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SUBJECT	GALILEO GNSS IN THE 1.3GHz BAND		
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Complete information on the planned Galileo Navigation Satellite System (GNSS) is not yet available because the system is still in the pre-development phase and much detail of the services to be offered is subject to commercial confidentiality. However, information on the planned spectrum occupancy and the signal details are available and other information may be inferred from the operation of GPS, a similar system which is planned will operate co-operatively with Galileo.

The paper describes what is now known about the proposed Galileo system design and its applications, with particular reference to the E6 (1260 -1300MHz) band. It also covers some of the political issues driving the programme and the frequency allocation situation.

It describes the operation of typical receivers and their ability to deal with interference, and gives practical illustrations of these effects. The likely effect of the Galileo transmissions on amateur 23cm receivers is analysed and found to be negligible.

However, there is the potential for most amateur 23cm transmissions to interfere with Galileo unless the Galileo receivers are designed and built to withstand it.

Finally the likely course of events is discussed and arguments that we might use to continue our use of the band are presented.

Potential Interference To Galileo From 23cm Band Operations

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2. Introduction

This paper describes the proposed Galileo system design and its applications with particular reference to the E6 (1260-1300MHz) band. It covers some of the political issues driving the programme and the frequency allocation situation. It describes the operation of typical receivers and their ability to deal with interference and gives practical illustrations of these effects. The likely effect of the Galileo transmissions on 23cm receivers is analysed and found negligible. However there is the potential for 23cm transmissions to interfere unless the Galileo receivers are designed and built to withstand them. In order to work robustly in the expected electromagnetic environment Galileo receivers will need to use the most advanced technology available. Finally the likely course of events is discussed and arguments that we might use to continue our use of the band are presented.

3. Galileo, History and Background

The Galileo programme is intended to provide the European Union (EU) with its own Global Navigation Satellite System (GNSS). Currently there are two major systems, the USA's Global Positioning System (GPS) and the Russian GLONASS. GPS was designed as a military system and, until 2000, the open signal's accuracy was intentionally degraded. The US has now pledged to maintain the full capability, free, open service signals and will give 6 years notice of any change to this position. Although essentially a military system, the civil applications have been wide ranging and are the basis of many businesses as well as supplementing and improving many existing navigation systems even though the users recognise that the US could degrade or jam the services should it judge that necessary for its security. GLONASS will not be discussed further, as it does not overlap our allocation and its future status is unclear.

Two programmes have been implemented to overcome some of the deficiencies of GPS as they affect the civil aviation industry, these are the USA's Wide Area Augmentation System (WAAS) and the EU's European Geostationary Navigation Overlay System (EGNOS). Their purpose is to monitor the accuracy and quality of the GPS signals and provide an instantaneous warning via geostationary satellite and data link should they degrade.

The EU view is that having its own GNSS is essential to its economic and infrastructure development, and that it cannot rely on GPS for reasons of availability and reliability of the signals. Furthermore, GPS gives no performance guarantee. There is a benefit to both GPS and Galileo in having more satellites in space, particularly in situations such as cities where the view of the sky is restricted. Because both systems would operate in the same frequency band and with comparable modulation schemes, it will be relatively easy to build receivers to use all the satellites in view.

In 1999, after many years of studies of candidate systems the EU launched the Galileo programme. The definition phase ran from1999 to 2001 and covered the definition of the architecture and services to be provided and the development and validation phase started in 2002. In this phase, the European Space Agency (ESA) will procure and launch two satellites, the first of which will be launched at the end of 2005. In 2007 the plan is to launch a mini constellation of four satellites to test the system in orbit. The cost of this phase is estimated as €1.1Bn and will be EU funded. The deployment phase, building and launching 26 satellites and building and deploying the ground segment is estimated as €2.1Bn with two thirds coming from industry and the rest from the EU. Commercial operation is planned to begin in 2008. The four principal countries involved in the work are France, Italy, Germany and the UK all of whom will benefit under "juste retour" with jobs and the housing of ground facilities.

Independent observers find this timescale unrealistic even without the usual funding delays and full operation in 2010 is probably more realistic.
The Galileo Joint Undertaking is, in essence, a body set up to organise the funding, the business plan and the risk sharing arrangements. Organisations of

other nations outside the EU have been joining this body, most significantly from China and Israel. This will, of course, help with the arrangements for hosting ground facilities outside the EU. In 2005 the Galileo Supervisory Authority will be set up as an agency of the EU Commission to control and manage all aspects of the project including security and all technical matters.

4. Galileo System Description

The system will operate in essentially the same way as GPS. Thirty satellites in 23,600 km orbits will carry atomic clocks and transmit accurate time signals using

spread spectrum modulation together with orbit data and other messages. A receiver synchronises itself to the satellites in view and by measuring the range to four of them can determine its position in three dimensions and obtain standard time. Higher quality receivers will use two or more frequencies making separate measurements to correct for ionospheric delay. The ground system, fully duplicated to provide resilience, will control the satellites through a series of uplink stations around the globe.

The services planned to be offered by Galileo are the following:

1. **The Open Service (OS)** provides position and timing free of user charge.

2. **The Safety of Life Service (SoL)** improves the open service by providing warnings to users when the OS fails to meet service standards.

3. **The Commercial Service (CS)** provides access to two additional signals, which can provide higher data rate throughput and help to improve accuracy. It also provides a limited broadcast message capability from service centres to users.

4. **The Public Regulated Service (PRS)** provides position and timing to specific users requiring high continuity of service with controlled access. Two PRS signals with encrypted ranging codes and data will be available.

5. **The Search and Rescue Service (SAR)** will enhance the international search and rescue system by broadcasting globally the messages emitted from distress beacons.

There is little more than this available about the services because of course what is actually offered will by decided by the competitors for the concession to develop and run Galileo.

The latest published information, reference [1], on the mapping of the services to the frequency bands is from June 2003.

The three Galileo bands are as follows:
E5 1164 - 1215 MHz carrying CS, OS and SoL
E6 1260-1300 MHz carrying CS and PRS
E1-E2-L1 (sometimes called L1) 1559 - 1591 MHz carrying CS, PRS and SoL

5. The Politics of Galileo

It is important to understand a few of the key issues around the development and deployment of this system. It is being strongly backed by the European

Commission as part of the drive to be independent of the USA, but because of its high cost (€3.2Bn to get it up and working is seen by some as an underestimate and, of course, the running costs are additional to this figure), it is essential to have industry involved in the funding in a Public-Private Partnership (PPP). The competition to choose the concessionaire to undertake the development and running of the system is on going and the decision is now scheduled for early 2005. Obviously there is currently no information on what the two competitors will offer; however, there will be two income streams, one from the IPR involved in equipment licensing and one from the two subscription services, the CS and the PRS.

The fact that there is a free service already available from GPS, used by many companies to offer enhanced services for profit (e.g. differential GPS for oil prospecting, car navigation systems), is a problem for the concessionaire. The open GPS signals are being enhanced by the addition of a second civil signal, called L2C, which will reach full operational capability (FOC) in 2010 and eventually a third wide bandwidth civil signal will be added. Furthermore, the existence of EGNOS and WAAS enhances the reliability of GPS for civil aviation and gives it much of what it wants without contributing to the costs of Galileo. Everybody would like the Galileo satellites to be available so that the coverage of GNSS, in urban canyons for example, would be improved, but no one wants to pay for them.

6. Is there a Requirement for a Galileo PRS?

There are serious issues around the PRS concerning the extent to which it will be used, for example, by European government agencies such as customs and immigration or by the police and paramilitary. The advantage being put forward to these agencies is that PRS will offer a more secure service to them than the open GPS and that in the event that the open services of both Galileo and GPS were jammed in order to prevent their use by a hostile power, there would still be a service available. The encryption and other tricks on the PRS signal would also give protection against spoofing or meaconing (see later). There is a cost involved however; both in new equipment and in user charges and the agencies will have to assess the costs against the risks. Some of the costs have probably not been recognised, for example the costs of certifying a police helicopter to use Galileo PRS rather than GPS as the input to its navigation system will be frightening.

There are also persistent stories that some countries wish to use the PRS for military purposes. Whilst there would be no objection to using the Galileo signals for tracking material or for logistics purposes by peacekeeping forces, the application to weapon guidance would raise serious issues. Another factor often overlooked in the discussion of the PRS is that to make the system robust requires much more than just protection of the signal in space, it requires secure

ground support facilities in whatever part of the world it is to be used; this is costly. It all adds up to a lot of money to pay for independence of the US system which is well established and which, with the second civil frequency added in 2010, will have a high level of robustness.

The recently published report of the UK House of Commons Transport Committee, reference [2], voiced serious concerns about the PRS - "The uses described for the PRS are hazy; the UK government has said it does not want to use it… The Committee urges the UK government to ensure that there is a real demand, that access can be properly controlled, and that it would not allow the use of PRS for military applications".

This situation will not be resolved or even clarified until the selected concessionaire(s) offer is available for examination. This will be a costly programme, whichever way it is funded.

7. The Frequency Allocation Situation

At the World Radiocommunication Conference in 2003, (WRC-03) a **Primary status allocation** was approved with no power flux-density (pfd) limits for the radio navigation satellite service (RNSS) in the 1260 -1300 MHz band.
The allocation was a result of studies conducted since WRC-2000 on sharing between RNSS and the radiolocation service in this band. The WRC invited interested parties to continue appropriate technical, operational and regulatory studies (including an assessment of the need for a pfd limit) on RNSS systems in the 1215 to 1300 MHz band. The purpose of the studies was to ensure that the RNSS would not cause harmful interference to the radiolocation (radar) service. All studies were to be conducted as a matter of urgency and in time for WRC-07. They are reported under WP 8B. There is a possibility for radar targets to be obscured by the signal from a Galileo satellite because the high gain of the radar antenna and tests carried out in the USA on working radars have demonstrated the potential problem, reference [3]. Some proposed measures to achieve compatibility include tailoring the RNSS signal to reduce overlap with the radar band, pfd limits on the RNSS signal and frequency separation. It is clear from the material already submitted to WP 8B that the USA is concerned about interference to its L-band ATC radar network, however many countries operate ATC and defence radars in this band so it is a much wider problem.
Wind profiling radars operate in the band 1270 to 1290 MHz and a recent study examined the level of protection that these would require in the presence of

Galileo E6 signals.

It should be noted that the WRC appears to wish to achieve a mode of operation and spectrum sharing in which up to five separate satellite GNSS systems can operate in the allocated spectrum 1215 to 1300 MHz. The Galileo organisation's stated essential requirement is to have the same regulatory regime in the whole of the band and to achieve regulatory protection of all radars through a footnote in the Radio Regulations. The position of the International Civil Aviation Organisation (ICAO) is "To support the incorporation of a single regulatory mechanism applicable to RNSS in the whole band 1215-1300 MHz as a necessary protection for important radars used for civil aviation purposes, and to support the incorporation of the agreed mechanism within an adequate regulatory framework having full mandatory force for current and future RNSS systems"

Galileo has to get a satellite up and running by April 2006 in order to claim the frequency allocation, and it is unclear which frequencies will be radiated by this satellite. It is likely that this will be the satellite built by Surrey Satellite Technology Ltd. (SSTL) although they are not responsible for the payload.

8. Potential interference from Galileo to 23cm amateur operations

The Galileo signal at the earth's surface is very weak and spread over a wide bandwidth, and will only be a source of interference to EME stations with large antennas. As a typical 23cm EME system uses a large, typically >3m, antenna, the satellite will only be present in the beam for a short time.

The Galileo PRS signal is planned to be -128dBm as received by a ***right hand circular polarisation*** (RHCP) antenna and spread over 40MHz. A 3m dish has 30dBi gain and a typical receive sensitivity would be -152dBm for a 500 Hz bandwidth. The bandwidth restriction means that the received power is -128dBm - 49dB = -177dBm. The antenna gain increases this to -147dBm. However, fortunately the EME standard is for ***left hand circular polarisation*** (LHCP) ***on receive*** and so there is an additional attenuation of the cross polarisation performance of the dish and feed, typically 20dB. Thus the operator will not experience a noise increase. With a 10m dish the increase will just be noticeable. There is a further factor to be considered and that is the spectrum shape of the Galileo signal: this tapers towards the band edges and so there is a further (estimated) 6dB reduction in the noise received. Systems using noise measuring receivers to measure moon noise (for dish pointing or system calibration) or to observe radio stars in this band will be more adversely affected. For example a 500kHz wide receiver with a 10m dish and receive system would see a noise increase of about 30dB as a satellite went through the beam which would make it virtually useless.

9. The operation of GNSS receivers and their typical response to interference.

In order to assess how amateur transmissions might interfere with Galileo receivers it is essential to understand a little about how these receivers might operate and about their capability to reject interference.

The signal structure of GPS and Galileo is similar and so the receiver characteristics of both will also be similar.

A receiver has to lock onto the satellite's carrier frequency, with correction for the Doppler shift, and synchronise its code generator to that of the particular satellite that it is receiving. The code is modulated onto the carrier by a process of phase reversals. When the receiver has achieved carrier lock and code synchronization, it is able to effectively make a measurement of the distance (called a "pseudo-range"), between the satellite and the receiver. A separate signal (in Galileo) also carries data giving the satellite orbit and other essential information which the receiver then decodes. When the receiver has gone through this process with four satellites, it is able to calculate its 3D position and velocity, and its clock is synchronised to the system standard time. Measurements to additional satellites will improve the accuracy of the measurements and provide resilience against intermittent loss of signal. Modern GPS receivers perform some of this process in digital form: in 5 years time virtually all of it will be digital. When a receiver is tracking a signal from a satellite the bandwidth of the code and carrier tracking loops can be very narrow. The code loop might be as low as 0.1Hz, the carrier loop 1kHz or less. The satellite's motion is highly predictable and so a stationary receiver, once the carrier is locked on, can easily follow the Doppler change. However, if the receiver is moving, for example in a vehicle, then a sudden change of direction could cause the carrier loop to lose lock.

To prevent this, either the receiver must allow the loop to operate at a wider bandwidth or the tracking loop must be “aided” by inputs form another sensor. In a fighter aircraft, for example, this aiding comes from the inertial reference system, in a vehicle it could come from a much simpler low cost gyro or dead reckoning system. These forms of coupled sensors are expensive. It is obvious from the foregoing that while a receiver is in tracking mode with the carrier and code operating as narrow bandwidth loops, it has a high ability to reject interference due to the narrow bandwidths. The loop characteristics are similar to a flywheel and a short interruption of one or more signals can be accommodated by the receiver.

There are many techniques that can be used to extend the ability of the receiver to keep tracking the satellite(s) in the presence of interference. Some examples are:

1 Tracking the code alone if the carrier lock is lost.
2 A dual frequency channel receiver may continue to track if the second

   channel is not affected by the interference.
3 A narrow band filter can be automatically steered in the processor to reduce the effect of a CW interferer.
4 Pulsed interference can be reduced by pulse blanking.

5 The use of multiple correlators, some new receiver chip designs use over 2000 to enable the signal to be tracked through fades and interference

6 Antenna nulling - a further significant increase in the ability of a receiver to withstand interference comes from the use of an adaptive antenna which can automatically steer nulls onto multiple sources of interference. It is possible to obtain 30dB of improvement with this technique.

Where receivers are most vulnerable is in the acquisition phase. If a receiver starts absolutely from scratch, i.e. unknown position, velocity and time (PVT), then it will have to search with wide loop bandwidths in order to find the signal and lock to the code. The more information it has about its PVT the faster it can acquire and the narrower the loops can be. Once a receiver is giving good PVT data then it is more difficult to interfere with, or jam. Where problems can arise is when the receiver is forced into a re-acquisition mode and where interference prevents it from then re-acquiring.

There is, obviously, a vast difference in receiver performance between those designed for leisure walking and those designed for civil aviation or for the most demanding military environments. A simple small receiver does not have the room for quality front end filtering or high dynamic range for example.
Finally spoofing must be mentioned, this is a technique for interfering with GNSS operation by transmitting either a simulated signal or a delayed version of a real signal with the aim of making the receiver display an incorrect position. In the proposed PRS it is intended to include cryptographic techniques to prevent this abuse.

10. Practical Interference Scenarios

This section will examine some interference scenarios.
The Galileo E6 signal is -128dBm as received by an isotropic circularly polarised antenna and in total has a 20MHz bandwidth That means it is roughly 30dB below thermal noise before signal processing. The Martlesham beacon on 1296.835MHz has an quoted erp of 700W (58dBm) referenced to a dipole The code modulator in the receiver operating at 5 Mchips/sec effectively turns this CW signal into a noise spectrum at its output so that if the receiver is tracking with, say, a 100Hz bandwidth, there is a processing gain (2x chip rate/tracking loop bandwidth) of 50dB. The tracking loop will continue to operate with an interferer about 5dB above the wanted signal. We will assume that as the beacon is near the upper E6 band limit and that the receiver matched filter attenuates it by 6dB. There is a further 3dB attenuation as the Galileo receiver has a CP antenna.

The margin required to continue operating is then -128 +5 - (58-50-6-3) = -122dB. This attenuation occurs at a range of 18 km. The approximate radio horizon of this beacon is 35km (there are a number of assumptions in this calculation but it indicates the scale of the potential problem).

A pertinent question, (perhaps even an FAQ) is …"so why hasn't this problem occurred with GPS which has been in use for a decade or more?" The answer is

that the simple GPS L1 (1575.42MHz) receivers are, indeed, vulnerable to interference but that their (approximately) 2MHz wide frequency channel is clear because it is protected to aeronautical standards. These receivers can be disrupted by relatively simple jammers designs for which are available over the internet but there are few reported instances of problems.

The study in 2001 of the vulnerability of the US transport system to GPS failures by the USA DoT's John A. Volpe Transportation Systems Center, reference [4], states that a 1W CW airborne jammer would break lock in a typical receiver at 10km and prevent lock at 85km. A jammer which more accurately mimicked the GPS waveform would be effective to > 900km. Other potential sources of interference are the harmonics of VHF/UHF base stations and mobiles which are stated to have been shown to deny operation out to 9km. It is noted that the fourth harmonic of the new Tetra deployment at 390MHz falls in band).

A study of interference to Civil GNSS applications by out of band interference has been undertaken for the Australian Global Navigation Satellite System Coordination Committee, reference [5]. Testing of the performance of typical GPS receivers in the presence of potential interference sources was carried out using commercial receivers. The study concentrated on interference affecting the GPS L1 signal and it looked, in particular, at the possibility of interference from the harmonics of UHF TV transmitters to GNSS. By a mixture of measurement and simulation the study determined that the typical third harmonic radiated from a 480kW TV Transmitter would disrupt GPS operation over a 3.5 km radius. There are plenty of high power TV transmitters in the UK who's second and third harmonics fall on the L1 frequency, but the writer has not heard of problems being reported.

At the other end of the scale there is a report of a 2mW jammer disrupting GPS operation over a 1nautical mile radius in a sea trial. This would represent about -100dBm at the receiver, exactly the level predicted by theory. In the lower part of the GNSS band both GPS and GNSS have to cope with the pulsed signals from the aeronautical distance measuring equipment (DME) and from TACAN and JTIDS / MIDS which are pulsed navigation systems and data links respectively. In addition Galileo receivers will have to cope with the navigation radars in the E6 band and their out of band transmissions as well. In a paper, reference [6], to be presented at the 2005 ION NTM Conference, the problem is highlighted but the solution is not obvious. For an excellent description of the GPS C/A code receiver jamming issue see reference [7].

11. What is likely to happen?

There is no doubt that GNSS will play an increasingly important, if not essential, role in the transport infrastructure operation in both Europe and the USA. The EU seems determined to possess its own system, independent of the USA and GPS.

However it still remains to be seen whether it can get the private sector to finance and run it for profit or whether it will have to heavily subsidise its operation. All NATO countries have access to GPS and so, in the light of other priorities for military equipment spending, it seems very unlikely indeed that there would be pressure from the European military for an independent system, especially when the US have said they would jam it, (or worse!) if it were perceived as a threat. The Galileo funding issue is not yet settled for development or for operation.

If Galileo goes forward as planned, with a year or two's delay, then as its usage becomes a more integrated and critical part of the infrastructure, the demand to have greater security, availability and reliability from the service will grow. This is happening already in the USA as the planned use of GPS for aircraft precision approach and landing comes closer to realisation. Air transport is more important in their infrastructure and so there is a need to see a way through to a highly robust civil GPS system.

The report by John A. Volpe, Transportation Systems Center, reference 4, reviewed this area and made many recommendations for improving robustness and availability, including research into interference mitigation and interference location. Everyone is beginning to recognise that the current GNSS ***does*** have vulnerabilities and that interference mitigation has to be an important and necessary component of the receiver system design.

Even if Galileo does not proceed we have to recognise that the 1260-1300MHz band will be used *at some time* for GNSS and that these systems will always have a rather weak signal at the earth's surface. Sharing the allocation with radar is/was relatively painless for the Amateur Services. Radars, even civil ones, are designed to cope with interference by employing a whole library of techniques developed over many years. Furthermore, because the number of radars is small and they are large installations and easily physically protected, the techniques can be kept secret where necessary. Although there are some who are calling for these bands to be effectively swept clear of interference sources this is (in my own view) impractical, especially where they are not protected by the stringent aeronautical regulations. Therefore if it is required to have a robust PRS service in the E6 channel then those receivers will have to incorporate ***very extensive*** interference rejection measures. The limit will be set by what can be released from military anti-jam technology into this para-military area, bearing in mind the virtual impossibility of keeping large numbers of the PRS equipments secure.

12. What can the Amateur Services do about it?

While Galileo might be delayed, it is unlikely to be stopped, although it is a possibility. Even if it is, then at some time (probably post-2007) another GNSS will take the allocation. This might lead to some limitations on continuous transmissions such as beacons, TV repeaters and FM repeaters below 1300 MHz.

Non-continuous signals such as ssb/cw ought to be much less of a problem to a robust PRS receiver and one can argue that 23cm amateur transceivers will be available for many years to come and probably constitute the largest quantity of potential jammers available to any person or organisation wishing to cause disruption. Therefore the PRS receivers should protect against them and therefore we should be allowed to continue.

We can argue that, to a moving vehicle, the signal from a typical amateur ssb/cw transmission will be very intermittent and therefore the receiver should be little affected by it. It would be useful to take some measurements of these sorts of signal levels. Obviously the terrain masking effect would be less for the police helicopter scenario but it would still be present to a degree.
EME operations are typified by a higher erp than normal "tropo" stations. However, the beam widths are small and so the duration of interference is short and a well designed receiver in a police helicopter for example would "flywheel" through it. The side lobe levels are about the same erp as a tropo station and the antennas, being large, are at low height, which considerably increases the intermittency of the signal at a distance.

A lot will depend on what arrangement is worked out to protect the radar operations, what is worked out at WRC-07 in order for both radar and Galileo E6 receivers to continue to operate. As someone said to the writer, "the radar guys will do the heavy work on this issue."

The IARU does not appear, as yet, to have understood the issue at all. To quote from the Region 1 WRC-03 report "The GALILEO allocation between 1260 and 1300 MHz (approved at WRC 2000) overlaps our amateur and amateur satellite allocations, but to date does not pose much of a threat. However, other spectrum users such as airborne and ground based radars are more concerned……. it was agreed that existing GPS systems put into operation before 2000 would not be subject to constraints, but that limits would be imposed on all new systems. From an amateur point of view, these new constraints will just provide a little ***extra protection"*** (added emphasis) "for us as well, and so this decision was a positive one from our point of view."

13. References

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