Initial Experiments for a Remote Imaging System based on Reflected GPS Signals

M Usman, D W Armitage

***Abstract*— Reflected GPS (Global Positioning System) signals can be utilized for remote sensing as they contain valuable information regarding the reflecting surface. An image of the area of interest can be generated if the direct and reflected signal are manipulated using Synthetic Aperture Radar (SAR) signal processing techniques. This paper describes the design of a two-channel GPS front end and data capturing device intended for the simultaneous acquisition of direct and reflected GPS L1 frequency signals, these signals are subsequently used for image reconstruction. Details of some initials tests and experiments to verify the functionality of the device are also presented.**

Index Terms— **GPS, Correlation, Imaging, RF front end.**

I. Introduction

THE Global Positioning System (GPS) was developed as a military navigation system for guiding missiles, ships and aircrafts towards their targets [1]. GPS satellites transmit free source of coherent radio waves illuminating the Earth's surface 24 hours a day which are received and processed by GPS receivers for extracting navigational parameters like position and velocity. Signals transmitted from GPS satellites are also reflected from objects present on the earth's surface. These multi path signals induce errors during navigation and have to be mitigated during position and velocity calculations. Interestingly, they can be utilized for various remote-sensing applications as they contain valuable information regarding the reflecting surface.

Analysis of scattered or reflected GPS signals has recently attracted a lot of attention because of their potential civilian and military applications. An image of the area of interest can be generated if the direct and reflected signal can be manipulated using Synthetic Aperture Radar (SAR) signal processing techniques. The SAR is a type of imaging Radar in which an effective long antenna is simulated by signal-processing means to enhance antenna aperture and thus improve image resolution. SAR can be of two types: mono-static, where the same antenna is used for transmission and reception purposes, whereas in case of bi-static SAR, separate antennas are utilized. The GPS satellites, a modified GPS receiver and its signal detection components (antennas), constitute a bi-static SAR system, which can be employed for passive microwave imaging purposes in case the GPS satellite is used as a 'transmitter of opportunity'.

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Possibility of using GPS signals reflected from the earth's surface as a new remote-sensing opportunity was first described in 1993 by the European Space Agency [2]. Most of the available literature discusses the collection of reflected GPS signals and with suitable algorithms utilize it, over the ocean to calculate mean sea height, wind speed, wind direction and significant wave height [3]. Over land to measure soil moisture content, biomass and bi-static imaging [4] and over ice to ascertain ice age, thickness and surface ice density [5]. The idea of 3D multi-static SAR imaging system, which utilized reflected GPS signals from objects on the Earth's surface was presented by Chris Rizos et al. [6]. The output of the matching filter was mentioned as: -

$$S_{ij}(\tau) = \int_{-\frac{Ts}{2}}^{\frac{Ts}{2}-\tau} S_{Rij}(t+\tau)\, S_{Rij}{}^{*}(t)\, dt \tag{1}$$

where Ts is the observation time, τ being the delay and $S_{Rij}(t)$ is the received signal and considered as an approximately linear FM signal. In fact, Bi-static radar systems have been studied and built since the earliest days of radar. As an example, the Germans used the British Chain Home radars as illuminators for their Klein Heidelberg bi-static system during the second world war. One of the key problems of any bi-static radar is the synchronisation between the transmitter and receiver. The GPS signals are optimized for proper synchronisation and hence provide relatively easy and accurate synchronization between the receiver and the transmitter. The advent of GPS solved many of the synchronization and timing problems that have previously limited the performance of bi-static radar systems [7]. M Cherniakov et al. have reported much work in the field of bi-static radars in general and utilizing different systems as

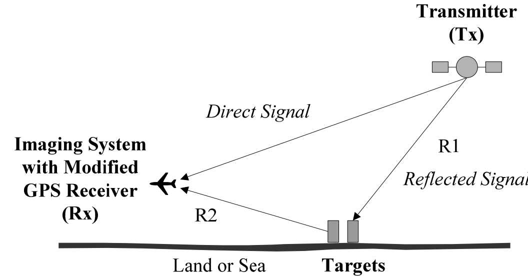

Fig. 1. Schematic representation of the imaging scenario for an airborne receiver.

transmitters of opportunity in particular [8] [9] [10].

Research by the same authors describes a bi-static SAR imaging system, which utilizes reflected GPS signals from targets on the Earth's surface [11]. Since the GPS satellites and receiver platform are in motion during the integration time, the signal obtained at the receiver position will be a Frequency Modulated (FM) GPS signal also termed as chirp signal owing to the constantly changing Doppler shift. This makes it possible for the bi-static SAR imaging system to obtain enough range and resolution simultaneously, since the frequency modulated GPS signal has pulse compression properties. A matched filter is employed in the received signal processing to improve the system resolution. Thus, the bi-static SAR system has the potential to develop low cost images of a localised area.

One possible arrangement of the transmitter, target and receiver geometry is shown in figure (1). As per the traditional SAR concept the receiver is airborne and can detect the presence of static or terrestrial targets as well as slow moving targets like ships. An alternate arrangement is a static receiver mounted on the top of a tower or hill. We know that the concept of generating an image by the correlation of direct and reflected GPS signals is based on the SAR principle in which the receiver or bi-static radar is to be kept airborne or required to sustain its movement in spatial domain. In order to simplify the experimental set up, it is possible to generate an image with a static receiver, if GPS data is acquired over longer period of time and processed in batches. The time can last from few minutes to a few hours. With the receiver being static the change is geometry is provided by the moving GPS satellite. One of the numerous possible applications with this type of set up are remote sensing for monitoring of landslides, long-term seismic studies and similar applications.

The objectives of the research were to study these imaging arrangements and scenarios in a software environment using Matlab®. The aim included development of suitable image reconstruction algorithms, simulation of noise and errors sources, design and assembly of necessary hardware, acquisition of weak reflected GPS signals and finally generation of image for the area of interest. The results of simulation performed have been recorded in [11]. The main goal was to demonstrate a practical imaging device with the design and assembly of a proof-of-concept hardware of the imaging system. The purpose of this document is to elaborate the hardware that has been prepared to materialize this goal.

There are many advantages of this type of system, which are as follows: -

1) GPS based target detection and imaging has the attraction that user can take advantage of the expensive GPS infrastructure maintained for navigation purposes and no dedicated transmitter is required.
2) GPS operates round the clock and its signals cover the entire earth surface. There are more simultaneous imaging opportunities, one for each GPS satellite in view. The GPS satellite with optimum geometry in terms of signal strength and visibility can be selected to receive the direct and reflected GPS signal.
3) One of the many advantages of the system is the cost effectiveness. The imaging hardware, comparable in size and complexity to a notebook computer, can be built for a fraction of the cost of traditional radars, space-borne equipment and other sensors.
4) In case of passive microwave imaging the operation will be covert (no signal will be transmitted as compared to ordinary radar) and therefore not susceptible to enemy jamming activities. Thus enabling the user to undertake radio silence surveillance of enemy territory.
5) Bi-static radar may also have counter stealth capabilities, since target shaping to reduce the mono-static RCS of a target will in general not reduce its bi-static RCS [7].

The GPS 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 helical antennas that provide gain towards the earth and have 50 W or less transmitters [1].

A. *Link Budget Calculations*

Owing to the large distance travelled by the transmitted signal the received power is very low and the Signal to Noise Ratio (SNR) is less than 0 dB (typically -16dB). Thus, the power spectral density of any given GPS C/A code signal is below the power spectral density of noise. It is converted to a usable SNR by correlation with a locally generated C/A code sequence that provides an effective processing gain (typically 30 dB) to improve the SNR ratio.

Considering the bi-static Radar scenario as depicted in figure (1), if power transmitted from a target is P_t and gain of transmitter is G_t, σ is the target cross section, R_1 is the Range from GPS transmitter to target, than R_2 the range from target to receiver is given by:

$$R2=\sqrt{\frac{PtGtGr\lambda^2\sigma}{(4\pi)^3 Rl^2 \Pr}}km \qquad (2)$$

The signal to noise ratio at the receiver for bi-static radar is given by

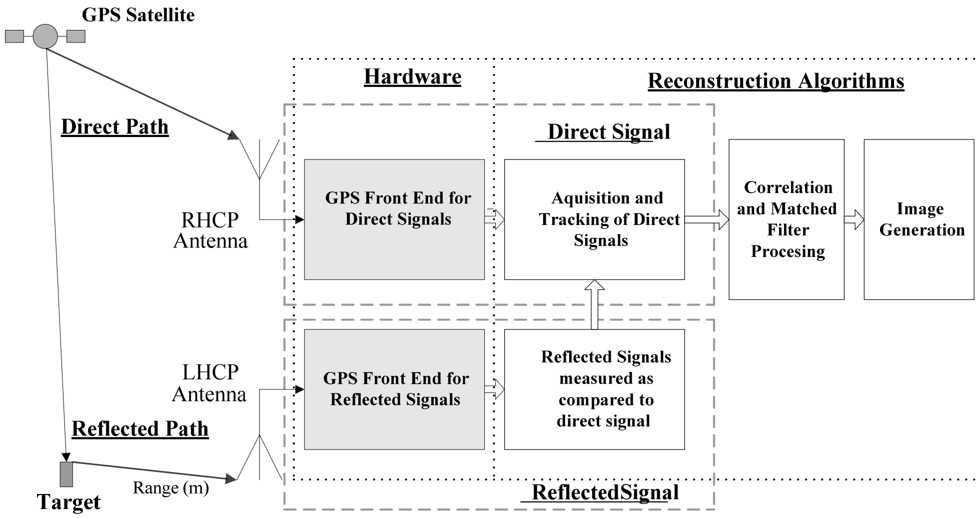

Fig. 3. The Imaging Scenario

$$\mathrm{SNR}=\frac{Pr}{Nr}=\frac{PtGt}{(4\pi)^3 R1^2}\frac{Gr\lambda^2\sigma}{R2^2 KTB_n} \quad (3)$$

Where Gr is the gain of receiving antenna, Pr is power received at the receiver, Nr = KTB_n and λ is GPS L1 wavelength [12]. The SNR plot for GPS L1 frequency and target cross section of $10m^2$ is shown in figure (2). It is evident that the SNR is very poor even at short distances, which is the main limitation for this type of passive microwave imaging radar. However, the processing gain obtained by correlating the signal for longer periods of time during reconstruction significantly improves the SNR and thus it is possible to generate an image for the area of interest. It will be further explained in section III.

The imaging system in high-level block diagram format is shown in figure (3). The nadir-looking GPS antenna receives the reflected signals. The amplitude reduces at every reflection since the reflection coefficient is less than one and some of the signal is absorbed. The polarization of the reflected GPS signal may also change from RHCP to LHCP depending upon the reflecting material type and angle of incidence. A custom made high gain LHCP helical antenna has been utilized as the nadir-looking antenna. The reflected signal is not expected to have enough SNR to permit successful signal acquisition. So the direct signal from a specific satellite received by the zenith antenna will be selected, locked and used as a reference to search the reflected signal.

The hardware comprises of a typical radio frequency front-

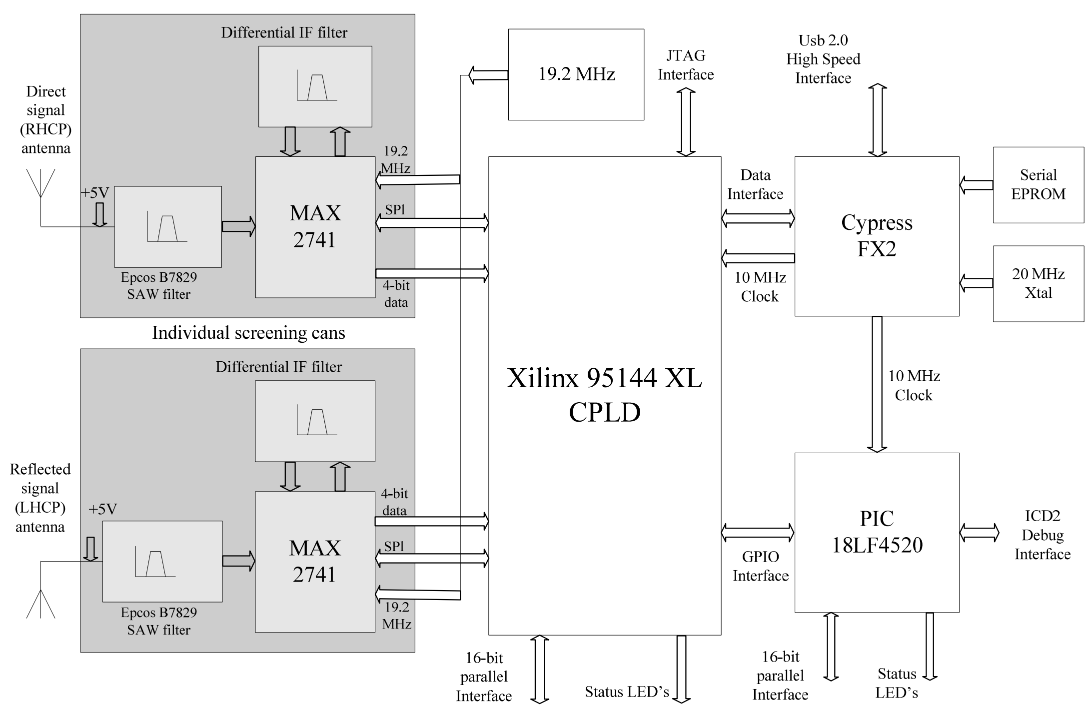

Fig. 4. Block diagram of the electronic circuit

NA

Value
60 mm
190 mm
47 mm
14^0
21
1000 mm
2 mm
190 mm
22.7^o

end of a GPS receiver including an ante[illegible] local oscillator, mixers, and an analogue-to-digital converter (ADC). The GPS signals will be received, am[illegible] own-converted and digitized into near base band samples, which will then be processed using software routines to acquire and track the direct GPS signal and later on matched filter processing with indirect signals will culminate the task of image generation [11].

II. Hardware Description

The most imperative design requirement for the data acquisition and collection device was a low-noise, dual-input GPS receiver operating in the GPS L1 frequency. The device should be able to simultaneously acquire the direct and weak reflected signals.

A. *Helical Antenna*

The main requirement of the GPS antenna was high gain and circular polarization. A custom made LHCP helical antenna having gain of 20 dBi was assembled to achieve this objective. More importantly being reverse in polarization as compared to direct signals and pointed away from GPS satellites, it delivered excellent immunity against direct signal interference. Direct signal interference is one of the many limitations in imaging systems using GPS as ‘transmitter of opportunity’. The interfering direct signal can mask the weak reflected signal and no matter how long we integrate the reflected signal cannot be detected and the targets in the image are no longer resolved. The actual parameters of the helical antenna have been summarized in table I and further details have been documented in [13].

B. *RF front end*

Initial design reviews led to the adoption of two MAX2741 IC's as the basis of the design. The IC is an L1-band dual-conversion GPS receiver which down converts the 1575.42MHz L1-GPS signal to a 37.38MHz first IF (intermediate frequency), and then a 3.78MHz second IF. An integrated 2 or 3-bit analogue to digital converter (ADC) (1-bit SIGN, 1 or 2-bit MAG selectable) samples the second IF and outputs the digitized signals. An integrated synthesizer offers flexibility in frequency planning to allow a single board design to be employed for reference frequencies from 2MHz to 26MHz. The integrated reference oscillator allows either TCXO or crystal operation [14].

The MAX2741 GPS front end offers a high-performance super heterodyne receiver solution with the benefit of using the system’s existing clock reference. The only external components required are the GPS RF filter, an IF filter a three-component PLL loop filter, and a few other resistors and capacitors. The MAX2741 integrates the reference oscillator core, the VCO and its tank, the synthesizer, a 1 to 3-bit ADC, and all signal path blocks except for the 1st IF filter. The typical application area for the receiver is less than 2 cm^2 [13].

The MAX2741 RF front-end LNA determines the noise figure for the receiver, defining the sensitivity and mixes the 1575.42MHz L1-band GPS signal down to a 1st IF of 37.38MHz. The image-reject mixer offers typically better than 30dB rejection of the image noise (1650.18MHz). The 2nd conversion stage consists of an active mixer, a variable-gain amplifier (VGA), and a tunable low pass filter. The IF mixer is configured for low side LO injection for a 2nd IF of 3.78MHz. Total gain of this stage is 62dB, and the VGA offers 51dB of gain adjustment. The on-chip low pass filter (LPF) further reduces out-of-band noise and band-limits the signal to the ADC, ensuring that the sampling process does not generate alias components. DC offset compensation at the ADC input is performed by an on-chip 4-bit DAC [14].

C. *ADC*

The on-chip ADC samples the down-converted GPS signal at the 2nd IF (3.78MHz). Sampled output is provided in either 2-bit (1-bit magnitude, 1-bit sign) or 3-bit (2-bit magnitude, 1-bit sign) formats, as determined by the ADC mode configuration bit. The ADC sample clock (system GPS clock) is derived either directly from the reference clock or from an RFLO divide-by-96 block to provide a 16.8MHz sample clock. Simulations performed have revealed that even 2-bit digital data from the down-converter will be enough to perform the signal processing [11].

Each MAX2741 is preceded by an EPCOS® B-series SAW filter and uses a discrete external IF filter. Antenna connections are via SMA sockets, each of which provides a +5V 50mA supply to support the use of an active antenna. The two receivers, along with their peripheral components, are housed in independent screening cans with multipoint connection to PCB ground.

D. Baseband Processing

The MAX2741's accept configuration information over their SPI interfaces from a Xilinx CPLD. This latter device acts as a signal switchyard for the entire design, permitting flexible interconnection of the various design elements. A Microchip PIC microcontroller is available to act as the source of this configuration data during 'standalone' operation. An interface is provided for connection to an ICD2 debugger. A simple example program has been written to pass a fixed configuration to the MAX2741's at power up.

Future upgrades of the system based on external environment will more likely result in the reconfiguration of the MAX2741 IC in response to changes in the received signals. This has not been implemented within the microcontroller program as the suitable configurations are still to be determined. Instead, an appropriate CPLD configuration is used to allow manual configuration of each receiver from the (PC-based) CEVA software, provided by Maxim. The microcontroller controls three status LED's and a pin header is provided for connection to its serial USART (can also function as two GPIO pins).

The two MAX2741 ICs share a common, high-precision 19.2 MHz VCXO. This oscillator has a low-voltage clipped-sine output but a buffered version of this signal is available in each of the 2741's 4-bit data output buses. A separate 24 MHz crystal provides a clock to the FX2 USB IC, which in turn provides a buffered 10 MHz clock signal to the CPLD and PIC microcontroller.

The CPLD is configured via a 6-pin JTAG interface. A basic code example has been developed in VHDL that allows the use of the CPLD for the flexible interconnection of signals. In future, it is likely to be used to provide additional buffering capability if the USB interface is used, possibly by the attachment of a larger FIFO memory to the 16-bit parallel port (PAR) currently used for connection to the DAQ card and CEVA software. The CPLD has provision for a full parallel interface connection to the FX2 USB device. Three status LED's are driven directly from the CPLD.

The Cypress FX2 provides the necessary hardware support for implementation of a USB 2.0 high speed interface. This has not been tested and will be implemented at later stages in the project. Presently, data has been captured using a National Instruments PCI-6534 DAQ board, connected to the parallel port of the CPLD, which acts as system interface to the PC. The GPS IF signal is stored in the HDD as eight bit data with the first 4 bits representing the direct signal and last 4 bits representing the reflected signal or vice versa. This data file is accessed during image reconstruction by suitable Matlab® commands.

The National Instruments PCI-6534 is a high-speed, 32-bit, parallel digital I/O interface for PCI bus that can perform pattern I/O and high-speed data transfer using a wide range of handshaking protocols at speeds up to 80 MB/s through onboard memory. Labview® software was used to control the DAQ board. File sizes up to 2×10^9 bytes have been captured in this manner.

A four-layer PCB (1.6 mm thick FR4) has been used. One of the internal layers is a ground plane, which is continuous, apart from (i) cutouts under the differential IF filters to reduce stray capacitance, and (ii) the creation of a 'ground peninsula' around the USB connector. The other internal layer is a split power plane, the design is strongly zoned to minimize power line noise into the two receivers and antenna supplies. Most circuit elements operate at 3 volts, with the exception of the 5 volt antenna supply and the 3.3 volt core voltage of the CPLD. Trace impedance is controlled in the antenna to MAX2741 connections and in the USB D+/D- differential pair. The assembled PCB is shown in figure (5). One front end (channel A) receives the direct signals from the satellites while the other (channel B) receives the reflected signals.

(a)

(b)

r (a) 50 m (b)

III. EXPERIMENTS

In order to test both channels of the GPS front end and data capturing device and to confirm that the signal received by the LHCP antenna is in fact the reflected signal an experiment was performed in front of a large brick building. The LHCP antenna was positioned so as to receive the signal bouncing off the building, as shown in figure (6).

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, as expected, 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 [13].

As mentioned above 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 (7a) 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 (7b). 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.

After thorough deliberation and based on the simulation results and practical constraints, it was decided to perform the experiment for data acquisition with the hardware positioned at a fixed geographical location in front of the University of Manchester's main building, the location of the direct and reflected antennas and target are shown in figure (8). A 0.5m^2 spherical target wrapped in aluminum foil was placed in front of the university building.

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. The most suitable satellite (in terms of signal strength and visibility) was GPS BIIRM-2 (PRN 31) and was therefore selected as the reference satellite.

In order for the GPS satellite to provide the requisite change is 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. During simulations it was deduced that a 30 seconds interval among the acquired files is just enough to resolve the targets. The GPS data provided about 2400 seconds for change in geometry, just enough to identify the target, but compromising the resolution.

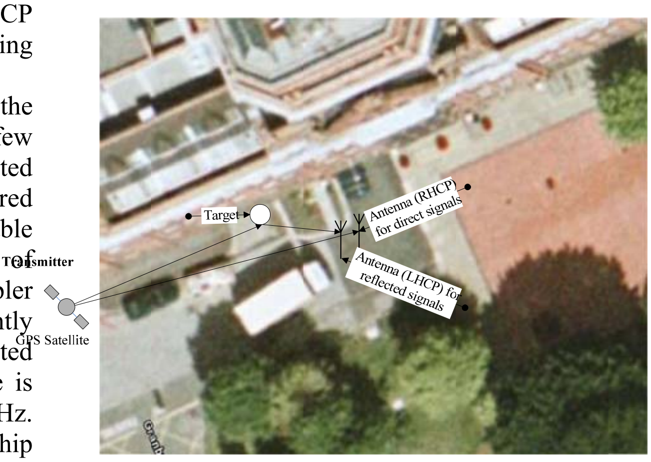

Fig. 8. Location of both antennas and the target in front of a large building

Figure (9) compares the image by reconstructing 2400

(a)

(b)

; 2400 sec of

seconds of actual data with a simulated signal of 2400 seconds. Further details have been provided in the research paper by same authors [15].

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. 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. Due to hardware limitations, the data files were acquired after an interval of every 30 seconds each, such low frequency for acquiring temporal samples induced an aliasing effect. In future it is recommended to modify the imaging hardware to acquire GPS data after every three seconds.

The exhibited images may seem very primitive, but it has to be kept in mind that no dedicated radar transmitter was utilized 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 data with the help of SAR technique was provided by the orbiting GPS satellite. This particular method has so far not been utilized in a practical environment for imaging purposes. In this context the efforts carried out to simulate and practically validate the results with the help of static or stationary dual front end GPS data capturing device or receiver are a novel achievement.

IV. FUTURE UPGRADES

The imaging hardware and the reconstruction algorithms can be further improved to fully exploit the 'signals of opportunity' as passive microwave imaging remains a challenging field of research.

A high gain LHCP antenna was utilized to ensure acquisition of weak reflected GPS signals, however, the antenna also received returns from other objects around the target. Some method needs to be devised in the image processing algorithm that ensures removal of ground and other clutter.

As mentioned in section II (D) that a simple program has been written for the Microchip PIC microcontroller to pass a fixed configuration to the MAX2741 IC at power up. This code needs to be upgraded to perform 'standalone' operations and adjust to changes in the incoming signals. It will be worthwhile to perform data transfer from GPS front end to HDD with the help of (Universal Serial Bus) USB 2.0 or even next generation USB 3.0, thus bypassing the NI DAQ card. Currently, a desktop PC is required to configure the MAX2741 IC with the help of CEVA software and house the NI DAQ card.

Incorporating these modifications will result in the acquisition of field data in a more efficient and convenient manner and a dual front end GPS receiver device housed in a small box, a laptop with removable HDD along with the antennas can be utilized for this purpose.

V. CONCLUSIONS AND RECOMMENDATIONS

This paper describes the design details of a two Channel data capturing device intended for simultaneous reception of direct and reflected Global Positioning System (GPS) signals for L1 frequency. Results of some initial tests to verify the functionality of the hardware suggest that device assembly has been successful. Further research will concentrate on the capturing of further GPS data in a suitable configuration for image reconstruction purposes. The front end of the device can also be modified to acquire GPS L5 frequency signals as well as Galileo (European Navigation Satellite System) signals thus improving detection range on account of their superior signal strength and better spatial resolution due to the larger bandwidth as compared to GPS L1 frequency signals.

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