

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 02-05-2006		2. REPORT TYPE Final Report		3. DATES COVERED (From – To) 15 March 2004 - 15-Sep-05	
4. TITLE AND SUBTITLE 'Passive' High Resolution RF Imaging				5a. CONTRACT NUMBER FA8655-04-1-3028	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Professor Mikhail Cherniakov				5d. PROJECT NUMBER	
				5d. TASK NUMBER	
				5e. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Birmingham Edgbaston Birmingham B15 2TT United Kingdom				8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD PSC 821 BOX 14 FPO 09421-0014				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) Grant 04-3028	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This report results from a contract tasking University of Birmingham as follows: The Grantee will investigate the feasibility of using Non-Cooperative Transmitters (NCTs) for Bistatic and Multistatic Radars (BR and MR). The candidate transmitters include Global Navigation Satellites Systems (GNSS) such as GPS (United States) and GLONASS (Russia). Key areas studied include transmitter availability, reliability, radiating power and signal bandwidth. High-resolution experiments will be made using the Russian GLONASS system.					
15. SUBJECT TERMS EOARD, radar					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18, NUMBER OF PAGES 41	19a. NAME OF RESPONSIBLE PERSON MICHAEL KJ MILLIGAN, Lt Col, USAF
a. REPORT UNCLAS	b. ABSTRACT UNCLAS	c. THIS PAGE UNCLAS			19b. TELEPHONE NUMBER (Include area code) +44 (0)20 7514 4955



**THE UNIVERSITY
OF BIRMINGHAM**

European Office of Aerospace Research and Development

PASSIVE HIGH RESOLUTION RF IMAGING

Systems based on GNSS signals reflection analysis

EECE, School of Engineering

University of Birmingham

UK 2004

This report presents research results in the passive radars based on non-cooperative satellites developments. It is a part of the broader topic undertaken in Microwave Integrated System Laboratory, Department of Electronic, Electrical and Computer Engineering, School of Engineering, University of Birmingham, UK.

EPSRC, EMRS DTC and EOARD (London) fanatically support the study. The report or parts of this report can not be published, duplicated or copied outside of the sponsoring institution without preliminary permission from University of Birmingham.

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1. INTRODUCTION

The relationship between human beings and nature has become highly sophisticated. Since the emergence of Man, we have been totally dependent on natural resources for food, raw materials, and sources of energy, to name but a few ways. Now however, our use of synthetic resources is influencing the environment in the form of climate changes, pollution and land corrosion. Our artificial structures: bridges, skyscrapers, power stations, roads, may be comparable to rivers and mountains; but even these man made creations are not protected from natural forces such as earthquakes, volcanoes, landslides and avalanches. In these circumstances, high quality remote monitoring of oceans, land and atmosphere; distant parameter evaluations of areas vulnerable to natural disasters and of artificial structures, are one of the most challenging problems facing modern science. These have a direct impact on global and regional economies, safety and ultimately quality of life, in both a short and long-term perspective.

It is difficult to understand the full scope of all the scientific, professional groups and institutions involved in remote sensing and/or those using such appropriate information. At the top of the list are geologists, geophysicists, oceanographers, environmentalists, meteorologists, seismologists and engineers. The directory of economy sectors using, and vitally depending, on such information is greater still: agriculture, transport, tourism, civil engineering, search & rescue services, sport, etc.

This report presents an innovative branch of the remote sensing tool and its applications across various sciences, namely: radar sensor based on electromagnetic energy emitting by Global Navigation Satellite Systems (GNSS) satellites. It is being exploited the new reality – artificial electromagnetic environment which is the consequence of the introduction of GNSS: GPS (US), Glonass (RU) and forthcoming Galileo (EU). GNSS signals are radiated around the clock, covering entire Earth surface from satellites which positions are known with centimetres accuracy and with nuclear standard timing. So, in the XXI-st century we are living not only under the Sun and Moonlights but also under the GNSS satellites EM emission and we can treat this artificial light similar to its natural counterparts.

1.1 Electromagnetic remote sensing

A variety of methods, tools, equipment and technologies are currently used for remote sensing: from simple binoculars, through to airborne electro-magnetic and electro-optical systems, to the sophisticated interferometric synthetic aperture radar (SAR) maintained on a space shuttle. Most of these technologies are based on the phenomena of *electromagnetic waves (EW)* scattering, reflecting, diffracting from or emitting by the observation objects or areas. For remote sensing various sensors located on land, vessels and space/airborne platforms are used, which provide all-weather 3-D mapping with metre order resolution, as well as change detection with millimetres sensitivity. In addition to the mapping objects geometry, EM waves can carry information regarding the materials electrical properties, presence of water, ice, magnetic components, temperature, dynamics, etc.

In most general terms, all tools for EM remote sensing have similar subsystems: for active systems (radar sensors) they have a transmitter and an appropriate antenna, for both active and passive (radiometer) systems there are receiver and antenna systems which select signals from a particular area. The size of this area is referred to as the resolution, or resolution cell size. The signal processing algorithms and data extraction are essentially different for different tools and applications. Various methods and technologies well complement each other. Remote sensing broadly uses all systems because different information can be obtained. In many cases scientists use appropriate information or data fusion for more comprehensive analysis.

1.2 Radar sensor principles

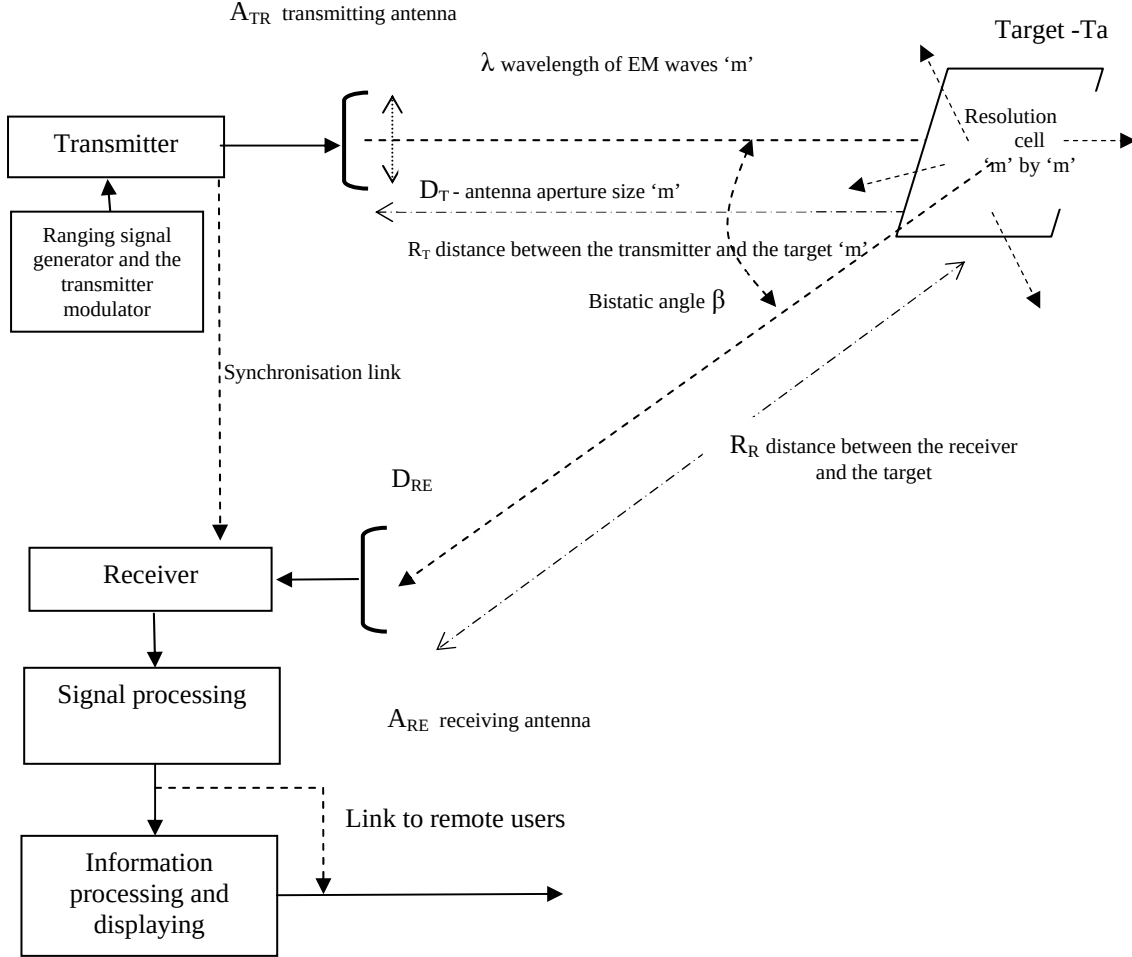


Figure 1: Generalised radar structure

Block diagram of generalised radar is shown in Figure 1. Three major components of the sensing can be considered: transmitting and receiving subsystems as well as the observation area.

Transmitter subsystem includes the transmitter itself and the transmitting antenna. Electrical signal of a given shape (modulated or non-modulated pulses alternatively modulated or non-modulated continuous waveforms) modulates high frequency sinusoidal carrier forming the ranging signal. Via the transmitting antenna it is radiated as EM wave into the direction of the searching object (target) or area. These EM waves can be characterised by their wavelength λ

(which refers to the carrier frequency f_c as $\lambda = c / f_c$, where c is a speed of light) and polarisation, that is the orientation of the electric field vector $\vec{E}$ in space. Another important parameter is the ranging signal spectrum bandwidth Δf . At a distance R_T these EM waves illuminate an area which size is specified by the transmitting antenna beamwidth θ_{TR} and the distance.

Electromagnetic waves are reflected by the target in different directions with different intensity and polarization and, including the direction of the receiving antenna. Reflected EW are picked up by the receiving antenna and transformed into electrical signals. This antenna has its own antenna pattern which maximum in general case should be pointed into the observation area. The signal is gained in the receiver and in modern systems converted into the digital format by analogue – to – digital converter (ADC). This digital replica of the received waveform is processed by a specialised or a universal computer. The signal processing can be conditionally split in two stages. Primary signal processing is aiming to extract signal from noise and interferences, evaluate the basic signal parameters as a delay, Doppler frequency shift, angle of arrival (AOA) and some others. Primary signal processing till some extent is common for different sensors. At the next stage – secondary signal processing, specific information for the given sensor's application are extracted. For example: a difference between polarization components of the received signal; fine structure of the signal Doppler spectrum; etc.

Lines transmitter – target and target – receiver forms the bistatic angle β . If $\beta=0$ the system refers as a monostatic, if β is small the radar refers as a quasi-monostatic. Otherwise this will be bistatic radar. Another specific case is when β is about 180 degrees and the sensor refers as forward scattering (FS) radar. In FS scattering case the received signal corresponds to the wave diffractions over the target as well as EM waves penetrating through the targets material. Figure 2 illustrates simplified topology of these systems (top view).

An interesting case of bistatic radar is shown in Figure 2-e. When the target is distributed (for example land or ocean surface) there is a specific mutual Tr-Ta-Re position where the received waveform corresponds to specular reflection from a particular area. These reflections in a general case are essentially stronger than other components of the reflected EW.

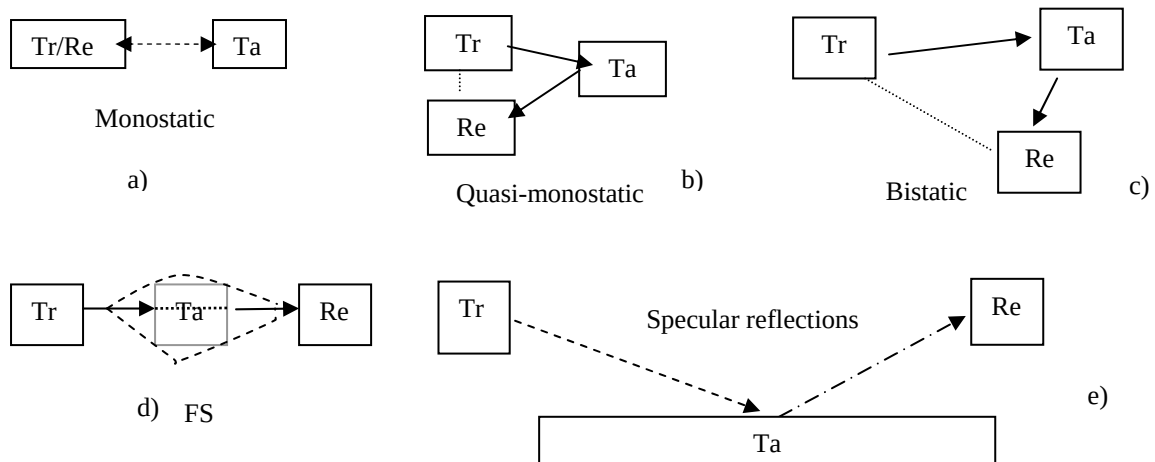


Figure 2: Sensors topologies

In bistatic systems the transmitter and the receiver are essentially separated. In a general case the transmitter can be specifically designed and build for the system use. Alternatively have already existing transmitter can be adopted, for example TV or Radio Broadcasting or Mobile Phones Base Stations and so on. The later refer as sensors with non-cooperative transmitter or with the transmitter of opportunity. This class of systems for remote sensing is in the focus of our study.

If the receiver has two channels and two spatially separated antennas is possible to measure a reflected signal phase difference between these channels. This gives an opportunity to provide measurements with the accuracy of a fraction of the wavelength i.e. centimetres. These systems refer as interferometric systems.

1.3 Resolution in radar sensors

Sensors' resolution is one of the main parameter and refers to the system ability to separately receive reflections from different targets or fragments of areas in time domain (range resolution), space domain (angle resolution) and Doppler frequency domain (Doppler or velocity resolution) – Figure 3. Under other equal conditions the resolutions are the best in monostatic radar and we will use it as the reference.

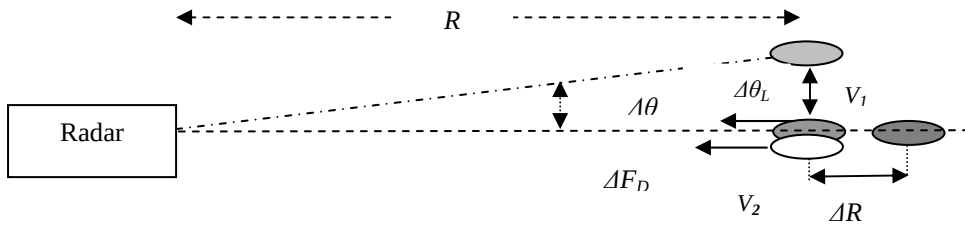


Figure 3: Radar resolution

Range resolution is specified by the ranging signal bandwidth and approximately evaluated as $\Delta R = 1/\Delta f$. For example: signal with 10 MHz bandwidth provides 15 meters resolution where 100 MHz signal provides 1.5 m resolution.

Angle resolution is specified by the antenna size and the ranging signal wavelength and approximately evaluated as $\Delta\theta = \theta \sim \lambda/D$ [rad] or a linear angle resolution at a distance R is about $\Delta\theta_L \sim \lambda R/D$. For example: $\lambda=0.25$ m, $R=5000$ m, $D=1$ m the linear resolution is approximately $\Delta\theta_L \sim 1250$ m where for $\lambda=0.025$ m it will be about 125m.

The Doppler resolution is related to the targets' speed. If there is a motion between the radar and the target with radial speed V then the received signal will have a 'Doppler shift' relevant to its carrier frequency which can be evaluated according $F_D = 2 f_c V / C$, where C is the speed of light. The Doppler resolution can be evaluated by the ranging signal duration or part of the signal that is coherently integrated over a time interval T_{CI} and $\Delta F_D = 1/ T_{CI}$. For example if the signal duration 0.1 s the Doppler resolution is 10 Hz. For the carrier frequency 1 GHz, this resolution corresponds to approximately 1.5 m/s targets speed difference.

1.4 Sensors with synthetic aperture

For remote sensing tools the resolution is very important parameters. For radio frequency sensing we can conditionally classify this ability as high: less than one meter resolution; as medium: from one to twenty five meters; and low-resolution systems: more than twenty five meters.

From the mentioned in 1.3 examples it is seen that the most difficult is to achieve even medium resolution and specifically at a distance above kilometres: this would require enormous antenna size. Fortunately there is the solution for this problem: sensors with synthetic aperture (SA), which widely used in the remote sensing. Let at least one – transmitting or receiving antenna will be positioned on a moving platform, space or airborne presumably. If signal will be properly integrated over a long time T_I , the platform displacement over this time $L_S = VT_I$ is acting as an equivalent (synthetic) aperture size).

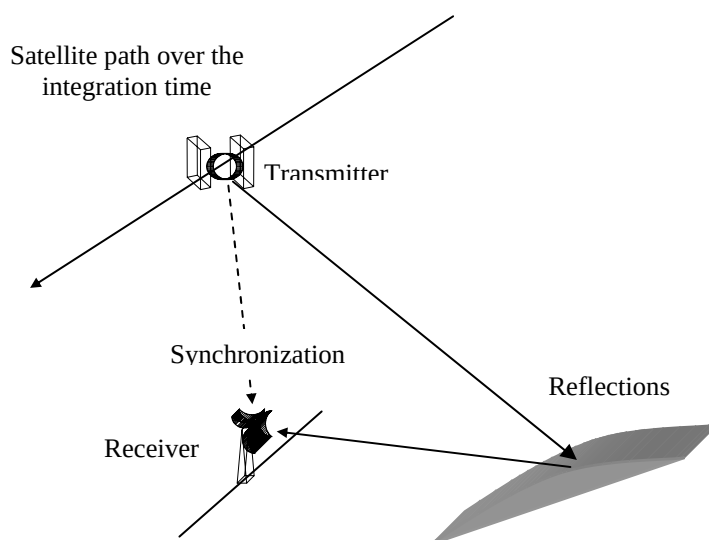


Figure 4: Aperture synthesis

For example if the antenna on an aircraft board flying with speed 200 m/s and the integration time is 10 s, the aperture length is 2000m and at wavelength 0.25 m the angle resolution $\Delta\theta$ is $\sim 10^{-4}$ radians. At a distance 5 km the linear angle resolution is 0.6 m. That fits into the category of high resolution. Of course, the theory and practice of SA is essentially more complex than the discussed above.

1.5 Electromagnetic remote sensing based on the GNSS signals reflections

Over recent years, there has been an increasing interest in Global Navigation Satellites Systems (GNSS) as an emitter of electromagnetic energy. Being reflected from the surface, these signals carry a lot of information for further analysis. They can be used in various ways to extract information about the earth's or oceans surface for example. Using radar terminology we are dealing with bistatic radar sensors with GNSSs as a non-cooperative transmitter (NCT). The receiver can be stationary positioned on a surface or on an aerial (aircraft, unmanned vehicle, balloon, etc), or any other platforms. The main applications for these systems were specified for meteorological purposes, land and surface monitoring, change detection, etc. Some of these applications require a high resolution that can be achieved by the aperture synthesis, some utilise only specular reflections from particular surface points, or the use of the directional antennas or analyse the direct signal analysis for various atmospheric study (i.e. forward scattering).

Having as the transmitter GNSS satellite and the receiver on an aircraft or on the ground the system can be referred as Space – Surface (SS) Bistatic Radar Sensor highlighting the fact that these sensors have essentially asymmetric structure with non-cooperative transmitter on a space segment. If the transmitter or receiver (or both) motions are used for the antenna aperture synthesis to provide high spatial resolution (small resolution cell size), this system can be classified as SS Bistatic Synthetic Aperture Radar with non-cooperative transmitter or SS-BSAR with NCT.

Similar to other radars, these systems can have interferometric structures and are referred to as SS Interferometric BSAR (SS-InBSAR). In this case, for example, the receiver has two separated antennas with phase comparison or signals' reception from different satellites with when possible phase comparison.

SS-BSAR with GNSS NCT is an innovative and in some instances, a universal tool for remote sensing. It can be used across different areas of science and fulfil different remote sensing tasks. This new sensor has features of passive and active systems, as well as introducing new peculiarities in comparison with existing systems.

Of course, these SS-BSARs are not aiming to replace all existing methods of monitoring, but will bring essentially new capabilities across the scientific field. It will revolutionize the monitoring process via the introduction of all weather, high performance, compact, light weight, sensitive and cost effective tools for scientists; and will be the engine for many inventions in this particular area, as well as introducing a new branch of industry in the future. In the longer term, these tools could be transferred from the science base into a broad range of monitoring equipment for end users. Two basic system configurations are shown in Figure 5: a- Aircraft based receiver and b – Ground based receiver.

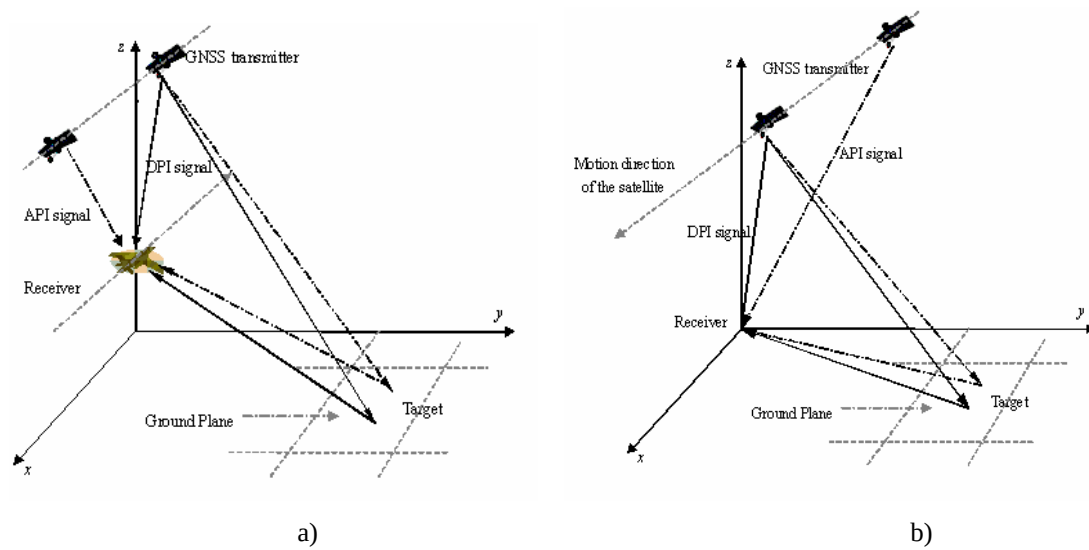


Figure 5: SS-BSAR topologies

1.6 Potential behind the technology

There are a number of reasons for the increasing attention given to GNSS reflection analysis by the research community. These are based on a number of unique possibilities presented by the technology, some of which are listed:

- a. Acts as stand alone or complement existing technologies (space and airborne radar sensors; ground based sensors; radiometers; optical and infrared systems) at the level of data and information fusion
- b. Available around the clock at entire planet territory
- c. Robust to any environmental condition (clouds, darkness, snowfalls, sandstorms...) due to low RF frequency band utilisation
- d. Portable and lightweight as does not contain transmitter
- e. Non-expensive as its hardware based on GNSS receivers which manufactured in a high volume as specialised integrated circuits
- f. Passive in a radio technical sense, does not require specific frequency band allocation and consequently not introduce radiofrequency interferences
- g. Universal at the hard and basic software level across broad areas of applications
- h. Analyse bistatic reflections obtained at different bistatic angles (from different satellites simultaneously or sequentially)
- i. Extremely high short and long term signal stability
- j. Simple synchronization as GNSS signals are optimized for this purposes
- k. Common time and frequency references for multistatic and multisites measurements
- l. Increasing number of available GNSS boosting the system performance

- m. Easy self calibration
- n. Multistatic systems introduce 3-D stereo-radio gram metric imaging
- o. Straight forward ways for the interferometric/change detectors developments
- p. High spatial resolution can be achieve via only satellites motions
- q. Defence
- r. to be continued

2. GLOBAL NAVIGATION SATELLITE SYSTEMS – TECHNOLOGY BASE FOR THE GENERIC MONITORING TOOL

One of space technology's triumphs was the introduction twenty years ago of the Global Positioning Systems (GPS), based on high orbiting satellites. Starting as a unique and presumably military system, nowadays GPS is as prolific as mobile phones and PCs, which are the expression of the last quarter of the 20th century technological breakthrough, used across different areas of science, business and industry. Two global positioning systems are now in use: the well known GPS (US) and GLONASS (RU) which will be full scale operational in the near future. 9-12 out of 24 active satellites from GLONASS  currently on the orbit. However one can already buy a GPS/GLONASS receiver, manufactured by Topcon LTD. In three to five years time the new European GALILEO positioning system will be in use, which will introduce a new generation of GNSS. The People's Republic of China has similar ambitions with its BEIDOU project. The main goal of these systems is accurate positioning and timing, as well as some other service functions.

In some ways, all these systems operate in a similar manner. Each system is based on about 30 satellites at the altitude ~22000 km, with an orbiting period of ~12 h. Each satellite transmits specific signals at L band. For positioning, the receiver accepts signals from at least three satellites at a time and synchronizes with these signals. After the mutual delays between signals are evaluated in an appropriate processor, the receiver's position, in absolute geographical coordinates, becomes available. Imagining that Galileo and GLONASS have already launched: ~ 90 satellites are operating above the entire Earth's surface around the clock and:

- At any geographical point from 15 to 30 satellites will be visible simultaneously above the horizon
- These satellites are orbiting with the precision of space mechanics in well-known orbits
- They generate coherently over a long period of time signals at ~1200 MHz to ~1600 MHz bands
- The signal stability is specified by the nuclear frequency standard – Hydrogen Master which provides long/short term stability 10^{-14} over 10 000 sec.

- Each satellite signal carries precise information regarding the satellite's current position that is easy to decode at the reception side
- The individual signal bandwidths are from ~0.5 MHz to ~10 MHz when the aggregate bandwidth is more than 60 MHz.

GNSS signals parameters **Table 1**

System	Signal	Power dBW (at 10° and 0 dBi ant)	Chip (rates Mcps)	Code (Sequence Duration ms)	Code (Length Primary/ Secondary)	Bandwidth MHz (nul-nul)	Centre Frequency MHz	Band (Aggregate bandwidth)	Range (Potential Range Resolution m)
Galileo	E5a _I	-158	10	20	10230/20	24	1176.45	24	15
	E5a _Q	-158	10	100	10230/10 0	24		24	15
	E5b _I	-158	10	4	10230/4	24	1196.91	24	15
	E5b _Q	-158	10	100	10230/10 0	24		24	15
	E5a+E5b	-152				51		48	7
	E6 _A	-155	5.115	TBD		40	1278.75	40	10
	E6 _B	-155	5.115	1	8184				
	E6 _C	-155	5.115	100	10230/50				
	E 6b+6c	-152				24			
	E6+E5							90	4
	L1 _A	-155	1.023	TBD		32	1575.42	32	11
	L1 _B	-155	2.046	4	8184				
	L1 _C	-155	2.046		8124/25				
	1b+1c	-152				24			15
	E5+E6+L 1							122	3
GPS	C/A	-160	1.023		1023	2.4	1.2 and 1.6		150
	L5	-154	10.0		Inf	24			15
Glonass	L3	-157	0.5		500	1.2			300
	P-code	-157	5.0		5000000	12	1.2 and 1.6		30

2.1 Expectations

The entire Earth surface is permanently illuminated by multiple coherent sources of electromagnetic energy, whose characteristics are precisely known and extremely stable. In spite of the artificial nature of these EM waves, they can be considered as a fundamentally natural phenomenon, and a number of systems, *with no direct relation* to the positioning or timing, could be developed, using as a basis this EM radiation. The scientific community has recognized this fact; first with some level of scepticism, but increasingly more and more research teams across the different branches of science are looking in this direction.

We can treat GNSS signals as similar to, for example, natural heat radiation. Infrared technology is used in many areas of science from metallurgy to medicine. Infrared signals received from a particular area carry important information regarding the object or its segments' properties. Of course, different scientists use different methods for such information processing, and are interested in different aspects of the extracted data. Nevertheless, they are all using the same tool – an infrared camera (receiver) for their research. Another example of passive observation is radiometry, which is also used across a wide range of science, and uses natural noise microwave radiation (re-radiation) from different objects and structures. The advantage of active monitoring systems is the use of coherent EM, which potentially carries more information when scattering, and more sophisticated algorithms can be used for signals processing.

Now using artificial signals emitted by GNSS, we can expand the arsenal of remote sensing technologies. SS-BSAR with GNSS as NCT introduces an intermediary between the passive and active systems approach, which benefits from both, as well as offering essentially new and unique features in remote sensing properties:

- From the passive systems – there is no need to use a transmitter, which is usually power consuming and essentially influences the tool weight, dimension and cost. The signals are available around the clock, and at any geographical point.
- From the active systems – the signals are essentially coherent and specific algorithms can be used, including antenna aperture synthesis and many others.

- Fundamentally new – each area is illuminated simultaneously from different angles by mutually coherent EM waves, and as a result stereo or even interferometric information can be extracted from the reflected signals. Using essentially coherent and synchronised GNSS signals, the monitoring of geographically separated areas can be made from the same reference.

Many other essentially new methods of remote sensing can be developed, based on the GNSS signal analysis. Some of these methods have already been discussed and many others are to follow.

2.2 Sensors with synthetic aperture

Many remote sensing application methods, based on the GNSS reflected signals analysis, can perform their full capacity if appropriate tools can pick up these reflections from reasonably small areas over a distance of kilometres. The receiving antenna diameter specifies the angle resolution. The simplified equation for this resolution in radian is $\theta = \lambda / D$; and the cell size at the distance R from the antenna is $\Delta r = \theta \times R = \lambda \times R \times D^{-1}$, where D is the antenna diameter. The receiving antenna diameter is the limiting factor in using these methods directly over a reasonably long range. If one wants to observe an area with 10 m resolution from the distance 10 km, the antenna diameter should be 250 meters (not a realistic case). The antenna with one-meter diameter provides this resolution from the distance of just 40 m. So, systems with reasonable antenna size operate over a short distance with reasonable linear resolution. This contradiction specifies the problem of the special tool development, where the key parameter is to obtain a high resolution using a receiving antenna of portable size. The discussing SS-BSAR approach helps to resolve the spatial resolution problem.

Two main system configurations are can be considered: -BSAR with an aircraft based receiver (Figure 5-a), and SS-BSAR with a ground base receiver (Figure 5-b). In both cases there are two receivers. One is the radar receiver (two channels in the interferometric case) that is picking up the reflected signal, and the second one is to receive the direct signals from the satellites for synchronization. The synchronisation receiver can be combined with multi-channel navigation receiver.

Taking into account that fundamentally a number of satellites are visible simultaneously above the horizon that illuminate the area under essentially different bistatic angles, the radiogrammetric signal processing can be applied to form a three-dimensional image.

2.3 Power budget evaluation

One of the critical points of SS-BSAR with GNSS is its power budget. It was calculated for two practical scenarios: the receiver is on a light aircraft with the radar antenna **1m** by **0.5m** (strip map mode), and a stationary antenna of the same size, on the ground. For the meters order cross-range resolution integrated signal-to-noise ratio calculations results are collected in Table 2.

SS-BSAR power budget

Table 2

RCS (m^2)	Distance Receiver-Target (km)	Receiver Speed (m/s)	Integration Time (s) - 1 m cross-range resolution	Signal-to-noise (Power ratio – dB)
10	3	50 or 180 k/h	12	17.8 – 12.5
10	10	50	36	5.3 – 7.3
50	10	50	36	26.7 – 14.3
50	10	100 or 360 k/h	18	13.3 – 11.2
250	30	50	108	44 – 16.5
250	15	100	27	44 – 16.5
250	30	100	54	22 – 13.5
250	30	150 or 540 k/h	36	14.7 – 11.7
250	30	200 or 720 km/h	27	11 – 10.4
1	3	0 (satellite motion only)	1000	148 – 21.7
1	10	0 (satellite motion only)	1000	44.2 – 16.5

From Table 2, one can see that the budget is tough. But for a stationary receiver we can ‘see’ $1 m^2$ targets from distance of 10 km with signal/noise ratio suitable for many applications. From the distance of 3 km, $1 m^2$ target scatters enough energy for change detection. For the airborne receiver the mapping and imaging the range reach 10 and more km against $50 m^2$ target.

2.4 Range, cross range resolution and interferometric sensitivity

Considering quasi-monostatic (bistatic angle is ~ 0 , i.e. the satellite, receiver and object are collinear) SS-BSAR which introduce the highest resolution, Figure 6 shows the potential cross range resolution obtained for different coherent integration intervals over which the antenna is synthesised by the satellite motion only.

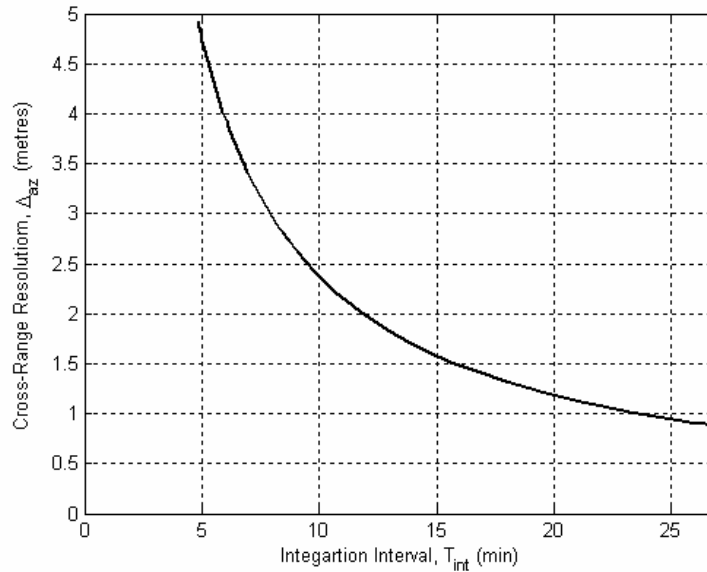


Figure 6: Cross-Range Resolution Versus Integration Time

For the airborne receiver the synthesis time depends on the target – aircraft distance and speed. The *one-meter* cross – range for appropriate speed and distance can be derived from Table-1. For example when the aircraft speed is 180 km/h and distance to the mapping area is 10 km, the synthesis time is ~ 36 seconds and for the distance 30 km it is ~ 100 seconds.

The range resolution entirely depends on the ranging signal bandwidth. Thus using GPS C/A code the monostatic resolution is ~ 150 m, for GLONASS P-Code it is ~ 30 m, for the Galileo main codes it will be ~ 15 m and for the Galileo combined code it is expected the best resolution around ~ 3 -5 m. So, our optimistic evaluation of the resolution area in SS-BSAR is ***$\sim$ about 3x1 meters.***

The SS-InBSAR (see Figure 7) interferometric sensitivity depends on the separation between the antennas and the distance (D) to the observation area. Some examples for the vertical antenna separation of 10 m are shown in Figure 7 for different antenna-target area angles η .

The expected rms accuracy of the interferometric coordinate estimation is 0.02-0.04 m when the reflections from ground (or similar) and a fraction of centimetre, for the reflection from radar signal enhancer, a corner reflector for example.

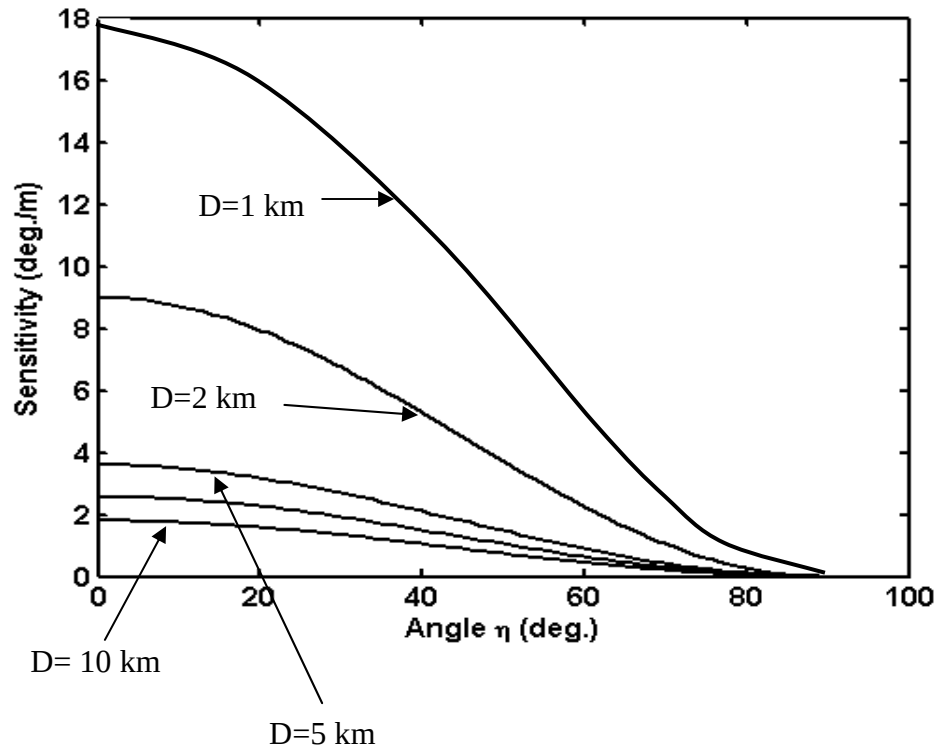


Figure 7: SS-InBSAR sensitivity

2.5 Sensors based on specular GNSS reflections

One of the most developed and promising area of GNSS signal analysis is based on the specular reflections from surfaces – lands or ocean, Figure 8-a, b.

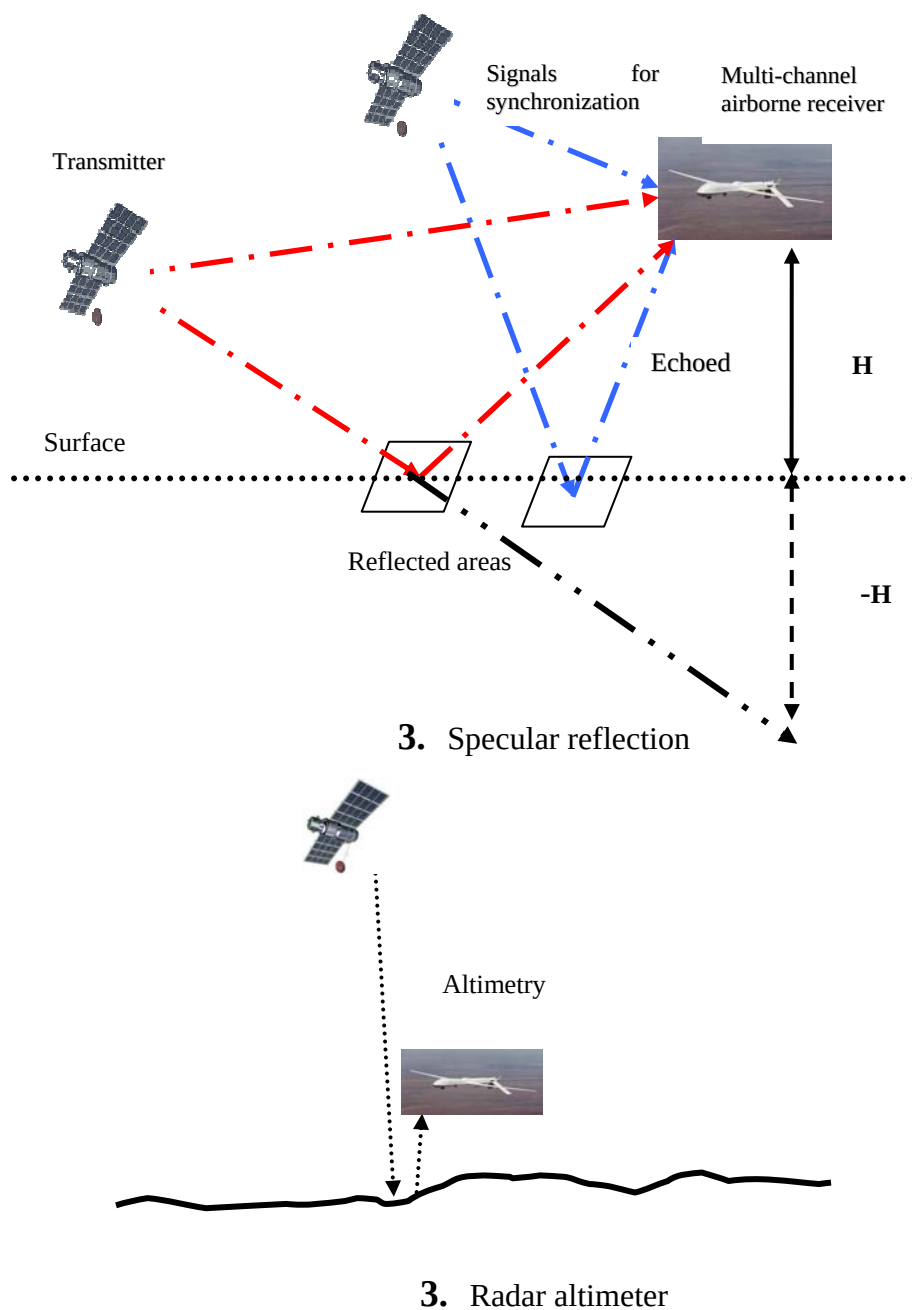


Figure 8: Sensor based on GNSS reflections

In these systems strong signals is reflected from the specific, but well predicted surface areas. Appropriate reflected signals have power of the direct signal order. Via the known satellites and the aircraft position can be calculated these reflections points. Analysing time and Doppler spread of the compressed signal the state of the surface can be derived. Similar, analysing the scattering matrix components some soil parameters could be evaluated. The reflected signal in these systems is essentially stronger than scattered signal considered in the previous sections. As the results the distance over hundred km can be achieved. Signals in these systems penetrate through the foliage or even ice. In spite of the fact that the numbers of points, which provide specular signal reflection relevant to a given aircraft's position, is limited this is the most promising tool for the land and oceans monitoring. With the increase in a number of acting satellites benefits these systems performance.

2.6 GNSS based forward scattering radar

Forward scattering radar (FSR) is a specific and very sensitive kind of bistatic radar. If a target is between the transmitter and the receiver it partly blocking the ranging signal and at the receiver side a lot of useful information can be extracted – Figure 9.

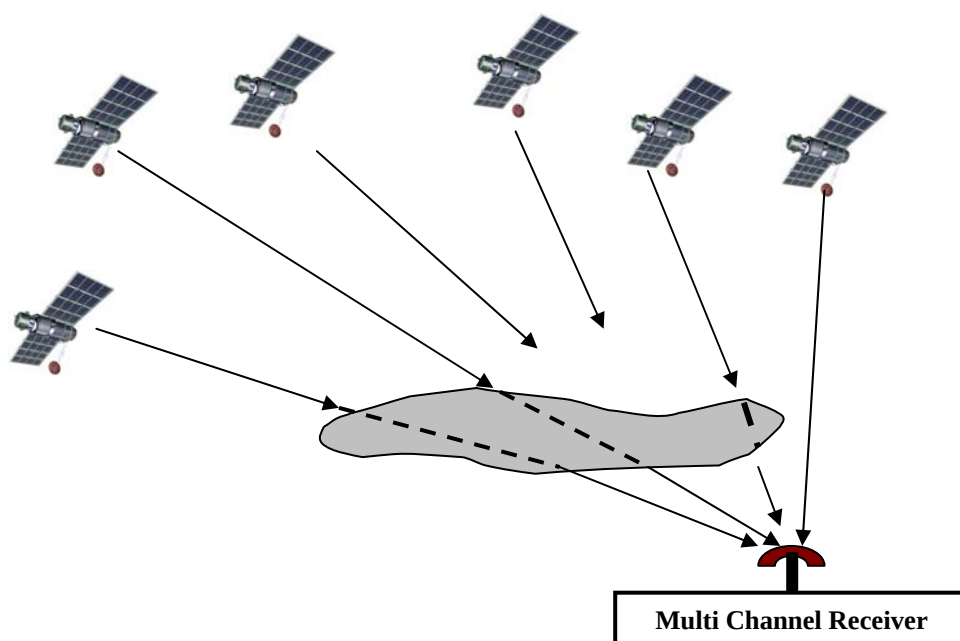


Figure 8: GNSS based FSR

Receiving signals parameters: power fluctuations, Doppler and time spread; depolarisation carry information regarding the object dimension, state, material and dynamics. Similar methods are widely used in satellite meteorology for weather predictions, ionosphere analysis, wind profiling, vapour estimation, etc.

3. GENERAL APPLICATION AREAS

GNSS reflections analysis can be used in a numerous remote sensing applications:

1. Imaging with potential resolution of meters sq.
 - 1.1 Forests areas controlling
 - 1.2 Foliage mass evaluation
 - 1.3 Coastlines and rivers banks displacement and corrosion
 - 1.4 Oceans state evaluation
 - 1.5 Tidal waves and tsunami evaluation
 - 1.6 Areas of natural disaster (floods) assessing
 - 1.7
2. Evaluation of the surface states and materials
 - 2.1 Salinity of farmlands
 - 2.2 Foliage density
 - 2.3 Level of moisture on farmlands
 - 2.4
3. Objects detection on the surface
 - 3.1 Vessels for the traffic control
 - 3.2 Iceberg routs tracking
 - 3.3
4. Radargrammetric imaging
 - 4.1 Polar ice monitoring
 - 4.2 Independent monitoring of construction sites (UN, Atomic Energy Agency...)
 - 4.3 Damage assessment (earthquakes, volcano eruptions, floods...)
 - 4.4
5. Change detection
 - 5.1 Deformation in superstructures (dams, bridges...)

- 5.2 Slops stability (rail, highways, open mines, construction sides...)
- 5.3 Disaster predictions (avalanches, landslides, volcanic eruptions...)
- 5.4
- 6. Radio meteorology
 - 6.1 Thunderstorms, hails, tornado predictions
 - 6.2 Wind profiling
 - 6.3
- 7. Radio communication
 - 7.1 Ionosphere monitoring
 - 7.2 Navigation systems corrections
 - 7.3

4. APPLICATIONS NOTES

A. Regional area monitoring.

The system layout is shown in Figure 5-a. A light aircraft or helicopter carries the receiving system, which is, except for the antenna, similar to that discussed above. Exploiting the fact of the aircraft or/and satellites motions, the high-resolution image can be synthesised. Further signals analysis gives information regarding the surface states and conditions: roughness, moisture percentage, wave dynamics, localised within the resolution cells. In comparison with the SAR currently being used (which are, perhaps, the most powerful tools for remote sensing), this technology is cheaper; the appropriate equipment is portable and can be installed on a light air platform or helicopter. More importantly however, is that by receiving coherent signals from different satellites we can obtain stereo-grammetric, multi-site images, which is not possible in the currently used system. Analysing the EM waves reflected at essentially different angles, we are obtaining not only the surface topology, but also information regarding its materials' properties. This configuration (but without the aperture synthesis) has been widely discussed for use in oceanography, altimetry, land monitoring, etc.

B. Local area monitoring.

For local area (restricted by the local landscape and the horizon 5-15 km) monitoring, the system in the configuration shown in Figure 5-b can be proposed. The main hardware is somewhat equivalent to a multichannel GPS (Galileo in future) professional receiver, connected to a PC. Through the one, low gain antenna, the receiver is synchronised to the desired Galileo satellites. Another, medium gain antenna is pointed to the observation area direction. Using the natural motions of the satellites and appropriate synthetic aperture algorithms, the scattered signals are received from the localized area. This system is portable, not expensive, and can be used by science during field trial  The obtained information is similar to that from SAR. However, where as SAR can only process the particular area once every few days, the proposed sensor can operate around the clock, and receive more scientific data due to the multi - satellites operational mode. Moreover, the EM waves from the satellites are now coherent, and the mutual satellites signals complex envelope carries a unique data not available in the traditionally used sensors.

C. Change detection via GNSS signals intreferometric measurements.

One of the typical problems in many areas of science is the detection and evaluation of small changes, variations and/or deformations in big natural or artificial structures. These sorts of systems are used for example, for: landslides, snow avalanches, dam movement  volcano eruptions, investigation and prediction. The most advanced approach is in the potentially dangerous area of observation by interferometric or differential radars. These radars should have a narrow antenna pattern and two receivers. From the received signals mutual phase variation, comprehensive information regarding the deformation is extracted. One of the main problems of the development of these systems is the requirement for high space resolution. This can be achieved by using radar with a big antenna size (for example, Ground Probe Ltd Radar), which operates over a relatively short distance (0.5-1 km). Alternatively, radar with small size antennas, but moving along the rails (LISA) is used with synthetic aperture signal processing. The problem can be resolved by applying the proposed system to these measurements, see Figure 9, i.e. SS-InSAR topology. For the high-resolution achievement the motions of the satellite is used. Over ~ 4 min observation time the 5×5 m (1×5 m after ~ 15 min) resolution can be achieved regardless of the distance between the receiver and the observation area.

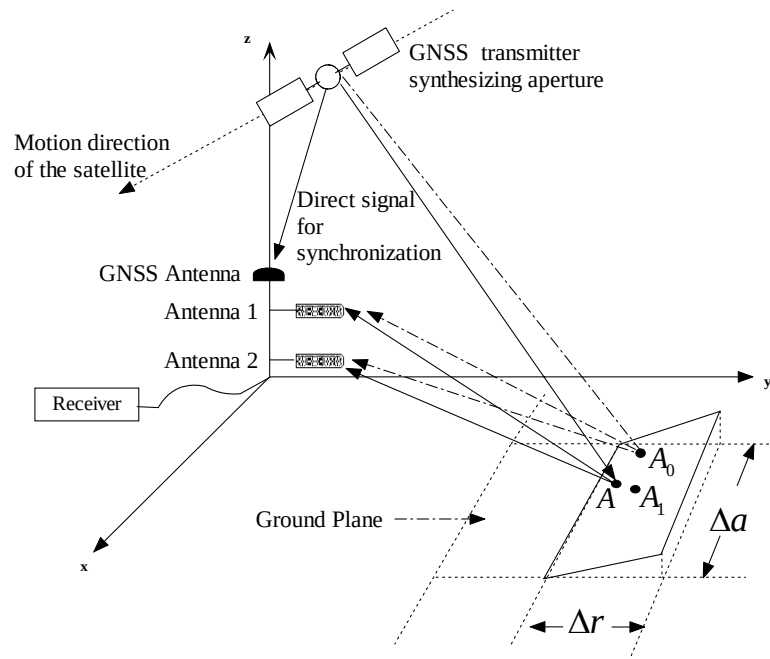


Figure 9: SS-InBSAR based change detector

5. EXPERIMENTAL SET-UP

5.1 Introduction

The past 20 years have been a time of renewed activity in bistatic radar (BR) systems. One of the peculiarities of BR is their potential to be used as non-cooperative transmitters (NCT)[1, 2]. The first key problem of BR with NCT is the transmitters' availability and reliability. Transmitters should not be deliberately switched off without appropriate preliminary discussions and/or authorisation. Ideally the system should have NCT diversity. This increases the system's reliability, and the multi-static system's architecture can be properly organised. The second two vitally important parameters are the NCT's radiating power and signal bandwidth. These must be big enough for target detection with a reasonable resolution.

From these points of view, some very attractive candidates are transmitters of Global Navigation Satellites Systems (GNSS), such as: GPS (US), GLONASS (Russia), GALILEO (Europe). These satellites provide easy and accurate synchronisation between the receiver and the transmitter. Using the relatively low frequency of the ranging signal makes microwave remote sensing a unique tool in terms of robustness to weather conditions. Currently, 8-16 satellites are visible above the horizon at any geographical area around the clock; and with the introduction of GALILEO, the number of simultaneously visible satellites will reach 24. This high redundancy in the number of available satellites facilitates the multi-static configuration.

This project focuses on space–surface bistatic synthetic aperture radar (SS-BSAR) using GNSS as the NCT, with the aim of providing high-resolution imaging. The system can potentially have two basic configurations: a receiver mounted on an aircraft, or a ground based receiver, as shown in Figure 10. Given the current time frame we are considering only the stationary receiver. In both cases, the power budget is set to sufficiently detect a stationary target of 50 m² (small truck) from a distance of 10 km, with a range resolution better than 15 m. A high cross range resolution can be achieved by aperture synthesis. If the receiver is on the ground, the transmitting satellite motion can be used to form a high cross

range resolution (this is a peculiarity of GNSS' use, as SAR imaging can be obtained even from a stationary receiver). Otherwise, the motion of both the aircraft and the satellite can be used for these purposes. The expected cross range resolution can be reduced down to 2-4 m. These are reasonable figures for many applications.

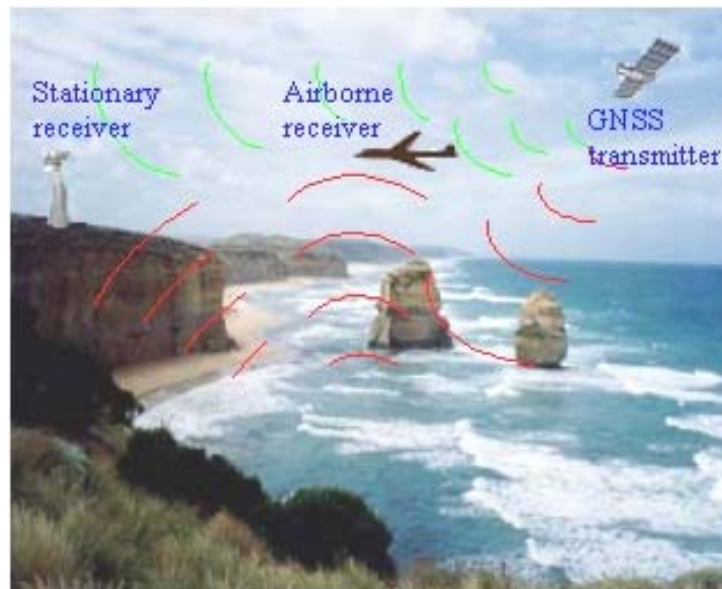


Figure 10: SS-BSAR for coastline displacement assessment

5.2 Brief Experiment Methodology- 'Moving Transmitter-Stationary Receiver'

For experiments with real satellites, GLONASS is used as the NCT, whose P-code provides a reasonably high range resolution of ~ 30 m (a quasi-monostatic case). This code was originally introduced for defence applications and was encrypted. Currently this code is not classified and can potentially be used for this project. In future, it is planned to use GALILEO, which provides a better range resolution. The use of GLONASS, instead of the prospective GALILEO does not affect the scientific value of the experiment.

Taking into account the technical difficulty of P-code fast synchronisation, the first stage of the experiment will be developed by using only the GLONASS C/A code for the determination of the satellite's position, and direct heterodyne P-code signal reception for synchronisation (refer to Figure 12). This is possibly due to the current state of GLONASS, as there are only 10 GLONASS satellites currently in orbit. The 3rd orbital plane satellites in

slot 18 and 21 are separated from each other by an angle of 135° . It is proposed to use satellite in slot 21 and using a directional Heterodyne Channel (HC) antenna we will receive a signal from mainly one satellite. A practical antenna with 12-15 dB directivity will be used. The beamwidth and area of the antenna can be expressed as [7]:

$$\theta_a \theta_v \approx \frac{4\pi}{G_D} \quad (1)$$

$$A \approx \frac{1}{\eta} \frac{\lambda^2}{\theta_a \theta_v} \quad (2)$$

where θ_a and θ_v (in radians) is the 3dB azimuth and vertical beamwidth of the HC antenna, $\eta = 0.7$ is the aperture efficiency. From Equation (1) a beamwidth ($\theta_a = \theta_v$) of 35-50 degrees is obtained, which is narrow enough to illuminate only the considered satellite. The area of the antenna obtained is $0.25 - 0.1 \text{ m}^2$.

Another reason that GPS satellites were not considered for experimentation was that currently there are 24 GPS satellites. This raises the question of whether we can use a practically feasible antenna to receive a signal from only one satellite. This is not certain at this stage and will be investigated in due course.

Plane/Slot	Frequency Channel	Launch Date	Introduction Date	Status
1/01				
1/02	04	10.12.2003	02.02.2004	operating
1/03	12	01.12.2001	04.01.2002	operating
1/04	06	10.12.2003	30.01.2004	operating
1/05	02	01.12.2001	15.04.2003	operating
1/06	-	10.12.2003	-	-
1/07	-	-	-	-
1/08	-	-	-	-
2/09	-	-	-	-
2/10	-	-	-	-
2/11	-	-	-	-
2/12	-	-	-	-
2/13	-	-	-	-
2/14	-	-	-	-
2/15	-	-	-	-
2/16	-	-	-	-

3/17	05	13.10.2000	04.11.2000	operating
3/18	10	13.10.2000	05.01.2001	operating
3/19	-	-	-	-
3/20	-	-	-	-
3/21	05	25.12.2002	31.01.2003	operating
3/22	10	25.12.2002	10.02.2003	operating
3/23	11	25.12.2002	31.01.2003	operating
3/24	03	13.10.2000	21.11.2000	operating

Table 3: GLONASS constellation status 11th of October 2004 (We are planning to use the highlighted satellite)

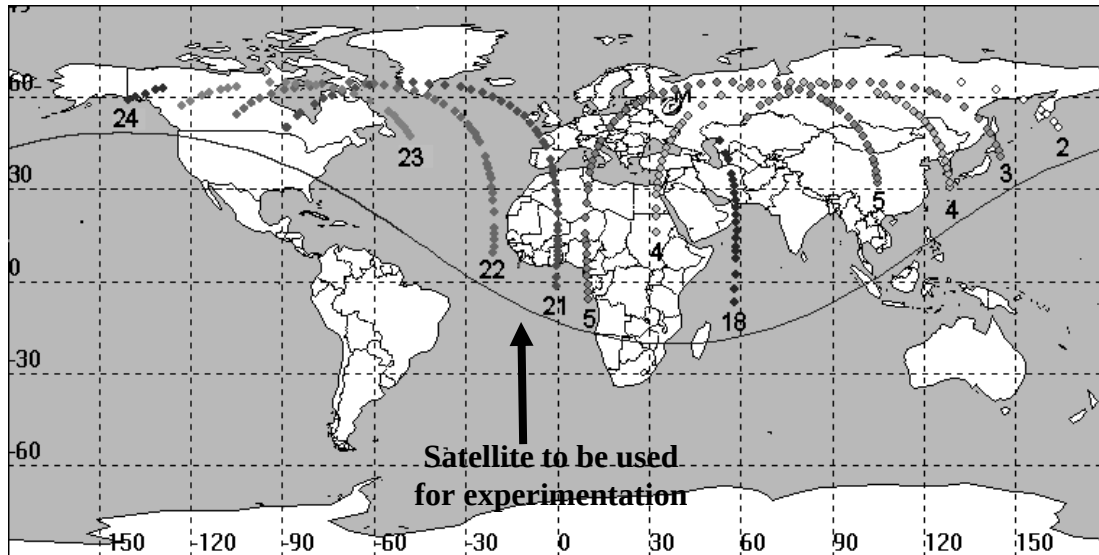


Figure 11: The trajectory of the GLONASS satellites as observed on the 11th Oct. 2004.

Figure 12 shows the diagram of the experimental set-up. The receiver is positioned first on the rooftop of a 5-storey building. The receiver will have three channels: Heterodyne Channel (HC), Radar Channel (RC) and the navigation GNSS channel. The HC directional antenna will be pointing directly at the satellite to receive the reference P-code signal for correlation with the reflected echoes from the observational area received at the RC antenna. The observation area will be $\sim 1\text{Km}$ from the receiver. At the observation area, a number of spatially separated corner reflectors will be positioned with different (10 m^2 and 100 m^2) radar cross-sections (RCS). The separate visibility of these reflectors will demonstrate the

resolution ability, whereas the signal-to noise ratio (SNR) of reflectors with different RCS will be used for the power budget conformation.

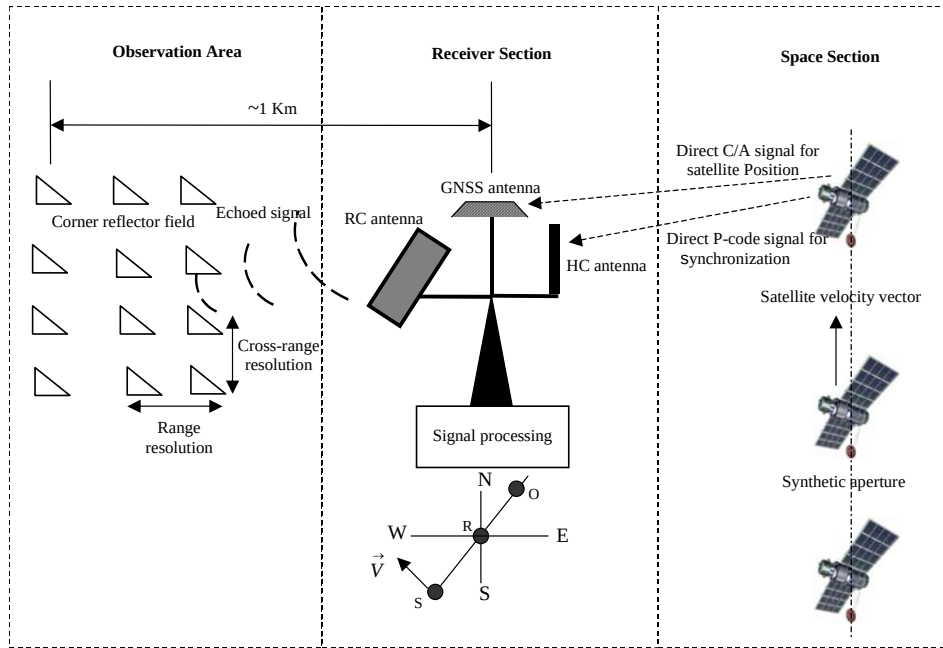


Figure 12: Moving transmitter-stationary receiver.

The GNSS channel will receive the C/A code for the determination of the acting GLONASS satellite position for signal detection and antenna synthesis. The satellite motion introduces Doppler shift in the HC signal. Therefore, the satellite co-ordinates provided by the GNSS receiver could also be used to remove the Doppler shift.

The cross-range resolution depends upon the coherent integration interval over which the antenna is synthesised. The cross-range resolution, in terms of relative velocity of satellite and integration interval, can be expressed as [7]:

$$\Delta_{az} = \frac{\lambda R}{V_s T_{int}} \quad (3)$$

where V_s is the relative velocity of the satellite with respect to earth, expressed as:

$$V_s = \frac{2\pi}{(T_e - T_s)3600} R \quad (4)$$

where $T_e = 24$ hours is the time period of earth rotation, $T_s = 11.15$ hours is the period of GLONASS, $R = 19100$ Km is the average height of the GLONASS satellite.

Considering quasi-monostatic radar, Figure 13 shows the potential cross range resolution obtained for different coherent integration intervals over which the antenna is synthesised by the satellite.

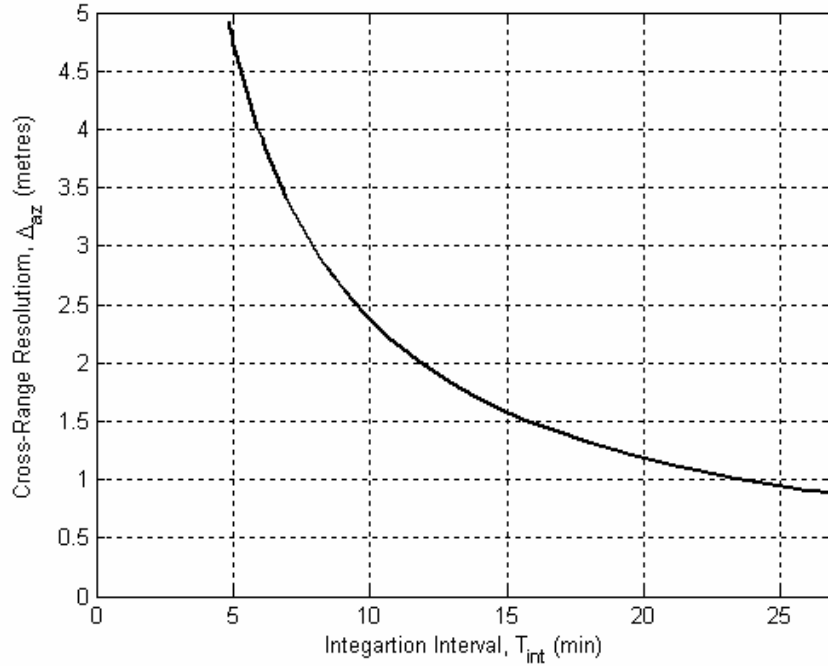


Figure 13 (Fig.6): Cross-Range Resolution Versus Integration Time

It is seen from Figure 13 that for a cross-resolution of 3 meters the integration interval obtained is ~ 10 min. Hence the length of the array L , (distance the satellite should travel to obtain 3 meters resolution) is ~ 1000 Km.

As described before, the HC receives the P-code signal using a special directional antenna pointing in the direction of the chosen satellite. Therefore the beam of the directional antenna must be wide enough for the satellite to fall within the beam, for every position of the satellite, along the entire length of the synthetic array. For that condition to be satisfied, the width of the beam at the range of the satellite must be at least equal to the length of the array synthesised by the satellite.

$$\theta_a R = L \quad (5)$$

For a cross-resolution of 3 metres, the minimum required beamwidth of the HC antenna is $\sim 4^\circ$ corresponding to minimum directivity [Equation (1)] of $(\theta_a = \theta_v) \sim 35$ dB. In practice this requires a very large antenna with an area [Equation (2)] of $\sim 16 \text{ m}^2$ to achieve this directivity and is practically not feasible for our experimentation. Therefore, as mentioned before, we will use an HC antenna with a low directivity of 12-15 dB, giving a beamwidth of 35-50 degrees which is broad enough to cover all satellite positions in the entire array length.

The following main goals are to be achieved as a result of the above experimentation:

- An understanding of the basic problems involved in setting up the experiment such as: satellite detection and tracking (by GNSS receiver), influence of interference from other satellites and non-ideal (low SNR and Doppler introduced due to satellite motion) HC signal
- Develop BSAR algorithms
- Confirm resolution and power budget.
- Hard-Software Basic design

5.3 Experimental Sub-Systems

The experiment uses GLONASS as the transmitter with a stationary receiver. Below we briefly discuss the receiver and its sub-systems.

Receiver Development

Figure 14 shows the block diagram of the receiver. The RC antenna is Left Hand Circularly  arised (LHCP), i.e. cross-polarized to the satellite transmitter. This is done to reduce the direct-path interference into RC. In contrast, the HC antenna is Right Hand Circularly Polarised (RHCP), to obtain a good reference signal. The signals received at the HC and RC are down-converted to baseband I and Q channels, through appropriate amplification and filtering.

The I and Q baseband channels are fed to a four-channel data storage system with 50 MHz sampling rate. The data acquisition system constructed is based on 1-bit resolution of the A/D converter, similar to that used in GNSS receivers, as it introduces no more than 2 dB loss.

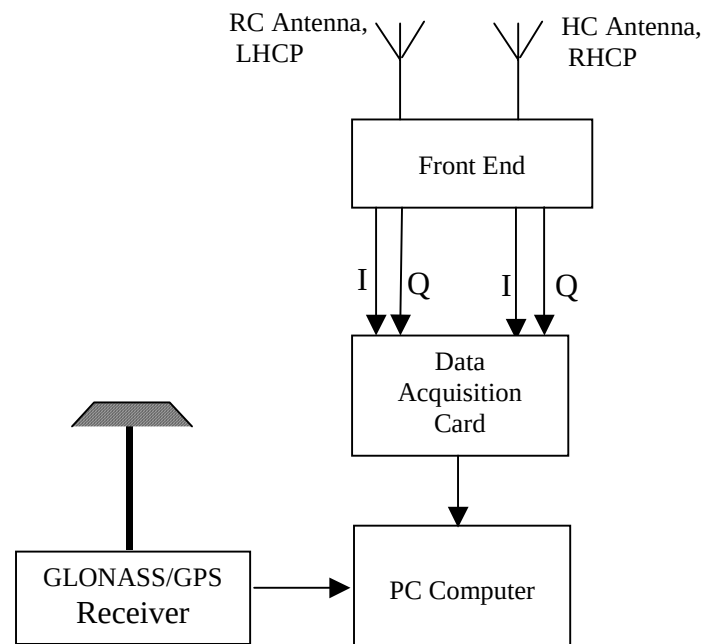


Figure 14: Receiver Block Diagram and subsystems photos

Front End

Figure 15 show the block diagram of the proposed front end of the receiver. It is designed for: GLONASS Signal- L1 band 1.6 GHz centre frequency, 10 MHz (5 MHz baseband) bandwidth.

The front end of the receiver is divided into three parts: Radio Frequency (RF), Intermediate Frequency (IF) and Baseband. The RF part consists of a low noise amplifier (1.5 dB noise figure) and a bandpass filter. The RF bandpass filter is to suppress any strong interference from adjacent channels. The IF part consists of a sharp 70 MHz Surface Acoustic Wave (SAW) filter, which extracts the required spectrum and six cascaded IF amplifiers with a total

gain of ~ 120 dB. These IF amplifiers raise the signal to the appropriate level required for the data acquisition system to function satisfactorily.

The input I and Q baseband signal is fed to a data acquisition system. The front end of the data acquisition system consists of four comparators which digitises the incoming I and Q signal by comparing it to a reference 0 V. Therefore, if the incoming signal is positive, logic 1 is generated at the output and logic 0 for negative value of the incoming signal.

A typical value of offset reference voltage of a comparator is 2 mv. Therefore the incoming signal level must be high enough to avoid any undesirable bias. Let 200 mv be the rms voltage required at the input of the data storage system. The required power at the input of the storage system can be expressed as:

$$P_r = \frac{V^2}{R} = \frac{0.2 \times 0.2}{50} \sim 1\text{mW (0 dBm)} \quad (6)$$

The attenuation due to I/Q demodulator is ~ -10 dB, hence the power required at the input of the I/Q demodulator to produce 0 dBm at the output is ~ 10 dBm.

The output noise power, (as the required signals will be buried under the noise) of the LNA can be expressed as:

$$P_{LNA} = kT_o(F-1)\Delta f_c \sim 100 \text{ dBm} \quad (7)$$

where $F = 1.5$ dB is the noise figure of the LNA, $k = 1.38 \times 10^{-23}$ W/(Hz-K) is the Boltzman constant, $T_o = 290$ K is the reference temperature, $\Delta f_c = 5$ MHz is the bandwidth of GLONASS signal and the receiver filters.

Total attenuations of the two filters [BPF1 (RF) BPF2 (IF)] and the mixer (M1) is ~ 10 dB. Therefore, the input noise power to the first IF amplifier is -110 dBm. Hence the total gain required to produce 10dBm at the input of the demodulator is ~ 120 dB.

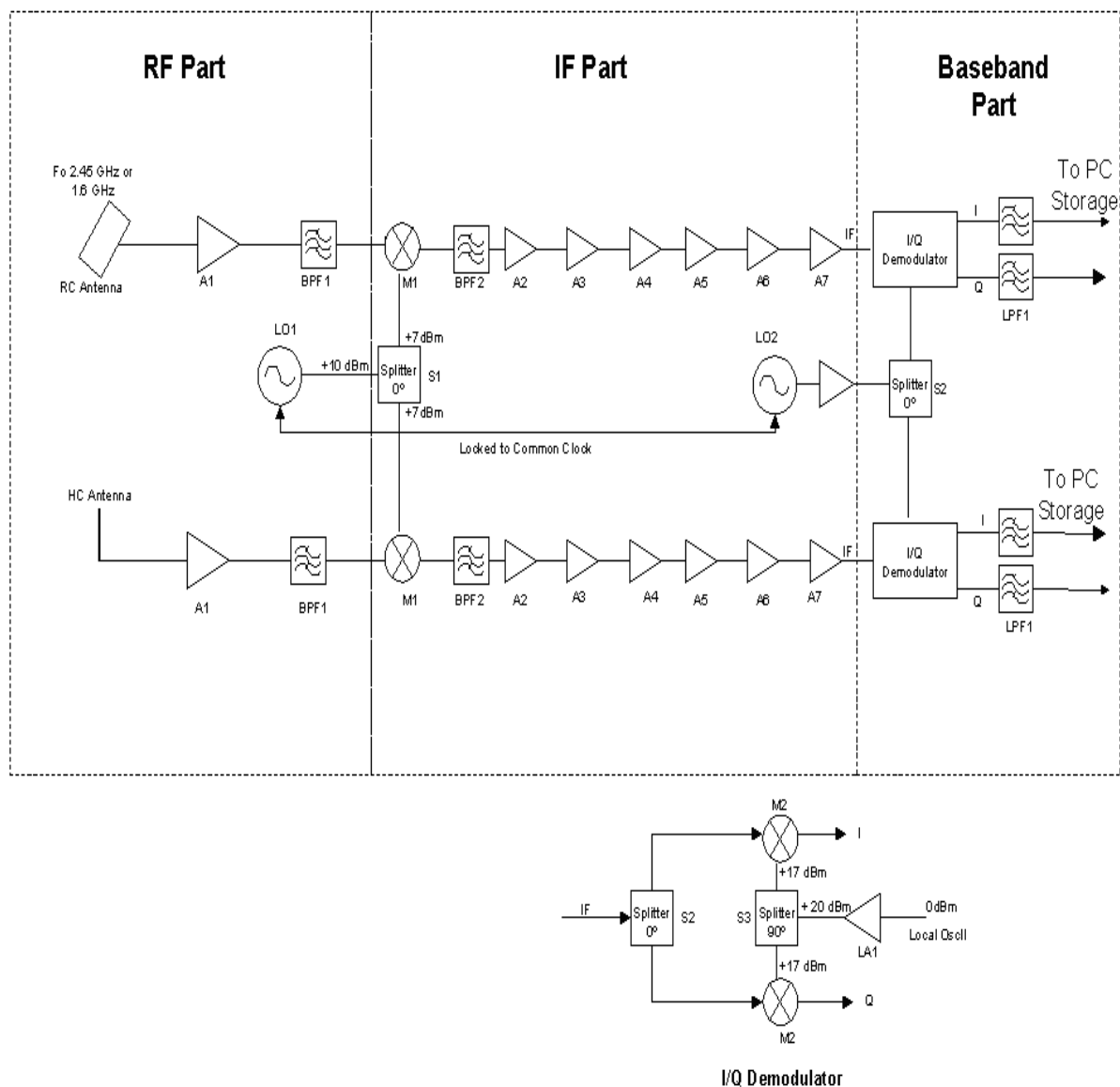


Figure 15: Front End of the Receiver (see Table A1 for full component specifications)

Data Acquisition System

The incoming analogue signals are acquired using a custom designed system consisting of three components:

1. Data comparator/digitiser
2. Data sequencer
3. Computer interface card

Figure 16 shows a block diagram of the developed data acquisition system. The data comparator/digitiser has been designed in such a way that it accepts analogue input (I and Q

signals) received from both the Heterodyne Channel (HC) and the Radar Channel (RC) antennae. This input is compared to a reference voltage and the resulting TTL output is presented to the data sequencer module.

The data sequencer module is an FPGA board that has been designed specifically to provide a suitable interface between the incoming digitised input and a commercially available computer interface card (see Appendix A for brief specifications). This module samples the 1-bit data from the four-channel output of the comparator/digitiser at a rate of 50MHz and arranges it in a 32-bit format suitable for transmission to the computer interface card. When a sufficient amount of data has been received and sequenced by this module, the resultant data is presented at the output and the module initiates data transfer to the computer interface card by driving 'data ready' and sampling clock signals.

The computer interface card used in this system is the *ADLink PCI-7300A ultra-high speed 32-channel digital I/O board* (see appendix A.1 for brief specifications). This board can accept input that is up to 32 bits wide at a maximum frequency of 20MHz. The received data is transferred to the computer's memory using very fast Direct Memory Access (DMA) in order to ensure timely storage and to minimise the possibility of data loss. A software application carries out the process of storing the data to permanent media for offline processing.

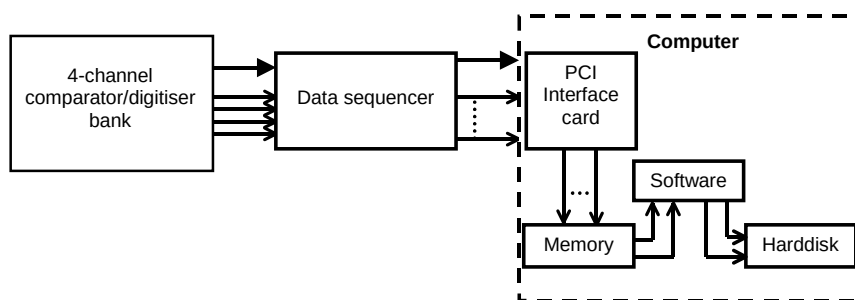


Figure 16: Data Acquisition System

GNSS Receiver

A GNSS receiver for the determination of the satellite's position has been bought from TOPCON. Currently, work is in progress to study and customise the software and satellite position extraction from the receiver.

6. BRIEF CONCLUSIONS

This report discusses in a broad sense the approach and areas of possible applications of bistatic radar based on signals from GNSS.

At the moment, experimental set-up hardware is ready for operation and the next stage of the project will be mainly dedicated to the concept experimental conformation (Figure 17).



Antenna system



Electronic block

Figure 17: Experimental set-up

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