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Burden Profile Measurement System for Blast Furnaces Using Phased Array Radar

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Abstract: The operation of the furnace depends largely on the handling of gas distribution which in-turn is reliant on the burden surface profile. The operation of the furnace depends largely on the handling of gas distribution. Charging of materials in the furnace is thus one of the most important control signals. Measurement of burden profile has been a challenge because of the harsh conditions inside the furnace. Phased array radar will suffice this purpose with no moving parts; however, it imposes its own challenges.The system has been designed in such a way that the antenna is decoupled from the electronics which protected against high temperature and dust. This paper implements a method which can provide continuous real time 3-D burden surface profile measurement at blast furnace.

Keywords: Blast Furnace, Profile, RADAR, Burden Distribution, Time Interval

1. Introduction

Blast furnace in steelmaking process is at present the main procedure for processing the iron ore in a steel plant. In more than 100 years of steel making, Blast Furnaces everywhere throughout the world are as yet considered as covert process [1] because of lack of instrumentation due to harsh conditions. Blast Furnace being the mother plant for a coordinated steel plant, any anomality will influence the overall production. Comparing all process variables that impact the furnace operation, burden surface profile is the most significant one to increase productive efficiency and reducing power resource consumption.

Till date, in absence of any continuous reliable measurements for burden distribution profile, there exists a reliance on numerical models and approximations to operate the furnace [2]. Passive Radar technology that makes use of the signal reflection from a remote object is in use for about 100 years. The emitted radar signal can be sent out from a 360° (omnidirectional) antenna in all directions or, highly focused, in one direction. For accurate distance measurement, it is mandatory to have a focused beam pointing at the target. The beam opening angle is typically in the range of 2 ... 5°. A smaller opening angle can only be achieved with very large antennas, not suitable to for the given size of distance measurement units in industrial process automation.

Obtaining a surface profile for blast furnace at an elevated accuracy, resolution and high data throughput is always a demanding task in the research field of metrology. Many non-contact methods have been proposed for surface profile measurement prior to this [3]. Various measuring principles are employed by these systems; including vision-based methods, interferometry, as well as time-of-flight. Among these measurement principles, time-of-flight is the most promising technology for burden profile measurement, as it offers extended measurement range with centimetre accuracy which is adequate for characterization of the burden surface dimensions. The laser and microwave are two other forms of electromagnetic waves that are commonly used for time-of- flight measurement, and which differ only by their wavelengths. On comparison, one overwhelming benefit offered by the microwave is its superior particle penetration property in an environment of high dust intensity, especially during blast furnace operation where the material powders are stirred by the up-rising hot blast.

Distances will be determined by measuring the time-of-flight of the radar signal from the emitter to the target and back to the receiver. The signals travel at the speed of light, known as approx. 300.000.000 m/s. For a 100meter stretch, the signal travels about 333 nanoseconds or 0,000000333 s (one way). Accurate and reliable distance measurement in industrial environment beyond a certain range requires that the effect of objects ranging into the radar signal is eliminated.

The application of most measuring technologies has been impeded by the unforgiving conditions in blast furnaces. To accomplish accurate estimations, a few strategies have been endeavoured in the previous decades.

A method for high precision local positioning radar using an Ultra-Wide Band concept has been demonstrated [4].The concept is based on standard Frequency modulated continuous wave radar principle combined with short pulses to fulfil the emission limits as per regulatory requirements. High accuracy in dense multipath environments is claimed using this concept for 1D, 2D and 3D localization. Frequency of operation used for demonstration is 7.5 GHz, with a bandwidth of 1 GHz (satisfying the FCC criterion for being termed UWB). Common FMCW approach was thus combined with UWB techniques to make use of advantages of both ideas.

Distance measurement is using RTOF measurement after high synchronization. FMCW concept is utilized for system design, and a working model is demonstrated. Precise distance and velocity measurements in multipath environments using an FMCW approach were studied by [5]. Multipath and Doppler phenomenon are two basic phenomena to be considered during radar-based measurements. This work explains in detail how to cope up with multipath and Doppler effects in an FMCW environment. Broadband measurement principle is used to reduce multipath effects and Doppler frequency shifts are evaluated to provide relative velocity measurements. The essential part of any FMCW radar based positioning system is the clock synchronization part. This portion usually limits the accuracy of the measurement. An FMCW concept is utilized which determines offset in frequency and time of two wireless units and hence obtain their relative distance in between. This method is robust towards multipath interference. A novel method for high precision clock synchronization for wireless systems and radio navigation is discussed in [6]. It discusses a novel approach for clock synchronization in FMCW principle-based systems. Accuracy obtained was of the order of 4-5 cms for a range of 200m, using an obtained clock synchronization of < 100ps and frequency synchronization of < 1ppb. Novelty of the study was that this accuracy was realized using a bandwidth of only 150 MHz. The concept can be extended to other frequency bands and is well suited for integration into other modulation principle systems. This principle being used can be easily extended to other frequency bands and better synchronization can be achieved with a larger bandwidth. A prototype system is also demonstrated for a 5.8 GHz ISM band system. Switched Injection Locked Oscillator was proposed as a novel and versatile concept for wireless positioning and localization concepts [7]. Application of the theory is discussed in terms of secondary radar systems. System can also be integrated along with Synthetic Aperture Radar (SAR) concept, for better accuracy and versatility. A switched injection locked oscillator transponder can produce an approximately phase coherent high power response to an interrogating signal and consequently allows for long range transponder systems and precise distance measurement between two units.

accuracy discussed. The utilized time domain measurements suppress multipath signals and can provide accuracies up to sub mm range. It can also be extended to 2D and 3D also.

Method

With a typical blast furnace geometry as shown in figure 1, using the concepts of radar, pulses are transmitted from the antenna, and they travel at the speed of light. Accuracy in distance measurement is directly correlated to time difference measurement accuracy in time domain.

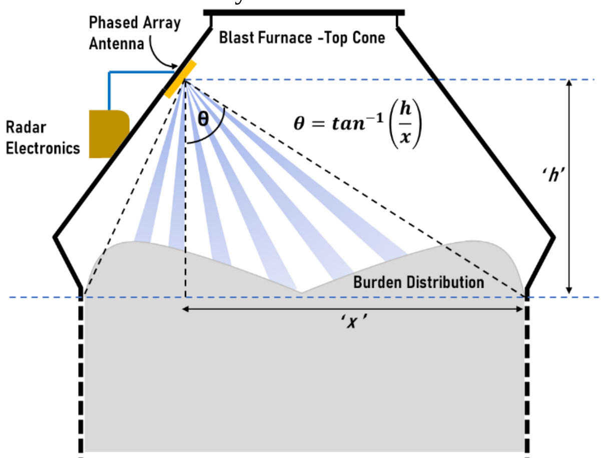

Figure 1 Blast furnace geometry

Typically, in the blast furnace scenario the maximum height for measurement 'h' is equal to the 5 meters from stockline. A meter distance corresponds to return time of flight of 6.67 nano seconds. Hence for measuring 5 meters the maximum time interval to be measured is 33.35 nanoseconds. A one nanosecond pulse extends in space for 30 cms. So, for accuracies desired in industrial measurements (of the order of mms/cms), the time interval measurement should also be very precise. Time interval measurement is the measurement of elapsed time between some designated Start and Stop phenomenon. In case of pulsed radar these signals are the transmitted pulse and the received echo. The signal of the emitting unit is received at the receiver. Any distance determination requires the exact measurement of the travel time of the signal.

Out of the methods mentioned in this paper, the TDC chips has been used which could beusedtomeasuretheshorttimeintervalsweexpectintheradarlevelmeasurement instrument. ACAMMes selectronic has been researching time interval measurement in the picoseconds range and the chips available to them is shown in table 1

Model	Resolution	Range
TDC-GP1	125ps	2ns-7.6μs
TDC-GP2	50p	3.5ns-1.8μs
TDC-F1	70p	0ns-3.9μs
TDC-GPX	81ps(I-mode)	Endless
	41ps(G-mode)	0ns->10μs
	27ps(R-mode)	0ns->10μs
	10ps(M-mode)	0ns->10μs

Table1:Typesoftime-to-digitalconverter chipsavailable

Profile Measurement

4.1 Ultrasonic

Profiling surfaces with high frequency focused ultrasonic pulses in air offers the advantage of being useable in environments where other non-contact methods are undesirable or impractical. The ultrasonic profiling method uses an ultrasonic focused beam with the beam impinging on the sample surface at nominally-perpendicular incidence (**Figure 1**). Time-of-flight allows fine time resolution over significant surface depressions. Surface depression profiles are calculated based on the time-of-flight images. The method relies mainly on knowledge of the velocity of ultrasound through air which remains reasonably constant at all times and locations if temperature is held constant. Additionally, it offers large-area scan capability and large (mm) vertical depth range.

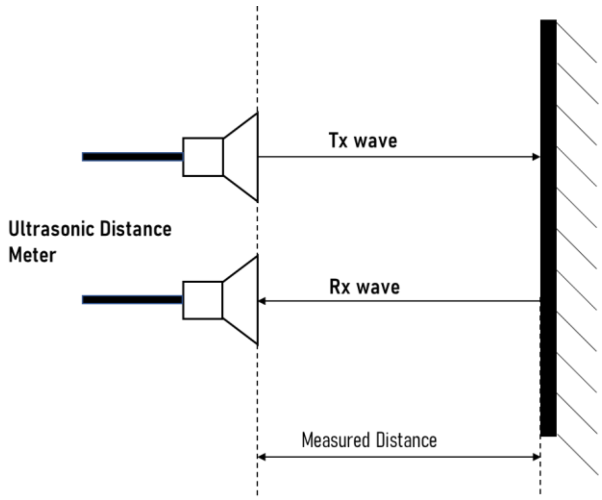

Figure 1 Ultrasonic profiling method

An activated ultrasonic system performs an x, y ultrasonic scan over the sample and obtains ultrasonic reflections from the top profile. As per recommendation, the precise time-of-flight of the front surface echoes is measured either to the intersection of a gate and the leading edge of the echo, or by gating a selected peak of the echo [12]. Gating the leading edge is recommended over gating the peak. Air-coupled ultrasonic surface profilometry is relevant to plate-like and curved surfaces.

This method is downright non-destructive, non-invasive, non-contact and not requires light-reflective surfaces [12,13]. However, the analysis does not account for the error due to electromagnetic interference that superimposes itself upon the signal and its scattering related effects. It is these factors that likely cause the most severe error in this method. When using an ultrasonic scanner, the scan has limited capacity of the X-Y interface, giving only 2D surfaces.

4.2 Laser

Diffraction theory states that any obstacle could be seen by an electromagnetic wave having a wavelength on the same magnitude as the geometric dimension of the obstacle [14]. Spreading a light beam atmospheric component "invisible" for other surrounding waves can be detected. Grounded on this theory, optical remote sensing techniques were urbanized in the last couple of decades [15]. Past few decades have also witnessed countless non-contact approaches, including vision-based methods, interferometry and time-of-flight for surface profile measurement. Amid these measurement principles, time-of-flight has been recognized to be the most promising technology for burden measurement, as it offers a comprehensive measurement range with centimetre accuracy. Microwave and laser are two methodologies of electromagnetic waves that are used for time-of-flight measurement differing only by their wavelengths. Furthermore, technological evolution in opto electronics and semiconductor devices have enabled surface profiling using 3D laser technology at elevated speed and within lower price.

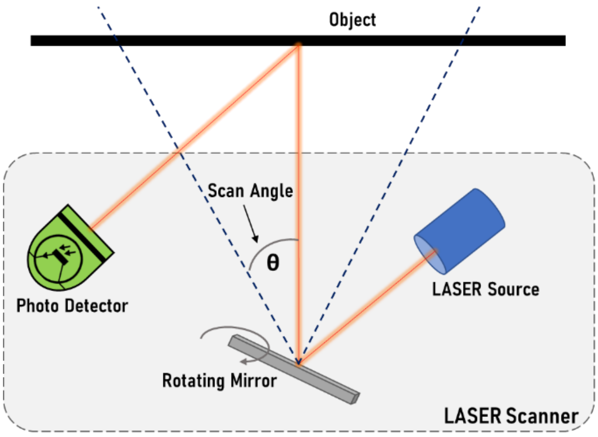

Figure 2 LASER scanner method

A laser head conveying range data with millimetre resolution is driven to scan all over the burden profile by a two-axis motorized servo mechanism. **Figure 2** depicts the working of the LASER scanner. By accumulating individual range data along with encoder positions of the servo mechanism, the 3D surface profile is attained. For visualization of the scanned surface, transformation from spherical coordinate system into Cartesian coordinate system is obligatory. Acquired data is then transmitted to a PC through a TCP/IP port for subsequent handling. As an alternative of continuous measuring, 3D laser technology can be applied at scheduled shut-downs during which the dust concentration inside the furnace is at lower levels. The laser is not always ideal for this set-up since it is best apposite for low or no dust environments. However, it's extremely narrow beam permits for level control in narrow vessels holding solids and can be directed to avoid obstructions interfering with the sensor operations. It can be boom for profile measurements where precise targeting is obligatory. Even for materials that don't flow freely, it can be used for monitoring build up when mounted above the monitoring point or directed toward the sidewall of the furnace. Constructed on the rigid body transformation and the invariant features, 3D image registration algorithm is applied to find out the transformation between the measurement and the blast furnace [16,17]. Subsequently, the data processing method was employed to determine the quadratic curve signifying the surface profiles of the falling materials. Consequently, the trajectories standing for the moving paths of the raw materials are assessed to gain valuable information for preventing blast furnace wall from serious worn-out as well as establishing burden distribution strategies for superior productivity and stability.

The laser spot being much smaller owing to its short wavelength nature, provides for a better measurement resolution. But, one overwhelming benefit offered by the microwave is its superior particle penetration property in dusty environment. Benefits of laser are that its adjustable, swivelling mounting projection is flexible up to 10 degrees [18,19]. The laser has a fast update rate of eight times per. Particle size is a mutual quality control parameter, affecting both the production process and the final properties of a product. Laser diffraction is a valuable tool for particle sizing, from the sub-micron to the millimetre range [20]. High repeatability combined with fast measurement technique that requires low sample amounts makes one of the standard burden profile measurement tools. Laser diffraction is a relative routine which uses the optical behaviour of particles to originate their sizes. The analysis theory assumes that the measured particles are spherical and reports their diameter. Apparently, for non-spherical particles this leads to a deviation from their real sizes. Nevertheless, as the shape-caused error remains consistent, this makes laser a highly reliable quality control tool.

The major drawback is that laser is not endorsed for use in dusty environments. It is problematic of using laser radiation into environments consisting of very high-water vapour level, acidic, high aerosol loading, and high temperature. A major problem in making time of flight range measurements in very high-density aerosol conditions is the signal processing required to extract the target return pulse position from the complex aerosol return signal. The selection of operating laser wavelength and repetition rate are based on an analysis of the optical characteristics of gases and aerosol forming the measurement environment together with the dynamic behaviour of the high temperature target. Although laser probes have high accuracy, their penetration through dust is poor. Thus, they can operate at their full capacity only during low-dust periods during BF operation and provide poor coke guidance during normal production. This limits its application in blast furnace. Additionally, it only measures a single point at any given instance, which could be problematic for materials that don't flow freely or pile unevenly in the burden profile. The falling materials in the burden might temporarily render the readings inaccurate. If mounted in an environment with any dust, it frequently needs an air purge option to retain the lenses free of build up for reliable performance.

4.3 Conventional Radars

The burden distribution topography is reliant on the charging materials such as coke, lump iron, sinter, fines and pellets. The knowledge of burden distribution ensures the possibility to control the gas distribution in the furnace and thus improving the gas utilisation. Microwave technology devours the potential to create a topographical image of the burden surface in the Blast Furnace by introducing radar interferometry. A fully functional technology has the prospective of measuring in real time thus paving path for the material distribution after each charging sequence can be updated, signally treated and delivered as a 3D topographical image. All this is expected to leading a better control of the gas distribution in the furnace and thus a better use of energy.

Radar works by radiating an electromagnetic pulse through the antenna, the emitted signal is then reflected off the material and received by the antenna as an echo. The emitting frequency is different from the frequency of the received signal; the frequency difference being proportional to the distance and the height of the material being measured. Radar is powerful across long ranges. With its 4° beam, it can be used in segmented bins with narrow compartments and excessive noise created during filling, extreme dust, or high temperatures. Moreover, it is ideal for bins where precise aiming is needed to avoid internal structure, the flow stream, or sidewall build up. Since high frequency radar works in high dust, it's quite reliable for measuring burden profile.

4.3.1 Radial Moving RADAR

Predictable RADARS utilize a traditional moving antenna mechanism, which mechanically changes the direction of its signal beams. With these RADARS only single scan measurement possible usually a top scan. **Figure 3** illustrates the antenna moves physically among set positions, transmitting and receiving radar signals at each position. Because rotating antennas can only update tracking information once per revolution, they offer slower and less-effective performance than phased-array technology. Additionally, with these it requires multiple installations to get the burden profile [21]. These multiple installations spike up the cost and with no moving part only a 2D profile or a pseudo 3D profile is obtained. They're also prone to mechanical problems that can result in sudden and complete failure to function.

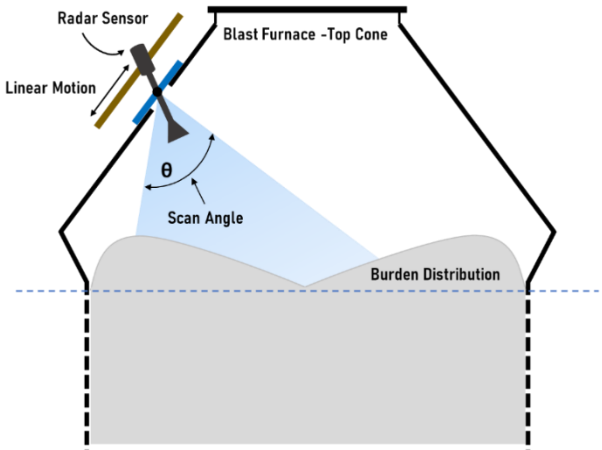

Figure 3 Single scan RADAR

4.3.2 Linear Moving RADAR

Radars determines the burden profile lengthwise a radius in the furnace by organising radars in a row matrix and providing spot measurements along the radius. A single radar measurement as shown in **Figure 4**, cannot fully reflect the actual situation of the burden surface inside the blast furnace. Hence. it can be only used as a simple fixed-point detection [22].

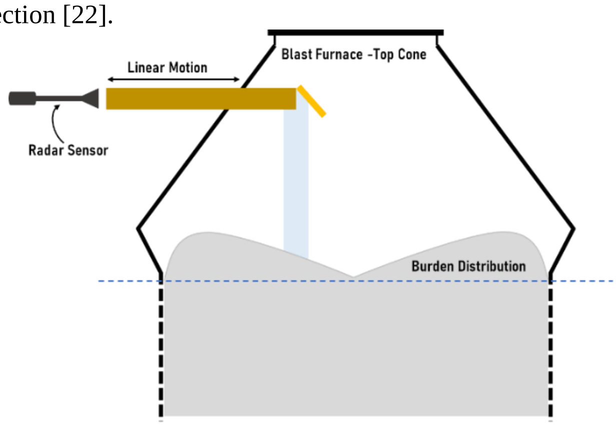

Figure 4 Linear scan RADAR

4.3.3 Multiple RADARs

In another approach, radar antenna is mounted on an axis that moves along the radius in the furnace constantly measuring the profile. Yet another application is to organise a number of radars as a square matrix in the furnace and use this information to get an image of the burden distribution. And yet in alternative approach, a virtual 3D imaging of the burden profile can be achieved with a reconstruction algorithm of multi-radar data [23]. A virtual 3D imaging of the burden surface is achieved with multiple radar array in the blast furnaces shown in **Figure 5**. The measurement chamber mounted at the top cone of the furnace consists of a microwave radar unit and a driving device which is capable of rotating the radar to measure the burden levels along a specified direction. Generally, the measurement can be accomplished within seconds for taking a radial burden profile. The burden level descending rate is evaluated from two profiles taken in the same charging interval.

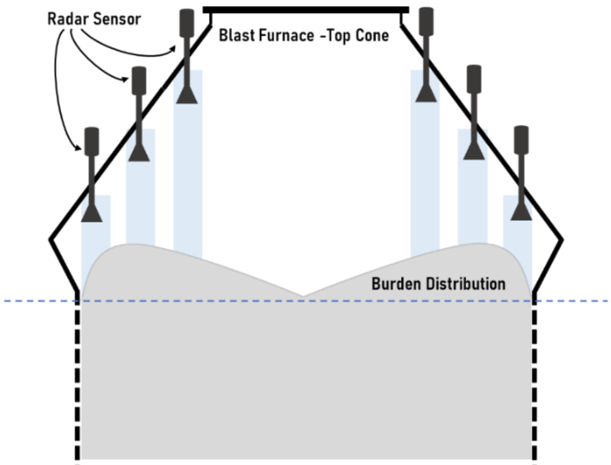

Figure 5 Multiple scan RADAR

Additionally, with these it requires multiple installations to get the burden profile. These multiple installations spike up the cost and with no moving part only a 2D profile or a pseudo 3D profile is obtained. They're also prone to mechanical problems that can result in sudden and complete failure to function.

Developed Solution

The solution developed for this is a Phased-array based radar system. They are fully solid state and don't rotate as there is no mechanical moving parts. Instead, they typically employ a grid made up of hundreds or thousands of fixed antenna elements, each of which transmits and receives a signal beam.

The phased-array design also offers built-in redundancy – it continues to operate even if some individual antenna elements fail. The consequence of individual element failures is usually only a slight degradation of sensitivity, and non-working elements can typically be replaced with limited downtime.

This system doesn't use any mechanical moving parts and easily deployable in blast furnaces of varying size and shape. The preferred installation location of the system is in the top cone of the blast furnace. Moreover, only antenna is placed inside the furnace and all other electronics on the outer side. Electronics can be ceramic made to tackle existing dusty and harsh environmental problem.

The schematic shown below explains the principle of operation. As shown in **Figure 6**, maximum scan angle is denoted θ. If 'x' is the stock line and the antenna height is 'h', then the maximum phase scan angle is

$$\theta = \tan^{-1}\frac{h}{x} \qquad \text{eq(1)}$$

The systems were designed and fabricated with the RF front end. For each of the section, The RF part and the Signal processing part are separately arranged as two different layers as shown in figure 2 & 3

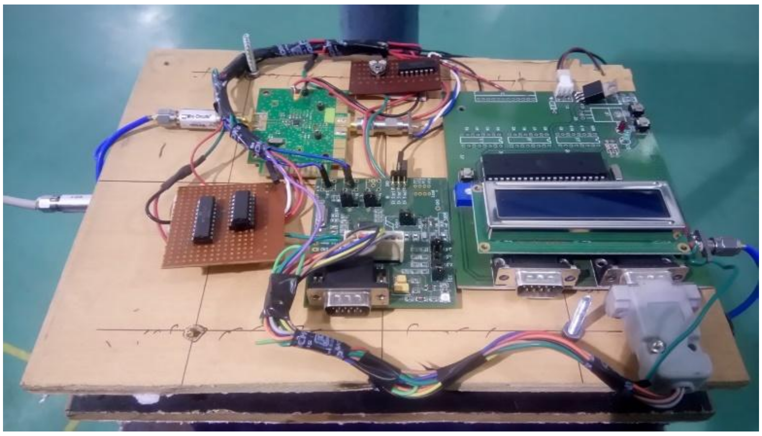

Fig. 2 Signal processing Section

Fig. 3 RF section of Transceiver

The transmitted pulses from the level measurement instrument are electromagnetic waves and are travelling at close to the speed of light. Since these pulses only have to travel a very short distance to the target medium (a maximum of 5m there and back), the time interval (TI) between the transmitted pulse and the received echo(s) is very short. Accurate TI measurement is therefore a crucial part of the pulse radar system.

The user requirements would specify that the instrument should be accurate to 1% of the full-scale distance, which for example is say, 5 m. This gives us a required accuracy of 50 mm. The resolution also needs to be very high at 50 mm. In the time-domain this corresponds to a resolution of about 333 ps. This means that we need to be able to measure TI's very precisely and resolve them accurately to 333 ps.

TI measurement is the measurement of the elapsed time between some designated START and STOP phenomenon. In the case of the pulsed radar system these phenomena are the transmitted pulse and the received echo. Detectors are used to detect the presence of these pulses and a time discriminator is used to extract the timing information from the pulses relative to these events and delivers a pulse of standard amplitude or width or both to the timing circuit. In other words, the time discriminator defines the points on the time-axis between which the TI is measured. The START and STOP inputs can either be separate or on a single common input. The input pulses cannot have infinite rise-time so the timing usually occurs when the pulse crosses a certain threshold. A time-interval meter (TIM), time-to-digital converter (TDC) or Time counter (TC) figure 4, then converts the measured interval into a digital value, which can then be displayed in a decimal form. A one shot measurement is the TI between a single transmitted and echo pulse. The resolution of the one shot measurement is therefore limited by the resolution of the analogue system or the least-significant-bit (LSB) of a digital system. The resolution can be improved upon by TI averaging in analogue systems and by interpolation in digital systems.

Fig.4 Time conversion circuit

TI averaging assumes that the factors limiting the resolution in the analogue system are random and that multiple constant measurements would let the random factors tend to zero thereby increasing the resolution. The process of interpolation involves calculating estimate values between the discreet time data and obtaining a better resolution limited only by the noise. The important specifications to consider in time interval measurement and for time interval meters are:

1. Minimum interval - The minimum time between consecutive pulses.
2. Minimum dead-time - The minimum time between the stop pulse and the next start pulse.
3. Minimum pulse width - The shortest pulse the TIM will recognize
4. Measurement range - The longest possible time the instrument can measure
5. Non-linearity - of the conversion process
6. Quantization step or LSB
7. Readout speed - How fast the instrument can produce a result

Experimental Setup

For our analysis, the cavity resonator-based method has been used [8]. The general construction principle of the cavity resonator involves around the circular waveguide design which is short circuited at opposite ends using metallic plates[9]. The final design takes the shape of cylindrical metal box [10][11]. An illustration for the cylindrical cavity resonator is shown in figure 5. Inside the cavity, the electric and magnetic fields exist as per the excitation mode. The stored energies are summation of the electric and magnetic fields within the cavity. The power dissipation takes place in the metallic wall and the dielectric material filling inside the cavity resonator. In our case the metal wall is made up of copper and the air is the dielectric inside. The volume of the hollow space and dielectric material filling determines the resonant frequency and Q-value of the cavity. As the concept of cavity resonator is similar to the circular waveguide is similar, the design equations from the various waveguide modes can be readily used. The transverse modes used in the cavity resonators are similar to waveguides which is the TE and TM mode.

The excitation of the cavity is usually done using a coupling device. The power is fed from the measuring equipment which is a vectored network analyzer to the cavity is through the coupling probe. [12][13]. The type and loading effect of the coupling devices is different for the TE and TM modes.

4.1 Design of cylindrical cavity

The design started with the simulation of cylindrical cavity resonator operating at TM010 using HFSS software. 99.9% high conductivity copper material has been used for fabrication. The inner surface has been coated with silver paint to decrease skin depth.

The cavity resonator thus designed resonates at 790 MHz **Figure 1** shows the copper cavity resonator dimensions used in the HFSS simulations. The radius of the cavity resonator is 150 mm, the height is 55 mm, the deeding coupling loop is designed on the middle of the metal wall with a radius of 5 mm. Corresponding to the TM010 mode, the electric and magnetic fields inside the empty cavity resonator is used for the measurement. The Q-value of the empty TM010 mode cavity resonators is decided by the intrinsic impedance of the air, the dimension of the cavity, the permeability and the conductivity of the cavity metal.

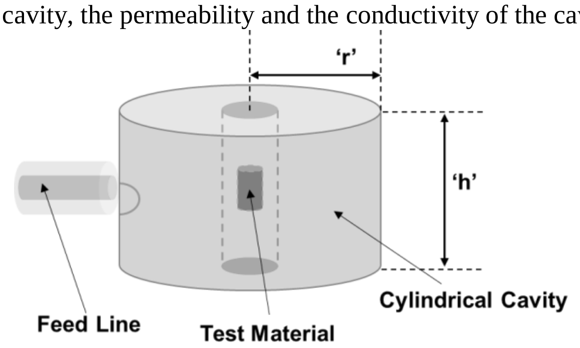

Figure 1 Cavity dimensions r=150mm, h=55mm

The measurements for permittivity or dielectric constant have been introduced and applied since many years ago [2]. The bulk dielectric constant measurements were usually measured using the ohmic resistance concept [3]. But as these methods were inaccurate, newer methods like waveguide [4][5], cavity resonator [6], Free space are used which are based on the concept of microwave engineering.

Further in the designing and development of radars the dielectric constant values play an important role to understand the echo properties which in turn provides insight for imaging capability and potential to acquire subsurface information and is one of the most promising approaches [7].

The coals to be charged in blast furnace may come from different sources/mines and possess different properties. These properties include dielectric properties of coals along with their other physical and chemical properties.

These properties integrate a central role in choice of frequency for heating/processing the material, type and geometry of applicator is best suited to processing the material and uniform will the heating of the work piece be at processing temperatures. It also empowers to understand the change in material's microwave absorption characteristics during processing keeping in mind thermal runaway and thermal insulation in microwave processing

The interaction of coal with microwaves and heating of coal mass by microwave depend on coal's dielectric properties. Hence, these properties of coals need to be measured for determining the optimum frequency of reflection or absorption for the phased array radar system.

Dielectric properties of the material to be measured are as follows:

- Dielectric constant (ε'): Material property which indicates how much energy is stored in material when microwave is applied externally.
- Material losses (ε"): Indicates the energy lost in form of heat when electromagnetic waves interacts

$$\varepsilon_r = \varepsilon' - \acute{\iota}\,\varepsilon'' \text{.........eq(1)}$$

Where, ε_r is the relative permittivity of material.

- Loss tangent (tan δ): Ratio of ε" and ε', tells how much energy is converted to heat as compared to stored or how effective is microwave heating [tan δ = ε"/ε'].
- Quality factor (Q): In context of material only (ignoring external factors in microwave setup), Quality factor is the inverse of Loss tangent [Q = 1/tan δ].

At microwave frequencies, the principle components that influences the reflection of waves are related to the dielectric properties of the materials. Regularly, the diverse dielectric materials will prompt the various losses and reflections for microwave frequencies. To assess the dielectric properties from the various materials serves as basic input requirement in the microwave designing.

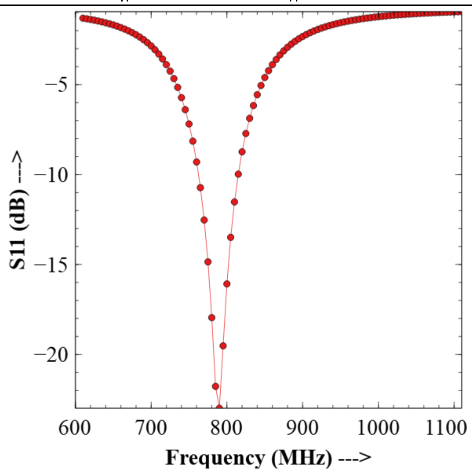

Figure 3 Measured resonant frequency of the fabricated cavity resonator using the VNA

Vector network analyzer measures the change in frequency (Δf) and quality factor shift (ΔQ) between empty cavity and cavity with sample. The data is fed in the equation (1) & (2) for computing the dielectric constant (ε') and loss constant (ε").

$$\varepsilon' - 1 = \frac{f_c - f_s}{2\, f_s} \frac{V_c}{V_s} \text{ ....eq(2)}$$

$$\varepsilon'' = \frac{Q_c - Q_s}{Q_c Q_s} \frac{V_c}{4V_s} \text{ ....eq(3)}$$

Where,
f_c = Resonant frequency,
f_S = Resonant frequency with sample,
Q_c = Quality factor of empty cavity,
Q_S = Quality factor with sample,
V_c = Cavity Volume,
V_S = Sample Volume.

Measurement for coal sample

An amorphous silica sample holder tube (~4 mm inner diameter and ~60 cm long) was used in this case to hold the crushed pelletized coal sample inside the cavitty. A thin quartz base is inserted by a glass blower partway up the sample-holder tube to make the top of the tube into the equivalent of a long test-tube. A small hole was put in the base (~ 1.3 mm diameter) to allow the cover gas (UHP argon) to flow up past the sample during the run.

Sample preparation and calibration techniques are often tailored to the properties of the specific samples. In the present case, the coarse grains of coal were ground with a mortar & pestle to make a finer powder, which was then pressed into pellets in a uniaxial press at ~ 21,000 psi. Surgical gloves or tweezers were used when working with the clean samples to assure continued cleanliness.

The sample mass is determined before the measurement, and, along with the sample dimensions, is used to calculate an initial bulk density.

The initial sample parameters were:

a) diameter – 3.64 ± 0.05 mm
b) length – 11.5 ± 0.20 mm
c) mass – 0.151 ± 0.003 g
d) color/appearance – two stacked black rods
e) room temperature initial density – 1.26 ± 0.06 g/cc

The steps involved in the measurement were:

Step 1: Collecting and weighing coal: Unpacking the received samples and weighing 2-5 g coal (or as required) for pellet formation.

Step 2: Preparing mold for pellet formation: Crushing (if needed) with mortar and pestle arrangement and filling the mold cavity with coal as shown in **Figure 6**.

Figure 6 Preparing mold for pellet formation

Step 3: Pressing of coal in mold with a manual hydraulic press as shown in **Figure 6**, removing pellet from mold and collecting it in sample transportation box.

Figure 6 Pellet formation

Step 4: Manual transfer of sample pellet (**Figure 7**) to measuring facility.

Figure 7 Sample pellet

4.2 Measuring process with data generation

4.2.1 Description of measuring facility:

Equipment used for measuring experiment were- Copper cavity, copper samples for calibration, split furnace, box furnace, Argon gas, gas cylinders and gas transportation tubes, mass flow controllers for gases, fused silica sample holder, vector network analyser (VNA), LabView software, actuator for sample holder movement. The pictorial descriptions of these equipment are described in figure 8,9,10,11,12.

4.2.2 Measurement procedure:

The procedure starts with calibration with copper sample and then with empty sample holder. Sample is then inserted in furnace for heating. Heated sample is transferred to cavity for certain steps of time and temperatures and VNA data collection is done. The above processes happen in Argon atmosphere. Sample is then extracted and data is collected in USB drive. Data for some of these steps are mentioned in next section, where example of a coal sample (Source 1) is given.

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Figure 8 Insulated copper cavity with split furnace mounted on it

Figure 9 Computer working as parameter controller and VNA on top of it

Figure 10 Bottom of cavity with sample holder's mounting and actuator

Figure 11 Actuator moved up and sample (in holder tube) inserted in to furnace for heating

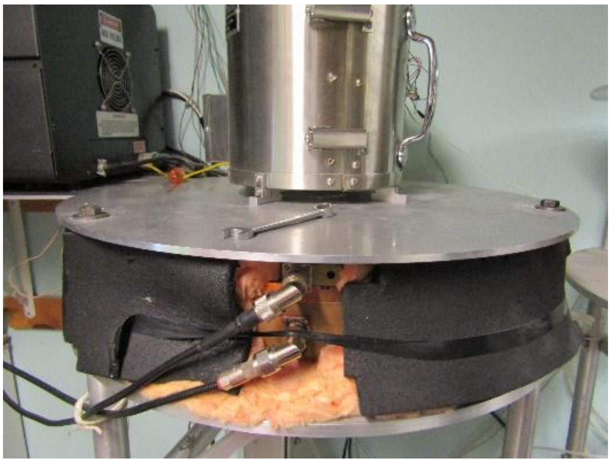


Figure 12 Sample getting heated in split furnace

The Post-Run Sample Characteristics:

The final sample properties, at room temperature were:

a) diameter – 3.45 ± 0.05 mm
b) length – 11.98 ± 0.1 mm
c) mass – 0.113 ± 0.002 g
d) color/appearance – unchanged, one black pellet formed by fusion of 2 pellets
e) room temperature final density – 1.01 ± 0.06 g/cc
f) DC electrical conductivity < 2 ohms, end-to-end, for a single pellet

RESULTS

4.1 Time measurements

Static measurement

To obtain static characteristics of the measurement system, 10000 sample readings are taken at a fixed distance between the antenna and backscatter plate. The original distance is measured as 3000 mm using LDM. It can be seen from the figure that the readings follow a Gaussian distribution. The plot shows the histogram of the RTOF (Return time of flight) measurement. Histogram of the recorded readings is shown in Fig. 5

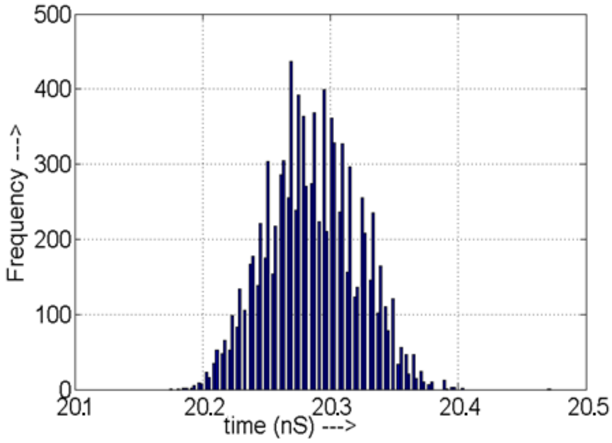


Figure5: Histogram of the recorded readings

Comparison of normal and double resolution data

Double resolution mode of the TDC has been invoked for this experiment. Here the resolution of the radar is much smaller than the normal mode. The readings are obtained for same static measurement conditions both in normal and double resolution modes as described in table 2

Table 2: Observations

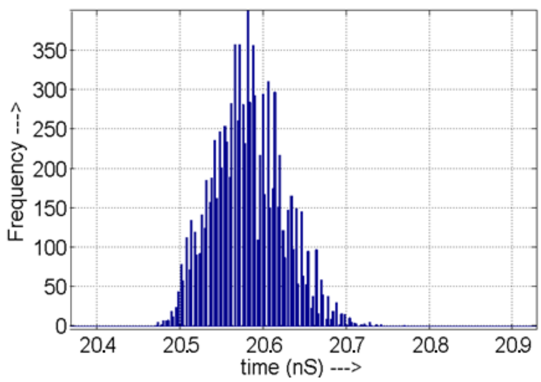
Measurement Mode	**Mean**	**Standard Deviation**
Normal	20.27 nS	122 pS
Double Resolution	20.25 nS	55 pS

It can be observed from Table 2 that there is not much deviation in the mean value of measurements obtained. However, a slight increase in overall standard deviation can be observed from the histograms.

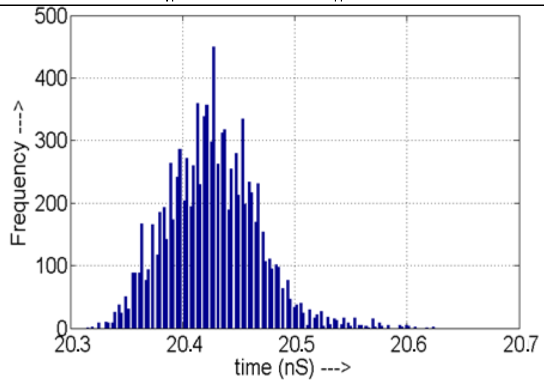
Dynamic Measurement

As the first step towards the dynamic measurement test using two known distances were conducted. The experiment is setup in the testing area up to 5m distance. It can be observed here also that the histogram follows a Gaussian distribution. Now, the distances are varied and readings are taken corresponding to the new distances.

Readings are taken at 2 different locations closely spaced. Original distance readings are taken using the LDM. The Gaussian plots obtained for 10000 data samples are shown in Fig. 6 obtained for a distance of 3050 mm and 3100 mm.



(a)



(b)

Figure 6: (a) Distance: 3100 mm; (b) 3050 mm

Table 3: Summary of measurement results

Distance(mm)	3050	3100
Calculated time of flight (nSec)	20.334	20.668
Measured time of flight (nSec)	20.431	20.580
Error (pSec)	97	88

4.2 Permittivity measurements

Calibration

For setting up the cavity, an initial calibration has been performed at room temperature. Using the measurement setup figure 2, reference measurements for pure Alumina rods figure 4 of known relative permittivity values (Er=9.1) has been taken. The measured values were compared against the known value to determine the accuracy of measurement.

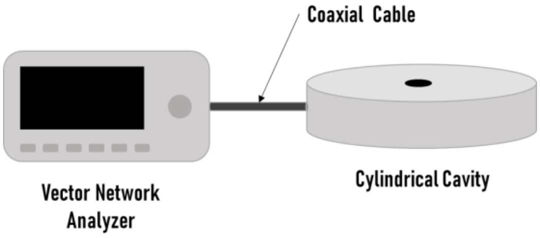


Figure 2 Measurement Setup

The resonance of the cavity for the TM010 mode was found at 790 MHz as shown in the figure 3

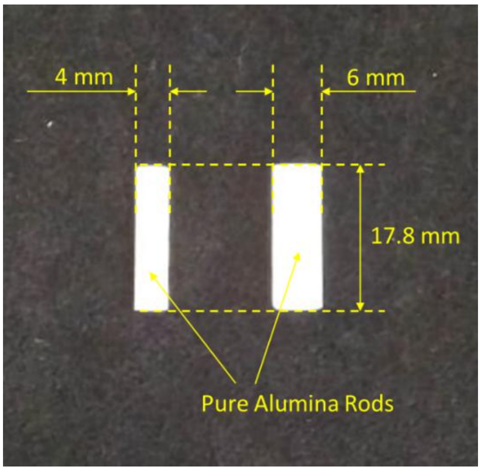
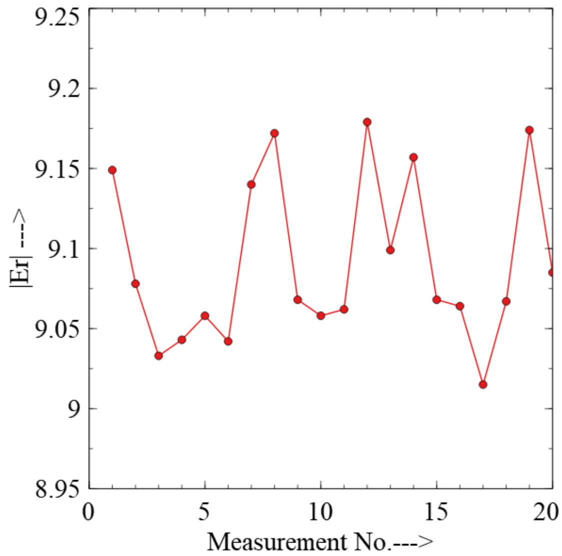


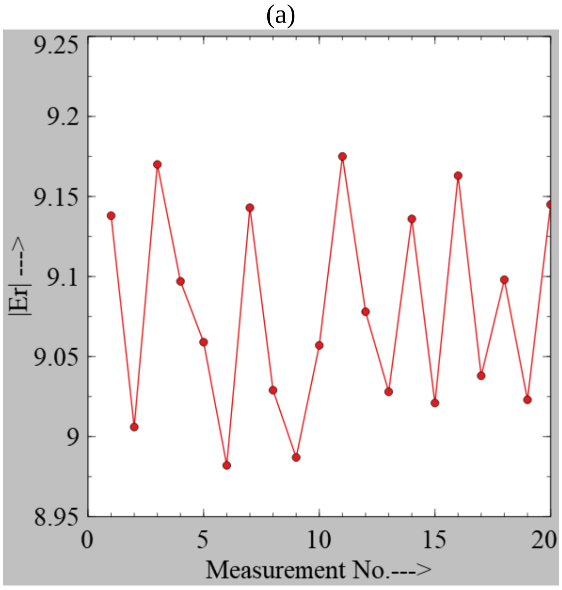
Figure 4 Alumina rods for calibration

	Sample #1	*Sample #2*
Length (mm)	**17.8**	**17.8**
Diameter (mm)	**4**	**6**

Multiple room temperature measurements have been taken using pure Alumina rods. The measured values of the dielectric constant for the rods is shown in figure 5.



(a)



(b)

Figure 5 Measured dielectric constant;
(a) 4mm (b) 6mm

Sample Size	*Mean*	*Error*	*Std. Deviation*
4mm	9.103	+ 0.033%	0.051
6mm	9.079	- 0.231%	0.064

The measurements provided extremely high accuracy with error of 0.033% and 0.231% for the rod diameter of 4 mm and 6 mm respectively. Hence is can be inferred that developed experimental setup is capable of measuring dielectric samples with very high accuracy. Further to this measurement of coal samples has been attempted.

1. Results

Dielectric property is one of the most crucial factors when scaling-up the MW technology for blast furnace measurements. The results of the absolute value of electrical permittivity has been plotted against the multiple measurement iterations in figure 13 and histogram plot in figure 14. The mean value |Er| for the 100 measurements is found to be 4.195 while the standard deviation obtained was 0.059 at room temperature (25°C). This sample has been taken from the first source

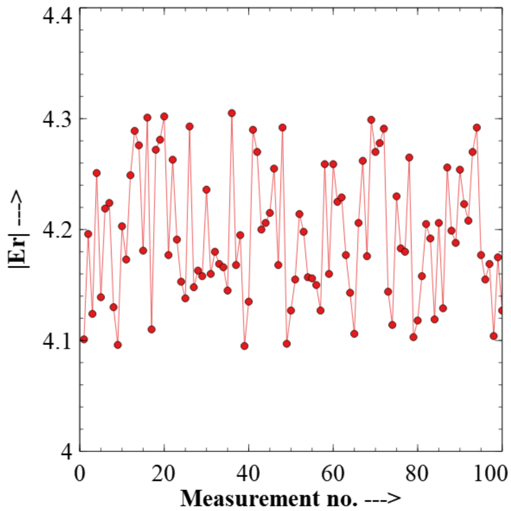


Figure 13 Room temperature (25°C) Dielectric constant of the coal sample.

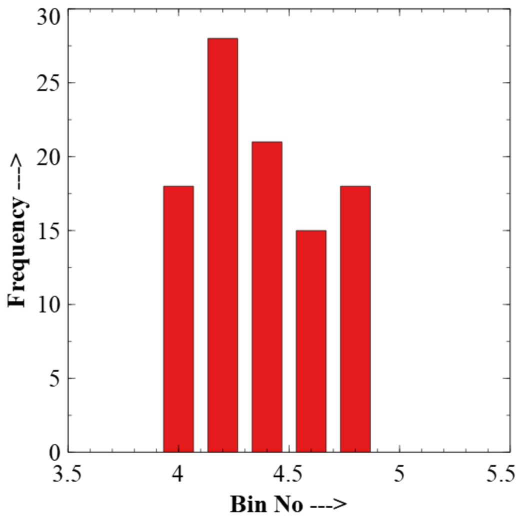


Figure 14 Histogram Plot for the 100 dielectric constant measurements of coal samples at (25°C)

After obtaining the dielectric constant values at (25°C) the heating cycle has been started for the coal sample from source1 using a box furnace. The run consisted of increasing the sample temperature in steps of ~50°C up to 600°C, and then reducing the temperature in 50°C steps to the room temperature. After each temperature step, the temperature is held for ~ 5 minutes to allow the temperature in the sample to stabilize and become uniform. After finishing each run, the mass was again determined (when possible) to within ±0.002 gm. The sample was then removed from the holder, the holder re-inserted into the system, and the empty holder values measured in 50°C steps up to high temperatures to test for contamination and background subtraction. A run has been done in 50°C steps up to 600°C with an empty sample holder to determine the shape of the "empty holder" subtraction values. The results obtained from these measurements is as shown in figure 15.

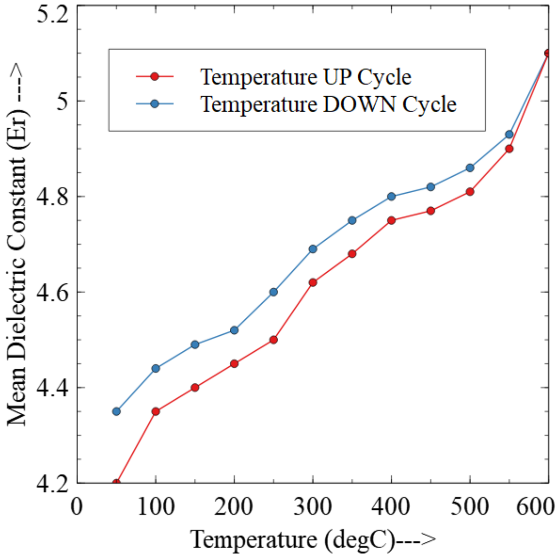


Figure 15 Dielectric constant of coal sample with respect to the temperature.

Further to this study coal samples from various location has been tested in the setup and the corresponding values has been plotted in the figure 16.

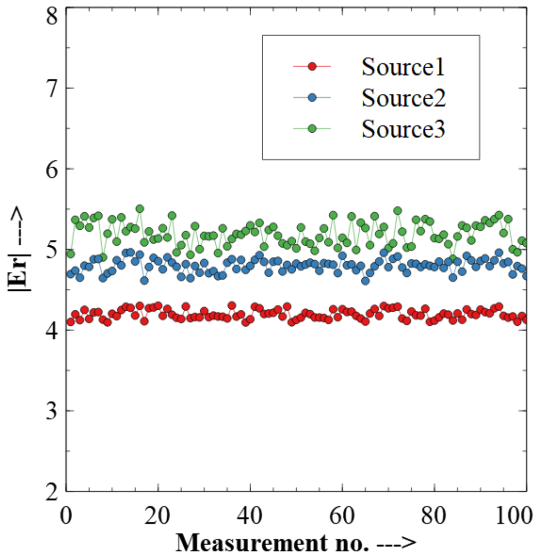


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Figure 16 Comparison of dielectric constant of coal samples from various sources

Sample Size	*Mean*	*Std. Deviation*
Source 1	**4.195**	**0.059**
Source 2	**4.798**	**0.080**
Source 3	**5.192**	**0.145**

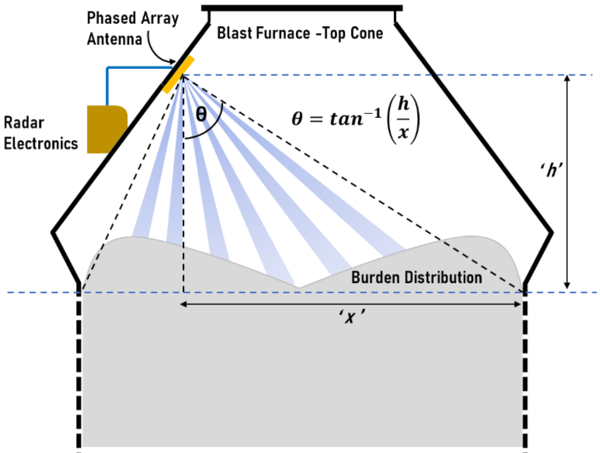

Figure 6 Principal of proposed method

5.1 Scanning Method

The burden distribution is directly related to efficiency and stable blast furnace operation. In a typical blast furnace construction, multiple scans will be required to take measurements. Number of scans will be inversely proportional to the beam size.

For obtaining the real-time burden surface radius profile, a mechanical phased radar system was installed on a furnace top. Burden surface heights in different locations are detected by single radar sensors. It employs a group of antennas to realize the antenna beam electric scanning by phase shifter. Imaging resolution and real-time performance can meet the requirements of industrial BF production. Thebeam-forming mechanism would steer the beam through the cross section of the blast furnace, producing a 3-D profile of the burden surface.

Figure 7 illustrates the cross-sectional view of the blast furnace. To continuously track the burden surface radial profile inside a blast furnace, the beam approaching from the radar scans the illuminated zones (yellow circles). Instead of multiple radars as aforementioned in prior art, only a single radar scans different radial profiles to attain precision in the data. After interpolating the data collected from these illuminated zones, the profile of the burden will be attained. However, resolution will be less if beam is more.

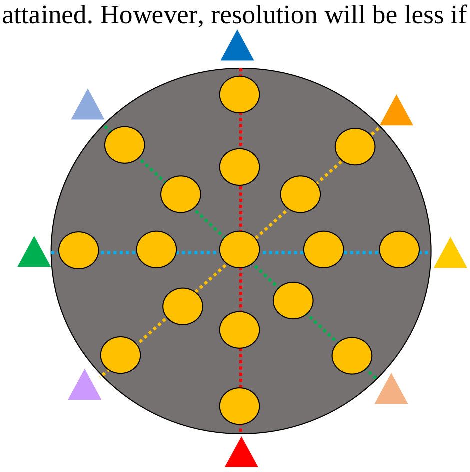

Figure 7 Blast furnace (Top view)

The higher the frequency of a radar ranging transmitter, the more focused the beam angle for the equivalent size antenna, but lower frequencies are not adversely affected by high levels of dust or steam. In steamy and dusty environments, higher frequency radar will suffer from increased signal attenuation. As shown in **Figure 8**, a measure of how well an antenna is directing the microwave energy is called the 'antenna gain' [24] which can be calculated as:

$$G = \eta \times \frac{4\pi A_e}{\lambda^2} \quad \text{.........eq(2)}$$

Where,
η = efficiency
A_e = Antenna Aperture
λ = Wavelength

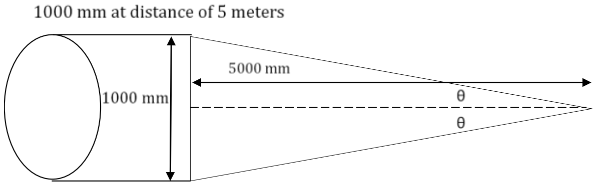

Figure 8 Antenna gain

θ= 5.7 deg, hence beam width required will be 11.4 deg

Configuration	No of elements	Beam width
2x2	4	35 deg
3x3	9	21 deg
4x4	16	10 deg

Hence no of antenna elements will be 4 x 4 = 16

Cross section of blast furnace profile is depicted in **Figure 9**. along with the scan from different diameters across the burden profile. The graph shows the profile data across different diameters from the illuminated areas of the top views.

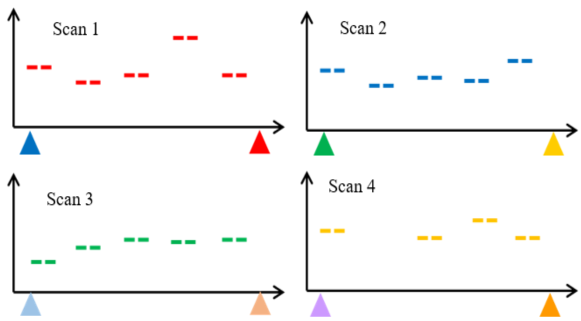

Figure 9 Data from scanning different diameters of the blast furnace

Each of the above graphs gives 1 dimensional data. In the below figure, the green circle depicts the data points between illuminated data points. These points produce interpolated data, which in turn can gives a higher resolution image. The final statistics is derived from using the below formula [25]:

$$y - y_1 = \frac{y_2 - y_1}{x_2 - x_1}(x - x_1) \quad \text{..........eq(3)}$$

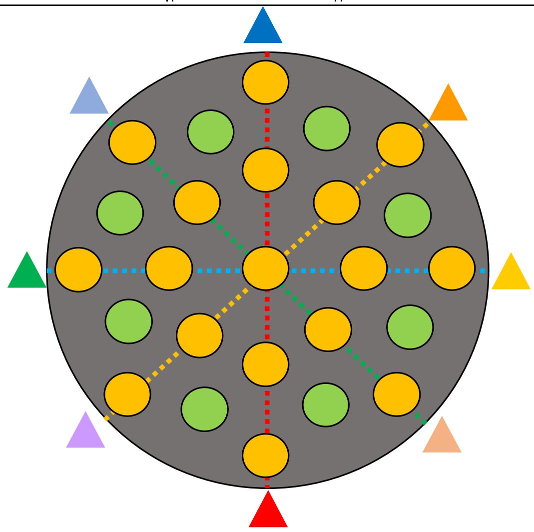

Figure 10 Interpolated Scan Mechanism

Results

A prototype online burden profile measuring system without enormous volume, heavy maintenance load and gas leakage risks were successfully developed at tata steel. Both laser and radar ranging technology were tested in the project. The radar ranging technology, operated at microwave frequency, was finally adopted for its excellent dust penetrability to be the kernel measuring device in the online burden profilometer.

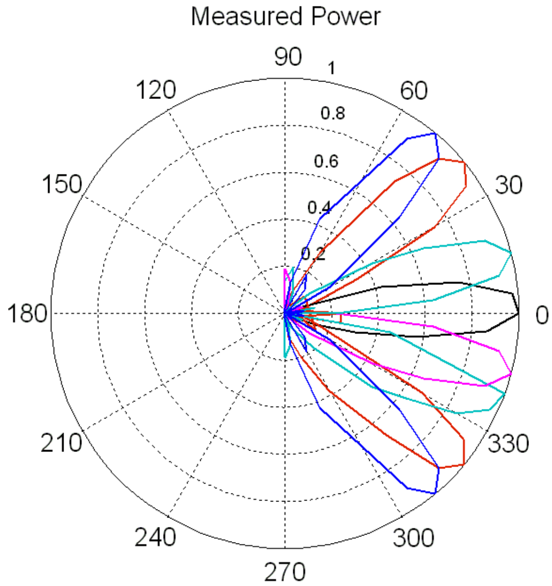

Figure 11 Measure antenna pattern

The measured radiation pattern from the phased array antenna proves that the antenna is capable of sweeping the beam to +- 50 degrees in both azimuth and elevation planes will be sufficient to generate a cross sectional profile of the blast furnace.

While the access to the actual blast furnace is restricted, the developed system was taken to the protype blast furnace designed with scaled dimensions for testing. The burden distribution was simulated using a heap of raw materials inside the vessel and subsequently the measurement was taken. The antenna mounting position has been indicated in figure 12 through the removed portion of the test furnace.

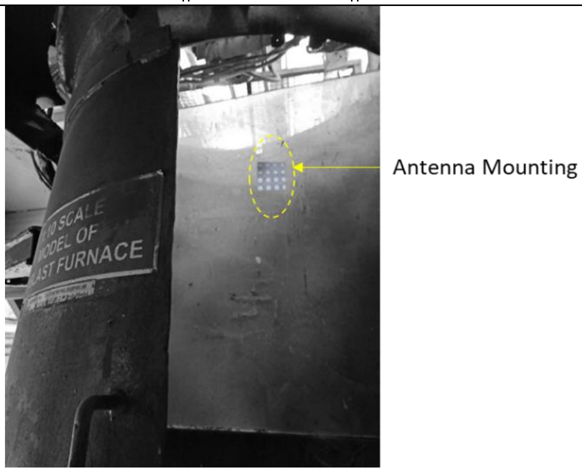

Figure 12 Trial Measurement at prototype blast furnace

The measurements results were analysed and subsequently normalized to obtain the burden profile distribution. The plot in figure 13 shows the heap profile of a vessel under filled condition having radius 5 meters

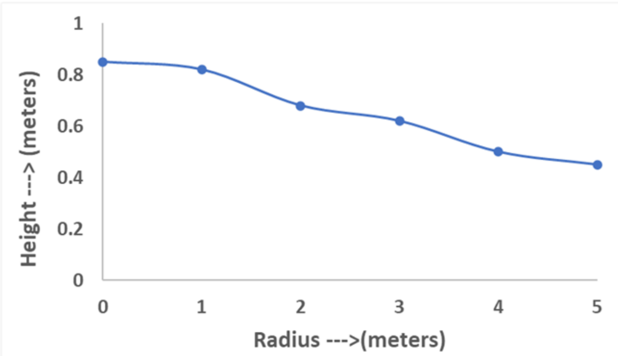

Figure 13 Measured profile for the heap in the protoype furnace (Normalized)

5.1 Comparison

Table 2 summarizes all the previous burden scanning methods in terms of their accuracy, measurement rate and error.

Table 2 Burden scanning methods

	Accuracy	Measurement Rate	Error
Mathematical Model	Low	Medium	High
Laser Based	High	High	High
Ultrasonic	Low	High	High
Radar Based	Low	Medium	Low
Proposed Method	High	High	Low

The error rate is showcased to be low only in RADAR based system. Even then conventional RADARs have multiple bottlenecks such as that of single line scanning, slow data rate and installation of multiple RADARs that speed up the cost and the maintenance. Moreover, phased array RADAR has high measurement rate and so do Laser and Ultrasonic. But in the latter two, they are not suitable for dusty environment even with high penetration rate. The proposed method is the only one checking high in accuracy and measurement and low in error reporting.

Conclusion

To precisely measure the burden profile with low errors and high accuracy, the phased array RADAR was employed with successful prototype development and testing of the same. The data achieved by the results showcased that number of scans to cover the whole BF cross-section is 17.and the scan time is 170 mSec. This can be a breakthrough in black box of iron making. Furthermost, the developed system may spur researchers and technologist to work on profile measurement in high temperature and dust enclosed environments.

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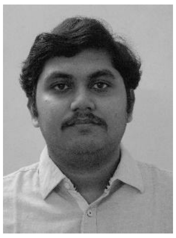

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