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Solar Radio Spectrography: Comprehensive Diagnostics for Space Weather Applications

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Abstract

In the framework of Space Weather, the radiophysics of solar radio emissions provides key information on solar energetic processes, allows to estimate their direct geoeffectivity as radio interferences, and to use them as precursors and proxies of energetic particle events. In this framework, we briefly review the diagnostics by solar radio spectrography, emphasising the wealth of physical information that can be derived upon suitable working hypotheses.

1 Introduction

Both the quiet and the active Sun originate a variety of radio emissions by thermal and non-thermal mechanisms [1], most of the latter ones associated with energetic phenomena. Hence, solar radio emissions provide a wealth of key information on these processes and, specifically, on plasma parameters at the source and along the propagation path from the Sun through the Heliosphere [2, 3, 4]. The relevance of solar radio physics for Space Weather science and applications is intrinsic to the fact that, on one hand, it provides fundamental tiles for a comprehensive modelling of energetic phenomena like, e.g., flares, prominence eruption, Coronal Mass Ejections (CME), and their precursors (when existing), and, on the other hand, upon suitable physical hypotheses it can foster the nowcasting and forecasting of solar energetic particle acceleration and CME propagation. Similarly, the prompt detection and characterisation of solar radio bursts in specific radio bands is a must for evaluating their interfering capabilities for radio communications with special attention to GPS signal degradation [5]. Solar radio observations can be carried out according to three main operational categories according to the instrument architecture: (1) multi-frequency radiometry; (2) radio spectrography; (3) radio imaging. The measure of Circular Polarisation sense and percentage is a must for a complete characterisation of solar radio emission mechanisms and propagation, but unfortunately it is available only in a subset of existing instruments. In the following, we briefly review the physical parameters that can be derived from solar radio spectrographs to point out the potentialities of such observations and their interpretation.

2 Characteristic Parameters of a Solar Radio Spectrum

A solar radio spectrum consists of the evolution of the radio flux density in the frequency-time domain (Figure 1). Hence, radiometric and polarimetric information is provided, but no spatial location of the source is available, apart from an indirect derivation of the radial altitude based on an adopted semi-empirical electron density model and on a specific radio emission model. Notwithstanding, many physical information on the source and background plasma are intrinsic to the radio spectrum as detailed in the following schematic description.

2.1 Time Domain

Total duration (Figure 1-A)

$$\Delta t_{tot} = t_{end} - t_{start}$$

Inferences: global geometry, energetics and evolution of the emission process(es).

Instantaneous duration (Figure 1-B)

$$\Delta t_{inst} = \Delta t|_f$$

Inferences are: local geometry, energetics and process(es) at the perturbed layer.

Instantaneous duration evolution in frequency:(Figure 1-C)

$$\Delta t_{inst}(f) = \frac{\partial \Delta t_{inst}}{\partial f}$$

Inferences are: - exciting agent dynamics; - density model and process(es) along trajectory; - propagation effects in medium.

2.2 Time at Single Frequency Domain

Radio flux density time profile at specific frequency $f = f_0$ (Figure 2-A)

$$S_f = S_f(t)$$

Inferences are: - response of the perturbed layer; - evolution of the instability; - diagnostics of the process.

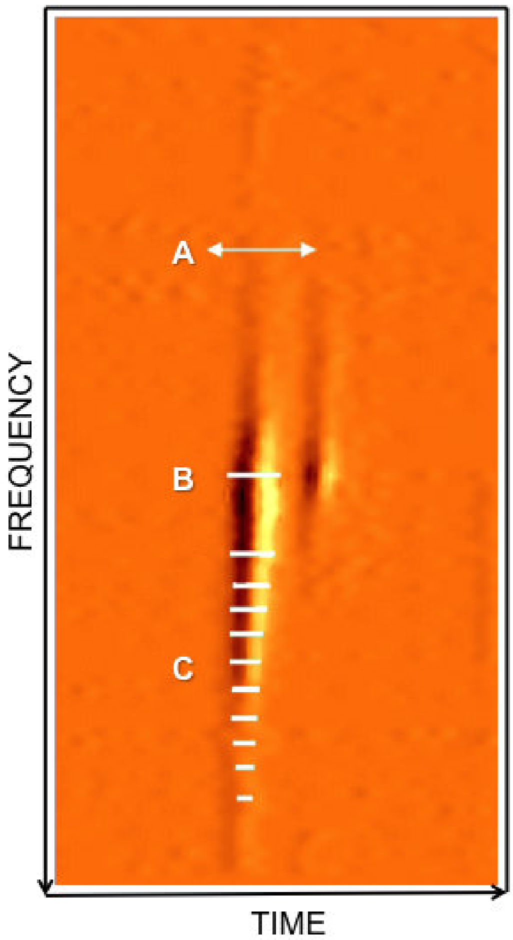

Figure 1. Simulated radio spectrum of fast frequency drift features. (A) Total event duration; (B) Instantaneous duration; (C) Evolution in frequency of instantaneous duration.

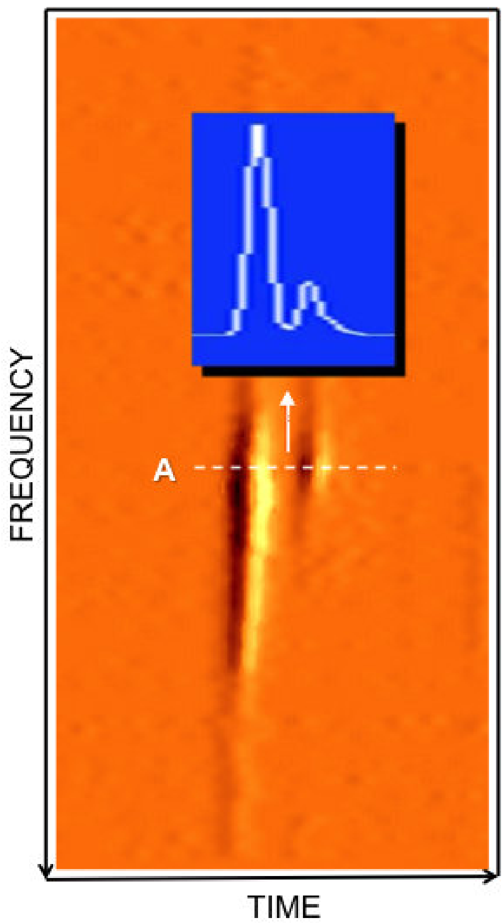

Figure 2. Same as in Figure 1. (A) Time evolution of radio flux density at a specific frequency $f = f_0$.

Polarisation time profile at specific frequency $f = f_0$

$$P_f = \frac{S_f^L(t) - S_f^R(t)}{S_f^L(t) + S_f^R(t)} = P_f(t)$$

Inferences are: - local geometry of perturbed layer; - local magnetic field; - local propagation effects.

Evolution of LCP, RCP modes delay in time domain and in frequency domain

$$\delta \dot{t}_{LR} = \frac{\partial t_{LR}}{\partial t}$$

$$\delta t_{LR}|_f = \frac{\partial t_{LR}}{\partial f}$$

Inferences are: - density model, propagation effects, and local process(es) along trajectory; - propagation effects in medium.

2.3 Frequency Domain

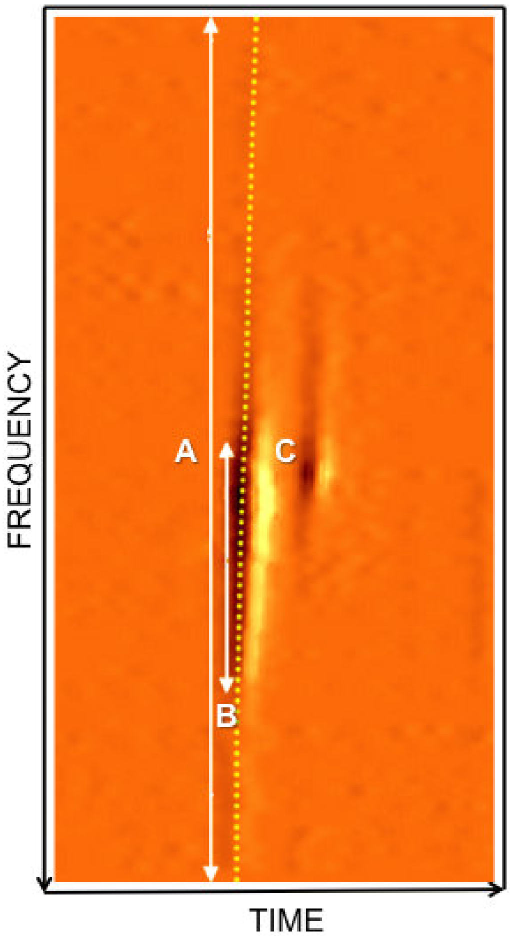

Figure 3. Same as in Figure 1. (A) Maximum event bandwidth; (B) Instantaneous event bandwidth; (C) Frequency drift.

Maximum bandwidth (Figure 3-A)

$$\Delta f_{\max} = f_{\max} - f_{\min}$$

Inferences are: global geometry, density model, and process(es) in the perturbed region.

Instantaneous bandwidth (Figure 3-B)

$$\Delta f_{inst} = \Delta f(t)$$

Inferences are: local geometry, density, and process(es) in the perturbed layer.

Frequency drift (Figure 3-C)

$$\dot{f} = \frac{\partial f}{\partial t}$$

Inferences are: - exciting agent dynamics; - density model and local process(es) along trajectory; - propagation effects in medium.

Frequency drift evolution

$$\ddot{f} = \frac{\partial^2 f}{\partial t^2}$$

Inferences are: - instability evolution; - density model and local process(es) along trajectory; - propagation effects in medium.

2.4 Energy Domain

Total power density (Figure 4-A)

$$P_{tot} = \int_{f_{min}}^{f_{max}} \int_{t_{\min}}^{t_{max}} S(t,f)\, dt\, df$$

Inferences are: global energetics of perturbed region (process(es) energetics; source model; instability character).

Spectral power density at $t = t_0$ (Figure 4-B)

$$P_t = \int_{f_{min}}^{f_{max}} S(t,f)\, df$$

Inferences are: instantaneous energetics of perturbed layers (global response of layers at time $t = t_0$; local process(es)).

Spectral power density at $f = f_0$ (Figure 4-C)

$$P_f = \int_{t_{min}}^{t_{max}} S(t,f)\, dt$$

Inferences are: energetics of single layer (response of single layer at frequency $f = f_0$); process in layer).

3 Comprehensive Diagnosing

As concisely described in the previous Section, the interpretation of solar (and interplanetary) radio spectra can provide a comprehensive set of diagnostics about the radio source, the perturbed region, the emission process(es), the crossed medium, and propagation effects, based on the analysis of the radio flux density and polarisation evolution in the time-frequency domain. Furthermore, the energetics of the radio emission is related to the exciter at the source. Anyway, it must be stressed that the consistency of the diagnostics is strictly dependent on the working physical hypotheses that have been adopted. In particular, the electron density in the solar corona has not been directly measured, and a set of semi-empirical models have been used. Another important gap is the lack of polarisation measurements as well as the availability of interplanetary radio measurements.

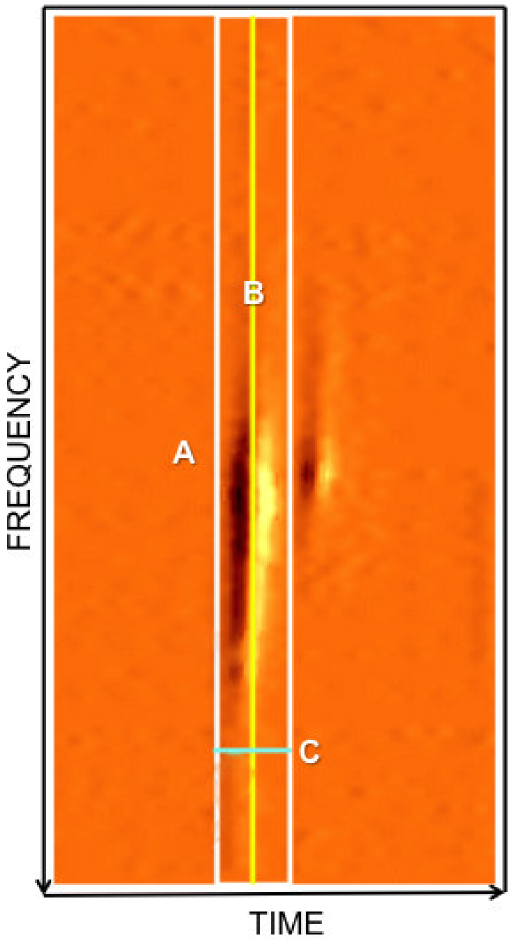

Figure 4. Same as in Figure 1. (A) Total power density of event; (B) Spectral power density at specific time $t = t_0$; (C) Spectral power density at specific frequency $f = f_0$.

4 Conclusions

Radiophysics of solar radio spectra has proven to provide powerful diagnostics of geoeffective solar phenomena via the analysis of solar radio events. Hence, solar radio spectrography plays a fundamental role in Space Weather monitoring and forecasting. Advancements both in theoretical modelling and in observational techniques are expected to significantly improve the physical information that can be derived.

5 Acknowledgements

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