

# ***System Performance Measurement With the mmWave Sensor***

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## **ABSTRACT**

This application report discusses system performance measurement results using Texas Instruments high performance mmWave sensor. TI's mmWave sensor is a 77-GHz, highly integrated, transceiver with a high-speed interface (CSI2) to send raw ADC data out for processing. The mmWave sensor includes the entire mmWave RF and analog baseband signal chain for three transmitters and four receivers, and a built-in self-test (BIST) capability to allow calibration and monitoring of the mmWave front end. TI's mmWave sensor portfolio includes single-chip radar devices with a programmable microcontroller (MCU), on-chip memory, and signal processing capabilities. During this system measurement, performance is evaluated by configuring the front end working in different modes. Performance evaluation conducted in the anechoic chamber measures range resolution, angle resolution, and angle accuracy. Outdoor measurement shows the ability of the radar to detect different types of targets in range. The measurement results demonstrate the system performance of the mmWave sensor and can serve as a reference to an application-specific radar system design.

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## 1 Introduction

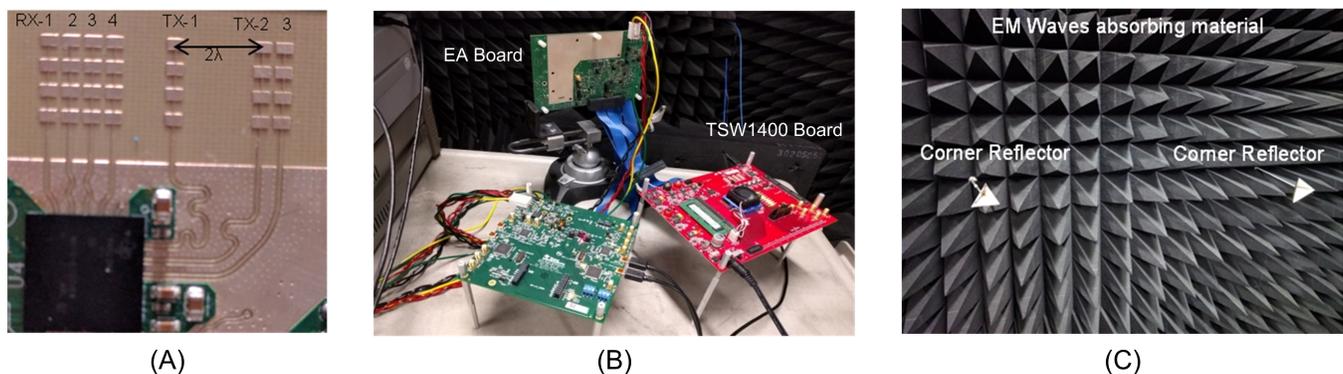
In recent years, there has been tremendous increase in the use of radar technology in various applications, including advanced driver assistance systems (ADAS), which improves driving safety, drone navigation for obstacle avoidance, contactless vital sign monitoring in healthcare, and more.

Traditionally, radar implementations have used discrete components (PA, LNA, VCO, ADC, and so on). However, recently more integrated solutions have become available. A CMOS-based, fully integrated radar that integrates all RF and analog functionality, as well as DSP capability, into a single chip represents the ultimate radar system-on-a-chip solution. This highly integrated solution reduces the cost and form factor, and also makes it efficient to implement advanced techniques to improve the system performance, as well as to enable better functional safety (ISO26262 ASIL standards) compliance using on-chip, processor-based, built-in, self-test capabilities.

Different applications have different requirements and involve different high-level algorithms to achieve the respective functionality. However, the system performance, such as range and angle measurement resolution, is fundamental to all the applications. This application report presents system performance evaluation results using TI's mmWave front end device in both indoor and outdoor conditions. The performance in indoor conditions is evaluated in terms of range resolution, with different signal bandwidth configuration and angle measurement accuracy and resolution. The outdoor condition test measures the ability to detect different types of objects in range.

## 2 Indoor Measurements

The measurement is conducted with the mmWave sensor characterization board with the etched antenna (EA) onboard, as shown in [Figure 1\(A\)](#). This 4-element antenna provides 10-dB gain in the boresight and approximately 5-dB gain at  $-60^\circ$  or  $60^\circ$  in azimuth. The EA board is connected to the TSW1400 board for data collection. The raw ADC data is sent to the TSW1400 through the LVDS-based debug interface and saved to the DDR memory. Data is further sent to a PC for post processing. The indoor test is carried out in an anechoic chamber, as shown in [Figure 1\(C\)](#). The following two subsections discuss the range measurement and angle measurement results, respectively.



**Figure 1. Etched Antennas (A); Measurement Setup (B); Anechoic Chamber With Absorbing Material (C)**

## 2.1 Range Measurement

This subsection discusses the range resolution measurement results. During the measurement, one corner reflector is placed at a fixed location, and the second corner reflector is moved in range with respect to the first corner reflector. Then, the raw ADC data is processed to generate a range profile plot. The range resolution is defined as the minimum separation required between the two corner reflectors such that the two peaks corresponding to the corner reflectors can be distinguished in the range profile.

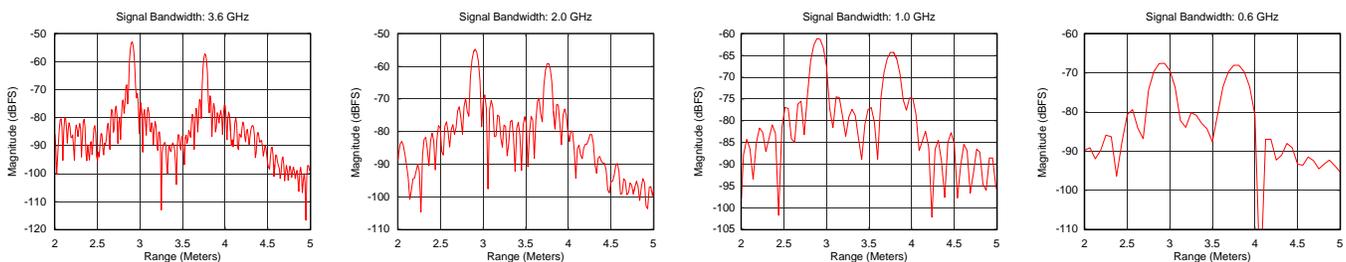
Because range resolution depends on the signal bandwidth, four bandwidth cases are measured, as listed in Table 1. If an FFT operation is used to obtain the range profile then the theoretical range resolution is given by  $C/2B$ , where  $C$  is the speed of light and  $B$  is the signal bandwidth,

**Table 1. Four Types of Signal Bandwidth**

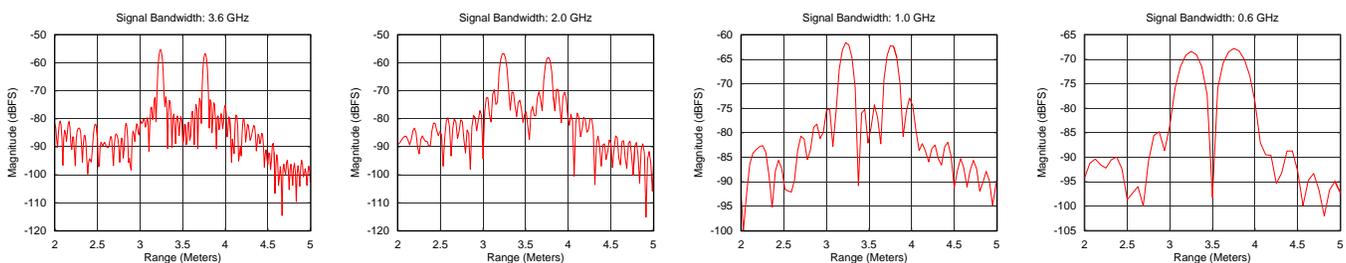
Chirp Duration ( $\mu$ s)	Frequency Slope (MHz/ $\mu$ s)	Bandwidth (MHz)	Theoretical Range Resolution (cm)
100	36	3600	4.17
100	20	2000	7.50
100	10	1000	15.00
100	6	600	25.00

Figure 2, Figure 3, Figure 4, and Figure 5 show the range profiles of the four types of signal bandwidth, with four different range separations of the two corner reflectors. We can observe that when the separation is 85 cm (Figure 2) or 50 cm (Figure 3), for all four bandwidth cases, two clear peaks are shown, corresponding to the range of the two corner reflectors. When the separation is reduced to 20 cm in Figure 4, and 10 cm in Figure 5, the two peaks start to merge with one another and it is more difficult to differentiate the two corner reflectors using a bandwidth of 1 GHz or 0.6 GHz.

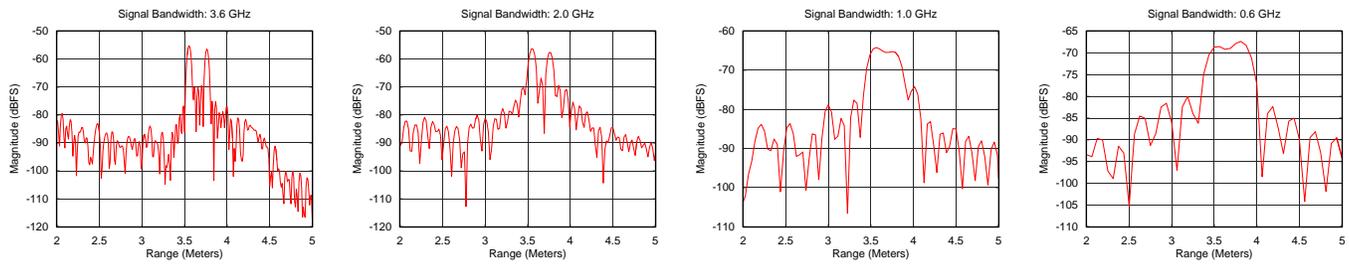
**NOTE:** No further experiments with lower range separation were conducted. The 4-GHz case should be able to resolve objects with a range separation of less than 10 cm.



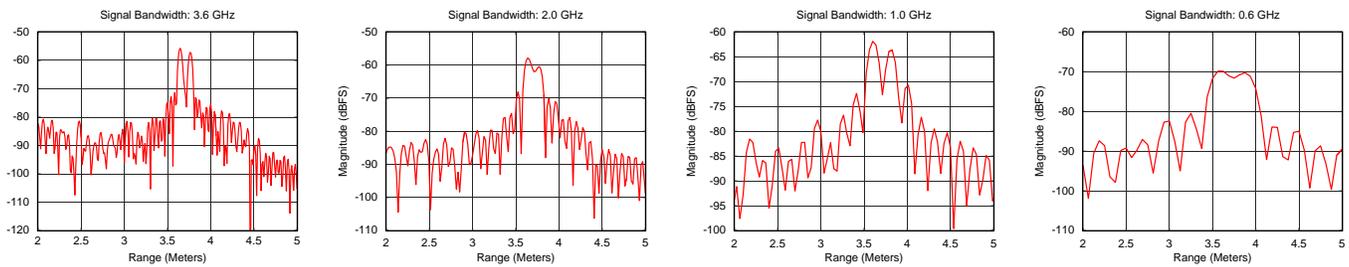
**Figure 2. Range Profile of Four Bandwidth Cases With Separation of 85 cm**



**Figure 3. Range Profile of Four Bandwidth Cases With Separation of 50 cm**



**Figure 4. Range Profile of Four Bandwidth Cases With Separation of 20 cm**



**Figure 5. Range Profile of Four Bandwidth Cases With Separation of 10 cm**

Range accuracy measurement is not covered in this application note, because range accuracy depends on the algorithm chosen to implement, varying from centimeters to micrometers.

## 2.2 Angle Measurement

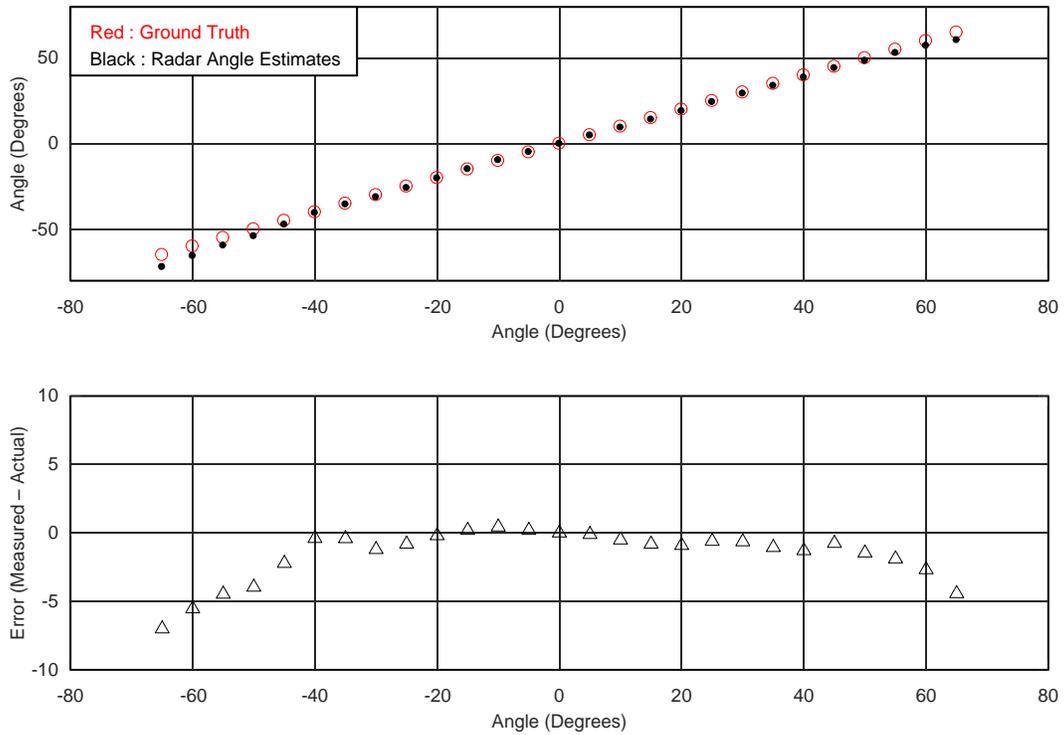
This subsection discusses the azimuth angle measurement accuracy and resolution. Accuracy evaluates the error in the angle measurement results, and resolution tests the ability of the sensor to resolve the angles of two targets with the same radial distance. The angle measurement performance depends on the antenna design, so results may not be repeatable when using a different antenna configuration. However, the results shown in this section provide a reference with a typical patch antenna design.

In the angle measurements, all data is acquired with the time division multiplexing MIMO chirp configuration. In other words, TX1 and TX2 alternate from chirp to chirp. This is possible because TX1 and TX2 are placed with separation of twice the wavelength, as shown in [Figure 1](#).

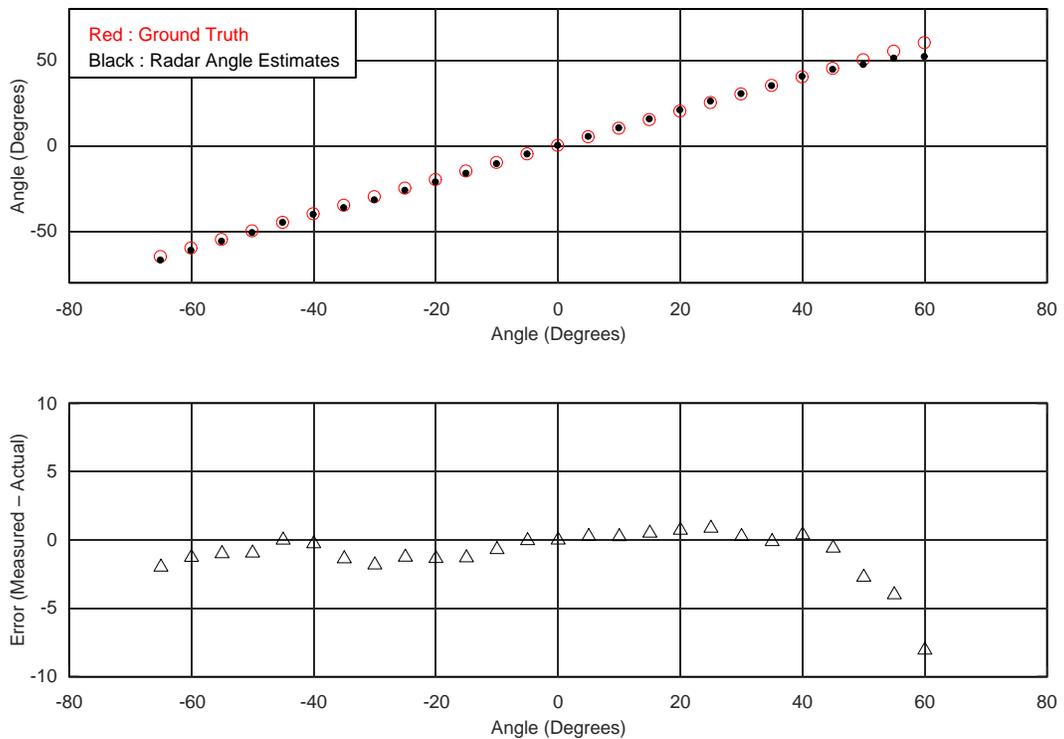
### 2.2.1 Angle Accuracy

In this experiment, a corner reflector is fixed at a location, about 2.6 meters away from the radar. The radar is mounted on a mechanical rotation stage, rotating in a range from  $-70^\circ$  to  $70^\circ$ , with a step size of  $5^\circ$ . Two signal bandwidth cases are tested. One case is 3.6 GHz, referred to as high-resolution mode in this section. The other case is 0.6 GHz, referred to as low-resolution mode. After raw data is collected, range FFT is applied to identify the corner reflector, followed by angle estimation using beam-forming on the range bin corresponding to the corner reflector.

[Figure 6](#) and [Figure 7](#) show the angle estimation accuracy when placing the object at different angles in high-resolution mode and low-resolution mode, respectively. We observe that the angle estimation error is less than  $1^\circ$  in the bore side, and the error increases as the incidence angle increases. The level of accuracy is similar in two range resolution modes, as shown in [Figure 6](#) and [Figure 7](#). However, in a practical scene, other objects may be in close range of the interested target, in which case, the range resolution matters.



**Figure 6. Angle Estimation Accuracy in High-Resolution Mode**



**Figure 7. Angle Estimation Accuracy in Low-Resolution Mode**

### 2.2.2 Angle Resolution

In this experiment, two corner reflectors are placed at different separation angles by changing their lateral distance, as shown in Figure 8. The distance between the radar and the midpoint of the two corner reflectors is fixed at approximately 2 meters. The lateral distance is changed to 20 cm, 60 cm, 80 cm, and 130 cm, respectively. The corresponding angle separation is approximately 5.7°, 17°, 22.6°, and 36°, respectively.

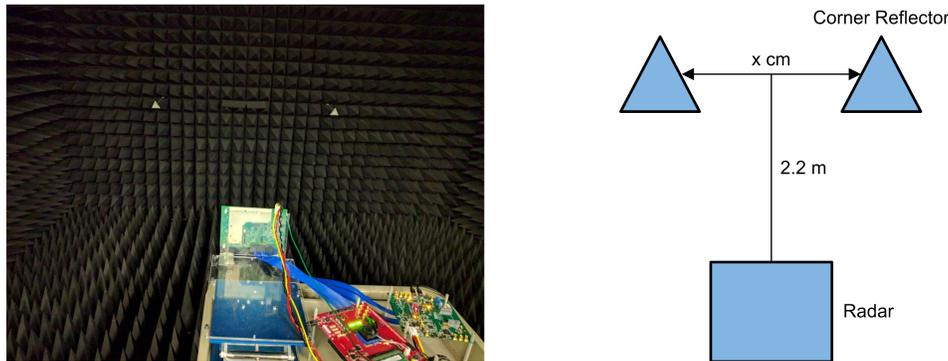


Figure 8. Experiment Setup for Angle Resolution Measurement

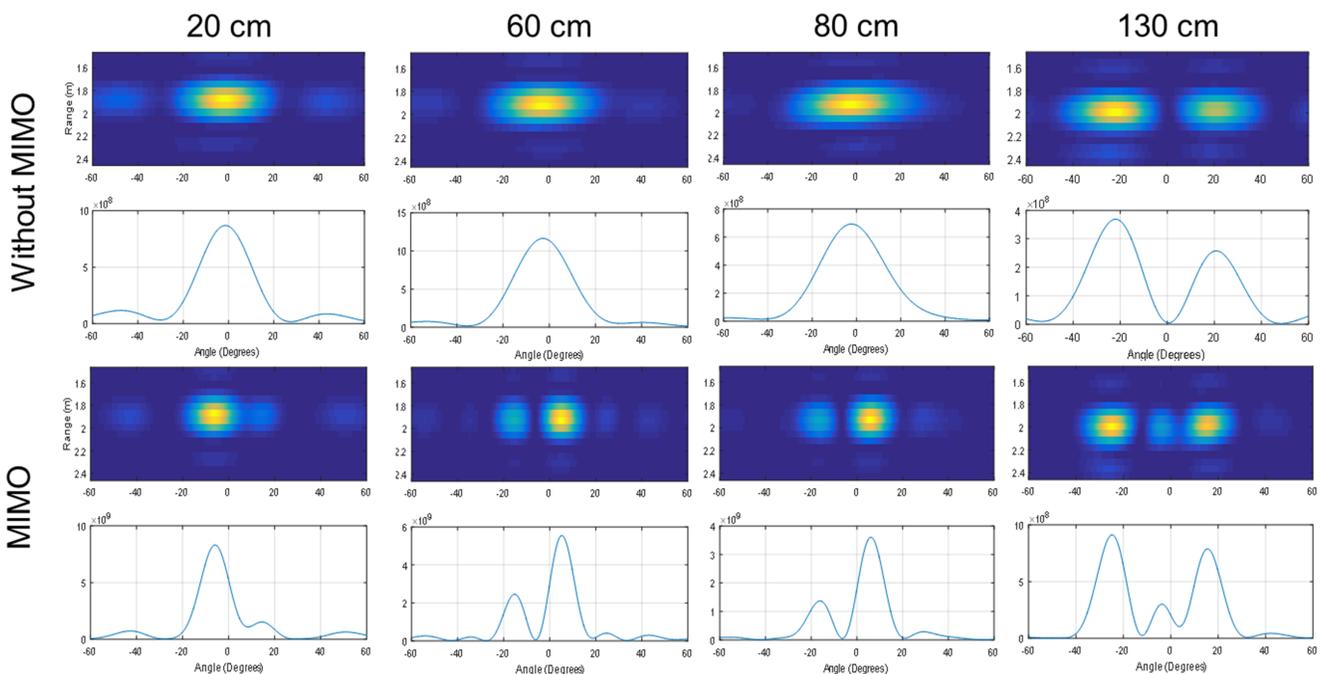


Figure 9. Range-Angle 2D Energy Plot With Different Angle Separation

Figure 9 shows the angle resolution measurement results. The top range and angle plot show the color-coded energy after range FFT and beam forming. The brighter spots correspond to the locations of the corner reflectors. Ideally, we should see two separate bright spots for the two corner reflectors. The bottom 1D spectrum plot shows the energy level as a function of angle at the range where the corner reflector is located. Figure 9 compares the performance with and without the MIMO technique. Without MIMO, the angle resolution is determined by the aperture of four receiver antennas. With MIMO, the angle resolution should be improved by a factor of 2. From the results, it is observed that with MIMO the radar sensor can resolve the two targets when separated by 17°. However, without MIMO, the separation angle must be at least 36° to be resolved sufficiently. The theoretically estimated angle resolution with four RX antennas and eight RX antennas is 35° and 17.5°, respectively. So the experiment results are close to the expected performance.

### 3 Outdoor Measurements

The outdoor measurement tests the ability to detect different types of objects at different distances. The test objects include a standard corner reflector with RCS of 0.1 square meters, pedestrian, and car. Two chirp configurations are considered during data collection, as shown in Table 2, referred to as high-resolution mode and low-resolution mode. The radar is mounted at approximately 0.5 meter above the ground, as shown in Figure 10. The radar is facing an empty parking lot. The measuring tape is fixed on the ground as a distance reference. For different tests, targets are placed at various distances.

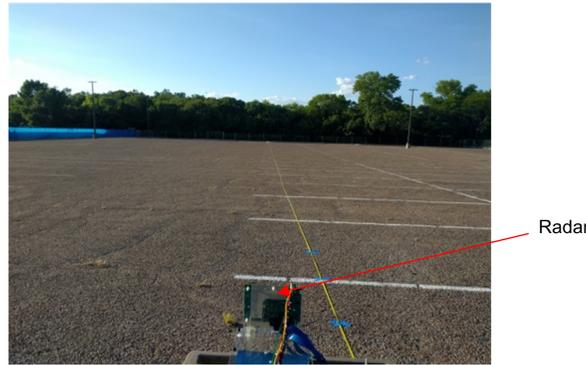


Figure 10. Outdoor Measurement Field

Table 2. Chirp Configuration of Two Resolution Modes

Parameters	High Resolution	Low Resolution
Bandwidth (MHz)	3600	600
Chirp duration ( $\mu$ s)	100	32
ADC samples per chirp	1000	256
Chirps per frame	32	128
Frame periodicity (ms)	40	40
Maximum beat frequency (MHz) $F_s$	10	8
Range resolution (cm)	4.16	25
Maximum unambiguous range (m)	41.6	64

The raw ADC data is analyzed by applying range FFT on RX1 channel only. Chirps within a frame are averaged to improve the SNR of the targets. In a typical FMCW signal processing chain, a second Doppler FFT follows range FFT to obtain velocity information. For a static object, this second step FFT is equivalent to averaging. Further, SNR gain can be achieved by signal integration along the receiver antenna array.

Figure 11, Figure 12, and Figure 13 show the outdoor range measurement results for the three types of targets. Range profiles of different tests are overlaid in different colors. The peaks correspond to the target locations in different tests. The x-axis is the range and the y-axis is the signal amplitude in dBFs.

Figure 11, Figure 12, and Figure 13 also show the range measurement for both high and low resolution. As the target range increases, the received signal amplitude decreases as expected. According to the results, the corner reflector with RCS of 0.1 square meters can be detected at 30 meters, a static pedestrian can be detected at around 27 meters, and a car can be detected at approximately 56 meters. All three targets are detectable at the maximum test distance at which the data is taken.

It is important to note that it does not mean that the device is only capable to detect objects to this range limit. The range performance also depends on chirp configuration and signal processing algorithm. The measurement presented in this application note is just to provide an example.

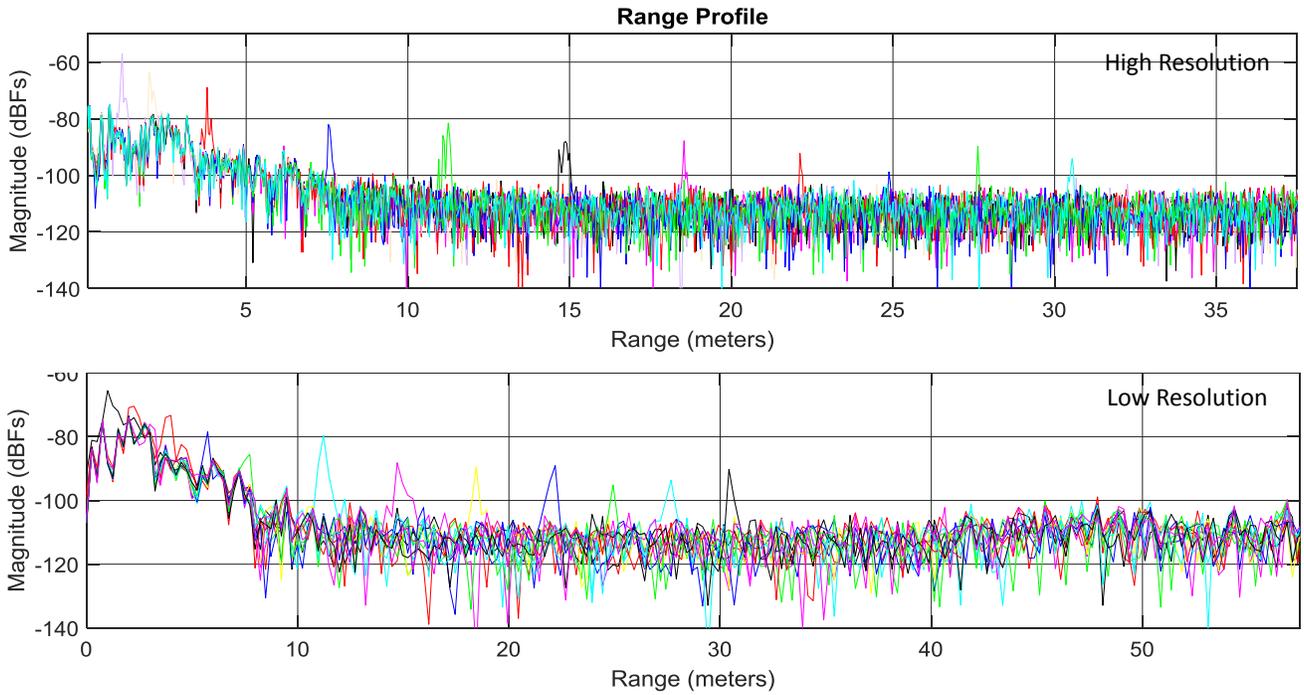


Figure 11. Range Profile of Corner Reflector (RCS = 0.1) at Different Distances

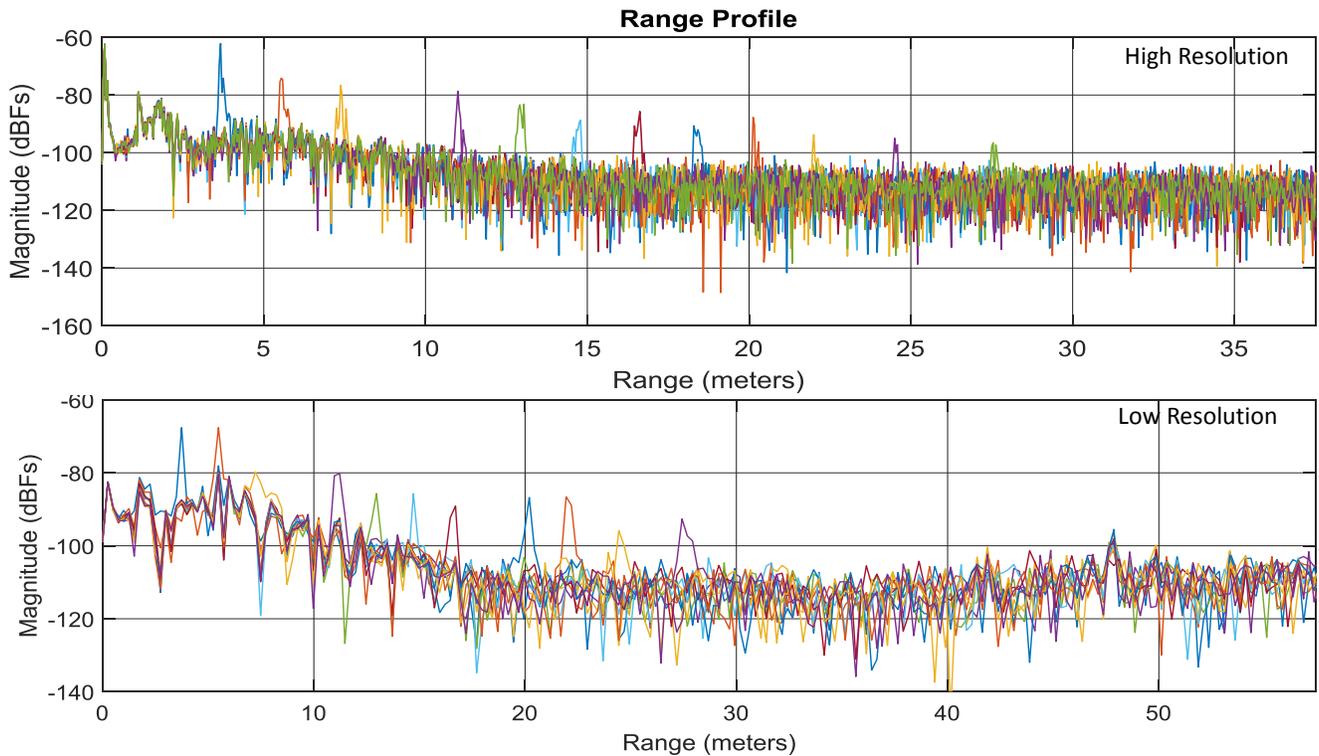
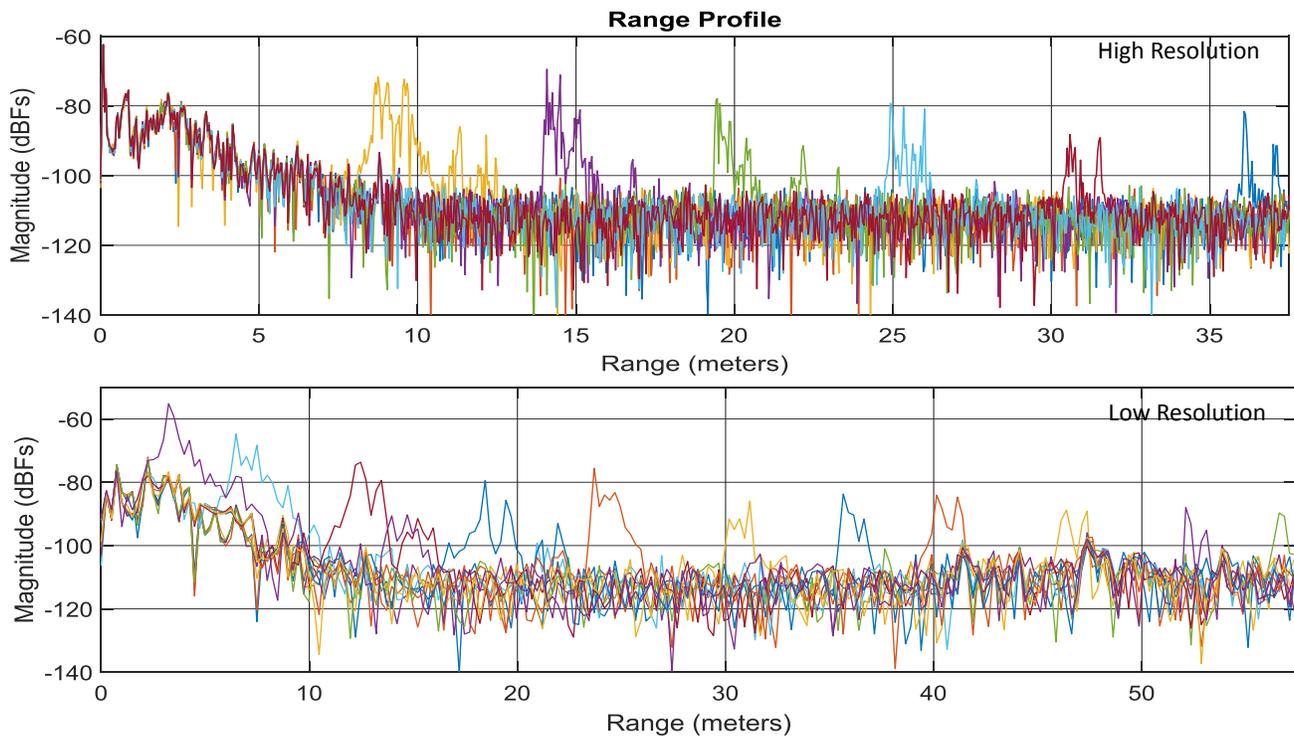


Figure 12. Range Profile of Pedestrian at Different Distances



**Figure 13. Range Profile of Car at Different Distances**

#### 4 Summary

In this application report, we presented the system performance measurement results using TI's mmWave sensor front end device. The front end is configured to work in different modes. The indoor performance evaluation covers range resolution as well as angle accuracy and resolution. The outdoor measurement shows the ability of the radar to detect different types of targets in range.

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