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Sonic anemometry of planetary atmospheres

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[1] The application of a recently developed model of sonic anemometers measuring process has revealed that these sensors cannot be considered as absolute ones when measuring spectral characteristics of turbulent wind speed since it is demonstrated that the ratios of measured to real spectral density functions depend on the composition and temperature of the considered planetary atmosphere. The new model of the measuring process of sonic anemometers is applied to describe the measuring characteristics of these sensors as fluid/flow dependent (against the traditional hypothesis of fluid/flow independence) and hence dependent on the considered planetary atmosphere. The influence of fluid and flow characteristics (quantified via the Mach number of the flow) and the influence of the design parameters of sonic anemometers (mainly represented by time delay between pulses shots and geometry) on turbulence measurement are quantified for the atmospheres of Mars, Jupiter, and Earth. Important differences between the behavior of these sensors for the same averaged wind speed in the three considered atmospheres are detected in terms of characteristics of turbulence measurement as well as in terms of optimum values of anemometer design parameters for application on the different considered planetary atmospheres. These differences cannot be detected by traditional models of sonic anemometer measuring process based on line averaging along the sonic acoustic paths. *INDEX TERMS:* 5494 Planetology: Solid Surface Planets: Instruments and techniques; 5794 Planetology: Fluid Planets: Instruments and techniques; 5409 Planetology: Solid Surface Planets: Atmospheres—structure and dynamics; 5707 Planetology: Fluid Planets: Atmospheres—structure and dynamics; *KEYWORDS:* sonic anemometer, planetary atmospheres, turbulence

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1. Introduction

[2] Sonic anemometers are sensors that are able to estimate wind speed vector by measuring the influence of local wind speed on the transmission of ultrasound signals between pairs of emitters and receivers that configure acoustic paths. This estimation is normally assigned to the geometric center of acoustic path midpoints [*Suomi*, 1957; *Bovsheverov and Voronov*, 1960; *Kaimal et al.*, 1968; *Cuerva and Sanz-Andrés*, 2000].

[3] Sonic anemometers present some advantages compared to other technologies such as cup anemometers, propeller or hotwire anemometers [*Wyngaard*, 1981; *Cervenca*, 1992]. First, sonic anemometers are able to measure the complete wind speed vector, whereas other technologies need to use three sensors or even they do not present such possibility. Second, sonic anemometers are especially robust and are the only type of sensors that simply requires an initial calibration, which means a clear advantage in harmful environments like the atmosphere. Finally, sonic anemometers can reach useful sampling rates in the order of 100 Hz, quite larger than the corresponding to cup anemometers [*Cuerva and Sanz-Andrés*, 1999] and present the possibility of measuring sound virtual temperature [*Nielsen and Larsen*, 2002; *Larsen et al.*, 1993].

[4] All these characteristics make sonic anemometers to be ideal candidates for atmospheric application. Since sonic anemometers have not moving parts and can be designed to have loss mass and power consumption they have become an adequate candidate for planetary exploration purposes both for atmosphere studies and for flying robots control [*Genese and Barnes*, 2001].

[5] Although, traditionally, sonic anemometers have been considered as absolute sensors (able to work independently from the type of fluid) [*Kaimal et al.*, 1968], recent developments on the theory of sonic anemometry have allowed to establish corrections in the measure of wind speed, temperature and their derived parameters which are flow/fluid dependent [*Cuerva and Sanz-Andrés*, 2000;

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Cuerva, 2001; *Cuerva et al.*, 2003]. This fact has opened the possibilities of optimization of sonic anemometry for its application in different planetary atmospheres.

[6] There are several techniques, being the most extended the one based in pulsed signals. The wind speed along each acoustic path is estimated from the transmission time of ultrasound pulses in both senses of the acoustic path. The estimation of the wind speed component along three acoustic paths gives rise to a measurement of the wind speed vector in one point.

[7] When one of the pulses is fired, the wind speed component parallel to the corresponding acoustic path, u_p, is added or subtracted to sound speed, c, giving rise to the effective velocity of propagation of the ultrasound pulse front. Let $t^{\pm}$ be the times required by the pulse front to cover the acoustic path length, l, in both senses, given by

$$t^{\pm} = \frac{l}{c \pm u_P} \tag{1}$$

which are valid for an uniform and steady wind speed field. The most extended algorithm to obtain the estimation of u_P from the measurements of $t^{\pm}$ is the one based on the inverses of travel times

$$u_P^M = \frac{l}{2}\left[\frac{1}{t^-} - \frac{1}{t^+}\right] \tag{2}$$

[8] The most important advantage of equation (2) is that u_P^M (where superscript M stands for measured) could be calculated independently from sound speed, c and therefore from the type of fluid (i.e. atmosphere).

[9] The sequence of pulses that leads to one estimation of wind speed vector occurs every certain time period, and frequently, wind speed measurement given by sonic anemometers results from block-averages of several wind speed estimations. Although this is not an intrinsic characteristic of sonic anemometer measuring principle, it has a remarkable influence in the measurement of spectral characteristics of turbulent fluctuation speed. [*Henjes et al.*, 1999; *Cuerva*, 2001]. In this paper only the effects of pulse transmission are considered.

[10] On the other hand, sonic anemometers present some errors in the measurement of mean wind speed values and spectral characteristics of turbulence that should be carefully considered in order to succeed in the goals cited above. Some of these errors are commented below.

[11] First, sonic anemometers structure distorts the measurement, due to the aerodynamic disturbances of transducers heads and supporting struts [*Wyngaard and Zhang*, 1985; *Grelle and Lindroth*, 1994; *Cuerva and Sanz-Andrés*, 1999]. This fact converts a sonic anemometer in a directional sensor.

[12] Second, aerodynamic disturbances affect the measurement of wind speed spectral characteristics [*Wyngaard and Zhang*, 1985]. The basic measurement process of sonic anemometers also affects the determination of these spectral characteristics. Traditionally, the effect of pulse transmission on the spectral measurements has been modeled by an instantaneous line averaging model [*Kaimal et al.*, 1968]. Instantaneous line averaging allows to characterize a sonic anemometer as a low-pass filter with important attenuation effects for values $kl > 1$ (k is the modulus of wave number vector). From this point of view, these sensors present a clear disadvantage when measuring high frequency turbulent fluctuation speed, versus hot wire anemometers, unless correction functions are applied to sonic measurements. The "line averaging" model obtains the measurement along each acoustic path, $u_P{}^M$, as an instantaneous line average of the speed values along the acoustic path

$$u_P^M = \frac{1}{l}\int_{-\frac{1}{2}}^{\frac{1}{2}} u_P(p)dp \tag{3}$$

[13] Equation (3) still models a sonic anemometer as an absolute sensor, since it does not introduce any additional dependency on the thermodynamic fluid properties. The main hypothesis behind equation (3) is that the turbulent fluctuation speed field is frozen and fixed during pulse transmissions. Such hypothesis were reviewed by *Cuerva* [2001], *Cuerva and Sanz-Andrés* [2000], and *Cuerva et al.* [2003], allowing a natural evolution of the turbulent speed fluctuation speed in the kinematic equations of pulse transmission through a turbulent flow. If such variations are considered, two new parameters appear, influencing the measurement. First the Mach number of the flow, representing the time variations of the turbulent speed fluctuation speed during such flying time of pulses and second the parameter $Z_B = z_B\,|\mathbf{u}_\infty|/l$ where z_B is a characteristic delay time that normally exists between pulses firings, $|\mathbf{u}_\infty|$ is the mean wind speed and l has been already defined as the length of the acoustic path. This second nondimensional parameter represents the number of times that the "frozen" turbulent speed field covers a distance equal to the acoustic path length, l, during the time between consecutive pulses firings.

[14] Given a sonic anemometer, the measurement of any wind speed turbulence spectral density function, F_{jk} (k_1), where k_1, is the wave number component along mean wind speed vector, depends on sensor's geometry, incidence angles of mean wind speed, nondimensional time delay between pulses firings and Mach number [*Cuerva and Sanz-Andrés*, 2000; *Cuerva et al.*, 2003].

[15] The presence of Mach number, initially not considered in the problem when time inverses algorithm was applied, should be understood as a correction factor that introduces a dependency on the thermodynamic characteristics of the explored flow/fluid (as for instance in the case of planetary atmospheres).

2. Behavior of Sonic Anemometers in Different Atmospheres

[16] One of the critical influences of thermodynamic flow/fluid characteristics can be observed on the limit wind speed measured by a sonic anemometer. In a critical situation of an acoustic path aligned with a sonic flow, the time needed by the pulse front to cover the acoustic path in sense opposite to wind speed vector (here referred as sense p_0^+ to p_0^-) will be infinity. Although Mach number does not equal unity, there is a limitation related to the electronic

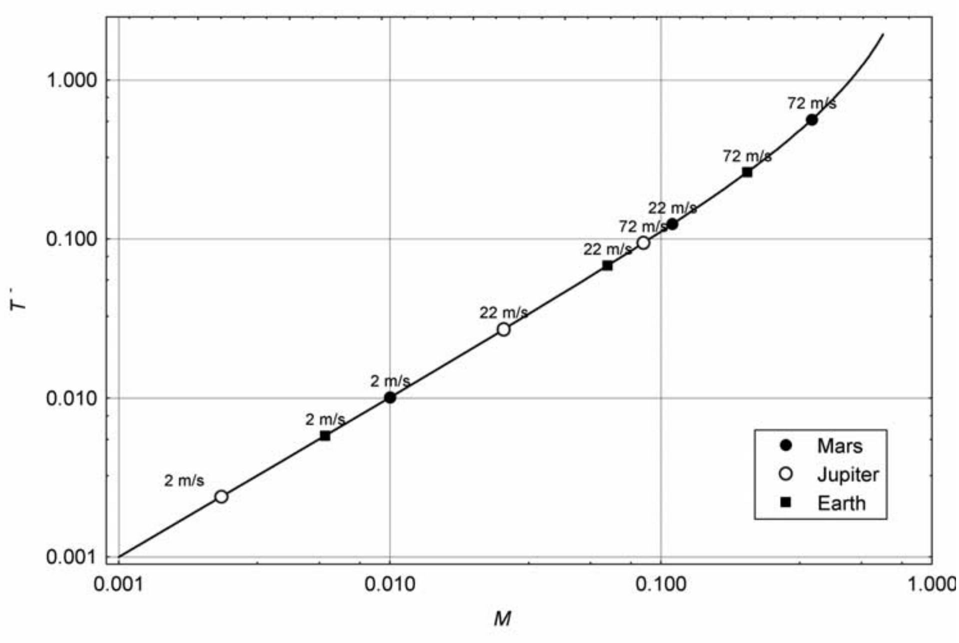

Figure 1. Variation of the nondimensional time required for the pulse front to cover the acoustic path, aligned with averaged wind speed vector, in an opposite direction to averaged wind speed vector T^- with Mach number *M*. Results are for Mars's, Jupiter's and Earth's atmospheres. The specific conditions of the cases analyzed are shown in Table 1. Three wind speed mean values have been considered.

time delay between pulses, z_B. t^-, the time needed by pulse to cover the length of the acoustic path, must be always shorter than the time delay between pulse firings whenever a nonparallel pulse sequencing is used. This limitation can be analyzed by using the travel time of pulse traveling in sense p_0^+ to p_0^- [*Cuerva and Sanz-Andrés*, 2000].

$$t^- = \int_{p_0^-}^{p_0^+} \frac{dp}{-c + u_P(p,t)} \tag{4}$$

where $p_0^{\pm}$ are the acoustic path extremes, *p* is the position of pulse front on the path and *t* is time. In a general case the wind speed component along the acoustic path in one point, *p*, of the such acoustic path at a time, *t*, is:

$$u_p(p,t) = u_r(1 + \varepsilon\delta(p,t)) \tag{5}$$

where δ is the stretched fluctuation component of wind speed vector component along the path and ε is the order of magnitude of the wind speed fluctuation component.

[17] In differential non dimensional form, the incremental time dT^- needed by the pulse front to cover a distance d*P* on the acoustic path in sense p_0^+ to p_0^- is given by

$$dT^- = \frac{\frac{M}{1-M}}{1 - \frac{M}{1-M}\varepsilon\delta(P,T)} dP \tag{6}$$

where *M* is the Mach number, $P = p/l$ is the nondimensional position of the pulse front along the acoustic path and $T = t\, u_r/l$, is the nondimensional time lasted from the beginning of the measuring sequence. The non dimensional time needed by the pulse front to cover the acoustic path in sense p_0^+ to p_0^- is given by

$$T^- = \frac{M}{1-M}\left(1 + \frac{M}{1-M}\varepsilon F^-\right) \tag{7}$$

where F^- is a Lagrangian average of the fluctuation component of wind speed vector, following the pulse front traveling in sense p_0^+ to p_0^- [*Cuerva and Sanz-Andrés*, 2000], which is expressed as

$$F^- = \int_{P_0^-}^{P_0^+} \delta\big(P, T_0^-(P)\big) dP \tag{8}$$

where $T_0^-(P)$ is the first order nondimensional time required by the pulse front to get from path extreme P_0^+ to point *P* on the acoustic path. Since F^- is the averaged value of flow speed component along the path, following the travel of the pulse front, there is not evidence to make this average equal to 0. [*Cuerva and Sanz-Andrés*, 2000; *Cuerva et al.*, 2003].If a steady and uniform wind speed field is considered ($\delta(p, t) = 0$), then $F^- = 0$ and equation (7) becomes

$$T^- = \frac{M}{1-M} \tag{9}$$

[18] In such conditions the limit nondimensional time delay between pulse firings must satisfy at least:

$$Z_{B\min} > T^- = \frac{M}{1-M} \tag{10}$$

Equation (10) indicates that nondimensional travel time for the pulse fired in sense p_0^+ to p_0^-, grows as *M* grows.

[19] Figure 1 shows this dependency. Obviously, equation (10) is not defined when $M = 1$, meaning that mean wind

Table 1. Planetary Atmosphere Properties

Planet	Temperature	Ratio of Specific Heats C_p/C_v, γ	Molecular Gas Constant R, J K^{-1} kg^{-1}
Mars	−110 °C	1.29	188.92
Jupiter	−143 °C	1.43	3745.78
Earth	25 °C	1.40	287.1

speed vector equals sound speed and therefore the pulse in sense p_0^+ to p_0^- would require an infinitely long time to cover the acoustic path length. On the other hand, for sensors immersed in the flow, large M could lead to shockwave development, so that this simplification could not be valid, even for an acoustic path aligned with the mean wind speed vector.

[20] For those situations where transducer heads are not immersed in the flow (therefore no shockwaves formation around transducer heads exists) equation (10) constitutes a directly applicable limit for sonic anemometer utilization. On the other hand, even for Mach numbers, beyond shockwave formation, equation (10) could be considered as a limitation, since it could lead to design restrictions which are flow/fluid (planetary atmospheres) dependent. To clarify this feature, three typical conditions in the atmosphere of Mars, Jupiter and Earth have been analyzed. Table 1 shows the parameter values considered for the atmosphere of each planet.

[21] A dimensional analysis of the situation allows us to establish practical consequences. If the travel time of pulse in sense p_0^+ to p_0^- is considered as a designing parameter for time delay between pulse firings, it is interesting to relate this magnitude to the acoustic path length, since a larger path length leads to a larger t^-. Equation (10) in dimensional form gives rise to

$$z_B = \frac{l}{c\left(1 - \left(\frac{|\mathbf{u}_\infty|}{c}\right)\right)} \tag{11}$$

[22] Figure 2 shows this relation for Jovian, Martian, and terrestrial cases. For the given conditions (see Table 1) a sonic anemometer operating in Mars atmosphere would require minimum values for time delay between pulse firings rather larger than in the terrestrial and Jupiter cases. A rather lower sound speed in the first case gives rise to this consequence. Standard sonic anemometers time delays are some 1 ms. Therefore in Mars's atmosphere these sensors would need an acoustic path length lesser than 0.15 m (for the given ranges of mean wind speed). This limit is not so strict in the terrestrial and Jovian cases since, for such acoustic path lengths, sonic anemometers could operate (for the given ranges of mean wind speed) with delays between pulses one half and one order of magnitude smaller for terrestrial and Jovian cases respectively.

[23] In the work of *Genese and Barnes* [2001] a flying robot is equipped with a 0.3 m single path sonic anemometer for flying control and atmosphere study purposes. For such path length, and for a mean wind speed $|\mathbf{u}_\infty|$=22 m/s, Figure 2 indicates a minimum time delay between pulses greater than 1 ms for Martian atmosphere, while this time delay for Earth and Jupiter's atmospheres is about 0.9 and 0.4 ms respectively.

[24] Additionally, for a given acoustic path length l_0, taking partial derivatives in equation (11) is possible to obtain the sensitivity of minimum time delay between pulses versus mean wind speed changes:

$$\left.\frac{\partial z_B}{\partial|\mathbf{u}_\infty|}\right|_{l_0} = \frac{l_0}{(c - |\mathbf{u}_\infty|)^2} \tag{12}$$

[25] Equation (12) is represented in Figure 3 for the three considered planets. Since sound speed in Jupiter for the given conditions is c_{JUP} = 835.87 m/s versus the corresponding values for Earth, c_{EARTH} = 346.15 m/s and Mars,

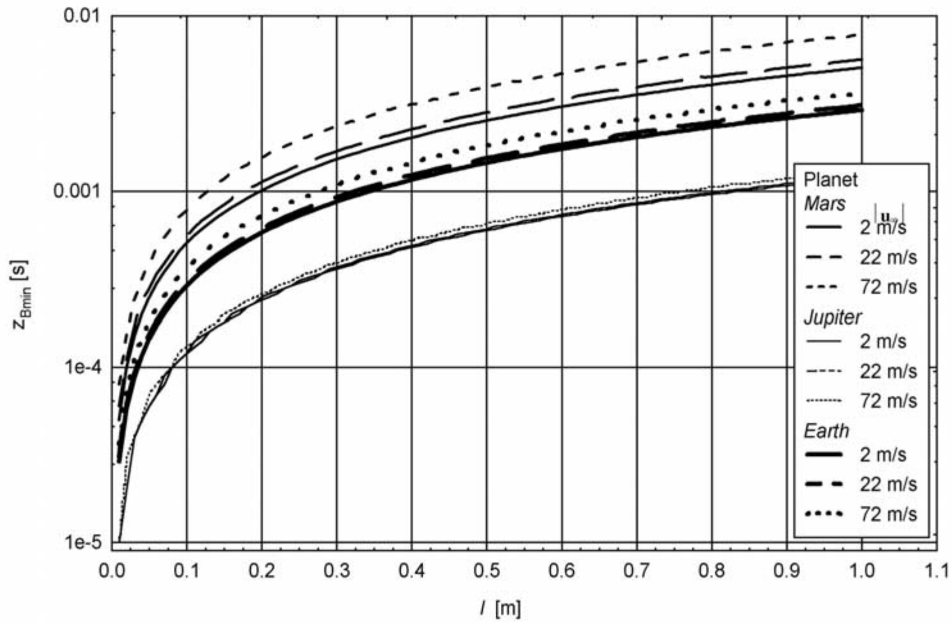

Figure 2. Variation of the time Z_B required by pulse in sense p_0^+ to p_0^- (opposite to mean wind speed) or minimum time delay between pulses firing, with acoustic path length l.

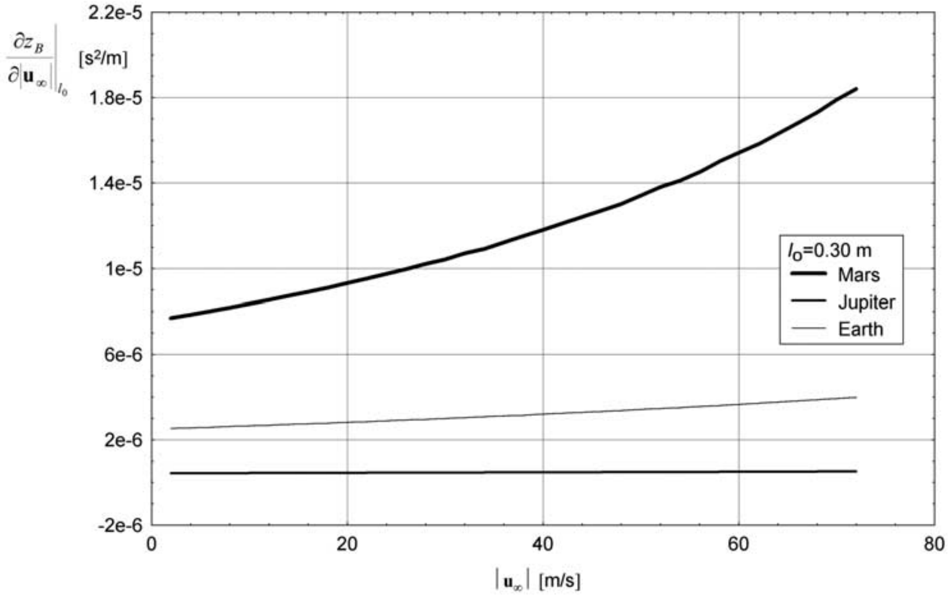

Figure 3. Sensitivity of minimum time delay between pulses versus mean wind speed for a given acoustic path length (l_0 = 0.30 m) for Mars's (temperature of −110°C), Jupiter's (temperature of −143°C), and Earth's (temperature of 25°C) atmospheres.

c_{MARS} = 199.62 m/s, the sensitivity to mean wind speed variations (see equation (12)) is, for the Martian case, the largest, intermediate in the terrestrial case and the smallest in the Jovian case.

[26] If the values for time delay shown in Figure 1 (considered as the minimum values for nondimensional time delays between pulse firings) are finally selected as design parameter, their effect in turbulence determination by the used sonic anemometer must be considered. In the work of *Cuerva and Sanz-Andrés* [2000], *Cuerva* [2001], and *Cuerva et al.* [2003] the effect of Mach number and time delay between pulse firings on the measurement of turbulence is studied. For the given conditions, specifically for a mean wind speed $|\mathbf{u}_\infty|$ = 72 m/s, and using a path length from the case described by *Genese and Barnes* [2001], l = 0.3 m, Table 2 indicates the operation Mach number and time delays between pulse firings for Mars Earth and Jupiter cases.

[27] Concerning the effect of a turbulent atmosphere [*Cuerva and Sanz-Andrés*, 2000], the effect on the spectral velocity tensor Φ_{jk} is considered. In this reference, the relation between the measured and the modeled theoretical longitudinal component (following $\mathbf{u}_\infty$ direction) of the spectral velocity tensor is given by

$$\Phi_{11}^M = \frac{1}{4}[G^+ + G^-][G^+ + G^-]^*\Phi_{11} \tag{13}$$

where superscript M stands again for "measured" and functions $G^\pm$ are defined as

$$G^\pm = \exp\left(-\frac{i}{2}\frac{Mk_1 l}{1 \pm M} - i\zeta(\pm)Z_B k_1 l\right)\left[\frac{\sin\left(\frac{k_1 l}{2}\frac{1}{1\pm M}\right)}{\frac{k_1 l}{2}\frac{1}{1\pm M}}\right] \tag{14}$$

where $\zeta(\pm)$ is

$$\zeta(x) = \frac{1-\mathrm{sign}(x)}{2} \tag{15}$$

[28] The spectral density function associated to the longitudinal component of wind speed vector (commonly referred as longitudinal turbulence spectrum) is normally calculated from the corresponding component of the spectral velocity tensor as follows:

$$F_{11}(k_1) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Phi_{11}(k_1,k_2,k_3)dk_2dk_3 \tag{16}$$

[29] The relation between the measured spectral density function and the corresponding real one is defined as relation of spectral components

$$R_{11}(k_1,l,M,Z_B) = \frac{F_{11}^M(k_1,l,M,Z_B)}{F_{11}(k_1)} = \frac{1}{4}[G^+ + G^-][G^+ + G^-]^* \tag{17}$$

[30] The relation of spectral components is referred to as "spectral transfer function, T_{jk}" by *Kaimal et al.* [1968].

Table 2. Operation Mach Number and Dimensionless, Z_B, Time Delay Between Pulse Firings for $|\mathbf{u}_\infty|$ = 72 m/s and Atmosphere Conditions Given in Table 1

Planet	Mach Number	Z_B	z_B [s]
Mars	0.36	0.5622	0.00232
Jupiter	0.09	0.0942	0.00039
Earth	0.21	0.2626	0.00109

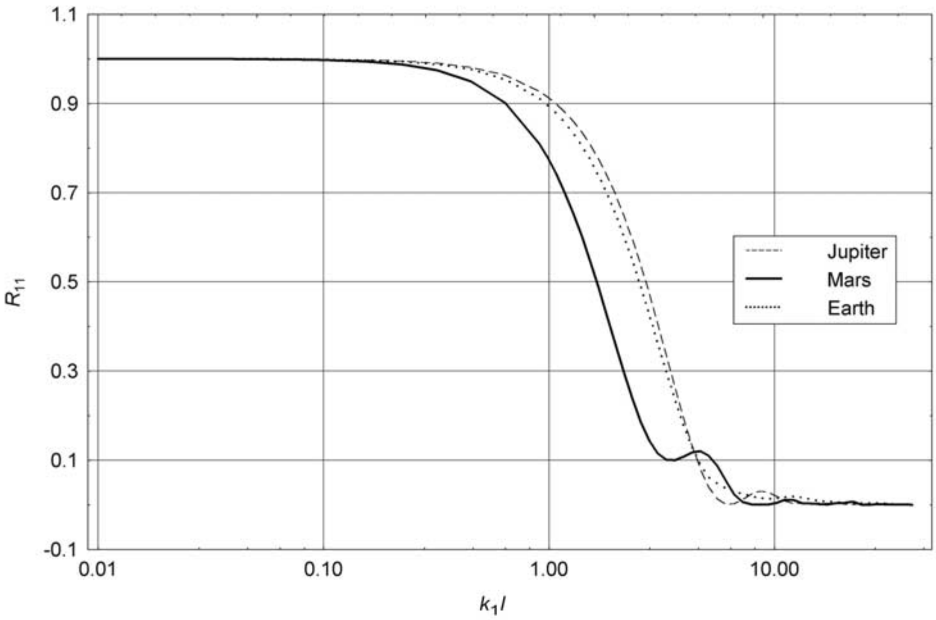

Figure 4. Variation of the relation of spectral components (longitudinal) R_{11}, with the wave number $k_1 l$, for Mars's, Jupiter's and Earth's atmospheres. The conditions of the simulations are given in Tables 1 and 2.

However Kaimal comments in this work that the term "spectral transfer function" is not fully appropriated since a specific form for the input turbulence is used in the determination of R_{11} (T_{11} of *Kaimal and Wyndgaard* [1968]). On the other hand, *Nielsen and Larsen* [2002] and *Larsen al.* [1993] use the expression "pseudo transfer function" because of similar reasons.

[31] This function indicates the influence in the measurement of turbulence of sonic anemometers measuring process. For the identical mean wind speed and for typical planet temperatures, Mars's atmosphere leads to greater errors in the measurement of turbulence than in the terrestrial and Jovian cases. In all cases the errors increase as longitudinal wave number increases as it is already known from *Kaimal*

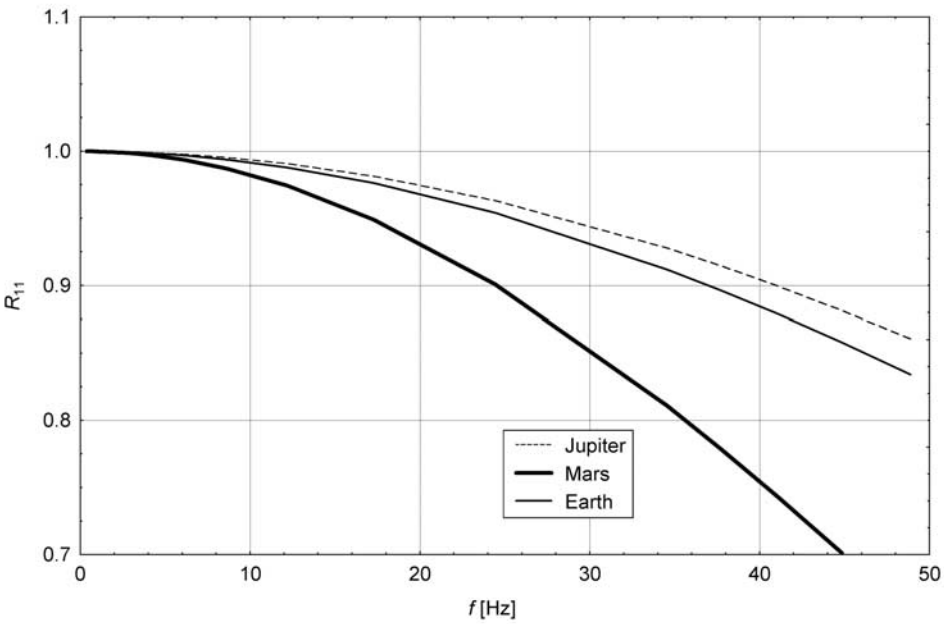

Figure 5. Variation of the relation of spectral components (longitudinal) R_{11}, with frequency f, of turbulence for Mars's, Jupiter's and Earth's atmospheres. The conditions of the simulations are given in Tables 1 and 2.

et al. [1968], *Silverman* [1968], *Nielsen and Larsen* [2002], and *Cuerva and Sanz-Andrés* [2000], but the difference in the behavior of the hypothetic sonic anemometer increases as well. The results presented in Figure 4 can be analyzed in dimensional variables once a mean wind speed and an acoustic path length are defined. The application of Taylor's frozen turbulence hypothesis can relate the longitudinal wave number with frequency of turbulent fluctuation speed f by

$$k_1 = \frac{2\pi f}{|\mathbf{u}_\infty|} \tag{18}$$

[32] Figure 5 shows, in the same way as Figure 4, that Martian atmosphere induces greater attenuations in the measurement of turbulence by sonic anemometers than in the terrestrial and Jovian cases. Attenuation levels of the spectral measurements around 10% for frequencies about 25 Hz in the Martian case are diminished down to 5% and 4% in the terrestrial and Jovian case respectively.

[33] Instantaneous line averaging models are not able to explain the differences between different planetary cases evidenced in Figures 4 and 5 by the new model applied. Instantaneous line averaging would provide identical results for the three different planetary atmospheres.

3. Conclusions

[34] New models of the measuring process of sonic anemometers allow us to quantify errors in the measurement of spectral characteristics of turbulent wind speed which are dependent on the composition and thermodynamic properties of the flow/fluid (ratio of specific heats, gas constant and temperature through Mach number) and that cannot be modeled by traditional "line averaging" theory.

[35] These new models also allow us to establish considerations for sonic design parameters, such as minimum time delay between pulse firings, Z_{Bmin}, which are also flow/fluid dependent and therefore dependent on the planetary atmosphere the sonic anemometer is intended to be used in.

[36] The presented analysis has revealed important differences in the way a same sonic anemometer measures the spectral characteristics of turbulent wind speed in the Martian, Jovian and terrestrial atmospheres, even for the same averaged wind speed.

[37] A lower sound speed (for the given typical temperatures) in the Martian atmosphere gives rise to higher errors in the measurement of turbulence spectra than in the Jovian and terrestrial cases. This lower sound speed leads, as well, to a larger sensitivity of sonic anemometer minimum time delay between pulses versus mean wind speed for the Martian case.

[38] Sonic anemometers are not absolute sensors when measuring spectral characteristics of wind speed since the relation of spectral components depends of the composition and temperature of the atmosphere the sonic anemometer is measuring in. Only in case of a uniform and steady flow field, a sonic anemometer behaves as an absolute sensor.

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