Gps Essay, Research Paper

The new Avionics Modernization Program (AMP) systems installed in the F-111E and EF-111A

have raised their share of questions, so I have decided to continue my series of “Everything You

Always Wanted To Know” handouts to you pilots, navigators, and maintenance technicians on

how the cotton-picken’ thing works. This informational pamphlet is an overview of the GPS

system as a whole, NOT the system- specific hardware that you find in your respective aircraft.

I’ll cover the basic theory of operation here, and if there proves to be sufficient interest in

platform-specific installation, that will be covered in a later supplement. THE BASICS GPS

works by triangulation, the process of finding where you are by the angle to fixed known points.

In the old method of DME position determination, you would tune one DME channel and draw a

circle on your chart around the DME transmitter, the radius of which was your DME reading in

nautical miles. Then you’d tune in a second DME station and repeat the process. On your chart at

this point there would be two circles whose lines intersected at two points. Even a vague guess of

your whereabouts would be enough to discard the bogus point, and you’d be left with a pretty

good idea of your position. Better yet, take a cut from a third DME transmitter and draw a third

circle on your chart. Now you’d have three intersecting circles and your position would be inside

the little triangle formed by the intersection of the three circles. Got the picture? This is basically

how GPS triangulates, except that instead of circles, we’re dealing with intersecting spheres.

TIMING IS EVERYTHING Think of GPS satellites as floating DME stations. They move along

in orbit and that complicates things but forget about that for the moment. How can we measure

distance? The satellites in the GPS are some 10,900 miles up, but they’re not geostationary

(they’d have to be much higher and thus would require more power to reach earthbound GPS

receivers) and they travel along at a ground speed of about five miles a second. Like DME, GPS

measures the time that it takes the signal to reach the receiver. However, unlike DME, the

receiver doesn’t have the benefit of a returning pulse from an interrogation to act as a baseline. It

relies purely on one-way timing. You can see right away how it begins to get complicated. The

speed of microwave communication is roughly the speed of light, and from 10,900 miles up, any

pulse from the GPS takes about 1/17 (0.059) of a second to reach us. The math is simple

enough. All we need to know is exactly when the signal left the satellite. And I do mean exactly.

An error of a mere .001 of a second would trash the fix by a factor of 180 miles or so.

Obviously, very accurate clocks are required. DO YOU HAVE THE EXACT TIME? Each

satellite carries four atomic clocks internally, each of which uses the oscillation of cesium and

rubidium atoms to keep extremely accurate time, accurate to within one second over more than

30,000 years. (For you graduates of the USAF Academy, that’s one part in 1013, or one part in

10,000,000,000,000). All satellites in the system are synchronized at exactly the same time and

they are kept within 176 nanoseconds of the Universal Time Code (UTC), plus accumulated

jump seconds to account for things like solar time. Navigation messages from the satellites

announce the difference between GPS time and UTC, providing self-recalibration of the clocks.

Okay, we have accurate clocks in the satellites. Now all we need are accurate clocks in our GPS

receivers, synch ‘em up and we’re in business. Of course, if your el cheapo K-Mart GPS receiver

had a cesium clock, it’d cost about $200,000 and be about the size of a desktop computer. The

way around that was to develop internal receiver clocks that are consistently accurate over

relatively short periods of time, as long as they’re reset often enough to keep them synched.

Here’s how the receiver clocks are reset: Remember how we explained that DME business, with

three intersecting circles? Well, GPS does the same thing, only it uses three intersecting spheres

to determine position. Let’s for a moment assume that the receiver clock and satellite clock are

exactly in synch. The receiver times the signal, figures the distance from three satellites and where

the three spheres intersect…voila…that’s our position. But, the receiver doesn’t know for sure that

its clock is perfectly sy! nched up with the satellites. Remember, a lousy millionth of a second

translates to a thousand foot error. So, just to be sure, the receiver listens for a fourth satellite. If

the fourth line of position doesn’t pass through the other three, the receiver knows something is

wrong, as it’s geometrically impossible for four mutually intersecting spheres to merge at the same

point unless the clocking is perfect. The receiver assumes, then, that because the fourth line

doesn’t jive with the others, its internal clock must be out of synch. The receiver then runs a

simple little software routine to adjust the clock until all four lines of position intersect the same

point. This is known as correcting clock bias and it’s how the receiver resets its clock. That’s one

of the things going on when your GPS receiver has just been turned on and you’re waiting for it to

initialize. RUNNING HOT AND CODE So much for the clock synching. Pretty clever, eh? It

gets better. We said that in order to measure distance, the receiver has to know exactly when the

signal left the satellite. Just having a clock set to satellite time isn’t enough. The receiver

determines range using something called pseudo-random code. Think of the code as looking like

the teeth on a carpenter’s saw, with a few broken off at random points. Each satellite transmits its

own random code. The receiver has a code generator pre-programmed to generate the exact

same codes (in 32 variations). When the receiver detects a satellite, it matches up the code, much

like aligning the patterns of broken teeth on two saws. Since it knows that the signal carrying the

code left the satellite at a certain time, all the receiver does is generate its matching code at

exactly the same time, effectively zeroizing the time between actual satellite transmission and

receiver generation. Follow? It then measures how long it takes ! another burst of random code

from the satellite to arrive and converts this time lapse to a distance measurement. It does this for

four satellites and the rest is simple math. Earlier, I said four satellites are necessary, with the

fourth required to synch the clock and three others for lines of position. Actually, if the receiver

operator knows his altitude, he can plug that into the receiver and that serves as one line of

position. Then, only two other satellite ranges are required to determine position. The third

satellite is used to synch the clock. This is known as two-dimensional navigation. If a lock is only

available from one or two satellites, there is no GPS fix. From three satellites, a two-dimensional

fix is possible. With four satellites being received, three-dimensional fixes are calculated. I should

mention here that as far as the GPS system is concerned, the presence of the earth is incidental;

position is given in relation to the orbiting sphere of satelli! tes and then converted to latitude,

longitude, and altitude. HELLO, CAN YOU HEAR ME? There’s another important reason for

random code; it relates to some basic GPS design limitations. In order to be affordable, GPS

satellites had to be relatively small and light. The Block II production satellites weigh just a little

less than a VW Beetle – about 2000 pounds. That means that power requirements are limited

and the radiated signal power is also quite low, something on the order of 40 watts. Think about

that. There’s a 40-watt transmitter floating out there almost 11,000 miles away and it has to

blanket a very large portion of the earth’s surface with a receivable signal. For comparison, a

typical communication satellite has much more power and it radiates such a directional signal that

a satellite dish is needed to receive and amplify the signal. For obvious reasons, ships, planes,

cars and other moving vehicles can’t have satellite dishes sticking out all over the place. Rather

than directing a high power signal, then, a GPS satellite spreads a very low power! signal over a

large area. It’s so low-powered that it’s completely hidden in the RF background hash of cosmic

rays, car ignitions, neon lighting, computer drive fuzz and so forth. That’s where random code

comes in. The receiver starts generating its own code and listening for matches in the background

noise. Once it has enough matches to recognize the satellite’s transmission, it drags the signal out

of the background muck and locks onto the signal using Automatic Gain Control (AGC) circuits.

When three satellites are locked up, navigation can begin. This is why a receiver can get by with a

very small, relatively non-directional antenna. The new handheld GPS units have antennas that are

only a couple of inches square or perhaps the size of a cigar. Not coincidentally, pseudo-random

code and low power makes the GPS system very hard to jam. For military purposes, this is

obviously very desirable. A BIG SYSTEM That’s the theory, and it works. In fact, it works very

well indeed. But it takes a whole lot of effort and money to keep it working. The GPS system

consists of three major parts: the user segment (that’s us), the ground or control segment (the

DOD geeks who run the thing) and the space segment. The space segment will eventually be

composed of 21 satellites, with three in-orbit spares. Right now, as this is being written in August

of 1992, there are 19 satellites in orbit, 18 of which are usable. Three more are due for launch by

the end of the year. The satellites are now being launched by Delta II expendable rockets. At one

time, the Shuttle was supposed to launch GPS satellites but that plan went down with the

Challenger. There have been no successful launches of GPS satellites by the Shuttle and probably

never will be. You’ll hear the term “Block I” and “Block II” used to describe satellites. Block Is

were the initial R and D birds and a few (four or five) are still ope! rating. They’re smaller than the

Block II production satellites and don’t have the same amount of military spook stuff aboard.

They’re also not selective-availability equipped. The full constellation of GPS satellites is due to

be in orbit by mid-1993, if all goes according to plan. (No guarantee there). Until then, the

system is deemed by the Defense Department to be under construction. THE BOYS IN BLUE

The U.S. Air Force’s 2nd Satellite Operations Squadron at Falcon AFB in Colorado maintains

the GPS system. These guys are the ground segment. They have monitoring stations at several

points on the globe, from which they keep track of satellite health, maintenance and so forth.

Make no mistake about it, GPS is a high-maintenance system. The satellites require regular

tweaking including data uploads, orbital positioning adjustments and clock maintenance. If the

ground segment stopped doing this constant maintenance, it’s said that the system would

“gracefully degrade” to complete uselessness in about two weeks time. So, as each satellite

whizzes along and completes one earth orbit every 12 hours, the Boys in Blue from Falcon talk to

it every few hours. Communications are uplinked in S-band at 2227.5 MHz and confirming

messages are downlinked on 1783.1 MHz. What do the ground guys tell the satellites? Well, we

mentioned basic maintenance items, including clock commands, power and! attitude messages,

new programming instructions. Occasionally, the satellite must undergo what’s called a

“momentum dump.” Each satellite has a series of gyroscopic wheels for stabilization. In space,

these wheels tend to accelerate and would do so indefinitely, eventually disintegrating. By

dumping the wheel energy periodically, this unpleasant scenario is avoided. ORBITAL

PERTURBATIONS Most of the uploading relates to routine navigation data, including almanac

and ephemeris information. Probably the most important is the ephemeris, which compensates for

the satellites normal orbital perturbations. As it circles the earth, each satellite is subject to several

major influences which cause its orbit to be less than perfectly circular. The major influence is the

earth’s equatorial bulge, but solar wind and other effects also take a toll. The GPS orbital

perturbations are defined by 16 constants and these are updated and uploaded at least once a

day (maybe more often) along with clock correction data. The satellite then rebroadcasts this and

your receiver decodes it as ephemeris data. The ephemeris tells the receiver exactly where the

satellite is so, when the receiver calculates distance, it’ll know exactly where the source of the

signal is; each satellite broadcasts its own ephemeris data. In addition, each satellite also

broadcasts what’s called an almanac. In! more general terms than does the ephemeris, the

almanac tells the receiver the location of all of the satellites in the GPS constellation. This lets the

receiver know when and where to look for satellites as it’s attempting to establish a fix. Your

receiver stores an almanac in its memory and that data is constantly updated when the receiver is

tracking satellites. If the receiver is turned off for several months, the almanac in memory will

usually remain usable enough for the receiver to find satellites and download a new almanac from

the next passing satellite. BITS, BITS, BITS Of course, all this data I’ve described here has to

find its way through 10,900 miles of space and atmospheric clutter and into your GPS receiver’s

computer memory. This is another one of the GPS’s elegant design features. Remember how we

explained that a communication satellite uses a relatively high powered, directional signal? Such a

signal allows for a rather dense data stream, which, when you think about it, is just what a

multi-channel communications satellite needs. There are lots of phone calls, fax bits, video pixels

and so on streaming down from space en route from one global place to another. The GPS data

stream, on the other hand, is just the opposite; very little information spread out over a wide,

non- directional signal. If satellite signals were soup, a communications satellite would be a rich,

thick minestrone, while the GPS would be chicken broth, and a pretty thin one at that. The GPS

data stream trickles down from each satellite in 1500-bit frames, each co! mposed of five

subframes 300 bits long. Subframes 4 and 5 are subcommutated 25 times each, which is a fancy

way of saying that to get a complete data message requires that 25 full frames be sent. A full

1500-bit frame takes 30 seconds to send. Do the math here and you’ll realize that the GPS data

rate is slower than slow – it’s 50 (yes, fifty) baud. If your computer downloaded this article at 50

baud, it would take about six hours. You could read the damn thing c-h-a-r-a-c-t-e-r by

c-h-a-r-a-c-t-e-r. The data subframes contain various housekeeping information. Subframes 1,

2, and 3 contain time and date information, user range accuracy, satellite health status messages,

clock correction, ephemeris data and some other odds and ends. Subframes 4 and 5 contain the

almanac, which, as we noted, is the location in space of all of the satellites in the GPS

constellation. It’s a fair amount of data and that’s why it’s subcommutated. If it weren’t and the

almanac were transmitted conti! nuously until complete, a GPS receiver would take about 12

minutes to initialize, every time you turned it on. Oh… and no navigating while you’re waiting.

WHAT’S IT DOING? So you hop into your newly-revamped USAF jet, turn on the GPS and…

it just appears to sit there. You read the manuals and learn that it needs a current almanac if one

wasn’t downloaded within the past nine months or if the receiver was moved more than a 1000

miles without having been initialized. What’s it doing? Well, for one thing, it’s looking for a satellite

so it can grab an almanac, which it must have in order to find the three or four satellites it needs to

fix a position. If the receiver is “dumb” and has no almanac at all or an outdated almanac, it’ll take

12.5 minutes to download. Why? Well, remember, the almanac is in subframes 4 and 5, each of

which takes 6 seconds to send. Because there are five subframes, though, the almanac is coming

through only 2/5ths (40%) of the time. It takes 25 full data frames to get a full almanac. Each full

frame takes 30 seconds, so 25 frames takes 12.5 minutes, which is why your manual gives 12.5

minutes as the download time. In cas! e you’re wondering, here’s what an almanac (or at least a

portion of one) looks like: Epoch: 48871.0000 MJD (almanac reference time 9-6-1992 0h

UTC); ID# Type smaxis(km) eccentri inclina rt.ascen arg.peri mean-ano Hlth 02 GP

26560.0520 0.011080 54.9026 342.9035 194.5554 224.6108 0 03 GP 26560.2633

0.013058 64.3151 063.1001 142.6658 053.7576 0 11 GP 26560.3892 0.013453 63.8026

062.4385 231.0716 209.1055 0 12 GP 26560.3892 0.012450 62.7486 299.5745 340.7176

015.4047 0 13 GP 26559.9161 0.004059 63.5554 061.4368 214.5911 099.5112 0 14 GP

26559.7802 0.004146 55.0626 165.4253 067.8533 134.7840 0 15 GP 26559.8959

0.007275 55.1120 106.2742 109.0210 264.1008 0 Got that? Once the receiver’s got it, it can

locate other satellites in the sky, download the ephemeris and other data and tell you where you

are, within a few feet or so. CLOSE ONLY COUNTS IN HORSESHOES So how accurate is

the GPS? You hear all kinds of incredible claims about the GPS being accurate enough to locate

a gnat’s ass while others say it’s only good for about 100 yards, give or take. Which is true?

Well, it depends. GPS is generally said to be available in two forms, PPS and SPS. Depending

on whose figures you want to believe, PPS or precision positioning service is accurate to about a

six-foot CEP (circular error of probability), but this mode is proprietary to the military and is

crypto-coded to keep it that way. SPS or standard positioning service is actually capable of the

same accuracy, but the Pentagon can invoke something called selective availability (SA), which,

in military jargon, can “adjust SPS resolution to any degree necessary.” SA currently degrades

the SPS accuracy to about 100 yards CEP, and the GPS usually delivers on that promise. SA,

by the way, is an intentional “dithering” of the clock accuracy and perhaps a contamination of the

ephemeris dat! a. Since the armed forces paid much of the GPS research, development and

launch costs, they insisted on having some sort of strictly military function for the system in order

to get their money’s worth. One last note about errors: I mentioned something called a

single-frequency receiver. That’s a bit misleading because I didn’t explain that GPS satellites

broadcast on two frequencies, called L1 and L2. L1 is at 1575 MHz, L2 is 1227 MHz. Military

receivers generally receive both L1 and L2, then compare the results from each to greatly reduce

the ionospheric errors affecting GPS signals passing through the atmosphere. Single frequency

receivers used by civilian aircraft and maritime traffic use a fixed mathematical model to allow for

ionospheric errors. In the proverbial nutshell, that’s how the Global Positioning System works. It’s

a great system now, and with projected improvements should be an integral part of aircraft

navigation for the next fifty years or so. “Everything You Always Wanted To Know” back issues

available: Number 1: Airborne Radar Principles Number 2: Interrogation Friend or Foe (IFF)

Number 3: Radar Fairings and Radomes Number 4: Electronic Countermeasures Number 5:

Tactical Air Navigation (TACAN) Number 6: Missile Guidance Techniques Phone the author on

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