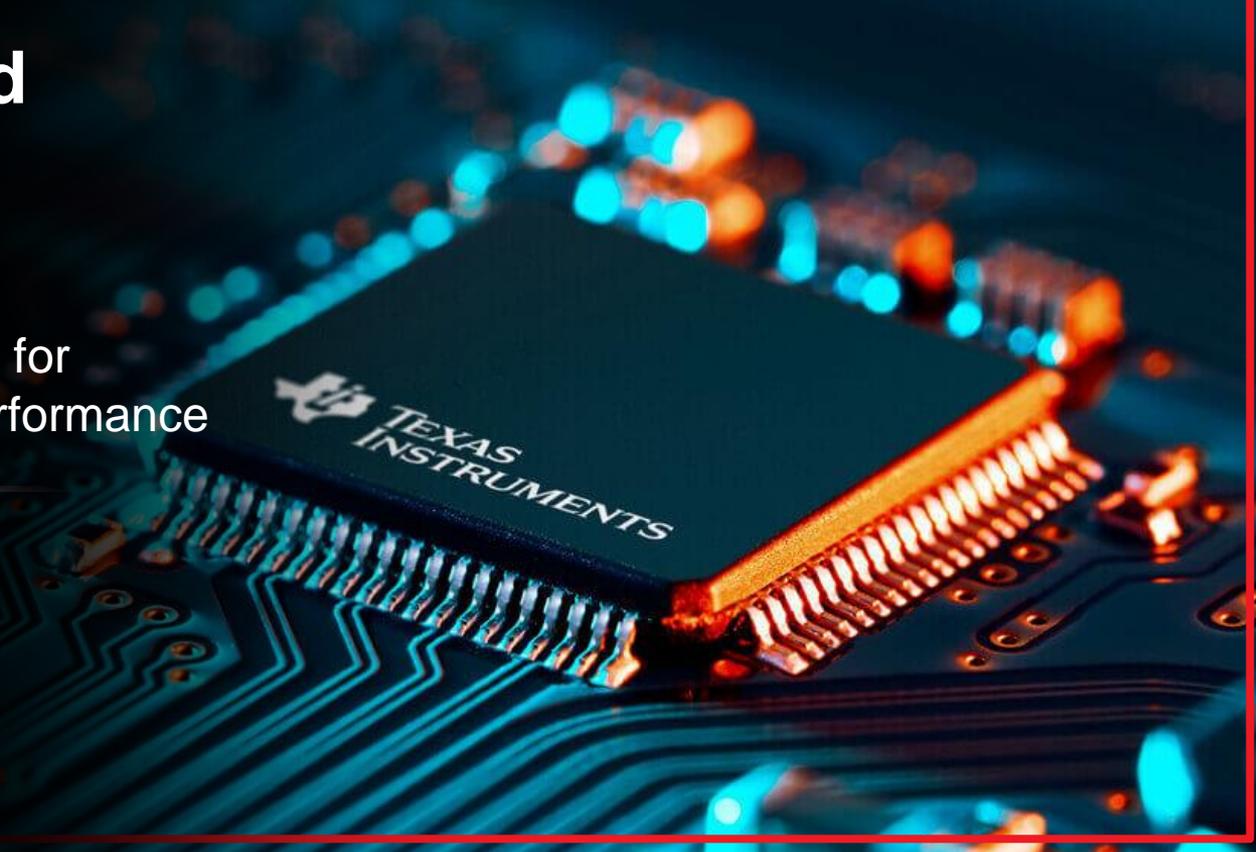TEXAS INSTRUMENTS

2024 Embedded Seminar

mmWave radar test-methodologies and tools for validating application performance

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Software Applications Engineer

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Systems Applications Engineer

Agenda

- Motivation – Why is it important to test correctly?

- Testing environment

- Good performance metrics

- Use-case examples and best practices

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Motivation

- Why dedicate an entire session to testing the application performance of mmWave radar?
  - **Variable Environments** - Radar behaves differently in different environments.
  - **Human-Centered Testing** - Radar may require people to walk/stand/sit to test. People are different sizes and move differently, which can cause variance in results.
  - **Quantifying Performance Improvement** - It's hard to know if you're getting better results if you're not testing the same thing ever time. Standardized testing helps clarify whether modifications make performance better or worse with clear accuracy metrics.

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Testing Environment

TEXAS INSTRUMENTS
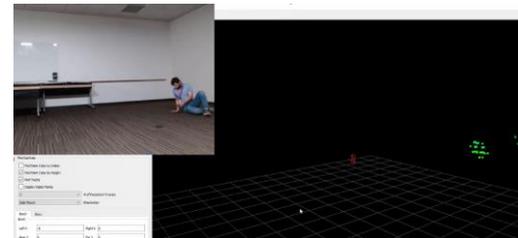
Testing Environment – Mimic intended usage

- The radar will perform very differently in different setups. They are strongly affected by the amount of clutter in the environment/density of the objects. **Therefore, it is best to test in an environment similar to the intended use-case. Testing in a different environment will yield different results.**
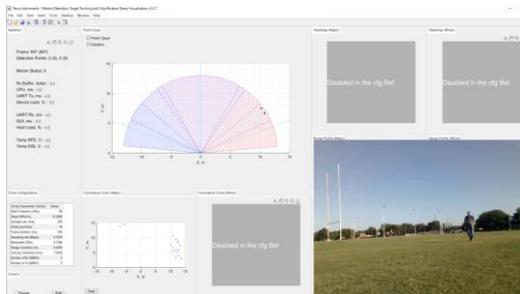
Video Doorbell should be tested outdoors
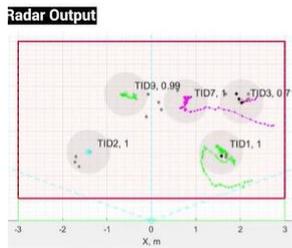
Radar for TV should be tested in a living room

Fall Detection should be tested indoors

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Testing Environment – Mimic intended usage

- If it is not possible to test in exactly the conditions the product will be deployed in, TI recommends considering the following factors to get as close a match as possible.
  - Indoors vs Outdoors
  - Cluttered Environment vs Open Environment
  - Density of People in the area (close together vs far apart)
  - Presence of ambient movement and objects (trees/bushes/fans/HVAC…)

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Testing Environment – Outdoor Testing

- To help account for errors, note weather conditions at the time of testing to explain slight variations in performance

- High temperatures and humidity can reduce the detection range of the radar, and wind can increase false alarm rate in the presence of bushes/trees.

- Make sure to secure the device firmly to the ground too, and limit the amount that the USB cord can pull on the EVM.

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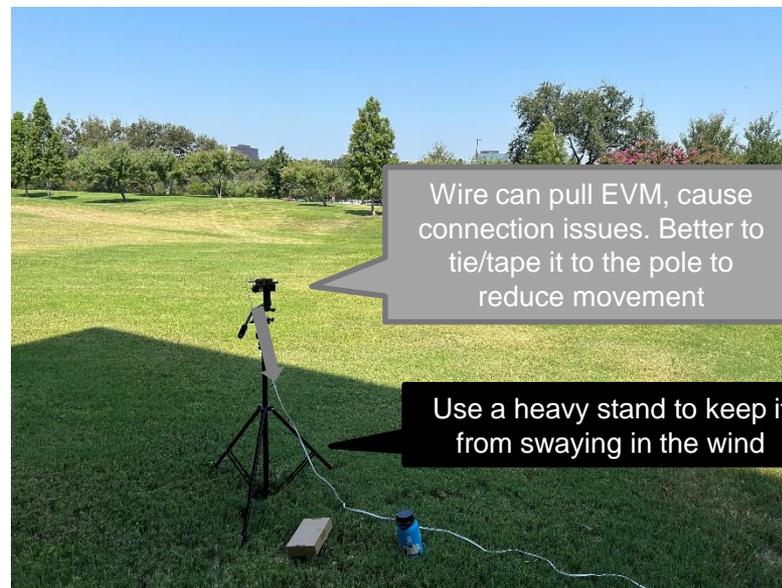
Testing Environment – Indoor Testing

- Indoor environments are often more cluttered than outdoor, and even harder to standardize

- Test in the same controlled environment every time, even if it does not fully mimic the use-case. **A standardized environment lets engineers understand if their changes are making performance better or worse.**
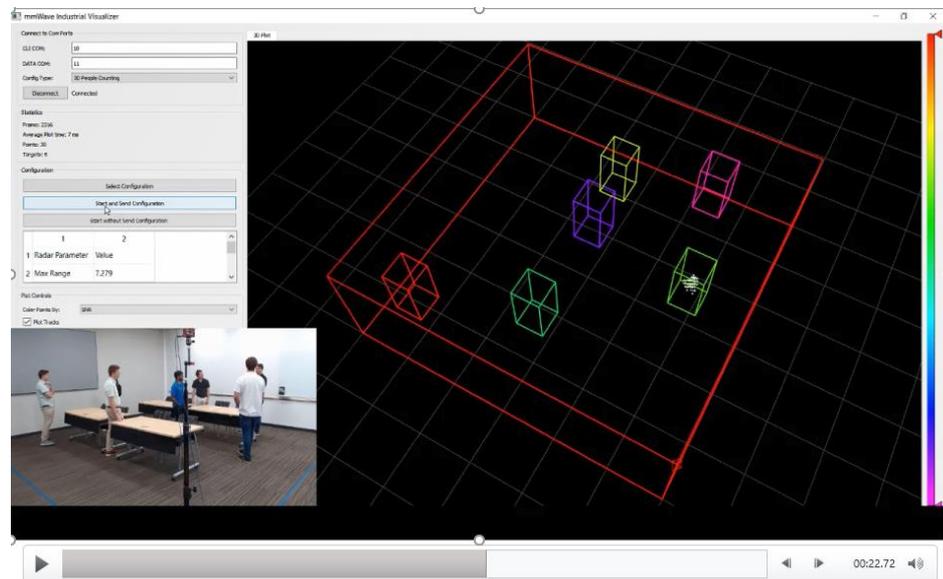
Simulated Conference Room Testing

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Designing a Test Plan

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Designing a test plan

- An effective test plan should consider the following:
  - What metrics should it use to gauge performance?
  - How will you analyze the data once it's collected
  - How will you save the data in case it needs to be replicated?
  - Do you need ground truth data to compare with?

- TI recommends taking a baseline measurement of performance, then planning sequential tests to make incremental improvements

- Lighting NEMA-7 Test Plan is a good example of standardizing performance when faced with human variables.

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Performance Metrics

- Good performance metrics can be easily quantified and tested.
- Users should consider what they want the radar to do. Some common test cases include:

Radar Application Goal	What should you measure?
Detect People at a distance	When a person approaches the radar or walks in the scene, what is the average distance they are detected at? How does this change over angle of arrival?
Count people in a room	What percentage of frames are the correct number of people detected?
Localize People	When a person walks along a predefined path, what is the difference between their true position and their estimated position?
Track People	Using a ground truth system, what is the average distance between tracker location and ground truth location for the detected tracks? What percentage of frames track the right number of people within X meters?

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Ground Truth Data

- Recommended Equipment : Zed2i Stereo Camera

- Point clouds from both devices overlaid

- Other tools and SW packages specific to people counting and tracking (automatic ML/AI people tracking) do also exist and can be paired with radar for ground truth

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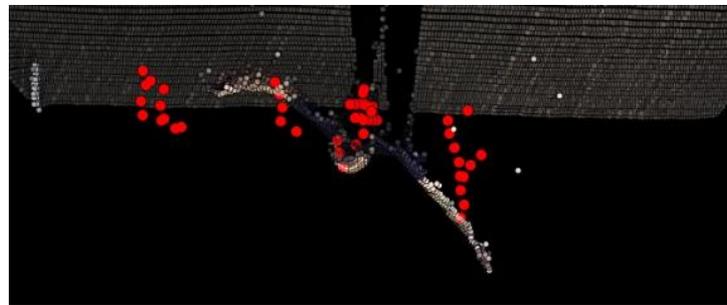
Tools for data analysis

- Industrial Visualizer gives JSON that exports frame-by-frame data off the device

- Use the guiMonitor command to choose what data to export
  - Point Cloud, Occupancy Status and Tracker are almost always useful
  - Cluster centroids and heatmaps can also be helpful for debugging and performance improvement

- *TI Pro Tip :* Program the visualizer to calculate the important metrics in real-time, rather than having to parse them after the fact.
  - Applications Visualizer in Radar Toolbox is open source python, easy to modify and extend to new applications.

```
10      "cfarCfg 2 8 4 3 0 10.0 0 0.9 0 1 1 1\n",
11      "aoaFovCfg -70 70 -40 40\n",
12      "rangeSelCfg 0.5 15\n",
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14      "compRangeBiasAndRxChanPhase 0.00 1.00 0.00 1.00 0.00
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16      "adcLogging 0\n",
17      "lowPowerCfg 2\n",
18      "factoryCalibCfg 1 0 40 0 0x1ff000\n",
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21      "mpdBoundaryArc 3  1 4 -16  15 0 3\n",
22      "mpdBoundaryArc 4  1 4  16  45 0 3\n",
23      "mpdBoundaryArc 5  1 4  46  75 0 3\n",
24      "mpdBoundaryArc 6  4 8 -75 -45 0 3\n",
25      "mpdBoundaryArc 7  4 8 -46 -15 0 3\n",
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28      "mpdBoundaryArc 10 4 8  46  75 0 3\n",
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30      "mpdBoundaryArc 12  8 12 -46 -15 0 3\n",
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36      "mpdBoundaryArc 18  12 16 -16  15 0 3\n",
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41      "clusterCfg 1 0.5 2\n",
42      "% profileSwitchCfg 1 1 1\n",
43      "sensorStart 0 0 0 0\n"
44      ],
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47      "data": [
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49              "frameData": {
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53                  "procTimeData": {
54                      "interFrameProcTime": 418,
55                      "transmitOutTime": 0
56                  },
57                  "powerData": {
58                      "power1v8": 4,
59                      "power3v3": 0,
```

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Saving Data Effectively

- When you save data off the device, how do you know what settings were used?

- We recommend that for EACH experiment, the tester saves the following:
  - Test Procedure – description or graphics
  - Test environment – description or photos
  - Configuration File – user needs to save
  - Individual EVM – user should mark and save
  - Binary running on-chip (and a commit ID if possible) – user needs to save
  - TLV Results – Streamed off the visualizer

- This helps ensure replicability if the results are called into question after the fact

	Name	Date modified	Type	Size
Config File	steering_vectors.cfg	5/30/2024 5:12 PM	CFG File	2 KB
Binary	SIGN_CHANGE_video_doorbell_demo_aop.Release.appimage	5/30/2024 4:30 PM	APPIMAGE File	257 KB
	pHistBytes_25.bin	5/31/2024 3:19 PM	BIN File	62 KB
TLV Results	pHistBytes_24.bin	5/31/2024 3:19 PM	BIN File	62 KB
	pHistBytes_23.bin	5/31/2024 3:18 PM	BIN File	66 KB
PPT Containing EVM, Test Env, Procedure	On_Chip_Steering_Vectors_Results.pptx	6/18/2024 11:08 AM	Microsoft PowerPoint Presentati...	1,841 KB

14

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Use-Case Examples

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Outdoor Presence Detection

- Typical EEs: Home surveillance cameras, video doorbells, security systems

- Goals: Use the radar to alert a system when presence is detected

- Challenges: Consistent results at different people/speeds, low ambient power consumption for always-ON usage

- Test Procedure:
  - Person walks in predefined paths towards and away from the radar. Detection distance for each path is measured, procedure is repeated at different angles.
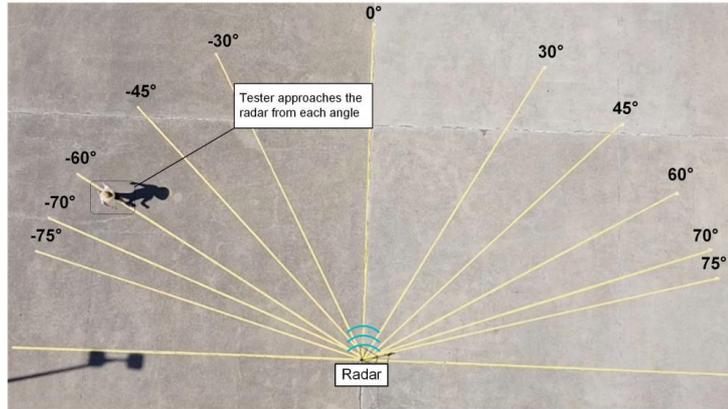
Figure 3-3. Detection Range Test - Bird's Eye View

Table 3-4. Test 1 - Detection Range

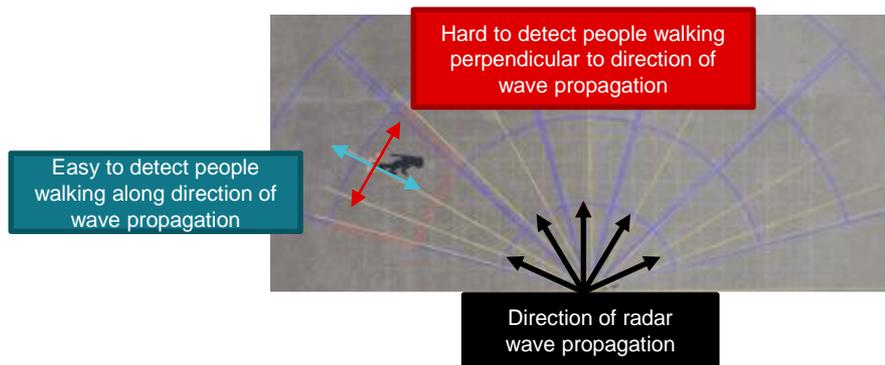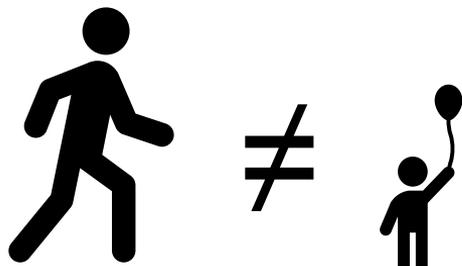| Angle (degrees)	Detection Distance (Average over 5 trials)
-70	6.06
-60	9.72
-45	12.02
-30	13.39
0	14.37
+30	11.97
+45	9.82
+60	8.69
+70	8.62

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Outdoor Presence Detection Considerations

- With presence detection, the radar may detect presence at different distance depending on the angle of arrival between the target and the object.

- Since antenna gain is a function of azimuth and elevation angle, it often makes more sense to describe the detection range based off angle (r,θ,φ) than it does to describe the detection range in a cartesian system (x,y,z)
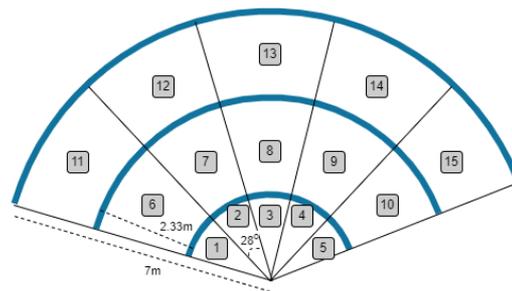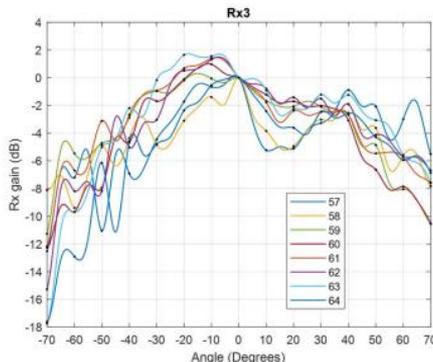
Outdoor Presence Detection Considerations

- Additionally, when describing detection distance, the amount of movement plays a big role. Larger subjects are detected further than smaller subjects, and a running subject will get detected more easily than a stationary subject. For consistent results, try to use similarly-sized people, and walk at a typical speed. Do not sway arms excessively.

- Direction of movement also affects detection distance. People moving towards/away from the radar get detected more easily than people walking parallel to the direction of propagation

Hard to detect people walking perpendicular to direction of wave propagation

Easy to detect people walking along direction of wave propagation

Direction of radar wave propagation

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Indoor People Counting Considerations

- Typical EEs : TV, HVAC, Lighting, Video Conference Systems

- Goals: Know the number of people in the room, potentially locations too

- Challenges: Consistent level of ambient movement, stationary people

- Procedure: Collect data over a long period of time to capture average-case behavior. Compare against ground truth system.
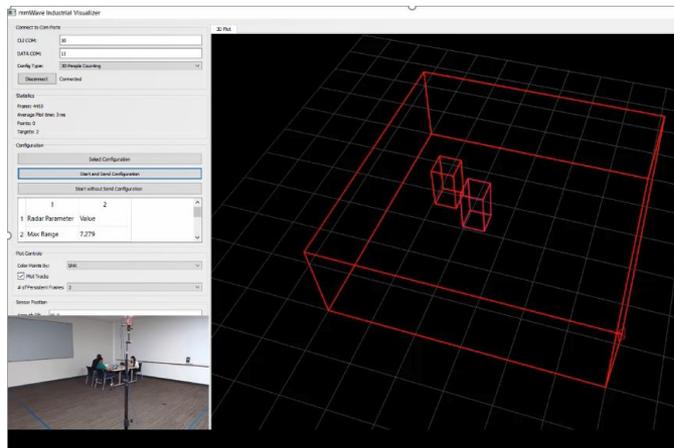
# Indoor People Counting Considerations

- Different error metrics can be used for people counting. Some options that TI has seen include the following:
  - % of time with exactly the correct number of people in the room
  - % of time with the correct number of people in the room (+/- 1 person)
  - % of time that the device can distinguish correctly between 0 and 1 or more people in the room (does the device know if the room is empty or occupied by at least 1 person)
  - % of the time with exactly the correct number of people in the room, saturating at a high value (e.g. options are 0,1,2,3,4+ people detected)

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Indoor People Counting Considerations

- The amount of movement in a scene is important to consider, especially in indoor environments

- Sensors placed in environments that may have moving and stationary people will likely have different performance depending on the amount of motion at a given time

- It often makes sense to look at average performance over a longer period of time, which may require ground truth testing equipment

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Indoor People Counting – Sitting Still

- When people sit still for a long time, the radar will sometimes lose their track.

- Performance varies depending on persons' movement, size, location, personal habits…

- Once a track is lost, it's quite hard to regain until the person moves again (needs to sit up/shift position, move slightly)….

- Solutions:
  - Measure average time until track is lost for the 1st time without any movement
  - Testing over many people & long periods of time to capture typical behavior
  - Use presence detection logic instead of tracker logic for stationary detection
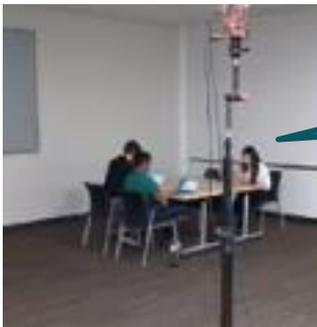
3 People

2 Tracks

TEXAS INSTRUMENTS
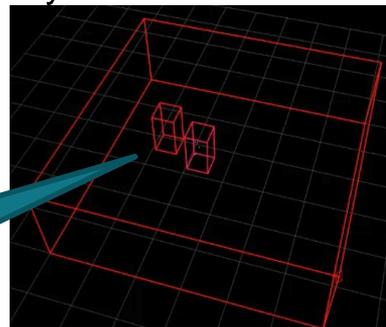
Further Resources

- [Video Doorbell Design Guide](#)

- Indoor Presence and Motion Detection Design Guide (Link to come)

- [Radar Toolbox](#)

- [Zed2 Camera](#)

- [NEMA Standard for Motion Sensors](#) (Not technically mentioned, but relevant)

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Localizing People Considerations

- A common challenge in testing the localization accuracy of the radar is getting ground truth data. How do you know a person's true 3D position at a single time?
  - Option 1 : Use a stereo camera or similar high fidelity localization tool.
  - Option 2 : Walking in strategically defined paths to measure error

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Localizing People Considerations

- Well-defined paths
  - If a person walks along a single line for a data capture, the error for every point, or every frame with a track can be estimated by assuming that the person is walking along the line, and estimating the distance between the detected location and its projection onto that line. If walking on a line that includes the radar's position, this can be easily done by measuring the error in azimuth degrees.

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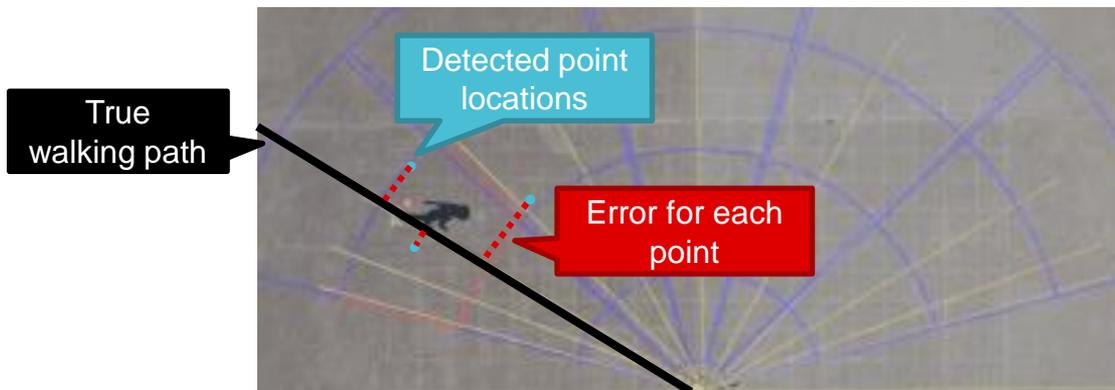
Performance Metrics

- Often times the radar BU will get some variation of this question
  - "The radar detects tracks that aren't there"
  - "The radar detects presence in a zone that isn't there"
  - "The radar allocates multiple tracks for the same person"
  - "The radar doesn't detect a person when they're in the field of view"
  - "The radar loses a person's track when they're stationary for a period of time"
- TI can offer ways to tune the performance, **but it's much easier if there are defined targets and metrics**

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Outdoor Presence Detection Considerations

- How are you defining presence? Is it based off the zone occupancy logic? Or based off whether a track is allocated or not?
  - The performance of the tracker tends to vary more than the performance of the presence detection logic. Presence detection logic nearly always gives increased range
  - Target distance @ 1st frame of detection helps reduce variance in results

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