Table 1: Normalised MSE [%] between symmetric (eqn. 12) and nonsymmetric (eqn. 5) receive filter designs for different receive filter lengths N_R and transmit filter excess bandwidth values α

N_R/α	0.1	0.2	0.3	0.4
9	0.0544	0.0226	0.0079	0.0018
11	0.0589	0.0259	0.0101	0.0030
13	0.1070	0.0449	0.0449	0.0035
15	0.1994	0.0783	0.0260	0.0043
17	0.1864	0.0753	0.0257	0.0047
19	0.2013	0.0872	0.0286	0.0031
21	0.2739	0.1106	0.0264	0.0002
23	0.2524	0.1100	0.0277	0.0002
25	0.1195	0.0522	0.0277	0.0003

SNR = 8dB, RRC transmit filter with N_{TC} = 25

Assuming a symmetric transmit filter for which the receive filter is to be optimised, we expect the symmetric receive filter coefficients (eqn. 12) to be practically the same as those for the nonsymmetric filters (eqn. 5). This is verified by a set of examples with different receive filter lengths N_R and transmit filter excess bandwidth values α. An AWGN channel with SNR = 8dB (i.e. no linear distortion) is assumed and the transmit filter was chosen to be an RRC filter of length N_{TC} = 25, employing the given α. The values of the normalised MSE between the two solutions are shown in Table 1. It is seen that the MSE difference is always < 0.3%, thus confirming that the resulting filters are the same for all practical purposes.

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Experimental validation of radiometric sensitivity in correlation radiometers

A. Camps, J. Bara, F. Torres, I. Corbella and F. Monzón

The prediction of the radiometric sensitivity of correlation radiometers based on the system parameters requires knowledge of the standard deviation of each measurement due to the finite integration time. Theoretical formulations have heen experimentally validated showing the dependence of the standard deviation with the measurement and extended for arbitrary oversampling factors.

Introduction: A correlation radiometer measures the complex cross-correlation of the random signals (thermal noise) collected by two antennas [1, 2]. Derivations of the standard deviation for each measurement due to thermal noise found in the literature are based on different assumptions or approximations. The formulation used in this Letter, derived in [3, 4], assumes two identical receivers, and that the normalised cross-correlation ($\mu = \mu_r + j\mu_i$) is measured. The standard deviations of μ_r and μ_i are given by

$$\sigma^2_{\mu_r} = \frac{1}{2\alpha_F^2 B\tau_{eff}}\left[1 + e^{-\pi\left(\frac{2\Delta f}{\sqrt{2B}}\right)^2} + \mu_r^2\left(1 + e^{-\pi\left(\frac{2\Delta f}{\sqrt{2B}}\right)^2}\right) - \mu_i^2\left(1 - e^{-\pi\left(\frac{2\Delta f}{\sqrt{2B}}\right)^2}\right)\right] \quad (1)$$

$$\sigma^2_{\mu_i} = \frac{1}{2\alpha_F^2 B\tau_{eff}}\left[1 + e^{-\pi\left(\frac{2\Delta f}{\sqrt{2B}}\right)^2} + \mu_i^2\left(1 + e^{-\pi\left(\frac{2\Delta f}{\sqrt{2B}}\right)^2}\right) - \mu_r^2\left(1 - e^{-\pi\left(\frac{2\Delta f}{\sqrt{2B}}\right)^2}\right)\right] \quad (2)$$

where B is the receiver noise bandwidth, α_F^2 is a filter type parameter ranging from 1 (rectangular-shaped filters) to $\sqrt{2}$ (Gaussian-shaped filters), $\tau_{eff} = \tau/Q$ is the effective integration time expressed as a fraction of the real integration time τ [5], $\Delta f = f_0 - f_{LO}$, f_0 is the centre frequency of the receivers and f_{LO} is the local oscillator frequency.

The main parameters of the interferometric radiometer under which the measurements were obtained are: f_0 = 10.68GHz, Δf = 0 (double-side band receivers, DSB), and normalised complex cross-correlations computed after I/Q demodulation with two baseband real 1bit/2 level (1B/2L) digital correlators. The frequency response is shaped at baseband with B_{BB} = 14.5MHz noise bandwidth lowpass filters ($B \simeq$ 29MHz, eqns. 1 and 2). With the former considerations, eqns. 1 and 2 reduce to

$$\sigma_{\mu_{r,i}} = \sqrt{\frac{1 + \mu_{r,i}^2}{\alpha_F^2 B\tau_{eff}}} \quad (3)$$

At this point it should be noted that:

(i) since the filter shape is not a perfect rectangle, nor a Gaussian, there is uncertainty in the α_F^2 factor [3]; Fig. 1 shows the measured frequency response of one LPF (Minicircuits PLP107) and the shape of a rectangular and Gaussian-shaped filter with the same noise bandwidth; it is apparent that the real filter more closely resembles the rectangular filter.

(ii) theoretical values for Q are given in the literature only for oversampling factors f_s/B = 2 and 4, as 2.46 and 1.82, respectively [5].

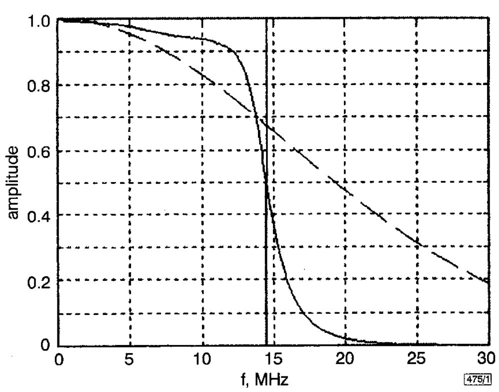

Fig. 1 *Frequency response of three lowpass filters with same noise bandwidth B_{BB} = 14.5MHz*

——— Minicircuits PLP107
– – – – Gaussian-shaped filter
Rectangular-shaped filter also shown

Effect of oversampling on τ_{eff}: To perform this measurement, RF uncorrelated noise is injected into both channels to obtain a zero mean cross-correlation $\mu_r = \mu_i = 0$. $\sigma_{\mu_{r,i}}$ is then computed out of 100 measurements at each integration time within the range 0.1s ≤ τ ≤ 1s. Finally, these measurements were repeated for different oversampling ratios (clock rates f_s = 29, 37, 50, 66.66, and 80MHz). Measured values of $\mu_{r,i}$ were then fitted to eqn. 3 by parallel straight lines (log-log plot) of slope –0.5. In principle, the effective integration time can then be determined, since the noise bandwidth and the integration time are known. Setting α_F =1, the measured values are $Q(f_s/B = 2) = 2.40$ and $Q(f_s/B = 4) = 1.81$, which compare very well with the theoretical values 2.46 and 1.82 [5]. If we force the theoretical value, $Q(f_s/B = 2) = 2.46$, then $\alpha_F = 1.012$, a value that is very close to 1, which corresponds to rectangular-shaped filters (Fig. 1).

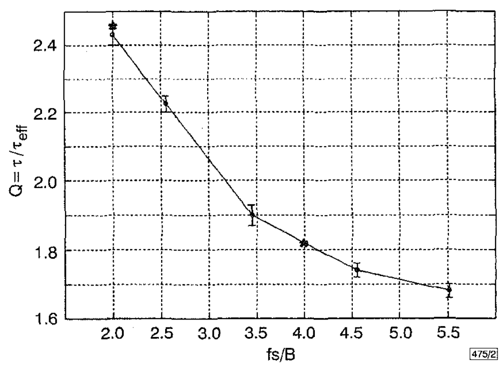

Fig. 2 *Measured 1B/2L digital correlator's effective integration time improvement with increasing oversampling factor*

✳ theoretical values [5]

Fig. 2 shows the measured values of Q against the oversampling ratio f_s/B. Uncertainty bounds are due to the uncertainty in the filter parameter α_F. Provided that $1B/2L$ digital correlators are used, such as in the L-band microwave imaging radiometer by aperture synthesis (MIRAS) currently under study at ESA, eqns. 1 and 2 can be more precisely evaluated from a more accurate value of the effective integration time. Note that the improvement achieved by means of oversampling reaches a saturation value $Q \simeq 1.65$ for $f_s/B > 5.5$.

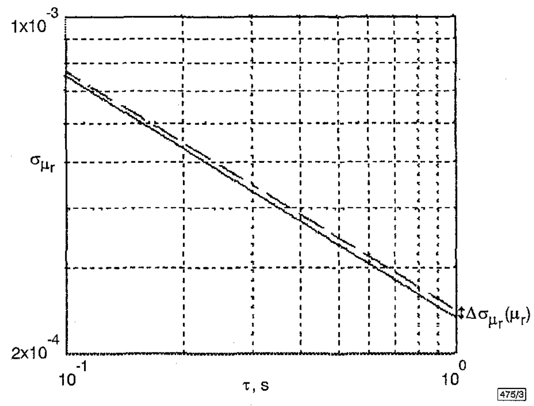

Fig. 3 *Standard deviation of* μ_r *for* $\mu_r = \mu_i = 0$ *and* $\mu_r \simeq 0.22$, $\mu_i = 0$

$f_s = 80$MHz, $B_{BB} = 14.5$MHz
——— $\mu_r = \mu_i = 0$
– – – – $\mu_r \simeq 0.22$, $\mu_i = 0$

Dependence of $\sigma_{\mu_{r,i}}$ *on actual measurement:* The dependence of $\sigma_{\mu_{r,i}}$ on the actual measured complex cross-correlation is given by the second and third addends in eqns. 1 and 2, or by eqn. 3 for DSB receivers. This dependence was verified by injecting correlated noise, generated by a 50Ω matched load at ambient temperature, to a nonresistive power splitter connected to both receivers. In our interferometric laboratory prototype the phase is calibrated by means of an adjustable phase shifter inserted in the *LO* branch of one channel, so as to obtain a real correlation ($\mu_i = 0$) [6]. For a matched load connected to receivers through a non-resistive power splitter, $\mu_r \simeq 0.22$, a value which is much lower than unity, mainly due to the noise temperature of the receivers [6].

Fig. 3 shows the measured values for σ_{μ_r} when uncorrelated noise is injected $\mu_r = \mu_i = 0$, or the phase shifter was set to obtain $\mu_r = 0$, $\mu_i \simeq 0.22$ (continuous line), and when the phase shifter was set to obtain $\mu_r \simeq 0.22$, $\mu_i = 0$ (dashed line). Note the increase in the standard deviation by a factor $\sqrt{[1 + \mu_r^2]}$. Similar results are obtained for σ_{μ_i}. Note that this increase is only significant for large correlation values (e.g. during calibration), and can be neglected for most measurements since $|\mu| \ll 1$, typically $|\mu| \simeq 10^{-4} - 10^{-2}$.

Conclusions: In this Letter we have presented an experimental verification of the theoretical formulation found in the literature to predict the radiometric sensitivity of correlation radiometers (e.g. interferometric and polarimetric radiometers), showing its dependence on the actual measurement. In the important case of 1B/2L digital correlators (the simplest correlators owing to their ease of integration and low power consumption), the improvement in effective integration time by means of oversampling has been assessed. Excellent agreement is found with theoretical values at $f_s/B = 2$ and 4. We have also discovered a saturation effect which occurs at $Q \simeq 1.65$ for oversampling factors > 5.5.

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Fully blind estimation of time delays and spatial signatures for cyclostationary signals

Yu Hongyi and Bao Zhang

A novel estimation of time delays and steering vectors is developed for cyclostationary signals, in the case when an array manifold and signal waveform are completely unknown. Simulation results show that the estimates are reliable.

Introduction: Recently, the joint estimation of time delays and spatial features has attracted much attention [1, 2] and, in most of the work, either signal waveforms or both the array manifolds and signal waveforms are *a priori*. However, in many scenarios, array manifolds and signal waveforms cannot be exactly determined. In this Letter, we consider the situation in which the array manifold and signal waveform are unknown and the desired signals exhibit some kind of cyclostationarity, while undesired signals and noise do not have this property. In fact, most man-made signals in many fields, such as communication, radar and sonar, exhibit cyclostationarity. Based on the property of multipath signal cyclic spectral correlation matrices, a novel method for the blind estimation of time delays and spatial signatures is proposed. This