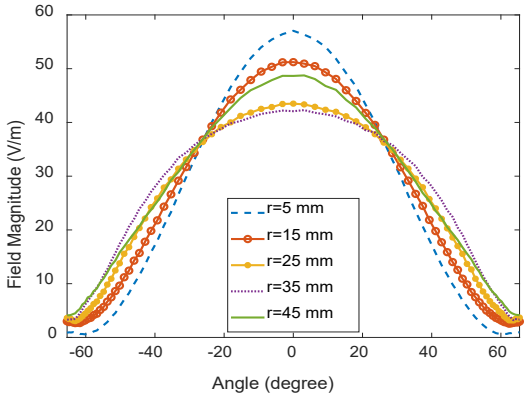
Aperture-matched double-ridged horn antenna[1]



(a) Antenna model

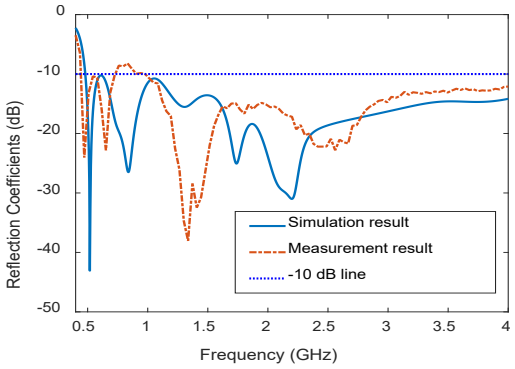


(b) Cross-section view

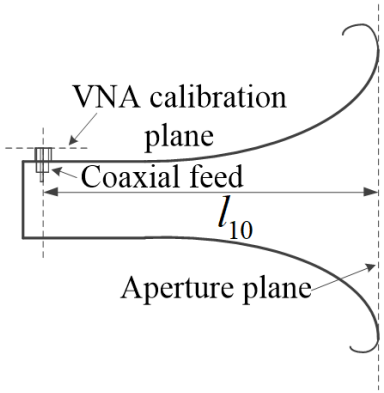


(c) Beamwidth changes at 2GHz

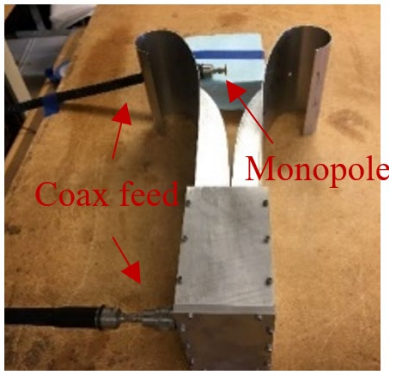
(d) Fabricated antenna



(e) Reflection coefficient



(f) Schematic of calibration

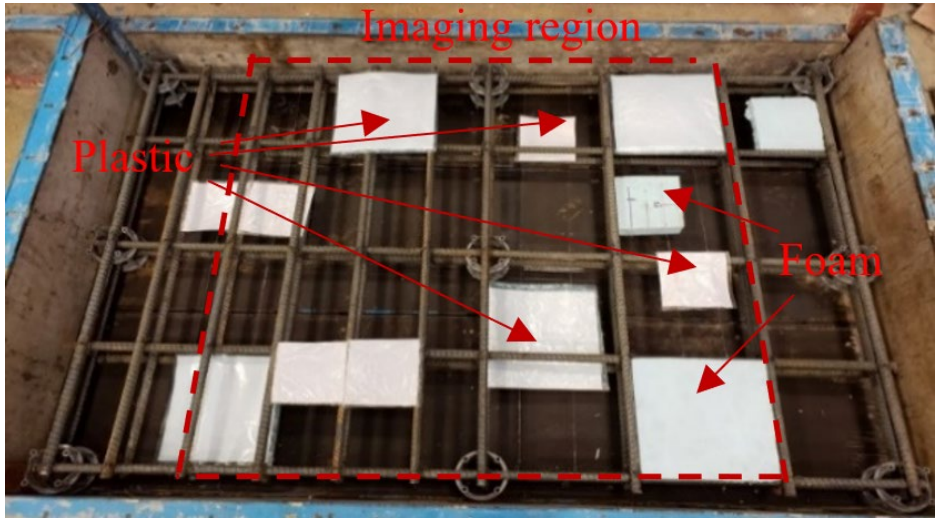


(g) Calibration setup

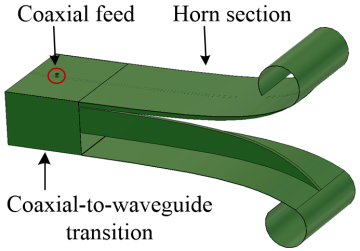
This antenna operates in 0.5~4GHz, and the phase reference is at the antenna aperture by the proposed calibration method.

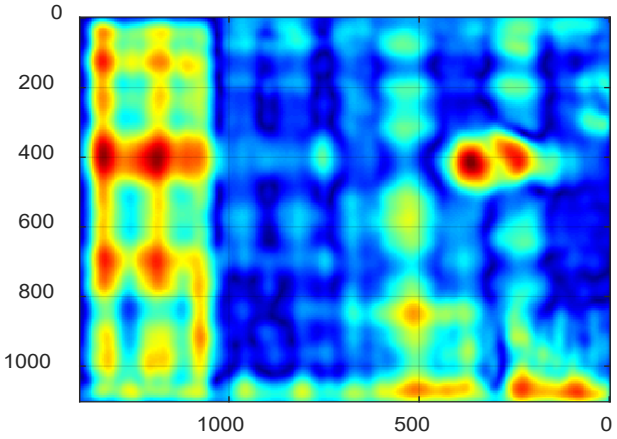
[1] Chao Liu, M.T. Al Qaseer, and Reza Zoughi, "Wideband Double-Ridged TEM Horn for Nondestructive Evaluation and Imaging Applications", *the 42nd Annual Meeting and Symposium of the Antenna Measurement Techniques Association (AMTA)*, July 2020. (Accepted)

Double-Ridged Antenna Imaging Results

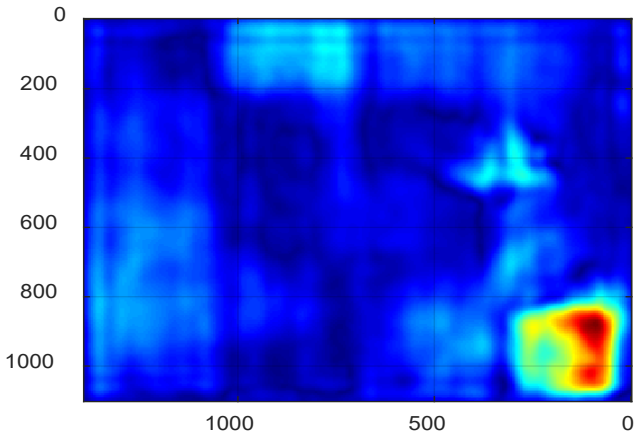


(a) The concrete with simulated delamination





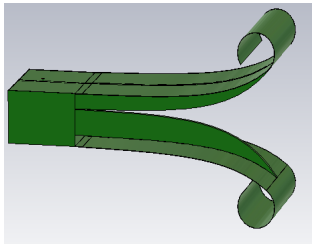
(b) Imaging results before calibration



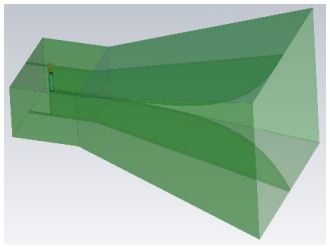
(c) Imaging results after calibration

- The images are produced at a depth around 100 mm using the whole operating frequency range.

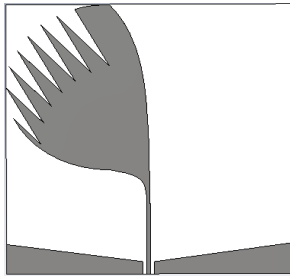
Antennas Comparison



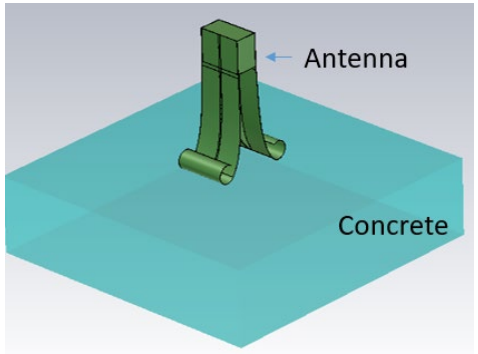
(d) TEM horn (Curved horn)



(e) Pyramidal horn



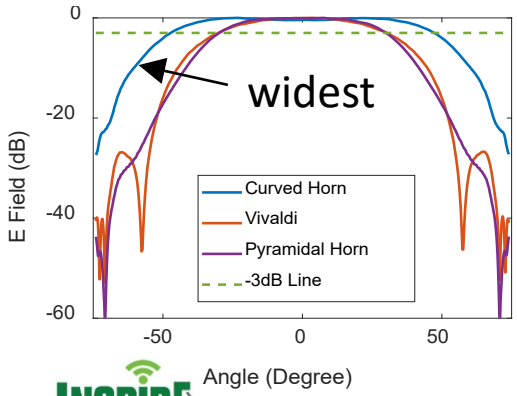
(f) Vivaldi



(h) E-field simulation setup

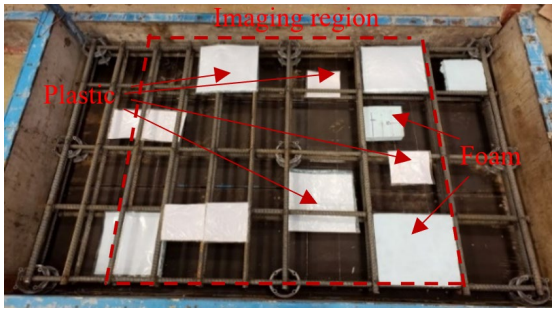
	Frequency	Plane	Curved Horn	Vivaldi	Pyramidal Horn
HPBW (mm)	2.5 GHz	H	95.7	58.6	58.6
		E	55.5	50.7	75.3
	4 GHz	H	84.7	43.9	36.9
		E	49.0	64.5	40.4
Center Magnitude (dB)	2.5 GHz	Center Point	32.2	35.2	35.2
	4 GHz		31.2	31.4	37.6

(g) HPBW and magnitude of the antenna patterns at 2.5 GHz and 4 GHz

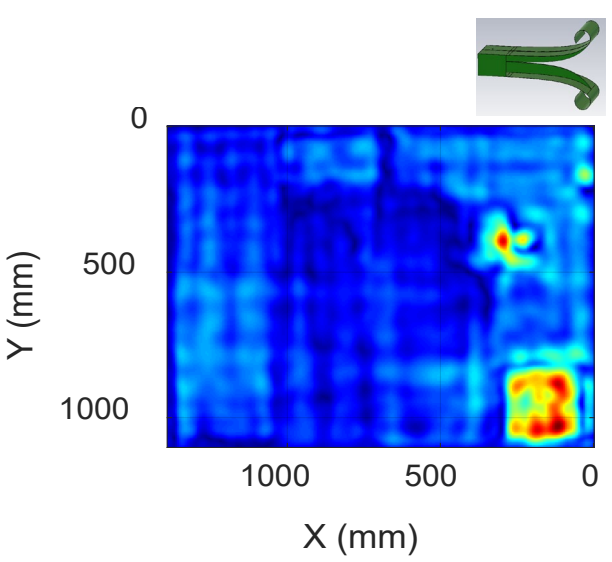


(i) Comparison of E-field patterns

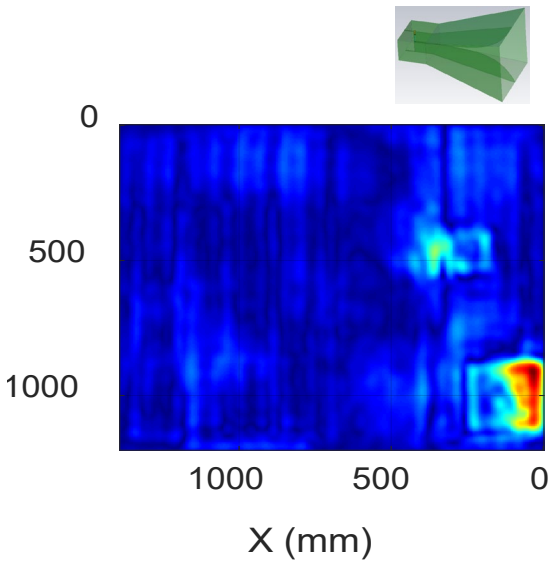
Antennas Comparison - Imaging



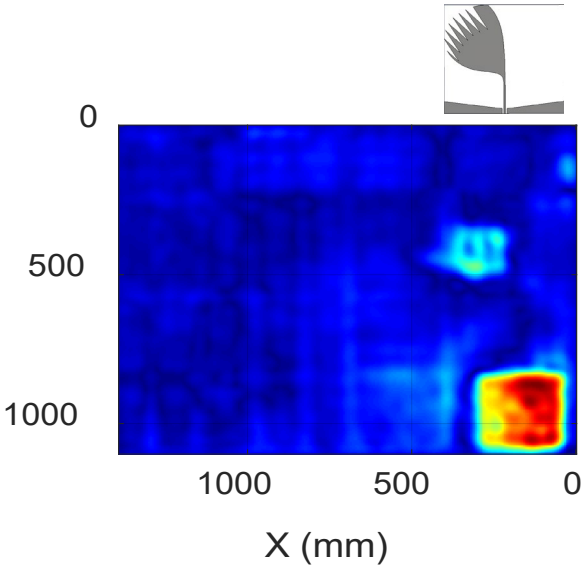
(a) Simulated delamination in concrete



(b) From TEM horn (Curved horn)



(c) From Pyramidal horn



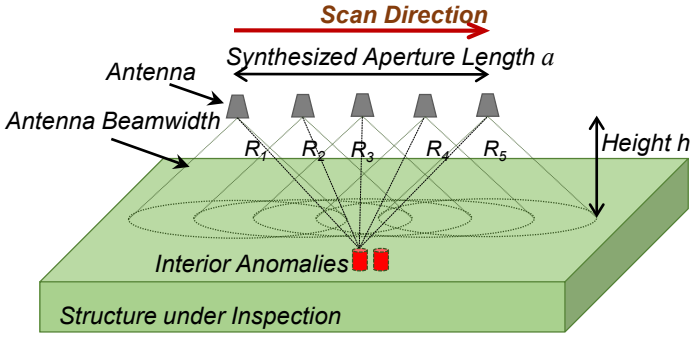
(d) From Vivaldi antenna

- Result produced by TEM horn shows more indications than the other two due to higher resolution, but also noisy.

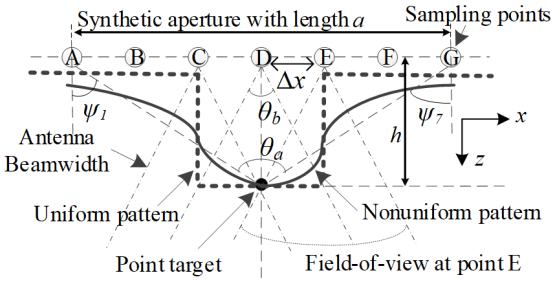
Antenna Pattern Effect to SAR Resolution

»Resolution is a critical parameter in a SAR imaging system for corrosion and concrete delamination detection

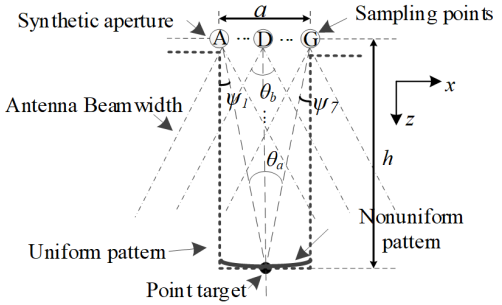
- Cross-resolution analysis



(a) SAR schematic



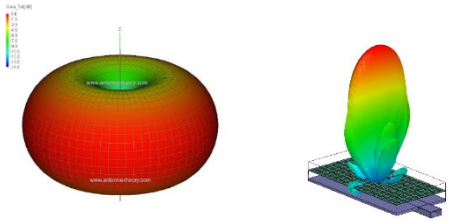
(b) Small *h/a*



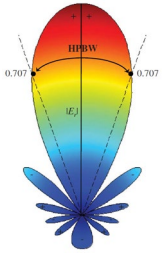
(c) Large *h/a*

- Cross-range resolution δ_x: the ability to identify two objects along the scanning direction;
- Uniform antenna gain pattern assumption, valid for remote sensing cases, is invalid for NDE applications.

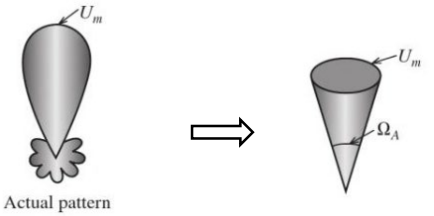
Antenna Patterns



(e) Actual antenna pattern examples[2]



(f) Antenna pattern model[3]



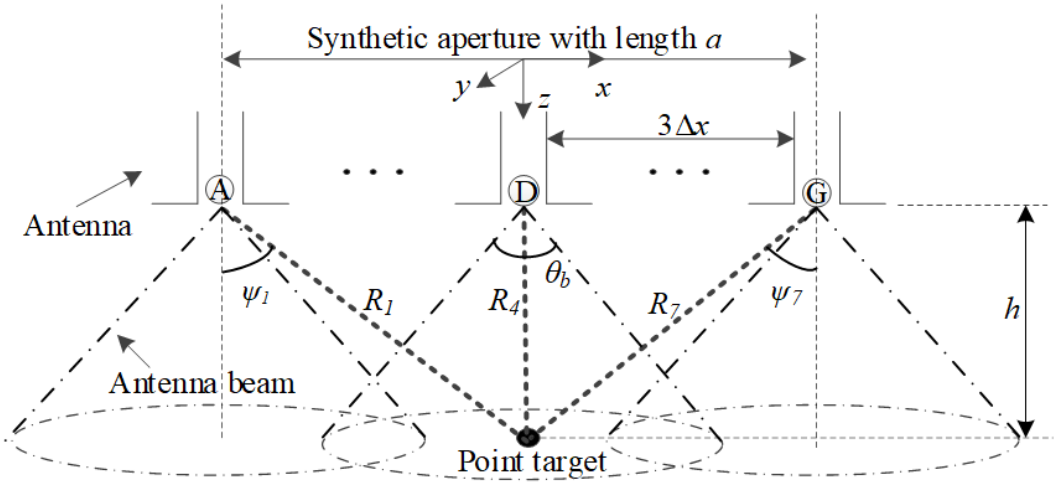
(g) Beam solid angle approximation[3]

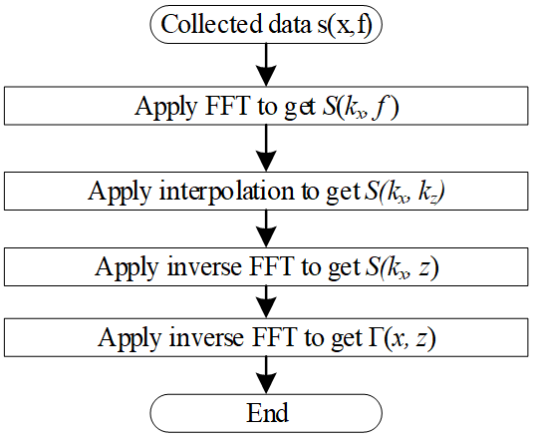
[1] Chao Liu, M.T. Al Qaseer, and Reza Zoughi, "Influence of Antenna Pattern on Synthetic Aperture Radar Resolution for NDE Applications", *IEEE Transactions on Instrumentation and Measurement* (*under review*).

[2] https://directory.eoportal.org/web/eoportal/-/radarsat-constellation

[3] W. L. Stutzman and G. A. Thiele, Antenna Theory and Design, 2nd ed. New York: Wiley, 1998.

Modeling of Antenna Pattern Effect



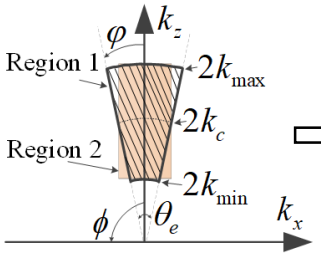


$$s(x_i, f) = \int_{-z_0}^{0} \int_{-a/2}^{a/2} [e(\psi_i)]^2 \frac{\exp(-j2kR_i)}{R_i^2} \Gamma(x, z) dx dz$$

[1] Chao Liu, M.T. Al Qaseer, and Reza Zoughi, "Influence of Antenna Pattern on Synthetic Aperture Radar Resolution for NDE Applications", *IEEE Transactions on Instrumentation and Measurement* (*under review*).

Antenna Pattern Effect to SAR Resolution [1]

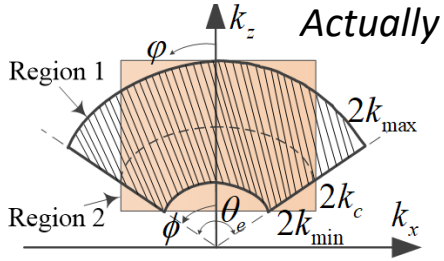
$$S(k_x, k_z) \approx [e(\psi_i)]^2, \; -\frac{\theta_a}{2} \le \psi_i \le \frac{\theta_a}{2}$$



(a) SAR spatial spectrum distribution in a narrow-angle case

Uniform distribution assumption[2]

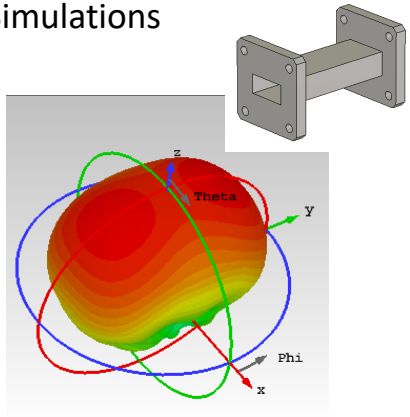
$$S(k_x, k_z) = \begin{cases} 1, & -k_{x,max} \le k_x \le k_{x,max} \\ & k_{z,min} \le k_z \le k_{z,max} \\ 0, & else\ where \end{cases}$$



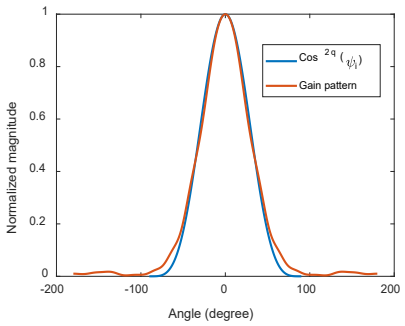
Actually nonuniform

(b) SAR spatial spectrum distribution in a wide-angle case

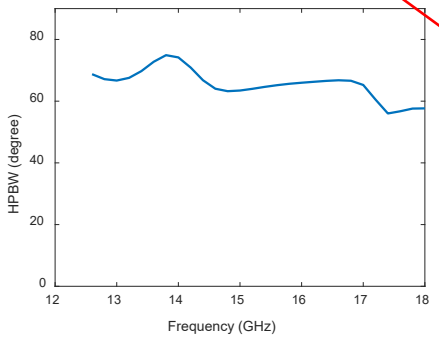
- Simulations



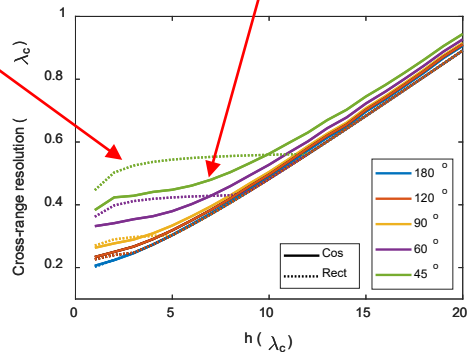
(c) Waveguide E-pattern at Ku band



(d) Antenna gain pattern approximation



(e) HPBW of the antenna vs. frequency



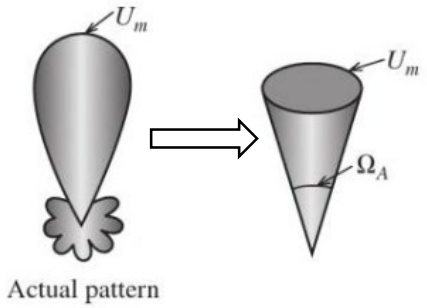
(f) Cross-range resolution results

- The average value of the HPBW of the Ku-band waveguide along the H plane is about 65.6, so q in (b) is 2.

[1] Chao Liu, M.T. Al Qaseer, and Reza Zoughi, "Influence of Antenna Pattern on Synthetic Aperture Radar Resolution for NDE Applications", *IEEE Transactions on Instrumentation and Measurement* (*Under Review*).

[2] V. T. Vu, T. K. Sjögren, M. I. Pettersson, and H. Hellsten, "An impulse response function for evaluation of UWB SAR imaging," *IEEE Trans. Signal Process.*, vol. 58, no. 7, pp. 3927–3932, Jul. 2010.

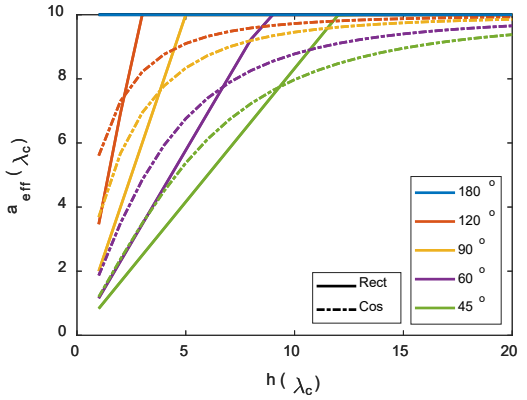
SAR Effective Aperture[1]



Antenna pattern: $e(\theta_i)=\cos^q(\theta_i)$

$$E_{cos} = 0.5 \cdot \sum_{i=1}^{M}[cos^q(\theta_i) + cos^{2q}(\theta_i)]$$

$$a_{eff,cos} = (E_{cos} - 1)\Delta x$$



(a) Previously mentioned antenna beam solid angle

(b) Formulas

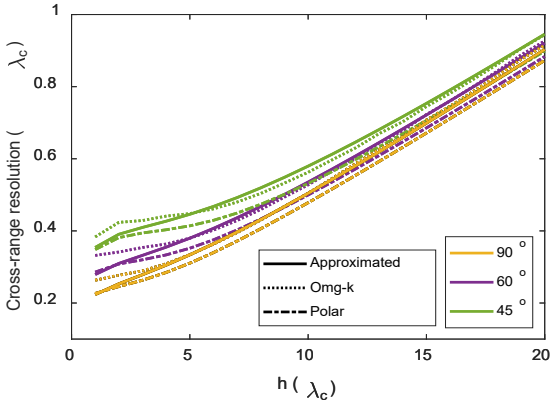
(c) Effective aperture length

- Effective aperture length is proportional to the effective integration angle which can be seen as aperture's beam solid angle.

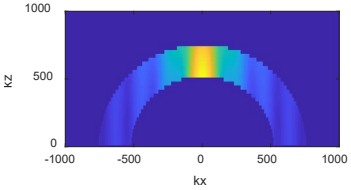
$$\theta_{eff} = 2 \cdot atan(\frac{a_{eff}}{2h})$$

$$\delta_{xo} = \frac{0.2211\lambda_c}{\sin(\frac{\theta_e}{2})}$$

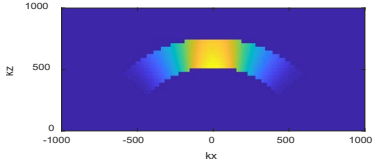
$$\delta_{xc} = \frac{2h\delta_{xo}}{2h+\delta_{xo}}$$



Using *rect* pattern



Using *cos* pattern



(d) Formulas

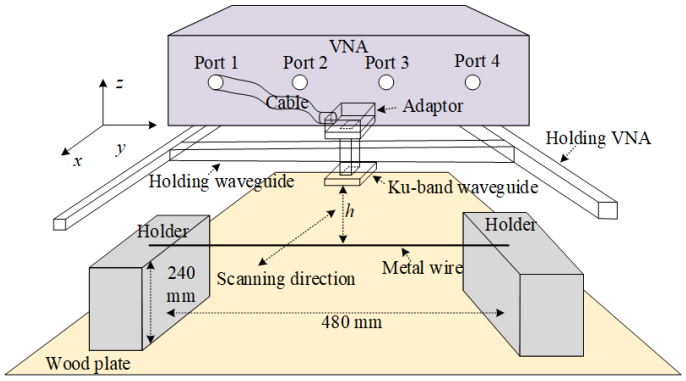
(e) Approximation results

(f) Spectrum of a point target with HPBW=45° and $h = 2\lambda_c$

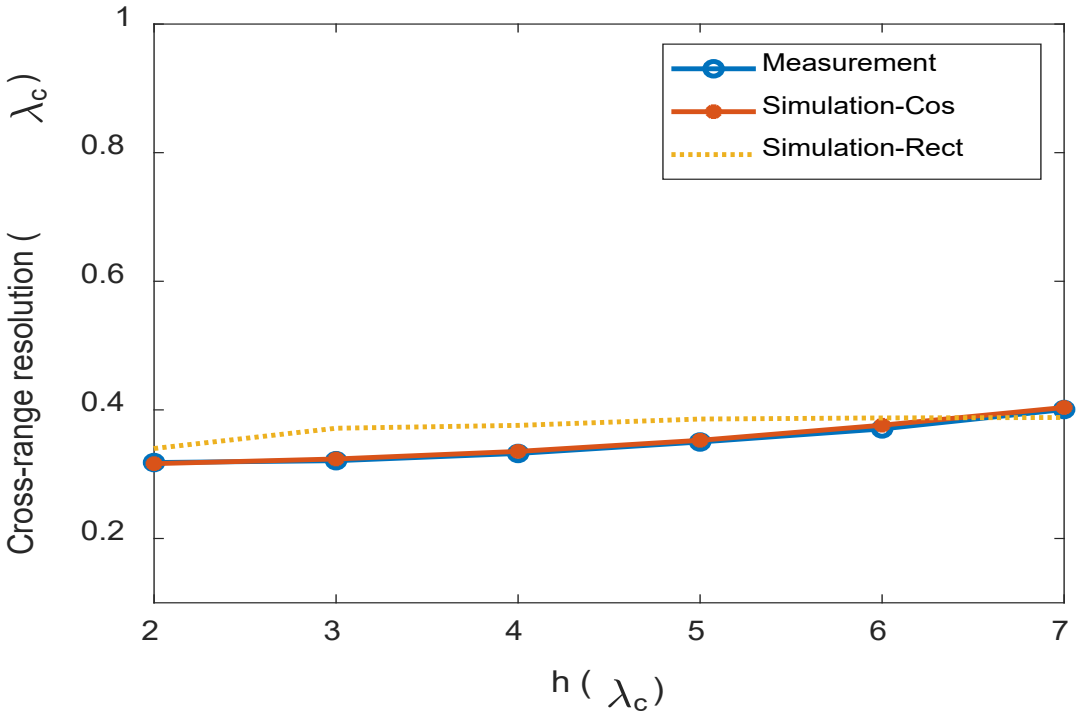
- Result in (c) labelled as polar is more accurate than Omg-k result at near-aperture depths.

[1] Chao Liu, M.T. Al Qaseer, and Reza Zoughi, "Influence of Antenna Pattern on Synthetic Aperture Radar Resolution for NDE Applications", *IEEE Transactions on Instrumentation and Measurement* (*Under Review*).

Measurement – Simulation Verification



Measurement setup schematic

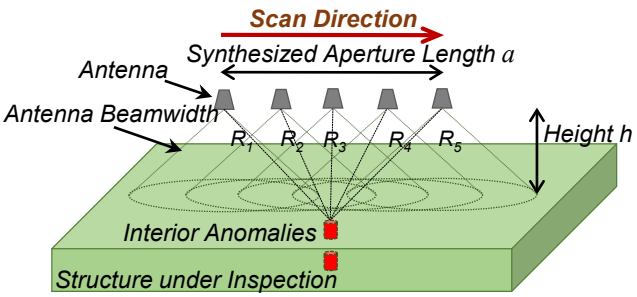


- 14.8~16.8 GHz is used here due to the relatively constant HPBW of the ku-band waveguide in its H plane.
- Using *cos* function to approximate antenna E-field pattern, and cross-range resolution simulation matches measured result.

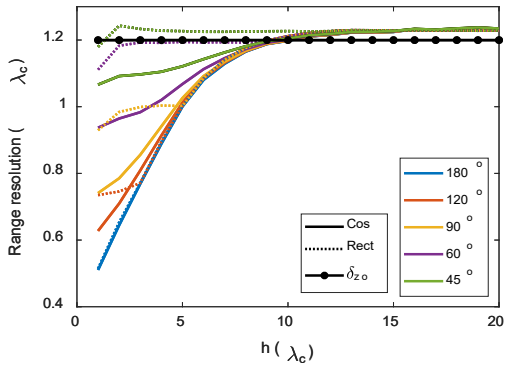
[1] C. Liu, M.T. Al Qaseer, and Reza Zoughi, "Influence of Antenna Pattern on Synthetic Aperture Radar Resolution for NDE Applications", *IEEE Transactions on Instrumentation and Measurement* (*Under Review*).

Antenna Pattern Effect to SAR Resolution[1]

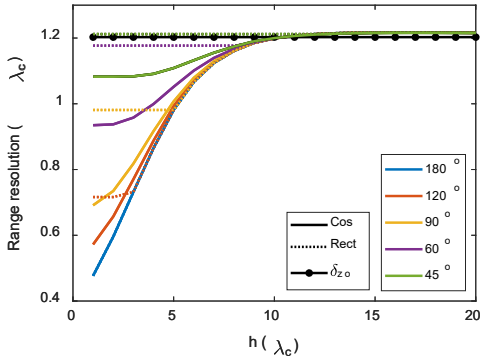
Range resolution



(a) SAR schematic with two objects in range direction



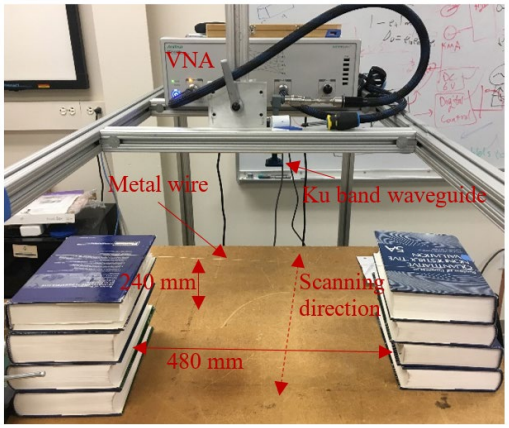
(b) Simulation results using omg-k SAR algorithm



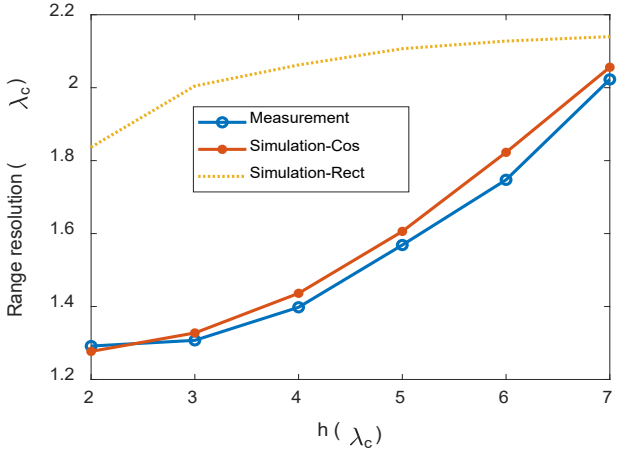
(c) Simulation results using polar-format integral

- Range resolution δ_z: the ability to identify two objects along the range direction.

- Measurement



(d) Measurement setup

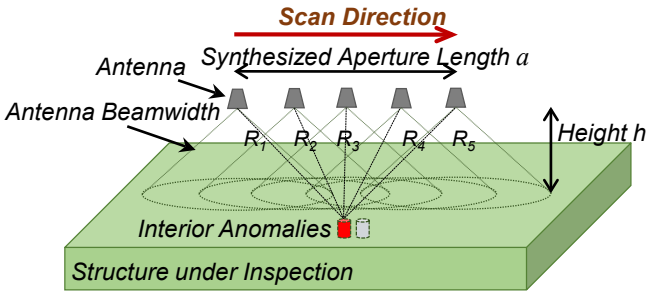


(e) Measurement results of range resolution

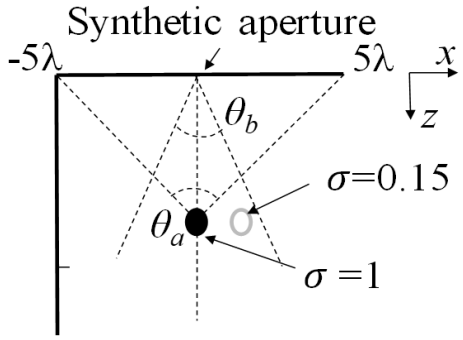
[1] C. Liu, M.T. Al Qaseer, and Reza Zoughi, "Influence of Antenna Pattern on Synthetic Aperture Radar Resolution for NDE Applications", *IEEE Transactions on Instrumentation and Measurement* (*under review*).

Antenna Pattern Effect to SAR Sidelobe Level[1]

- Influence of SAR sidelobe to signal-to-noise ratio (SNR)

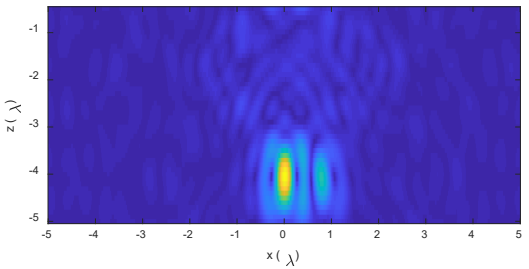


(a) SAR schematic with two targets



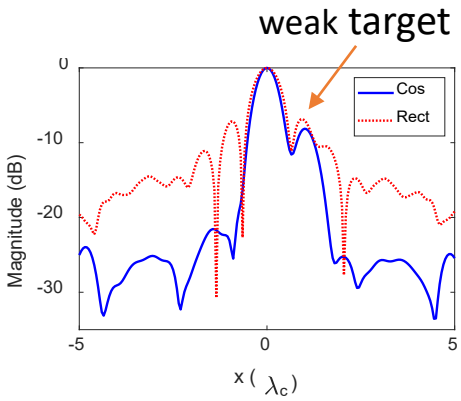
(b) SAR imaging scene

Depth =4λ in air, distance =0.8 λ



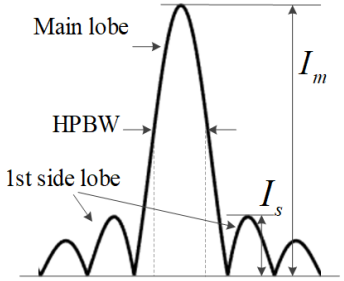
(c) Produced SAR image

- SAR sidelobe level plays a significant role in sensing weak-scattering objects nearby a strong one.



(d) Signals along cross-range direction

$$PSLR = 20\,log_{10}\left(\frac{I_s}{I_m}\right)$$



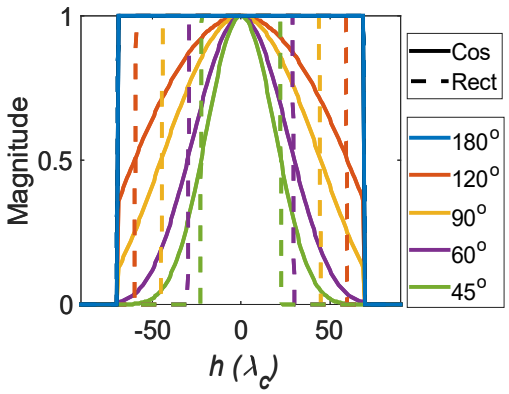
(e) Shape of SAR Impulse pulse response function

- SAR sidelobe level is traditionally assumed that of a *sinc* function.

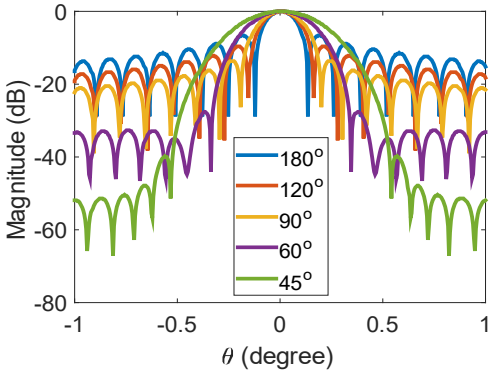
[1] Chao Liu, M.T. Al Qaseer, and Reza Zoughi, "Antenna Pattern Effect to Synthetic Aperture Radar Imaging system side lobe level for NDE Applications", *IEEE Transactions on Instrumentation and Measurement*, 2020. (*to be submitted*)

Antenna Pattern Effect to SAR Sidelobe Level[1]

- Weighting effect

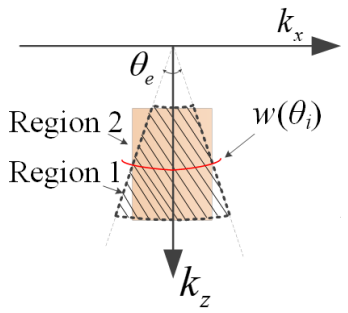


(a) antenna patterns



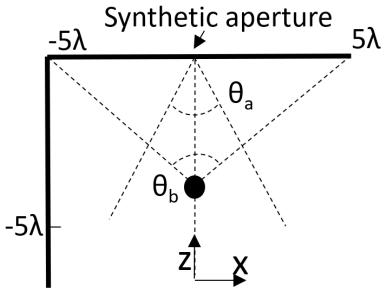
(b) IFFT over antenna patterns

$$w(\theta_i) \approx [cos^q(\theta_i)]^2,\ -\frac{\theta_a}{2} \le \theta_i \le \frac{\theta_a}{2}$$

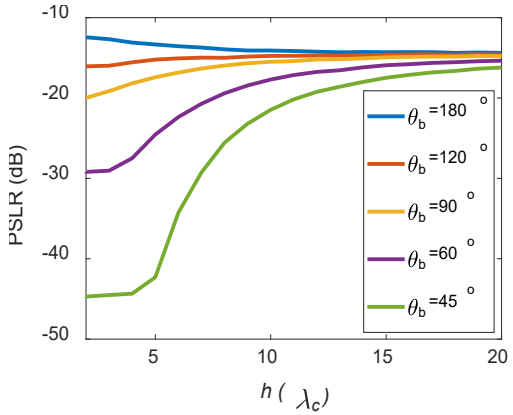


(c) Spectrum weighted by antenna gain pattern

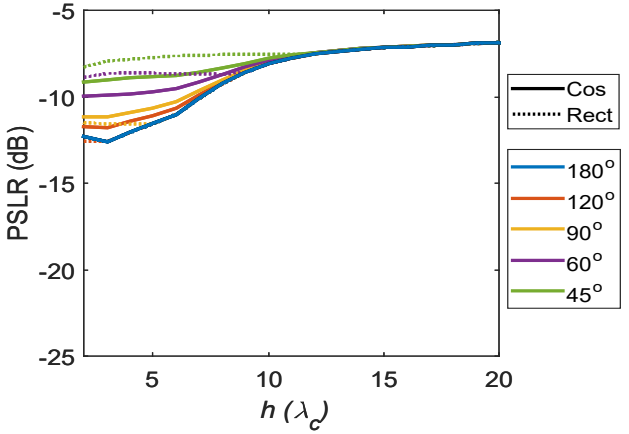
- Influence of antenna pattern to SAR sidelobe along cross-range direction is like a weighting function.



(d) SAR imaging scene



(e) Cross-range PSLR simulation results

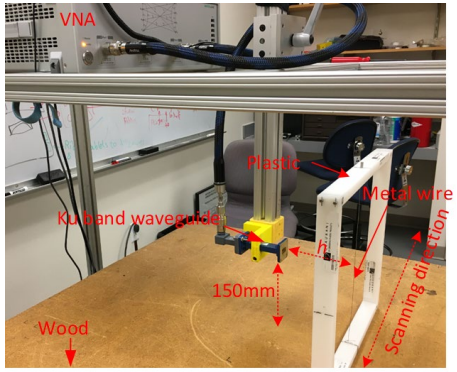


(f) Range PSLR simulation results

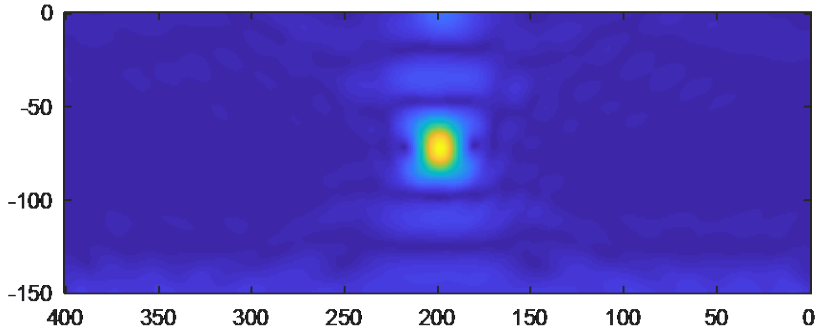
[1] Chao Liu, M.T. Al Qaseer, and Reza Zoughi, "Antenna Pattern Effect to Synthetic Aperture Radar Imaging system side lobe level for NDE Applications", *IEEE Transactions on Instrumentation and Measurement*, 2020. (*to be submitted*)

Antenna Pattern Effect to SAR Sidelobe Level[1]

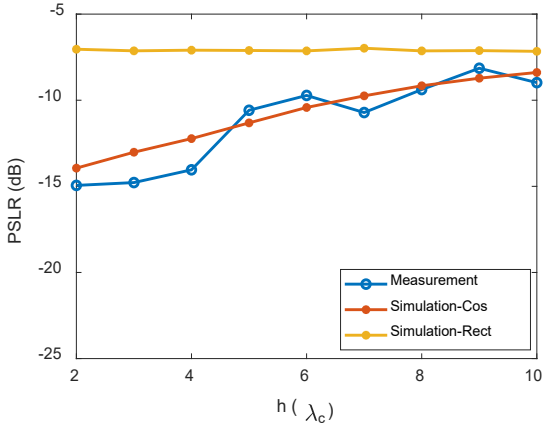
Measurements



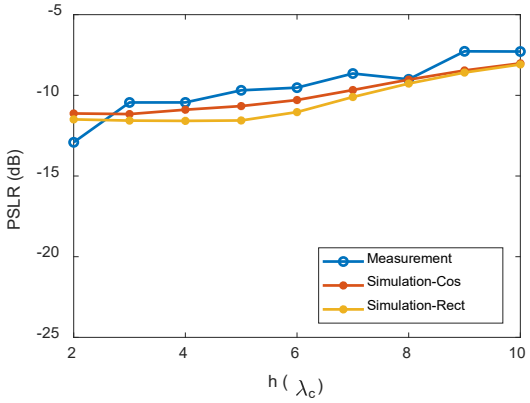
(a) SAR imaging scene



(b) Measured SAR image at $4\lambda_c$ depth



(c) Measured PSLR along cross-range direction



(d) Measured PSLR along range direction

- Measurement results match the simulation results, verifying the correctness of the proposed theory.
- PSLR along the range direction is also given. It is not strongly affected by the antenna gain pattern.

[1] Chao Liu, M.T. Al Qaseer, and Reza Zoughi, "Antenna Pattern Effect to Synthetic Aperture Radar Imaging system side lobe level for NDE Applications", *IEEE Transactions on Instrumentation and Measurement*, 2020. (*to be submitted*)

Publications

[1] Chao Liu, Stephona Barker, Liang Fan, Mohammad Tayeb Ghasr, Genda Chen, and Reza Zoughi. "Microwave High-Resolution 3D SAR Imaging of Corroded Reinforcing Steel Bars in Mortar Subjected to Accelerated Electrochemical Corrosion" *Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure* (2019: Aug. 4-7, St. Louis, MO) (2019)

[2] Mohammad Tayeb Ghasr, Stephona Barker, Chao Liu, Genda Chen, and Reza Zoughi. "Detection of Delamination and Effect of Rebar Corrosion in a Pedestrian Bridge Deck Using Microwave SAR Imaging Approach" Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (2019: Aug. 4-7, St. Louis, MO) (2019)

[3] Chao Liu, M.T. Al Qaseer, and Reza Zoughi, "Wideband Double-Ridged TEM Horn for Nondestructive Evaluation and Imaging Applications", *the 42nd Annual Meeting and Symposium of the Antenna Measurement Techniques Association (AMTA)*, July 2020. (Accepted)

[4] Chao Liu, M.T. Al Qaseer, and Reza Zoughi, "Influence of Antenna Pattern on Synthetic Aperture Radar Resolution for NDE Applications", *IEEE Transactions on Instrumentation and Measurement* (*Under Review*).

[5] Chao Liu, M.T. Al Qaseer, and Reza Zoughi, "Antenna Pattern Effect to Synthetic Aperture Radar Imaging system side lobe level for NDE Applications", *IEEE Transactions on Instrumentation and Measurement*, 2020. (*to be submitted*)

Thank you