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How to actually use mmW Sensing

Fundamentals of mmW

Millimeter waves (mmW) are essentially RF signals with free-space wavelengths (λ) ranging between 10mm and 1mm. Applying the formula:

$$f = \frac{c}{\lambda}$$

where *c* is the speed of light (roughly 3×10^8m/s), their corresponding frequencies (*f*) lie between 30GHz and 300GHz. In practice though, most mmW modules operate within a narrower frequency range of 24GHz-81GHz, where most common unlicensed or ISM bands are located.

In contrast to microwaves, for which it only takes a metal mesh with a few centimeters (about an inch) of grating to block a significant portion of the radiated RF signal (e.g. Faraday cage in your microwave oven), mmW signals pass through a mesh with 1 inch grating easily.

This is one of the main features of mmW, behaving almost like visible light in most use case scenarios, where the target object is (but not always necessarily) in the line-of-sight. If you're familiar with ultrasonic sensors or Lidar, you can think of mmW as the middle ground since it has the precision of those optical sensors, as well as the reliability of RF in most weather conditions/obstructions.

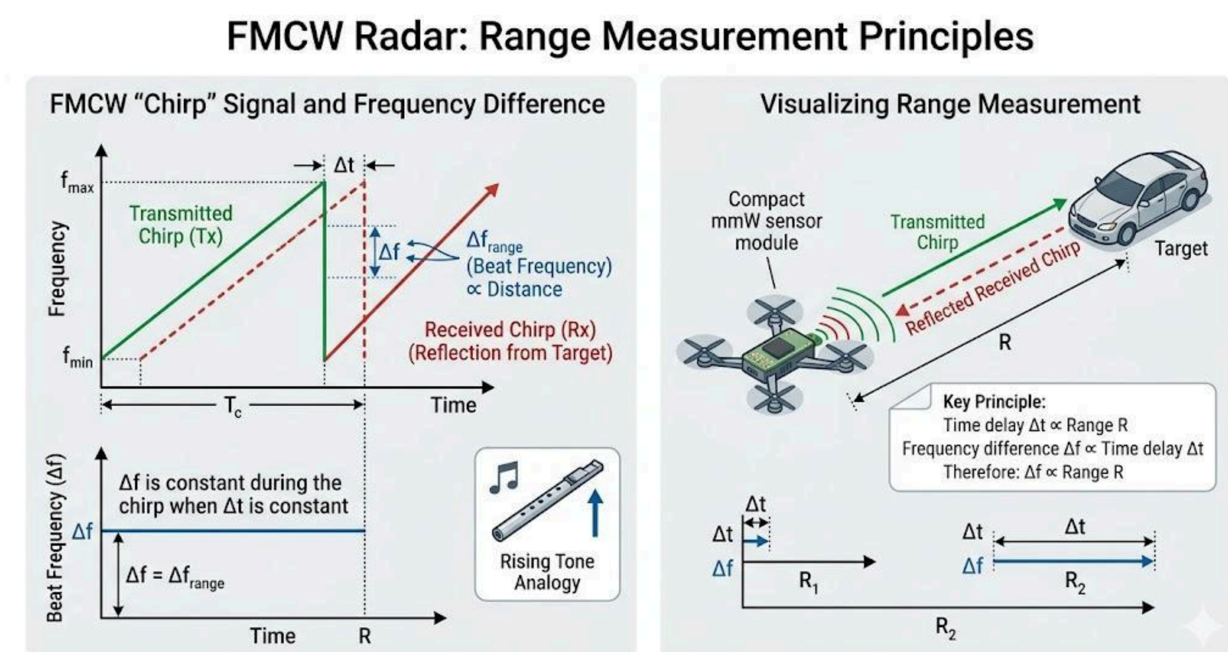
Key takeaway

"mmW has the precision of optical, but combined with the reliability of RF in most weather conditions/obstructions."

Principles of mmW Sensing

Most modern mmW modules transmit FMCW (Frequency Modulated Continuous Wave) signals. Instead of sending out a single "ping", it sends out a "chirp". Imagine the sensor rapidly sweeping its frequency upward, like a slide whistle going from a low note to a high note. This sweep is called a chirp. The sensing is performed as follows:

1. The sensor sends a chirp.
2. The chirp hits an object (like a wall or another drone) and bounces back.
3. By the time the reflection gets back to the sensor, the "outgoing" chirp has already moved to a higher frequency.
4. The sensor compares the frequency of the received signal to the current outgoing signal. The difference between those two frequencies tells you exactly how far away the object is.



Knowing where an object is, in most cases, isn't enough for a robot or unmanned aerial systems (UAS). You need to know how fast it's moving and where it is in 3D space. Taking advantage of small wavelengths of mmW, even a tiny movement in the target causes a shift in the phase of the returning signal. By sending a sequence of chirps very quickly, the sensor can calculate the Doppler Shift. In a UAS application this allows a drone to distinguish between a stationary tree and a moving bird, or even measure its own ground speed with high precision.

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Key Benefits of mmW

One of the main benefits of mmW modules is their reliability in all weather and lighting conditions. Lidar systems or cameras are prone to producing highly noisy data if there is too much light (glare) or too little (darkness), or if the air is thick with dust or rain. Wavelengths in mmW systems are right in the sweet spot, i.e. large enough to ignore small particles like raindrops or smoke but small enough to reflect off solid objects.

Unlike a camera, which has to compare two sequential frames and perform computations to guess if an object is moving, mmW uses the Doppler Effect to get instantaneous velocity. A drone equipped with mmW radar can detect the speed of a car approaching at 60 mph the millisecond it detects the first reflection.

Another upper hand of mmW modules is their compactness in size. For instance at 77GHz, the wavelength is about 3.9mm. Since antennas need to be around half the wavelength large, you can fit a massive array into a space the size of a penny. This small footprint is why mmW is so beneficial for UAS and small autonomous robots where every gram of payload matters.

Key takeaway

"Wavelengths in mmW systems are right in the sweet spot, large enough to ignore small particles like raindrops or smoke but small enough to reflect off larger objects."

Understanding the Specifications of mmW hardware

Operation Frequency

The operation frequency of a mmW module is a fundamental trade-off between physical size, and sensing precision. Higher frequency means shorter wavelength, which allows for use of smaller antennas to detect higher range resolution.

Below is a list of common off-the-shelf mmW modules and their specified parameters that are relevant for RF and sensing. As it can be seen, there are 3 common frequency bands: 24GHz, 60GHz and 76-81GHz.

Product	Application	Frequency	Transmit Power	Antenna Beamwidth	Max. Range
DFRobot C4001	Motion detection	24GHz	n/a	100° x 40°	25m
DFRobot C1001	Monitoring & detection	60GHz	6dBm (4mW)	100° x 100°	11m
Jorjin MM5D91-00	Presence detection	60GHz	4dBm (2.5mW)	90° x 80°	10m
SeedStudio MR60FDA1	Motion detection	60GHz	6dBm (4mW)	60° x 60°	6m
Texas Instruments AWR1843AOP	Automotive radar	76-81GHz	6dBm (4mW)	60° x 60°	100m
Texas Instruments IWR1843AOP	Motion detection (industrial)	76-81GHz	6dBm (4mW)	60° x 60°	50m

24GHz band: Suited for basic motion detection (like a smart light) or simple sensing. However, since the bandwidth is narrow, the range resolution is poor (< 50cm). If two objects are closer than 50cm, they look like one blob. The antennas are also relatively large, making it bulky for a small drone or a compact robot.

60GHz band: Considered as the indoor/industrial band and can be used for UAS indoor navigation, gesture control or warehouse robots. Although, 60 GHz sits at a specific resonance point where oxygen molecules absorb the signal, drastically limiting the range (often <20m). While that sounds bad, it's actually a benefit for indoor robots as it prevents your sensor from getting interference from a robot in the next room, and it's very hard for someone to "snoop" on the signal from outside.

76-81GHz band: Regarded as the gold standard for autonomous movement, its high bandwidth (around 4GHz) enables sub-4cm range resolution. The antenna sizes at these frequencies are also tiny so that manufacturers can put them directly on the chip package. For a drone, an antenna-on-package (AoP) sensor is the size of a micro-SD card, while providing enough resolution to detect a power line or a thin tree branch.

Maximum Range & Range Resolution

Maximum range (R_{max}) is often limited by the link budget, which is related to transmit power and antenna gain. In digital systems-on-chip (SoC) though, it's also limited by your sampling rate. It is defined by the famous radar equation:

$$R_{\max} = \sqrt[4]{\frac{P_s G^2 \lambda^2 \sigma}{P_{e_{\min}} (4\pi)^3}}$$

where P_s is transmitted power (in Watts), G is antenna gain (converted to linear units from dB), σ is radar cross section of the object (in m^2) and $P_{e,min}$ is the minimum received signal (in Watts). Range Resolution (d_r) is only determined by the bandwidth (BW).

$$d_r = \frac{c}{BW}$$

Example case: If you need to see a car at further than 100 meters, you need a module with a high-gain antenna array (i.e. with low beamwidth). If you only need to detect a person at a few meters you can sacrifice range for a wider dispersion of signal. Assume you have 4 GHz of bandwidth (e.g., 77 GHz to 81 GHz), your range resolution is about 3.75 cm. If you only have 1 GHz of bandwidth, your range resolution is 15 cm.

In other words, transmit power and antenna gain define the maximum range whereas bandwidth defines the minimum distance of an object you are able to detect.

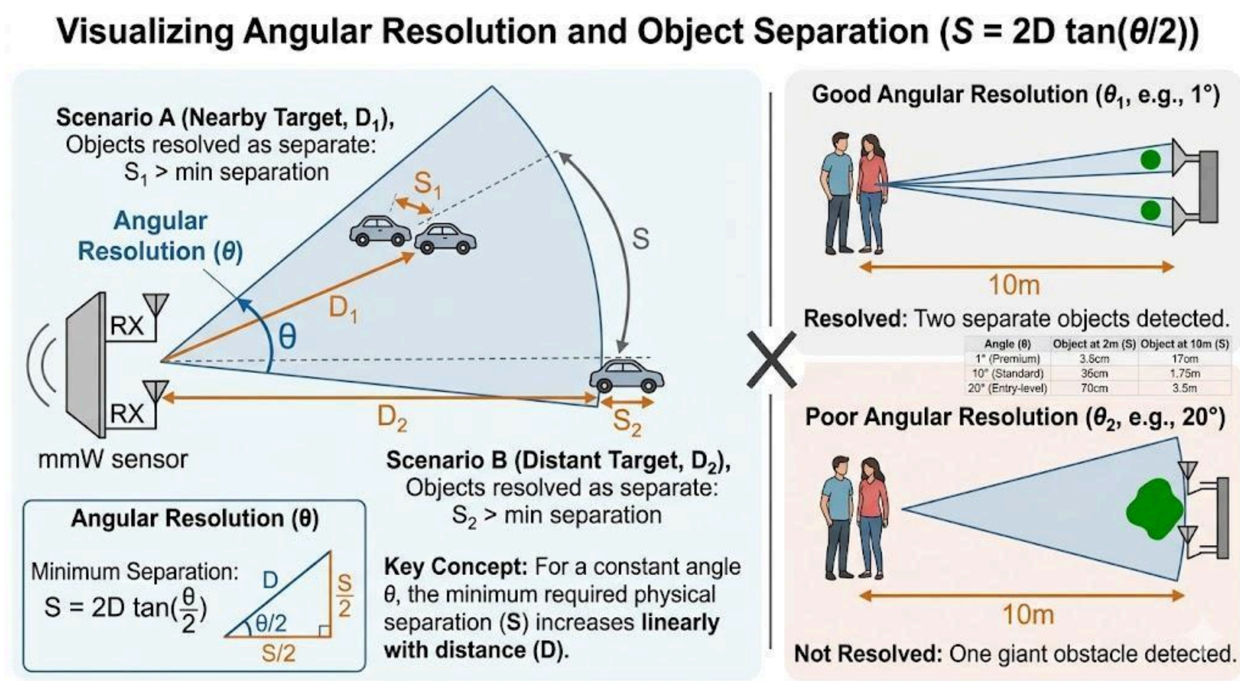
Angular Resolution

Angular resolution (θ) can be translated into a physical distance (S) between objects using:

$$S = 2 \cdot D \cdot tan(\frac{\theta}{2})$$

where D is the distance from the sensor. Understanding how angular resolution actually translates into a detectable object at a distance. Below is a table of calculated S as a function of θ and D.

Angular Resolution (θ)	**Object at D = 2m**	**Object at D = 10m**	**Object at D = 50m**
1° (Premium)	S = 3.5cm	S = 17cm	S = 87cm
10° (Standard)	S = 35cm	S = 1.75m	S = 8.7m
20° (Entry-level)	S = 70cm	S = 3.5m	S = 17.6m

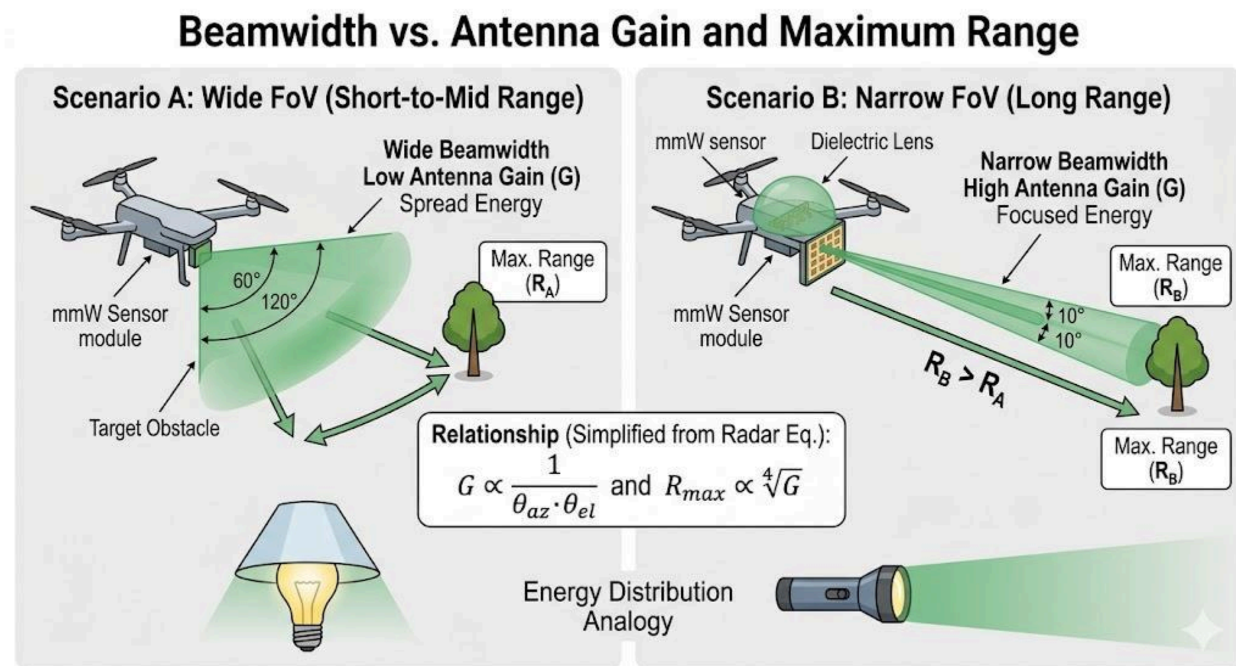


Example cases: In case you are building an automated parking system and need to distinguish a concrete pillar from a car door at 10 meters, a 15° resolution is not sufficient since it will just see one giant obstacle. You would need a module with more Rx antennas (which narrows the beam hence, higher gain). In another example, if two people (at D = 10m away) are standing 10 cm apart, a S = 17cm resolution sensor will see them as one single blob. That means if your application includes e.g. gesture control you need higher resolution. If you are just sensing presence, lower resolution should be fine.

Field of View (FoV)

Field of View (FoV) defines whether a sensor detects the entire surrounding or focuses on a specific region. If a sensor has a narrow FOV, it allows detection at a higher range. If it's too wide, the energy is spread out in space so that anything further than a few meters away would be too far to detect. The amount of transmit power of a mmW module is strictly limited and it's usually around several mW. Focusing that into a tight beam (e.g., 10° FOV) makes a tiny spot very far away visible and this is how long range automotive radar works. If you spread the beam out to cover a whole room (e.g., 120° FOV), you can see everything in front of the sensor, but the energy doesn't reach nearly as far.

It can also be noticed that most mmW modules have a wide horizontal FOV (azimuth) but a narrow vertical FOV (elevation). This is crucial for drones to detect obstacles to their left and right while moving forward. But if the vertical beam is too wide, it constantly reflects off the floor, creating a massive amount of noise that hides the actual obstacles to care about.



Application-Based Selection

All things considered, this table can help you narrow down your module search:

Application	Most Critical Aspect	Favorable Datasheet Parameters
Human presence	Field of view (FoV)	Wide angle (beamwidth > 90°)
Gesture control	Range resolution	High bandwidth (> 4GHz), high frame rate
Medical monitoring	Sensitivity	High frequency (> 60GHz), high ADC bits
Traffic monitoring	Angular res. & max. range	High-gain antenna array (beamwidth < 20°)