Doppler Telemetry System for the Evaluation of Low Speed Movements in the Atmosphere

Mihail E. Tănase, Corneliu I. Toma, Dan Gh. T. Popa, and Ioan Lie

Abstract: This paper is a result of the work done by the authors in the field of movement evaluation at low speed in the atmosphere and low costs of the movement execution. Theoretical and constructive solutions are offered for telemetry of the following features of movement: instant and average speed, movement sense and direction, instant position related to a fixed referential. The presented solution, the Doppler radio-telemetry system with active fixed referential - described in the paper - was practically realized and experimentally its utility has been demonstrated.

Keywords: Mobile referential, fixed referential, Doppler shift in frequency, Doppler signal extractor.

1 Introduction

For the movement evaluation of high-speed vehicles (above 100 m/s) and high costs of the movement execution in the atmosphere - sonic and supersonic airplanes, spaceships, Earth satellites, huge meteorites - are in use equipments for Doppler radio-telemetry with passive fixed referential, sophisticated and very expensive. These systems are emitting, through a system of special antennas, very high frequency electromagnetic waves (GHz order). The reflected waves, by fixed or mobile objects in the atmosphere, are received by a second system of antennas, they are processed, and the obtained Doppler signal offers information regarding
the characteristics of the own movement in reference to a fixed or mobile referential [1, 2].

In some situations, imposed by specific practices, it is necessary to evaluate terrestrial or maritime movements with speed under 30 m/s, at low cost of movement realization. For example: in hydro-energetic systems, ship access in and out the harbors, surveillance systems for the access of some vehicles in restricted areas, in robotics, high performance rowing. In those situations comes out the necessity to evaluate low-speed movements executed with low costs. In this case is required a high-performance, low-cost telemetric device, sometimes easy relocated.

Based on the studies and experimental research [3, 4, 5, 6] the following necessary conditions for the movement characterization telemetric equipment, were imposed:

a. elimination of the Doppler shifts of parasitic frequencies, caused by the similar movement of other objects with similar characteristics;
b. working in a duplex system, for simplifying the equipment and making it more compact, and decreasing its volume and weight;
c. creation of the technical conditions for a facile extraction of the Doppler information, through which are determined: the instant speed, the average speed over a chosen period, the movement sense and direction.

2 The Structure of the Telemetry System for Movement Characteristics

Eliminating Doppler shifts for parasitic frequencies requires the exact selection of the movement to be evaluated and its separation from other movements taking place simultaneously in the same space and around the fixed or mobile referential. The mobile referential is the mobile who’s movement is studied, while the fixed referential is the fix reference point (or mobile) to which the movement is reported.

For the selection, the authors are proposing the activation of the fixed referential, in the sense that this one is changing the frequency \( f_1 \) of the signal emitted from the mobile referential MR into \( f_2 \neq f_1 \) and it emits the signal with frequency \( f_2 \) towards MR. This way, the frequency \( f_2 \) takes out the Doppler shift in frequency \( \Delta f_1 \), caused by the movement of the MR in relation to the active fixed referential AFR. The \( f_2 \) frequency signal, received by MR, suffers a new Doppler shift due to the same movement. The adjacent, but insignificant movement, are producing the \( \Delta f_{1p} \) parasites, that are no longer received by MR, because it does not receive the reflected signal of \( f_1 \) frequency, but only the \( f_2 \) frequency signal.

The functioning in duplex mode is realized by the insertion of a diplex filter between the emitting/receiving amplifiers and the antenna. This is required both
for the mobile and the active fixed referential. In this way, a single antenna is used, which leads to a small volume and less weight electronic equipment for the AFR, easy to be moved if necessary.

In order to provide the technical conditions for the extraction of the Doppler information, it has to take into account that, at low speeds $\Delta f_2 \ll f_2$, so it is practically neglected and impossible to be separated from $f_2$. The authors are proposing amplitude modulation with carrier suppression for the $f_2$ frequency signal obtained by AFR, with a low frequency signal $f_j$, so that $f_j + \Delta f_2$ and $f_j - \Delta f_2$ be two distinct values, easier to be recognized technically. This requires to add to the AFR equipment a low frequency $f_j$ signal generator (with good stability, in time and with the temperature), and a symmetric modulator based on analogue multiplication cells.

Resuming, the $f_2$ frequency obtained on AFR, should be identically reproduced by MR, which is necessary in order to obtain the Doppler signal $f_j \pm \Delta f_2$.

The activation of the fixed referential by frequency change $f_1/f_2$, working in duplex mode, and the accurate reproduction of the $f_2$ frequency on MR, requires the following conditions and limitations when choosing the two frequencies:

a. frequency values should be greater than 100 MHz, so that the two antennas (on AFR and MR) to have reasonable dimensions and to be easily removable;

b. frequency values for $f_1$ and $f_2$ should be closed, in order to ensure practically the same efficiency for emission and reception, close to the maximum, for a single antenna system;

c. the $f_2$ frequency should, however, be far enough from $f_1$, so that the diplex filter could separate them, with a reasonable small immitance;

d. the frequency $f_2 > f_1$ should not be in the harmonics field of the $f_1$ frequency, in order to simplify the construction of the emitting and receiving amplifiers;

e. the two frequencies should be in the band forbidden to civil applications and must not coincide with neither one of the image frequencies used for radio broadcasting, radiotelephony and television;

f. the $2^{\text{nd}}$ and $3^{\text{rd}}$ order harmonics of the two frequencies should comply with the limitations at point e.

With these conditions and with the approval from the regulatory body in controlling and assigning frequencies for civil applications, it has chosen the following frequencies: $f_1 = 140$ MHz and $f_2 = 160$ MHz.

The activation of the fixed referential through frequency change and through the amplitude modulation with a low frequency signal, by ensuring the identity of the $f_2$ frequency obtained on AFR and MR, are leading to a telemetry system for movement characteristics named Doppler Radio-Telemetry System with Active
\textbf{Fixed Referential.} Based on the experience obtained through research and realization contracts [3, 4], the authors are proposing the electronic equipment structure for this Doppler radio-telemetry system as shown in Figure 1.

The equipment on the mobile referential is generating the $s_1(f_1)$ and $s_2(f_2)$ signals, by using a frequency synthesizer with two PLL loop, PLL1 and PLL2, and a signal generator with the reference frequency $s_r(f_r)$.

In order that the signal $s_2'(f_2 \pm \Delta f_2)$, obtained by the electronic equipment on the fixed referential, to have identical carrier frequency as $f_2$ from $s_2(f_2)$, it is necessary that the frequency synthesizer PLL3 works with the same reference frequency $f_r$. This is possible only if $f_r$ is obtained by dividing the $f_1$ frequency contained by the $s_{iA2}$ signal received by the A2 antenna,

$$s_{iA2} = k_m A_{e1} \sin([\omega_1 \pm \Delta \omega_1]t + \varphi_0) + \sum_{j=1}^{n} s_{p_j}(\omega_{p_j}t + \varphi_{p_j})$$  \hspace{1cm} (1)

with

$$A_{e1} = A'_{e1} k_{DF11} k_{A11}$$  \hspace{1cm} (2)

where: $k_m$ is the attenuation of the electromagnetic wave, emitted by the antenna A1, introduced by the propagation in the atmosphere up to its reception by the antenna A2; $A'_{e1}$ is the amplitude of the signal with $f_1$ frequency at the output of the emission amplifier EA1; $k_{DF11}$ is the attenuation introduced by the diplex filter DF1 for the $f_1$ frequency signal; $k_{A11}$ is the attenuation introduced by the emitting...
antenna A1, while $s_{pj}$ are the parasitic $f_{pj}$ frequency signals of the propagation environment.

The parasitic signals could have frequencies far from $f_1$, and very attenuated by the A2 antenna and the diplex filter DF2, but it is also possible to have some near the $f_1$ frequency. Those are less attenuated by the antenna and the filter, and they could be found at the output of the receiving amplifier RA1, $s_{r1}$, where

$$s_{r1} = A_{r1} \sin[(\omega_1 \pm \Delta \omega_1)t + \varphi_0] + k_{A2}k_{DF2}k_{RA1} \sum_{j=1}^{n} s_{pj}(\omega_{pj}t + \varphi_{pj})$$  \hspace{1cm} (3)

The presence of those parasitic signals can pollute the frequency of the reference signal $s'_r$, this is why, we must introduce the selection circuit for the $f_1$ frequency (FSC$_{f_1}$). The structure of this circuit is presented in Figure 2.

Fig. 2. The structure of the $f_1$ frequency selection circuit - FSC$_{f_1}$: M1, M2 - SSB modulators with carrier suppression; GX - $f_x$ frequency generator; BPA - band-pass amplifier; LA - limiting amplifier

The M1 modulator is receiving the $s_{r1}$ signal, expressed by the relation (3), and the $s_x$ signal, expressed by relation

$$s_x = A_x \sin(\omega_x t + \varphi_x)$$  \hspace{1cm} (4)

and it produces the signal $s_{m1}$, through an active low-pass filter, expressed by relation

$$s_{m1} = A_{m1} \sin[(\omega_1 - \omega_x)t + \Delta \omega_l t + \varphi_0 - \varphi_x] + \sum_{j=1}^{n} A_{pj} \sin[(\omega_{pj} - \omega_x)t + \varphi_{pj} - \varphi_x].$$  \hspace{1cm} (5)

The $f_x$ frequency is chosen so that, by the band-pass amplifier’s action (BPA), all parasitic frequency signals ($f_{pj} - f_x$) will be eliminated. The $f_x$ frequency is set to 130 MHz, and GX is realized in order to generate this frequency, with good stability in time and with the temperature. The difference $f_1 - f_x = 10$ MHz and for this frequency a band-pass filter with a bandwidth of 1.5 kHz can be realized.
Thus, the \((f_1 - f_x)\) frequency signal is cleaned up of the parasitic signals \((f_p - f_x)\). At the output of the BPA, the signal \(s_{im2}\) is obtained

\[
s_{im2} = A_{im2} \sin[(\omega_1 - \omega_x) t + \Delta \omega_1 t + \varphi_0 - \varphi_x].
\]  

(6)

In order to eliminate \(\varphi_x\) and \(f_x\), the signal \(s_{im2}\) is the modulating signal for the symmetrical modulator M2, which receives as carrier the \(s_x\) signal. At the output of the symmetrical modulator M2, through an active high-pass filter, the upper lateral band of the \(s_{im2}\) signal is selected.

Precautionary, in order to remove any trace of the modulation and demodulation operations (the inter-modulation frequency signals), we have to insert a limiting amplifier, LA, so that its output signal only contains the \(f_1\) frequency and the Doppler shift in frequency \(f_1 \pm \Delta f_1\)

\[
s_{LA} = A_{LA} \sin[(\omega_1 \pm \Delta \omega_1) t + \varphi_0].
\]  

(7)

The signal \(s_{LA}\) is frequency divided by the digital divider DD, so the \(f_1/N_1 = f_r\) is the same frequency as the reference signal of the \(f_1/f_2\) frequency synthesizer.

\[
s'_r = A'_r \sin\left[\left(\frac{\omega_1}{N_1} \pm \frac{\Delta \omega_1}{N_1}\right) t + \varphi_0\right].
\]  

(8)

The PLL3 loop and the signal generator for the reference frequency signal \((FSC f_1 \text{ and DD})\) are forming a \(f_2\) frequency synthesizer with the same function, and practically identical to the PLL2 loop from the mobile referential equipment. The signal generated by PLL3 is \(s'_2(f_2 \pm \Delta f_2)\) expressed by

\[
s'_2(f_2 \pm \Delta f_2) = A'_2 \sin\left[\left(\frac{\omega_1}{N_1} \pm \frac{\Delta \omega_1}{N_1}\right) t + \varphi_0\right]
\]  

(9)

with: \(\omega_1(N_2/N_1) = 2\pi f_1(N_2/N_1) = 2\pi f_1 N_2 = 2\pi f_2\).

The electronic blocks \(FSC f_1\), DD and PLL3 are forming together the frequency changer \(f_1/f_2\), the motivation for the activation of the fixed referential. This is satisfying the condition that \(f_2\) obtained on the AFR to be identical to \(f_2\) obtained on the MR, while the chosen value for \(f_2\) satisfies the imposed conditions. The structure of the frequency changing block is, as well, a contribution of the authors, while the practical implementation confirmed the correctness of the solution.

The Doppler information that allows the determination of the moving sense and of the momentary speed are the 

\textit{sign and the value of the Doppler shift in frequency.}
The value of the Doppler shift in frequency is very small compared to $f_2$. Thus, for a terrestrial or navy vehicle with $5 \text{ km/h} \leq v \leq 220 \text{ km/h}$ it results: $0.75 \text{ Hz} \leq \Delta f \leq 33 \text{ Hz}$.

The maximum value of $33 \text{ Hz}$, compared to $f_2 = 160 \cdot 10^6 \text{ Hz}$ is extremely small, this is why we have to use the theoretical, but easy to realize, trick of introducing the amplitude modulation of the $(f_2 \pm \Delta f_2)$ frequency signal, with a low frequency signal $f_j$. For that, a low frequency generator LFG is introduced in the AFR equipment, as well as a symmetrical modulator with carrier suppression MO.

LFG is generating, with good time and temperature stability, a signal $s_j(f_j)$ with $f_j = 400 \text{ Hz}$. For $\Delta f_{2\text{med}} = 10 \text{ Hz}$, $f_j + \Delta f_{2\text{med}}$ and $f_j - \Delta f_{2\text{med}}$ are two distinct values, that could be technically separated. The signal at the LFG generator’s output is

$$s_j = A_j \sin(\omega_j t + \varphi_j). \quad (10)$$

At the output of the MO symmetrical modulator, the signal $s_{m0}$, attacking the emitting amplifier EA2, is

$$s_{m0} = A_{m0} \sin(\omega_2 t + \Delta \omega_2 t + \omega_j t + \varphi_0 + \varphi_j) + A_{m0} \sin(\omega_2 t + \Delta \omega_2 t - \omega_j t + \varphi_0 - \varphi_j). \quad (11)$$

The $s_{m0}$ signal, amplified by EA2, then passed through the diplex filter DF2, is emitted by the A2 antenna and received by the A1 antenna, as the $s_{iA1}$ signal

$$s_{iA1} = k_m k_{A2} k_{DF22} k_{EA2} s_{m0} + \sum_{j=1}^{n} s_{p_j} (\omega_j t + \varphi_j) \quad (12)$$

where: $k_m$ is the attenuation of the electromagnetic wave of frequency $f_2$ through the atmosphere, $k_{A2}$ is the attenuation introduced by the antenna A2 at the emission of the electromagnetic wave of frequency $f_2$, while $k_{EA2}$ is the amplification given by EA2.

The received signal is passed through the diplex filter DF1, amplified by the receiver band-pass amplifier RA2 and then arrives to the entrance of the block able to extract the Doppler signal, as the signal $s_{r2}$, expressed by

$$s_{r2} = A_{r2} \sin(\omega_2 t + 2\Delta \omega_2 t + \omega_j t + \varphi_0 + \varphi_j) + A_{r2} \sin(\omega_2 t + 2\Delta \omega_2 t - \omega_j t + \varphi_0 - \varphi_j). \quad (13)$$

The parasitic signals $s_{p_j}$ are attenuated, mostly by the antenna A1, by DF1 and RA2, and finally by the circuits of the symmetrical SSB-SC modulator from the block realizing the extraction of the Doppler signal.
3 Doppler Signal Extractor

The extractor of the Doppler signal (DSE) must accomplish the following functions:

a. elimination of the carrier $f_2$ by processing the signals $s_2(f_2)$, expressed by

$$s_2(f_2) = A_2 \sin(\omega_2 t + \varphi_0)$$

and $s_{r2}$, expressed by (13);

b. centering the Doppler shift in frequency, in order to establish its sign, and so to determine the movement sense of the mobile referential related to the fixed one;

c. to reject the pulse $\omega_j$ and to generate the Doppler signal, containing the information regarding the movement speed.

For the concrete realization of these three functions, the quadrature modulation and demodulation is used, specific for the Doppler effect [6]. The authors proposed the DSE structure in Figure 3.

The symmetrical modulator M1, together with the active low-pass filter AF1, are forming a modulator with suppressing the carrier component and the upper sideband. The output signal of this LSB-SC modulator, $s_{m1}'$, is passed through the LA1 amplifier, that is cleaning the signal of parasite signals and is fixing it to the amplitude $A_m$

$$s_{m1} = A_m \cos(\omega_j t \pm 2\Delta\omega_2 t + \varphi_j) + A_m \cos(\omega_j t \mp 2\Delta\omega_2 t + \varphi_j).$$

M2 is a symmetrical modulator, receiving the signal $s_{r2}$ and the modulating signal $s_2(f_2)$, dephased by $\pi/2$, so that

$$s_2(\omega_2) = A_2 \sin(\omega_2 t + \varphi_0 + \pi/2).$$

M2 together with the active low-pass filter AF2 are suppressing the carrier component and the upper sideband and are selecting the lower sideband, $s_{m2}'$. Amplified, limited and cleaned of parasite signals with LA2, it becomes

$$s_{m2} = A_m \sin(\omega_j t \pm 2\Delta\omega_2 t + \varphi_j) - A_m \sin(\omega_j t \mp 2\Delta\omega_2 t + \varphi_j).$$

The signals $s_{m1}$ and $s_{m2}$ are in quadrature. Therefore, the modulators M1, M2 together with the $\pi/2$ phase-shifter and the active low-pass filters AF1, AF2 make up a quadrature modulator.
Fig. 3. The structure of the Doppler signal extractor (DSE): M1, M2 - high-frequency suppressed-carrier type modulators; M3 - low-frequency suppressed-carrier type modulator; AF1, AF2 - active low-pass filters for selecting the lower sideband to M1, respectively M2; LA1, LA2 - limiting amplifiers; AF3 - active low-pass filter for \( f_j = 400\) Hz.

The first function, the elimination of the carrier \( f_2 \), has been realized.

By summing the signal \( s_{m1} \) and the quadrature of the \( s_{m2} \) signal, \( s_{m2}^{\prime} \), with the circuit SUM, it obtain either

\[
s_{ax1} = 2A_m \cos(\omega_j t + 2\Delta\omega_2 t + \varphi_j)
\]

with \((+2\Delta\omega_2 t)\) indicating the mobile referential approaching the fixed one, or:

\[
s_{ax2} = 2A_m \cos(\omega_j t - 2\Delta\omega_2 t + \varphi_j)
\]

with \((-2\Delta\omega_2 t)\) indicating the mobile referential removing from the fixed one.

The two signals are graphically represented for \( f_j = 400 \) Hz and \( \Delta f_2 = 10 \) Hz, by the diagrams from Figure 4.

The signal \( s'_j \), represented with continuous line, is the signal of frequency \( f_j = 400 \) Hz. The graphic of the signal \( s_{ax2} \), drawn with dotted line, represented at the right of the signal \( s'_j \), signifying the removal from the ordinates axis, while the \( s_{ax1} \) signal, drawn with dashed line, is at the left of the signal \( s'_j \), signifying the approach to the ordinates axis. This is similar to the movement of the mobile referential regarding the fix one.

Because these two signals can never appear concomitantly, the axing signal was written down synthetically with \( s_{axi} \) with \( i=1 \) for \( \Delta\omega_2 > 0 \) and \( i=2 \) for \( \Delta\omega_2 < 0 \).

By obtaining the signal \( s_{axi} \) that, processed by the Doppler signal analyzer (DSA), gives indications regarding the sense of the vehicle movement regarding the fix referential, the second function has been realized - the centering of the Doppler shift in frequency.
The separation of the Doppler signal, a sinusoidal function, having as argument only the Doppler shift, is realized through the symmetrical modulator M3 and the active low-pass filter AF3. The modulated signals are $s_{m1}$ and $s_{m2}$, expressed by relations (15) and (17) respectively. The obtained Doppler signal is

$$s_D = A_m^2 \sin(4\Delta \omega t) = A_D \sin(4\Delta \omega t).$$

(20)

The signal $s_D$ is processed by the Doppler signal analyzer (DSA), which gives the instant value of the movement’s speed, through the relation

$$v = \frac{v_f \cdot 1}{8\pi \cdot \frac{1}{\Delta t}} \left[ \arcsin \left( \frac{s_D}{A_D} \right) \right]$$

(21)

where $v_f$ is the speed of the electromagnetic wave in atmosphere, $v_f = 2.99691 \cdot 10^8$ m/s and $f_2 = 160 \cdot 10^6$ Hz.

4 Conclusions

The proposed structures for the Doppler radio-telemetry system with active fixed referential, for the frequency changer and for the extractor of the Doppler signal are corresponding to the appointed purpose - to evaluate the low speed movements executed with low costs.

From the analysis of the proposed structure for the Doppler signal extractor, it is determined that the proposed artifice: the amplitude modulation of signal $s_j(f_2 \pm \Delta f_2)$ with a signal $s_j(f_j)$ of low frequency $f_j$ toward which $\Delta f_2$ will not be an
extremely small value any more, was correct. Theoretically, it was possible to obtain:

- the axing signal $s_{ax}$ of the Doppler shift in frequency, on which basis, the Doppler signal analyzer can determine the sense of movement of the mobile reference towards the active fixed one;

- the Doppler signal $s_D$, a sinusoidal signal that contains in its argument only the Doppler shift in frequency $\Delta f_2$, information needed for calculating the instant speed of movement of the mobile referential.

In order to test in laboratory the electronic equipment of the Doppler radio-telemetry system with active fixed referential, it has been used the effect Doppler simulator in the atmosphere [7]. At controllable Doppler shifts, it has been finalized the Doppler signal analyzer, establishing the programs and the integration constants used for the determination of the instant speed, of the average speed for the given period of time, of the movement sense and of the instant distance between the mobile referential and the fix one.

The electronic equipment of radio-telemetry system has been experienced by introducing in a vehicle the electronic equipment from the mobile referential and in another vehicle the electronic equipment from the active fixed referential. Each vehicle was equipped with a $\lambda/2$ antenna. The mobile referential vehicle has started near beside the active fixed referential vehicle with zero distance. It departed with a virtually constant speed, making 4 km - the distance indicated by the vehicle board and by the Doppler signal analyzer. DSA indication was growing as the vehicle got further. When the vehicle returned, as it approached, DSA distant indication decreased and when the vehicles have got side by side, in the initial position, the distance indicated by DSA was zero.

So, it can be affirmed that, from the practical point of view, the movement evaluation elements were obtained.

The technical solution for centering the Doppler shift in frequency and for the separation of the Doppler signal, through intermediate modulation with $s_j(f_j)$, is a contribution of the authors.

The structure of the Doppler radio-telemetry system with active fixed referential and the structure of the Doppler signal extractor, are also contributions of the authors.

These two structures can be implemented with commercial professional electronic circuits. These circuits are of high performance, but cheap at the same time, with low and acceptable costs of the whole equipment, as a result. This kind of conception of the structure is also a contribution of the authors.
References


