Radar Signals Analysis and Modellization

in the

Presence of JEM Application

to

Civilian ATC Radars

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ABSTRACT

This paper describes the application of a simulation software and the comparison of its results with actual data recorded from operating ATC radars in S and L bands. Results obtained in an application on actual signals (relative to commercial aircraft echoes) collected from observations on the echo received at an ATC radar system are presented. These signals were recorded along many field experiments carried out by the authors on a recording system specifically developed for this purpose.

Due to the constitutive and operative characteristics of the systems, the results are affected by a low spectral resolution and a strong aliasing which give rise to problems in a correct analysis. The observed results have been related to the physical phenomena generated by the structure of the complex target we suppose to be made of a rigid body and rotating parts which originate such a modulation on the echo signal that it is known in related literature as Jet Engine Modulation (JEM). These phenomena may be regarded as a signature of the particular couple "engine-aircraft body" and in some flight conditions may offer significant help to a correct characterization of the aircrafts.

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INTRODUCTION

Air traffic has steadily increased in these past years so that the need to optimize the amount of information which can be extracted from a radar system has become pressing.

The problem of air target spectra characterization and how these spectra can be exploited both for detection enhancement ant target identification, is challenging.

It is well known that the rotating propellers or compressor blades of aircraft engines introduce modulation phenomena on the aircraft spectral response. With reference to jet powered aircraft taken into account, these phenomena are known in related literature as Jet Engine Modulation (JEM) [1]. It is possible to verify that such energetic components of the spectral response can be regarded as modulation effects due to the first stage of the engine fan [2].

It has been observed that such phenomena are deterministic and supply a considerable contribution to the total energetic content of the signal and it is reasonable to think these being related to the particular couple

Table 1. Radar Parameters

Name	ATCR-33K	ATCR-44K
Location	Fiumicino	Linate
Frequency	2.76 GHz	1.27GHz
Band	S	L
Peak Power	1.2 MW	1.2 MW
Rotation speed	15 RPM	6 RPM
Unamb. range	80 NM	150 NM
Beam Width	1.5 deg	1.2 deg
Pulse length	1 μs	1.5 μs
PRF (Average)	1000 Hz	446 Hz
Time on Target	16.6 ms	33.3 ms
Sweep on Target	17 Sweeps	15 Sweeps

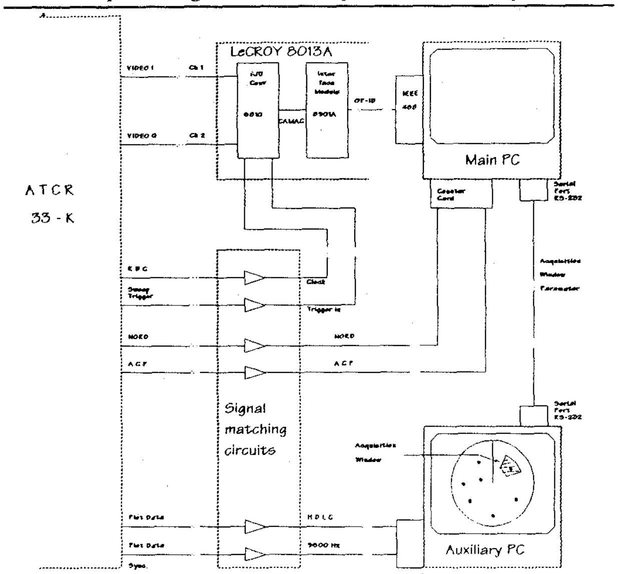

Fig. 1. Acquisition System Layout

"engine-aircraft body" may be regarded as a signature used for classifiation of targets [3].

An electromagnetic model of the backscattered signal of an incident radar wave by rotating blades may assume each blade to act as a rigid, homogeneous linear antenna [4]. Each point P of this antenna causes a Doppler shift of the radar frequency according to its instaneous velocity. This formulation neglects diffraction effects from ends of the line and constitutes a physical optics approach [5].

In order to compare this model to actual data, the aircraft body response (i.e., RCS, Doppler shift) and the radar equipment pre-processing (i.e., antenna lobe, pulse shape, undersampling) have to be added to the model.

EXPERIMENTAL MEASUREMENTS

In order to validate both in a qualitative and quantitative sense, the phenomena explained above, numerous measurement campaigns have been effected on S and L band systems.

The main objective of these campaigns was to gather various targets (civilian, military, turbojet and turbofan aircrafts, sea and land clutter) in different operative conditions of the system and to obtain a data base for evaluation of statistical parameters useful for the signal characterization.

For this reason, a flexible recording tool has been developed [6]. This tool has been designed with particular consideration for aspects of portability and adaptivity to various radar systems. It is based upon a Personal Computer and a fast A/D converter which is able to acquire both "in phase" and "in quadrature" (I and Q) video channels.

The layout of this recording tool is illustrated in Figure 1 as connected to an ALENIA ATCR 33-K system. In this sketch an Auxiliary PC can be identified; it provides an on-line decoding and PPI presentation of Plot Data which comes out from the system's extractor.

Measurement campaigns were carried out at Fiumicino Airport in Roma and at Linate Airport in Milano, Italy. In Table 1 some of the parameters of the two radas involved in the experimental setup are reported.

Results reported here are mainly concerned with the S band radar [7].

A few words about the recording procedure are useful. Once the target has been designated, automatically the recording equipment, using the information coming from the tracking PC, centers the window on the aircraft estimated position and records the I and Q signals belonging to that window. The process of centering the window and recording is repeated at any antenna turn, until the operator stops it. A number of auxiliary informations about the setting of the recording equipment and environment is recorded among with raw data.

Off-line, from the original window, a subset of I and Q data, containing only one target, is isolated for subsequent analysis. To detect moving targets from clutter, a clutter canceller is applied to the video signal samples [8].

SPECTRAL ANALYSIS OF ATC RADARS ECHOES

In the case of JET-powered aircraft the rotating blades of fan and turbines are internal to the engine ducts and thus the visibility depends on the aspect angle, while in turboprop-powered aircraft the rotating blades are always exposed. In either case the spectral signature is controlled – in addition to the RCS – by the dimensions, geometry, number of rotating blades and by the rotation speed [5].

The phenomena called Jet Engine Modulations (JEM), have a general validity and can be observed in a large majority of measurements, at least for S-band systems which were mainly considered. In any case, the characteristics of an ATC radar raise some problems for correct interpretation of information present in the spectral response. In particular, the low Pulse Repetition Frequency (PRF), about 1 Khz, typical of ATC systems, strongly limits the unambiguous band of the spectrum and

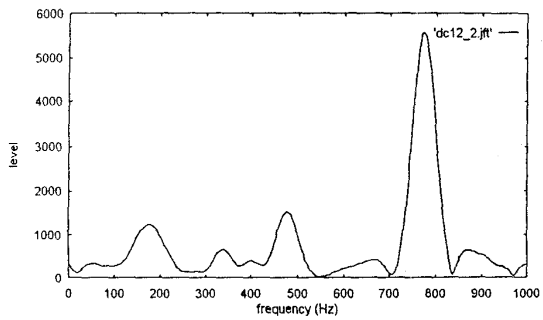

Fig. 2. Typical Spectrum for Turbo Jet Aircraft (DC9) in S-Band

cause aliasing effects which are present both for Main Doppler Line (MDL) and for JEM lines. Moreover a dwell time (related to the antenna main lobe) of a few tens of milliseconds cause poor spectral resolution.

As a general result for aircraft with head-on aspect, Doppler spectra show that the upper side band contains a higher energetic contribution than the lower side band [9] and this asymmetry can be related to the blade pitch of the propeller [10, 11].

Because of the operative characteristics of ATC radars, there are no more than 32 independent samples for each target acquired upon successive sweeps. On these samples, an interpolated FFT – over 512 points – has been calculated and generates a spectrum on which the various modulation components can be detected. Figure 2 pesents a typical spectrum for a jet aircraft.

The correct attribution of MDL has been made possible from kinetic considerations, integrating the same target over more scans and making use of auxiliary information. From this analysis it follows that MDL, for the majority of cases, is the component with the highest energetic contents, even if there are cases in which JEM contents are higher than Main Doppler.

Measurements on an L band system have been carried out. Although data analysis is still in progress, it seems that modulation phenomena appear to be much less evident than in S band radar. Figure 3 shows an example for an approaching B737 aircraft at a range of 27 n mi.

MULTISCANNING COMPARISON

From previous considerations, it follows that an en-route aircraft, recorded in various positions of its path, give rise to a spectral resopnse which has a rigid translation according to the change of Doppler frequency, while the Jet Engine Modulation (JEM) spacing, which is characteristic even on ambiguous spectrums.

In Figure 4, spectra of the same aircraft in different positions are shown. The highest lobe is the Main Doppler Line (MDL), the side lobes are due to JEM effect. It is possible to see how the spectra have similar shapes; in the sixth record no modulation appears because there is no geometric visibility of the fan from the radar.

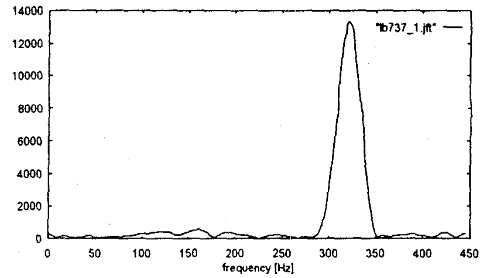

Fig. 3. Example of Spectrum from an L Band ATC Radar (B737 Turbojet Aircraft, Record LB737-1)

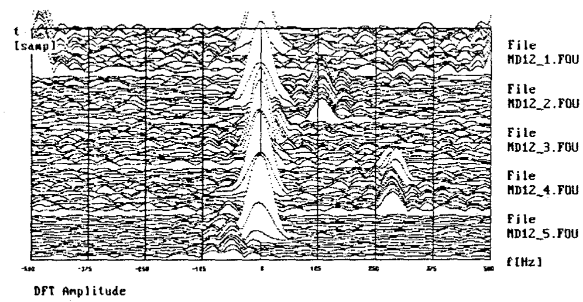

Fig. 4. Superimposed Spectra of the Same Aircraft in Different Positions of Its Path

This is true when the target is on-course, when its speed is constant and the JEM frequency spacing follows the relation:

$$\Delta f = n_b \, \omega r / 60 \ [\mathrm{Hz}] \qquad (1)$$

Where

- d_b number of blades;
- ωr[RPM] rotation speed;

SIMULATION MODEL

For signal simulation, a model well known in literature [4, 10, 12, 13] has been used with slight modifications in order to use it with ATC radar and to consider actual target made by a large body and some rotating engines [8, 11, 14].

The simulation model involves several parameters of the radar-target system. In particular, the following hypothesis for radar equipment have been considerd:

- Pulse Dopper Surveillance Radar with coherent pulses;
- Rotating antenna with ideal vertical radiation pattern;
- Horizontal radiation pattern $G(\Theta)$ given (for instance Gaussian or sinc^2);
- Pulse shape $I(t)$ given (for instance Gaussian or rectangular).

The parameters which characterize radar equipment for modeling purposes can be summarized as follows:

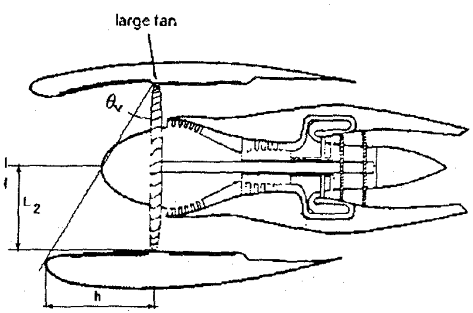

Fig. 5. Turbofan Engine and Its Ducts

- fo [Ghz] carrier frequency;
- PRF [Hz] Pulse Repetition Frequency;
- Tr [s] antenna rotation time;
- ΘB [deg] half power antenna beamwidth;
- T [ms] pulse width;
- G(i) antenna lobe shape (i = index of the sweep emitted) e.g.:

$$G(i)= sinc^2[\frac{2p}{PRF \cdot T_r q_B} i] or \quad G(i)= e^{-2.776[\frac{2p}{PRF \cdot T_r q_B} i]^2} \qquad (2)$$

- I(t) Pulse shape for each sweep emitted e.g.:

$$I(t)= Ae^{-\frac{2}{\tau^2}t^2} \quad or \quad I(t)= rect(\frac{1}{t}t) \qquad (3)$$

The hypotheses about the target refer to a commercial aircraft with turbofan or turbo-propeller engines. In the case of JET-powered aircraft the rotating blades of fan and turbines are internal to the engine ducts, in the case of turboprop-powered aircraft the rotating blades are exposed. We can define a visibility function of the fan based upon Figure 5. The simplest function is zero for aspect angles less than ΘV and one for aspect angles greater than ΘV.

The following parameters can be used to characterise the target:

- V [kn] Target ground speed;
- Θ[deg] view angle which is positive if the aircraft is approaching, negative if departing, zero if transverse view (Figure 6);
- D [n mi] positon in range i.e., distance from target to radar;
- ϕP [deg] engines blades pitch angle;
- L1 [m] radius of engine nozzle;
- L2 [m] radius of engines main rotor (i.e., length of the blades plus nozzle radius);
- N_b number of blades;
- V(Θ) FAN visibility function;
- wr [rpm] rotation speed;
- k″ constant indicates the amplitude of return signal due to engines scaled to the one due to body.

The model used for the single sweep i can then be expressed as:

$$s_i(t)= A \cdot I(t - iT) \cdot G(i) \cdot e^{j(2\pi f_d t - \frac{4\pi f_0 D}{c})} \cdot [1 + V(\theta) K'' \sum_{n=0}^{N-1} s_{ni}(t)] \qquad (4)$$

where, for each blade n, the term sni(t) is given by

$$s_{ni}(t) = \left[\alpha + \beta \cos\left(\omega_r t + \frac{2\pi n}{N}\right)\right] \cdot \operatorname{sinc}\left[\frac{4\pi f_0}{c} \cdot \frac{(L_2 - L_1)}{2} \cdot \cos(\theta) \cdot \sin\left(\omega_r t + \frac{2\pi n}{N}\right)\right] \cdot e^{-j2\pi \frac{(L_2+L_1)}{\lambda} \cos(\theta) \sin\left(\omega_r t + \frac{2\pi n}{N}\right)} \qquad (5)$$

where

- fd [Hz] Doppler frequency shift due to target speed;
- C [m/s] light speed;
- λ [m] radar wavelength; and

$$\alpha = \sin(|\Theta| + \Phi p) + \sin(|\Theta| - \Phi p);$$
$$\beta = - \operatorname{sign}(\Theta) [\sin(|\Theta| + \Phi p) - \sin(|\Theta| - \Phi p)]; \qquad (6)$$

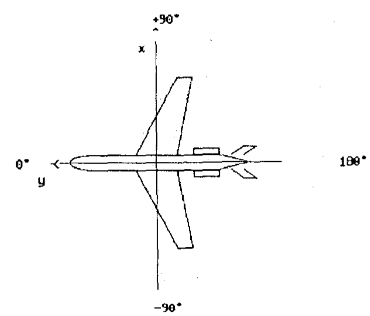

Fig. 6. View Angle Definition

SIMULATION RESULTS

In order to present the analysis results some further considerations shall be done:

1. Fan blades are often partially hidden by the ducts, but in any case half of the visible blades move toward the radar and the other half move away from the radar (Figure 7, on next page).

2. As is shown in Figure 8, because the blade is designed to generate an air flow moving from forward to rear, if the propeller (or the fan) is observed with a positive view angle, the visible surface of the blade – from an optical point of view – moving away from the radar is larger than the other one that is moving toward the radar, but the energetic contribution of this blade – at the ATC radar frequencies – is greater, and that is probably due to the cross section of the leading edge that is greater than the one of the trailing edge [10, 15].

Figure 9 shows the simulation of return signal from a B747 aircraft with CF6-50E engines illuminated with the S-band ATCR-33K radar superimposed to the actual signal of an aircraft of the same type having the following parameters: V = 501.6 km, Θ = 64 deg; D = 40.8 n mi, ϕp = 35 deg, L1 = 0.35 m; L2 = 1.1 m; N = 38; ωr = 3330 RPM and K″ = 0.4.

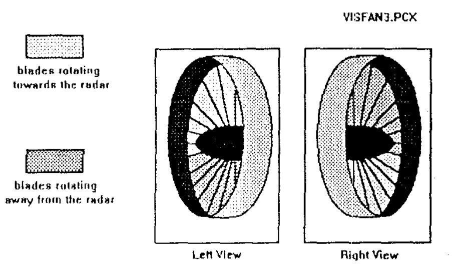

Fig. 7. Fan Blades Partially Hidden by the Ducts. In Grey, Half of the Blades Move Away from the Radar, in White, Half of the Blades Move Toward the Radar

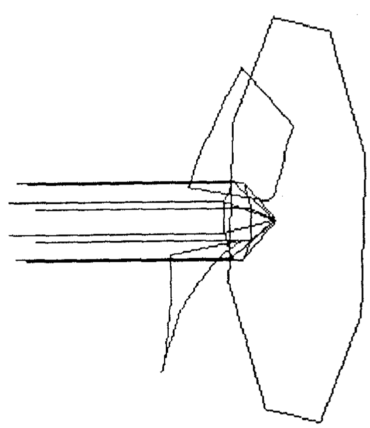

Fig. 8. Twisted Blades Showing Different Edges. The Blade in the Upper Side of Figure is Moving Toward the Radar and is Showing the Leading Edge (Thick Line). The Blade in the Lower Side is Moving Away from the Radar and Shows the Aerofoil Surface and Its Trailing Edge

It can be seen that the simulation model and the recorded signal present a good match, at least in amplitude, while very poor considerations about the phase can be done.

Figure 10, on next page, shows the Fourier spectra of the simulated and actual signals of Figure 9. In this figure it can be seen how the Doppler and JEM lines match (even in the asymmetry of spectrum).

With the L-band radar parameters the JEM phenomenon cannot be detected, and it has to be remarked that this result is in accord with our actual L-band data that do not show JEM line.

Figure 11 on next page, as an example the Fourier spectrum of an L-band actual signal and the superimposition to a spectrum generated by an aircraft having the same characteristics of the actual one, as it follows: v = 296.8 km; Θ = 44 deg; D = 26.61 n mi; ϕp = 30 deg; L1 = 0.13 m; L2 = 0.54 m; N = 27; ωr = 7546 RPM; and K″ = 0.4.

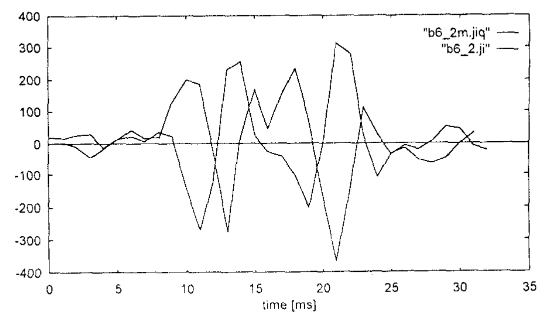

Fig. 9. Simulated Return Signal from a B747 Aircraft with CF6-50E Engines Illuminated with the S-Band ATCR-33K Radar. (Grey = Simulated Signal; Black = Actual Echo)

It can be seen that the simulation model and the recorded signal have a good match, and in this case, depending on the L-band radar parameters, no JEM phenomenon can be detected.

CONCLUSIONS

This paper has presented an analysis of the ATC radar return signal and a comparison with a simulation model. It has been shown that the simulation model has a good degree of correlation with the actual data in the majority of cases, but it is very difficult to evaluate the right parameters for model computing. In fact, due to the strong aliasing introduced by the radar equipment, little inaccuracy in ground speed or aspect angle determination can cause a strong error in evaluating model parameters.

The spectrum asymmetry – with reference to the cross section of propeller blades – has been investigated and evaluated in an analytical way.

Furthermore the correlation between the radar band and the JEM phenomenon has been investigated showing that the spectra obtained from L-band signals present unappreciable JEM phenomena, with respect to

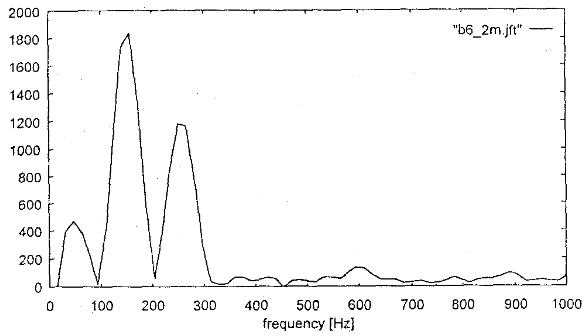

Fig. 10A. Amplitude of Fourier Spectrum of the Simulated Signal of Figure 5

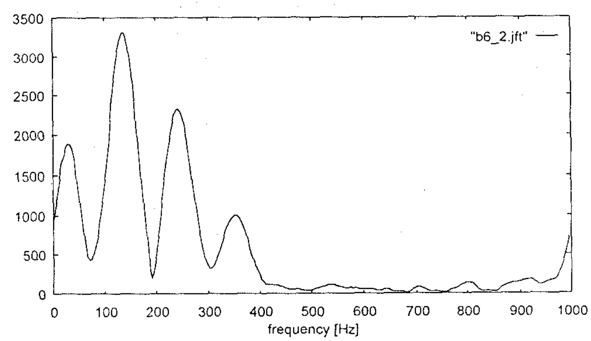

Fig. 10B. Amplitude of Fourier Spectrum of the Actual Signal of Figure 9

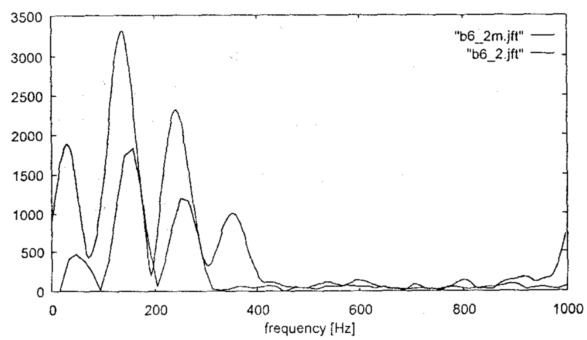

Fig. 10C. Superimposition of Spectra of Figures 10A and 10B

the S-band signals in which JEM phenomena have energy even comparable with the aircraft body signal.

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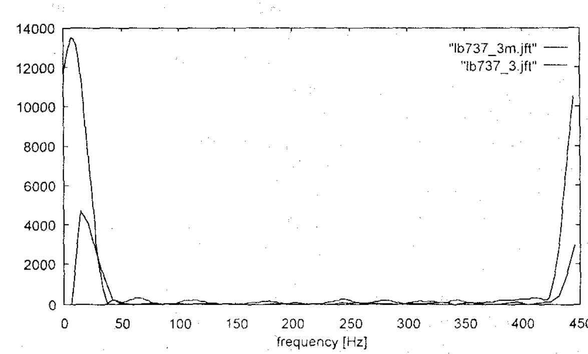

Fig. 11. Fourier Spectrum of Simulated and Actual Return Signals from aB737 Aircraft with JT8D-15 Engines Illuminated with the L-Band and ATCR-44K Rada

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