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Atmospheric flow measurements using the PIV and HWA techniques

Abstract: *Alcântara Space Center (ASC) is the Brazilian gate to the space where rockets of different sizes are launched. At ASC there is a relative topographical variation, coastal cliff, which modifies the atmospheric boundary layer characteristics and can cause interference for operations of rockets. In the present work, a simplified model (mock-up) was studied in a wind tunnel. A scale factor of 1:1000 was used and the atmospheric flow was measured using the hot wire anemometer (HWA) and particle image velocimetry (PIV) techniques. Using of HWA it was possible to calculate values of average wind speed and fluctuations in a set of points of the section of tests that representing the region of the ASC. Through these measures, other meteorological parameters that represent the atmospheric flow, such as the friction velocity (u_*), the roughness length (z_0) from the logarithmic profile and the alpha exponent (α) of the power law were calculated. With the use of the PIV's technique, the streamlines and the vorticity fields were obtained and it was noticed that the vorticity generated downwind of the coastal cliff has a strong turbulence (vorticities around 2000 s^{-1}). A rectangular building (simulating the mobile integration tower) was inserted at the mock-up and the downwind turbulence was similar to the one generated by the coastal cliff.*
Keywords: *Alcantara Space Center, Wind profile, Turbulent intensity, Vorticity, Stream lines.*

INTRODUCTION

The knowledge of the atmospheric flow at the Space Launch Centers (like Kennedy Space Center – the US Space Port, and French Guiana Space Center – French/Europe Port) is very important due to its influence on the research & development (R&D) of the rockets. The trajectory, guidance and control of the rockets are influenced by the wind profile, especially near the surface, as well as the wind loads at surface and upper air. Up to a height of 1000 m, 88% of the trajectory corrections are due to the winds, while there are only 3% of wind corrections above 5000 m (Fisch, 1999).

Alcântara Space Center (ASC) is the Brazilian gate to the space where rockets are launched and it is located at the north coast of the state of Maranhão, close to the Equator. This region has a very special topography, with a smooth surface (ocean) close to a rough surface (continent). At the border there is a step (coastal cliff) with a 50 m of height, as shown in Fig. 1. The launch pad of the rockets is located close to this border (150 m) and it suffers an intense turbulence due to the modification of the wind profile blowing from the ocean to the continent.

Figure 1:   Alcântara coastal cliff.

Although the wind data are usually made at meteorological stations, vertical profile measurements (like an anemometric tower or mast) give a detail of the winds in certain localizations. In general, the characteristics of the wind are divided in four groups: the vertical profiles of wind characteristics, the speed, the turbulence intensity and the spectral turbulence (Liu, 1990). Johnson (2008), for example, made a complete compilation of the main climatic elements that influence rocket launchings in the United States, giving a special attention to the winds (surface and upper air). Kwon, Lee and Sung (2003) made experiment studies using a wind tunnel to analyze the

atmospheric conditions of the island of Oenaro-Do, where the space center of South Korea is being constructed.

The wind tunnels are used by micrometeorology science due to its advantage of controlling the flow, which optimizes the data collection, the sensitivity analysis and the scientific insights. In the recent applications found in the literature using wind tunnels, it can be cited simulations with the coupling between forest and atmosphere (Novak *et al.*, 2000) that analyzed the turbulent structure of the atmosphere within and above canopy, pollutant dispersion fields immersed in obstacles (Mavroidis, Griffiths and Hall, 2003), besides simulation of the air flow for complex topography (Cao and Tamura, 2006). Recently, Abu-Mulawech (2005) carried out a detailed analysis of the influence of the forward facing-step problem related to different heights for a mixed convection (natural and forced).

The objective of this work was to study the atmospheric flow in the region of ASC through experiments in wind tunnel. The analysis was performed through the wind profiles, fields of vorticity, streamlines, turbulent intensities and fluctuation of the wind speed in each point of the interest region, using data obtained with the hot wire anemometry (HWA) and the particle image velocimetry (PIV) techniques. The results were obtained from the MSc dissertation of Roballo (2007) and from the PhD thesis of Pires (2009).

WIND PROFILES AT NEAR-NEUTRAL CONDITIONS

Neutral stability conditions are scarce in the real atmosphere (Arya, 2001). For strong winds with mean hourly wind speed higher than 10.0 m/s, the flow is sufficient turbulent to mix vertically the atmosphere and suppress the thermal (buoyancy) effects (Loredo-Souza, Schettini and Paluch, 2004). At the near neutral conditions, the atmospheric turbulence is purely originated from the wind shear (mechanically driven) and depends on the friction of the surface and the vertical wind shear. This work assumed a neutral stability at ASC due to the strong winds, independently of the hour of day (daily cycle) for both wet and dry conditions (seasonal cycle). A complementary study using a different data set made with sonic anemometer (Magnago, Fisch and Moraes, 2010) confirmed this hypothesis.

There are some theoretical and experimental laws to represent the wind profile, like logarithmic and power law, respectively (Arya, 2001). The vertical variation of the mean wind speed (U) up to approximately 100-150 m above a roughness surface can be represented as (Eq. 1):

$$U(z) = \left(\frac{u_*}{k}\right)\ln\left(\frac{z}{z_0}\right) \tag{1}$$

where:

u_* is the friction velocity (m/s);

k is the Von Karman´s constant and assumed to be 0.40;

z_0 is the roughness aerodynamic length (m).

An observational study (Roballo and Fisch, 2008), using a wind tower (70 m height) at ASC, has obtained values of roughness aerodynamic length between the classes 0.0-0.1 m. The friction velocity was in the interval between 0.3 and 0.4 m/s for the wet period and between 0.4-0.5 m/s for the dry period. These results will be compared with the measurements made at the wind tunnel.

The power or wall law is defined by the Eq. 2:

$$\frac{U(z_r)}{U(z_n)} = \left(\frac{z_r}{z_n}\right)^a \tag{2}$$

where $U(z)$ and $U(z_r)$ are mean wind speed equivalent to a height z and a reference height z_r, respectively.

The value of z_r is assumed to be 10 m as it is the value suggested by the World Organization of Meteorology (WMO) to represent the surface wind. The exponent alpha for the observational study by Roballo and Fisch (2008) was found to be in the range of 0.20-0.25 (dimensionless).

Usually statistical means and fluctuations are used to represent the turbulent structure, but in this work the concept of the turbulence intensity was used, defined as the ratio between the standard deviation (σ) and the mean wind speed (U) (Eq. 3):

$$I = \frac{s}{U} \tag{3}$$

LOCALIZATION OF THE REGION OF THE STUDY

The ASC is situated at the village of Alcântara at the north coast of the state of Maranhão, at geographic coordinates 2°19' S, 44°22' W, 50 m above sea level and at a distance of 30 km to the city of São Luís. This facility is the main Brazilian Space Center where Satellite Vehicle Launcher (VLS, acronym in Portuguese) and rocket soundings (like SONDA II, SONDA III, VS30, VS40 and VSB-30) were being launched for the last 20 years. Figure 2 shows the respective localization of the ASC, the Mobile Tower

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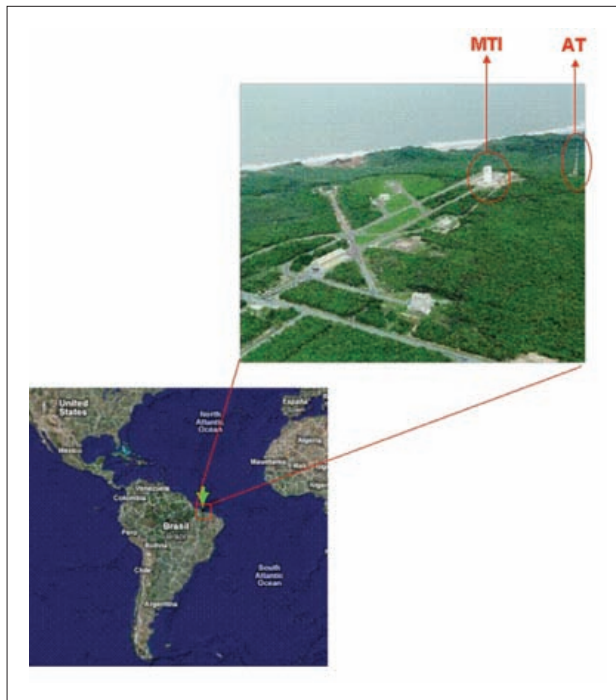
Figure 2:   Geographic localization of ASC, MTI and AT.

Integration (MTI), where the rockets are launched, and the anemometric tower (AT) whose data has been used and compared with the simulations.

The climate of Alcântara shows a seasonal rainfall regime divided into two different periods: a wet period from January to June and a dry period from July to December. During the wet period, the precipitation is typically around 200 mm per month, while at the dry season the rainfall is lower than 20 mm per month. The winds are very distinct between both seasons: during the wet season (March is a characteristic month), the winds are weaker and associated with the trade winds. The wind direction is from east up to 5000 m, with wind speed around 7.0 and 8.0 m/s between the levels of 1000 and 3000 m. For the dry season (September), there is a superposition between the trade winds and the sea breeze, producing stronger winds. The direction is from east up to 8000 m height, reaching maximum velocities between 10.0 and 15.0 m/s at 2000 m. The sea breeze is more intense during the dry period because the thermal difference between oceanic and continental surface. The air temperature and humidity do not present seasonality and their values are very typical of the tropics (Fisch, 1999).

METODOLOGY

The experiments were carried out at the wind tunnel installed at the Professor Kwein Lien Feng Laboratory in the Technological Institute of Aeronautics (ITA, acronym

in Portuguese), constructed for the Plint & Partners LDD Whokingham Bershire England (Serial n ° TE 44/5065). This wind tunnel is an opened conventional model, subsonic (Fig. 3a). The test sections have the dimensions of 0.46 m x 0.46 m with length of 1.20 m. For the first tests a canal apparatus made by wood was used (with an open lid and internal width of 0.41 m) to allow the fully development of the boundary layer profile (Fig. 3b). The air flow is produced by electric fans with the power of 30 hp. The wind generated in the tunnel is of 33 m/s, approximately equivalent to 120 km/h. The scale in this tunnel is 1:1000.
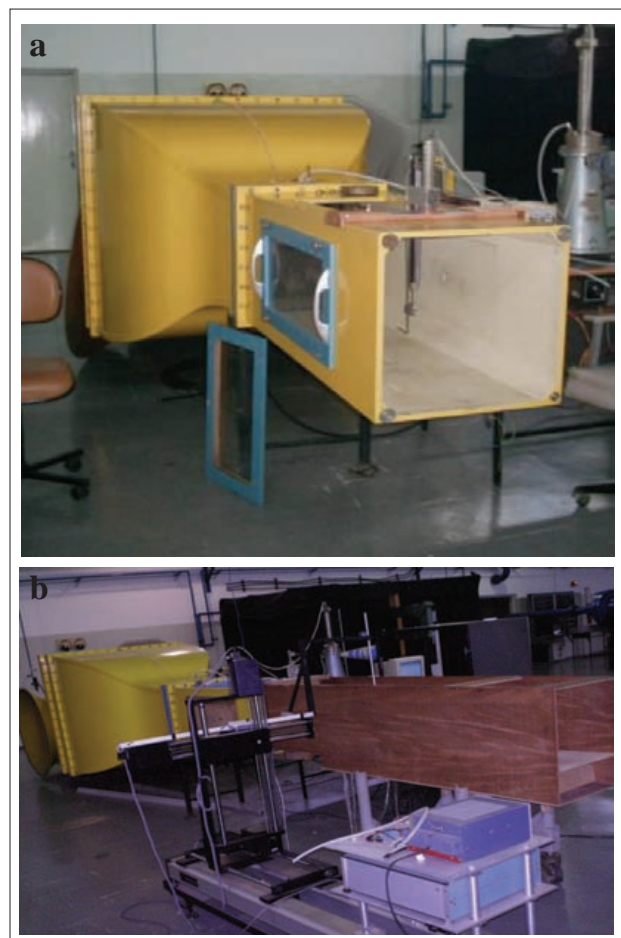

Figure 3:   The wind tunnel (a) and an overview of the wind tunnel with the woody extension (b).

Measurements with hot wire anemometer (HWA)

The HWA used was a 5 μm tungsten probe constant temperature anemometer (CTA) from Dantec (AN-1005 HWA System) with a sample rate of 1 kHz. There was no spectral information collected during the tests. The uncertainties of the measurements were computed as 0.02 m/s and were described in Roballo (2007).

At the mock-up developed to represent the atmospheric flow in Alcântara, it was necessary to install few spires in order to simulate the atmospheric wind profile. These spires consist of triangular steel plates, which were positioned in the entrance of measurements chamber and combined with the roughness (a carpet was used) to produce the boundary layer profile for the wind flow (Santa Catarina, 1999).

Figure 4 represents a lateral view of the mounted mock-up. It was also possible to observe an apparatus (to represent the coastal cliff) that was inserted after the adjustment of the boundary layer inside the wind tunnel. Some measurements were made without the "apparatus step" that simulates the coastal cliff in order to adjust the exponent alpha of the power law (Eq. 2) to a value of 0.15. This value is typical of smooth surface, like the ocean (Blesmann, 1973).
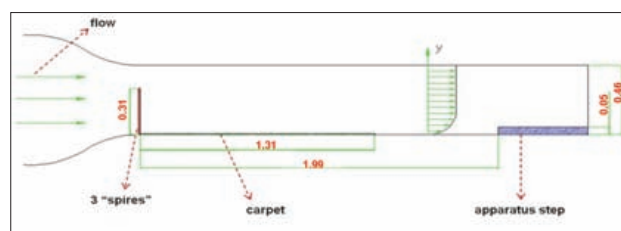

Figure 4: Lateral view of the mounted mock-up.

After the adjustment of the boundary layer profile, a step apparatus was inserted in order to represent the coastal cliff (Fig. 5). This coastal cliff was positioned at a distance of 1.99 m. In order to fully investigate the role of the coastal cliff in creating turbulence, besides this experiment (Experiment 1), three others experiments (2, 3 and 4) were designed and simulated at the wind tunnel:
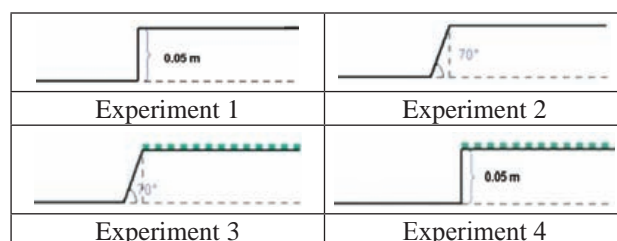

Figure 5: Schematic representation of the experimented models investigated in the wind tunnel.

a) apparatus smooth step (90°) – Experiment 1;

b) apparatus smooth step (70°) – Experiment 2;

c) apparatus smooth step (70°) with local vegetation (simulated by woody cubes of 0.003 m) – Experiment 3;

d) apparatus perpendicular step (90°) with local vegetation – Experiment 4.

The measured heights were controlled by a positioning system which is able to move in three directions. The heights of measurements were: 0.006, 0.01, 0.02, 0.03, 0.04, 0.07, 0.09, 0.11, 0.13, 0.15, 0.17, 0.19 and 0.21 m, and the first six correspond to the levels of AT (Roballo and Fisch, 2008). The maximum speed obtained was close to 22.0 m/s corresponding to a Reynolds number (Re) in the order of 10^4. The height length considered was 50 m (equivalent to the height of the cliff).

Figure 6 represents a schematic design of the measurements. A coordinate system (x,y) was used as a reference system, where the negative x values correspond to the ocean (upwind of the coastal cliff) and the positive x values correspond to the continent (downwind).
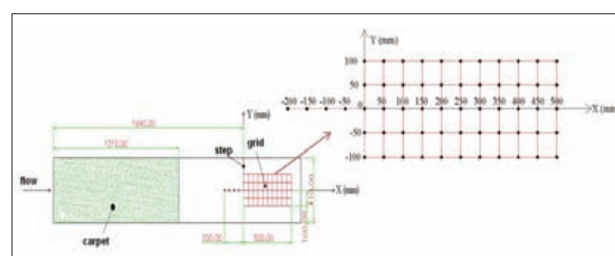

Figure 6: Superior view of the experimental design with the coordinates x (longitudinal) and y (lateral).

Measurements with particle image velocimetry

For the second tests, the devices used for the formation of a typical atmospheric profile were: insertion of spires, a screen (0.005 x 0.005 m) and a carpet for fine adjustment. The screen was introduced in order to reduce the length necessary to form the atmospheric profile (AP) to be at the optical access to particle image velocimetry (PIV). Techniques of generation of atmospheric profile in short test section wind tunnel were described by Pires (2009). It was formed at 1.42 m from the screen and with a height approach of 0.20 m. Figure 7 shows a schema of the experimental apparatus used.
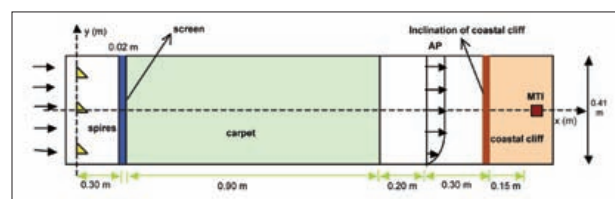

Figure 7: Experimental apparatus used for the experiments of the AP and of the ASC region.

Experiment 1 (Fig. 5) was reproduced using the technique of PIV. So, the MTI (represented by a wooden block of dimensions 0.01 x 0.01 x 0.05 m) was inserted and it was observed its influence on the turbulence structure. The

MTI has the same effect in the flow as a building. A study about building amplification factors (BAF) for sources near buildings was carried out by Thompson (1993) in a wind tunnel. BAF are defined as the ratio of the maximum ground-level (or building-surface) concentration observed to the maximum observed for the same source in the absence of the building. This study described a point-source release of no buoyant material at various positions near isolated rectangular buildings located on flat terrain, where low and high releases were analysed, and concluded that in low releases may be entrained into the building's highly turbulent flow region and result in high pollutant concentrations on the building surface where building air intakes are located and high releases may result in increased concentrations at ground level downwind of the building as a result of the building's influence on the mean flow field.

The free wind speed (u_∞) ranged from 27 to 30 m/s corresponding to a Re of the order 10^4 based on the height of the coastal cliff of 40 m. This was the maximum Re values obtained for this wind tunnel. In the atmosphere, the Re is higher basically of the order of 10^6.

Air flow velocity fields were obtained using a two dimensional PIV system. The test section flow was seeded with smoke particles, approximately 0.005 m in diameter, using a Rosco Fog generator. An Nd-YAG, 200 mJ/pulse laser of 532 nm wavelength, was employed to illuminate the flow field. A vertical laser sheet was created using an articulated arm (Fig. 8) and a set of lenses with thickness adjustment of the laser. A 60 mm m diameter Nikkor lens (Nikon®) were fitted to 12-bits high-resolution digital camera (HiSense 4M, Dantec Dynamics) that uses a CCD with 2048 x 2048 pixels and a 7.4 μm pixel pitch to record the flow field. The instantaneous images were processed using the adaptive-correlation option of the commercial software Flow Manager 4.50.17, developed by Dantec Dynamics. A 32 x 32 pixels interrogation window with 50% overlap and moving average validation was used. The camera and the source of the laser were located in a three axes system positioning.

As shown in Fig. 9, for the accomplishment of the measurements with PIV, the mock-up was painted in flat black color in order to minimize the reflections of the laser that intervene with the measurements. The region of the experimental apparatus was isolated to prevent accidents caused by laser reflections and to minimize the influence of the surrounding light in the measurements.

RESULTS AND DISCUSSION

Figures 10a and b represent, respectively, the profiles of the wind speed and the fluctuation of the wind along
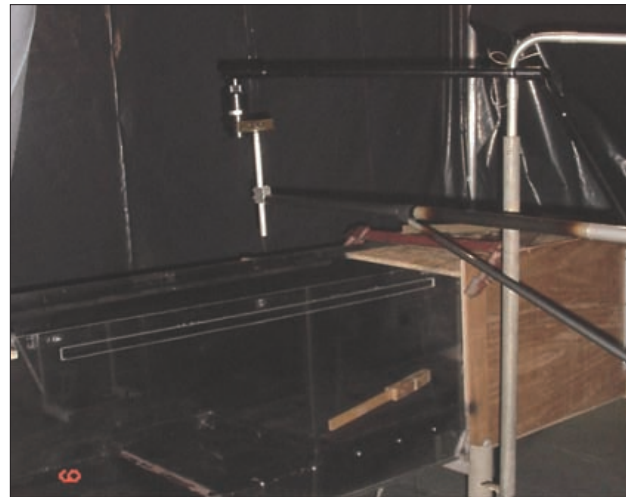

Figure 8: Section of test and articulated arm.

Figure 9: Particle generator and experimental apparatus.

the central line. The heights had been normalized by the height of reference δ = 0.21 m, as well as the values of wind speed had been normalized by the wind speed at this height. It is possible to observe that upstream of the step (x < 0, in Fig. 6) the mean of wind profiles had presented characteristics of uniform flow, with low values of fluctuations. In the region of the step (x = 0), it was observed that mean wind flow pattern was disturbed, with the formation of regions with high values of fluctuations. This was mainly observed close to the surface (up to the normalized height of 0.2) and for a longitudinal distance corresponding a height of 200 m from the edge.

Figure 11 shows mean flow field of vorticity and velocity obtained from the PIV measurements. The mean vorticity is a measure of the turbulence was computed by (Eq. 4):
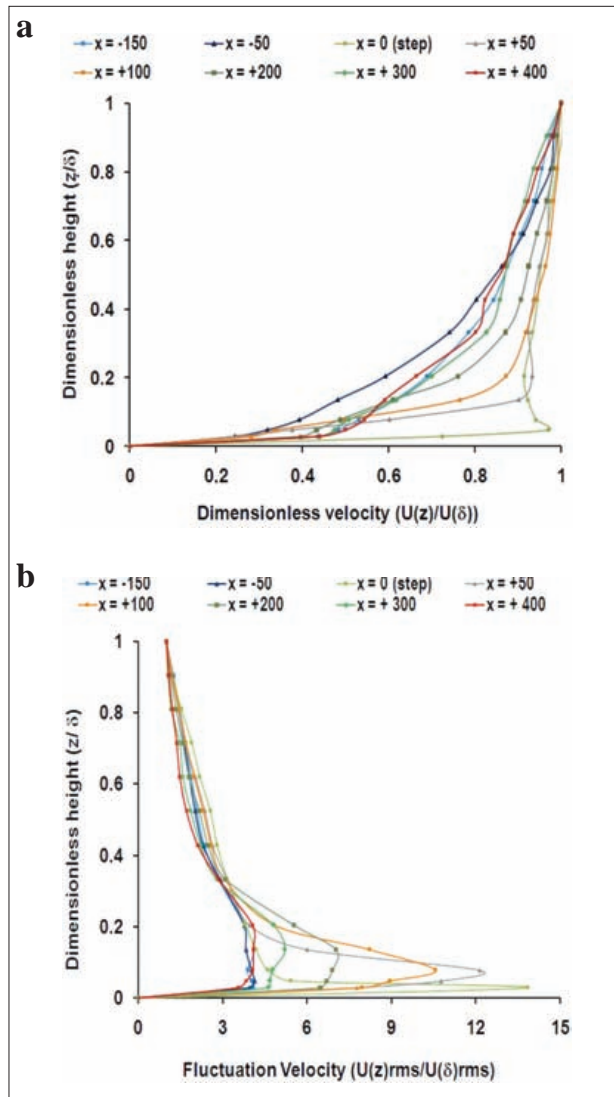
Figure 10: Average velocity profile (a) and fluctuating velocity profiles (b) along the central line obtained with the HWA.

$$\Omega_z = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} \tag{4}$$

The negative values is for clockwise rotation and positive values for anti-clockwise. It can be observed a separation region on the coastal cliff corner with the formation of a recirculations bubble. For this situation, the Re was 7.5×10^4. The increase of the fluctuation cited above is related to the recirculation region caused by the coastal cliff (Fig. 11a) and the highest fluctuations of the turbulence can be seen through the vorticity field (Fig. 11b), where it is possible to observe negative vorticities values (-2000 s⁻¹), because reverse flow.

The turbulent intensity (Eq. 3) was computed for the levels of the anemometric tower (6, 10, 16.3, 28.5, 43 and 70 m) and is shown in Fig. 12. It is possible to observe that *I* is very high
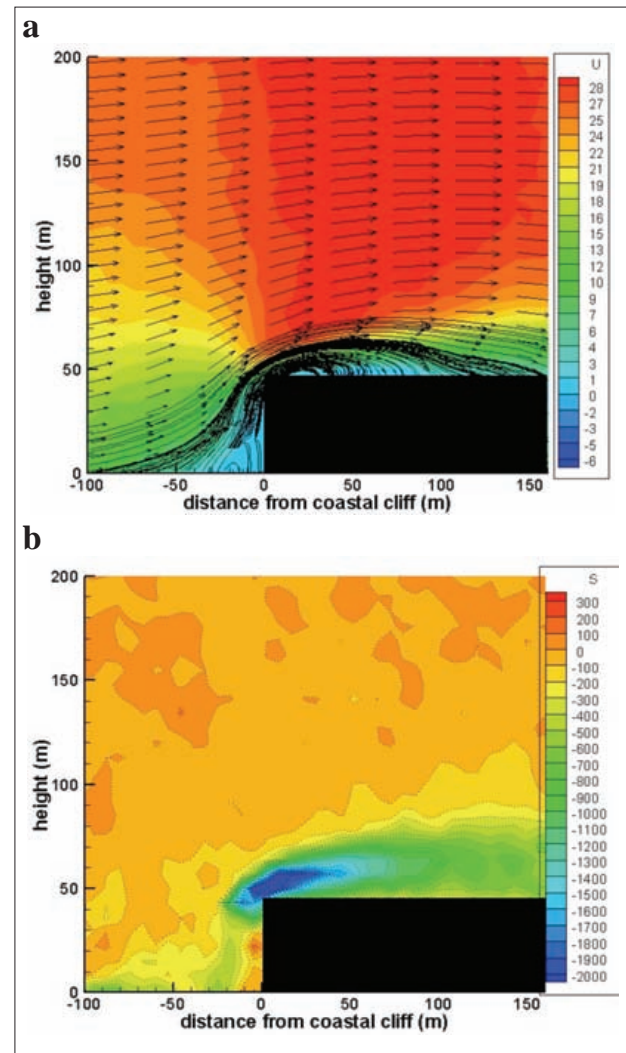

Figure 11: (a) PIV velocity flow field. (b) Mean vorticity flow field.

close to the surface, especially close to edge, where values of 0.7 at level 1 were reached. There is also a significant decrease of *I* with height, and at the level 6 (equivalent to 70 m height) the turbulent intensity is around 0.1 for all positions along the central line. The distance of 300 m (upstream of coastal cliff edge) was estimated as the distance where the turbulence originated by the edge disappears.

The values of the exponent alpha from the power law were obtained from the linearization of the Eq. 2, which resulted in Eq. 5:

$$\log\left(\frac{U(z)}{U(z_r)}\right) = \alpha\left[\log\left(\frac{z}{z_r}\right)\right]\log \tag{5}$$

These values were also obtained by plotting *log (U(z)/U(z_r))* against *log (z/z_r)*. The alpha was computed from the adjusted linear regression (angular coefficient). Figure 13 shows an example of the procedure.
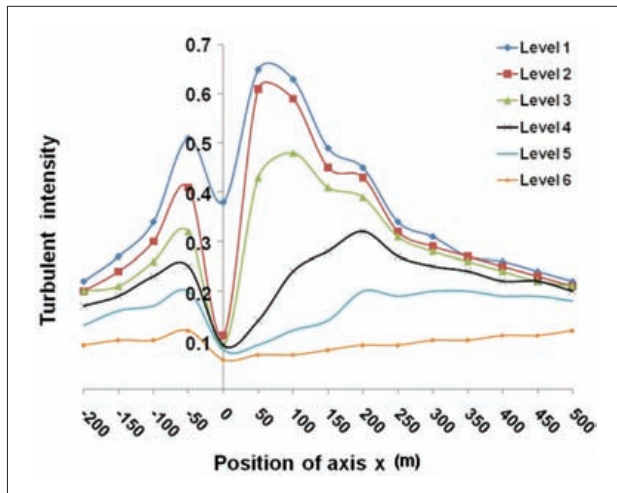
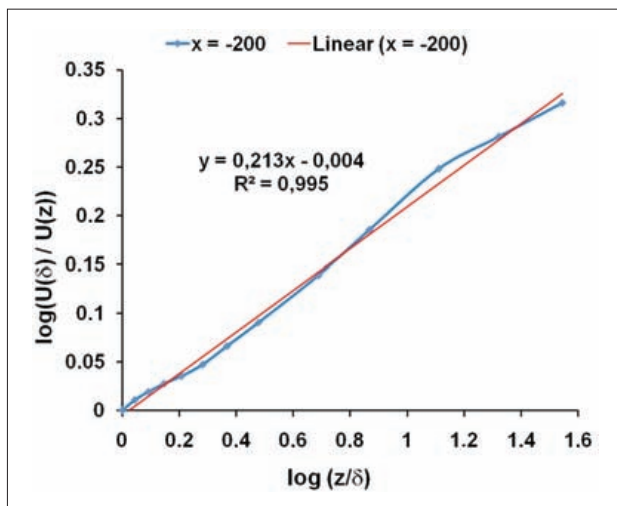Figure 12: Turbulence Intensity distribution along the central lane (position y = 0).

Figure 13: Example of the determination of alpha by Eq. 5.

From Table 1, which summarizes the results from all experiments, it is possible to notice that the power law cannot be applied close to the border due to the region of re-circulation. Upstream the coastal cliff (at x = -200 m), all values of alpha were very close. This is an indication that the coastal cliff will not influence this position

anymore. The values of alpha at x = 200 m are higher than the values founded by Roballo and Fisch (2008), although similar values are obtained at a distance of 300 m.

The meteorological parameters (u_* and z_0) of the logarithmic law (Eq. 1) were also computed and compared with the observations of Roballo and Fisch (2008). The distributions for u_* and z_0 at the central line (position y = 0) are shown in Figs. 14 and 15, respectively. At the
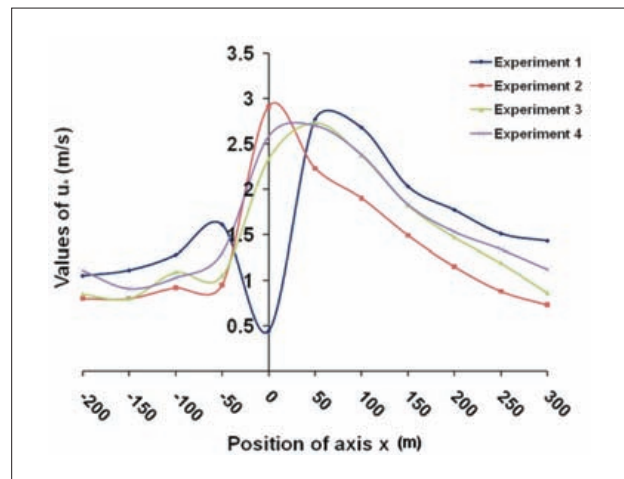

Figure 14: Distribution of u*.
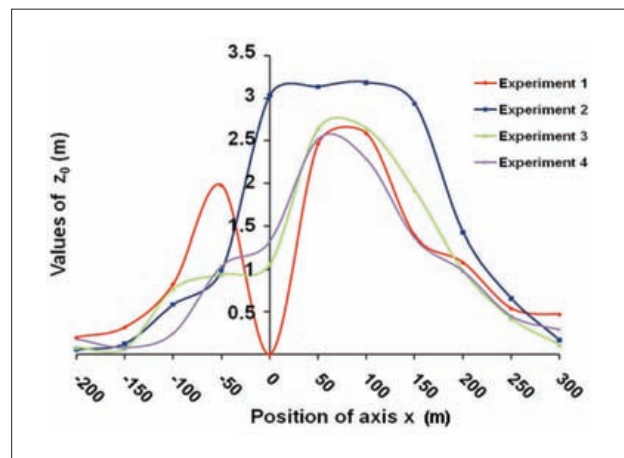
Figure 15: Distribution of z_0.

Table 1: The alpha values for the central lane

Position (m)	ALPHA			
	Experiment 1	Experiment 2	Experiment 3	Experiment 4
x = -200	0.21	0.20	0.21	0.22
x = -150	0.24	0.24	0.22	0.22
x = -100	0.31	0.34	0.36	0.28
x = -50	0.40	0.41	0.41	0.41
x = 200	-	0.46	0.34	0.35
x = 250	0.24	0.39	0.27	0.28
x = 300	0.24	0.30	0.24	0.28

position of the edge (x = 0), there is an abrupt decrease of the values of u_* and z_0 for Experiment 1. For the others experiments, this variation is not so intense due to the higher degree of smoothness from the topography (Experiments 2 and 3) or the inclusion of the vegetation (Experiment 4). The results from the inclusion of the vegetation indicates an increase of the mixture of the vertical transports. The values of z_0 at the position 200 m showed very high numbers and this situation can be associated with lower Re of 10^4 (instead of the typical value of 10^7 for real atmosphere). This situation (Fig. 12) permits the re-circulation zone to be longer (at the wind tunnel measurements) than it is in reality. At the position x = 300 m from the edge the roughness presents a value of 0.1 m, similar to the observed values obtained by Roballo and Fisch (2008).

Table 2 presents the results for u_* for all the experiments and the observations. The dimensionless value corresponds the ratio of u_* (for experiment values at the wind tunnel as for observation values) with the characteristic velocity in the wind tunnel. This procedure was used with the purpose of to allowing a comparison between observational and the experimental results. The Experiment 2 presented the best agreement between measurements and observations.

Figure 16 shows results of PIV measurements with the presence of MTI. It is possible to observe changes in the flow pattern when reaching the MTI, illustrated by the stream lines (Fig. 16a). After the MTI the flow seems to form a von Karman street vortex.

The vorticity generated at the coastal cliff (Fig. 16b) has the same intensity of those generated on the MTI (-2000 s⁻¹) and these are the zones of higher turbulence.

It is possible to verify that upstream the MTI, the vorticity of flow is of approximately -900 s⁻¹ and that downstream

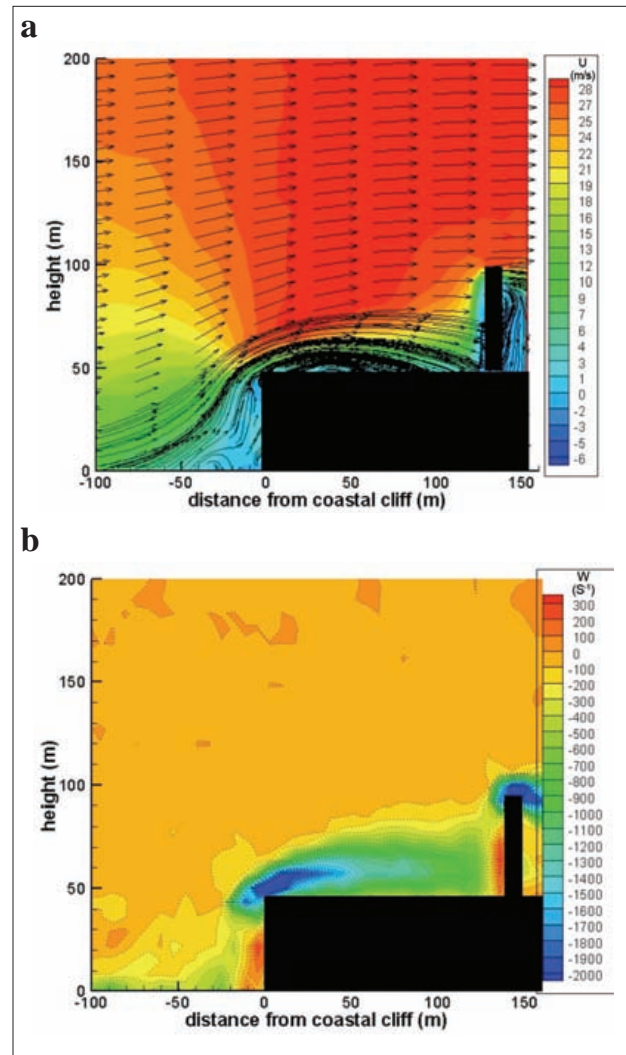Figure 16: (a) stream lines and (b) vorticity with the MTI.

it reaches a positive vorticity in the value of 300 s⁻¹. A similar situation occurs very close to the coastal cliff. The negative vorticity values occurs in the recirculation regions.

Table 2: Comparisons of the values of $u*$ for all experiments

Comparison of u_* experiment *versus* observation		u_* (m/s)	Characteristic velocity (m/s)	Dimensionless value	Re
Wind Tunnel	Experiment 1	1.80	22	0.08	6.52×10^4
	Experiment 2	1.20	22	0.05	6.52×10^4
	Experiment 3	1.47	22	0.06	6.52×10^4
	Experiment4	1.53	22	0.07	6.52×10^4
Observations	Wet period	0.3-0.4	8	0.04	2.37×10^7
	Dry period	0.4-0.5	10	0.04	2.92×10^7

Obs.: The magnitude order of the Reynolds number (Re) is lower in the wind tunnel due to reduction of scale of the height of the coastal cliff, which in this case is 0.05 m.

CONCLUSIONS

The HWA technique was proved to be very appropriate for mean wind profiles and fluctuations measurements at the ASC simulation in wind tunnel. Due to the limitation in the wind tunnel's velocity, high Re typical of the atmosphere (order of 10^5 or 10^6) was not obtained. However, this study developed an initial procedure to understand the atmospheric flow at ASC using wind tunnel, presenting important behaviors such as the displacement, the formation of circulation bubble and the reattachment of the flow on the tunnel surface.

With the PIV technique it was possible to get a general view of the flow based on streamlines and vorticity. A modification of the flow when reaching the step (coastal cliff) was verified, as well as the formation of the recirculation region. During the second tests, measurements had been conducted with the simulation of the MTI existing in the ASC, where the rockets are positioned for the launching. An alteration of the flow was observed by the streamlines in the place, forming a von Karman street vortex. The vorticity in the localization of the MTI resulted in the same one that was occurred during the passage of the flow by the coastal cliff.

Comparing the results of velocity flow map and mean vorticity obtained with PIV and turbulence intensity values obtained with HWA, it was observed that the highest values of turbulence intensity occurs in the identified flow separation regions and that the lowest turbulence intensity was observed in the free stream regions, as expected.

REFERENCES

Abu-Mulawech, H.I., 2005, "Turbulent mixed convection flow over a forward-facing step – the effects of step heights". International Journal of Thermal Sciences, Vol. 44, No 2, pp. 155-162. doi: 10.1016/j.ijthermalsci.2004.08.001.

Arya, S.P., 2001, "Introduction to micrometeorology", 2nd edition, Elsevier ISE, Maryland Heights, MO, USA, 420 p.

Blessmann, J., 1973, "Simulação da estrutura do vento natural em um túnel de vento aerodinâmico", Ph.D. Thesis, Instituto de Aeronáutica e Espaço, São José dos Campos, SP, Brazil.

Cao, S. and Tamura, T., 2006, "Experimental study on roughness effects on turbulent boundary layer flow over a two-dimensional steep hill". Journal of Wind Engineering and Industrial Aerodynamics, Vol. 94, No 1, pp. 1-19. doi: 10.1016/j.jweia.2005.10.001.

Fisch, G., 1999, "Características do perfil vertical do vento no Centro de Lançamento de Foguetes de Alcântara (CLA)". Revista Brasileira de Meteorologia, Vol. 14, No 1, pp. 11-21.

Jonhson, D.L., 2008, "Terrestrial environment (climatic) criteria guidelines for use in aerospace vehicle development. (NASA/TM-2008-215633)", NASA Marshall Space Flight Center, Huntsville, AL, 472 p.

Kwon, K.J., Lee, J.Y., Sung, B., 2003, "PIV measurements on the boundary Layer Flow around Naro Space Center", In: Proceedings of the 5th International Symposium on Particle Image Velocimetry, Busan, Korea, pp. 22-24.

Liu, H., 1990, "Wind engineering: a handbook for structural engineers", Prentice Hall, Upper Saddle River, NJ, USA, 224 p.

Loredo-Souza, A.M, Schettini, E.B.C, Paluch, M.J., 2004, "Simulação da camada limite atmosférica em túnel de vento", In: Möler, S.M, Silvestrini, J., Anais da IV Escola de Primavera Transição e Turbulência, Vol. 4, Porto Alegre, Brazil, pp. 137-163.

Magnago, R.O, Fisch, G., Moraes, O.L.L., 2010, "Análise Espectral do Vento no Centro de Lançamento de Alcântara (CLA)". Revista Brasileira de Meteorologia, Vol. 25, No 2, in press.

Mavroidis, I., Griffiths, R.F., Hall, D.J., 2003, "Field and wind tunnel investigations of plume dispersion around single surface obstacles". Atmospheric Environment, Vol. 37, No 21, pp. 2903-2918. doi: 10.1016/S1352-2310(03)00300-5.

Novak, M.D., et al., 2000. "Wind tunnel and field measurements of turbulent flow in forests. Part I: Uniformly thinned stands". Boundary Layer Meteorology, Vol. 95, No 3, pp. 457-495.

Pires, L.B.M., 2009, "Estudo da Camada Limite Interna desenvolvida em falésias com aplicação para o Centro de Lançamento de Alcântara", Ph.D. Thesis, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil, 165p, Available at: <http://urlib.net/sid.inpe.br/mtc-m18@80/2009/06.22.18.27>.

Roballo, S.T., 2007, "Estudo do escoamento atmosférico no Centro de Lançamento de Alcântara (CLA) através de medidas de torre anemométrica e em túnel de vento. (INPE-14824-TDI/1264)", Master of Science dissertation, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil, 137 p, Available at: <http://urlib.net/sid.inpe.br/mtc-m17@80/2007/06.12.18.07>

Roballo, S.T., Fisch, G., 2008, "Escoamento atmosférico no Centro de Lançamento de Alcântara (CLA): parte I - aspectos observacionais". Revista Brasileira de Meteorologia, Vol. 23, No 4, pp. 510-519.

Santa Catarina, M.F., 1999, "Avaliação do escoamento no Centro de Lançamento de Foguetes de Alcântara: estudo em túnel de vento, Relatório Final de Atividades de Iniciação Cientifica". Instituto Tecnológico de Aeronáutica, São José dos Campos, SP, Brazil, 72 p.

Thompson, R.S., 1993, "Building amplification factors for sources near buildings: a wind-tunnel study". Atmospheric Environment, Vol. 27, No 15, pp. 2313-2325.