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Design of radar receiver system for HF coastal radar

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Abstract: Radars working in high-frequency (HF) band covers frequencies between 3 MHz and 30 MHz with wavelengths of 100 m to 10 m. Due to these large wavelengths, HF radars are not appropriate for operation from satellites. For remotely sensing of the ocean HF radars are basically operated from the coast. Remote sensing by means of HF radar is based on sky wave or ground wave propagation. Refraction by the ionosphere allows large propagation ranges to be achieved. This paper deals with ground-wave propagation and presents a novel system for a HF radar used only for single channel of 5MHz (range-200Km), for application of sea scattering radar, in which radar receiver system is designed with receiver consist of a magnetic loop antenna operating at 5MHz used for reception, and receiver section containing front-end unit which has matching circuit for received signal with initial amplification blocks and a back-end unit consisting of amplifier unit to boost received signal with filter unit to get desired signal filtered out, and also signal processing unit. This paper mainly focuses on design of radar receiver section.

***Keywords*—High frequency radar, HFR, radar receiver system, long-range.**

I. Introduction

HFR system utilizes EM waves in the 3–50 MHz frequency band. It uses the conductivity of the ocean to transmit the modulated EM waves beyond the horizon and the sea surface acts as a diffraction grating to backscatter the signal back to the receiver. The theory of HF and VHF propagation across the rough sea was developed by Barrick [1][2] and, Stewart [3] was the one who proposed the use of HFR system for operational oceanography in the coastal region. The advantage of HFR system is its high resolution mapping capability (both in spatial and temporal) and near-real time data transmission. HFR observations along the Indian coast can provide us information on the surface dynamics in the coastal zone. In this paper we are focused on designing a HF radar receiver system operating at 5MHz frequency for the application of sea scattering, which is ocean currents. This paper mainly looks into the calculation required for minimum and maximum signal levels required for proper reception and processing, and also gives design of receiver section. The post processing of signal received like ADC conversion, DSP, FFT averaging is already present, so receiver design and analysis through software means is carried out, in which parameters like gain, cascaded gain, noise figure of receiver are more elaborately explored.

In the following, section II presents the constraint condition and selection of multi-frequency radar waveform parameters. Section III introduces the system hardware architecture and FPGA implementations of digital down converter. In section IV introduces the system software design. In section V the hardware test results is given, and in section VI our conclusions.

II. PRINCIPLE OF HIGH FREQUENCY RADAR

The HF radar we are using is similar to that of coastal radar (CODAR), in which radar sends radio waves and listens to the scattered signal from the surface wave that have specific wavelength of particular range. After which system directly measures the speed of the waves that scatter the radar signal, and difference between the measured speed and the know speed of the wave are the ocean surface current, Basically the radar work on calculation of main three factors– range of target, speed of target and their difference which is ocean current. In the HF radar the transmitted signals get scattered in all direction by random sea waves. but, the radar signal returns directly to its source only when it scatters of a wave that is exactly half of the transmitted signal wavelength and it adds coherently to form a strong return of energy at a very precise wavelength – Bragg scattering principle. The backscattered signal exhibits a doppler shift from the transmitted frequency. According to the deep-water linear wave theory, the returned signals are concentrated at a known position (first-order peak) in the absence of an underlying current. But, in the presence of ocean currents, an additional shift in the first-order peak is observed [7]. This shift in frequency is deduced to get the current velocity in a radial path (towards or away from the radar). The predicted doppler shift from deep water linear wave theory in the absence of a current field is given as,

$$f_b = \pm (g f_r / \pi c)^{1/2} \quad (1)$$

where f_r is the transmitted frequency, g the acceleration due to gravity and c is the speed of light. In the presence of an underlying current, the first-order peaks shift from
theoretical value as,

$$\Delta f = 2V_r f_r / c \qquad (2)$$

where V_r is the radial velocity, away from or towards the radar. Single HF radar system measures only the radial velocity (towards or away from the radar) and radials from at least two sites are required to calculate two-dimensional surface current (speed and direction).

III. RECEIVER SYSTEM

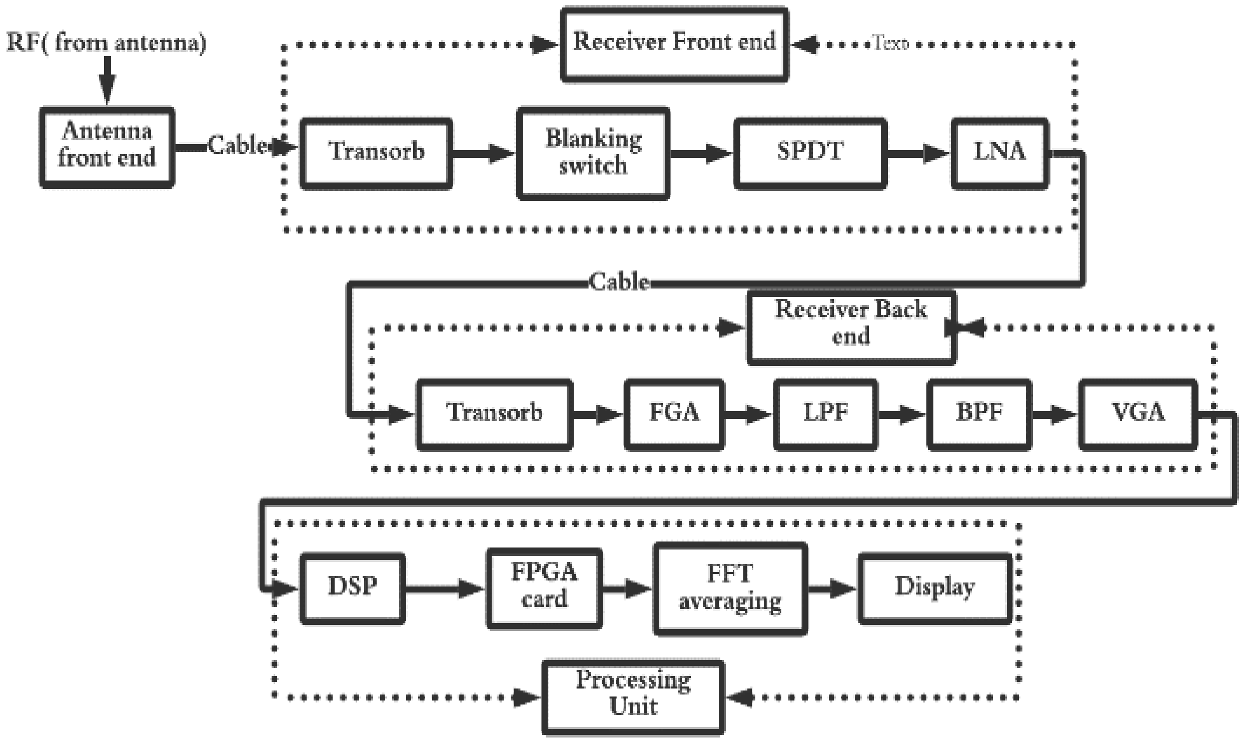


Fig.1 Block diagram of HF radar receiver section

The HF radar receiver section consist of a receiver antenna which is a magnetic loop antenna which operates on 5MHz frequency and the receiver section which has front end and back end circuit of radar receiver section. In which its front end contains- Transorb, SPST, SPDT, LNA, and back end contains- LNA, LPF, FGA, BPF, VGA and also has processing unit which deals with operation like DSP, FFT, use of FPGA card for signal processing etc. as shown in block diagram above.

The antenna front-end of receiver contains matching circuit and basic amplifier for signal strengthening for the processing of signal received. The receiver front-end has a transorb or we can say protection diode, after which the transorb is connected to blanking switch (SPST) and it is followed by SPDT switch. Then the signal is amplified through low noise amplifier.

The signal which is amplified by LNA is sent through cable to receiver section back-end, the back-end consist of various components like transorb, fixed gain amplifier, low pass filter, band pass filter and also variable gain amplifier. The signal is then provided to signal processing unit which basically contain ADC, DSP block, FFT averaging and also FPGA card with a display to show output which is already present so not included in design.

A. Calculation of received signal-

To determine the received signal, we consider signal to noise ratio equation and then evaluate the equation by substituting different range values to get signal level at minimum and maximum range of HFR.

Signal-to-Noise Ratio Dependence on Radar and Environmental Parameters and Definitions

$$S/N = \frac{P_t\, G_t\, L_c\, D_r\, F^4\, \sigma_o\, \Delta A\, \lambda^2\, \tau_i}{(4\pi)^3\, R^4\, kT\, F_a} \qquad (3)$$

Where, S/N -Signal-to-Noise ratio, Pt -Transmitter output power, Gt -Transmit antenna power-gain, Lc -Cable losses, Dr -Receive antenna directive gain, F -One-way attenuation factor, σo -Normalized radar cross section of first-order Bragg scatter, ΔA -Area inside radar cell, λ– Radar wavelength, τi - Integration time, kT - Internal receiver front-end noise, Fa -Factor by which external noise at HF exceeds internal noise.

For Calculation of only signal, remove the noise part from above equation (kT Fa), $\Delta A = R\, \Delta R\, \Delta\Theta$ and substituting for different values of R, we get signal level as.

Table.1- Range vs Signal

R(Km)	5	20	100	150	200
S(dBm)	-91.8	-109.95	-130.92	-136.2	-140.1

Table shows above given various values of signal level corresponding to the range of radar i.e. with respect to range what are signal levels obtained are represented. Formula and values are taken from [5][6].

B. Noise figure calculation-

$$N = KT_0 B \tag{4}$$

Where,

K = Boltzmann's constant = 1.38×10^{-23}

T_0 = room temperature= 290°K (17°C)

B = bandwidth = 100 KHz (≈1MHz)

Above given formula for noise figure is general formula for calculation. Now consider noise floor which can be expressed as, Noise Floor-

$$NF = (F_a + 10 \log_{10} B - 174) \text{ dBm} \tag{5}$$

Where,

$F_a = 52 - 23 \log_{10} F(\text{MHz}) = 35.923$ (≈36.1)

Table.2- BW vs Noise floor

BW(KHZ)	50	400	500	1M
Noise Floor(dBm)	-91.09	-82.06	-81.09	-78.08

C. ADC calculation -

Let us consider 16-bit ADC operate at max 1.5V, If last 5-bits of ADC gets lost due to noise (i.e. 2^5)

So,

For 16-bits we have $2^{16} = 65{,}536$

Now for each bit we get,

$$\frac{1.5V}{65{,}536} = \frac{1500 \text{ mV}}{65{,}536} = 0.0228 \text{ mV}$$

And for noise contain bits $2^5 = 32$

Therefore, now $32 \times 0.0228 = \underline{0.7324 \text{ mV}}$

If we convert voltage to power level or signal level then, we get 0.71 mV corresponding to -50 dB

So received signal should be amplified to get us output of signal level increased. In our case we must have gain more than 90 dB (Including all losses). So that we can get output level below -50 dB. Which will give us faithful output after ADC.

In the table below max gain represent the amount of maximum gain which system can (radar receiver system including front end and back end) provide so that our output signal level should not exceed specified power level.

In our system max output level, we can obtain at the end of receiver system is limited to +16 dB as its voltage level corresponds to 1.41 V.

i.e. + 16 dB → 1.41 V

as ADC can maximum have output till 1.5 V

And minimum gain in receiver is to represent that output level should not fall down below – 50 dB after processing, so as to have faithful reception of signal.

Table.3- BW vs Max. gain

BW(KHZ)	50	100	400	500	1M
Max. gain(dBm)	101	98	92	91	88

D. HFR design, analysis and simulation –

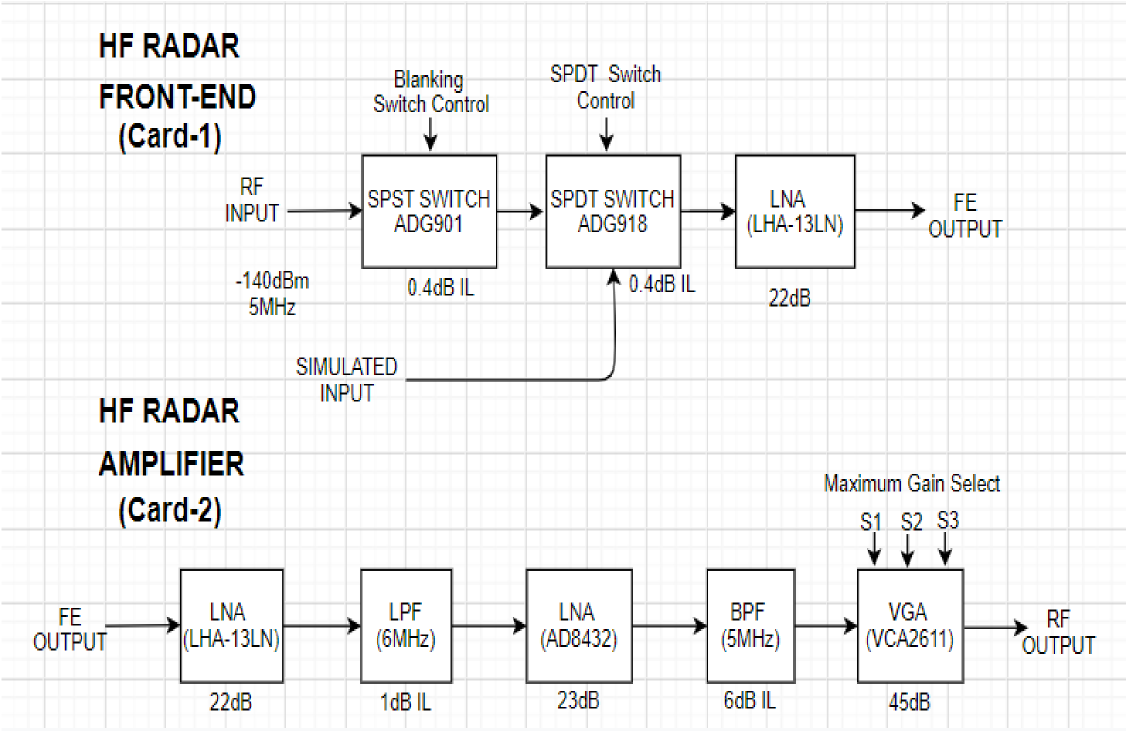


Fig.2 Block diagram of HF radar receiver section card-1&2

The HF Receiver RF receiver Contains LNA, Band Pass Filter (BPF), Gain Block, Low pass Filter (LPF), Band Pass Filter (BPF), Variable Gain Amplifier (VGA) and signal will be passed to post processing unit via Analog to Digital Converter (ADC). HF Radar Front-end (Card-1):

Table.4- HF card-1 components

Sr. No.	Front-end (Card-1) Stage	COMPONENT
1	SPST Switch	ADG901
2	SPDT Switch	ADG918
3	Optocoupler	HCPL2631
4	Bi-Directional Voltage-Level-Translator	TXS0102
5	LNA	LHA-13LN+

The ADG901 is wideband switches that use a complementary metal-oxide semiconductor (CMOS) process to provide high isolation and low insertion loss to 1 GHz. The ADG918 is wideband switch using a CMOS process to provide high isolation and low insertion loss to 1 GHz, the above SPST switch this SPDT switch consist of wide range of application provided with a low insertion loss which is more than sufficient for receiver, as receiver needs to be sensitive for weak signal to be observed.

In the receiver system we use optocoupler for providing use as line receiver and also the control signals for switches and to carry forward the received signal from switches to translator and to LNA, The HCPL-2631is a dual-channel optocouplers consist of a 850 nm AlGaAS LED, optically coupled to a very high speed integrated photodetector logic gate with a strobable output.

The TXS0102 is two-bit non-inverting translator is a bidirectional voltage-level translator and can be used to establish digital switching compatibility between mixed-voltage systems), it serves the purpose of I2C / SMBus /UART for receiver communications purpose.

LHA-13LN+ is an advanced wideband amplifier that offers extremely high dynamic range over a broad frequency range and with low noise figure. This kind of LNA is suitable for initial amplification purpose as it provides with high gain with a low noise figure which is important factor while designing a receiver section.

HF Radar Amplifier (Card-2):

Table.5- HF card-2 components

Sr. No.	HF Amplifier (Card-2) Stage	COMPONENT
1	LNA1	LHA-13LN+
2	LPF	LPF (6MHz)
3	LNA2	AD8432
4	BPF	BPF(4.5-5.5MHz)
5	VGA	VCA2611
6	Op-Amplifier	OPA842

As explained LHA-13LN+ is an advanced wideband amplifier that offers extremely high dynamic range over a broad frequency range and with low noise figure. This kind of LNA is suitable for initial amplification purpose as it provides with high gain with a low noise figure which is important factor while designing a receiver section.

The AD8432 is a dual-channel, low power, ultralow noise amplifier with selectable gain and active impedance matching. The VCA2611 is a variable gain amplifier which has variable gain of 0 to 45 dB which can be controlled through select pin of the same, and has a high bandwidth of upto 80 MHz and require very low control voltage signal of 0.2 to 3V. Both the filters LPF and BPF are butterworth type and are designed in SAMEER. The OPA842 provides a level of speed and dynamic range previously unattainable in a monolithic op amp, In this receiver we use this opamp as a buffer before post processing of the signal, basically buffer for ADC

Simulation of HF Radar (Card-1+card-2)-

The simulation is carried out in SystemVue software

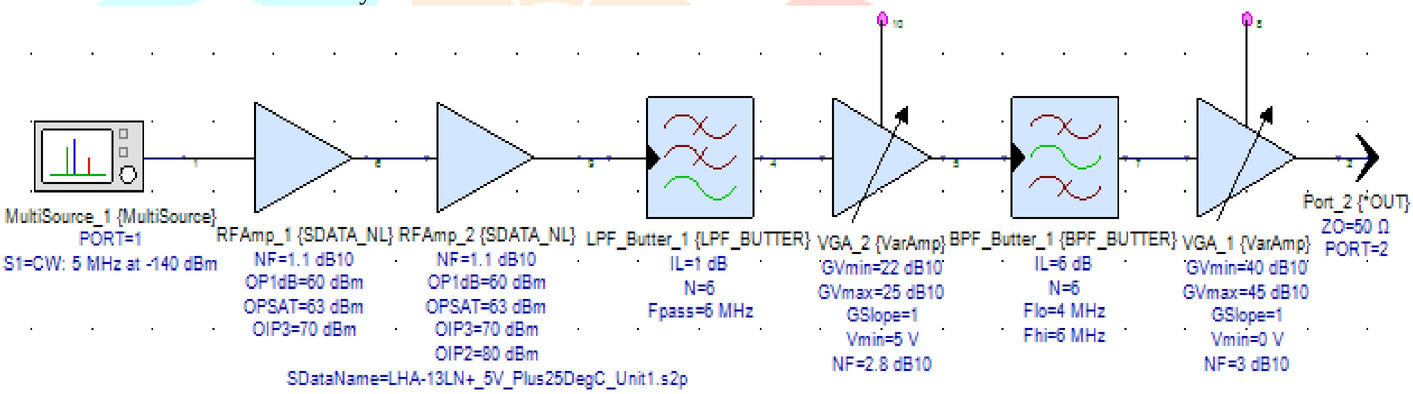


Figure 3 – Total receiver system simulation

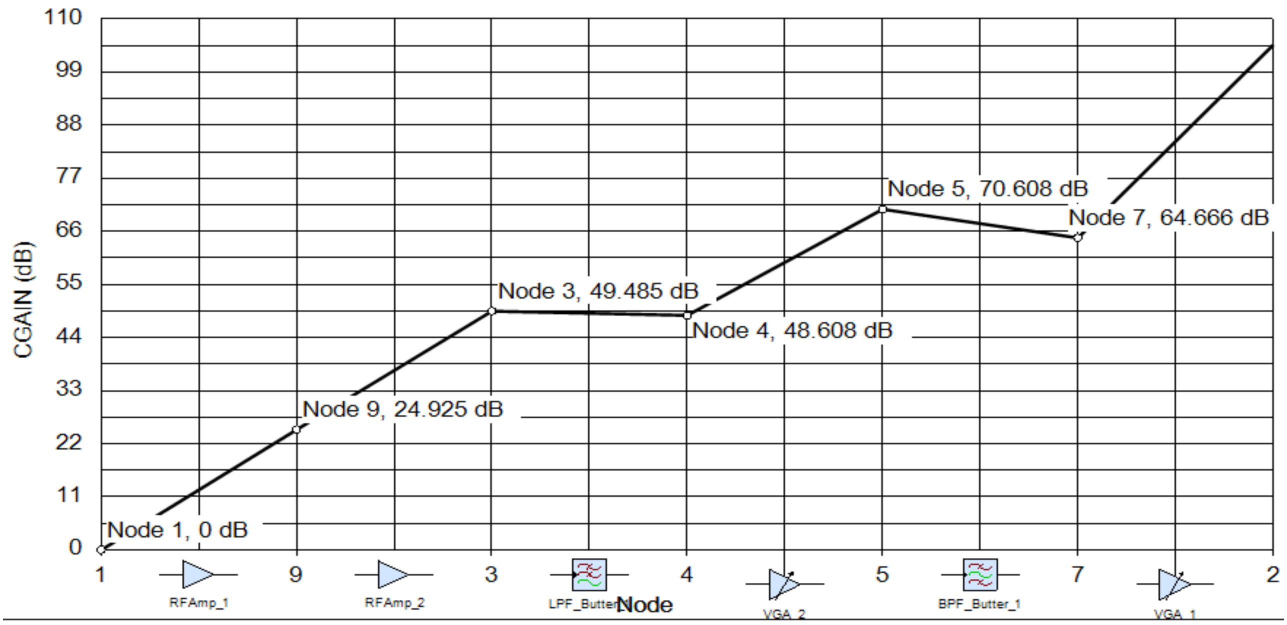
In this simulation we consider a low noise amplifier along with front end receiver section components containing protection diodes, SPST and SPDT switches and control circuits. And in amplifier filter unit we have low pass filter and a band pass filter with low noise amplifier/ fixed gain amplifier and also a variable gain amplifier to adjust the last stage. The components which are placed in simulation are included with their respective s-parameter file taken from their components data sheet to exert actual values of components and their results are as follows.

IV. RESULT

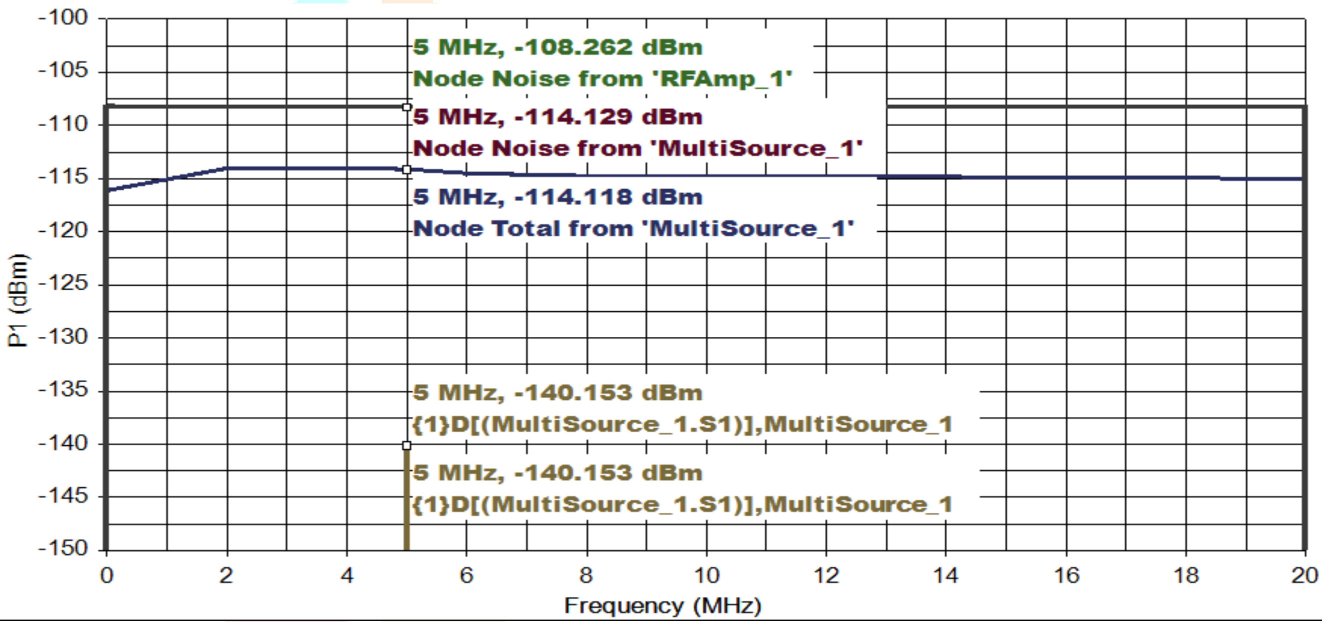
The simulation result of total block chain of receiver system is as shown below,

Figure 6 – Total receiver system result table

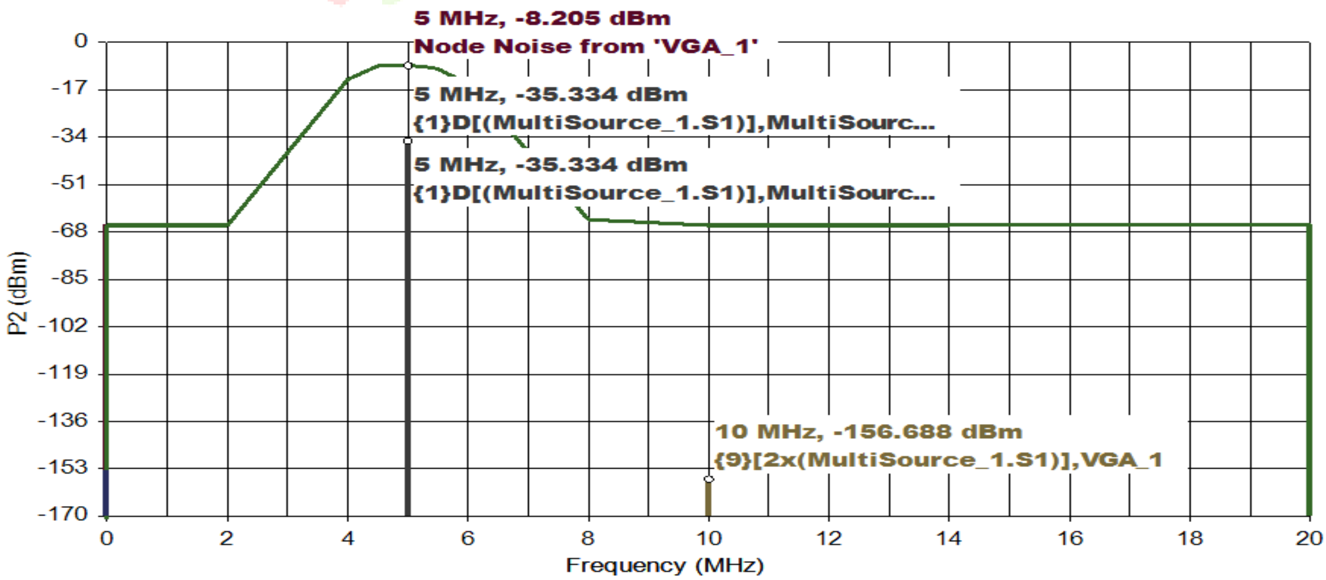
Index	Parts	CF(MHz)	DCP(dBm)	CNP(dBm)	Gain(dB10)	Cgain(dB10)	CNDR(dB10)	CNF(dB10)	SDR(dB10)
1	MutliS..	5	-140	-113.9	0	0	-26.02	0	201.9
2	RFAmp1	5	-115.74	-88.6	24	24.2	-27.02	1.032	136.3
3	RFAmp2	5	-90.8	-63.7	24	49.1	-27.04	1.025	115.7
4	LPF	5	-90.8	-63.7	0	49.1	-27.04	1.025	155.7
5	FGA	5	-69.4	-42.2	21.4	70.6	-27.14	1.12	48.8
6	BPF	5	-69.4	-42.2	0	70.6	-27.13	1.118	141.4
7	VGA	5	-29.4	-2.2	40	110.5	-27.13	1.118	61.3



Graph.1-Cascaded gain graph (gain at each node)



Graph.2-Spectrum graph at port 1



Graph.3-Spectrum graph at port 2

The figure 6 gives detailed report of all individual components and total chain of receiver, in which the table shows the individual gain of each component and cascaded gain of total receiver, also it gives proper detailed representation of each component noise figure and cascaded noise figure of receive too, with noise power at every stage along with cascaded noise power, that is the table represents DCP- desired channel power, CNP-channel noise power, Gain- straight gain, Cgain-cascaded gain, CNDR-carrier to noise and distortion ratio, CNF-cascaded noise figure, SDR- stage dynamic range. The graph 1 gives actual graphical representation of cascaded gain overall receiver system which we simulated with losses of each component and compounded noise figure. The graph 2 and 3 represent the spectrum at port 1 (input port) and at port 2 (output port), in which the total spectrum comprises of all individual pieces of spectrum through nodes, the spectrum like signals, intermods, harmonics, thermal noise, phase noise etc. In the graphs above we show signal, node noise and signal levels, where as in graph 3 we have a harmonic at 10MHz which is due to VGA.

The link budget analysis shows that the decided RF receiver architecture will result in a cascaded gain of almost 110 dB and cascaded noise figure of 1.118 dB. Therefore, for input signal with strength -140 dBm, the signal will get amplified to level of -29.4 dBm.

V. CONCLUSION

This paper introduces a design of High-frequency radar receiver system specifically for 5 MHz operating frequency (which has long range of 200 Km). In which the system is designed through calculation of minimum and maximum signal received, and also calculation of noise figure along with use of various post processing components. The simulation results show that radar receiver system can achieve gain of 110 dB with very less noise figure of whole system. The scheme is based on HF coastal radar (Seasonde radar), making it flexibility and convenient for parameters configuration (like gain control according to varying signal level), suitable for different situations and easy to implement on variety of digital radar receivers operating at different frequencies and parameters.

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