SCOPING A DOCUMENT ON RECOMMENDED PRACTICES FOR SYNTHETIC APERTURE RADIOMETRY

H. Brian Sequeira, Corina Nafornita

Johns Hopkins University Applied Physics Laboratory, Laurel, MD USA
Communications Dept., Politehnica University of Timisoara, Romania

ABSTRACT

In the framework of the newly formed IEEE Signal Processing Society Synthetic Aperture Standards Committee, a Synthetic Aperture Radiometry Working Group (WG) is in its formative stages to develop a document that describes recommended practices for exploiting aperture synthesis to construct thermometric images of scenes from which to derive useful information such as salinity of oceans and floating ice, moisture of soils and early detection of signs of conflagration. The WG will consider the impact of performing aperture synthesis on architectural and performance aspects of an array of radiometers. This WG will identify and describe a preferred set of architectural and performance features for each radiometer as well as array configurations of these that lend themselves to accurately locating and registering images of scenes of interest. This undertaking will be conducted with oversight by bodies under the IEEE Standards Association (IEEE-SAS) and sponsored by the IEEE Signal Processing Society (IEEE-SPS).

Index Terms**—**radiometry, imaging, aperture synthesis, standards, practices, IEEE Signal Processing Society Synthetic Aperture Standards Committee, working group

1. INTRODUCTION

IEEE-SPS has begun an initiative to develop standards and recommended best practices for applying aperture synthesis to a broad range of disciplines: radar, sonar, channel sounding, optics, MRI, quantum apertures, and radiometry. For this purpose, the Synthetic Aperture Standards Committee (SPS SASC) was created. Its purpose is development, validation, and dissemination of technical standards that describe the processes, procedures, and hardware necessary to correctly perform synthetic aperture measurements in electromagnetic environments. These measurements can be used to accurately characterize propagating and scattered electromagnetic radiation in wireless communication channels. In the framework of the SPS SASC committee, several study and working groups have been created, one of them being for Radiometry [1], which occupies the subject of this paper.

The Synthetic Aperture Radiometry WG will embark on an unprecedented activity to develop a document that describes recommended practices for exploiting aperture synthesis to construct thermometric images of scenes from which to derive useful information such as salinity of oceans and floating ice, moisture of soils [2] and early detection of signs of conflagration [3].

The proposed recommended practices will describe fundamental limits, procedures, and signal processing steps for aperture synthesis of arrays of radiometers, including a single radiometer element; the document will also introduce terms and metrics used to quantify its performance limits. The recommended practice will define arrays of such elements in a number of configurations to establish constraints and performance that accompanies each. The recommended practice will also describe platforms from which instruments operate and the advantages and disadvantages of each setting.

Application of aperture synthesis to radiometry is a relatively young subject of investigation because of certain differences that it bears with its more mature counterparts. Mature embodiments of synthetic aperture techniques rely on emitters whose signal characteristics are well known. Matched-filter receivers capture echoes of the emitted signal that are back-scattered from the scene. On the contrary, in radiometry, emitters embedded in the scene provide sources of illumination whose characteristics are random. A receiver with bandwidth, B, centered about a carrier frequency, f_c, selects that portion of the emitted spectrum, whose power spectral density is uniform over B for thermal (black-body) noise. The band-pass filter B eliminates the mean of the illumination and permits only complex deviations, $\upsilon_c(t) = \upsilon_{\mathrm{Re}}(t) + j\upsilon_{\mathrm{Im}}(\mathrm{t})$, from the mean to propagate through the receiver. Subscripts Re and Im denote the real and imaginary parts of the deviation at time instant, t. A significant property of $\upsilon_c(t)$ is that

$$\int \upsilon_{\mathrm{Re}}(t)\, \upsilon_{\mathrm{Re}}(t+\tau)\, dt = \int \upsilon_{\mathrm{Im}}(t)\, \upsilon_{\mathrm{Im}}(t+\tau)\, dt = 0;\ \tau \neq 0 \qquad (1)$$

In words, the time sequence of the detected illumination is random, and therefore, aperture synthesis through combining of time-sequenced samples of the scene is not available to radiometry. This fact has architectural and performance consequences for the individual radiometer element, as well as its relationship to other radiometer elements that comprise the synthetic aperture. The Radiometry WG will explore these consequences in detail, and the following description intends to provide a flavor for the kind of deliberations that they will undertake.

The paper is organized as follows: in Section 2, the radiometer receiver element is presented; Section 3 discusses the case of array of radiometers; Section 4 presents the array construction; Section 5 describes calibration processes; Section 6 discusses limitations and finally the last section presents the conclusions.

2. RADIOMETER RECEIVER ELEMENT

A radiometer is an instrument that measures noise. It does so by converting noise fluctuations that impinge on its input into a DC voltage at its output. Modern radiometers represent the DC voltage in numerical format through analog-to-digital conversion (ADC). In addition to the impinging input noise, the radiometer generates noise internally through thermal (Johnson), carrier transport (shot) and carrier recombination mechanisms present in devices that transform noise fluctuations into DC voltage. Evidently, the transformation process is non-linear, and internal noise can combine additively and multiplicatively with the noise from the scene. For example, during heterodyning to frequency-translate input noise to a lower intermediate frequency (IF), local oscillator (LO) noise grafts multiplicatively onto the input signal. Furthermore, image noise from frequency down-conversion contaminates the desired input noise as well. Likewise, unintended non-linearity from nominally linear stable amplifier stages up-convert recombination noise to the receiver's band. The WG will examine these mechanisms and recommend architectures that best mitigate these noise-contaminating factors.

An important aspect of radiometer design is that it preserves the random nature of the noise, as given by Eq. (1). It should not introduce spurious temporal correlation into the noise sequence where none originally exists. Such spurious correlations arise from a variety of causes and we briefly describe these here.

Mismatch between receiver stages causes multiple reflections that combines every current sample with others generated multiple round-trip times ago, and thus introduces correlations among them. This acquires significance in situations where optimum noise performance requires a mismatched input.

ADC introduces correlation in a number of ways. Amplitude quantization [4] introduces correlation in an originally uncorrelated sequence if the quantization step is comparable with the root-mean-square (rms) deviation of the noise. Time quantization introduces correlation in at least two ways: if the sampled spectrum contains subharmonics of the sampling rate, the samples are no longer random, but cluster around the sub-harmonic frequencies. Wideband systems can suffer from this effect. Yet another source [5] of spurious correlation arises from the need to Nyquist sample the noise that propagates through the filter bandwidth, B. The filter response lingers an amount $t_F \sim 1/B$, after application of stimulus, and Nyquist sampling sets an upper bound, $t_{Sampling} \leq \frac{1}{2} t_F$. Thus, the lingering effect of past samples inevitably introduces correlation. The WG will address such issues in considering recommended practices.

An ideal radiometer does not suffer from impairments that we list above. Under ideal circumstances, the internally generated noise is represented as a temperature, T_{Rx}, and, after integrating the input noise for a duration, t_{int}, it achieves a temperature sensitivity ΔT, as shown in (2):

$$\Delta T = (T_{Scene} + T_{Rx})/(B t_{int})^{\frac{1}{2}} \qquad (2)$$

where T_{Scene} is the temperature of the scene of interest. We now discuss aperture synthesis using arrays of radiometers.

3. ARRAY OF RADIOMETERS

Owing to sequential temporal sampling not being available, aperture synthesis in radiometry must appeal to other methods of sampling.

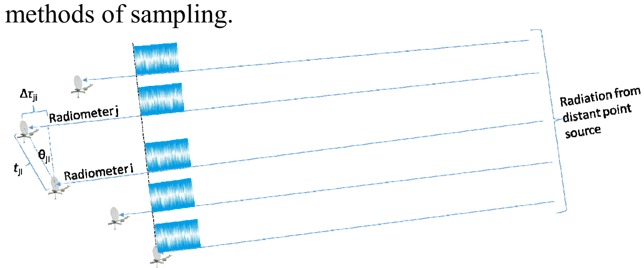

Figure 1 – Emission from a distance source impinge on an array of radiometers at different times, owing to their spatial separation. The time difference of arrival between any pair directly relates to the angle of arrival to that pair.

Spatial sampling is a promising approach for the effective achievement of aperture synthesis. In this method, correlation among arrayed pairs of radiometers obtains the time difference of arrival between the pairs of emission from a distant source (Fig. 1). Cross correlation offers several advantages: internally generated noise within each radiometer is uncorrelated with any other and is therefore suppressed. Likewise, gain fluctuations in each radiometer is uncorrelated with those in any other radiometer and therefore suppressed. Of course, realization of this advantage requires special care in the distribution of stimuli such as LOs and sampling clocks to the array of radiometers.

The spatial separation, D_{ji}, between radiometer elements i and j, furnishes a corresponding time, $t_{ji} = D_{ji}/c$ where c is the speed of light. Cross-correlation provides a time difference of arrival, $\Delta\tau_{ji}$, which is achromatic, and which yields the angle of arrival of the emission relative to the perpendicular bisecting plane between pair i-j according to the formula

$$\theta_{ji} = \sin^{-1} (\Delta\tau_{ji} / t_{ji}) \tag{3}$$

The smallest resolvable time difference is $\Delta\tau_{min} = 1/B$, and the corresponding minimum resolvable angle is

$$\Delta\theta_{min} = \sin^{-1} \left((B\, t_{ji})^{-1}\right) \tag{4}$$

Better spatial resolution requires wider spatial separation between radiometer elements and wider bandwidth for each element. The main obstacle for large separation is that cross-correlation requires overlap of antenna beams of the radiometers at the scene. To achieve this, with widely separated elements, and to obtain large coverage, requires antennas with wide beams (low-gain). Low gain reduces sensitivity [6] of the radiometer elements, and the attendant wide beam increases its susceptibility to interference. There is a further complication that arises when an array of widely-spaced radiometers is moving. In this case, each radiometer's reception experiences a significantly different Doppler shift from that of its widely-spaced neighbor, and requires pre-processing prior to performing cross-correlation.

An emerging initiative [7] is underway to increase bandwidth between 500 MHz and 1400 MHz. Effort has begun to meet the challenges of man-made interferences in this frequency range as well as sampling wide bandwidth as mentioned previously. The WG will explore optimum combinations of element spacing and bandwidth and assess limiting performance in certain circumstances.

4. ARRAY CONFIGURATIONS

Three independent baselines, D_{ji}, are needed to locate the position of an emitter unambiguously. However, as with all triangulation systems, such determinations are subject to geometric dilution of precision (GDoP) and position dilution of precision (PDoP). GDoP and PDoP mitigation needs sufficient number of baselines of proper relative orientation. One pattern [2] comprises 3 linear arrays arranged in a Y-configuration, much like the very large array (VLA) in Socorro, New Mexico. Baselines may be formed by selecting one element from each linear array to form the vertices of a triangle whose sides form optimum baselines for precise location of the source. Small triangles deliver better coverage but poorer spatial resolution, while the converse is true for large triangles. The WG will explore other configurations that could be gainfully utilized in some situations.

Thus far, our discussion has been limited to one receiver per antenna element. Certain radio stars are known to emit noise that is polarized. Magnetic dipole moments of O_2 also emit polarized radiation when aligned by Earth's magnetic field. In such cases, polarimetric radiometry is useful for supplying information about the mechanisms behind the radiation. Each antenna element has two receivers to detect each basis polarization; either horizontal (H) or vertical (V), or right-hand circular (RHC) and left-hand circular (LHC). The WG will examine some challenges to be confronted when extending aperture synthesis to polarimetric radiometry.

Although cross-correlation between radiometers is the mainstay of our signal processing approach, signal models of impairments are configuration dependent. The WG will construct models that match specific functions, e.g., polarimetry, and configurations outlined above.

5. CALIBRATION

A major portion of the WG's effort will be devoted to calibration of the array and its implication for its elements. We briefly describe the need for measurement and correction of systematic errors in the following.

5.1. Clock synchronization

Evidently, cross-correlation requires that clocks for timing and sampling be synchronized among elements. If element spacing is large, so that each element is on a separate platform, e.g., a formation of aircraft or a constellation of satellites, then attention must be given to tying all on-board clocks to a common reference. Because in this case, the platforms are moving in sync, the manner in which time is distributed to each platform and its method of verification deserve consideration. In cases where all elements are situated on a single platform, consideration must be given to ensure that spurious cross-correlations do not occur due to noise from a common LO, or jitter from a common sampling clock that is distributed to all the elements.

5.2 Delay, gain and phase mismatch between elements

Mismatch between propagation delays among elements needs to be determined and corrected during the cross-correlation process. The WG will explore calibration methods that perform this function.

Mismatch in the complex gain between elements also needs determination and correction. Phase difference in gain between elements is equivalent to a delay that contributes systematically to error in angle. In extreme, if gains of two elements are in phase quadrature, a null results from cross-correlation regardless of the input. For the polarimetric case, phase correction between basis channels is significant, so as to not distort the polarization state of the input.

Each cross-correlation is scaled by the magnitude of the gain of the elements by the factor $(G_i G_j)^{1/2}$, so, for radiometric measurements, the mismatch in magnitude of the gain must be determined and corrected. Again, for polarimetric applications, the mismatch in magnitude of the gain between channels must be determined and corrected to minimize polarization distortion. These items lie within the scope of the WG as will an analysis of the impact of post-calibration residuals.

6. LIMITATIONS

The WG will describe limitations to synthetic aperture radiometry. These limitations arise from platforms and the scenes themselves. We have already described limitations on spacing between elements. Another type of limitation arises when the available correlation time is too short to either suppress unwanted noise adequately or to enhance the desired noise. For example, platform motion may not allow sufficient time for the scene to reside within the beam of the array. Else, the spatial and temporal variations of temperature in the scene are too rapid relative to the correlation time. The WG document will nod to these limitations.

7. SUMMARY

This paper describes the scope of the effort undertaken by the Synthetic Aperture Radiometry WG as it relates to synthetic aperture radiometry, in the framework of the newly formed IEEE Signal Processing Society Synthetic Aperture Standards Committee. We welcome participation and input from the community at large to the WG's effort in this discipline.

8. REFERENCES

[1] P3339 Synthetic Aperture Radiometry Working Group, [Online] https://sagroups.ieee.org/saradiometry [Accessed Jan. 20, 2023].

[2] A. Camps, "Microwave Aperture Synthesis for Earth Observation: Application for SMOS Mission," http://www.tsc.upc.edu/prs.

[3] S. Bonafoni, "Microwave Radiometry Imaging for Forest Fire Detection: a Simulation Study," *Progress In Electromagnetics Research*, Vol. 112, 77–92, 2011.

[4] B. Widrow, "Statistical Analysis of Amplitude-Quantized Sampled-Data Systems," *AIEE Trans. Control Systems*, pp 1-12, Jan. 1960.

[5] C. Bretherton, "The Effective Number of Spatial Degrees of Freedom of a Time-Varying Field," *J. Climate*, vol. 12, pp. 1990-2009, July 1999.

[6] N. Skou, D. LeVine, *Microwave Radiometry Systems: Design & Analysis*, 2nd Edition, Ch. 8, p. 78, 2006.

[7] J. Johnson, *et al*, "Microwave Radiometry at Frequencies From 500 to 1400 MHz: An Emerging Technology for Earth Observations", https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8244653/