How many satellites do we need?

From a pure geometry standpoint, if you have sight of three GPS satellites and know the distances to them, that should be enough to determine your 3D-position in space, i.e., your coordinates and altitude. (Actually, that would result in two possible locations. But one is so far out in space that this ambiguity can be resolved.) You can easily see how that works by imagining a string being attached to each satellite, having the length of that known distance. Tie the open ends of those three strings together and then try to move that knot so that all three strings are taut. There will be only two points for which you can accomplish that, one near the surface of earth and the other far out in space (see Figure 1, below). So, is the sight of three GPS satellites sufficient to get a position fix?

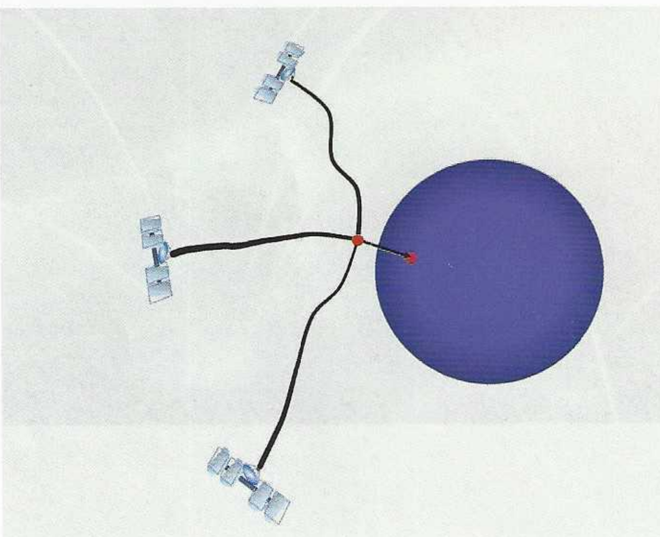

Figure 1

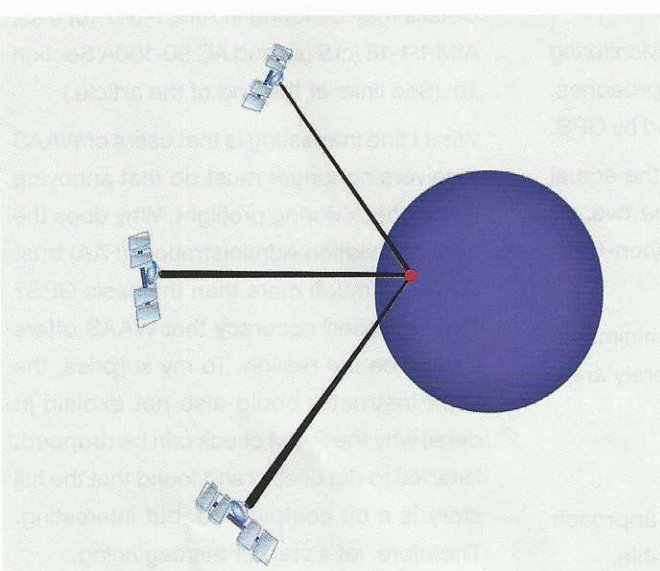

Figure 2

> ***"... users of WAAS receivers no longer must do that annoying RAIM check during preflight."***

Not really. Those distances to the satellites are being measured by the amount of time it takes for the signal to reach our receiver. The signal leaving the satellite is encoded with a time stamp and that is compared to our receiver's clock. That time difference multiplied by the speed of light is the distance of the satellite.

That however takes two ultra-precise clocks, accurate to a few nanoseconds. The clocks in the satellites are indeed of such high quality, but for cost reasons, the clocks in a common GPS receiver is several orders of magnitude less accurate. Even if we could sync our receiver clock to be absolutely correct at a specific time, it would fall out of sync again within seconds. What that leaves us with are three inaccurate distances, all incorrect by the exact same amount. This is what is called pseudo ranges. How can those pseudo ranges help us find our position?

Let us go back to the example with the three strings. If you shorten all three strings by 1 foot and pull them taut again (see Figure 2, below left), you'll arrive at a different location. Repeat that a number of times and connect the resulting points. This will form a line and our position must be somewhere on this line; it is called the line of position (see Figure 3, at right).

To find out where on this line we are located, we need a fourth satellite. For that fourth satellite we also have only a pseudo range. Let's also attach a virtual string to it and tie the open end to our knot. Now there will be only one point on our line of position on which all four strings are taut which signifies our position (see Figure 4, at right).

You could also think of it in a different way. We could pick from those four satellites four groups of three satellites each. Each of these groups gives us a line of position. The point where these four lines intersect – or nearly intersect – is our current location.

In summary, we need four GPS satellites in sight to determine our position with a conventional GPS receiver. With currently 31 GPS satellites in operation, chances are quite good that we will have four of those in sight and not too close to the horizon.

> *"... WAAS improves the GPS system by increasing accuracy, monitoring satellite health and adding three additional navigation satellites."*

For this reason, aviation grade GPS receivers are equipped with a mechanism called Receiver Autonomous Integrity Monitoring (RAIM). What RAIM does is use a fifth satellite to check the plausibility of the position delivered by the other four. Which of the five is taken for that purpose does not matter. There are five different ways to pick four satellites out of five. Our receiver calculates five different positions, one for each such pick. If all positions are sufficiently close together, we have a valid position fix with a very high degree of probability.

That is the reason we need five satellites in sight to determine our position and have a plausibility check that those satellites are all working correctly. The RAIM prediction we need to do during preflight is nothing else than a calculation of whether we will have five satellites in sight near our destination airport, for the duration of our approach (plus some safety margin), and not too close to the horizon where they could be obstructed by obstacles.

What is FDE?

What will happen if the RAIM mechanism concludes that the five calculated positions do not match? The simplest reaction of the GPS receiver would be to light up an indicator and tell us that our position fix is unreliable, upon which we would initiate a missed approach.

Can't the GPS receiver find out which of the five satellites is at fault and then calculate a correct position from the other four? No, it can't, at least not with only five satellites in view. If we had a sixth satellite in sight, some smart algorithm could do exactly that. This algorithm is called Fault Detection and Exclusion (FDE). So FDE is kind of refinement of the RAIM mechanism, a smart RAIM so to speak.

By now we need six satellites in sight to determine our position, have RAIM and FDE. Luckily, we have six satellites in view most of the time, but not always and everywhere. Certain satellite constellations, high surrounding terrain, extreme northern or southern latitudes, the fault of one or more satellites, all those things can be reasons for having fewer satellites in sight. That's why the FAA insists on doing those RAIM predictions while we are planning our flight.

Integrity the other way around

So far, we have been talking about the basic GPS system. How did WAAS then change things, you might ask. Isn't WAAS only about improved accuracy? The answer is: WAAS is a lot more than that. Let us quickly review how WAAS works.

The accuracy of the pseudo ranges, i.e., the distance measurement to the GPS satellites, is degraded by various influences, for example atmospheric distortions in the ionosphere or by small deviations of the satellite clocks, to name just two. By placing a network of 38 ground stations across the country, each of which knows its exact geographic location, and by seeing how that location deviates from the current calculated GPS position, a correction table can be calculated that helps compensate these deviations. This correction table is sent up to a geostationary satellite and from there distributed to all WAAS-equipped GPS receivers on the ground. A simple, yet genius idea! The real implementation of that idea is a lot more complex. Besides those 38 Wide Area Reference Stations in the U.S. there are three Wide Area Master Stations that consolidate the data and do the correction calculations. There is not only one, but there are three geostationary satellites that distribute the correction signal back down. Redundancy everywhere!

The designers of WAAS even went one step further. The ground stations not only determine the position deviation, but also monitor the health of each satellite. A run-away satellite clock is now detected within seconds and that health status is now distributed within seconds to the WAAS receivers. Therefore, instead of doing all that integrity checking (RAIM and FDE) in thousands of receivers, the ground stations now perform the heavy lifting and make things so much easier for the receivers – a huge advantage. This is why integrity checking is so much easier in a WAAS receiver. With WAAS in place and operational, we don't need six satellites in sight for a guaranteed position fix, but only four.

Nevertheless, each WAAS receiver still contains the conventional RAIM check and FDE, just in case the WAAS system is not operational, which sometimes happens, if only rarely. In those cases, which you find out about in the NOTAMs, the pilot still must do RAIM predictions in preflight – just as for a basic GPS receiver!

GEO satellites are great!

The three geostationary satellites not only distribute the WAAS information, but also serve as normal GPS navigation satellites. With three more GPS satellites, the average number of satellites we have in sight increases accordingly and thus makes a "GPS hole" less likely. And as they are geostationary, they are visible over almost the entire U.S. all the time, making them even more valuable for us. The other 31 GPS satellites are in medium height orbits that brings each of them in sight only about a third of the time during their orbit.

In summary, WAAS improves the GPS system in several ways:

- Increased accuracy.
- Satellite health monitored centrally and distributed to all receivers.
- Three additional navigation satellites.

All that increases the availability of WAAS to such a level that a RAIM prediction is no longer required by the FAA (except for times where we have a WAAS outage). That's really what changes the way GPS is used. It now can be regarded as a fully reliable alternative to ground-based navigation aids.

31 GPS Satellites - 12,000 miles
3 WAAS Satellites - 22,000 miles

- The GPS system was fully operational for the first time in 1993 with 24 satellites.
- At the time of this writing, 31 GPS satellites are operational.
- The three GEO Satellites are: Eutelsat-117 (117°W), Galaxy-30 (125°W), SES-15 (129°W).
- There are currently six uplink systems in use (parabolic antennas).
- GPS satellite positions over ground repeat every ½ sidereal day, i.e., approximately 11 hours and 58 minutes. GPS satellites have a spherical orbit with a semi-major axis of 26,559.8 km (see GNSS Solutions – Orbital Precession, 2020 SPS Performance Standard, page 40). For that reason "GPS holes" usually tend to repeat roughly every 12 hours. ⊕

LINKS:

GPS.GOV – Space Segment

FAA – WAAS: How it works

GNSS Solutions – Orbital Precession, 2020 SPS Performance Standard

Understanding GPS: Principals and Applications

GPS IIR Rubudium Clocks: In-Orbit Performance Aspects

FEATURE