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Radar Interferometric Measurements With a Planar Patch Antenna Array

Emil Nilsson and Lars Baath

Abstract—A planar patch antenna array has been made for radar interferometry. The antenna array consists of 32 rectangular patches on a ceramic loaded teflon substrate. The patches are individually coupled to the microwave electronics in two orthogonal circular polarizations. The radar interferometer is intended for topographic imaging in industrial environment, in this case, a blast furnace producing hot metal for the steel and metal industry. Ordinary imaging techniques with IR or visible radiation are not possible to use due to high temperatures, scattering from dust and particles. A model of blast furnace burden material surface was measured and detected.

Index Terms—Industrial control, interferometry, microstrip antennas, radar imaging, synthetic aperture radar.

I. INTRODUCTION

INTERFEROMETERS have been successfully used in astronomy research for decades and are known to produce high-resolution images of the sky brightness distribution. This measurement technique may also be adopted for use in industrial environment on the ground. The antenna array described in this paper was designed for use in such an application, topographic measurement in a blast furnace. The hostile environment inside a blast furnace make mechanical moving parts such as scanning reflector antennas very costly. While radio astronomy imaging is based on measurements of incoherent point sources, the method here will be on a coherent distributed source. Furthermore, the imaged surface is supposed to be continuous, connected, and free from shadowed areas.

A. Application

The blast furnace process, Fig. 1, is the dominating process for reduction of iron ore into iron since several hundred years back. It has shown to be difficult to find a cheaper process for iron production than the blast furnace. The burden surface of the blast furnace is continuously loaded with raw materials from the top through a rotating chute. While iron and slag is tapped from the bottom of the furnace, the loaded raw materials descend, meeting the hot reduction gases. The temperature is maintained by injection of coal powder or oil that mix and combust with

Fig. 1. Schematic of the blast furnace process.

the hot blast air. By observing the burden surface at the top of the furnace, it is possible to get diagnostic information from the process. This information can also be used to distribute raw material at the top in a controlled manner to keep a symmetrical surface and optimal flow of material through the process. Today, the use of traditional measurement methods, such as laser and ultrasound, are very limited due to dust, particles, pressure variations, and vibrations. The presented work is a first step in realization of a new method to acquire vital information from within the blast furnace process.

B. Implementation of the Interferometer

The complete interferometer consists of patch antenna array, cable harness, switch matrix, microwave- and control-electronics, and a back end PC, Fig. 2. The patch antenna array was covered by a ceramic window and mounted in a protecting steel tube cooled with nitrogen. The antenna array was accessed with the switching network. Measurements have to be synchronized with the furnace material distribution system, a rotating chute, that periodically distort the sensing electromagnetic field. A single patch was dedicated for the illumination of the burden surface.

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Fig. 2. Block schematics of Interferometer.

Fig. 3. Elementary interferometer showing bandpass receiver amplifiers, the geometric time delay τ_g , and the receiver with low-pass filter bandwidth f_{LF} .

II. THEORY OF THE INTERFEROMETER

A. Emission From Surface

The radar interferometer illuminates the target, consisting of reflective surface elements that will be imaged, with continuous electromagnetic waves that are stepped in N_ω discrete frequency channels with a free-space wavelength centered around λ_0 . Here, the target is modeled as a spatially discrete apparent brightness distribution vector $\mathbf{B}$, associated with a vector $\mathbf{r} = \hat{\mathbf{r}}|\mathbf{r}|$ of 3-D spatial coordinates with its origin in the interferometer phase center, see Figs. 3 and 4. We also assign a vector $\mathbf{r}_{TX}$ of spatial coordinates with its origin in the transmitter antenna position. The coordinate vectors elements are numbered

by the index variable i . The surface brightness is proportional to the output illuminating power P_{out} , and the square of the radial distance to each surface element of area dA_i and its associated backscattering coefficient σ_i^0 . Assuming a narrow-band system, σ_i^0 is treated as constant over all frequency channels. The illumination intensity is considered constant over the imaged area. The approximate system coherence time is, with definition from [1], the time τ_c for which the rms phase error is less than one radian. We stop the fringe rotation physically by mixing the received signal with the transmitted signal as reference. Thus, τ_c is determined by the phase noise performance of the oscillators. An expression for available brightness for each geometric surface element dA_i and frequency channel becomes

$$B_{avail,i} = \frac{P_{out}\sigma_i^0\tau_c}{4\pi|\mathbf{r}_{TX,i}|^2}dA_i. \quad (1)$$

Backscattering coefficients for different material surfaces can be measured or estimated with existing models such as Kirchhoff method or IEM [2]. Each frequency sample is integrated over a time equal to the reciprocal of a low-pass filter cutoff frequency f_{LF} . Signal-to-noise ratio (SNR) improves as we lower the system noise bandwidth by reducing f_{LF} . When the reciprocal of f_{LF} becomes greater or compatible with τ_c , the integration changes from coherent to incoherent. With the assumption that $\tau_c \gg f_{LF}^{-1}$, the brightness is

$$B_i = \frac{P_{out}\sigma_i^0}{f_{LF}4\pi|\mathbf{r}_{TX,i}|^2}dA_i. \quad (2)$$

B. Reception of the Surface Emission

By sampling the reflected returning wavefront at coordinates on a uv-plane corresponding to different baseline lengths in number of wavelengths, and orientations in a vector $\mathbf{u}$, here numbered by the index variable k , a vector $\mathbf{V}$ of complex amplitudes of the spatial angular frequencies are measured for each microwave frequency channel ω_l . The index variable k represents the base lines made up by the combination of antenna elements m and n . See Figs. 3 and 6.

If we, in an incoherent case, assume a nondepolarizing surface and an available flux density $S = \sum_i B_i/(4\pi|r_i|^2)$ at the collecting antenna element with effective area A_a and impedance η_a , the antenna voltage is

$$\tilde{V}_a = \sqrt{\frac{A_a S}{\eta_a}}. \quad (3)$$

With all antenna elements equal, we normalize $\sqrt{A_a/\eta_a}$ to unity. Since we cannot establish any phase of $\tilde{V}_a$ with respect to the transmitted signal, the brightness cannot be resolved in range. As a consequence, only 2-D sensitive visibility functions can be made by cross correlating antenna voltages

$$V_k(\tau) = \tilde{V}_{a_m}(t) \star \tilde{V}_{a_n}(t - \tau). \quad (4)$$

Cross correlation between flux components from different parts of the surface averages to zero. In the spatial frequency domain, we get

$$V_k = \sum_i \frac{B_i}{4\pi|r_i|^2} \exp(j2\pi\mathbf{u}_k \cdot \hat{\mathbf{r}}_i). \quad (5)$$

Fig. 4. Interferometric measurement setup with coke material surface and interferometer above. An alternative, possibly moving, transmitting antenna placed externally of the antenna array.

With a coherent stepped frequency system the flux density at each frequency channel ω_l and antenna element m , may be described with

$$S_m(\omega_l) = \sum_i \frac{B_i}{4\pi|\mathbf{r}_i|^2} \times \exp\left(\frac{-j\omega_l(|\mathbf{r}_{TX,i}| + |\mathbf{r}_i + \mathbf{r}_m|)}{c_0}\right) \quad (6)$$

with $\mathbf{r}_m$ being the offset for antenna element m from interferometer phase center and c_0 being the speed of the electromagnetic radiation in free space. The phase of the flux density S , is measured with reference to each transmitted angular frequency ω_l through the stepped sequence. The complex amplitude received at each antenna element becomes

$$V_{a_m}(\omega_l) = \sqrt{\frac{A_a S_m(\omega_l)}{\eta_a}}. \quad (7)$$

With transformation to time domain, we get

$$\tilde{V}_a(\tau_r) = \sum_l V_a(\omega_l) \exp(j2\pi\omega_l\tau_r) \quad (8)$$

the delay time τ_r corresponds to different radial distance from the interferometer. For each resolved radial delay time cell τ_r and baseline u_k , we form the visibility function

$$\mathcal{V}_k(\tau_r) = \tilde{V}_{a_m}(\tau_r) \tilde{V}_{a_n}^*(\tau_r). \quad (9)$$

In the coherent case, the contribution from each surface element have to be summed with phase. If we define the complex amplitude from surface elements dA_i and dA_j as received at delay τ_r with antennae m and n , (9) can be written as

$$\mathcal{V}_k(\tau_r) = \sum_i V_{a_m,i} V_{a_n,i}^* + \sum_i \sum_{i \neq j} V_{a_m,i} V_{a_n,j}^* \quad (10)$$

or

$$\mathcal{V}_k(\tau_r) = \sum_i \frac{B_i}{4\pi|\mathbf{r}_i|^2} \exp(j2\pi\mathbf{u}_k \cdot \hat{\mathbf{r}}_i) + n_{\text{speckle}} \quad (11)$$

where the complex noise term n_{speckle} represents all cross-correlation terms $i \neq j$ between surface elements. The speckle depends on the structure of the surface, but is unlikely to extend more than one wavelength in physical surface coordinates. This multiplicative speckle noise is stationary in time and cannot be averaged out.

The pairwise combination of antenna elements eliminate the sensitivity to the position of the transmitting antenna, as long as the Fraunhofer approximation holds, meaning that the transmitter antenna is within or close to the antenna array. This is the same as $\mathbf{r}_{TX} = \mathbf{r}$ being true. We can lower the spatial coherency, or reduce speckle noise, of the surface brightness by letting our illumination come from different directions during the measurement. It can be realized by switching between different transmitter antennas on the interferometer. By changing the position of the transmitting antenna, the speckle will vary in phase and amplitude since the propagation path $|\mathbf{r}_{TX,i}| + |\mathbf{r}_i + \mathbf{r}_m|$ in (6) changes.

C. System Performance

Since we sample a finite aperture with a limited number of points, sidelobes resulting in a dirty beam occur. Reduction of sidelobe energy can be performed by a weighting value w_k for each baseline, but this reduces the effective aperture size and thus the angular resolution. There are a number of known methods from astronomy for deconvolution of dirty images of incoherent sources made with a dirty beam, such as CLEAN and MEM [3]–[5]. Modified techniques are also proposed for coherent distributed sources [6]. The dirty image with weighting function is the set of the following volume elements:

$$d_i(\tau_r) = \sum_k w_k \mathcal{V}_k(\tau_r) \exp(-j2\pi\mathbf{u}_k \cdot \hat{\mathbf{r}}_i). \quad (12)$$

This gives a dataset of radially stacked 2-D images in non-Euclidian angular coordinate system. Transformation to other coordinate systems can be performed by a resampling procedure.

A second-order error causing aberration will be introduced since we assume planar wavefronts and a small antenna, i.e., Fraunhofer diffraction. The far-field distance R_{ff} where the Fraunhofer approximation starts to hold is given by

$$R_{ff} \gg \max_k |u_k|^2 \lambda_0. \quad (13)$$

For our interferometer, the far-field approximation is valid for distances greater than 849 mm. In the blast furnace, the interferometer is situated three to four meters above the burden surface. The usable field of view for the interferometer is set by the individual antenna element opening angle. Requirements from the application sets this parameter to at least 90° . The maximum measurable field of view with the interferometer is determined by the requirement that geometrical time delay in Fig. 3, τ_g should be less than f_{LF}^{-1} . This however is of no concern in our case since the maximum baseline length covers only a few wavelengths and the stepped frequency method give us an instantaneous bandwidth, f_{LF} , of a few tenth of kHz. Further, the coherence time of the used signal source is far greater than τ_g .

The angular resolution, or half-power beam width, in radians, of a two element interferometer is determined by the wavelength of the radiation and the length of the baseline u_k , see Fig. 6, spanned by the antenna elements

$$\theta_k = \frac{1}{2u_k}. \quad (14)$$

Compared with a uniformly illuminated circular aperture this is an improved resolution by a factor of two [7]. In the current application, a resolution of about 10° has been considered to be sufficient. With $\lambda_0 \simeq 27$ mm and a interferometer diameter of 150 mm, we are well within the required resolution. The effective interferometer solid beam width Ω_b is set by the baseline coverage in two dimensions, and the illumination, or weighting, function used. Note that all surface elements dA_i within the solid beam width Ω_b are summed to produce the received brightness in each angular pixel. The number of such surface elements scale as $|r_i|^2$, the brightness from each fixed surface element scales as $|r_i|^{-2}$. The brightness received by the interferometer system per beam solid angle is therefore independent of the distance. The illumination of each surface element is dependent on the distance to the transmitter $|r_{TX}|^{-2}$. The brightness per resolution pixel received by the radar interferometer signal is therefore proportional to $|r_{TX}|^{-2}$. Radial full width at half power, Δr , of the synthesized pulse is

$$\Delta r \simeq 0.44 \frac{c}{f_{BW}}. \quad (15)$$

In our case, the bandwidth is $f_{BW} = 600$ MHz giving a $\Delta r \simeq 220$ mm. The number of baselines in an interferometer is [1]

$$M = \frac{N(N-1)}{2} \quad (16)$$

where N is the number of physical antenna elements. It would be preferred if each baseline gave a unique sample of the uv-plane since redundant baselines add no new structural information about the target, assuming a completely incoherent surface brightness. Redundant samples merely increase the SNR. Although some methods [8] are proposed for minimum

Fig. 5. Measured crosstalk between antennas, imaged as a false surface reflection of -16 dB referenced to maximum power. All coordinates are spatial Cartesian and in millimeters. Color indicates surface element radial distance from interferometer phase center.

Fig. 6. Interferometric antenna array with baseline u_k marked. Each square is a patch antenna.

redundancy in distribution of the antennas, it is also known that if N is large enough, it is sufficient to spread them out in a random fashion, as in this work.

D. Crosstalk

Lack of isolation in the signal path and unwanted transmission between antenna elements in the interferometer is considered as crosstalk. Two dominant contributors are identified, air and substrate coupling in the antenna array. The two components will have different wave numbers causing the amplitude of the crosstalk signal to vary along with the frequency stepping, as the two components interfere. The crosstalk signal can be modeled as a false surface, or rather as a 3-D distributed false target, see Fig. 5. It is then possible to modify the visibility function as follows:

$$\mathcal{V}_{talk,k} = \sum_i \left(\frac{B_i}{4\pi|r_i|^2} + C_i \right) \exp(j2\pi \mathbf{u}_k \cdot \hat{\mathbf{r}}_i) + n_k + n_{speckle} \quad (17)$$

where the vector $\mathbf{B}$ still is the true brightness representing the connected surface, and $\mathbf{C}$ is a virtual brightness vector emanating from crosstalk. It is, of course, possible to calibrate the interferometer and then subtract $\mathbf{C}$. Other arrangements may be considered where we physically rotate the interferometer and remove invariant components, or a parameterized model of $\mathbf{C}$ used to minimize the energy in the image.

E. Noise Analysis

Our observations are samples of a visibility function in the presence of noise $\mathbf{n}$, associated with each baseline [3], expressed as

$$V_k = \sum_i \frac{B_i}{4\pi|r_i|^2} \exp(2\pi j \mathbf{u}_k \cdot \mathbf{r}_i) + n_k. \quad (18)$$

We can treat the influence from surface brightness as an increase of individual antenna noise temperatures, T_A , with a certain amount of coherence between antennas. If the actual surface brightness was completely spatial incoherent, the output from the interferometer would be independent of its absolute position in the measurement plane. However, a clear evidence of a high degree of spatial coherence, is the speckle detected in our images. This implies that the van Cittert–Zernike theorem does not hold, making the target unsuitable for direct synthesis mapping.

Each receiver and antenna system will contribute with a thermal noise T_S for each baseline. Based on two different assumptions, $T_A \ll T_S$ or $T_A \gg T_S$, we get two SNR expressions [1]. The first assumption is a surface brightness just detectable over the receiver thermal noise and the other is when having a strong surface reflection dominating over the receiver thermal noise. If we assume a nondepolarizing surface and an available flux density $S = \sum_i B_i / (4\pi|r_i|^2)$ at the collecting antenna area A , the received power density is

$$kT_A = AS \quad (19)$$

and the SNR becomes

$$\text{SNR} = \frac{AS}{kT_S} \sqrt{N_\omega}. \quad (20)$$

The above result is for $T_A \ll T_S$. For the other extreme, $T_A \gg T_S$, we get $\text{SNR} = \sqrt{N_\omega/2}$. If we have a number of N antennas, SNR is improved due to the increased collecting area A . SNR is increased by a factor $\sqrt{N(N-1)}$ which goes as N for large N . SNR can be optimized with the weighting function $\mathbf{w}$, but it will not have any large effect if our antennas are practically identical. It could be argued that failing antennas should be excluded from the mapping synthesis.

We have earlier concluded that $\tau_c \gg f_{\text{LF}}^{-1}$ for a coherent system. It should be mentioned that phase noise modulating the signal will cause a integration loss in the low-pass filter [9]. Phase deviations due to noise can be modeled with a zero-mean Gaussian probability function characterized by its standard deviation σ_{pn} in radians. Assuming a small standard deviation, in practice only a few degrees. The loss can then be approximated by

$$L \simeq 10 \log_{10}[\exp(-\sigma_{pn}^2)] = -4.343\sigma_{pn}^2 \text{ dB} \quad (21)$$

given a large number of integrations.

Fig. 7. Simulated reflection from changes in a reflecting surface 1600 mm below and 1000 mm offset from the phase-center of the interferometer. Intensity is normalized and coded by color.

F. Required Assumptions for Reconstruction of Target From Data

The reconstruction of reality from the 3-D dirty image will not by itself result in a unique image. Any reconstruction from limited data, such as an interferometer, requires additional *a priori* information to choose from a large number of “true” images, see [10], having the same noise level. The *a priori* assumptions for radio astronomy are usually that all emission originates from a small part of the sky and that the emission is always positive. Usually, the reconstruction is then made with a clean algorithm, where the point spread function of the interferometer is deconvolved from the dirty image [11].

The 3-D topographic images discussed here can be uniquely defined with the following assumption.

- 1) The image is restricted to a specific volume, e.g., the geometric enclosure of the blast furnace.
- 2) The frequency is sufficiently high so that only the surface will reflect and the volume can be represented by a surface in three dimensions.

Following these assumptions, the reconstruction can be limited to fitting a surface in three dimensions. We suggest using a maximum entropy method (MEM) [12] to fit the smoothest possible surface to the measured complex visibility data.

III. RESULTS

The radar interferometer was verified by measurements on single-antenna elements and on a complete interferometer setup. A microwave vector network analyzer was used for the measurements in both cases. Presuming a stationary target surface, the switch matrix was used to scan through the available interferometry data. Results presented here are from simulations with single and multiple discrete targets and from measurements.

A. Simulation

The radar interferometer was modeled with computational software simulations, able to simulate response from single or multiple discrete radar reflectors. The simulations were used for optimizing the performance of the interferometer and for verification of measurements. The result for a single reflector at a vertical distance of 1600 mm below the antenna is shown in

Fig. 8. Antenna impedance matching measurement, before and after individual tuning of impedance matching network.

Fig. 7. Resolution and point spread function of the system are verified by this approach. Simulation shows the interference between sidelobes from different parts of the surface, resulting in ghost surfaces that screen the real surface. By simulations, it is possible to investigate the impact of crosstalk on image quality. Magnitude of signals caused by crosstalk can be several orders stronger than the signal magnitude caused by reflection from the sensed surface.

B. Measurements

Measurement of single-antenna elements show individual variations in both radiation and impedance matching over frequency. The different constituting parts of the antenna elements was found shifted in frequency in the opposite direction making manual tuning necessary. The graph in Fig. 8 shows impedance matching before and after manual tuning.

The measurements of the complete interferometer were performed by transmitting an outgoing wave from one of the antenna elements in the array. The voltage at each of the receiving antennas is then sampled in a sequence that takes about 30 s to complete. Signal power emanating from crosstalk will be considerable compared with the signal power originating from reflections from the surface. The magnitude of this crosstalk was not calculated but rather measured after the fabrication of the interferometer. The crosstalk was partly filtered out by signal processing and reduced by using a transmitting antenna separated from the array. Rejection of unwanted double wall reflections contributing to spurious surface detections was made by use of circular polarized waves. Inherent isolation between the circular polarizations in the microwave electronics is better than 25 dB.

By measuring small, manually induced changes in an otherwise stationary surface made of coke, we could test the sensitivity and geometrical properties of the system, see Fig. 9. Some sidelobes appear around the main lobe in the measurements.

The crosstalk between antennas will appear as a false target, screening the true image brightness B . Surface waves with different wave numbers and amplitude interfere causing a complicated spatial field distribution over the antenna array. Fig. 5 shows a Fourier transformation of a cold sky measurement, containing only crosstalk energy.

Fig. 9. Measured reflection from changes in a coke surface. Intensity is normalized and coded by color.

Except from antenna crosstalk caused by mutual coupling, thermal noise and speckle, unwanted energy in the images will come from sidelobes of specular reflections. If all sidelobe responses are removed, the true image would be dominated by specular reflecting geometric surface areas. Since the perceived surface brightness of each angular resolution element will be proportional to R^{-2} , parts of the surface close to the antenna appear as very bright.

IV. CONCLUSION

Although the individual antenna elements was shifted in frequency response, the complete antenna array made interferometric measurement possible after manual tuning. The shifted performance among the antenna elements is probably caused by the circuit topology being too sensitive to the fabrication process tolerances.

Future work concerning the hardware will be on minimizing crosstalk and to integrate a protecting radome in the antenna array design.

Signal processing development will concern surface models for topographic extraction using *a priori* known surface height

statistics, e.g., a Markov Random Field. The polarimetry technique will be relevant since the coke surface evidently depolarized the reflected wave. This property of the coke gives reason to reconsider the use of circular polarization for rejection of double wall reflections. At the same time, it presents the possibility to get more information from the interferometric data, information such as size and structure of the particles of the surface. Combined with reflectance magnitude this can be used for qualitative classification of the distributed burden material.

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