The Effects of the Receiver Altitude in GPS Bistatic Altimetry

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***Abstract*: The direct GPS signals are successfully used in navigation and positioning application. However, reflected GPS signals can also be viewed as useful source for remote sensing information. In this paper, the system parameters that affect the system performance are presented. These parameters include coherent time, footprint area, SNR, range rms error, and number of coherent pulses. Three different scenarios for GPS bistatic measuring are proposed in this paper based on the altitude of GPS bistatic receiver. The comparison among system parameters are discussed in the three scenarios.**

***Keywords:* Global Positioning System, Remote sensing, range rms error, Signal noise ratio, bistatic altimetry.**

I. INTRODUCTION

The remote sensing of the earth from outer space has been used over the past decades for a variety of applications such as weather sensing, climate sensing, topography sensing, etc [1] [2]. Many of the specific space remote sensing applications require at least one if not more, satellite-based platform where each satellite may cost hundreds of millions of dollars to build, launch into orbit, and control. On the other hand, many specific satellites are currently in orbit, and transmit information on frequencies of interest. One group of satellites currently in orbit is the GPS satellite constellation. These 31 satellites cover the entire surface of the earth. The GPS navigation data stream (50 Hz) is spreaded by a specific GPS codes (P-code or C/A code). The chipping rate of P-code is 10.23 Mchips/sec and C/A code is 1.023 Mchips/sec [3]-[4]-[5]. GPS satellites transmit signals in L-band frequency range (specifically 1575.42 MHz and 1227.6 MHz). This frequency range is convenient for remote sensing of soil moisture and ocean surfaces [2].

Since Martin-Neira proposed using the GPS reflected signal in remote sensing applications at 1990 [6], many researches have been done in this field and others are continually issued [7]-[8]. The GPS satellites transmit incident waves towards the Earth, these transmitted waves may be used as the power source for bistatic measurements. By using a sensitive receiver to measure the scattered signals from the ground, the bistatic signals reflected from the surface may be range gated and measured. As a result of these measurements, information about the target (reflected surface) can be retrieved. Therefore this subsidiary use of the GPS satellites saves tremendous cost for performing bistatic measurements of the Earth surface.

The GPS bistatic radar can be used to measure the wind speed and direction of ocean surface where the reflected GPS signal from ocean surface contains information about sea surface roughness, which depends on the surface wind speed. Another application is the measurement of the sea surface height, which can be obtained from the relative delay between the direct and the reflected GPS signals. As well as the GPS signals are very sensitive to the dielectric constant of the reflected surface, therefore it can be used in soil moisture remote sensing. Moreover GPS bistatic radar can be used in iceberg detection which is very critical data in marine application.

The scattered GPS signals are gathered by special receiver and then compared with the direct signals. Because of the transmitters (GPS satellite) and the receiver are separated, the system is called GPS *bistatic* radar and the receiver is called GPS bistatic receiver. The GPS bistatic receiver may be carried on a low orbit satellite, aircraft or even fixed on high tower [9]-[10]-[11]-[12]. The receiver contains two antennas, the first one is RHCP up-looking antenna to receive the direct signals, and the other one is LHCP down-looking antenna to receive the reflected signals. The main function of

GPS bistatic receiver is measuring the path difference between the direct and reflected signals; this measurement can be used to retrieve the desired remote sensing information. The receiver may be attached with recording device to record the remote sensing information and then this information can be recovered after the measuring time or even connected with telemetry system to send the information on time to ground station to analyze [9]. We should note that the GPS bistatic receiver may just gather the ranging data then the ground station analyzes this data to retrieve the remote sensing information, or the GPS receiver is attached with computing system and necessary software to retrieve the intended remote sensing information [9].

By using GPS in the remote sensing applications, a countless advantages over conventional systems can be obtained, that including:

– The user takes the benefits of using GPS satellites. The GPS transmitted signal covers the entire earth’s surface all times.

– The GPS bistatic system has a potentially higher surface resolution compared with the microwave radiometry. The resolution can be achieved because GPS systems use the highly stable carrier and coded modulation structure of the illuminating signals.

– Low power consumption because no need for transmitter in the GPS bistatic system.

– Inexpensive, compared to alternative remote sensing systems.

This paper describes the GPS bistatic system and discusses the system performance in three different scenarios for measuring techniques. The paper has the following structure: in section II, the general description about GPS bistatic system is presented. In section III, the parameters of GPS bistatic system that affects the system performance are introduced. In section IV, the study of three different measuring scenarios each with different altitude of GPS bistatic receiver and comparison among them are presented. Finally in section V, some concluding remarks are discussed.

II. DESCRIPTION OF GPS BISTATIC SYSTEM

Traditional altimetry, such as Topex/Poseidon and Jason-1, is limited to looking in the nadir direction and obtaining one height observation at a time below the altimeter [13]; by contrast, as high altitude GPS bistatic receiver, installed on low earth orbit satellite (LEO) or even on aircraft, with an antenna pointed toward the earth's surface can, in principle, track about 10 GPS reflections simultaneously, therefore providing a coverage that is an order of magnitude denser than traditional nadir viewing altimeters.

The geometry of the GPS bistatic system is illustrated as in Fig.1. As shown in the figure and for simplicity, the earth contour is considered as a sphere. The parameters of the figure are as following:

γ	the receiver's viewing angle.
θ	the elevation of the scattering signal with respect to local tangent plane (incidence angle).
R_1	the mean distance from the transmitter (GPS satellite) to the receiver antenna footprint on the earth's surface.
R_2	the mean distance from the receiver to the receiver antenna footprint on the earth's surface.
h	the receiver's altitude.
H	the transmitter's (GPS satellite) altitude $\cong$ 20,000 km.
R	the earth's radius.
α	the angle between the GPS satellite and the specular point as seen from the earth's center.
Θ	the angle between the GPS satellite and the receiver as seen from the earth's center.

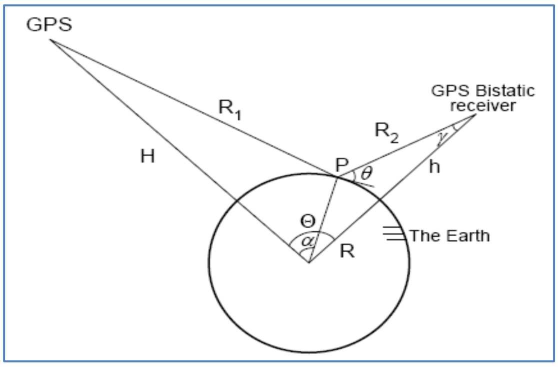

Fig.1. Geometry of GPS bistatic system

As illustrated in the figure, the following relations between parameters can be easily deduced,

$$R_2 = (h+R)\cos\gamma - \sqrt{R^2 - (h+R)^2\sin^2\gamma} \quad (1)$$

$$R_2^2 + R^2 + 2R_2R\sin\theta = (h+R)^2 \quad (2)$$

$$R_1 = -R\sin\theta + \sqrt{(H+R)^2 - R^2\cos^2\theta} \quad (3)$$

$$R_1^2 = R^2 + (H+R)^2 - 2R(H+R)\cos\alpha \quad (4)$$

$$\Theta = \frac{\pi}{2} + \alpha - \gamma - \theta \quad (5)$$

If the reflected surface is smooth, the GPS signal is reflected by only one point (specular point) with the same frequency of incident signal. But because the reflected surface, in general, is rough with respect to GPS signal wavelength (≅19 cm), the GPS signal is reflected by an area surrounding the specular point (the point on the reflected surface that satisfy the minimum delay of reflected waves between transmitter and the receiver); this area is called as a *footprint* area of the GPS scattering signal.

There are several factors that determine the shape of the GPS bistatic footprint area; these factors include the elevation angle of the scattered signal, the direction of the incidence plane (the plane contains the GPS, the receiver, and the specular point) relative to the receiver velocity, the receiver height, and the range and Doppler filter implemented in the receiver [9]. The footprint size can be determined by two parameters: *iso-range lines* and *iso-Doppler lines*.

The equal range line (iso-range line) can be defined as the difference between direct and reflected signals is constant. As indicates in [6], the specular point will be somewhere on the earth's surface between the receiver and the transmitter and the iso-range lines represented as concentric ellipses around the point of specular reflection (P) and the separation between them will decrease as we go further away from the point of specular reflection as indicated in Fig. 2.

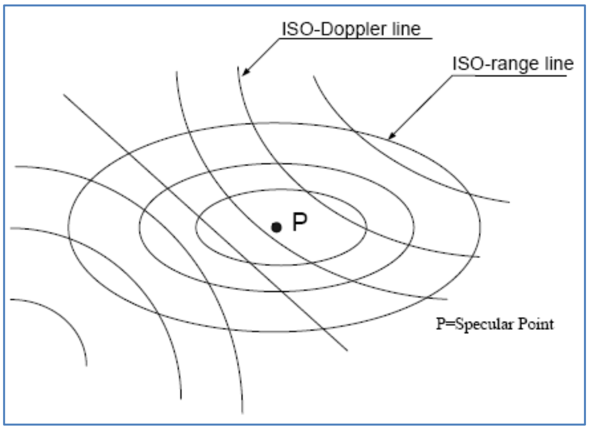

Fig.2. The footprint area of GPS scattering signal on the earth's surface

The semi-major and minor axes of the iso-range ellipses are given as [13] and [14]

$$\rho_{a_m} = \sqrt{\frac{2c\tau\bar{H}}{\sin^3\theta}m} \quad (6)$$

$$\rho_{b_m} = \sqrt{\frac{2c\tau\bar{H}}{\sin\theta}m} \quad (7)$$

Where ρ_{a_m} is the semi major axis of the ellipses of the pulse limited footprint area around the specular point, ρ_{b_m} the semi minor axis of the ellipses of the pulse limited footprint area around the specular point, m multiplication number of the chip size take the values $(1,2,3,\ldots)$. θ is the elevation of the scattering signal with respect to local tangent plane (incidence angle), and τ chip period ($1/10.23 \times 10^6$ for P-code and $1/1.023 \times 10^6$ for C/A code)

and

$$\bar{H} = \left(\frac{1}{h} + \frac{1}{H}\right)^{-1} \quad (8)$$

also the iso-Doppler lines are very important aspect which determines the shape and size of the footprint. The transmitter, receiver, and the target have three independent velocity vectors. At the receiver side, the Doppler frequency shift between the direct and reflected signals is changed according to these velocities. The iso-Doppler lines can be represented by hyperbolic lines [6] as shown in Fig.2.

III. SYSTEM PARAMETERS

A. Signal-to-Noise Ratio (SNR):

The signal-to-noise ratio is a basic factor which describes the performance of any wireless communication system. In GPS bistatic system the signal to noise ratio will be computed in two steps, the first step is computing the signal-to-noise ratio for one pulse where "pulse" refers to one chip of the GPS pseudorandom code. The second step is expanding the computation for several pulses. The equation of the signal to noise ratio for the single pulse in bistatic mode can be written as following [9]

$$SNR_o = \left(\frac{P_t G_t \lambda^2}{32\pi^2 R_1^2 \cos\theta (KT_o B)}\right) \sigma_o(0^0) \left(\frac{1}{F}\right) \qquad (9)$$

Where SNR_o is the signal to noise ratio for a single pulse, P_t is the transmitted power by GPS satellite, G_t is the transmitter antenna gain, R_1 the mean distance from the transmitter (GPS satellite) to the receiver antenna footprint on the Earth's surface, λ is the wavelength of the radiation signals, B is the signal bandwidth, K the Boltzman's constant, $\sigma_o(0^0)$ is normalized monostatic radar cross-section at an incidence angle of 0^0 (nadir direction), F is the receiver's noise figure, and T_o standard room temperature =290 K.

The reflected signal is correlated with the replica code in order to perform the altimetry measurement. Each correlation is carried out over a time duration M code chips called pulses. As the correlation process is performed coherently, an improvement by the factor of M is achieved on the signal to noise ratio. Therefore, the signal-to-noise ratio at the output of the M-pulse correlator is [14]

$$SNR_M = M(SNR_o) \qquad (10)$$

B. Coherent time:

The previous equation indicates that the signal-to-noise ratio is directly proportional to the number of coherently pulses M. Now we shall provide an estimation of the number of pulses M that can be added coherently by computing the coherence time of the signal. The computation takes into account the relative speed between the receiver and the target, but the movement of the reflected surface (normally ocean surface) is neglected as well as the contribution of the speed of the transmitter.

Consider the receiver is moving at the velocity $\acute{v}$ relative to the target, which consists of the pulse-limited footprint area, if we assume the transmitter in the direction perpendicular to the velocity of the receiver, the Doppler bandwidth of the signal coming from the pulse-limited footprint will be [6]

$$B_d = \frac{\acute{v}\rho_{b_m}}{\lambda R_2} \qquad (11)$$

where B_d is the Doppler bandwidth of the reflected signal, ρ_{b_m} is the semi minor axis of the ellipses of the pulse limited footprint area around the specular point, and R_2 is the distance from the receiver to the target. By neglecting the speed of the ocean and the transmitter, the coherence time T_{coh} of the signal is therefore be given by:

$$T_{coh} = \frac{1}{2B_d} = \frac{\lambda R_2}{2\acute{v}\rho_{b_m}} \qquad (12)$$

And the estimated number of pulses that can be coherently added will be

$$M = \frac{BT_{coh}}{2} = \frac{\lambda B R_2}{4\acute{v}\rho_{b_m}} \qquad (13)$$

C. The range accuracy:

The range accuracy is an important factor that describes the performance of the GPS bistatic system. The range error depends on several factors including the period of the chip code and the exact algorithm used in the receiver in correlation process. The range rms error can be expressed according to [9] as

$$\sigma_c = k\frac{\lambda_{code-chip}}{VSNR_M} \quad (14)$$

where σ_c is the range rms error (m), k is constant which roughly equal to 0.5 [9], $VSNR_M$ is voltage-to-noise ratio and given by taking the square root of equation (10), and $\lambda_{code-chip}$ is chip wavelength $=3\times10^8/10.23\times10^6$ for P code and $3\times10^8/1.023\times10^6$ for C/A code.

IV. THE EFFECT OF RECEIVER ALTITUDE

Three scenarios for GPS bistatic measuring will be taken in this section, firstly the GPS bistatic receiver is carried on Low Earth Orbit (LEO) satellite at altitude 800 km, secondly, the receiver is carried on aircraft flies at level flight (without maneuvering) at altitude 2 km. Finally, the receiver is fixed on high tower at altitude 0.1 km.

In these scenarios the receiver viewing angle γ is taken equal to 40°, T_o□□290 K, λ□□0.19m (for L1 signal), F=2 dB, $\sigma_o(0^0)$=12 dB [6], the receiver velocity is $\acute{v}$□□7.5 km/s for LEO, 300 km/h=0.0833 km/s for aircraft, and for fixed receiver $\acute{v}$ equal to the target velocity which is taken as 5 km/h or 0.00139 km/s, the transmitted power multiplied by the transmitted antenna gain $P_tG_t$equals to 25 dBW [6], Table.I. presents the numerical values of the system parameters in the three scenarios.

Table I. parameters values for three scenarios of GPS bistatic system

	Receiver Altitude =800 km		Receiver Altitude =2 km		Receiver Altitude =0.1 km		Remarks
	C/A code	P code	C/A code	P code	C/A code	P code	
R_1(km)	21567	21567	21171	21171	21171	21171	Equation (3)
θ	43.65	43.65	49.98	49.98	49.99	49.99	Equation (2)
B (MHz)	2	20	2	20	2	20	RF bandwidth $\approx \tau/2$
ρ_{a_1}(km)	39.5480	13.0080	2.0165	0.6633	0.4510	0.1483	Equation (6)
ρ_{b_1}(km)	25.4210	8.3615	1.2962	0.4263	0.2898	0.0953	Equation (7)
Footprint area (km^2)	790	85	2.1	0.22	0.1	0.011	$=\frac{\pi\rho_{a_1}\rho_{b_1}}{4}$
SNR_O(dB)	-9.18	-18.78	-8.51	-18.11	-8.51	-18.11	Equation (9)
R_2(km)	1095.3	1095.3	2.6	2.6	0.1	0.1	Equation (1)
$\acute{v}$(km/s)	7.5	7.5	0.0833	0.0833	0.00139	0.00139	
$T_{coh}(\mu s)$	545.8	1617.3	2297.5	6808.6	30782	91223	Equation (12)
M(No. of coherent pulses)	606	17048	2553	71768	34202	976500	Equation (1)
SNR_M(dB)	18.65	23.45	25.56	30.36	36.84	41.64	Equation (10)
σ_c(m)	47.33	2.92	21.35	1.32	5.83	0.36	Equation (14)

Figures.3. to 6. represent a family of curves that illustrate the behavior of GPS bistatic system versus the variation in GPS chip period "τ". Fig.3. shows the variation in footprint area for the one chip with respect to chip period τ for our three scenarios. As shown in the figure, the footprint area decreases as τ decreases, and as expected, the footprint area increases by increasing the height of the GPS bistatic receiver.

Fig.4. shows coherent time T_{coh}versus chip period τ. It can be illustrated from this figure that T_{coh}increases as τ decreases. This can be easily deduced by equation (12) where $T_{coh}$is inversely proportional to $\rho_{b_m}$and ρ_{b_m} increases by decreasing . Also this figure shows that T_{coh} increases by decreasing the relative velocity between the target and the GPS receiver, for that reason the last scenario where GPS receiver fixed on 0.1 km altitude gives the best values for T_{coh}. Although this good characteristic, most of GPS bistatic experiments are carried out by receivers carried on LEO satellite or aircraft to cover dense measuring areas that can't be done by fixed receiver.

Equation (10) shows that the number of coherent pulses M effects directly on the performance of $SNRM$ versus τ. As expected, Fig.5. shows that $SNRM$ increases by decreasing τ or decreasing the relative velocity between the target and the GPS receiver. Finally, the range rms error versus variation of τ is shown in Fig.6; it is clear that the range rms error decreases as τ decreases and the relative velocity between the target and the receiver decreases.

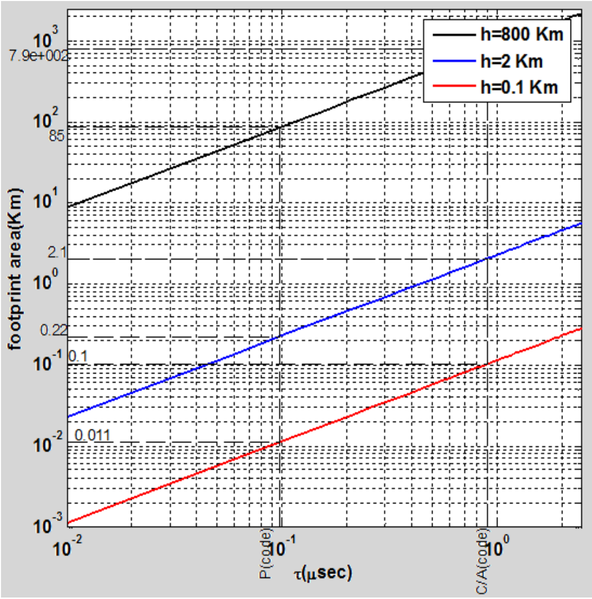

Fig.3: Footprint area versus versus chip period τ

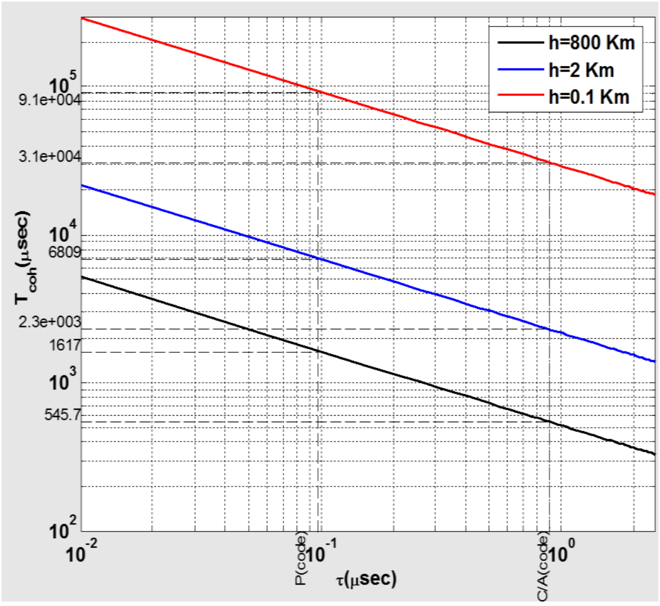

Fig.4: coherent time T_{coh} versus versus chip period τ

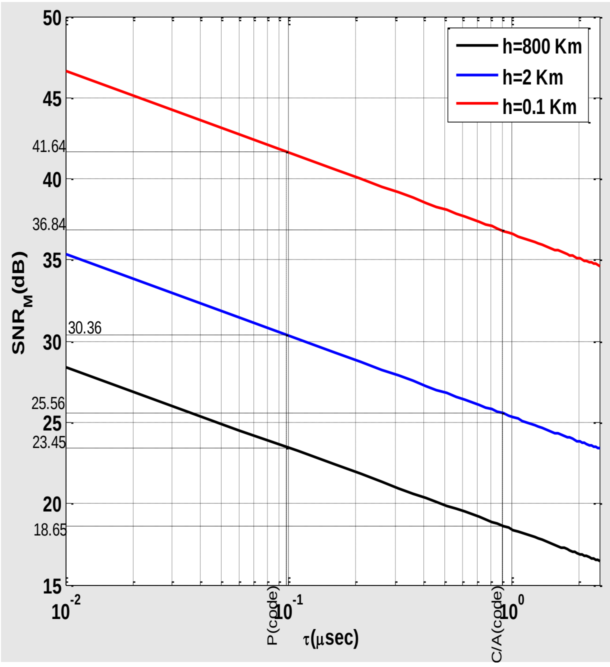

Fig.5: SNR_M versus versus chip period τ

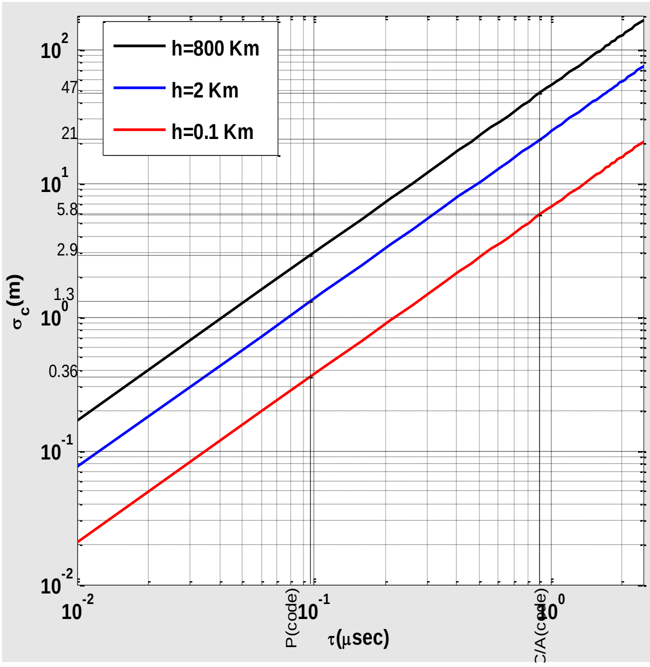

Fig.6: range rms error $\sigma_c$versus versus chip period τ

V. CONCLUSION

The height effects of GPS bistatic receiver on measurement parameters have been assessed. The research have shown that the system performance is going better for low relative velocity between the target and the GPS receiver, in this case T_{coh}, M, $SNRM$, and σ_c improve as $\acute{v}$ decreases. Although the previous remark indicates the advantages of fixed GPS receiver, most of the GPS bistatic experiments were carried out by LEO satellite or aircraft to satisfy a dense measuring areas and high number of visible GPS satellites.

The GPS bistatic system is still under research and development. The signals structure of new GPS satellites will be more adequate for remote signal such as decreasing the chip period τ [16]. The ongoing studies and research of GPS bistatic system tell us we may be in the way toward Global Remote Sensing System (GRSS).

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