Progress In Electromagnetics Research C, Vol. 44, 161–174, 2013

DESIGN, ASSEMBLY AND TESTING OF A HIGH GAIN LHCP HELICAL ANTENNA FOR RECEPTION OF REFLECTED GPS SIGNALS

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Abstract—This paper describes the design, assembly and field testing of a LHCP (Left Hand Circularly Polarized) high gain helical antenna. The antenna is to be utilized for the reception of reflected Global Positioning System (GPS) signals, which are correlated with the direct signals to form an image of the area of interest. Thus the antenna forms a constituent element of a remote imaging system. Owing to the low power of the reflected GPS signals the major design parameter was obviously high gain, while maintaining the polarization integrity of reflected GPS signals.

1. INTRODUCTION

The idea to exploit reflected GPS signals as a tool for remote sensing was initially described in 1993 by the European Space Agency [1]. Research by the same authors described a bi-static SAR imaging system, which utilized reflected GPS signals to form an image of the area of interest [2]. However, as compared to ordinary radar the incoming reflected GPS signals have very low power levels. As part of the research endeavor the aim was to overcome this core problem.

The GPS satellite signals are transmitted using direct sequence spread spectrum (DSSS) techniques and transmit RHCP (Right Hand Circularly Polarized) signals on two carrier frequencies named $L1$, the primary frequency at 1575.42 MHz and $L2$, the secondary frequency at 1227.6 MHz. GPS satellites have an array of 10 monofilar axial

Received 13 June 2013, Accepted 26 September 2013, Scheduled 10 October 2013
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helical antennas that provide gain towards the earth with 50 W or less transmitters. Owing to the large distance travelled by the transmitted signal the received power is very low and about -160 dBW. The Signal to Noise Ratio (SNR) is even less than 0 dB (typically -16 dB) [3].

The reflected GPS signal are even weaker and the polarization of GPS signals may be reversed after reflecting from a surface and become LHCP. The strength of the reflected signal depends upon the surface roughness and the dielectric properties of the reflecting object [4]. Following the inverse square law, the signal reflected from a conducting sphere with a radius of 10 cm would attenuate at a rate (expressed in dB) of approximately $20\log_{10}(R/0.1)$, where R is the range from the 'point reflector' to the observation point. For example, at a range of 25 m the attenuation will be about 48 dB. Thus ignoring antenna gain the signal level would be approximately 48 dB below that of direct signals received by a RHCP antenna.

In order to detect and acquire the weak reflected GPS signals a custom LHCP helical antenna has been prepared that furnishes 20 dBi of pure antenna gain. A Wi-sys® 30 dB GPS $L1$ frequency in line amplifier was also utilized during acquisition of weak reflected signals. It is pertinent to note that improving the antenna efficiency in terms of gain thus enhancing the SNR is of paramount importance. The inline amplifiers will not improve the weak reflected signal and if the signal is not strong enough in the first place it will be only amplifying noise. However, the inline amplifier did help to compensate the losses in the antenna cable and some of the amplifier induced noise was cancelled during the signal acquisition in which the received signal is correlated with a locally generated signal for extended time duration.

Measurements made by a LHCP GPS antenna have been documented in [4–6]. However, detailed design and characteristics for such an antenna is generally not available in the open literature. Many research endeavors discuss the LHCP antenna as a functional block in their diagrams or procure it as an off-the-shelf item. The purpose of this research paper is to document and detail the design, assembly, limited laboratory and field testing results of a LHCP helical antenna designed specifically for the reception of reflected GPS signals.

2. ANTENNA DESIGN

The design requirement of the GPS antenna employed in the imaging system was high gain and circular polarization. During antenna selection various options were explored and even tested. However, two choices stood out from the rest, an offset parabolic dish of size 1.5 meters with helical feed and LHCP high gain helical antenna.

The former was not selected on account of its size and possibility of direct signal interference. The latter was best suited as it provided compact size and high gain. Moreover, having reverse polarization as compared to direct GPS signals and pointed in opposite direction it delivered excellent immunity against direct signal interference. The signal attenuation resulting from polarization mismatch can be any value between infinity and zero as in case of circular polarization the RHCP and LHCP are mutually cross polarized. An ideal RHCP antenna will not receive any signal radiated by a LHCP antenna and vice versa.

The parabolic dish could have been positioned behind the GPS antenna as shown in Figure 1 in order to change the polarization of reflected GPS signals and provide more gain. The 180 cm C/KU band prime focus parabolic dish antenna available from Maplin Electronics, UK, was studied to be utilized for this purpose. The GPS antenna can be positioned in the place of LNA at the focal point of (also acting as the antenna feed point) a parabolic dish reflector and connected by low loss coaxial cable to the imaging system. However, the main impediment expected with this setup was that the RHCP antenna may also acquire direct GPS signals. This is evident from Figure 1 as the direct signal may cause interference and even mask the weak reflected signal.

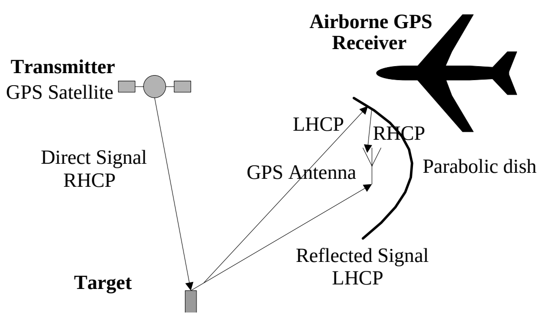

Figure 1. Parabolic reflector used to provide gain and change signal polarization.

2.1. Basic Helical Antenna

The fundamental concepts of the simple helical antenna were established by Kraus in 1947. It has a basic three dimensional geometric form and can be left or right handed [7]. The helical beam antenna is a rudimentary structure possessing a number

Table 1. The geometrical parameters of the helical antenna.

Parameter	Description	Relationship
D	Diameter of the helix	
C	Circumference of the helix	πD
S	Spacing between turns	
α	Pitch angle	$\tan^{-1} S/\pi D$
λ	One GPS Wavelength (190 mm)	
L	Length of one turn	
N	Number of turns	
A	Axial length	NS
d	Diameter of helix wire	

of interesting properties including ease of assembly and circularly polarized radiation.

The important parameters that will be used to describe the helical antenna throughout this text have been summarized in Table 1. Varying the dimensions of these parameters can control the output of the antenna. The two main parameters that can be used to optimize the radiation pattern are the number of turns and the circumference of the helix. The beam width can be reduced and thus the directivity augmented by increasing the number of turns.

The helical antenna consists of a conducting wire wound in the form of a screw thread. There are two main modes of operation of the helical antenna, the normal mode and axial mode. The latter, also termed as the end fire mode, has only one major lobe of the radiation pattern and it is in the direction of the axis of the helix. To achieve the end fire pattern, the diameter and the spacing of the coil must be large fractions of the operating wavelength. Circular polarisation is achieved by restricting the range of the circumference of the antenna to $3/4 < C/\lambda < 4/3$ [7].

2.2. Input Impedance

The input impedance is dependent upon various parameters including wire radius, location of feed point, number of turns, helix diameter and pitch, frequency and shape of conductor as well as the influence of the antenna's mechanical support [8]. Classical literature states the terminal impedance of an axial mode antenna to be approximately $140\,\Omega$ ($Z_{in} = 140C/\lambda$). However, the research stated in [8] specified it to vary between $90\,\Omega$ and $270\,\Omega$. It is imperative to match the antenna to a $50\,\Omega$ transmission line in order to minimize signal loss, this can be achieved by using a quarter-wave matching transformer between the feed line and the feed point of the helix or increasing the conductor size between the end of the helix and the feed point.

Scatter parameters (also called S-parameters) are used extensively to measure the input impedance with the help a vector network analyzer or VNA as shown in Figure 3. $|S_{11}|^2$ denotes the power reflected from input port and S_{11} is equivalent to the input complex reflection coefficient. When utilizing a VNA with a system impedance of Z_0, the parameter S_{11} is equal to:

$$S_{11} = 2\left(\frac{Z_{in}}{Z_{in}+Z_o}\right) - 1 = \frac{Z_{in}-Z_o}{Z_{in}+Z_o} \tag{1}$$

And thus the input impedance can be calculated by the following equation (with $Z_0 = 50\,\Omega$):

$$Z_{in} = Z_o \frac{1-S_{11}}{1+S_{11}} \tag{2}$$

2.3. Gain of the Antenna

There are many expressions listed in the technical literature regarding gain or directivity of the helical antenna. The theoretical gain given in [7] is as follows:

$$G = 15NS\pi^2 \frac{D^3}{\lambda^3} \tag{3}$$

King and Wong [9] detailed the results of an extensive study of pattern and gain characteristics of helical antennas (1 to 8 wavelengths long) in the UHF frequency. Although, the authors selected an antenna with a cup-shape ground plane, the peak gain may be empirically expressed as:

$$G_p = 8.3\left(\pi\frac{D}{\lambda}\right)^{\sqrt{N+2}-1}\left(N\frac{S}{\lambda}\right)^{0.8}\left[\frac{\tan\left(12.5\frac{\pi}{180}\right)}{\tan\left(\alpha\frac{\pi}{180}\right)}\right]^{\frac{\sqrt{N}}{2}} \tag{4}$$

and the gain in dBi $= 10\log_{10}(G_p)$. Where all the parameters of (3) and (4) are as described in Table 1.

Another empirical formula for the gain of a helical antenna in dBi, is listed in [10] and is reproduced below:

$$\text{Gain (dBi)} = 11.8 + 10\log_{10}\left(C_\lambda^2 N S_\lambda\right) \tag{5}$$

where C_λ and S_λ are respectively, the circumference and spacing between turns in terms of one GPS wavelength.

However, Emerson [11] noted that there are conflicting claims for the antenna gain and summarized extensive numerical modelling calculations for the helical antennas. He concluded that the maximum possible gain is up to 4 or 5 dB lower than those derived from the original Kraus formula. The maximum gain increases much more slowly with increasing antenna length than the simple Kraus formula would predict. Moreover, the gain is almost independent of wire diameter or the presence of a short feed stub between the ground plane and the start of the helix. An empirical expression for the maximum possible gain of the helical antenna as a function of its length L in wavelengths (for lengths L between 2 and 7 wavelengths) is:

$$\text{Gain (dB)} = 10.25 + 1.22L - 0.0726L^2 \tag{6}$$

The half power beam width is given by the following quasi-empirical relation [7]:

$$\text{HPBW} = \frac{52}{\frac{C}{\lambda}\sqrt{N\frac{S}{\lambda}}} \quad \text{(degrees)} \tag{7}$$

According to the graph shown in Figure 2 a 21-turn antenna should furnish a gain of about 17 dBi (average of two values). In order to achieve optimum circular polarization the ratio C/λ should be equal to 1 and the spacing of the turns should be $S = \lambda/4$ or $0.25C$ [7]. With these parameters the total axial length (NS) of the antenna came out to be one meter. The actual parameters of the antenna have been summarized in Table 2.

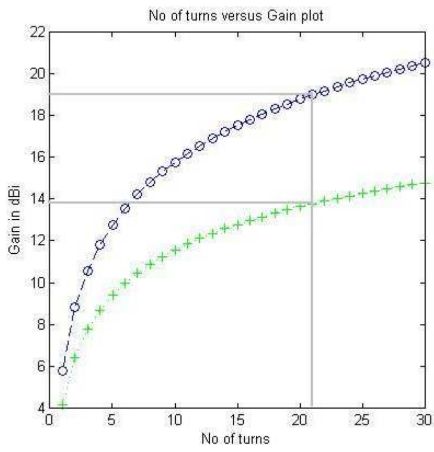

Figure 2. Antenna gain plot, the plot with circles shows Equation (5) and plot with plus signs shows Equation (6).

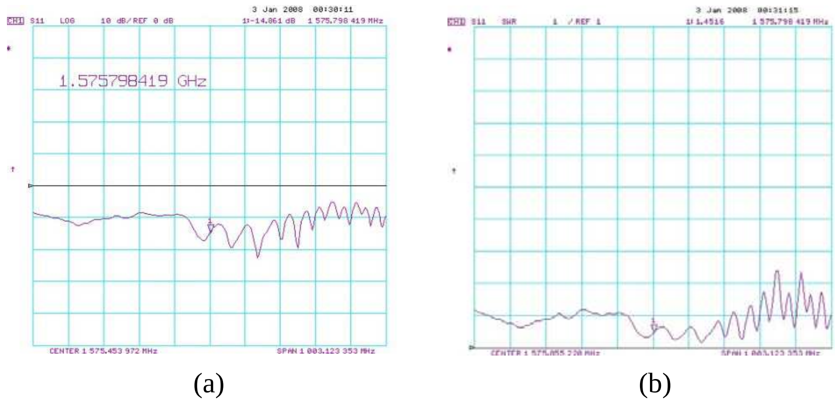

Figure 3. VNA plot for the LHCP antenna, showing S_{11} and VSWR.

Table 2. Actual parameters of the helical antenna.

Parameter	Description	Value
D	Diameter of the helix	60 mm
C	Circumference of the helix	190 mm
S	Spacing between turns	47 mm
α	Pitch angle	14°
N	Number of turns	21
A	Axial length	1000 mm
d	Diameter of helix wire	2 mm
HPBW	half power beam width	22.7°

2.4. Antenna Assembly

A clear acrylic Plexiglas plastic pipe with diameter 60 mm and wall thickness of 3 mm and having length one meter was utilized as form for the winding. Acrylic plastic or Plexiglas has high surface resistivity thus making it an ideal insulator with dielectric constant ranging from 2.6 to 3.4. The tube having outer circumference equal to one GPS wavelength provided the requisite size and support for the 14 swg (2.0 mm) enameled copper wire to be utilized as the helix coil without interfering the GPS signal. The conductor size is not critical and may vary from 0.005λ or less to 0.05λ or more [7]. For a 2 mm wire it turned out to be 0.01λ. A two mm thick square aluminium sheet having one side equal to GPS wavelength (190 mm) was employed as the base plate. An SMA connector was used to connect the helix wire to a RG-58 Coaxial cable.

3. ANTENNA TESTING

3.1. Impedance Matching

The S_{11} measured with the Vector Network Analyzer (Agilent 8753ES) was 0.5678 at 1.57542 GHz, thus Z_{in} as per Equation (2) comes out to be 181.58 Ω. In order to perform the impedance match between the antenna and cables, a copper strip (17 mm × 71 mm) was soldered with the helix wire, which effectively increases the conductor size between the end of the helix and antenna feed-point [12]. After the rectification, the measurements on a Vector Network analyzer revealed the S_{11} as −14.86 dB (0.14) and input impedance being 72 Ω, VSWR as 1 : 1.45 and return loss only 0.18 dB. A VSWR value of less than two is considered to be acceptable in practical scenario [7].

3.2. Gain Measurements

Due to lack of suitable testing equipment and facilities it was deemed necessary to perform the antenna gain measurements by comparison with a certified and tested antenna. A RHCP antenna having similar parameters (as the LHCP antenna) was prepared with the intentions to compare it with an off-the-shelf Trimble Bullet™ III GPS antenna. It is an active RHCP antenna with a specified gain of 35 dB as given in its datasheet. An acquisition diagram for 5 ms integration time for Trimble's Bullet™ III GPS antenna is shown in the Figure 4(a). It was found that to obtain a comparable SNR for the data collected with the custom made RHCP antenna, the signal has to undergo a coherent integration for 200 ms. For each two fold increase in integration time

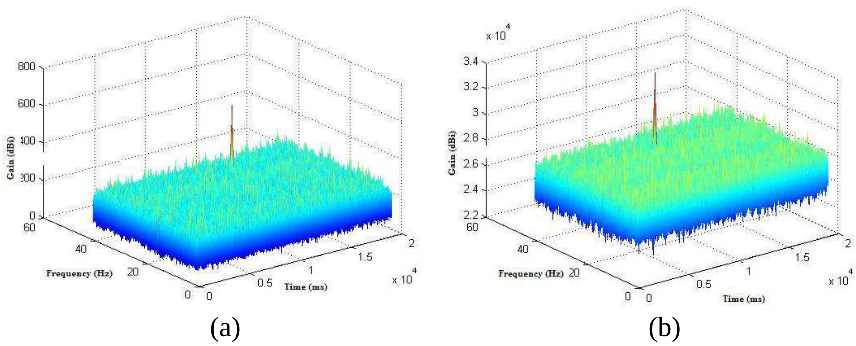

Figure 4. Comparison of acquisition plot for (a) Trimble Bullet III antenna (acquisition time of 5 ms) and (b) passive custom made RHCP antenna (acquisition time of 300 ms).

the processing gain should enhance by 3 dB. Thus, the gain is about 18 dB lower for the custom antenna as compared with the Trimble's Bullet™ III GPS antenna. According to these calculations the gain is about 17 dB, which is in between the two curves of Figure 2 and thus conforms to the theoretical calculations.

3.3. Further Gain Improvements

Initially a square plate was utilized as the ground conductor for the antenna. In order to further enhance the gain of the helical antenna, the shape of the ground conductor was modified. Instead of a square plate the ground conductor was made in the form of a truncated cone with optimal dimensions of the cone based on GPS $L1$ frequency [13]. Diagram of modified antenna is shown in Figure 5. It has been stated in [13] that the helical antenna above the conical ground conductor has lower axial ratio and lower sidelobes than antenna above the square ground conductor. This enhancement is due to the conical ground plane, which suppresses sidelobes in directions that are close to horizontal directions and below, thus also suppressing back radiation. The function of the cone is that it acts not only like a reflector (which collects and directs the energy spilled into the sidelobes), but also acts similar to a horn antenna that creates its own radiation pattern, which favorably interacts with the pattern of the helical antenna [7].

As mentioned in [13] the optimum dimensions of the cone will be when $B_2 = 2.5\lambda$, $B_1 = 0.75\lambda$ and $h = 0.5\lambda$ (where λ is equal to one GPS wavelength and equal to 0.19 m). For these dimensions, the

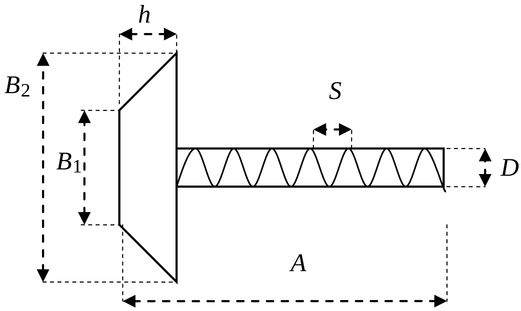

Figure 5. Simplified antenna diagram.

Figure 6. Assembled LHCP helical antenna.

peak gain is specified to be about 3 dB higher than the optimal square plate. Thus an inline GPS amplifier with gain of 30 dB will improve the overall antenna gain to 50 dB, enough to perform measurements for the reflected signal. The finished antenna is shown in Figure 6.

4. ACQUISITION OF REFLECTED GPS SIGNALS

After the GPS signal has been converted to IF frequency the code offset and carrier Doppler shift are calculated with the help of signal acquisition process. If the satellite is visible, the acquisition process determines the coarse values of carrier frequency and code phase of the satellite signals [3]. The code for the GPS signal acquisition has been developed in Matlab® based on the parallel code phase search acquisition. This method is the most efficient in terms of computational efficiency among several methods available for this purpose [14].

In order to confirm that the signal received by the LHCP antenna is in fact the reflected signal a set up similar to Figure 7 was arranged. The direct signal was acquired by the off-the-shelf RHCP Trimble Bullet™ III GPS antenna. The experiment was performed in front of a large brick building. The RHCP antenna was directed towards the satellite, while the LHCP helical antenna was positioned so as to receive the signal bouncing off the building at a distance of about 25 m. The most suitable satellite (in terms of signal strength and visibility) was GPS BIIRM-3 (PRN 12) and was therefore selected as the reference satellite. The satellite elevation and azimuth were calculated with the help of a commercial GPS receiver. The antenna was roughly positioned so as to receive the reflected signals of the reference satellite from the wall.

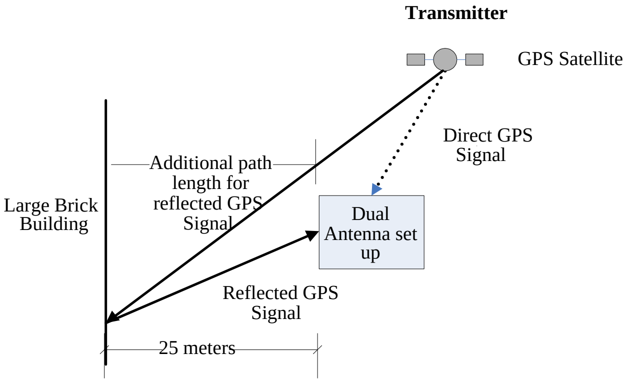

Figure 7. Set up for detection of reflected GPS signals.

As expected a very strong signal was received with the RHCP GPS antenna, yielding good acquisition even for few ms of integration time. The comparatively weaker reflected signals acquired by the LHCP antenna required much longer integration times (200 ms) to achieve comparable SNR. Longer acquisition time results in the cancellation of uncorrelated noise, thus improving the SNR. The Doppler frequency of both signals is the same but code offset is slightly different corresponding to the extra distance that the reflected signals have to travel.

The length of one GPS C/A code is 1023 chips and is transmitted with a frequency of 1.023 MHz. Taking into account the speed of light the length of one chip can be calculated to be 300 m. The signal is sampled at 19.2 MHz. Thus each code sample corresponds to about 15 meters. It is possible to distinguish between the direct and reflected signal if the path length between direct and reflected signal is a multiple of 15 meters.

During the experiment performed the difference in code samples of direct and reflected signal was 3 or 4 which came out to be about 45 to 60 meters and corresponds to the round trip distance between antenna and the large brick building or reflective surface. Figure 8(a) compares the direct and reflected signal correlation peaks clearly depicting this path difference. The scale for the correlation value (y-axis) is different for both signals on account of the varying acquisition time.

In order to verify the results, GPS IF data was collected at a position of only two meters away from the building or reflecting surface. A path difference of only one code samples was observed among the direct and reflected signal as shown in Figure 8(b). A near specular GPS reflected signal was received suggesting an optimum geometry for reception of reflected signals. Thus the experimental results substantiated that the signal present at the LHCP antenna is in fact the reflected signal and construction of the hardware has been successful.

The image is generated by the correlation of direct and reflected GPS signals using matched filter processing and based on synthetic aperture radar (SAR) techniques. The authors have developed customized reconstruction algorithms in this regard [2]. To acquire data for image generation purposes, the imaging hardware including the two antennas and data acquisition device was positioned in front of the University building and a $0.5\,\mathrm{m}^2$ spherical balloon wrapped in aluminum foil was used as a target. During acquisition of data for imaging purposes the nearby buildings formed an urban canyon type environment thus limiting a clear of the view of the sky.

In order for the GPS satellite to provide the requisite change is

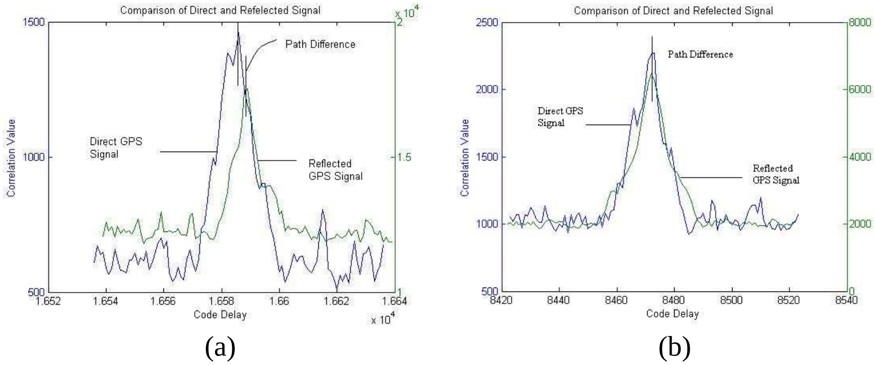

Figure 8. Comparison of direct and reflected GPS signals for (a) 50 m, (b) 4 m (round trip distances).

geometry, 80 files were down loaded at an interval of about 30 seconds each. The length of individual file was 4 seconds, but only the first few milliseconds of each file were used during the reconstruction process. The GPS data provided about 2400 seconds for change in geometry, just enough to identify the target, but compromising the resolution. Figure 9 compares the image by reconstructing 2400 seconds of actual data with a simulated signal of 2400 seconds. In future it is recommended to perform signal acquisition in an open environment to have a clear view of the sky and thus increasing the chances of receiving more GPS satellites and for extended duration. The target can be seen in the middle of the diagram, as the antenna's main lobe was aimed roughly towards the target center. Unfortunately, an increase in the integration time also resulted in more signal being received by the highly directional antenna and some of the signal was not received from the target, but bounced off from nearby objects and building front.

As evident from the results, although it is roughly possible to distinguish the target, there is excessive backscatter or clutter and noise exhibited in the images. The situation was exacerbated due to the fact that the high gain LHCP antenna was placed in front of a large brick building. The antenna was designed to acquire the weak reflected GPS signal, but returns from objects around the target were also received and displayed in the image. The exhibited images may seem very primitive, but it has to be kept in mind that no dedicated radar transmitter was available during the experiments. The target has been detected in a hostile environment with the help of extremely weak reflected GPS signals that are omnipresent, but exhibit an appalling SNR. It is further apprized that the change in geometry to process the

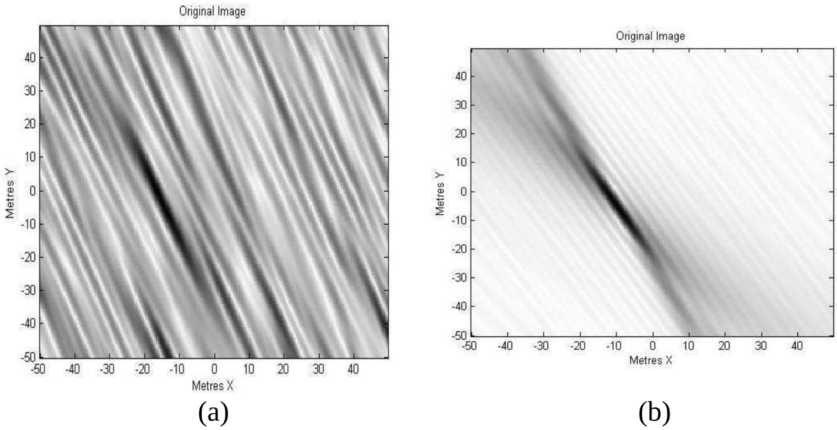

Figure 9. Comparison of image obtained by reconstructing 2400 sec of (a) actual signal, (b) simulated signal.

data with the help of SAR technique was provided by the orbiting GPS satellite and the imaging hardware was positioned at a fixed geographical location. This particular method has so far not been utilized in a practical environment for imaging purposes.

5. CONCLUSIONS AND RECOMMENDATIONS

The paper describes the design, assembly and field testing of a LHCP (Left Hand Circularly Polarized) high gain helical antenna designed for the acquisition of reflected Global Positioning System (GPS) signals. The interference between direct and reflected signal has been minimized on account of the fact that there is considerable polarization mismatch between both antennas and the LHCP antenna is highly directional. The performance can be further improved by using four LHCP antennas to form an antenna array [7]. The next phase of the project will be to gather further data for generation of image using the algorithms developed for this purpose. The weak reflected signal is to be extracted for correlation with the direct signal and subsequent image generation.

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