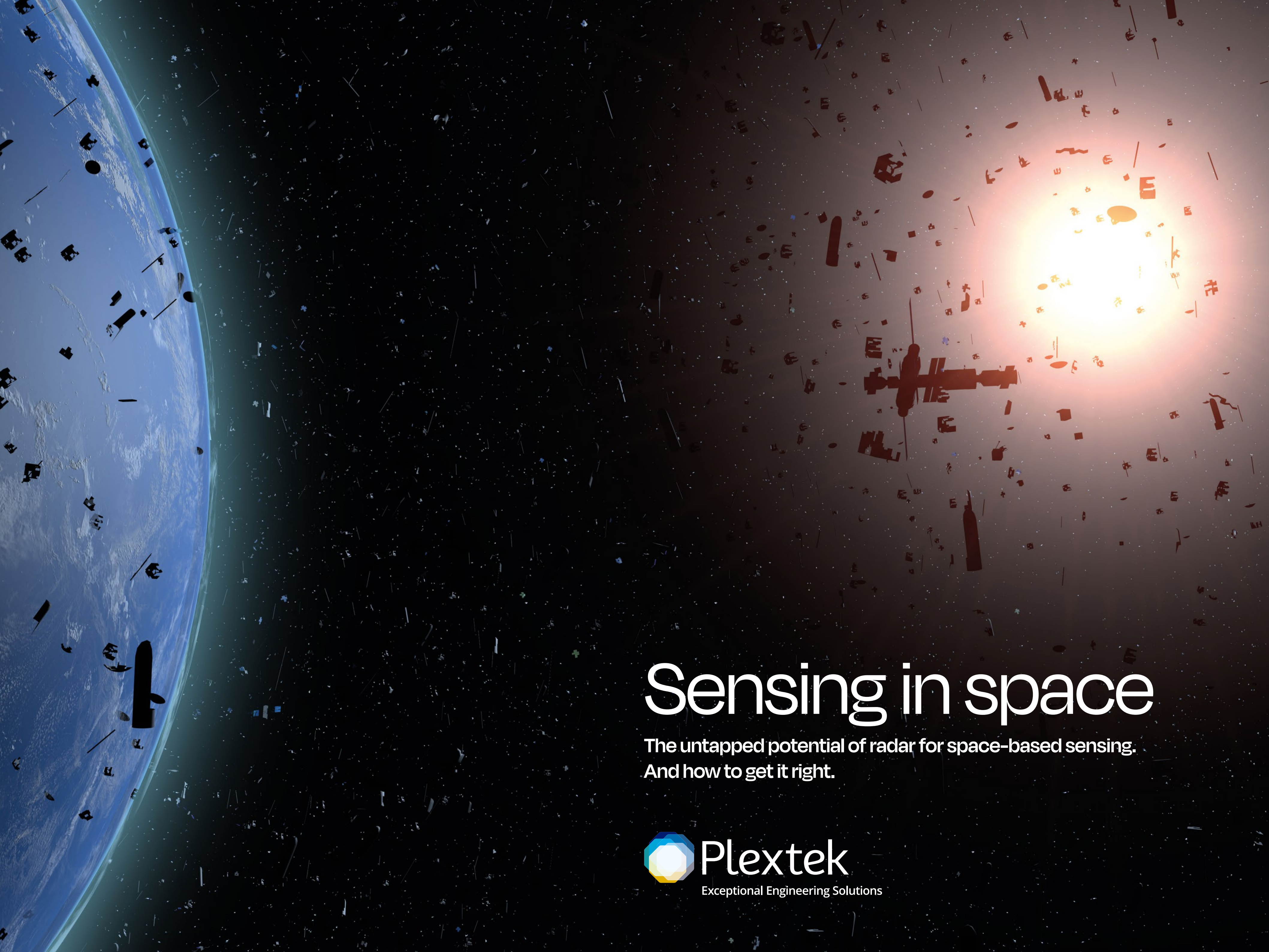

Sensing in space

The untapped potential of radar for space-based sensing.
And how to get it right.

Plextek
Exceptional Engineering Solutions

Introduction: Why space sensing matters

Space holds vast promise. Orbiting satellites have already enabled global communications and allowed us to learn about our planet's climate. This is just the beginning. Companies that exist today are dreaming of mining asteroids, putting giant solar farms in space, setting up satellite manufacturing facilities in orbit, and building settlements on the Moon.

But with development comes responsibility. Space has long been like the Wild West. To function as a mature economy, it will require enforceable regulations, including the monitoring and control of orbital zones and the establishment of precise orbital corridors. The growing levels of space debris – from dead satellites to peeled-off paint flecks that hurtle through space faster than bullets – also represents a real concern for this burgeoning industry.

As spacecraft evolve, sensing designs will need to be both functional and fit for purpose. They will need to be robust, lightweight, capable of working in extreme conditions, able to survive launches, and be affordable and scalable to support today's space innovators as they plot their course into business' final frontier.

Both the opportunities and threats will require greater sensing capabilities for the space industry. Spacecraft and satellites will need to locate targets and dock precisely, whilst threats and obstacles – no matter how small – will need to be detected and avoided accurately and routinely.

In this paper, we explore the role of radar to deliver this sensing capability. We believe, as we will argue, that whilst LiDAR is often the go-to today, radar will eventually become the *de facto* space based sensing technology.

We will explain radar, how it works, and why it is suited to space. It will also discuss considerations for space companies when deploying any sensing technology.

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Part 1: Why radar should be on your radar

We advocate radar because it has a number of benefits over optical technologies. When designed optimally, it offers good range and large area coverage, sufficient resolution for nearly all foreseeable space sensing applications, and can work in all visibility conditions – when the Sun is in line of sight, during an eclipse, and in dust for missions on celestial bodies.

With the right expertise, mmWave radar can be designed for low cost, size, weight, and power, and to avoid moving parts that can break – all important considerations when putting it onto a satellite or spacecraft.

How radar works

We'll start with a simple explainer of radar sensing (feel free to skip this part if you are already a radar expert).

Imagine you are standing in a pitch black room, firing rubber balls in every direction. Some will hit surfaces that bounce them straight back at you. If you know the speed and direction of the ball, and you time how long it takes to hit you (and you are good at mental arithmetic), you could work out the positions of the rebounding surfaces. Taking all those data points, you could build up a picture of the room around you.

Radar sends out electromagnetic (EM) waves rather than rubber balls, but the principle is analogous – we measure the reflections and use it to calculate the position of objects relative to the radar.

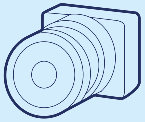
We can be more accurate than our ball firer, measuring precise positions of objects, and even features on objects, in some cases down to millimeter accuracy. We can even measure how the object is moving by looking at frequency changes in the returned wave, known as Doppler shift.

All of which of course needs a very precise signal, very precise measurement, and carefully designed algorithms that turn information embedded within the electromagnetic waves into actionable data on what is being seen, for by humans or machine decisions.

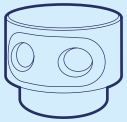
> Radar excels in detecting objects over long distances, and those moving quickly. It is unaffected by lighting conditions and less affected by fine particles.

Sensing technologies: The options

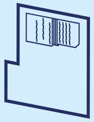
There are three primary approaches for autonomous platforms:



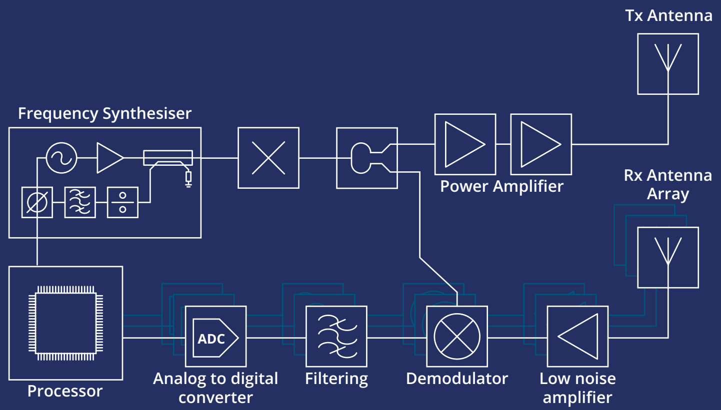
Optical cameras
Can capture detailed, color-rich images mimicking human vision, but highly dependent on lighting conditions and struggle in very bright, dark or high contrast environments.



LiDAR (Light Detection and Ranging)
Uses laser pulses with short infrared wavelengths to capture very detailed depth images and create high-resolution 3D maps but tends to only work well in good conditions. But its laser light is scattered and absorbed by fine particles such as dust, limiting its applications on celestial bodies such as asteroids and moons. Furthermore, its performance is degraded when the Sun is within its field of view.



Radar (Radio Detection and Ranging)
Uses radio waves to detect objects and measure their speed, distance, and bearing. It offers lower resolution than LiDAR but excels in detecting objects over long distances, and those moving quickly. It is unaffected by lighting conditions and less affected by fine particles.



The anatomy of a radar

A radar typically consists of the following components, contained on a printed circuit board.

- **Frequency synthesizer**
  Generates the signal.
- **Amplifier**
  Amplifies the signal.
- **Modulator**
  Controls the frequency as the signal moves across its bandwidth.
- **Antenna**
  Transmits the signal into space.
- **Receiving antenna**
  Receives the signal response (there may be many of these in an array).
- **Low noise amplifier**
  Amplifies the return signal. This needs to be very efficient to amplify signal and remove any noise.
- **Demodulator**
  Extracts data from the signal by removing modulation (the signal contains information waves and carrier waves. Demodulation removes the carrier waves, like taking a letter out of an envelope).
- **Analog to digital converter**
  Digitize to extract information into a digital format.
- **Post Processing**
  Classification to use relevant information to define what has been detected.

The best wavelength for space sensing?

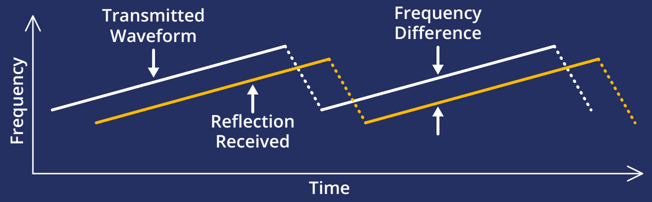
The wavelength of an electromagnetic signal plays a crucial role in determining the size of the objects you can detect. If the object is larger than the wavelength, the signal will tend to reflect strongly, making detection easier. However, if the object is smaller than the wavelength, the signal tends to bend or diffract around it, making detection more difficult.

Long wavelengths travel great distances and pass through many obstacles, which makes them ideal for long-range sensing. However, they lack precision. Think of a large ocean wave. If it encounters a small boat, the wave will mostly roll past it, barely disturbed. You might detect the boat from the way the wave changes, but you wouldn't know much about its shape or details. These long wavelengths are excellent for detecting large objects but aren't suited for detecting small objects nor picking out fine detail.

On the other hand, short wavelengths such as those used by lasers (of order a thousandth of a mm) are great at providing detailed information, but over a smaller area. Imagine shining a laser beam on a textured surface. Every bump and flaw will be highlighted, revealing intricate details about the surface. However, this kind of precision comes with trade-offs—it requires more time and energy to cover a large area, and it would only work in a very clean environment, since even dust particles would scatter the beam.

In practice, you need to choose a wavelength that is tuned to the size of what you're looking for. If you go too small, you'll end up obtaining more detail than necessary and risk interference from objects you don't care about. This is especially important for missions on planetary surfaces, where the environment can be full of dust, though less of a concern in space, which is largely empty.

Wavelength alone doesn't tell the full story, however. Radar systems typically transmit pulses that cover a range of wavelengths, i.e. they have bandwidth. Using just one wavelength can make it hard to tell the difference between two closely spaced objects. Frequency Modulated Continuous Wave (FMCW) radar, for instance, sweeps through a range of frequencies in each pulse and this in turn enables a radar to discriminate between objects at different ranges.

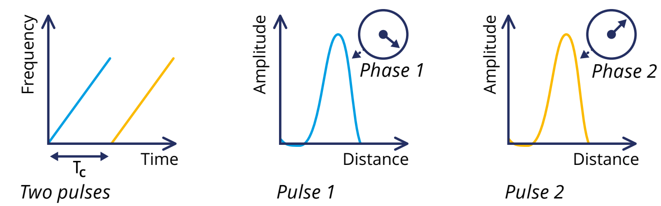


For FMCW radars the frequency difference between the transmitted and the reflected wave encodes the distance to that object.

The ability to discriminate between objects at different ranges is called range resolution, and the range resolution improves with increased bandwidth. In FMCW radar, the duration of the pulse can be increased to improve the signal to noise ratio, to improve the radar's ability to detect and distinguish between targets.

Radar can measure the speed of objects, and movements within objects such as a loose part hanging off a satellite that is moving counter to the satellite trajectory.

The phase difference between pulses encodes the target's velocity.



Why mmWave Radar?

Radar has been around for a long time, but has recently advanced significantly in its detection ability, particularly thanks to research and innovations coming out of the automotive sector. This has led to mmWave radar. These operate at frequencies of 30–300 GHz, which as the name suggests, produces a wavelength of 1–10 mm.

We argue that mmWave is the ideal balance for many space applications. It is much more accurate than traditional microwave wavelength radar (a few centimeters in wavelength), which has insufficient resolution for picking out smaller spacecraft features. mmWave radar is also cheaper and more practical than LiDAR, and although LiDAR has better resolution, such precision comes at a cost of high-power requirements and is rarely needed for most space applications.

mmWave radar sits perfectly in the middle. It can have a wide field of view – an antenna can emit a wave that travels over a wide angle and detect objects down to a few mm in scale. That offers sufficient resolution to see small details like detached paint flecks or loose parts, and for navigation when docking to another spacecraft. It does all this with low weight and power requirements, and no moving parts.

Radar can measure the speed of objects, and movements within objects such as a loose part hanging off a satellite that is moving counter to the satellite trajectory, even at Low Earth Orbit speeds of over 7 km per second. This is achieved by measuring the Doppler effect, where the wavelength of the signal effectively gets squashed or elongated as it bounces off an object that is moving towards or away from it.

Because space is fairly empty, radar is not impacted by unwanted clutter that would scatter mm-scale waves – it can just peer out and detect anything in its range. However, on lunar and planetary missions where sub-mm sized dust particles can obscure the view of a short wavelength LiDAR system, radar can continue to operate reliably due to its longer wavelength.

A final benefit is that radar is not affected by the Sun. The main alternative, LiDAR, uses wavelengths in the infrared (IR) part of the EM spectrum. That means it can be interfered with by other IR sources, and the Sun is a big source. It is not dissimilar to how human eyes process information – they can detect phenomenal detail in good light but imagine trying to keep a plane in focus as it crosses between you and the Sun (don't actually do this!). Although the Sun does emit waves in the radio frequencies used by radar, they are at far lower levels, have very low impact, and even where they are an issue, can be mitigated through signal processing.

Part 2: Beyond the wavelength – optimizing sensing technologies for space applications

So far, we have made a case for mmWave radar for space sensing. But wherever you settle, there is much that can be done through clever engineering to get the most out of your sensing solutions and overcome some of the trade-offs. In this section, we will discuss this, particularly in relation to radar but much also applies to LiDAR.

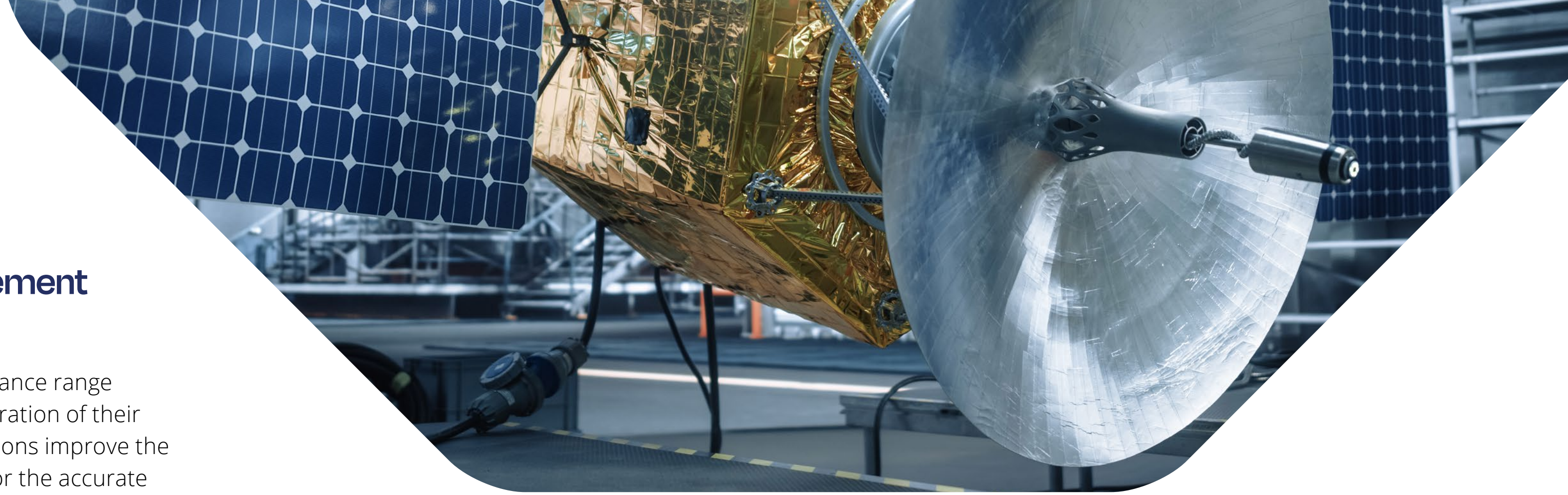
Maximizing the field of vision

Radar waves reflect off surfaces and features with some of the signal returning back to the radar. By increasing the receiver size, more signal can be detected, and so more detail gained (just like a zoom lens on a camera). This is usually done via a panel with an array of receivers, or alternatively with receivers dispersed over several satellites. The challenge in either case is ensuring all receiving antennas are synchronized. Signals from the different receivers are combined to increase the signal-to-noise ratio and determine the angle of arrival.

We can also use a technique called SAR (Synthetic Aperture Radar) processing to 'make the receiver bigger'. This involves taking multiple radar measurements from slightly different positions as the craft moves through space and offsetting the change in position through onboard calculations. SAR processing enables the resolution of a much larger antenna, without the added weight and physical dimensions.

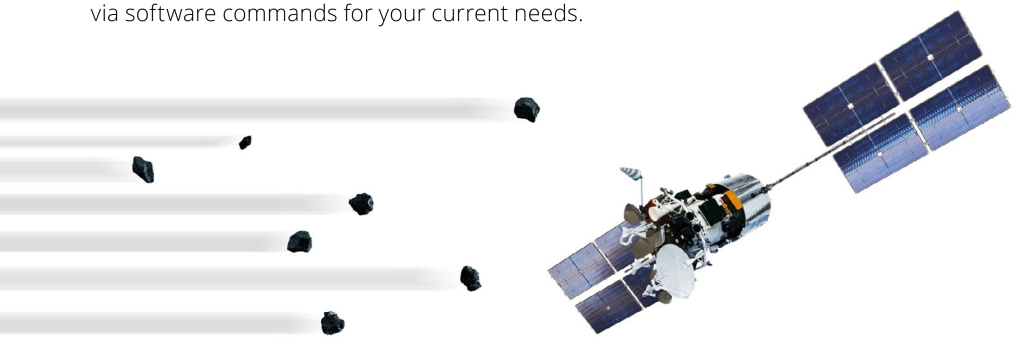
> By increasing the receiver size, more signal can be detected, and so more detail gained (just like a zoom lens on a camera)

Any use case can deploy a mix of these and other techniques to navigate trade offs and get the best from the signal for the mission's needs. And of course, the final design can be tested to provide accurate readouts of its range and angular resolution, and margins of error and limitations, which support better decisions with the resulting data.



Navigating distance vs movement detection trade-off

Radar systems, including FMCW radar, balance range and velocity detection by adjusting the duration of their transmissions. Longer duration transmissions improve the maximum unambiguous range, allowing for the accurate detection of distant objects, whilst shorter transmissions enhance the ability to accurately measure the velocity of fast-moving objects. This balance is influenced by the range-Doppler ambiguity problem, where optimizing for unambiguous range detection can compromise velocity measurement and vice versa. Modern radar systems can dynamically reconfigure their settings via software to address these trade-offs. So, if you want to detect debris hurtling past you or far away satellites, radars can be rapidly re-configured via software commands for your current needs.



> Whether you want to detect debris hurtling past you, or far away satellites, radar can be rapidly re-configured with software for your current needs.

Low Size, Weight, Power, Cost (SWaP-C)

Beyond its sensing capabilities, the next big concern for any satellite-based system is minimizing size and weight (to keep launch costs down and ensure it can be accommodated on compact spacecraft) and minimizing power (to ensure continued operation in space and reduce hard-to-remove heat generation).

The high frequency of mmWave radar already enables a small antenna. The wavelength defines the size of the antenna required to obtain a certain angular resolution, so the smaller the better from a size and weight perspective. Antennas can be further reduced in weight using techniques such as plating a lightweight plastic antenna with a metallic machined waveguide, rather than machining a metal antenna from a block of metal.

The benefits of reducing the wavelength have a cutoff point – once you get into the infrared wavelength of LiDAR, you need optical components to transmit a focused beam, rather than the wide angle antennas used for radar. Traditionally this meant rotating the beam across the detection space, requiring mechanical parts with a higher chance of failure than fixed parts. More recently, solid-state LiDAR has allowed fixed omnidirectional LiDAR, but this comes at a high cost.

mmWave radar also benefits from low power consumption, requiring only a few watts – similar to an energy efficient LED light – to generate the radar signal and run the processing algorithms.

Cost can be kept down by using off-the-shelf components where possible and customizing them for the use case, with a particular focus on antenna design. An optimized antenna captures a better signal, and so reduces the need for signal amplification electronics, so designing the radar around the antenna is a good starting point for low SWaP.

The algorithms that turn the signal into insight

The returning signal will contain lots of information that can be extracted to gain insights. The time it took to return tells you the distance to the object it bounced off. Changes in wavelength tell you how that object was moving. We can even gain insights into some material properties and structure by looking at changes to wave polarization.

Algorithms and machine learning can be used to look at micro-Doppler shifts across the object to pick out the different ways it is moving. Micro-Doppler is the unique Doppler signature of the object you are observing based on differences in the velocity of different components of the object. Consider a person walking towards you – their body would move at one velocity, but their arms would swing back and forward at different velocities. This set of Doppler returns is like a 'fingerprint' for that object and can be used to classify what is being seen, for example if there is spinning or a loose part flailing around.

Part 3: Designing sensing technology for space

Having a good radar is all very well, but it also needs to work reliably and autonomously in the challenging conditions of space. If things go wrong, there is no nearby mechanic to pop over and fix it. There are a number of considerations, but the main ones are protection from radiation, and heat removal.

Radiation

In space, there is no protective atmosphere so components are exposed to ionizing radiation both from the Sun and from outside the Solar System. This takes two forms: total ionizing dose (TID) and single event effects (SIE). The background TID accumulates over time and can gradually degrade performance of electronics, similar to how long exposure to the Sun damages the skin. With electronics this is due to changes in the arrangement of atoms in the crystal lattice of the device. SEE involves high-energy charged particles striking an electronic component, causing transient currents and charges. In precision electronics like semiconductors or memory storage, this can cause errors in processing, calculations or timing that the radar relies on, whilst the induced currents can cause permanent damage to the electronics.

The inherent low voltages of mmWave radar, when paired with careful electronic design, help minimize the risk of system lock-up when a high energy charged particle causes a surge in current. However, these measures do not eliminate the possibility, so additional protective systems are needed, which include mechanisms for excessive current.

Physical shielding helps prevent radiation reaching the electronics. Aluminum is a good material for lightweight shielding, stopping all low to mid-energy charged particles. Weight can be saved by shielding only the most sensitive components or shielding one side, then controlling the craft orientation so that side always faces the Sun.

So-called RAD-hardened components are designed for high radiation environments but can cost 10-1000x more than non-hardened components and are often a little behind the cutting edge by the time they have completed certification. Again, there are trade-offs, how much hardening you need depends on the mission and risk profile.

No amount of hardening eliminates all risks, so protection must also be built in through resiliency systems. These can be components that detect problems and correct them or reset the system. For example, Error Correction Code stores backup information which it can cross reference with the main memory, and correct simple errors, or detect more complicated ones to trigger higher-level responses. Similar approaches of using multiple or backup systems can be used across most components.

Heat

The other big issue is heat. Electronics create heat which needs to be removed, or they will fail. On Earth, heat can be convected away by the air - but there is no air in space. Spacecraft must radiate heat away using specialized materials that absorb heat from surrounding objects and release it as infrared radiation. These need careful selection and integration to maximize heat removal whilst keeping size and weight down.

> Companies with eyes on the long term business potential of space may also be starting to think about scalability.

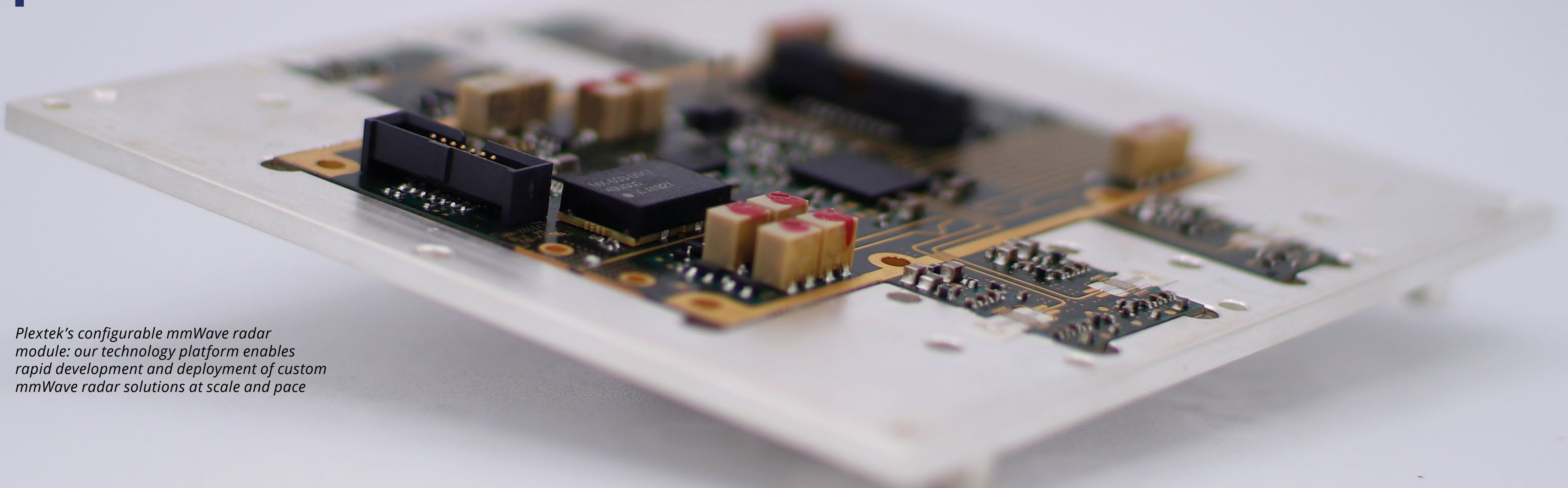
Practical considerations

Integration

Once we are happy that the solution is fit for purpose, questions might turn to the practicalities of deployment. A first might ask whether it integrates. Any system should come with emulators so it can be simulated within the rest of the spacecraft, ensuring it works and can communicate with the rest of the system before any field testing. If this sounds obvious, consider the fate of the 1999 Mars Climate Orbiter which missed its planned orbit because one component supplier used imperial units and another used metric.

Scalability

Companies with eyes on the long term business potential of space may also be starting to think about scalability. This may not be a concern for one-off missions, but companies that plan to launch lots of satellites over the coming decades, should start to consider the foundations of a sensing design that can scale as their business does. That means working with reliable suppliers of key components that can be customized for different missions, which are unlikely to be made redundant or face constant supply chain issues.



Plextek's configurable mmWave radar module: our technology platform enables rapid development and deployment of custom mmWave radar solutions at scale and pace

Part 4: The future of space sensing

We have focused on today's sensing challenges such as debris removal and docking. But longer term, radar has so much more to offer as we reach further into space. Its ability to build detailed pictures of objects without being obscured by dust makes it ideal for lunar, planetary and asteroid exploration, mapping, and mineral extraction.

For example, it could play a key role in moon missions, such as supporting the ESA's vision of establishing a base on the Moon that could become a permanent settlement. Meanwhile, companies like Axiom Space and Blue Origin are developing commercial space stations that will replace those operated by governments, and serve commercial customers, researchers, and even space tourists. As space becomes more commercial, sensing will be needed for docking and safety.

In conclusion, mmWave radar offers a robust, low SWaP, scalable sensing solution for space, with sufficiently high resolution for most use cases, without the downsides of energy demands and range limitations that come with LiDAR. For all these reasons, we believe radar will become the main sensing technology in space as the industry matures.

> As space becomes more commercial, sensing will be needed for docking and safety.

How Plextek can help

Plextek is a consultancy with deep expertise in low Size, Weight and Power (SWaP) sensing, from antenna designs to ML algorithms. We have developed mmWave radar technology, largely based on off-the-shelf components, which can be customized for specific applications. This has already been proven in space through a debris detection mission and is currently being implemented into the CLEAR debris removal mission, spearheaded by ClearSpace.

But there is no one-size-fits-all when it comes to sensing. Our team can work with space missions to assess if mmWave radar is right, and where it is, identify optimal configurations, software, and security to deliver against your performance and SWaP-C goals.

Project:

Game-Changing Radar for the CLEAR Mission

Developing vital radar technology for the CLEAR mission, advancing space debris removal techniques to safeguard operational satellites and spacecraft.

↘ **Find out more**

Our award winning mmWave radar technology improves the safety and efficiency of operations in Satellites & Space

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