Periodic structures, high impedance and semitransparent surfaces in antennas for centimeter and millimeter precision of positioning with the Global Navigation Satellite Systems

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Periodic structures, high impedance and semitransparent surfaces in antennas for centimeter and millimeter precision of positioning with the Global Navigation Satellite Systems

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Abstract. In designing GNSS high-precision positioning antennas it is desirable to achieve Π-shaped pattern which is homogeneous in the top semi-sphere up to the local horizon and has rapidly decreasing gain in the downwards directions. Such requirements as minimal loss factor and compactness are reasonably applied. Patch antennas with substrates formed of periodic metal structures have been developed, the structures substituting common dielectrics. High impedance surfaces are employed in design of ground planes. Convex and flat ground planes are discussed and presented; the antenna with a large flat impedance ground plane has allowed to achieve the level of positioning error below 1mm rms (root mean square) in real time. The antenna serves as a reference for research purposes. Semitransparent surfaces have been considered as means to obtain a sharp drop of the gain (cutoff) while crossing a local horizon. Plane and concave structures have been treated, and potentials for cutoff are also shown. Practical helical travelling wave and backfire antennas have been realized, with the 1.5mm-rms-positioning error being achieved. In addition to positioning, the antennas are considered as sensors in atmospheric research.

1. Introduction
High precision positioning with the Global Navigation Satellite Systems (GNSS) is achieved [1] in differential mode when a moving object (rover) is positioned with respect to a base station. Path propagation delays of signals from all satellites in view are measured by base station and rover receivers, base station readings are transmitted to a rover in real time, the difference in propagation delays of each signal is calculated at the rover. RTK (Real Time Kinematic) algorithm is applied to resolve ambiguities in carrier phases and to estimate clock offsets, this allows to achieve cm – precision of positioning. The signals of the satellites are grouped into the so-called the Upper L-band and the Lower L-band with frequencies of (1545...1610) and (1160...1300)MHz respectively, the signals being right-hand circular-polarized (RHCP). The error contribution that is unique to a site is known as ground multipath. The error originates from unavoidable reflections of satellite signals from a terrain underneath the antennas. To mitigate the multipath, it is desirable to achieve a reasonable approximation to Π-shaped antenna pattern which is homogeneous in the top semi-sphere up to the local horizon and has rapidly decreasing gain in the downwards directions. Such requirements as minimal antenna noise figure and compactness are applied.

The paper reflects the developments done in Moscow Technology Center of Topcon Corp. (Japan). For a broader view of GNSS antenna technology the reader is referred to [2,3].
2. Periodic Structures as Patch Antennas Substrates.
With the common patch antennas the bandwidth is proportional [4] to the substrate thickness. To avoid the use of thick RF ceramics in L-band, light weight metal structures have been developed. In figure 1, a parallel-plate waveguide is partially filled with a structure of metal ribs located at \(-b < z < 0\). Then, in the case of \(b, d \ll \lambda\) (with \(\lambda\) being a free space wavelength) the slowdown factor \(\beta\) of the wave propagation in \(x\) direction in the domain \(0 < z < d\) is \(\beta = \sqrt{\varepsilon_{\text{eff}}} \approx \sqrt{1 + b / d}\) [5]. Here \(\varepsilon_{\text{eff}}\) is equivalent to effective dielectric permittivity of the substrate. The antenna structure of circular polarization is shown in figure 2. Next, with TM\(_{10}\) cavity mode of a patch antenna, the electric field intensity in the area near the antenna center of symmetry is small. Removing pins of the central area has led to the patch stack with substrates in the form of a capacitive frame. At figure 3; the frame is a structure of interlapping metal pins. To estimate \(\varepsilon_{\text{eff}}\) one is to mention that for a linear polarized patch antenna the slowing down performance of the structure is a product of two factors: the propagation of a wave through a chain (figure 4.a) and the capacitive load to radiation impedance (figure 4.b); estimates [1] have shown that \(\varepsilon_{\text{eff}}\) on the order of 4…6 is achievable with the common manufacturing process.

![Figure 1. Parallel-plate waveguide filled with a structure of ribs.](image1.png)

![Figure 2. Dual band patch antenna with comb substrates.](image2.png)

![Figure 3. Dual band patch antenna with capacitive frame.](image3.png)

![Figure 4. a) Equivalent chain circuit of longitudinal structure, b) capacitive load to radiation impedance \(G_c\), \(L\)-resonant patch size.](image4.png)

3. High Capacitive Impedance Ground Planes.
For antenna gain reduction in the directions underneath the antenna, a flat metal ground plane is a common arrangement. Potentials of the approach are limited: in 2-dimensional approximation the field intensity underneath the ground plane is proportional to \(\sqrt{\lambda / L}\). Here \(L\) is the ground plane size. Opposite, with high capacitive impedance ground planes in the same approximation the gain decreases as \((\lambda / L)^{3/2}\). The latter is equivalent to antenna pattern null formation in the horizon direction for substantially large \(L\). To increase the said gain and thus to improve tracking of low elevated satellites by a receiver, a convex impedance structure [7] has been developed (figure 5). To achieve a high capacitive surface impedance and broadband functionality, a straight pins structure is utilized. As discussed in [7], as the radius of curvature decreases, the gain in the directions underneath stays almost constant within a reasonable range of radii while the gain for low elevation satellites improves rapidly. Figure 6 illustrates the antenna pattern of the developed structure in comparison [1] to a common Choke Ring ground plane antenna originally designed by Jet Propulsion Laboratory (JPL) of the USA. For correct understanding of the plots one is to mention that the carrier phase multipath error is proportional [1] to antenna down-up ratio in the form of \(F(\theta^\circ) / F(\theta^\circ)\). Here \(F\) is the antenna gain pattern and \(\theta^\circ\) is the elevation angle with respect to a local horizon.

Flat impedance ground plane of large \(L\) has been employed to approximate the \(\Pi\)-shaped pattern. At figure 7, the ground plane is 3m in diameter. Within the physical optics approximation [1,8], the down-up ratio of the antenna is setup by the ground plane size while the gain for low elevations is defined by the distance in between the pins structure and the antenna element in the center. With the antenna, it is for the first time that the error of positioning below 1mm root mean square (rms) has been demonstrated.
4. Semitransparent surfaces.
Semitransparency is understood as obeying boundary conditions for electrically thin sheet in the form \( \vec{n}_g \times (\vec{H}^+ - \vec{H}^-) = E / Z_g \). Here \( \vec{n}_g \) is the unit vector normal to the sheet, \( (\vec{H}^+ - \vec{H}^-) \) is the discontinuity of the magnetic field intensity on the two sides of the sheet, \( E \) is the electric field intensity, \( Z_g \) is the complex grid impedance that characterizes the sheet. The sheets of interest are grids of strip conductors with embedded impedances [9]. To achieve a \( \Pi \)-shaped pattern, radiation from a parallel plate waveguide with semitransparent walls has been considered [10], the profile of \( Z_g \) has been synthesized and dimensions have been evaluated. The approach has led to practical implementation in the form of quadrifilar helix antennas shown in the next Section. Another implementation [11] is a concave screen (figure 8). At the figure, the perfectly conducting portion is shown by a solid line and the semitransparent by a dashed line. The arrangement allows to achieve a sharp drop of the gain while crossing the desirable light-shadow boundary. For large radius \( b \) of a screen, the screen is synthesized analytically within the geometrical optics approximation, for smaller radii a numerical optimization procedure has been applied. Figure 9 illustrates the patterns that are achievable for initially cardioid pattern of the source. The 20-dB drop of the gain is realized by a screen with radius of 2 wavelength.

5. Helix antennas for mm precision of positioning.
Helix antennas with embedded impedances (figure 10a) and of backfire type with alternating winding angle (figure 10b) have been developed [10,12]. Type of the gain pattern achieved is shown in figure 11. Real time error in positioning is illustrated in figure 12. Here, the multipath contribution falls below
thermal noise, besides the noise the remaining error is estimated at 1mm rms. The result is valid for comparatively short distances between base station and rover. As the distance increases, the contribution of tropospheric gradients becomes noticeable. The technology is of potential interest for tropospheric slant delays estimates at precision of about 0.5mm rms.

6. Conclusions

Practical antennas for high precision positioning that utilize periodic structures of various kinds have been developed. The structures form artificial dielectrics, high impedance and semitransparent surfaces. Π-shaped antenna patterns with a 20 dB drop of the gain within +/-10 degrees angular sector about the local horizon have been realized. Precision of positioning of 1mm rms has been demonstrated.

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