Synthetic Aperture Radiometers

IEEE Synthetic Aperture Radiometry Study Group

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In our lick-off meeting in July, an overview acquainted us with radiometry. This exposure focuses on radiometers.

What Does a Radiometer Do?

- A Radiometer measures a static moment of a randomly varying electromagnetic distribution
  - The statistics of the distribution does not vary over the measurement period
  - All moments are static over the measurement period
  - The measured moment is the variance, σ^2, of the distribution. The (static) mean, $\bar{x}$, is filtered out by a band-pass filtering operation within the radiometer.

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We start with the what and how of a radiometer. This slide answers the what of a radiometer. It measures one of the moments of a random electromagnetic signal distribution. That distribution follows Planck's law and for frequencies at which the quantum of energy is smaller than thermal energy, the spectral distribution is uniform over a small fractional bandwidth. Inherent in this definition is the appearance of measurement period and the constraints that apply to it. One of the constraints is that the statistics governing the distribution does not change over the duration of the measurement period. In other words, over the duration of the measurement, if the distribution is uniform, it remains uniform and does not change to a Gaussian, Weibull, log-normal, Rician, or any other distribution. Second, the moments of the distribution are static during the measurement period. Because the moments are static in time, band-pass filtering in a radiometer eliminates the mean of the distribution and measures only the average square of the deviations from the mean, or the noise power.

How Does a Radiometer Do So?

- A Radiometer converts σ^2 to a DC voltage or numerical representation thereof
  - Conversion is non-linear (requires attention to handling of spurious products)

How the radiometer performs its function is by converting noise power to a DC voltage. This conversion is inherently non-linear and should alert the listener to spurious responses that accompany non-linear operations.

Operations Performed by an Ideal Radiometer

- Ideal Amplification
- (Non-linear) RF-to-IF Frequency Translation by ideal multiplier
- (Non-linear) Power-to-Voltage Conversion by ideal multiplier
- Ideal Filtering

Operations performed internal to every radiometer are amplification, frequency translation, power to voltage conversion, and filtering. In an ideal radiometer none of these operations generate internal noise of their own. Amplification and filtering are perfectly linear. Non-linear operations are confined to perfect multiplication.

In many developments the term "nonlinear" is used to connote behavior that is dependent on the amplitude of the input stimulus. This is different from the connotation here. The term as used here is to signify that time invariant system parameters such as gain are no longer time invariant but instead are modulated by random fluctuations generated within the system. Because gain multiplies the input stimulus to develop a response, there is a multiplicative effect in which the response involves a product of the stimulus with an independently time-varying gain.

Characteristics of Electronic Components

- Components generate internal noise of different physical origins
  - Transport-independent
    - Johnson
  - Transport-dependent
    - Shot
    - Generation/recombination (different spectral characteristics)
- Small-signal parameters of active components are bias dependent → Noise on bias modulates gain → Output response contains conversion products of input noise with internally generated noise (origin of noise in oscillators)
- Passive element values also subject to noise fluctuations that generate products with input noise (e.g., dielectric response related to dipole alignment that is subject to thermal fluctuations)

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In practice, components used to implement these operations do generate internal noise that combines either additively or multiplicatively with the noise of interest. In general, these internally-generated noises arise from various physical mechanisms and have spectral characteristics that differ in general from that of the noise of interest. Moreover, the internally-generated noise may often dominate the noise of interest. Nevertheless, the radiometer is sensitive to changes in noise in the scene.

Multiplicative noise arises from nonlinear effects that exist even with intended linear circuits. For example, small-signal transconductance or current gain of amplifying devices are known to be bias dependent. Therefore the resulting gain of the circuit is bias dependent. Noise on the bias lines modulate the gain of the circuit which multiplies the input stimulus to generate the output response. Thus, a multiplicative response arises that combines the externally applied input noise with the internally generated noise of the implementing devices. This causes effects such are frequency translation of internally generated noise into the band of interest. Such mechanism is responsible for phase noise seen in oscillators.

Such parametric effects are also manifest in passive components. For example, dielectric response originates from alignment of aggregates of atomic dipoles to an external field. However, this alignment can be dislodged by thermal motion of the lattice in which the dipoles reside, and this leads to fluctuations in the dielectric response and by extension in the capacitance of the component which contains said dielectric. Again, this time-varying capacitance multiplies the input stimulus to generate a response that is subject to the same conversion mechanism as in parametric amplifiers.

Impairment of Radiometer Operations

- Ideal amplification
  - Additive noise from transport-dependent physical mechanisms
  - Multiplicative noise from parametric conversion of internally generated noise to band of input noise
- Heterodyne conversion (implementation in computational domain preferred)
  - Added external and internally generated noise from image band
  - Added noise from intermodulation products (local oscillator)
- Square-law conversion (implementation in computational domain preferred)
  - Spurious products caused by deviations from perfect square law

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The effects from real devices compromise ideal operations in radiometers from both additive and multiplicative effects: in amplifiers additive noise from non-transport and transport mechanisms, and multiplicative noise from unintended non-linear behavior. In RF-to-IF and square-law conversion degradation is due to departure of the non-linearity from pure multiplication.

The Synthetic Aperture Advantage

- Internally generated radiometer noise uncorrelated between different radiometers in a synthetic aperture array
  - Correlation between radiometers suppresses internally-generated noise by amount related to duration of measurement period
  - Correlation enhances detection of input noise that illuminates all radiometers in the array while providing angle of arrival and distance information

Synthetic aperture techniques provide a partial antidote to these departures from ideal behavior because internally-generated noise in separate radiometers is uncorrelated. Thus, the contribution from additive uncorrelated noise vanishes if the outputs from such radiometers are correlated. Only the noise input that illuminates both radiometers simultaneously correlate to provide a response. This process requires adequate measurement time to average out the uncorrelated contribution to the noise.

Multiplicative phase noise may be handled by well-designed filtering that follows the squaring operation. Multiplicative amplitude noise needs more intricate handling.

Synthetic Aperture Cautions

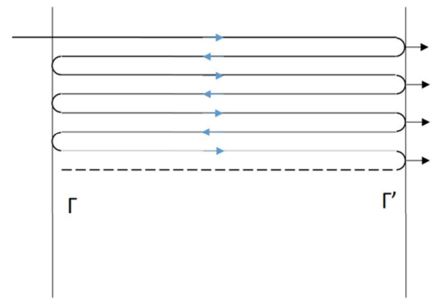
- Mitigate conditions that insert spurious correlations into the system
  - Focus on stimuli common to the array
    - Local oscillator (LO) distribution for RF-to-IF conversion (phase noise)
    - Sampling clock distribution for digitization (jitter)
    - Calibration signal distribution
  - Implementation features
    - Careful selection of filters and associated sampling rate
    - Mismatch (see next slide)

Although correlation provides a remedy for handling most of the internally generated noise, there are architectural and implementation considerations for ensuring that spurious correlations and offsets do not appear at the output. It becomes imperative to closely examine stimuli such as LO, sampling clock and calibration that are common to all array elements to ensure that spurious signals from these stimuli do not provide false correlations.

We addressed at the kick-off the inherent correlation among output samples due to the memory of the anti-aliasing filter. Such memory effect can arise from other causes as well. One of those causes is mismatch.

Spurious Correlation Owing to Mismatch

- Current amplitude is a linear superposition of past amplitudes multiple round-trip times earlier



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As the graphic shows, mismatch between two discontinuities that have reflection coefficients, gamma and gamma prime, causes multiple reflections between them. Such multiple reflections cause samples to consist of the current voltages as well as voltages present at multiple round-trip times earlier. This causes output samples to be correlated even if the input is not.

Situations such as these affect implementation decisions for synthetic aperture arrays. For example, it is well known that low-noise amplifiers (LNAs) have an optimum match for lowest noise. However, for no spurious correlation, gamma = 0. We may opt to use gamma = 0 and obtain poorer LNA noise performance with the understanding that extra internally generated noise may be correlated out. Such considerations also affect the choice of calibration source and its accompanying source match..

Aly's Presentation

- Synopsis of posted reference material (how it informs the standard)