Channel Leakage Cancellation for Software Defined Radio (SDR) Narrowband Radar Interferometry Using GNU Radio

Victor Cai and Jon Kraft

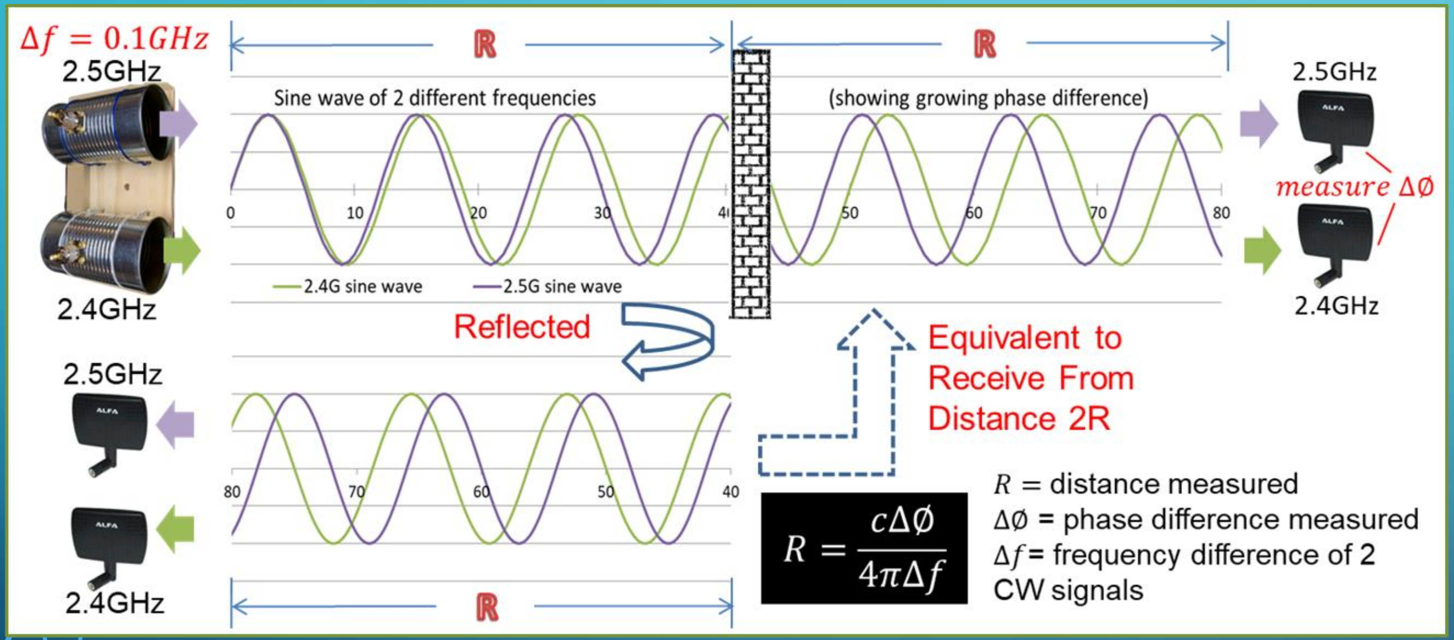
Analog Devices Inc., Longmont, CO, USA

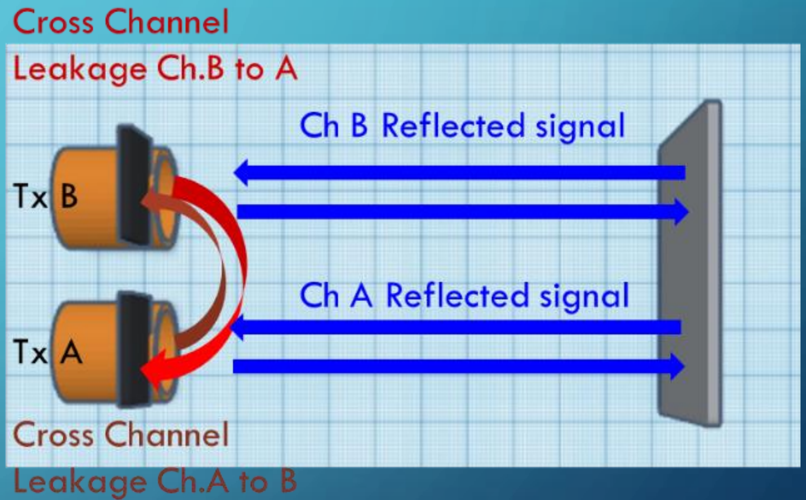
ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

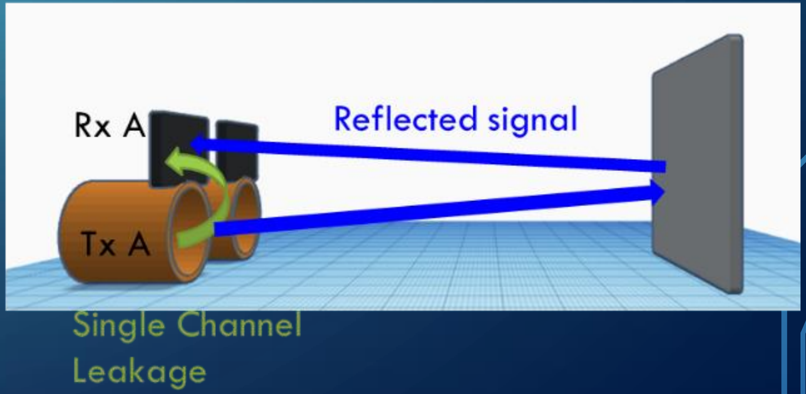
GRCon21
CHARLOTTE, NC

BACKGROUND & PROBLEM STATEMENT

- Traditional distance sensing Pulse and FMCW radars require ultra-wide bandwidth
- Emerging SDR technology with limited bandwidth (not feasible for distance radar)
- MFCW - Two channel narrowband interferometry radar technology using SDR was introduced in GRC2020
- Distance sensing accuracy limited by leakage from transmitter to receiver integrated in the same SDR module
- Major improvement in distance sensing accuracy by introducing software-based leakage cancellation







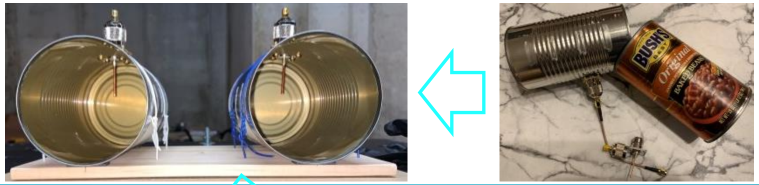
- MFCW radar: two different frequencies of CW waves with slightly-different wavelengths
- For a specific distance, the phase difference between the two frequencies is used to determine the distance of the object.

BUILDING RADAR AND TEST SYSTEM

- Two SDRs and 4 antennas used for a 2 channel MFCW radar
- Doppler radar tap off signal from 1 channel sharing the hardware

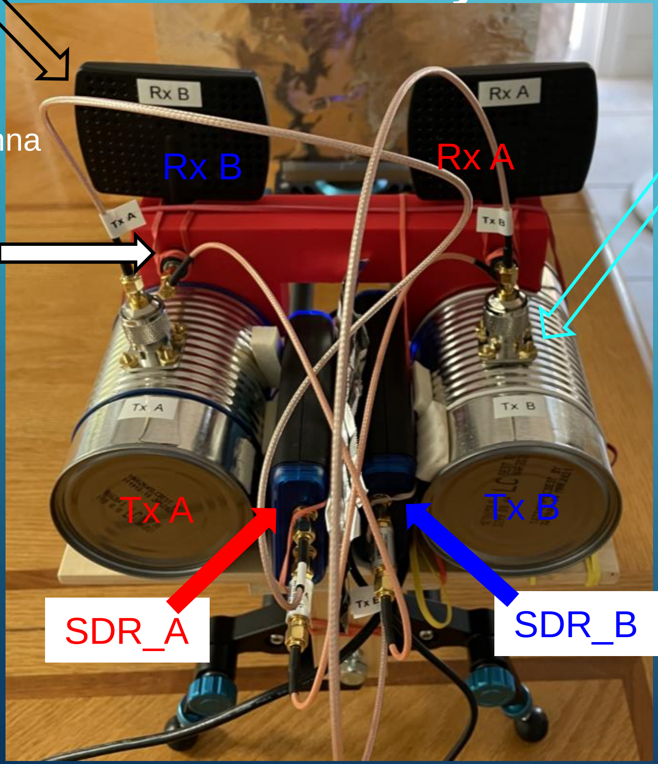
Two 2.4GHz WiFi Panel Swivel Antennas

2 Antenna made from tin cans and connectors

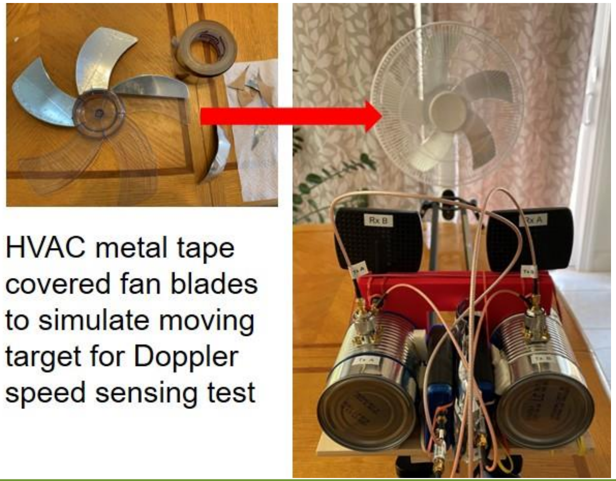


3D Printed Antenna Mounting Bridge

Radar Assembly



Doppler Speed Sensing Test Setup



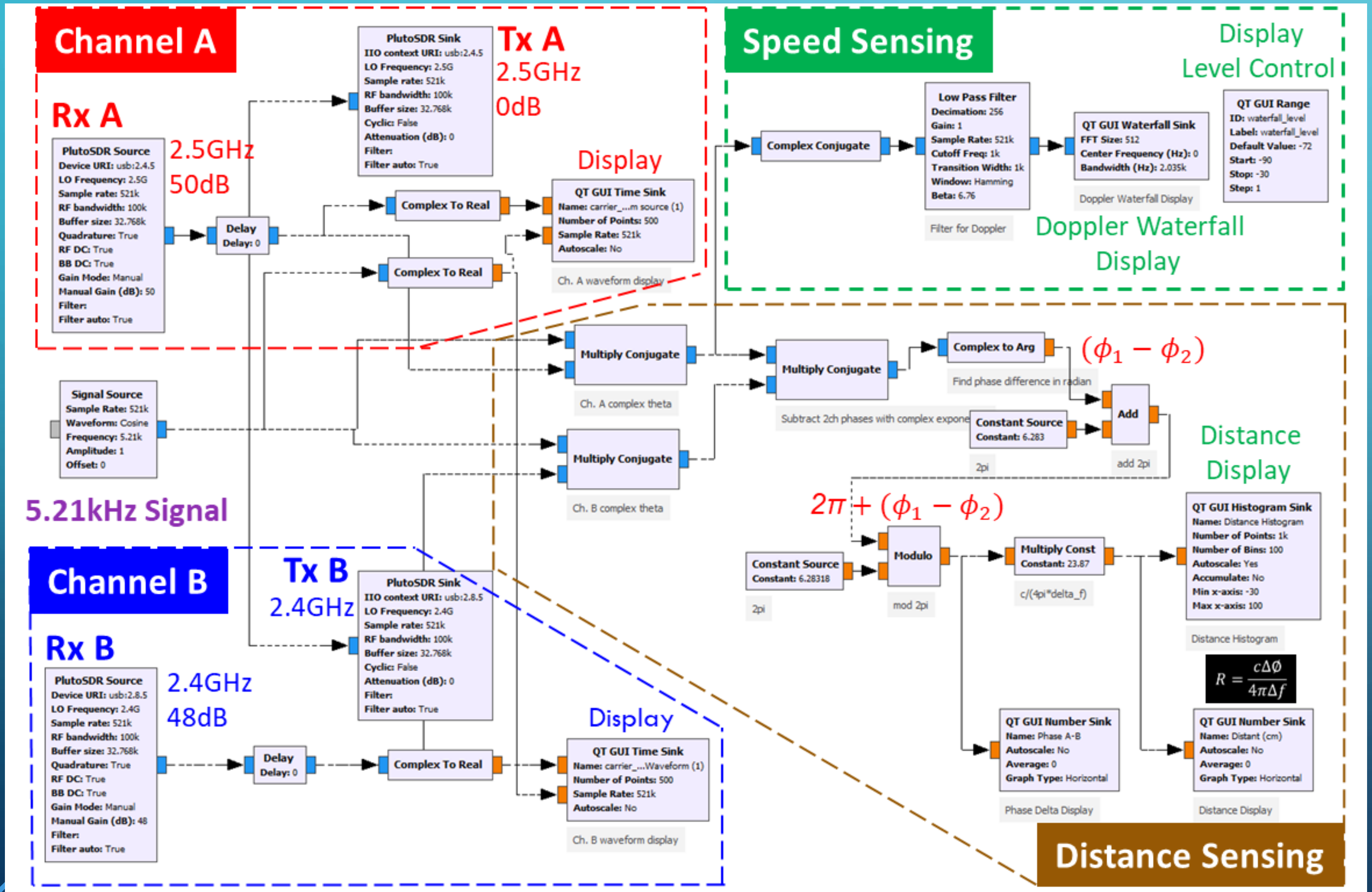
HVAC metal tape covered fan blades to simulate moving target for Doppler speed sensing test

Radar and Distance Sensing Test Track

Sliding target made with aluminum foil wrapped cardboard for distance sensing test

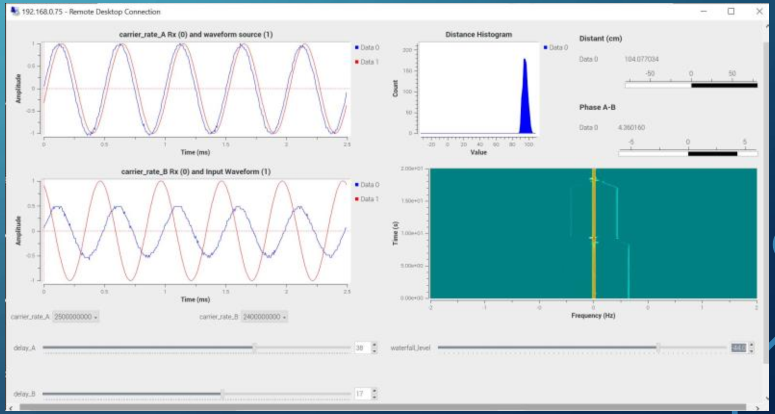
BASIC MFCW RADAR SOFTWARE FRAMEWORK

- Radar algorithm developed with GNU Radio flowchart-based software
- Two channels transmit and receive (2.5 and 2.4GHz), phase deltas used for distance sensing
- Speed sensing is implemented through a low pass filter and FFT spectrum analysis block



Visualize 2 channels
Waveforms & phases

Distance sensing
histogram and numbers



Initial phase
delay calibration

Doppler speed sensing shift
frequency "Waterfall"

PROBLEM WITH DIRECT PHASE SUBTRACTION ALGORITHM

- Radar accuracy is tested by moving target in 1cm increments
- Originally used direct linear phase subtraction
- Erroneous results showing negative distance as a result of direct linear subtraction of two phases measured from two radar channels
- Need to develop a more sophisticated algorithm to correct erroneous output

Issue with the direct subtract algorithm:

ϕ_1 *domain* ⇨ $[-\pi, 0)$ | $[0, \pi]$

ϕ_2 *domain* ⇨ $[-\pi, 0)$ | $[0, \pi]$

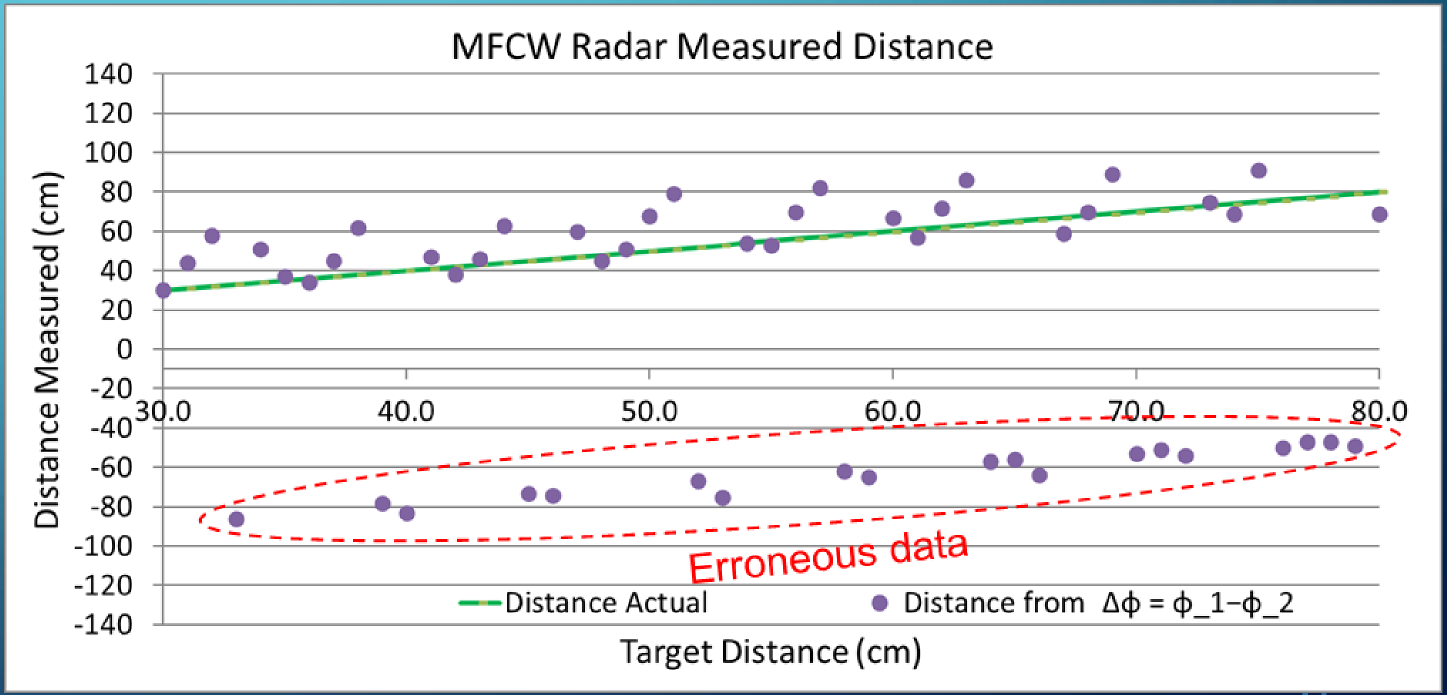
$\phi_1 - \phi_2$: $[-2\pi, 0)$ | $[0, 2\pi]$

$$R = \frac{c\Delta\varnothing}{4\pi\Delta f}$$

-2π $-\pi$ 0 π 2π

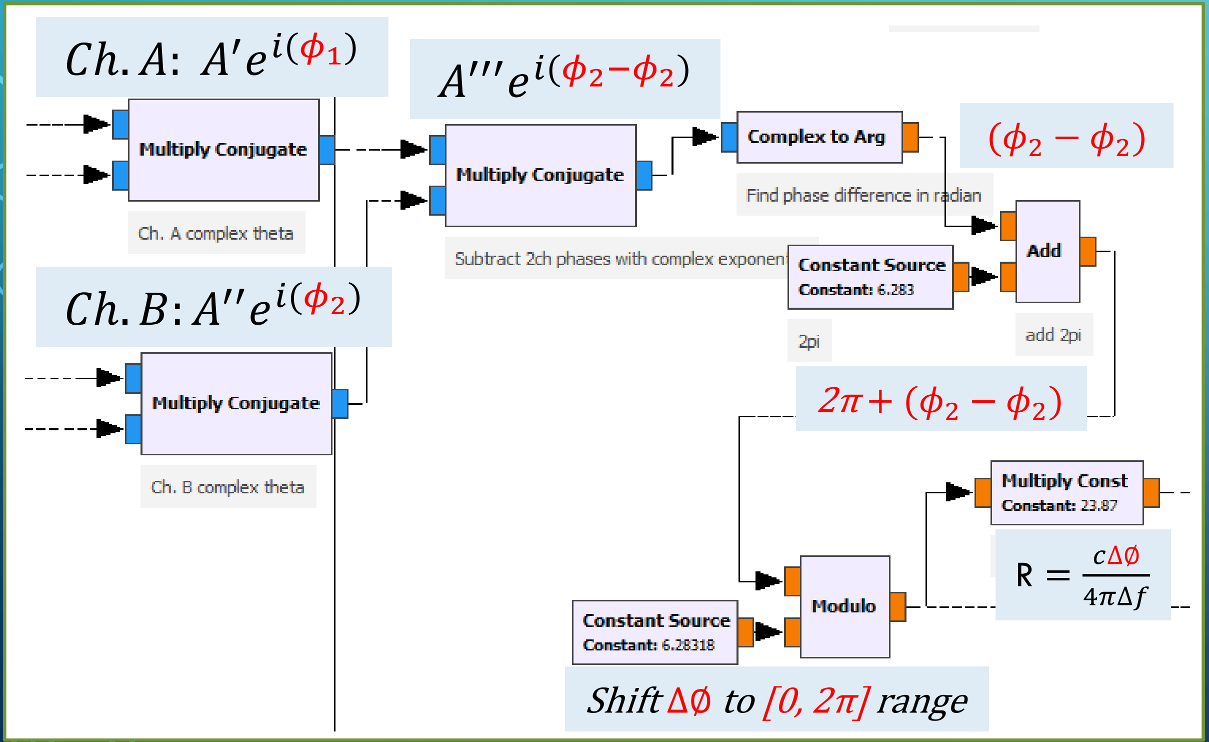
-150cm   -75cm   0cm   75cm   150cm

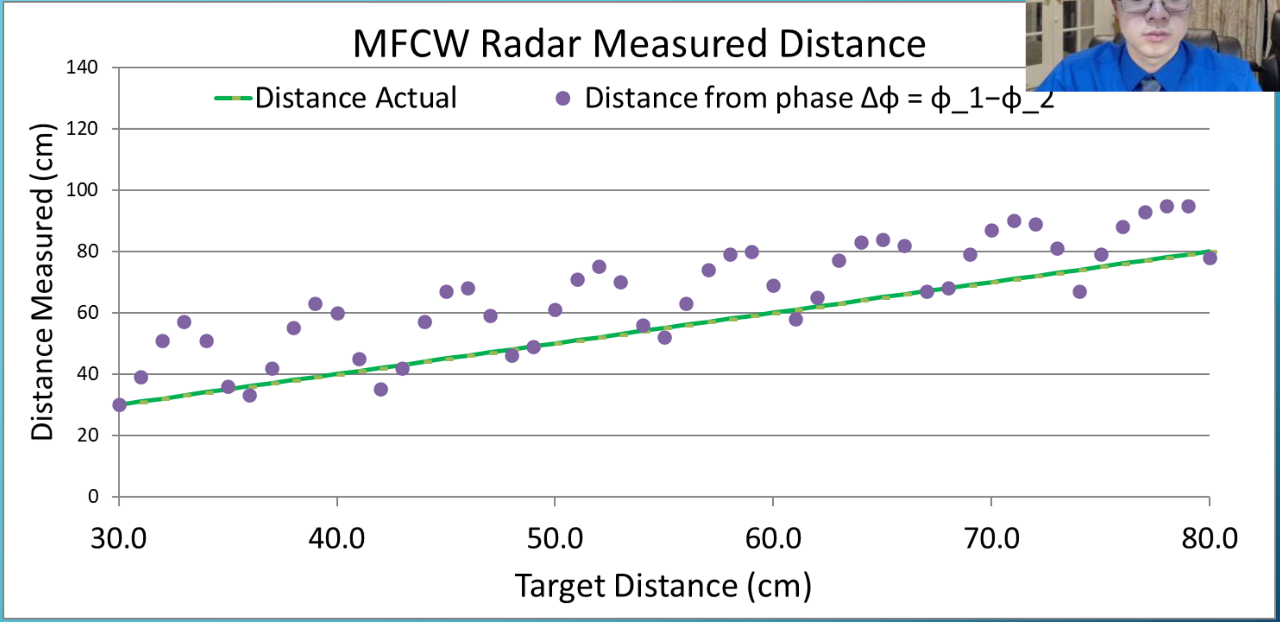
Erroneous data | *Correct data*



MFCW RADAR DISTANCE TEST (BEFORE LEAKAGE COMPENSATION)

- Dual SDR MFCW radar achieved distance measurement accuracy of 25cm
- Using complex "Multiply Conjugate" instead of linear subtraction: $e^{i(\phi_1)} * e^{i(-\phi_2)} = e^{i(\phi_2-\phi_2)}$
- Created an algorithm without erroneous negative distance: ***Modulo [(2π*** $+ (\phi_2 - \phi_2)), 2\pi$***]***
- Measured distance showed periodic oscillation





Algorithm developed without erroneous output:

$\Delta\emptyset$ *from* $e^{i(\phi_2-\phi_2)}$ ⇨	[-π, 0)	[0, π]
Transpose: $\Delta\emptyset = \Delta\emptyset + 2\pi$ ⇨	[-π, 0)	[0, π]
Modulo shift value $> 2\pi$ *down by* 2π ⇨	[0, π]	[-π, 0)

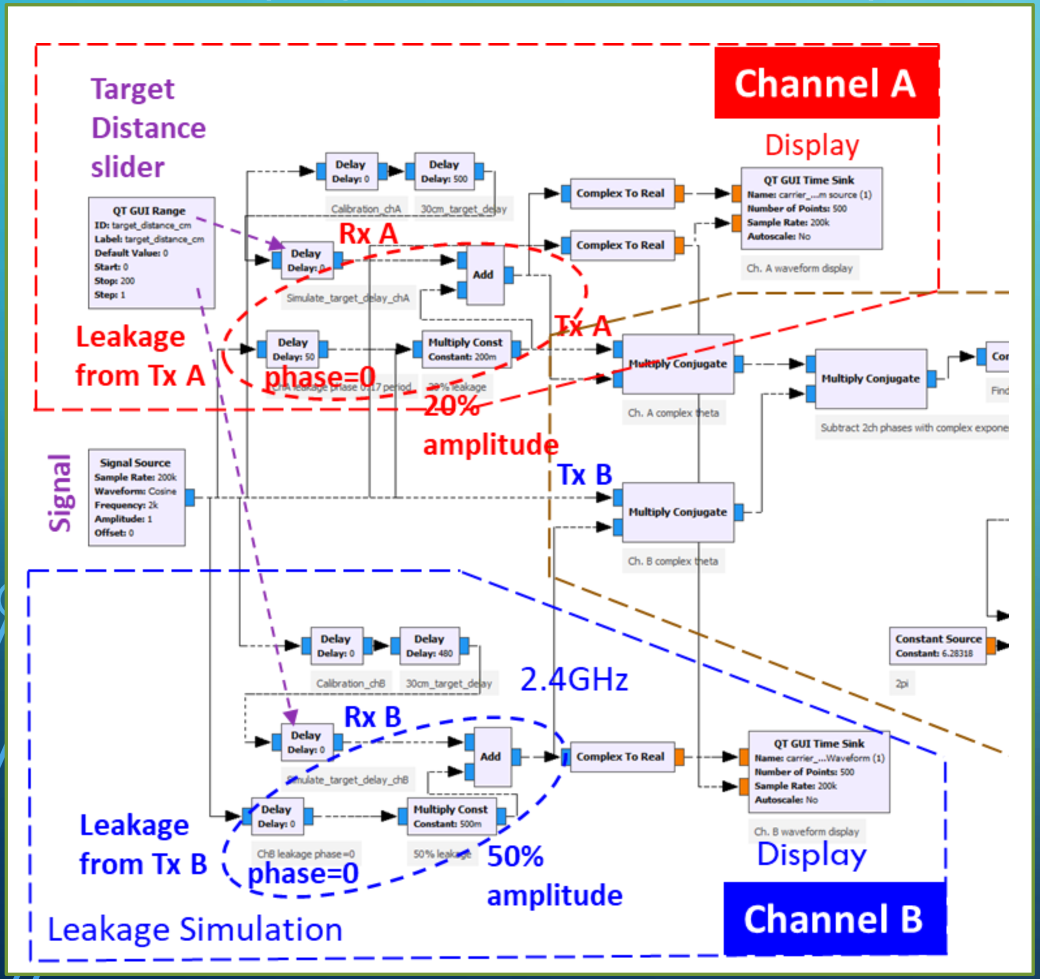
$$R = \frac{c\Delta\emptyset}{4\pi\Delta f}$$

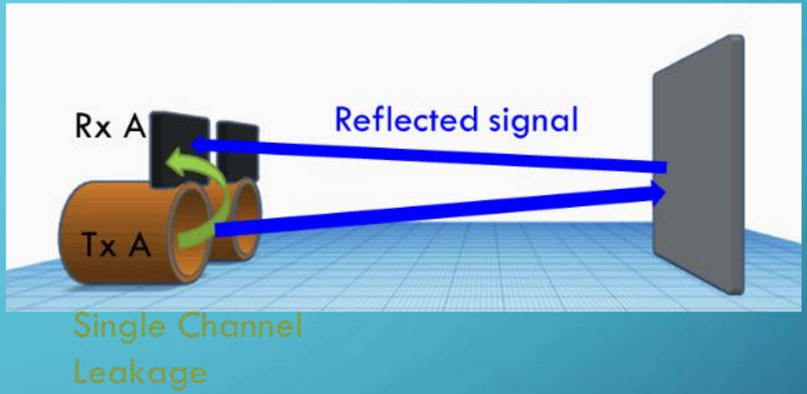
Correct data

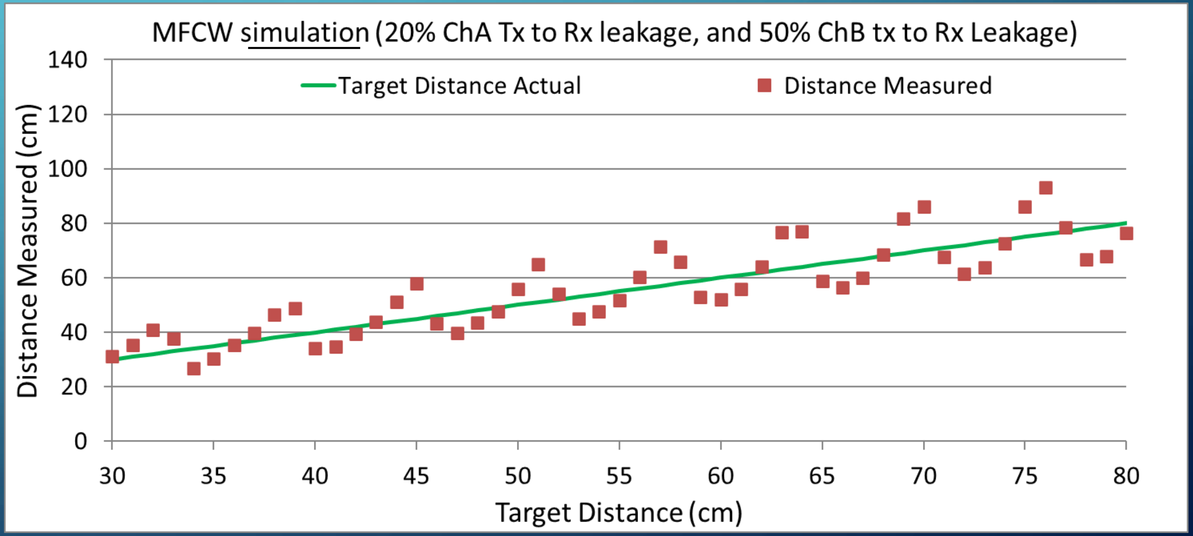
SIMULATE THE IMPACT OF THE LEAKAGE SIGNAL

- Use the simulation capabilities in GNU Radio Companion to <u>inject adjustable percentage of leakage</u>
- Simulation result indicated a strong 50% leakage will create the 25cm distance error observed

Simulation program in GNU Radio Companion







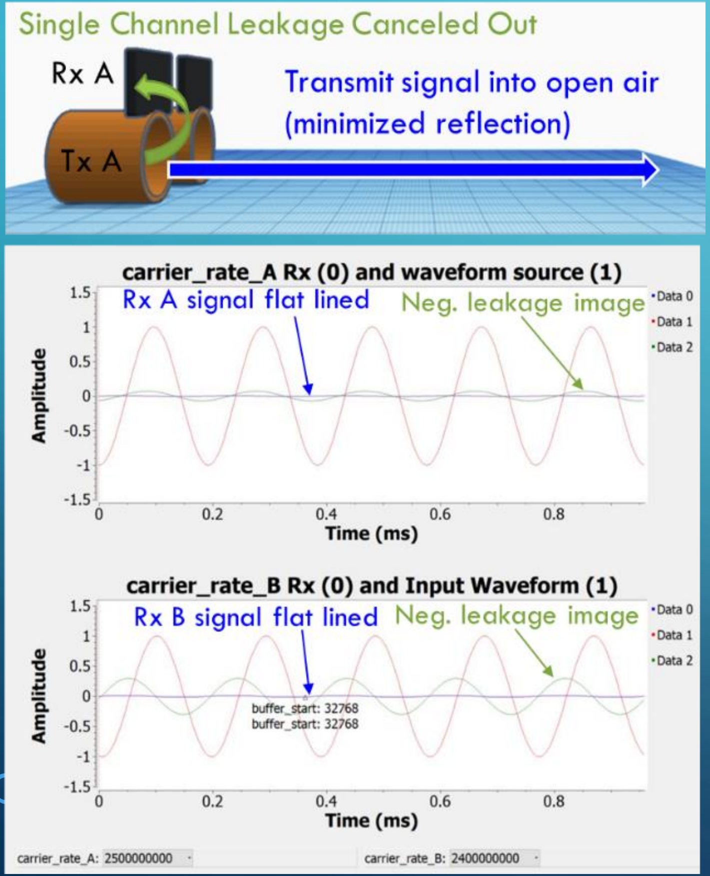
Note: Cross channel leakage data simulation also produced similar impacts (see paper for details)

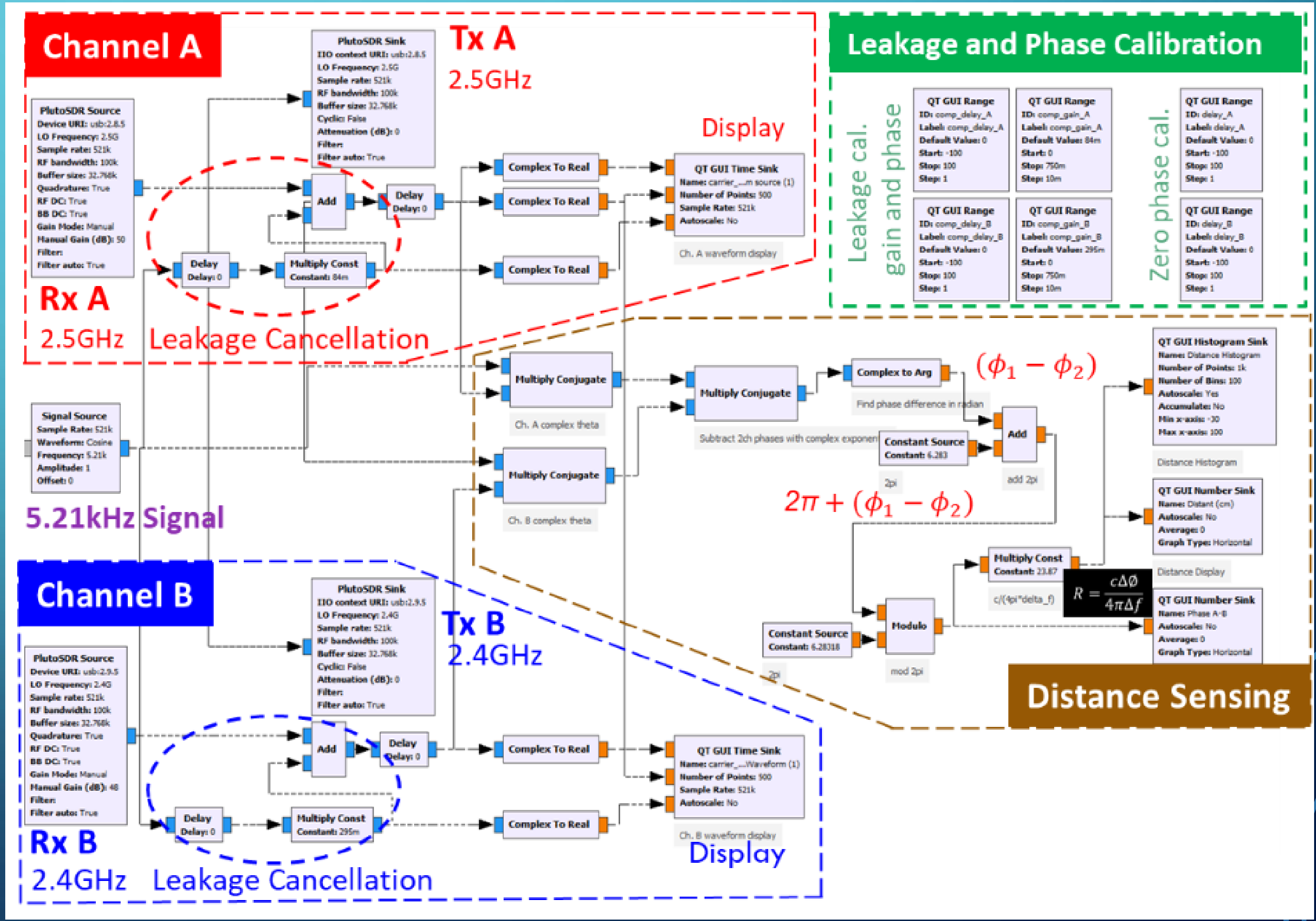
LEAKAGE COMPENSATION TECHNIQUES

- Add an open-air leakage calibration step with target removed (only leakage feeding the Rx)
- Because these leakage signals are the same frequency as the 5.21kHz signal used to modulate the two SDR, we can simply add a new offset signal equal in amplitude, but 180° phase shifted.

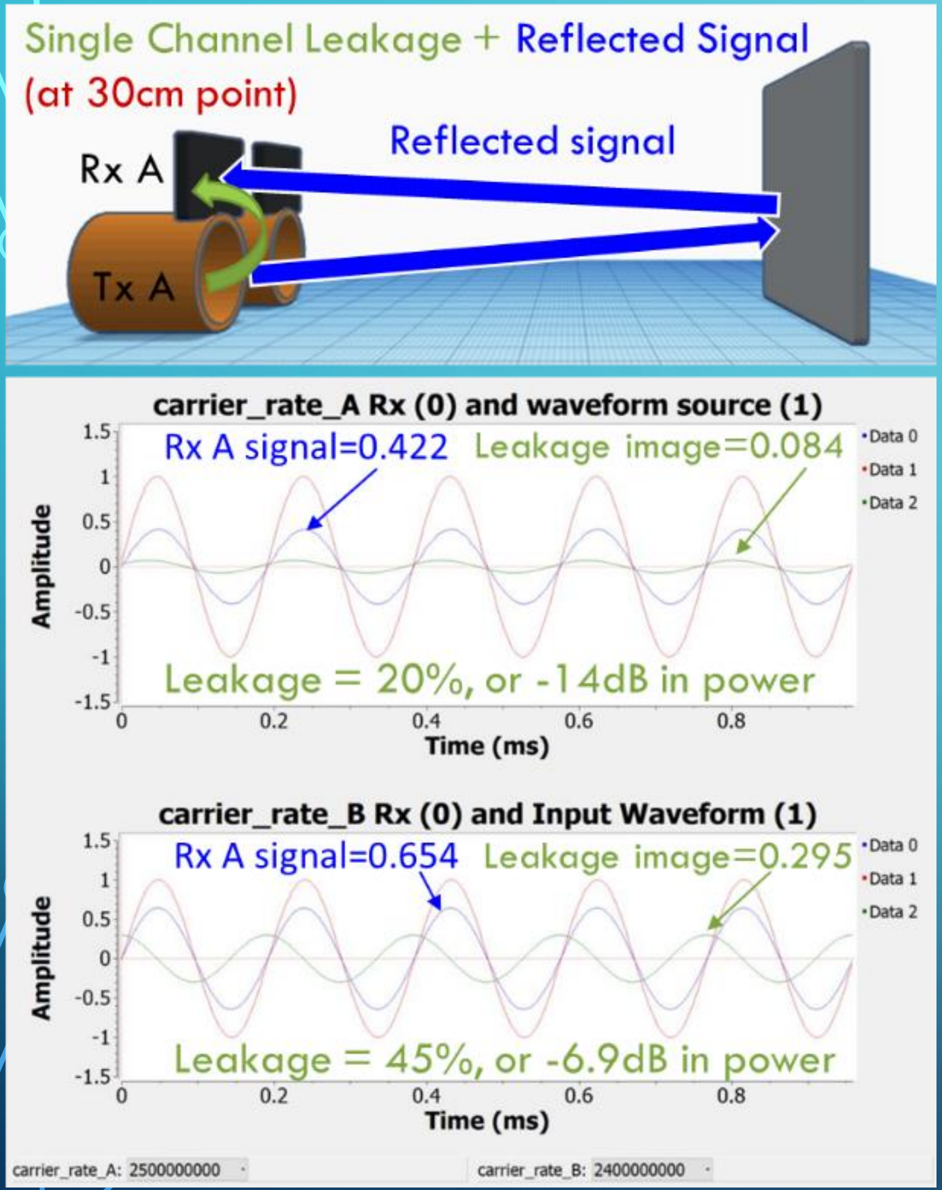
Compensation signal with amplitude and phase control by GNU Range Sliders during the open-air calibration.

Open air calibration with target removed



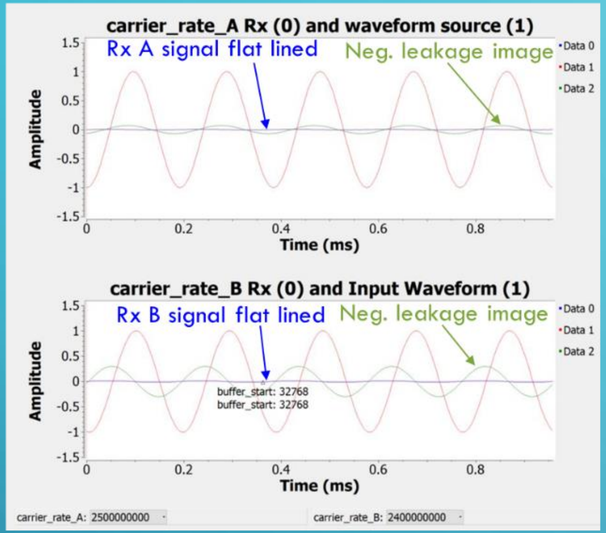


LEAKAGE QUANTIFIED

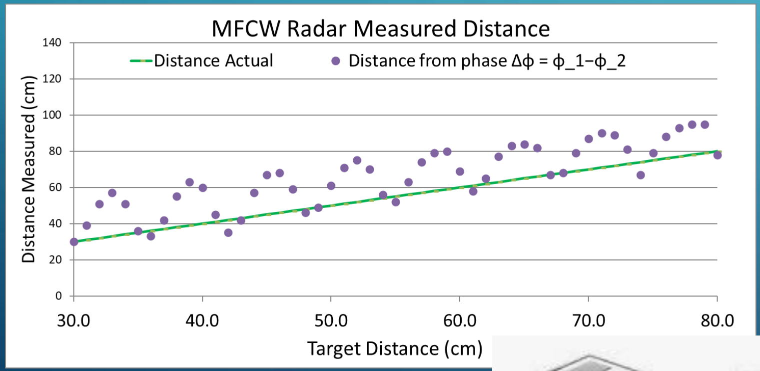


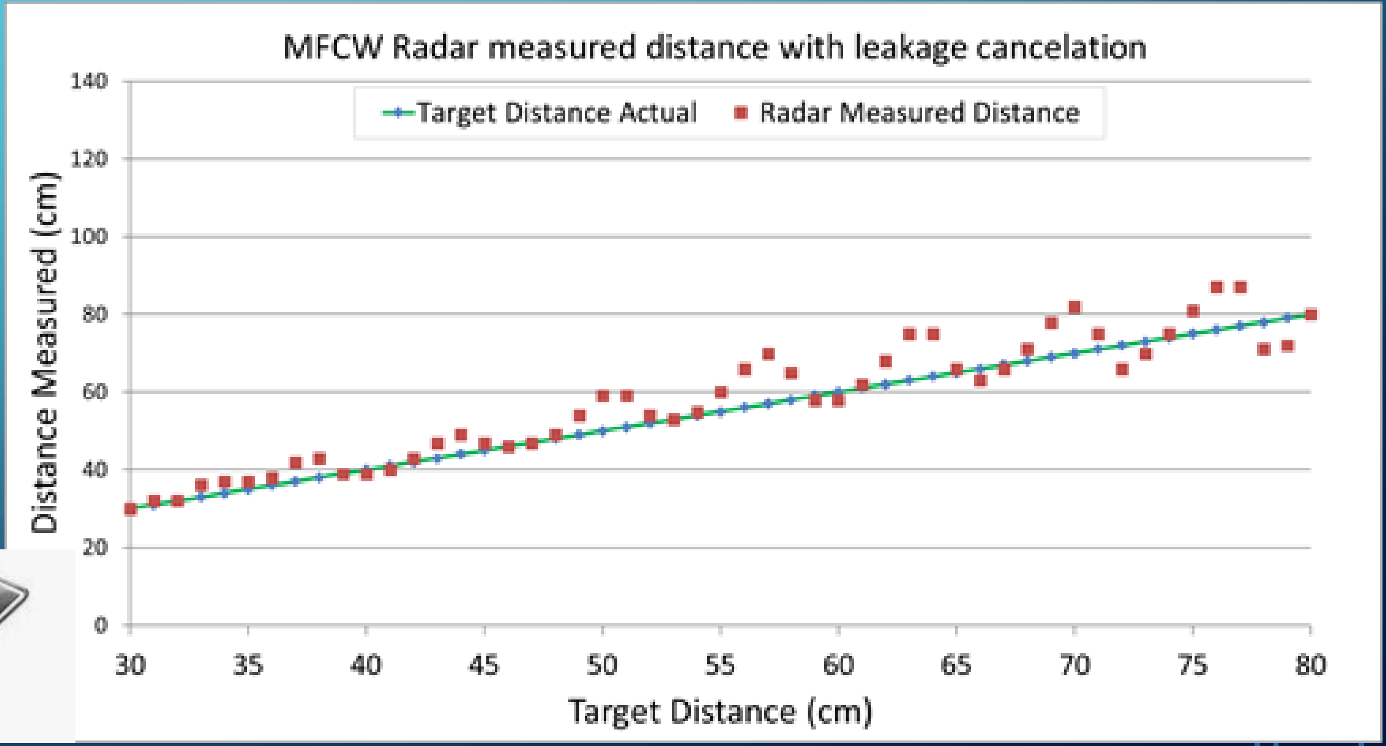
- To quantify the single channel leakage, the received Rx signal after leakage cancellation and the leakage amplitude are plotted in comparison
- Significant leakage detected, as much as 20-45% of the amplitude (-14dB leakage in channel A and -6.9dB leakage in channel B)
- Explained that compensation is necessary to achieve accurate phase measurements
- In MFCW, cross channel leakage is negligibly small (as the SDRs are transmitting and receiving distinct frequencies)
- Dominant leakage is single channel leakage from the Tx to Rx within the same SDR.

MFCW RADAR DISTANCE TEST (AFTER LEAKAGE COMPENSATION)

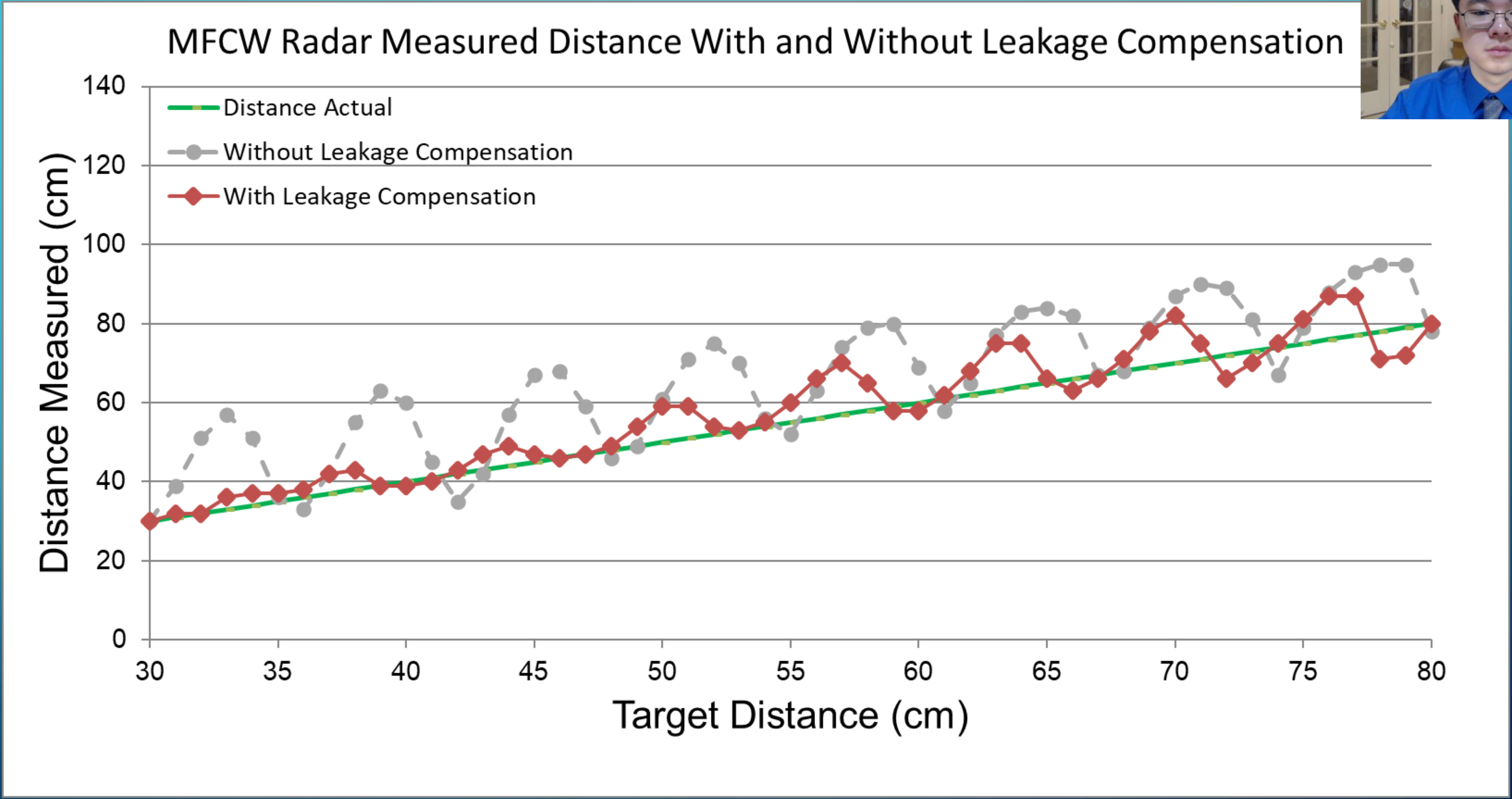


- Open air leakage calibration/cancellation successfully flattened out the leakage signal
- With leakage compensation distance sensing accuracy significantly improved to 12cm
- Within near-end 50cm range accuracy, superior single digit accuracy is achieved.





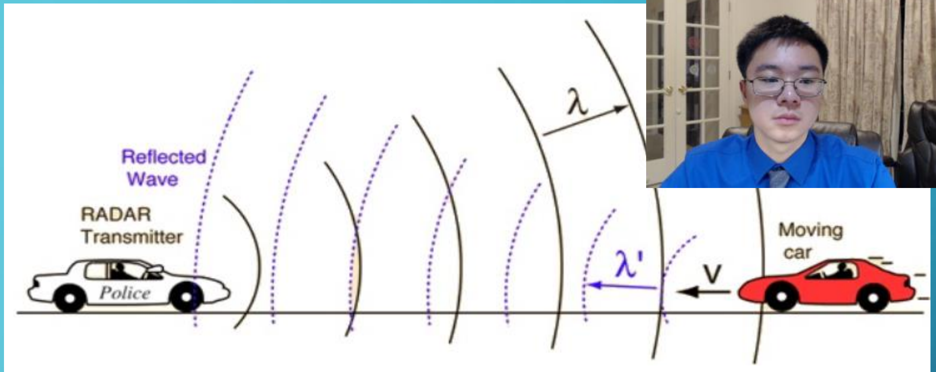
BEFORE AND AFTER LEAKAGE COMPENSATION



RADAR VELOCITY SENSING TEST

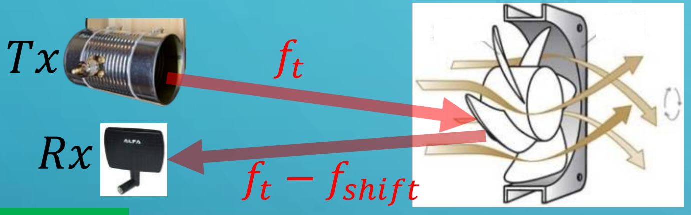
- Using spinning fan blades to emulate an object of constant velocity moving toward or away from radar
- Computed frequency shift using FFT and displayed in "Waterfall" format (spectrum in time lapse manner)

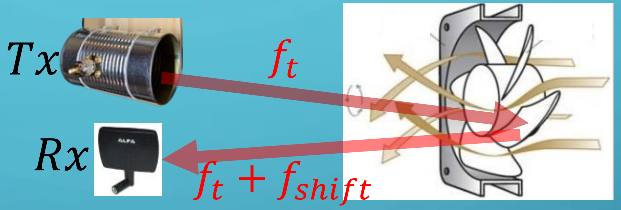
Radar detected larger frequency shift with fan turning on highest speed (v=5.0m/s). Shift frequency disappears when fan is turned off and becomes negative when reverse the fan direction.

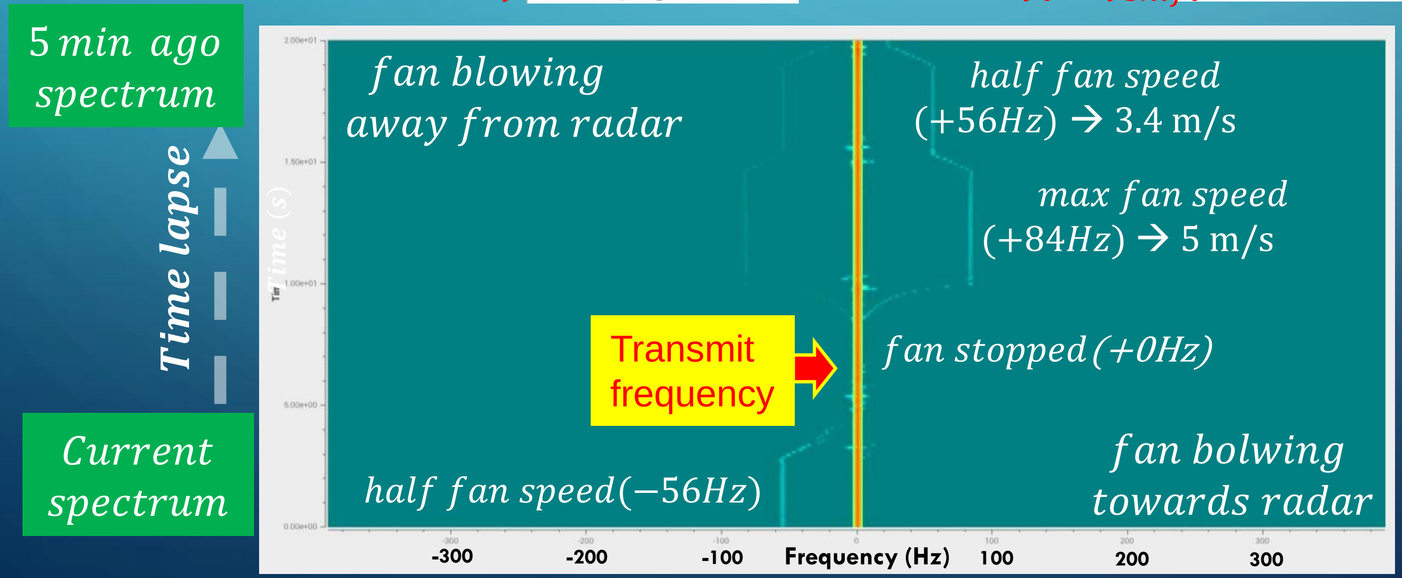


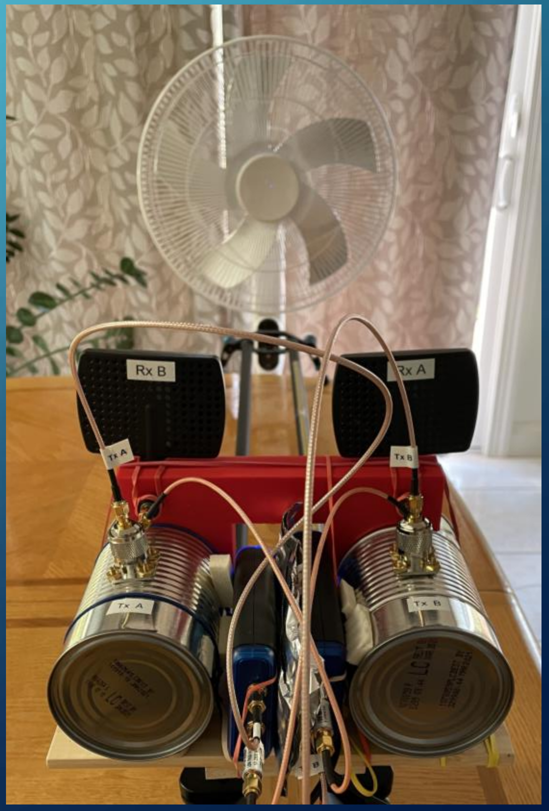
$$f_{shift} = f_r - f_t = 2\text{v}\frac{f_r}{\text{c}}$$

f_r: *reflected frequency*
f_t: *transmitted frequency*
v: *target velocity*
c: *speed of light*









CONCLUSION

- New multi-channel interferometry radar solution: This project demonstrated that distance sensing is indeed possible using very bandwidth-limited low cost SDR
- Five magnitudes less bandwidth usage: This first MFCW distance sensing radar using low cost SDR achieved range resolution of 12cm while only using a few KHz BW. In comparison, a traditional Pulse or FMCW radar would have to use almost 1GHz BW to achieve that resolution.
- SDR phase measurement accuracy challenge: SDR with both an RF transmitter and a receiver integrated in the same module has inevitable leakage from transmit into the receive path, creating unintended non-linear distortion in phase measurement.
- New algorithm developed for leakage cancellation: By applying a negative image of the leakage signal in GNU Radio, a successful spectrum leakage cancellation was demonstrated, enhancing radar distance sensing accuracy to 12cm (comparable to the wavelength of 2.5GHz signal used)

ACKNOWLEDGEMENT

In November 2020, the coauthor Victor Cai was fortunate enough to find a Co-Op position and a great mentor Jon Kraft at Analog Devices Inc. (ADI). After reviewing my independent dual-SDR MFCW research, he guided me to simulate channel leakage with GNU, which sparked my leakage cancellation idea in MFCW to resolve the lingering periodic variation in the distance measurement.

Thanks to all the GRC organizers and reviewers for the chance to share my work as a high school student, intern and radio enthusiast. The issue of channel leakage was first brought to my attention in one of the reviewer's comment in my GRC paper from last year.

Thank you for the GNU community collaboration and freeware spirit which enables young radio enthusiasts like me to perform research and push innovation forwards.

REFERENCES

[1] Cai, V. (2020). Designing a Narrowband Radar using GNU Radio and Software Defined Radio for Tomography and Indoor Sensing. Proceedings Of The GNU Radio Conference, 5(1). Retrieved from https://pubs.gnuradio.org/index.php/grcon/article/view/67.

[2] Suleymanov, S. (2016). Design and implementation of an FMCW radar signal processing module for automotive applications [Unpublished master's thesis]. U of Twente.

[3] Adib, F., Mao, H., Kabelac, Z., Katabi, D., & Miller, R. C. (2015). Smart homes that monitor breathing and heart rate. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.

[4] Marimuthu, J., Bialkowski, K., & Abbosh, A. (2016). Software-Defined radar for medical imaging. IEEE Transactions on Microwave Theory and Techniques, 64(2), 643-652.

[5] Adib, F., & Katabi, D. (2013). See through walls with wi-fi! SIGCOMM 2013.

[6] Wolff, C. (n.d.). Range resolution. Radartutorial. Retrieved June 17, 2020, from http://radartutorial.eu/01.basics/Range%20Resolution.en.html

[7] Collins, T. F., Getz, R., Pu, D., & Wyglinski, A. M. (2018). Software-Defined radio for engineers. Artech House Mobile Communications.

[8] Zhu, J. (2017). Low cost, software defined FMCW radar for observations of drones [Unpublished master's thesis]. U of Oklahoma.

[9] Anderson, M. G. (2018). Design of multiple frequency continuous wave radar hardware and micro-doppler based detection and classification algorithms. University of Texas at Austin: Texas Scholar Works. Retrieved October 10, 2019, from https://repositories.lib.utexas.edu/handle/2152/4000

[10] Charvat, G., Williams, J., Fenn, A., Kogon, S., & Herd, J. (2011, 01). Build a small radar system capable of sensing range, doppler, and synthetic aperture radar imaging. MIT Open Course Ware. Retrieved 09 10, 2019, from https://ocw.mit.edu/resources/res-ll-003-build-a-small-radar-system-capable-of-sensing-range-doppler-and-synthetic-aperture-radar-imaging-january-iap-2011/

[11] Frank, A. (n.d.). Cantenna Calculator Aka Circular Waveguide Antenna [Computer program]. https://www.changpuak.ch/electronics/cantenna.php

[12] Melzer, A., Onic, A., Startzer, F., & Huemer, M. (2015). Short-range leakage cancelation in FMCW radar transceivers using an artificial on chip target. Journal of Selected Topics in Signal Processing, Vol. 9, No. 8.

[13] Freitas, L. (2018, November 23). Software defined doppler radar with limesdr mini. Software Defined Doppler Radar with LimeSDR Mini. Retrieved October 10, 2019, from https://luigifreitas.me/2018-11-23/software-defined-radar-cw-doppler-radar-with-limesdr