# Thermal Characterisation of RF GPS Receivers

Daniel K. Ntumy[1], Sunday C. Ekpo[2] Bamidele Adebisi[2] and Angham Sabagh[2]

[1]Department of Electrical Engineering, Ecole Superieure Des Technologies Electronique, Informatique Et Infographie, Bordeaux, France
ntumydaniel@yahoo.com

[2]Department of Electrical & Electronic Engineering, Manchester Metropolitan University, Manchester, M1 5GD, UK
cookey_sunday@ieee.org; B.Adebisi@mmu.ac.uk; A.Sabagh@mmu.ac.uk

***Abstract*—Various global positioning system (GPS) receivers have continued to champion location-finding in both the terrestrial and the space environments. In this paper, the effect of temperature surges (and space radiation) on the sensitivity of GPS receivers is investigated. The device–under-test (DUT) was a low noise amplifier (LNA) module with an integrated filter for a GPS application. The LNA device was first investigated over a frequency of 2–20 MHz at room temperature (25 $^{o}$C) and then impacted with a solar radiation dose until the DUT reached a temperature of 40 $^{o}$C in 20 minutes. The DUT was then cooled down to 19 $^{o}$C and its noise figure (NF) and gain measured. The test results and analysis indicate that as the temperature increases, the amplifier loses its sensitivity. The receiver subsystem gain decreases and its NF increases as the temperature of the DUT builds-up. The thermal noise (at 40 $^{o}$C) increased the receiver NF by approximately 100% from the ambient value of 3.5 dB. After cooling the LNA to 19 $^{o}$C, the receiver regained its sensitivity by nearly 3 dB. This investigation promises to enhance the design and development of GPS transceivers for terrestrial and space applications.**

***Index Terms*— gain, GPS, low noise amplifier, noise figure, receiver, sensitivity, temperature.**

## I. INTRODUCTION

THE proliferation of global positioning system (GPS) receivers has transformed and revolutionised terrestrial and space navigations [1, 2]. The current technology trend of the GPS device is for more sensitivity and reliability in critical applications in dynamic complex environments [2–4]. Several factors relating to the active device technology, receiver subsystem design and fabrication constraints have determined the key performance parameters (KPPs) of the GPS receiver [3]. The KPPs of the RF GPS receiver span the signal gain, noise figure, dynamic range and sensitivity [4–7]. However, the environment and operation times play a vital role in determining these time-changing KPPs through its physical quantities such as temperature and/or solar radiation [5–7]. Changes in the environmental temperature exert a direct influence on the gain and noise figure of the GPS receiver front-end subsubsystem [2, 4].

This paper is organised as follows. Section II explains the thermal and solar profiles of a LNA. The GPS receiver characterisation parameters (including subsystem and equipment specifications and the adopted measurement technique) are presented in section III. The findings of the research are stated in section IV. This section also carries the fabricated GPS LNA on a PCB as well as the gain, noise figure and equivalent temperature measurements that were carried out. Section V concludes the paper.

## II. IMPACTS OF SOLAR RADIATION ON ELECTRONICS

Particles that are emitted from different sources located within and beyond our solar system have been found to generate solar radiation [8, 9]. The effects of space radiation include degradation of micro-electronics, optical components and solar cells; data corruption; noise on images; system shutdown; and circuit failure and/or damage. These affect both the terrestrial and space communication subsystems and systems [10–14]. For instance, space satellites have experienced electronic and electrical systems failure while cruising their orbits. Similarly, aircraft flying polar routes have shown avionics malfunctions that have been attributed to the solar radiation events.

An amplifier's stability is a measure of its immunity to spurious oscillations. Data communications receivers are increasingly expected to be unconditionally stable at any load and source conditions and at any frequency margin within the operating bandwidth [5, 6]. The LNA is a major subsubsystem within the RF/microwave receiver subsystem front-end. Its design for wireless applications have been mostly driven by the active semiconductor device (III-IV) technologies (GaAs and InP) [5, 6, 15]. While GaAs-based RF/microwave systems have a somewhat natural "radiation hardness" against space radiation, silicon-based semiconductor devices are naturally radiation-prone. For instance, a single event latch-up (due to a high energy particle in space) can cause a single metal oxide semiconductor transistor to generate parasitic bipolar transistor between its drain and source region. This can amplify the avalanche current caused by heavy ion cosmic ray particles to a very high level that causes localised heating and component performance degradation.

## III. GPS RECEIVER CHARACTERISATION

### *(A) Introduction*

This paper presents the effects of heat energy from solar radiation on the low noise amplifiers (LNAs) performance. The objective is to measure and evaluate the characteristics of a GPS LNA under three conditions: (i) before exposure to solar radiation (i.e., room temperature and commercial-off-the-shelf condition); (ii) after exposure to solar radiation; and (iii) after cooling. Noise figure and gain have been derived at each stage to verify the effect of the variation of temperature on the performance of the LNA and hence, the sensitivity of the receiver.

The LNA is the first active device in the receiving chain of a GPS receiver. Hence, its NF directly adds to that of the system. It is a major subsystem-level design requirement that the LNA should add as little noise as possible whilst providing enough gain to overcome the noise contributions of the subsequent stages. This is illustrated using the Frii's formula as follows:

$$F_T = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + ... + \frac{F_n - 1}{G_1 G_2 ... G_{n-1}} \qquad (1)$$

where $F_T$ is the total noise factor and $F_n$ and $G_n$ are the noise factor and available power gain of the *n*th stage respectively. The system noise figure is obtained from (1) as:

$$NF(dB) = 10 \log_{10} F_T \qquad (2)$$

In most RF/microwave receivers for navigation and satellite applications, the "effective noise temperature, $T_e$" is utilised to describe the noise performance of a device. $T_e$ is a function of the sky noise, line losses, antenna noise temperature, ambient temperature and receiver noise factor. The effective noise temperature refers to the "equivalent temperature of a source impedance into a perfect (noise-free) device that would produce the same added thermal noise power, $N_o$." $T_e$ is estimated as follows:

$$T_e = \frac{N_o}{kGB} \qquad (3)$$

or

$$T_e = T_o (F - 1) \qquad (4)$$

where *k*, *B* and $T_o$ are the Boltzmann's constant (1.3806 x $10^{-23}$ J/K), operating bandwidth (Hz) and thermodynamic temperature (K) respectively.

Thermal noise power is independent of the centre-design frequency of the GPS receiver. In dynamic environment applications (such as spacecraft, aircraft and automobile), an optimal tracking bandwidth is required to obviate serious degradation in the dynamic tracking performance [2]. Hence, a trade-off between narrow tracking loop bandwidth (for filtering noise due to thermal effects) and wide tracking bandwidth (for tracking vehicle dynamics) is carried out in the GPS subsystem design. The goal is to minimise errors in a dynamic environment during signal tracking.

Moreover, the performance of a GPS receiver is assessed by a certain signal quality metric called signal-to-noise ratio (SNR). For low-end GPS receivers, the last stage of the intermediate frequency (IF) filtering has a bandwidth of approximately 2 MHz. This IF filtering bandwidth increases up to 20 MHz for high-performance receiver models [4]. The noise power, $N_o$, in the bandwidth is obtained using (3). $T_e$ is dominated by the ambient temperature value and equipment noise factors; a typical value of $T_e$ for a GPS receiver is 513 K [4]. This results in $N_o = kT_eB$ = -128.9 dBW (and noise density of -201.5 dBW/Hz) for an 18-MHz GPS receiver bandwidth.

To characterise the impact of solar radiation on a LNA, the device has to be investigated over the probable operating temperatures that it will be exposed to. In this paper, three temperature regimes and/or conditions were considered to evaluate the response of a GPS receiver to the thermal noise power changes in a dynamic environment.

### *(B) GPS Receiver Subsystem Measurement Specifications*

The device under test is a LNA module with an integrated filter. It is traditionally designed for GPS band applications at 1.575 GHz. The LNA under investigation uses the GaAs enhancement-mode pHEMT process to achieve high gain with a very low noise figure. It has a drain voltage $V_{dd}$ of 2.85 V and a drain current of 8.0 mA. The specified forward transmission gain ($S_{21}$) and NF are 13.5 dB and 0.82 dB respectively.

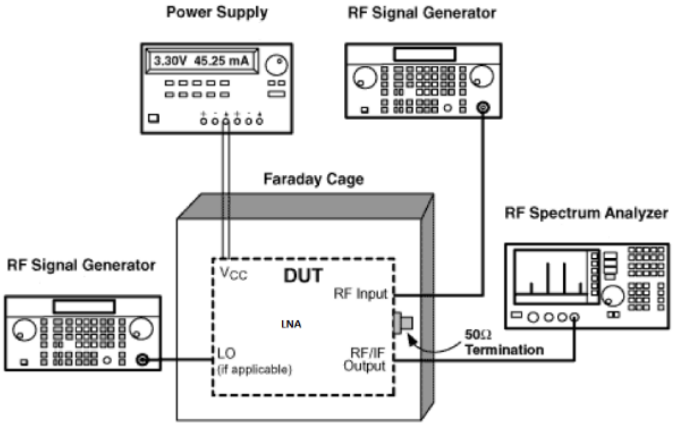

Fig. 1. LNA Characterisation Schematic (Cold Noise Method)

The measurement setup for a LNA characterisation using the cold noise technique is shown in Fig. 1. For the presented GPS LNA, the following hardwares were utilised: spectrum analyser (after Rohds & Schwarz HMS 3000 3GHz); Function generator (TG120 Tti – 20 MHz); DC Power supply (Kingsun UTP3702); and a 50-Ω resistor. Figures 2 shows the fabricated GPS LNA on a printed-circuit board (PCB). The complete measurement setup is illustrated in Fig. 3.

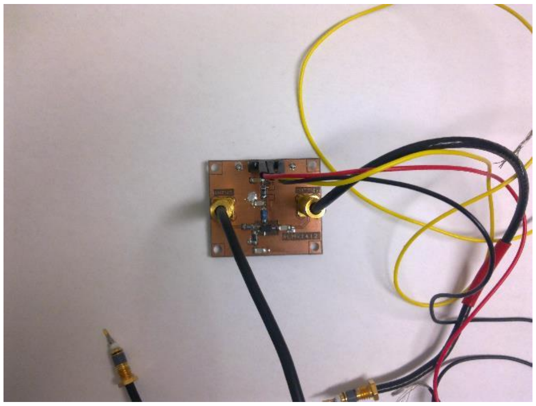

Fig. 2. Fabricated GPS LNA on a PCB

The cold noise (or gain) method was adopted to characterise the LNA performance under three different conditions as stated in the introduction of this section. The cold noise technique is amenable to RF-to-baseband systems characterisation in device production testing. It relies on measuring the cold noise power of the DUT when a 50-ohm termination is applied to its input to maximise the power transfer or minimise the signal reflection from the load. This method also requires the gain of the device to be measured. The gain is been measured by measuring the signal level directly from the output of the signal generator and then with the amplifier in circuit. After the gain and noise power are obtained, the NF is calculated according to (5) as:

$$NF|_{dB} = P_{cold} - (-174\,dBm/Hz) - 10\log_{10} B - G|_{dB} \tag{5}$$

$P_{cold}$ is measured cold noise power. The value -174 dBm/Hz is the thermal noise power associated with the temperature 290 K.

It is the product $kT$ in dBm. The $P_{cold}$ measurement can be obtained from the spectrum analyser by terminating the DUT input with a 50-ohm load and setting the frequency sweep from, say, 2 to 20 MHz. Figure 3 illustrates the measurement setup utilised to study the LNA performance. The LNA was first investigated at room temperature (at 25 °C). Secondly, the DUT was heated for 20 minutes and the temperature was measured as 40 °C. This introduced electrical noise into the GPS receiver (LNA) due to the random movement of electrons in its semiconductor material. The resultant voltage fluctuates rapidly and alternates in sign to give a zero average value. After the LNA performance was evaluated at 40 $^{o}$C, it was left in a laboratory freezer for 48 hours. This was carried out to investigate the possibility of the DUT regaining its sensitivity after being cooled below 40 $^{o}$C. The amplifier was removed from the freezer and the entire characterisation procedure was repeated for the LNA at 19 °C.

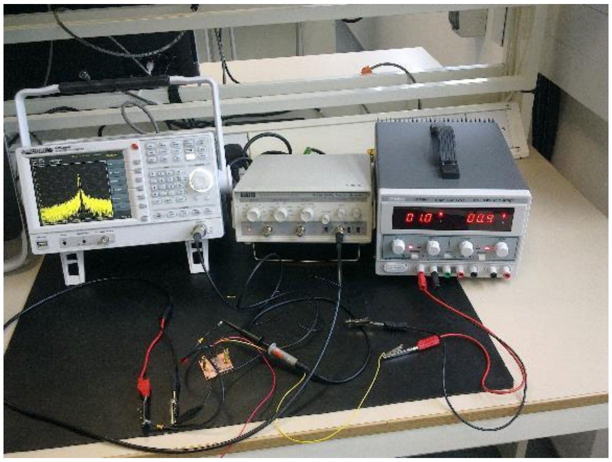

Fig. 3. LNA Measurement Setup

## IV. RESULTS AND DISCUSSION

Figures 4 to 6 show that as the temperature increases, the amplifier begins to lose its sensitivity. Figure 4 shows the forward transmission gain (S21) of the GPS LNA. The original (non-solar-radiated) perfomance of the device indicates a quasi-linear response over the operating frequwncy band. In an actual receiver subsystem, this response would be expected to be maximumat the centre-design (or resonant) frequency. For the purpose of this investigation, this was not considered a major issue as the focus of the characterisation is on the deviation of the DUT performance following a thermal surge. It is evident from Fig. 4 that the gain of the amplifier gain decreases by approximately 3.5 dB over the operating bandwidth. Furthermore, the response is “alternating” after the amplifier was radiated to 40 $^{o}$C. This shape is still noticed in the LNA’s response at 19 $^{o}$C. However, approximately 1.8 dB gain difference is observed between the measured COTS value and the cooled LNA value at 19 $^{o}$C.

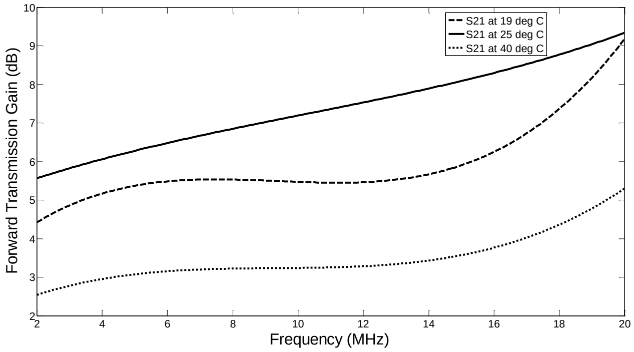

Fig. 4. Forward Transmission Gain (S21) of the GPS LNA

In Fig. 5, the original NF at ambient temperature (25 $^{o}$C and COTS reference) depicts a typical broadband dome-shaped response exhibited by most RF/microwave receivers over a given operating frequency range. After exposing the LNA to a solar radiation until the temperature reached 40 $^{o}$C, the NF response becomes “snaky” and exhibits inband ripples with a corresponding tendency to oscillate over the operating bandwidth. After cooling the amplifier to 19 $^{o}$C, the NF improves but the “alternating or snaky” shape of the thermal impact can still be noticed in its response. Hence, once an active device such as a LNA is exposed to a solar radiation source, the system performance degrades. It loses its ability to receive signals from distant transmitters because the more sensitive the receiver, the better its ability to receive signals from distant transmitters. In the case of the GPS and satellite receivers, the noise level coming from the antenna can be far less and limited by the sidelobe radiation and the background sky temperature to values often below 100 K [14]. In these scenarios, a 3-dB change in the receiver noise figure may result in a much more than 3 dB SNR change.

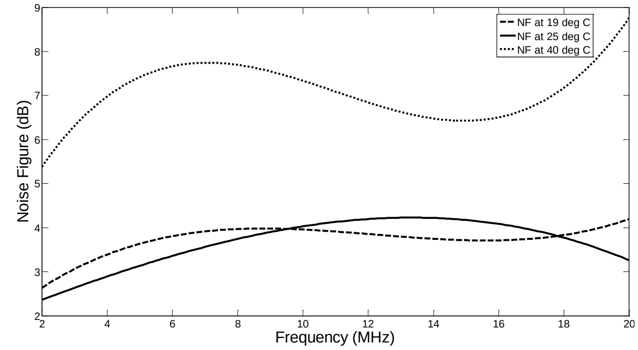

Fig. 5. Noise Figure of the GPS LNA

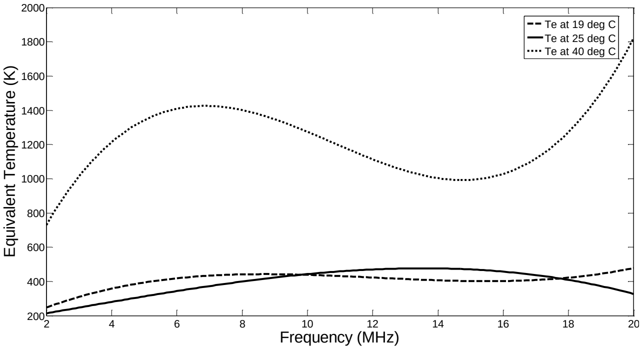

Fig. 6. Equivalent Noise Temperature of the GPS LNA

The result of Fig. 6 shows the equivalent noise temperature of the GPA LNA. The *T*e response at 19 $^{o}$C and 25 $^{o}$C almost approximates though the “alternating” shape due the effect of the thermal noise is still noticeable at 19 $^{o}$C. The presented effective temperature range at 25 $^{o}$C (Fig. 6) is well within the reported typical value for GPS receivers at ambient temperature. However, this was exceeded to values well above 800 K following the solar radiation impact on the receiver subsubsystem. At 19 $^{o}$C, the effective temperature of the GPS receiver was decreased to approximately 400 K over the operating frequency bandwidth of 18 MHz.

## V. Conclusion

This paper presents an investigation of a GPS receiver subsubsystem for both space and terrestrial communications applications at RF/microwave frequencies. The GPS LNA was characterized under three operating thermal conditions. At ambient temperature, the gain and noise figure of the LNA were measured. The device0under-test was solar-radiated to 40 $^{o}$C and then cooled to 19 $^{o}$C. approximately 3.5 dB gain was lost at 40 $^{o}$C as opposed to the 1.7 dB gain recovered by cooling the amplifier to 19 $^{o}$C. The reported GPS LNA investigation reveals very interesting results that can help RF/microwave engineers design and model subsystems for different operating environments and applications. Also, the appropriate heat-sinks and/or thermal dissipators can be designed for both space-borne and terrestrial GPS receiver systems to ensure that accurate navigation functionalities are reliably sustained.

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