BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 63 (67), Numărul 3, 2017
Secţia
ELECTROTEHNICĂ. ENERGETICĂ. ELECTRONICĂ

MICROSTRIP PATCH ANTENNAS FOR GPS APPLICATIONS

BY

CRISTIAN ANDRIESEI[1,2,*] and IULIA STICEA[1]

[1]Technical University “Gheorghe Asachi” of Iaşi,
Faculty of Electronics, Telecommunications and Information Technology,
[2]AT&C Technology SRL, Iaşi, Romania

Received: August 28, 2017
Accepted for publication: September 29, 2017

Abstract. This paper reviews the patch antennas particularly designed and implemented for GPS applications, as proposed in the literature. Trying to offer useful design insights about performances, typical design parameters and constraints, technology, implementation and measurement, this study encompasses all single band GPS patch antennas reported so far in the scientific literature. Such review might be a good starting point when addressing the method of diagramming ideas to identify new antennas and possibly research directions, as well.

Key words: antenna; GPS; microstrip; patch.

1. Introduction

The global positioning system, widely known as GPS (GPS: The Global Positioning System), is the most popular member of global satellite navigation systems (GNSS), being developed by U.S.A to determine the instantaneous location almost anywhere on Earth. This navigation system is currently operated and maintained by the US Air Force. Primarily designed by and still used within military systems (sea, land, air defense), GPS implementations reached the large masses, being widely deployed in portable devices, GPS tracking tag, automotive applications (currently a strong emerging field) and transportation (cars, planes, trains). In accordance with the general recommendations freely available on the same website (Best Practices), beyond the requirement of using

[*]Corresponding author: *e-mail*: candriesei@etti.tuiasi.ro

good transceivers and DSPs, two aspects are critical for keeping the service quality as high as possible: antenna and cybersecurity. Both are related to some extent, especially when talking about GPS jamming which is a topic of high interest in defense systems. Whilst not critical for most civilian applications, very strict requirements are imposed to antennas used in satellite altitude determination, aircraft landing systems and defense related applications.

Regarding the antenna, microstrip antennas are almost a standard in GPS applications, being preferred to other constructive designs thanks to their ease of implementation, performances, low size and cost. And among them, microstrip patch antennas are the most widespread and studied in literature, other designs being proposed as well, such as monopole, slot, ring, dipole, loop and spiral microstrip antennas. However, these microstrip antennas come with a major drawback, *i.e.* their narrow bandwidth, fact that makes dual-band antennas more attractive for practical implementations, implemented by stacking patches or surrounding a circular patch with two concentric annular rings, as reported in literature. Beyond these, implementing a single band patch antenna is more critical for understanding the fundamentals of GPS antennas.

A critical issue for GPS receivers is represented by multipath signal propagation, generally caused by the reflections generated by the objects surrounding the receiver, which inserts errors in differential positioning by corrupting the direct line-of-sight signals from the GPS satellites. The multipath signals are represented by diffracted and reflected signals, as well. The diffracted signals are near the horizon type and they have right-hand circular polarization (RHCP) so that the antenna radiation pattern should have very low co-polar power to reject them. The reflected signals come from below the horizon and have left-hand circular polarization (LHCP) so that the antenna has very good cross-polarization performance to have them rejected. The multipath interference can be minimized by using a low back lobe antenna, a conventional approach making use of a choke ring ground plane, consisting of multiple concentric rings shorted at the bottom and open at the top. However, the main drawback is that the antenna size is increased. Alternative solutions involve vertical choke ring, artificial magnetic conductor, Electromagnetic Band Gap (EBG) structures, etc. Finally, it is worth mentioning that an ideal GPS antenna should possess an excellent circular polarization.

A review dedicated to GPS antennas is justified by the continuous interest shown by the scientific community to this topic, more than 100 articles being counted in the literature (conferences and journals), covering either GPS or multiband antennas. In addition, many patent applications were proposed during the last 20 years but this particular literature does not make the subject of this study. Such review is useful as preliminary step in applying the method of diagramming ideas (Andriesei, 2017) to identify new patch antennas architectures and even new research directions, if possible. Antenna design and implementation are covered in the following sections from different perspectives, such as frequency bands allocation (Section **2**), software design tool (Section **3**), substrate (Section **4**), polarization (Section **5**), patch geometry (Section **6**), antenna interface and input impedance (Section **7**) and other particular design parameters (gain, AR, size, etc) in the last Section **8**.

2. Frequency Bands for Navigation Services

The frequency bands allocated to navigation services are resumed in Table 1, where GPS standard can be easily identified, *i.e.* L1 (1,575.42 MHz) and L2 (1,227.60 MHz). Commercial filters designed for navigation services are

Table 1
Frequency Bands Allocated to Navigation Systems

Application	Frequency Bands (MHz)	Commercial Filters
Navigation, Rx f_0 = 1,223 MHz	1,196 – 1,250 (GNSS), 54 MHz	B3596
Navigation, Rx f_0 = 1,278.75 MHz	1,273.75 – 1,283.75 (GNSS /L6 Band), 10 MHz	B3428
L-Band	1,452 – 1,496	B8844
L-Band SatCom	1,518 – 1,559	B5163
Navigation, Rx f_0 = 1,542 MHz	1,525 – 1,559 (GNSS L Band), 34 MHz	B3421
Navigation, Rx f_0 = 1,565.5 MHz	1,525 – 1,606 (GNSS), 81 MHz	B3424
Navigation, Rx	1,559.052 – 1,563.144 (COMPASS, GNSS, BeiDou), 4.092 MHz	B8813, B8819, B8839, B8636, B9621, B3913, B3412, B3413, B4348, B4353
GPS	1,572.42 – 1,578.42	B3923
GPS, Autom. Telem.	1,574.42 – 1,576.42	B3923, B3528
Navigation	1,573.92 – 1,576.92	B4300
Navigation, Rx f_0 = 1575.42 MHz	1,574.42 – 1,576.42 (**GPS**, GNSS), 2 MHz	B8813, B8819, B8839, B8636, B9621, B9457, B3913, B3412, B3413, B3517, B3414, B3519, B3423, B3415, B4348, B4353, B4327, B4308
Automotive telematics f_0 = 1588.655 MHz 34.47 MHz	1,573.42 – 1,577.42 1,571.42 – 1,605.89 1,597.55 – 1,605.89	B4313, B4310, B3401, B3913, B3412, B3413, B3517, B3414, B3519, B3423, B3415, B4348, B4353, B4327
Navigation, Rx	1,597.55 – 1,605.89 (GNSS), 8.34 MHz	B8813, B8819, B8839, B8636, B9621, B3913, B3412, B3413, B3517, B3414, B3519, B3423, B3415, B4348, B4353, B4327
Satellite navigation	1,626.5 – 1,660.5	B5153
Satellite navigation, Aircraft surveillance, Tx	1,626.5 – 1,675	B5143

resumed as well, the spectrum mask and frequency constraints being of great help when designing RF transceivers, the single standard (Fig. 1) and wideband commercial filters (Fig. 2) fitting well the standard specifications. More details about GPS standard, data encapsulation and modulation can be found in the Interface Specification (IS-GPS-200).

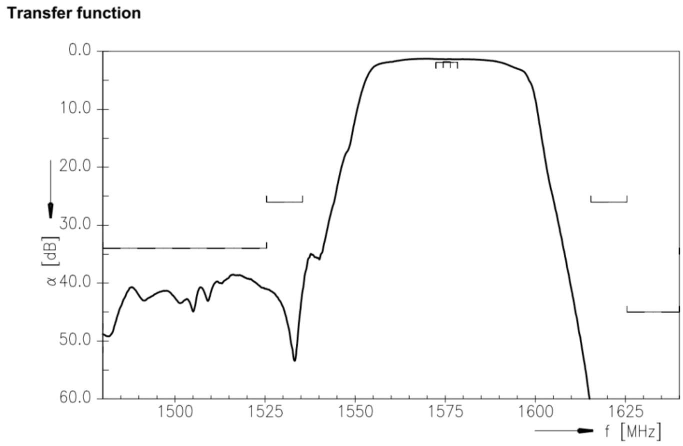

Fig. 1 – Frequency response for B3923 SAW filter (GPS/Galileo applications).

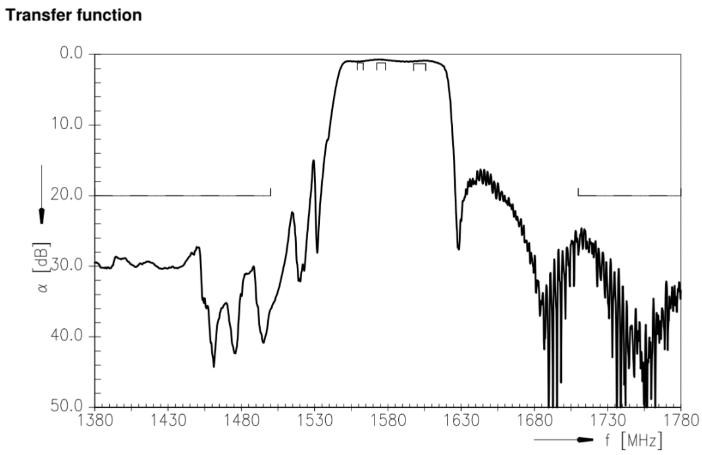

Fig. 2 – Multistandard SAW filter for navigation systems (B4348).

The product B8636 addresses also BeiDou -the Chinese satellite navigation system that comprises E1, E2, E5B and E6 overlapping Galileo, formerly known as COMPASS- and GLONASS or GNSS (Russian navigation equivalent, GLONASS M and K1 being currently in service, with K2 and KM in design). According to ITU policies, BeiDou satellites will have priority in exploiting all these 4 bands, being developed before the Europe's Galileo navigation system.

As can be noticed from the table and figures above, GPS applications developed within L1 frequency band make use of 2 MHz or 6 MHz bandwidth only, sufficiently narrow to favor microstrip patch antennas. Good return loss is critical for GPS antennas, as can be noticed from the following datasheet of a Qorvo L1/L2 GPS diplexer (890084), shown in Fig. 3.

L1 Band – L2 Band Specifications					
Parameter [3]	Conditions	Min	Typical [4]	Max	Units
Nominal Impedance [5]	Single Ended	-	50	-	
Antenna Return Loss	1574.397 – 1576.443 MHz	11.0	16	-	dB
	1565.19 – 1585.65 MHz	11.0	16	-	
	1226.577 – 1228.623 MHz	11.0	20	-	
	1217.37 – 1237.83 MHz	10.0	20	-	
Isolation	1574.397 – 1576.443 MHz	37	17		dB
	1565.19 – 1585.65 MHz	37	41		
	1226.577 – 1228.623 MHz	36	39		
	1217.37 – 1237.83 MHz	35	40		

Fig. 3 – Minimum return loss of 10 dB imposed to GPS antenna.

3. Optimized Design for GPS Antennas

Based on the scientific articles reported so far in literature and addressing GPS applications, with implemented or simulated (and optimized) antennas, an interesting conclusion that could be drawn about the design process is that all articles make use of optimization process. This means that no standard (mathematical) formula is mentioned nor applied to set the patch size. A single reference (Chen et al., 2009) focused on optimizing square-ring patch antennas and addressing GPS applications mentioned a resonant frequency formula, slightly modified compared to the case of conventional square patch antenna. In this particular case, a coefficient q affecting the effective dielectric constant was extracted by means of repetitive simulations and the formula was validated experimentally.

Since the use of a professional design tool is of utmost importance when it comes to model and manufacture a real (commercial) antenna, a review of the software tools preferred for antenna design would be of great interest. In this regard, the following software modelling tools have been reported for single band GPS antennas:

1. *Ansys High Frequency Structure Simulator* (HFSS) is clearly reported by 9 references, such as (Chen *et al*., 2009; Deng *et al*., 2015; Wang *et al*., 2012; Friedrich *et al*., 2015; Heidari & Dadgarnia, 2011; Chou & Chiu, 2006; Nascimento *et al*., 2006; Nascimento *et al*., 2007; Labadie *et al*., 2014), where the last one makes use of *Matlab* tool as well.

2. *CST Microwave Studio* is clearly reported by 6 references, such as (Zaid *et al*., 2016; Khosravi *et al*., 2015; Bao & Ammann, 2013; Bang *et al*., 2011; Bilotti & Vegni, 2010; Lim *et al*., 2010).

3. *IE3D* (Mentor Graphics) was reported by a single reference (So *et al*., 2015).

4. A mixture between *Ansoft Designer* (MoM) and *Empire* (FDTD) was used in one research (Baggen *et al*., 2008).

5. *FEKO*, another MoM tool, has been reported in one reference (Aloi *et al.*, 2014).

Other 6 articles proposing or studying different GPS antenna architectures do not specify the software used for design and modelling: (Narbudowicz *et al.*, 2016; Tang *et al.*, 2010; Basilio *et al.*, 2008; Bao *et al.*, 2006; Boccia *et al.*, 2003; Huang *et al.*, 1997).

4. Substrate for GPS Antennas

Choosing a particular substrate for GPS antennas is not an easy task since a trade-off between several parameters should always be under consideration: frequency performances, efficiency – with direct influence over the antenna size, cost and (system) integration. According to the results reported so far in literature, the following materials have been chosen for GPS antennas:

1. *FR4* – 7 references – seems to be the most used substrate material, as reported in (Deng *et al.*, 2015; Labadie *et al.*, 2014; Lim *et al.*, 2010; Bilotti & Vegni, 2010; Chen *et al.*, 2009; Nascimento *et al.*, 2007; Nascimento *et al.*, 2006). It is interesting to notice that 5 of them make use of HFSS design tool. FR-4 is a low-cost technology with good performances at lower frequencies from GHz range, including GPS L1 band. This low-cost advantage comes with additional complexity on the antenna design, an important drawback, mainly due to the inaccuracy of FR-4 relative permittivity and its high loss tangent. It may be ideal for prototyping and testing design concepts but not appropriate for commercial applications where low-loss RF laminates are used.

2. *Rogers* family (rogers) – 5 references – is the second most reported substrate material, different materials being tested successfully for GPS antennas, such as RT 5880 (Zaid *et al.*, 2016), RT 5870 (Heidari & Dadgarnia, 2011), Duroid 6002 (Basilio *et al.*, 2008), TMM10 (Bao *et al.*, 2006) and RO3003 (Huang *et al.*, 1997). One reference makes use of CST, a second one uses HFSS for simulations while the others don't report any software tool. Despite of lacking such information, the Rogers family is included by all microwave simulators, therefore there will be no problem in designing an antenna using any of these substrates. However, the fabrication cost will increase as the dielectric loss tangent lowers to 0.0012 for Duroid and 0.0048 for RO3003 (as used in literature), much smaller compared to FR-4 ($\tan\delta=0.02$).

3. *Taconic* substrates (4taconic) – 3 references – are cost effective substrates with better performances compared to FR4 and many substrate types, among them TLY-5 (Narbudowicz *et al.*, 2016), RF-43 (Khosravi *et al.*, 2015) and CER-10 (So *et al.*, 2015), from the same organic-ceramic laminate Taconic ORCER (taconic), being tested. It is interesting to notice that all three references use different simulators (IE3D, CST).

4. *EBG* (electromagnetic bandgap) substrate has been reported by a single reference (Baggen *et al.*, 2008), a technology that reduces the multipath effects, the designed antenna showing stable phase center. Despite these clear

performances, such technology may raise problems during the modelling step, hence appropriate modelling tools should be chosen carefully.

5. *$LiTaO_3$* substrate has been reported by a single reference (Tang *et al*., 2010). This technology allows antenna integration together with the SAW filter and reduces the antenna size thanks to better radiation efficiency (about 33%), obvious advantages that makes this substrate a good candidate for implementing small GPS antennas. However, the simulator is not mentioned, appropriate modelling tool should be chosen carefully.

5. Antenna Polarization and Design Challenges

Regardless of military or civilian GPS applications, the antenna is the most important RF device of the navigation system, a good design ensuring that the GPS antenna receives signals from satellites correctly. The antenna is expected to cover as many satellites as possible and reject the multipath and cross-polarized signals which are reflections generated by high-rise building that degrade positioning accuracy inside the city. On one hand, such broad beam coverage required in the upper hemisphere, *i.e.* wide angle coverage, makes the GPS system vulnerable to intentional electromagnetic jamming (critical in defensive systems). On the other hand, the best way to reject cross-polarized signals is to make use of circularly polarized signals, solution that comes with the main advantage of suppressing reflected signals. In this regard, microstrip patch antennas can exhibit good circular properties with low profile and are easy to model, clear advantages that favour them in comparison with other antenna topologies.

Circularly polarized (CP) patch antennas already became a standard for GPS applications, thanks to their broad beamwidth and good circular polarization, *i.e.* low axial ratio AR, ideally AR $\leq$ 1 dB which is difficult to fulfil for planar antennas but easier for 3-D antennas. In addition, circular polarization has the obvious advantage of increased flexibility in orientation angle between transmitter and receiver. However, the price is higher backward radiation and less forward radiation, *i.e.* more noise from the bottom and hence lower expected C/N ratio. Several techniques have been proposed in literature to overcome this limit and allow broadbeam AR in the case of GPS patch antennas. However, such improvements still didn’t reach the market, as long as simple antennas (*i.e.* CP patches) are commercially available worldwide thanks to their low cost and miniaturization capabilities, yet with the price of degraded AR toward the horizon. In addition, a trade-off between (antenna) miniaturization and frequency performances should be taken into account, particularly at lower GHz frequencies (including GPS frequencies).

Regarding the antenna polarization as reported in the literature, it is interesting to notice that:

a) 3 references don’t make any statement about the polarization of the designed/studied antenna (Wang *et al*., 2012; Basilio *et al*., 2008; Bao *et al*., 2006);

b) 14 references clearly focus on designing RHCP (right hand circular polarization) antennas, such as (Narbudowicz *et al*., 2016; So *et al*., 2015; Friedrich *et al*., 2015; Khosravi *et al*., 2015; Bao & Ammann, 2013; Bang *et al*., 2011; Tang *et al*., 2010; Bilotti & Vegni, 2010; Chen *et al*., 2009; Baggen *et al*., 2008; Nascimento *et al*., 2006; Chou & Chiu, 2006; Boccia *et al*., 2003; Huang, 1997);

c) All others 6 report GPS antennas circularly polarized (CP), without mentioning whether they are RHCP or LHCP.

From practical point of view, designing RHCP GPS antenna is mandatory to comply with the current GPS requirements.

6. Patch geometry

As expected, the most used patch geometry for implementing GPS antennas is the rectangular one (Fig. 4).

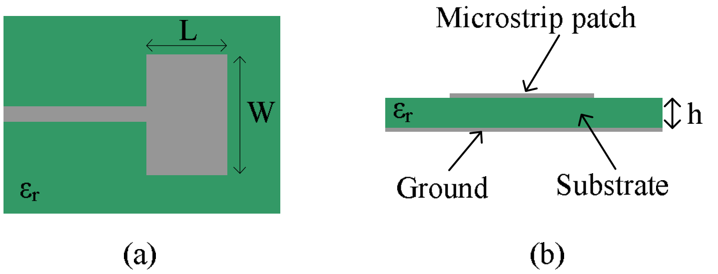

Fig. 4 – Basic shape for rectangular patch antenna.

This geometry, either the basic rectangular patch or modified square (for improved performances), has been reported by 15 references: (Huang *et al*., 1997; Nascimento *et al*., 2006; Chou & Chiu, 2006; Bao *et al*., 2006; Nascimento *et al*., 2006; Baggen *et al*., 2008; Chen *et al*., 2009; Lim *et al*., 2010; Bilotti & Vegni, 2010; Heidari & Dagarnia, 2011; Bao & Ammann, 2013; Deng *et al*., 2015; Friedrich *et al*., 2015; So *et al*., 2015; Zaid *et al*., 2016).

The second choice for antenna shape is the circular one, as reported in Khosravi *et al*., (2015), Labadie *et al*., (2014) and Basilio *et al*., (2008).

Other designs make use of particular shapes, such as elliptical patch (Boccia *et al*., 2003), Koch fractal structure (Tang *et al*., 2010), 3D cone for defense applications (Bang *et al*., 2011) or (irregular) hexagon patch (Wang *et al*., 2012).

One reference proposes two antenna designs, one with square patch and another with circular patch, to validate a particular design method (Narbudowicz *et al*., 2016).

7. Antenna Interface, Input Impedance

Several conclusions can be drawn regarding the GPS antenna interface and input impedance, as reported in literature:

1º 50 Ω input impedance is usually targeted in GPS applications, mainly because of the SAW filter inserted after the antenna (normally designed to have 50 Ω at both input and output). In addition, if the antenna is to be tested after implementation, it should have 50 Ω interface, all microwave analysers being 50 Ω matched. Several articles clearly report an input impedance of 50Ω for the GPS antenna, as in Friedrich *et al*., (2015), Labadie *et al*., (2014), Chen *et al*., (2009), Basilio *et al*., (2008), Baggen *et al*., (2008), Nascimento *et al*., (2007), Nascimento *et al*., (2006), Huang *et al*., (1997). For the last reference, the measured input impedance was 40 Ω instead of 50 Ω, as simulated/designed.

2º The most difficult part in designing a good impedance matching for GPS patch antenna is to minimize and even annihilate (if possible) the imaginary part of the input impedance, usually inductive behaviour characterizing the antenna input impedance. According to the antennas design techniques reported in the literature, the fractal electrodynamics concept can compensate the high antenna input inductance without changing substantially its real part (Nascimento *et al*., 2006). In this case, a very small reactance is achieved (–1.3j Ω). Using a fractal gap capacitor to match the antenna to the coaxial feed line may be another solution as well, as reported in the literature (Nascimento et al., 2006).

3º Other two references report 100Ω input ports (Bang *et al*., 2011) and 100,...,300 Ω differential input impedance for measured and simulated antenna, respectively.

4º All other references report S_{11} antenna performances without mentioning the targeted input impedance (supposed to be 50 Ω).

8. Antenna Gain, AR, Size, Temperature Stability and Measurements

(Boresight) Gain represents another important antenna parameter. According to the literature, different GPS antenna gains have been reported, ranging from 1.8 dBi (Zaid *et al*., 2016) to 8.23 dBi (Boccia *et al*., 2003), 8.85 dBi (Basilio *et al*., 2008) and 10 dBi (Bilotti & Vegni, 2010). Two articles report good RHCP/LHCP gain (ratio) of 30.8 dBi (Khosravi *et al*., 2015) and 27.16 dBi (So *et al*., 2015).

Furthermore, several considerations can be made about AR:

1. The AR value should as closed to 0 dB as possible. In this regard, low AR values were reported, such as 0.25 dB (Lim *et al*., 2010) and 0.6 dB (Bao *et al*., 2006) for GPS antennas.

2. The AR performance will be degraded depending on the operating environment and fabrication error while the AR evaluation is dependent on the application (such as vehicular use, where the elevation angle is critical).

3. The AR of the broadside mode deteriorates with elevation angle, good performances meaning the achievement of low AR values or keeping AR as low as possible for higher elevation angles.

Regarding the AR values, significant difference between simulated and measured AR has been reported in the literature, such as simulating 1.5 dB and measuring 2.8 dB as reported in (Friedrich *et al.*, 2015). Such errors should always been taken into account.

The antenna size is another interesting aspect. While a 2.5×2.5 cm^2 commercial patch antenna has been used in a particular research (Aloi *et al.*, 2014), different antenna sizes are reported in the literature, depending on the design method, ranging from 1.72×1.72 cm^2 (So *et al.*, 2015) and 1.8×1.8 cm^2 (Tang *et al.*, 2010) to 15×15 cm^2 (Khosravi *et al.*, 2015).

The frequency stability with temperature has been reported in one reference only, where 1 MHz deviation was reported within 20ºC,...,60ºC (Huang *et al.*, 1997).

Antenna measurement is the last and most important step of the antenna design. While several articles only report simulations and others measurements without mentioning any detail about the experimental setup, 5 articles report measurements conducted in anechoic chambers, out of which 3 belong to universities, as mentioned in (Narbudowicz *et al.*, 2016; Khosravi *et al.*, 2015; Labadie *et al.*, 2014). Among these, the third reference is the single one mentioning and taking into account the gain measurement error particular to anechoic chamber, equal to 0.32 dB, an important detail that can be taken into account in the research activity.

9. Conclusions

An original review of the patch antennas addressing GPS applications (L1 band) was conducted in this paper. Different design perspectives were taken into account to classify and compare the performances of the antennas proposed so far in the literature. A similar review will address multiband implementation of patch antennas, covering GPS standard as well.

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ANTENE MICROSTRIP DE TIP PATCH PENTRU APLICAȚII GPS

(Rezumat)

Acest articol sintetizează antenele microstrip de tip patch, proiectate şi implementate special pentru aplicații GPS, aşa cum au fost propuse în literatură. Cu intenția de-a oferi indicații utile pe parte de proiectare cu privire la performanțe, parametrii tipici de proiectare şi constrângeri, tehnologie, implementare şi măsurători, acest studiu acoperind toate antenele de tip patch proiectate pentru aplicații GPS raportate în literatura ştiințifică. O asemenea sinteză poate constitui un bun punct de start în aplicarea metodei diagramei de idei pentru identificarea unor noi antene şi, dacă este posibil, a unor noi direcții de cercetare.