# A novel method for mitigation of false echo in radar-based positioning system in high scattering zone application areas

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**Abstract:** Conventional radar systems are rugged but prone to false echoes from various surrounding metallic structures which are always present in the industrial site. This paper presents a methodology for false echo mitigation in radar-based positioning system which is suitable for industrial conditions, specifically at steel plants. It can be used in various positioning requirements of rail-borne vehicles like overhead cranes and coke oven machines. In this method, the round-trip time of flight (RTOF) technique is used to measure the distance between two nodes. The echo signal is a frequency shifted active return, for eliminating false echoes, thus enabling distance measurement with very high degree of precision and accuracy even in a scattering environment. This method eliminates the problem of false echoes which is present with conventional radar systems. Using this method, the distance between the stations can be accurately determined over a range of 500 metres with precision in millimetres.

**Keywords:** round-trip time of flight; RTOF; radar; laser; false echo; positioning.

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## 1 Introduction

Accuracy and precision are crucial assets of good measurement techniques. The same applies to the measurement of distance, where contact measurement practices have always carried negligible error. However, with advances in technology and new demands in growing industries, efforts and implementation of next generation of distance measurement and positioning techniques are conceivable using non-contact methods. Distance measurement and positioning in the industrial arena provides a new dimension for the advancement of the relevant technologies. Global positioning system (GPS) is one such example in this realm, which uses a constellation of satellites to determine an object's position on the earth (Roehr et al., 2007a).

Over the last few decades, wireless technology is the biggest contribution given to the mankind. This technology has conquered the heights and limits beyond our sight. Each region of this technology plays an important part in our lives, and in the business. While measuring distances without any mesh of wires or cables can be extremely useful in many applications, but it does have its own challenges (Liu et al., 2007). Gaining the equivalent accuracy and precision as that of the contact methods of distance measurement is the utmost task in this wireless domain (Urruela et al., 2006). Once achieved, this precision and accuracy will continue even when the object is moving.

The wireless measurement can be carried through the transmission of waves. Waves are of two types longitudinal and transverse (Tse and Viswanath, 2005). The former is the example of sound/mechanical waves. Although these waves are highly energetic and can be transmitted over distances, their measurement suffers from temperature and pressure deviations (Vossiek et al., 2003). The latter includes the electromagnetic waves, further classified as visible and the non-visible range. Electromagnetic radiations are transverse waves and travel at the speed of light. The visible spectrum includes the LASER devices. Measurements done by LASER are very precise but they suffer enormously in the dusty environment (Slutej and Koloni'c, 2009). Also, LASER measurements are error-prone when the alignment is not proper.

On the other hand, the non-visible spectrum of electromagnetic waves consists of the microwaves, whose frequency ranges from several megahertz to few gigahertz. These waves are used in the RADAR systems to detect and measure the distance of various objects. Primarily, the distance is measured by using time of flight (TOF) principle (Vossiek et al., 2007). This method tends to have some drawbacks/challenges like clock synchronisation. Even a nanosecond offset in the clocks can generate an error of several metres in the measured distance. To overcome this, proposed invention uses round-trip time of flight (RTOF) method where measurement is carried out using the single clock. RTOF measurement using passive reflectors in presence of other scattering objects suffers additional delay due to multipath propagation. This affects the measurement statistics greatly and needs to be rejected. Hence, a novel measuring instrument with active return with frequency shift has been developed which measures distance with very high precision and accuracy using RTOF.

LASER systems are widely used in positioning systems which are precise but they suffer enormous inaccuracy in a dusty environment and erroneous alignment. On the other hand, passive RADAR-based positioning system works well in dusty environments and performance not get altered much in erroneous alignment conditions. Conventional RADAR systems are rugged but prone to false echoes from various surrounding metallic structures, usually present at the industrial site. This affects the measurement statistics greatly and limits the range to few 100 metres. Passive RADAR system suffers from multipath propagation from various surrounding metallic structures which are usually present at the industrial site. This affects the measurement quality greatly and needs to be improved. The proposed technique uses active return with frequency shift to measure distance with very high degree of precision and accuracy. The system uses two active trans-receiving stations at either ends and the distance between them can be accurately determined within few millimetres over a range of 500 metres.

## 2 Theory of operation

There are mainly three types of measurement principles being used these days: angle of arrival (AOA), received signal strength (RSS) and systems based on the time of propagation of signal which can be further sub-divided into the following parts: time of arrival (TOA), RTOF and time difference of arrival (TDOA).We use the concept of RTOF, where the propagation time of the signal from the transmitter along with the time taken for the echoed signal to reach to the transmitter station is measured for getting the information regarding the local positioning in the industrial environment (Zhang et al., 2006; Patra, 2016).

**Figure 1** Radar transceiver with return signal reflected by the object (passive radar) (see online version for colours)

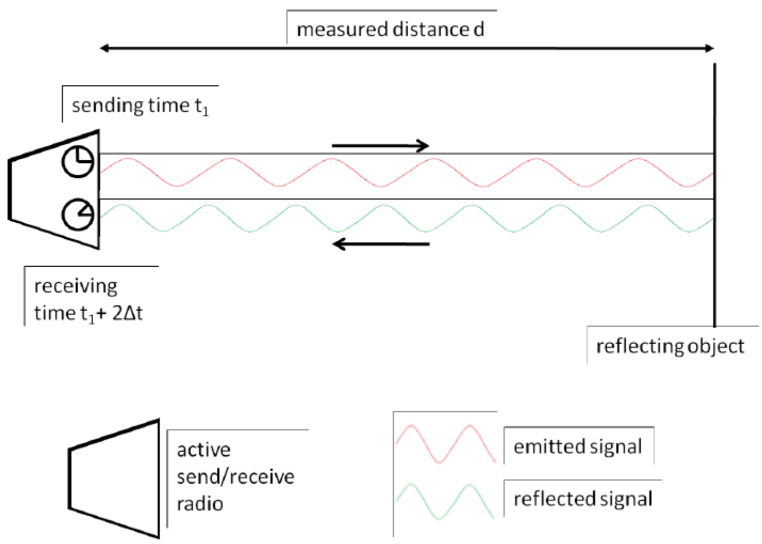
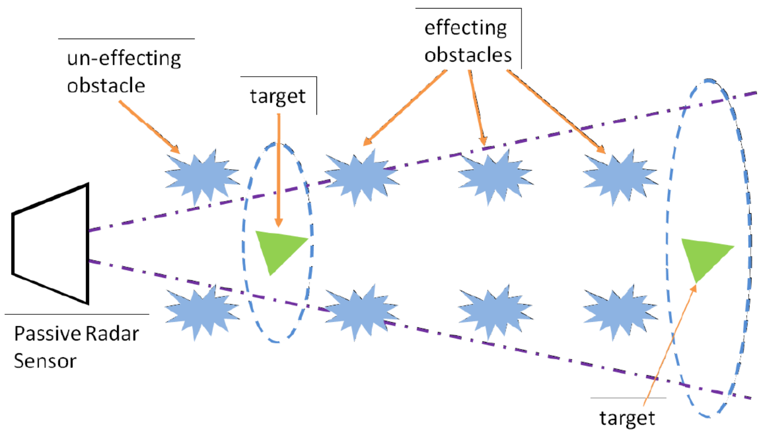



**Figure 2** Effect of signal opening angle with passive radar (see online version for colours)

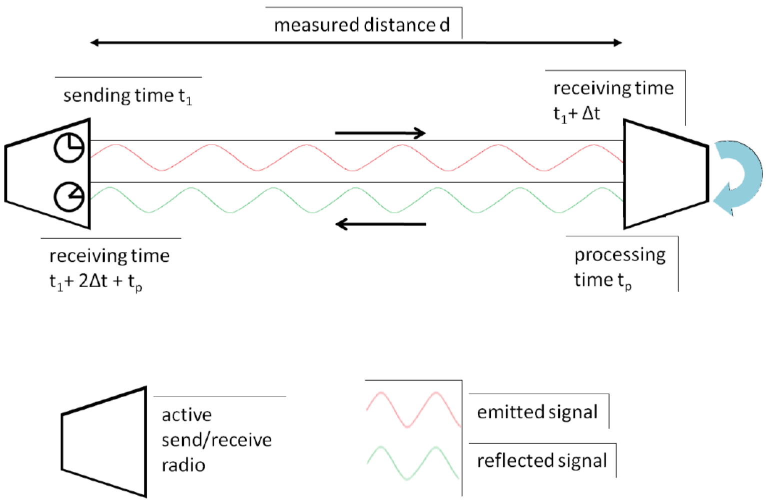


Passive radar technology, as shown in Figure 1, uses signal reflection from a remote object (suspected target) based on RTOF method (Kossel et al., 2000). The emitted radar signal can be sent out from a 360 antenna in all directions or, highly focussed, in one direction. For accurate distance measurement, it is mandatory to have a focussed beam pointing at the target. The beam opening angle is typically in the range of 2 to 5. A smaller opening angle can only be achieved with very large antennas, not suitable for the given size of distance measurement units in industrial use of radar technology. Figure 1 depicts the phenomenon of passive radars.

The passive mode of radar operation is well-suited for aerial or marine navigation systems since they use massive antennas with much higher signal power along with dedicated frequency bands, making the system robust for detecting large distant objects like aeroplanes or ships. However, this method does not work well in the industries where there are multiple metallic scattering objects nearby. These possess challenges in measurement like

- Target identification: it refers to the selective echo, only from the intended source (target), to identify target (Smith and Goggans, 1993).
- Multiple echoes: it refers to the different received signals corresponding to the same transmitted pulse. This may come from various nearby scattering objects in the field of view of the radar antenna.

**Figure 3** Two radar (master/slave) signal emitter cum receiver, return signal encoded by slave (active radar) (see online version for colours)




As depicted in Figure 2, a narrow beam antenna is used to measure the distance from the target. As the distance between the antenna and the target is increases, the beam footprint also gets bigger. This will result in everything within this beam diameter to reflect the signal as a target and is likely to strongly affect the accuracy of the distance measured. A near target is likely to be detected properly, despite other obstacles around. However, a far target will only be 'seen' among a number of other radar reflecting objects and cannot be identified as a single target with a precise distance. To mitigate this problem of passive radar technique, the active radar technique is used which can be readily used in the industrial domain.

Active radar technique, as shown in Figure 3, uses two radar transceivers facing each other, one component acting as a master and the other as a slave. A highly focussed unidirectional signal is transmitted by the master. On receiving this signal, the slave quickly encodes the signal according to some predefined algorithm and then transmits it back to the master (Roehr et al., 2007b). The master is guaranteed to receive this active encoded signal in a very precise time because of the dedicated nature of the system. This makes it highly preferred mode of radar operation in the industrial domain (Stelzer et al., 2004).

**Figure 4** Two radar (master/slave) signal emitter cum receiver, dual frequency operation (enhanced active radar) (see online version for colours)

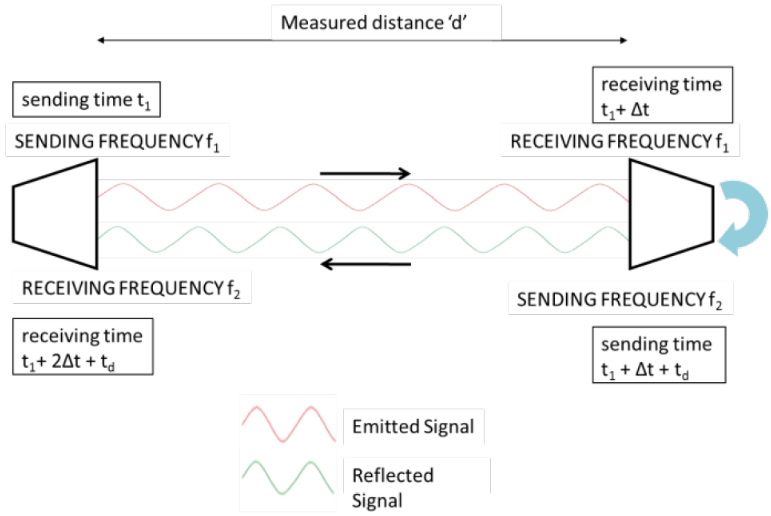
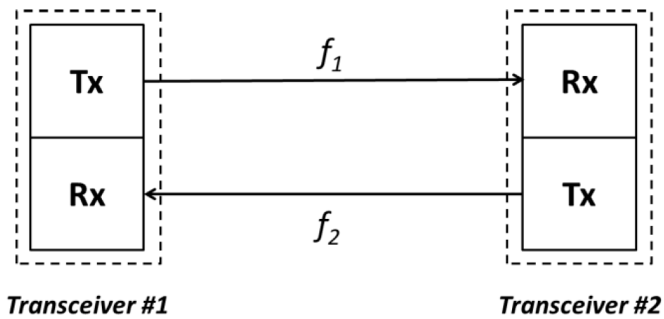



**Figure 5** The frequency link between transceiver #1 and #2




In the active mode of radar operation, the master accepts only the active encoded data sent by the slave, neglecting all echoes generated by any number of obstacles present in the path. This clearly mitigates the obstacle problem mentioned previously. The above technique of active radar is very much suitable for industrial applications; however, this technique induces a considerable degree of error due to encoding techniques, which may arise concern in extremely high precision systems. Hence a further improved technique has been devised which uses two separate frequency bands for master and slave.

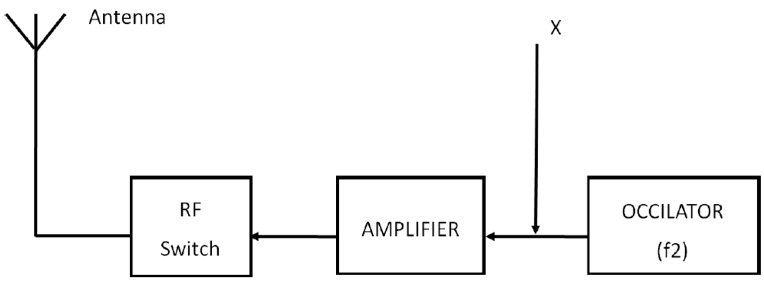
This enhanced active radar technique, shown in Figure 4, uses two separate frequency bands for the master and the slave, and implements band stop filter (BSF) along with relative components to eliminate the need of encoding the signal, thus eliminating its overhead. The master transmits at frequency $f_1$, which is received by the slave, and on receiving this signal the slave transmits at frequency $f_2$, which is further received by the master as a feedback. The enhanced active radar technique is suitable for environments requiring extremely high precision measurement, where the encoding process of conventional active radar technique may induce some degree of effective inaccuracy.

The method uses two active trans-receiving stations of different frequencies of uplink and downlink to measure the distance between two points using return time of flight, as shown in Figure 5. These two trans-receiving stations can be termed as master and slave. They are separated by a distance ($d$) which has to be measured. The signal sent by master at the time ($t_1$) is received by the slave at the time $t_1 + \Delta t$, where $\Delta t$ is the TOF between the stations (propagation delay). The value of $\Delta t$ increases with increase in the distance between the master and slave, i.e., $\Delta t$ is directly proportional to the distance, '$d$'. The Slave provides a delay of time ($t_d$) (processing delay), to the signal in addition to the propagation delay. Hence, the master receives the signal at $t_1 + 2\Delta t + t_d$ time. The return time of flight is calculated by the difference of the reception time ($t_1 + 2\Delta t + t_d$) and the transmission time ($t_1$) at the master. While calculating the RTOF the fixed processing delay from the slave ($t_d$) has been subtracted. Thus the distance between the stations ($d$) is calculated as half the product of the speed of light ($c$) and RTOF. The accurate distance between both the transceivers can be calculated by the formula:

$$RTOF = \frac{2d}{c} = 2\Delta t + t_d. \tag{1}$$

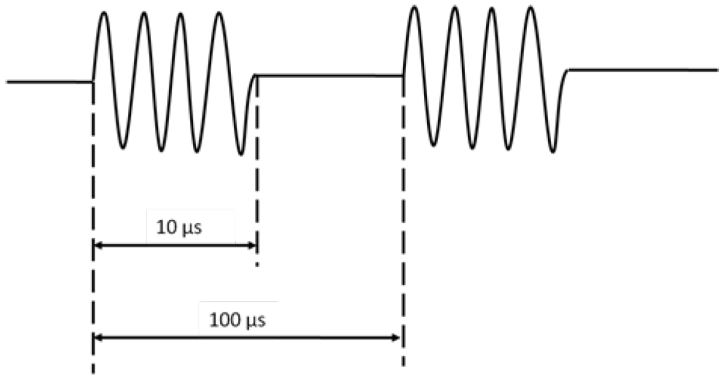
Transmitter section consists of an oscillator tuned to frequency $f_1$, which is then amplified and fed to RF switch. Transmitter section consists of an oscillator tuned to frequency $f_2$, which is then amplified and fed to RF switch. The transmitter is a pulsed RF source (Vossiek and Gulden, 2008) as shown in Figure 6. Power required at antenna input is 10 dBm.

**Figure 6** Transmitter section block diagram



The amplitude shift keying (ASK) modulated pulse requires an ON time of 2 micro sec, with a frequency of 10 kHZ. ASK signal produced should have a power level of 10 dBm when ON, and during OFF, the power level should be < –90 dBm. The pulsed RG signal from transmitter is shown in Figure 7.

**Figure 7** Pulsed RF signal from transmitter




The maximum range at which a target can be located that the leading edge of the received backscatter from that target is received before transmission begins for the next pulse. This range is called maximum unambiguous range or the first range ambiguity. The pulse-repetition frequency (PRF) determines this maximum unambiguous range of given radar before ambiguities start to occur. This range can be determined by using the following equation:

$$R_{\max} = c \times (PRF - \tau)/2 \tag{2}$$

where *PRF* is the pulse repetition frequency, $R_{\max}$ is the maximum range, $\tau$ is transmitting time, $c$ is the speed of light.

Receiver section starts with the signal received from RF switch. The received signal is at a frequency $f_2$. During simulation, the received power, corresponding to the minimum and maximum range have been calculated using Friis transmission, as given in the following equation:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \tag{3}$$

where $P_r$ is received power, $P_t$ is transmitted power, $G_t$ is gain of transmitting antenna, $G_r$ is gain of receiving antenna, $\lambda$ is wavelength at that frequency, $R$ is distance between transmitter and receiver.

Band stop filter (BSF 1) has been used to avoid the leakage signal from the RF switch from entering the amplifier. BSF is having a very high insertion loss of –50 dB in the stop band. Low noise amplifier (LNA) has been selected with a very low noise figure and to provide sufficient amplification. The second stage of BSF has been implemented after the amplifier (BSF 2). Following this, a digital step attenuator (DSA) is used to provide attenuation for implementing automatic gain control. After DSA, the second stage of amplification is required, followed by a BPF at $f_2$ frequency. Signal should then pass on to a limiter before feeding it into the envelope detector. The overall receiving section block diagram is shown in Figure 8.

**Figure 8** Receiving section block diagram

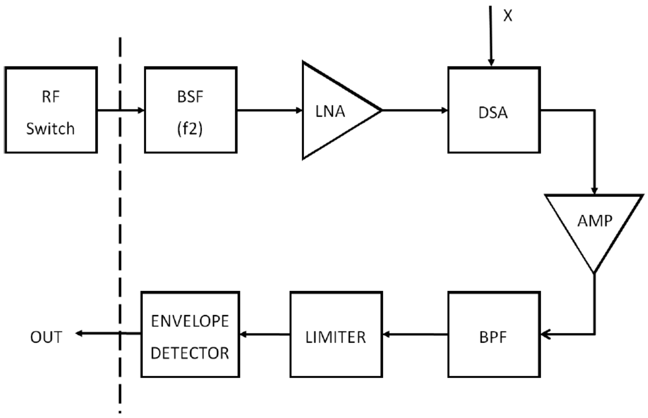



**Figure 9** Block diagram showing frequency propagation for transceiver 1

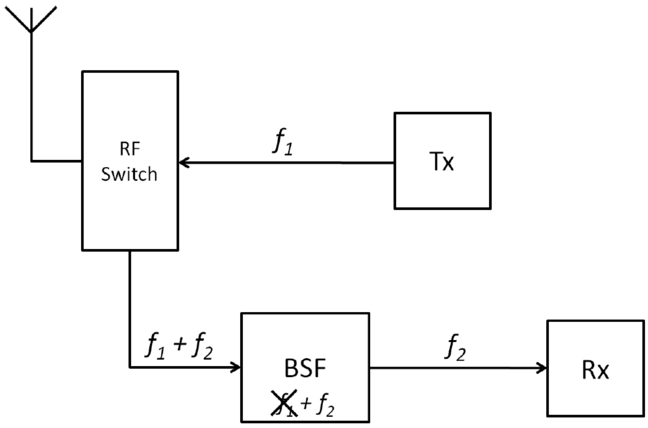
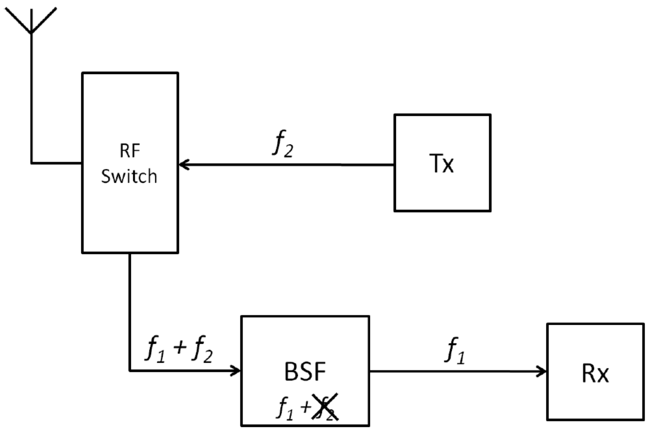



**Figure 10** Block diagram showing frequency propagation for transceiver 2



The station uses a pulsed clock source to start transmission. The ON time of the clock denotes transmission time whereas the off time corresponds to reception time. The same clock source is used to generate a modulated ASK signal from the oscillator operating at a frequency ($f_1$). An RF switch has been used to share the same antenna between the transmitter and the receiver. The echo signal is then received back and amplified using LNA which is fed to the envelope detector for retrieving the clock signal. The output of the envelope detector is converted to digital logic and this received clock signal is fed to the TMC as STOP signal and thus the delay is measured. This delay is directly proportional to the distance between the stations whose distance has to be measured.

A BSF has been used in the receiver section to improve the system performance. It has the dual purpose of filtering out the leakage from the transmitter part through the switch. Also, it rejects the unwanted reflections from the scattering objects in the field of view of the antenna with frequency ($f_1$). Only the return of the slave is considered in the receiver which has a different frequency ($f_2$). The automatic gain control (AGC) unit in the receiver improves the dynamic range of the receiver by taking care of the varying received signal power level for different distances.

**Figure 11** Band stop implementation using lumped elements (see online version for colours)

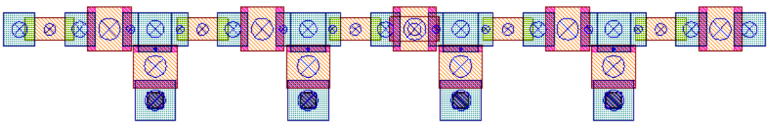
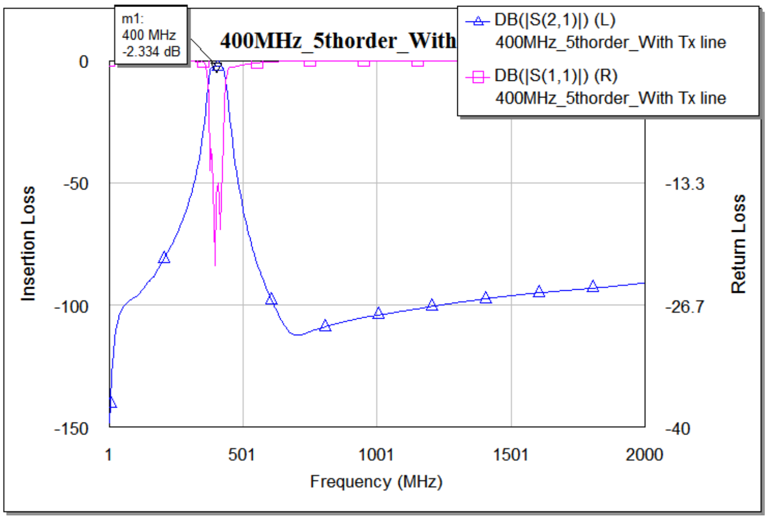


**Figure 12** Circuit simulation response for lumped element band stop filter (see online version for colours)




The input power at the envelope detector is maintained at 5 dBm using link budget calculation, such that the clock sent from the other station can be retrieved at envelope detector output. The primary purpose of the slave station is to echo the signal back to the base station. Additionally, it synchronises and amplifies the received signal from the master station. Initially, the base station is in receiving mode; it receives the signal from the master station and amplifies it using an LNA which is fed to the envelope detector followed by digital logic level conversion for retrieving the clock pulse from the master. The delay circuit provides a known delay ($t_d$) to synchronise the master and slave station. This ensures that the master is in receiving mode when the transmission sequence of slave station starts. The transmission frequency of the slave station is ($f_2$). The slave station similarly uses a BSF in its receiver section to reject unwanted echo from the scatter and the transmitter leakage signal. The overall architecture for the transceiver #1 and transceiver #2 has been shown in Figures 9 and 10.

As Figure 9 depicts, the BSF of transceiver 1 is configured to stop the frequency $f_1$ which itself transmits, allowing it to receive only the frequency $f_2$ which is transmitted by transceiver 2. Similarly, Figure 10 shows the BSF of the transceiver 2 is configured to stop the frequency $f_2$ which itself transmits, allowing it to receive only the frequency $f_1$ which is transmitted by transceiver 1.

**Figure 13** Full-wave simulation model for the micro-strip band stop filter (see online version for colours)

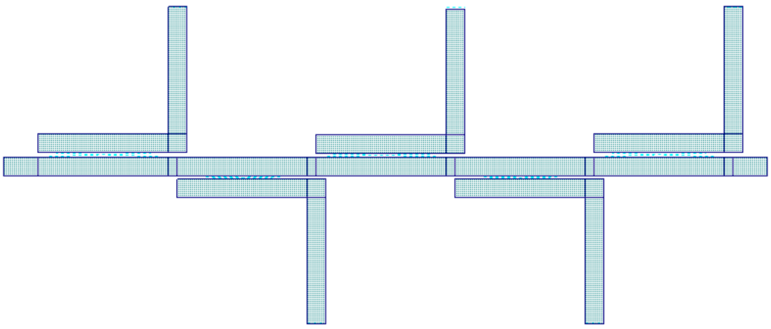
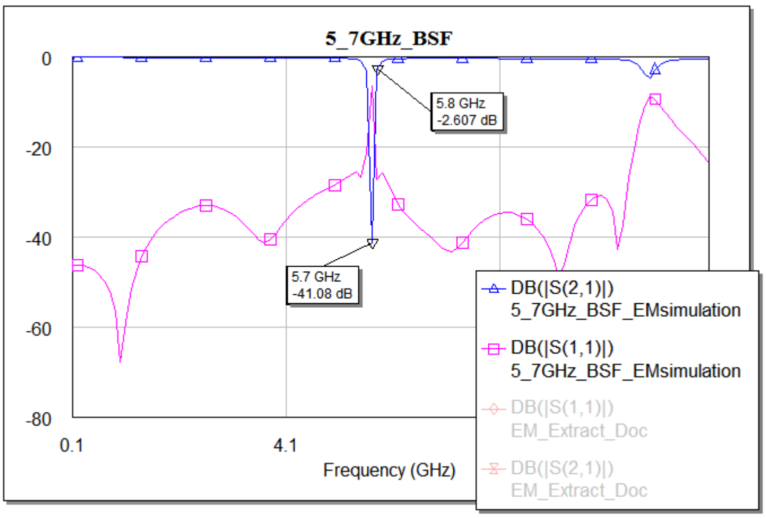


**Figure 14** Full-wave simulation response for micro-strip band stop filter (see online version for colours)



A BSF is a combination of a low pass filter and a high pass filter in a parallel connection. It blocks the signals falling within a small frequency band and passes all frequencies below or above that frequency band. Because of this characteristic, it is also termed as band elimination filter, band reject filter or a notch filter. It has two cut-off frequencies, any frequencies falling between these two cut-off frequencies are attenuated, and rest frequencies are passed. An implementation of a lumped BSF has been shown in the Figure 11.

**Figure 15** Full-wave simulation model for the band-pass filter (see online version for colours)

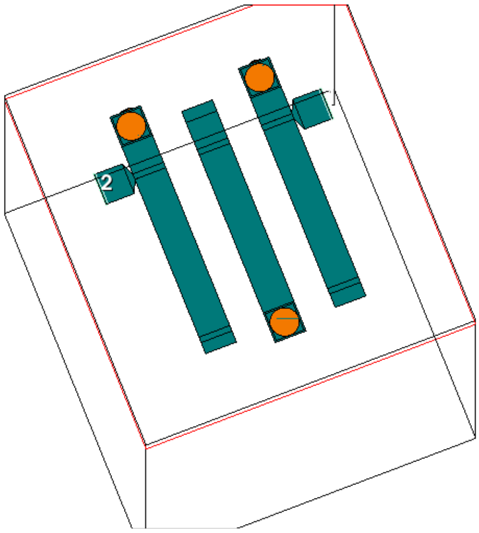
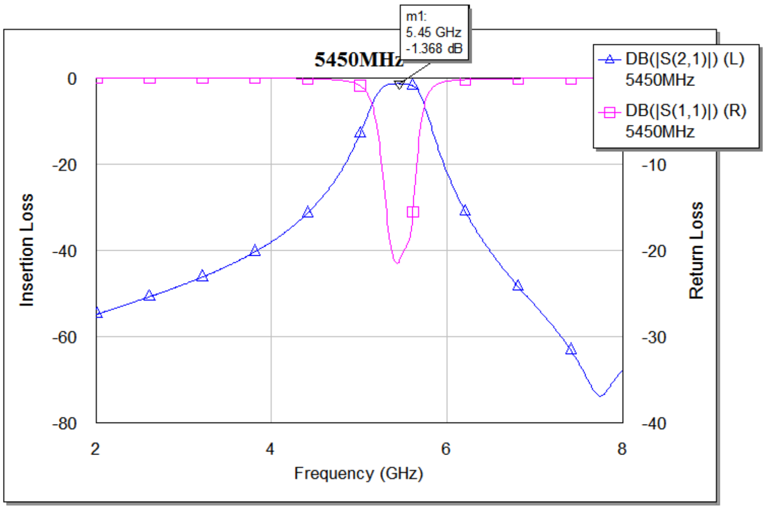



**Figure 16** Full-wave simulated frequency response for the band-pass filter (see online version for colours)



The simulated S-parameters are shown in Figure 12. The stop-band of this lumped element filter is at 400 MHz. However, the lumped element filter works well up to MHz frequencies. For higher frequencies distributed element approach has been used, consisting of micro-strip elements as shown in Figure 13. The simulated results show that the stop band occurs at 5:7GHz. The response is shown in Figure 14. Similarly, a 5,450 MHz (interdigital) band-pass filter has also been simulated and implemented for improving the receiver selectivity, as shown in Figure 15. The simulated results (Figure 16) show low insertion loss of –1.368 dB at pass band, centred at 5,450 MHz.

## 3 Hardware implementation

After successful simulation for the individual components, the design implementation has been done. The positioning system for the plant environment has been made mechanically stable and robust. A single layer, double-sided PCB was designed and simulated with additional features like AGC, temperature compensation circuitry and RS485 communication link built into it. Figures 17 and 18 show the actual photograph of the in-house developed prototype system. The radar module consists of three major blocks: RF module, signal processing unit and power supply. The whole assembly has been encased in a machined aluminium block.

**Figure 17** Final product layout of the digital board with appropriate power conditioning circuitry (see online version for colours)

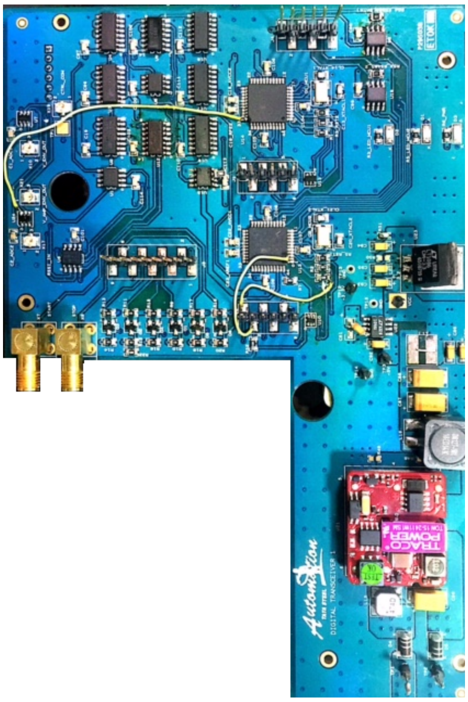
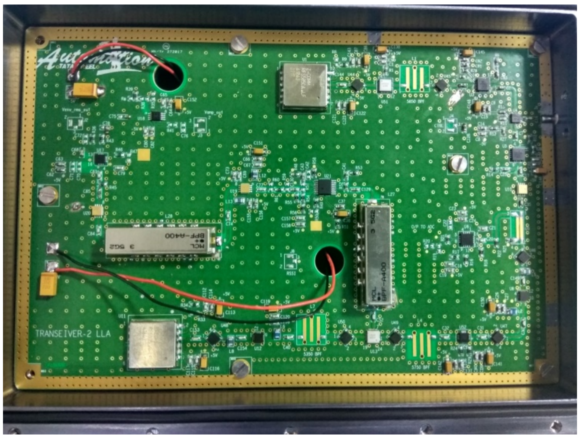


**Figure 18** Final substrate layout design along with the RF components with proper shielding (see online version for colours)



## 4 System performance

Field trials for the radar-based positioning system (Figure 19) at the actual site have been conducted. The distance between a fixed position and a moving object (overhead crane) has been determined by measuring the return time of flight method. The output data obtained was time value which can be easily converted to distance reading. This required a one-time calibration, which was performed with the help of laser distance metre. Also, during each of the readings, it was observed that the measurements followed Gaussian distribution, as shown in Figure 20. Gaussian distribution of the measured data was result of multiple random processes in the measurement link.

**Figure 19** Actual photograph of the radar system (a) transponder station with antenna, and (b) base-station with antenna facing the transponder (see online version for colours)

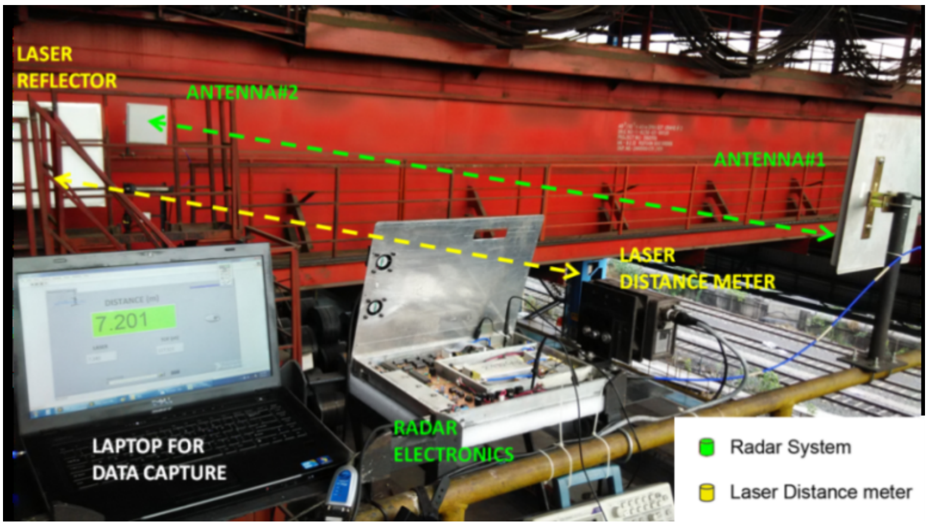
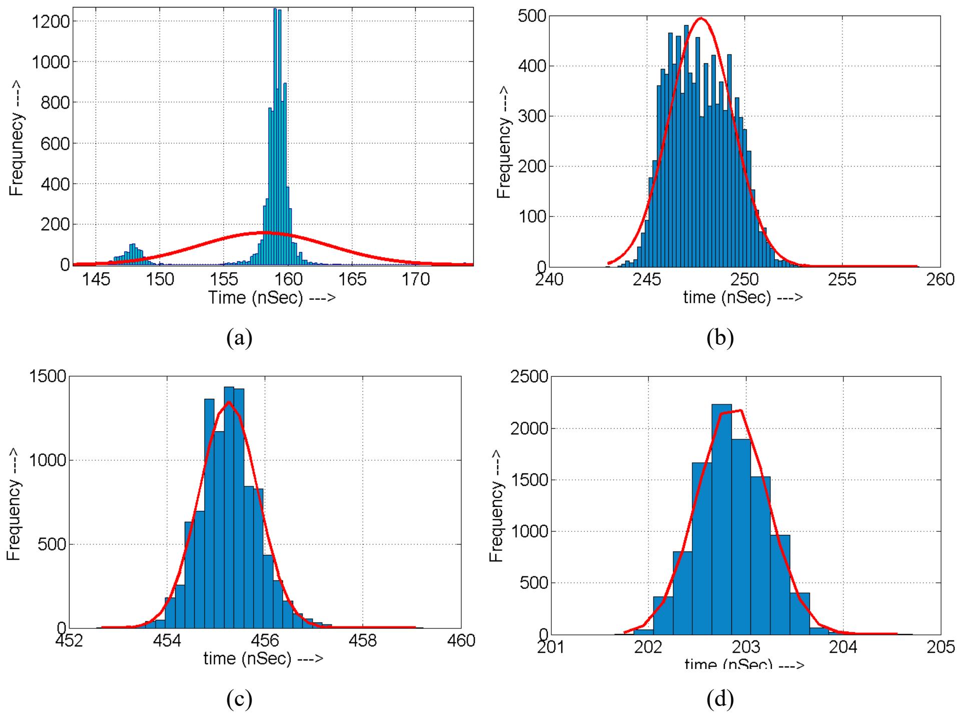


**Figure 20** Measured RTOF before implementation of filters for (a) sample 1, (b) sample 2, and measured RTOF after implementation of filters for (c) sample 1, and (d) sample 2 (see online version for colours)




The results using only active radar and enhanced active radar have been compared. Figures 20(a) and 20(b) show the measurement result with active radar without using the BSFs. It can be seen that the standard deviation for the measurement is quite large as compared to the Figures 20(c) and 20(d), where enhanced active radar with frequency shift was used, thus enabling to measure distance much precisely.

## 5 Conclusions

There are various distance measuring techniques available for positioning requirements, however; only few are suitable for industrial requirements. The system should be robust and should not get affected by the various scattering objects present at industrial site. In this paper a novel method has been discussed which uses active radars with frequency shift over the passive radars in the industrial environment where scattering and false echoes are dominant. It uses an effective radar system for accurate measurement of the distance based upon the return propagation TOF. The system can be used in various rail-borne vehicles within the steel plant and employed in a practical environment for the local positioning measurement. It was observed that the measurement was accurate and efficient. The data was accumulated employing the active radars which not only made the measurements precise but also reduced multipath distortions emerging due to the dusty environment present in the steel industry.

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