Astrophysical Phenomena Revealed by Space VLBI
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Noise Reduction in the Presence of Strong Spectrally-Isolated Signals

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Abstract

Observational and theoretical study of data taken with VSOP and ground radio telescopes, and correlated with the DRAO correlator at Penticton, shows that the addition of a strong, spectrally-isolated signal can significantly reduce the noise level in other spectral ranges. We describe this process, and suggest applications for novel detection experiments and hardware.

1 Introduction

Interferometry is based upon correlation of signals from astrophysical sources at different locations. Those signals are noiselike: the signal at any instant is drawn from a Gaussian distribution. Unless the signals at the two locations are perfectly correlated, they are drawn from a covariant Gaussian distributions. The covariance of the distributions is the average correlation, the quantity that interferometry seeks to measure.

Radio-astronomical signals are nearly always digitized; in other words, they are sampled to form a discrete time series, and quantized to a finite set of possible amplitudes. Sampling limits the frequency range that can be represented. Quantization reduces the signals that can be represented within that frequency range, and therefore adds noise. For continuum signals, effects of quantization on signal, noise, and derived correlation are well understood (see, for example, Thompson et al. 1986).

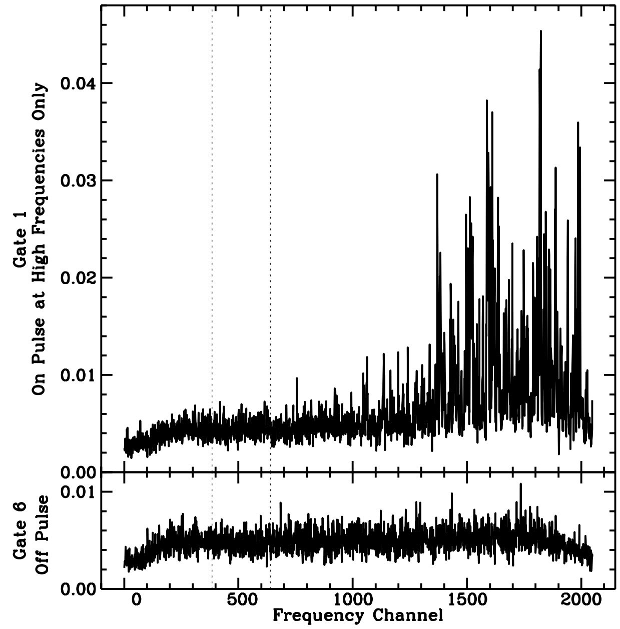

Figure 1: Spectra in gates "on" and "off" pulse. Upper panel: Gate is on pulse. Because of pulse dispersion in the interstellar plasma, the pulse has arrived only at high frequencies (high channel numbers). Scintillation produces ragged spectrum. Lower panel: Gate is off pulse. From Gwinn et al. 2000.

Radio-astronomical signals often vary spectrally. This spectral variation can be represented as covariances between the Gaussian-distributed signals observed at different times; indeed, correlation spectroscopy and spectral-line interferometry rely on measurements of these temporal correlations. A Fourier transform forms cross-power spectra from these temporal correlations. ("FX" correlators Fourier transform the signals before correlation to produce essentially identical power spectra.) In either case, noise from quantization affects the final spectrum.

Figure 1 shows cross-power spectra for the Vela pulsar, taken on the Tidbinbilla-Mopra baseline as part of VSOP observations, on 1997 December 10. The data were correlated at the Canadian VLBI correlator in Penticton, British Columbia. Correlation functions were formed in gates synchronized with the pulse, with widths of 1 msec. Because the pulsar signal varies strongly each pulse, quantizer levels are different, as expressed in terms of the standard deviation of the input signal, on

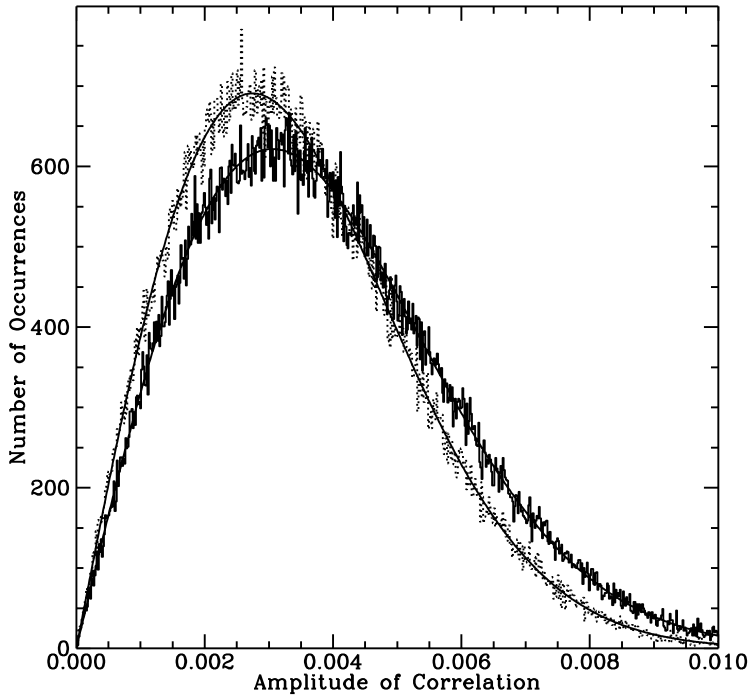

Figure 2: Noise in spectra shown in Figure 1, from channels between the vertical lines in that figure. Solid curve: Noise in "off" gate. Dotted curve: Noise in "on" gate, with pulsar. Histograms show amplitude of correlation; curves show results of fits for Gaussian noise. From Gwinn et al. 2000.

and off pulse. The effect is greatest at learge-aperture antennas, such as Tidbinbilla. Correlation in a gate near the beginning of the pulse detects strong, scintillating signal at high frequencies and no signal at low frequencies because of interstellar dispersion. Correlation in a gate off pulse shows only noise.

2 Quantized Spectrally-Varying Noise

Statistics for correlation of quantized, spectrally-varying, noise differ from those for continuum noise. We have computed these statistics, and compared results with computer simulations and with observations (Gwinn et al. 2000). We consider cross-correlation of two signals (or auto-correlation of one); we suppose that each signal is complex, and consists of spectrally-varying Gaussian noise. Variance and covariance as a function of frequency thus completely characterize the signals.

When formed from many samples, the cross-power spectrum is drawn from a Gaussian distribution at each frequency, and is completely characterized by its average and variance. The average of the cross-power spectrum, over many realizations, is proportional to that of the unquantized signals (or is related linearly, for an autocorrelation). The variance of the spectrum depends on the spectra of the signals, and on the quantizer levels. Specifically, the variance of the noise of the cross-power spectrum is a product of linear functions of the normalized autocorrelation spectra of the two signals.

When a strong, spectrally-isolated signal appears in part of the band, the noise in the remainder of the band is actually reduced. This fact is predicted theoretically and observed in observations of the Vela pulsar, where dispersion causes the signal to appear first at higher frequencies (Gwinn et al. 2000). Figure 2 shows noise for the same spectral region, for the two spectra shown in Figure 1. The spectrally-isolated signal 'attracts' some of the noise added to the signal by quantization.

The fact that adding a noiselike signal in one part of the band reduces noise in another suggests the possibility of deliberately adding spectrally-clean, narrowband noise to the signal before quantization. The noise need not be identical, or even correlated, between stations; however, use of the recorded band is most efficient if noise is added to the same frequency range before correlation. Related 'dithering' techniques have been used in high-end digitization techniques, including commercially available sampling oscilloscopes (Bartz 1993). For 4-level digitization the theoretical improvement in SNR is about 20%, representing an approximately 10% increase in dish diameter.

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