GPS: Where are we? … Where are we going?
*By **George Irvin (04/98)***

The Basics Reviewed

A few short years ago, the number of EU PPL-IRs who had heard of BRNAV-5 or TSO C-129a was probably nil. Not today! Avid readers of NETWORK know an SV when they see one and by now are steeped in the intricacies of pseudo-range step detection and in the relative merits of health-word checking at 5 versus 7 minute intervals. But just in case you've been insufficiently avid, here is a quick review of the basics.

All pilots learn to plot the 'triangle of position' using three relative bearings and LOPs. Imagine yourself wanting to fix the aircraft's position without visual clues or NDBs and VORs from which to get relative bearings. One solution would be to have two independent DMEs and draw the distances as arcs of a circle. Of course he arcs would intersect at two points on a given altitude plane and a third DME would be required to give you a unique fix. In three dimensions you would also need three DMEs. And just in case one of the three DMEs was slightly out, it would help to get a plot from a fourth DME.

The analogy with GPS should be clear. The distance of your aircraft from at least three satellites at known positions must be measured very accurately for 3-D navigation. To do that with GPS, accurate time is needed, so the clock from a fourth satellite is needed. Adding a further satellite signal tells you whether anything is wrong; i.e., it provides RAIM (Receiver Autonomous Integrity Monitoring) capability. Your aircraft's DME works by interrogating a ground station which sends back a reply on a different frequency. Basically, distance is measured by measuring the time between emission and reception and multiplying by ½ times the speed of light. As explained in an earlier article in NETWORK (Bertorelli, 1997),[1] GPS differs slightly in that the transmitter is not interrogated; rather, the GPS satellite sends out a signal (in 'pseudo code'), giving its position co-ordinates and time at the precise time of transmission and the GPS receiver measures the time it takes for the signal to reach the aircraft and thus can calculate distance (or 'pseudo range').

The receiver does this by generating its own pseudo-code and listening for the very faint transmissions of similar code by the satellites. When a match is found, the receiver 'locks on' to that satellite and the process continues until sufficient satellites have been identified. All this requires the use of super-accurate caesium clocks. Since your receiver doesn't have a built-in atomic clock, the real trick comes in having the signal from the satellite(s) continuously update your receiver's time-keeping. Like the DMEs above, three satellites are required to produce intersecting spheres of position while the fourth synchronises your receiver's clock. Any more satellites will further improve the accuracy.

If your GPS receiver is RAIM enabled, it will use the fifth signal to spot any large discrepancy in the intersecting spheres of position and flag the problem. If six satellites are being tracked, the receiver might also be able not only to detect that a faulty satellite is present, it could also determine which one and exclude it. This feature, which is called Fault Detection and Exclusion (FDE) is preferable to merely raising an alert since it permits navigation to continue. Each satellite also transmits a statement about its own health. This message element can be set unhealthy either by the satellite's own built in test capability or by command from the ground

---

[1] See Bertorelli, P. (1997) 'You don't have to be a rocket scientist to understand---but it helps'NETWORK 8, April.

Master Control Station. The receiver can regularly check each health message (ie, carry our 'health word checking') and exclude any satellite marked unhealthy from its position calculations.
At present, about 25 US GPS satellites of different vintages (Blocks I, II and IIa) are positioned in approximately 12 hour orbits sending out L-Band frequency (L1) signals to civilian aircraft. The Russians operate a similar system known as GLONASS. In principle, the American system is extremely accurate as long as it is well-maintained by the USAF which not only monitors the satellites but uploads information to each once a day pertaining to exact time, ephemeris error[2] and other potential problems without which the system's accuracy would degrade. Indeed, as most readers will be aware, the system will become even more accurate some time soon when Selective Availability(SA)---- intentional dithering of clock accuracy---is turned off. Current horizontal error (under 100 metres, 95% of the time) will be reduced to about 15 m (95%). And it will become very much more accurate when the next generation of satellites and/or ground stations emitting signals on a different frequency is in place, a matter to which we return below.

What are the Problems?
Our avionics boxes---even the clockwork type---have to meet certain basic Required Navigational Performance (RNP) standards with respect to the limits of their accuracy, the violation of the integrity of these limits, the availability of the signals from which the boxes take their information and their continuity. Hence, any box (including your GPS) should flag any degradation of its operation---and, of course, if a transmitted signal degrades or fails, a backup should be available else the pilot should know immediately. This is why your VOR, localiser and glideslope needles must show flags, VORs (and some NDBs) have backup transmitters and ILSs are continuously monitored.

So what can go wrong with GPS? For one thing, there are problems of system accuracy, integrity and continuity. In some parts of the world at some parts of the day, there are not enough satellites well above the horizon (5 degrees) to give capture the five signals necessary for RAIM. If you fly through such an area, you will be in a 'RAIM hole' and should integrity degrade, the system won't flag you. Also, the weakness of GPS signals makes them susceptible to interference from other electronic signals---recently, a Russian firm shook the GPS community by announcing that it had marketed a handheld GPS and GLONASS jammer!

Most important, the closer you get to the ground, the more likely it is that the signal will degrade either because of local interference or simply because terrain obstructions may cause loss of reception of one or more satellites. Not only can GPS sometimes go wrong but, at present, it is simply not sufficiently accurate at all times to be used for precision approaches.

The other problem with GPS is the 'human interface' problem. If you are flying, say, an overlay approach which requires a course reversal and where the missed approach procedure reads "up to 2000 AGL on runway track, then right to intercept Alfa Bravo Charlie VOR radial 247 to WAKKO intersection", you may find yourself far busier with pushing the right buttons on the GPS box than flying the needles and twiddling the OBS the old-fashioned way. That's because you have to do both!

---

[2] Ephemeris error arises because a satellite's orbit is not perfectly circular, mainly because of the 'bulges' in the earth itself.

Consider a simple NDB holding pattern. You have programmed your GPS to fly from ABC VOR to Delta Echo Foxtrot NDB whence you would normally turn right to the LOM to intercept the localiser. GPS boxes have 'auto-sequencing'; i.e., as you pass over the ABC VOR, the display will scroll to the required course, distance and time to the next waypoint (the DEF NDB). Most of the time that's great, but what do you do when ATC instructs you to hold at the NDB? Unless your box has a 'hold' function, when you cross DEF the GPS display will scroll on to the next programmed waypoint (in this case the LOM). The same is true when doing a VOR or NDB procedure. Suppose you have to fly the 'ABC' VOR radial outbound to 5D, do a procedure turn, and re-intercept the reciprocal inbound. Program the sequence to read ABC--5D--ABC. As you pass overhead the VOR outbound, set your CDI (or HSI) to the outbound course and set the GPS in HOLD mode (OBS mode in King parlance) checking one reading against the other. Start the procedure turn at 5D, take the GPS out of hold mode and dial in the inbound course; (don't forget to twiddle the OBS at the same time). Simple…my left foot!

At a recent AOPA-US seminar in Austin, Texas, one grizzled veteran estimated that 40 hours of combined ground and flight instruction on the specific make and model of GPS unit being used was probably the minimum required for most current IFR pilots before they could execute consistently safe GPS approaches in IMC conditions. Add to this the fact that one box differs from the next both in its capabilities and in the positioning and function of buttons and knobs and the current state-of-the-art begins to look decidedly problematic. As anybody knows who already has a GPS box, familiarising oneself with the equipment is a long process.

An equally vexing problem arising from the diversity of interfaces is how IREs (examiners) are to examine GPS proficiency? It seems likely that in future, the layout and functions of different boxes will need to be standardised and, equally, that boxes will need to interconnect with existing instruments far more easily than at present. As Rod Machado suggested at the Rotterdam AOPA safety Seminar last June, future GPS boxes may end up functioning *behind* our familiar instrument faces and knobs---leaving the pilot free to twiddle the knobs and follow the needles much as he or she has been trained to do.

The TSO C129 standard

Although the FAA does not require GA aircraft to carry IFR-approved GPS receivers, the FAA has approved those GPS boxes conforming to FAA Technical Service Order (TSO) C129 for IFR supplemental navigation and published GPS overlay approaches. TSO C129 says, in essence, that such receivers must meet certain standards of airworthiness, accuracy, continuity and integrity and---most important---that they should be RAIM enabled (i.e., flag any error within a certain time period). Some C129 boxes are approved for supplemental IFR enroute navigation and terminal navigation only, namely, Class A2 boxes. A somewhat more robust receiver is required by the FAA for IFR non-precision approaches, the C129 Class A1 box.

The current controversy over 'approved boxes' leading to Eurocontrol's decision to postpone implementation of the BRNAV standard (intended originally for VOR/DME and DME/DME area navigation) until 23rd April 1998 arises in essence from the fact that Eurocontrol has laid down very general guidelines and left member states to set their own standards within these (see the excellent pieces by Dunn and Crocker, Jan. 1998).[3] Eurocontrol has no authority for airworthiness, which is the task of the JAA in Europe.

TSO129a is a specification which extends C129. It was added by the FAA to cover flights operating in the transoceanic environment where other means of radio navigation are not

[3] See Dunn and D. Crocker (1998) 'BRNAV Update' *NETWORK* 11,July.

available. This calls in essence for more stringent receiver standards of health-word checking (every 5 instead of 7 minutes or HWC-5 and of RAIM-hole prediction; i.e., a receiver-run program predicting those parts of the route where less than the five satellites required for RAIM may be visible. Similarly, Pseudo-range Step Detection is required; the receiver must flag the user if it calculates that a change in position has been made which is incompatible with the aircraft's performance. Both these features are useful if there are too few satellites in view for RAIM to be operative.

Moreover, Eurocontrol requires aircraft filing IFR to carry out RAIM-hole prediction over the intended route of flight; ie, run a program predicting those parts of the route where less than the five satellites required for RAIM may be visible. A further twist is that of augmenting GPS altitude information with that from the aircraft's pressure altimeters (baro-aiding). The key question is, of course, whether Eurocontrol has not engaged in overkill by requiring expensive and arguably quite unnecessary levels of redundancy for GA aircraft which may never operate in the transoceanic environment for which C129a was intended.

Most European states have accepted TSO C129 receivers for supplementary navigation since BRNAV TSO C129a is required by the JAA. Some EU member-state authorities seem to have accepted *de facto* the adequacy of the TSO C129a specification to the European (ECAC) environment; e.g., France, Germany and Belgium. Others have insisted on such a restrictive version of C129a (plus further conditions on acceptable mask angle and automatic baro-aiding) that no manufacturer can meet with a current receiver which would fit in a typical light aircraft; eg, the UK. Still others such as The Netherlands are sitting on the fence.

Part of the misunderstanding here is the difference between use of GPS for supplemental navigation and for BRNAV. But mostly it is associated with the use of the terms "supplementary, primary and sole means" of navigation. ICAO attempted to define these terms, but in different communities the words have been interpreted so widely that they have been deliberately dropped by the JAA in there latest leaflet (No 3. Rev. 1).For BRNAV, the term "Stand Alone GPS Navigation System" has been defined.

What Box?

For most readers, the crucial question is quite simply what GPS box to choose? In the UK, the CAA seems to be ready to approve the Garmin GPS-155 and the possibly the Trimble 2101 as C-129a compliant. As I write this piece, a major Dutch avionics firm I use at Rotterdam has still not received a list of approved boxes from RLD. A Belgian pilot (and member of the PPLIR Executive) first installed his box, and then took his case to Brussels where he eventually received approval.

What is most worrying, though, is that the decision to adopt C129a appears to have been taken without regard to the 'human interface' problem. Some of the best C129-compliant IFR boxes in use in the United States---the Northstar M-3 and Apollo GX-55 are currently given tops marks by American pilots on AVSIG----will not, it seems, figure on any approved list in the EU!

Not only is there much confusion about what boxes will pass muster where, there is even more confusion about whose law prevails. The current author interviewed the Manager of an Avionics Engineering company at an airfield in the south of England where a German-registered aircraft was having its C129 (not C129a!) compliant GPS receiver uncoupled from the HSI. The D-reg owners were furious, said the Manager; the aircraft had landed in the UK and been grounded by a CAA official who argued that, because it was in UK airspace, it must conform with UK regulations. Multiply this by 15 differing EU standards---or 35 in the case of ECAC

(European Civilian Aviation Conference) and the absurdity potential of the current situation rises exponentially.

Finally, there is no guarantee that current TSO C129/129a compliant boxes will be compatible with the new GPS systems on the horizon, WAAS and EGNOS. According to one source, WAAS/EGNOS receivers will need to meet the RTCA DO-229 specification while TSO C129/129a came from DO-208. Little wonder, then that the FAA has not made GPS compulsory for all IFR flights in the United States.

Adopting a voluntary approach and encouraging pilot feedback appears to have generated far more accumulated GPS pilot experience and feedback *per capita* in the US than in the EU. On the other hand, the FAA has not yet introduced area navigation into airspace as crowded as parts of Europe.

To WAAS or not to WAAS?

While general aviation pilots in the EU wrestle with the mysteries of which IFR GPS to buy and how and where to use it, the boffins are already at work creating the next generation of receivers and transmitters. The problem with the current system is that it is simply not good enough—particularly in the vertical axis---to meet the accuracy and integrity standards required for CAT I ILS approaches. For a CAT I approach, the pilot will need to see a flag within about five seconds---which means that 'health word checking' will have to be greatly improved since without RAIM it takes a current GPS system about 30 minutes to warn pilots that a particular satellite is broadcasting invalid data while with RAIM the time required is about 5 minutes.

If the CAT I problem can be cracked, in principle, every approach to every airport can be an ILS approach! A fantasy come true? … read on. The solution to the problem of using GPS for precision approaches is to broadcast differential corrections and system integrity signals to GPS (DO-229) receivers---what is termed 'augmentation'. The FAA at present plans to do this by using satellites broadcasting these corrections non-stop on the GPS frequency so that your box (suitably software equipped) will flag errors within seconds. Not only that, the FAA's corrections will remove the effects of the SA, introduced by the US Department of Defence, so that the full accuracy of GPS will be available to civil users. This is known as the Wide Area Augmentation System (WAAS) and is meant to be operational by 2001.

All this sounds marvellous but for some minor glitches. First, the new system is horrendously expensive---a current half-billion dollar programme that is estimated by some to require more than one billion dollars to complete. Secondly, some experts claim it still won't be accurate enough for Cat I. It is currently accepted that below 200 feet AGL, Cat II and III operations, will need to rely on Local Area Augmentation (LAAS); if the critics are correct, the same will be true for Cat I. Finally, the EU has 5 until very recently seemed determined to launch its own version of WAAS--- the European Geo-stationary Navigation Overlay System (EGNOS), which will use INMARSAT satellites already in orbit. Negotiations are ongoing to provide interoperability between WAAS and EGNOS, the only large difference planned being that EGNOS is also intended to augment GLONASS in addition to GPS. The Japanese are intending to launch a new satellite called MTSAT which will also carry a similar WAAS like service called MSAS.

In a recent piece in *The Aviation Consumer* on what is now called'GPS-2', Gary Picou argues that ground-based augmentation is far cheaper and probably more effective that the satellite systems proposed on both sides of the Atlantic.[4] Augmentation is achieved by transmitting a

[4] Picou, G. (1997) 'A cheaper mousetrap' *The Aviation Consumer*, XXVII (10), October.

second set of signals on a different frequency; ground based augmentation is sometimes referred to as Differential GPS or DGPS. Several ground-based systems could be used is the US including the USAF Ground Wave Warning Network (GWEN) or even civilian Loran, due to be decommissioned in the US in 1999 but still with us in the EU. Indeed, a joint German-Dutch experiment with Loran has demonstrated that Loran-augmented GPS can provide 2 metre accuracy at a range of 600 miles. Moreover, Loran stations are in place and their signals are less prone to solar magnetic interference.

The main contender for the LAAS system also comes from the FAA and will use the VHF frequency currently occupied by ILS and VOR. As these systems are planned to be phased out in favour of GPS, their frequencies will become available. A network of LAAS stations would provide the same integrity benefits as WAAS and provide a far higher accuracy of typically under one metre. Even supposing ground-based augmentation to be unacceptable for some reason, if the USAF were to put up another six satellites, release the L2 frequency for civil use, switch on its C/A code and switch off SA, then GPS would do pretty well everything that WAAS can do at a fraction of the price.

So why soldier on with WAAS and EGNOS? The answer is simple. WAAS gives an additional ranging source, higher accuracy and a valuable integrity signal for the whole of the North American continent. EGNOS will provide a similar service for the Atlantic Ocean, Europe, Africa, and India. The world dominance of GPS as the future major navigation means is deeply worrying to some politicians who would like to rely on a home-based system. Hence EGNOS is seen as a political as well as technical monitor of the GPS signals. It is also the stepping stone to a European Satellite Navigation System which, unlike WAAS/EGNOS, would be independent of GPS signals. This system is seen by the politicians as a European contribution to an international civil satellite navigation system.

The Russians, at meetings held with the European Tripartite Group that runs the EGNOS programme, have offered to participate in the creation of this future system. What is the appeal of EGNOS to the rest of the world? Take China: in the same way as Beijing hedges its bets by purchasing similar aircraft from Boeing and Airbus, if Beijing fears that the US may wobble its GPS, it can always purchase its own EGNOS.

Cynics might say that since the GPS signal is free, WAAS/EGNOS is a convenient way for the FAA/Eurocontrol to get the user to pay. In particular, the Association of European Airlines has recognised that their members may be called upon to pay for the operation of EGNOS and have registered their objections in the strongest terms to the European Commission. The sensible solution seems to be ground-based DGPS, but where geo-strategic interests are at stake, sensible scientific and economic argument tends to be pushed aside.

True, GPS is revolutionizing navigation, but the tale is neither simple nor straightforward. One thing seems certain. The small commercial operators and private owners who make up European GA are already paying dearly for their lack of political clout. Unless they get their act together, they may well find themselves paying a great deal more as the next generation of global navigation systems emerges.

It is now broadly agreed by the experts that a backup is needed to WAAS/EGNOS. On this side of the Atlantic, one suggestion (backed by UK-NATS) is to use DME-DME and remove the ageing and costly VOR system fairly quickly. The main UK carriers are happy since they have been promised no extra charges if they adopt EGNOS receivers. Since VFR general aviation in the UK doesn't pay for anything---so the argument goes---they don't get to vote. Per contra, instrument-rated GA gets to buy a whole new set of boxes, the cost of which will make 8.3 MhZ spacing and Mode-S look like small change. It might be cheaper simply to trade in your aircraft on one which already has INS!