METHOD OF RECOVERY SYSTEM VALUES OPTIMIZATION AND ITS APPLICATION

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Abstract

The present work deals with the preliminary design features of a high performance ground recovery system for small orbital payloads based on parachutes with an air bag for impact attenuation. The paper shows and discusses the method for determination of system optimum area of the drag parachute, necessity of parachute reefing and optimum sea-level rate of descent which provide the minimum system mass. After this method the parachute construction is characterized by a certain parameter, which takes into account aerodynamic characteristics and main aspects of rational design, such as relative sizes, sections load, strength loss and expenses. The sequences of the system optimum values calculations for the SARA orbital platform are given. Use of this method provides the increase of the system safety and system total mass and volume decrease in comparison with the basic system.

Keywords: parachute design, system mass, optimum values.

1. INTRODUCTION

The orbital platform SARA will be used to perform microgravity experiments in space (Moraes, 1998), and its recovery at ground must be safe and soft, in order to protect the payload inside it from high ground impact. Systems based on parachutes with impact attenuator are the most adequate choice, due to its proven reliability and low cost. The development of such a system includes the consideration of determination of parachutes area and mass, drag and stress analysis of the parachutes, flight and impact (crash) simulation, materials selection and testing. A good concept and design leads to maximization of performance and, consequently, to weight minimization of the complete system, that is of great importance for space systems (Deweese, Schultz & Nutt, 1978).

The design of recovery systems makes varied demands on the state-of-the art over a broad range of operational conditions and complexity of performance requirements characteristics of modern aerospace vehicles and research instruments. The recovery system technology has benefited from rapid improvement in the rigor of analytical methods made possible and practical by development of complex and flexible computer programs. While empirical data and full-scale testing are still of major importance to the design process, the facility with which system and component designs can be executed and analyzed, their performance predicted, and test data reduced and evaluated has both speeded the design process and improved depth and quality of results. A number of different parachute design programs are now developed in great detail (Peterson, 1990). When the input of new basic system parameters, comprehensive series of similar designs can be compared with respect to performance, weight, and drag efficiency for a single application.

Development of a design procedure starts with essential design criteria, sizing, staging, performance, opening loads analysis, strength of materials and parachute mass, packing volume, and choice of methods for parameters optimization. Taking system mass as the design criteria, the optimum values of the system parameters are determined by means of equalization to zero of partial derivative of system mass function with respect to the parameter which is optimized.

2. RECOVERY SYSTEM MASS DETERMINATION

On the whole the recovery system mass can be presented as the sum of its main parts.

2.1 Parachute framework mass

The parachute framework mass can be calculated as a sum of its elements in all sections:

$$m_f = \Sigma\, l_i\, w_i\, n_i \tag{1}$$

$$l_i = l_i^{*}\, S^{1/2} \tag{2}$$

$$w_i = p_i / (g\, l_{pi}): \tag{3}$$

where l_i length of parachute elements, m
n_i number of section elements
w_i material specific mass, kg/m
l_i^{*} element specific length, dimensionless
S parachute canopy area, m^2
p_i section element strength, N
g gravity acceleration, m/s^2
l_{pi} material break length, m.

For Nylon cords and ribbons $l_{pi} = p_i/(g\, w_i) \approx 30$ km, for Nylon cloth $l_{pi} \approx 20$ km and for Kevlar materials $l_{pi} \approx 58$ km with consideration that for Kevlar elements the dynamic load is approximately in 1.5 times more than for Nylon elements (Knacke, 1992).

The number of elements n_i can be determined from parachute section strength condition:

$$\alpha_i\, p_i\, n_i = \eta_i\, r_i\, f_s\, F_x \tag{4}$$

$$F_x = C_k\, C_D\, S\, R_R\, \rho\, V_o^2 / 2 \tag{5}$$

$$R_R = (C_D\, S)_R / (C_D\, S) \tag{6}$$

where α_i loss factor due to joint, abrasion, fatigue, water, oil, temperature ($\alpha_i = 0.6 \div 0.9$)
f_s safety factor ($f_s = 1.3 \div 2.5$)
F_x maximum parachute force, N
r_i section load factor (section load ratio to parachute force), dimensionless
η_i section strength margin, dimensionless
C_k parachute opening force factor, dimensionless
C_D parachute nominal drag coefficient, dimensionless
ρ air density, kg/m^3
V_o initial parachute velocity, m/s
R_R parachute reefing ratio, dimensionless.

Taking (2), (3), (4) and (5) for (1) we have, (Koldaev, 1989):

$$m_f^* = m_f / m_c = R^2(V)\, K(S)\, K_m\, R_R \qquad (7)$$

$$R(V) = V_o\,(2g\, l_p)^{-1/2} \qquad (8)$$

$$K(S) = C_k\, R_m \qquad (9)$$

$$K_m = f_s\, C_D^{-1/2}\, \Sigma\, l_i^*\, r_i\, \eta_i /(\alpha_i\, l_{pi}^*) \qquad (10)$$

$$R_m = \rho\, (C_D\, S)^{3/2} / m_c \qquad (11)$$

$$l_{pi}^* = l_{pi} / l_p \qquad (12)$$

where $R(V)$ parachute velocity ratio, dimensionless
$K(S)$ parachute structure parameter, dimensionless
K_m parachute framework mass parameter, dimensionless
R_m parachute mass ratio, dimensionless
l_{pi}^* relative material break length, dimensionless
l_p basic break length (l_p = 30000 m)
m_c capsule (platform) mass, kg.

The value K(S) as approximation functions of R_m ratio and parachute opening dynamic factor C_x is shown in Table 1, (Koldaev & Moraes, 1997). Dynamic factor C_x depends on type and porosity of parachute and is determined as ratio of F_{max} to medium drag force in infinite mass condition by wind tunnel test. For several parachute types C_x = 1.1÷1.5, (Lobanov, 1975).

Table 1. Approximation of parachute structure parameter K(S)

R_m value	$R_m < 10^{-2}$	$10^{-2} < R_m < 1$	$R_m > 1$
Parachute type	Drag parachute	Intermediate parachute	Main parachute
Reefed	$C_x R_m$	$R_m(0.12+(0.06-C_x/2)\lg R_m)$	0.12
Non - reefed	$C_x R_m$	$R_m(0.25+(0.125-C_x/2)\lg R_m)$	0.25
Des reefed	$C_x R_m$	$R_m(0.6+(0.3-C_x/2)\lg R_m)$	0.60

The K_m parameter from (10) means dimensionless universal parachute quality parameter that takes into account as parachute aerodynamic characteristics as main aspects of rational design and can be used to compare parachutes of different types, areas and purposes of their use. K_m value for same systems is shown in Table 2. It was determined from (5) and (7) as:

$$K_m = m_f\, l_p\, g\, (C_D\, S)^{-1/2} / F_x \qquad (13)$$

Table 2. Parachutes data (Knacke, 1992) and parameters K_m and K_b

m_c (kg)	m_p (kg)	m_f (kg)	C_DS (m^2)	V_o (m/s)	V_e (m/s)	C_k	K_m	K_b
50	2.5	1.4	18	120	6.7	0.13	9.2	0.66
150	6.8	5.0	28	120	9.1	0.21	10	0.40
300	13.2	9.7	56	120	9.15	0.15	9.6	0.46
500	21.0	14.9	95	120	9.15	0.11	9.4	0.50

2.2 Air bag mass

The air bag casing mass we can calculate after the following formulas (Koldaev & Moraes, 1998):

$$m_a = w_a S_a = w_a H_b 2\pi R_c = w_a H_b (S_c \pi)^{1/2} \tag{14}$$

$$m_c V_e^2 / 2 + m_c g H_b = \eta_a G m_c g H_b \tag{15}$$

$$T_a = f_{sa} R_c P_{max} = f_{sa} (S_c / \pi)^{1/2} G m_c g / S_c = w_a G l_a \tag{16}$$

where w_a specific cloth mass, kg/m^2
S_a area of air bag casing, m^2
S_c capsule done area, m^2
H_b required height of air bag, m
V_e system rate of descent at impact initial moment, m/s
η_a efficiency of air bag, dimensionless ($\eta_a \approx 0.65$, Knacke, 1992)
T_a stress tension for cylindrical air bag, N/m
G capsule maximum acceleration, g
P_{max} air bag maximum pressure, Pa
l_a break length of air bag casing cloth, m.

Taking H_b from (15) and w_a from (16) for (14) we have:

$$m_a^* = m_a/m_c = V_e^2 f_{sa} /(g\, l_a (\eta_a - 1/G)) \tag{17}$$

2.3 Total mass of recovery system

$$m_s^* = (\Sigma (R_j^2(V) K_j(S) K_{mj} R_{Rj} + S_j w_{cj} /m_c) + N_R m_R + V_e^2 f_{sa} /(g\, l_a (\eta_a - 1/G)))(1+K_b) \tag{18}$$

where m_s^* recovery system mass ratio to capsule mass, dimensionless
j parachute number (stage)
w_{cj} specific mass of parachute canopy cloth, kg/m^2
N_R number of reefed parachutes
m_R mass of each complete set of reefing equipment, kg
K_b relative mass of binding and packing equipment, dimensionless.

Mass of each complete set of reefing equipment lies in the interval $m_R = 0.1 \div 0.4$ kg and depends on the type of pyrotechnic knife and parachute opening force.

Binding equipment includes pieces for putting the parachutes and air bag into action, risers for joining system components and other furniture. Packing equipment includes parachutes bags, swivels, system container. According to statistic data, relative total mass of binding and packing equipment to system mass lies in the value $K_b = 0.4 \div 1.0$ (depends on the type of system composition). Value of K_b for some recovery systems is shown in the Table 2. Calculated system mass versus rate V_e is shown in the Figure 1.

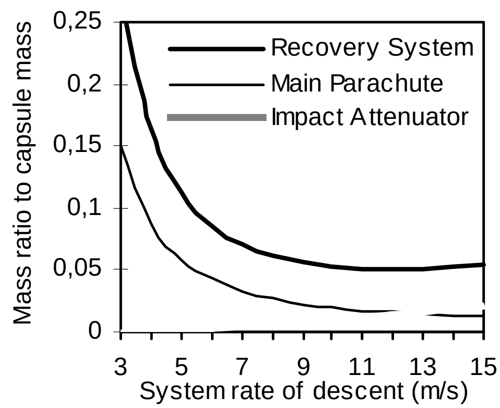

Figure 1. Components mass of SARA recovery system

3. OPTIMIZATION OF SYSTEM VALUES

Settled (critical) rate of system descent depends on parachute and capsule drag area sum, is equal to initial velocity of the next stage and may be calculated from force equilibrium as:

$$m_c\, g = ((C_D S)_j + C_c S_c)\, \rho_{j+1} V^2_{crj} / 2 \qquad (19)$$
$$V^2_{crj} = V^2_{oj+1} = 2\, m_c\, g / (\rho_{j+1}\, ((C_D S)_j + C_c S_c)) \qquad (20)$$

where j index of the first (drag) parachute
$j+1$ index of the next (main) parachute
V_{crj} settled (critical) rate of descent, m/s.

Hence, taking (20) for (8) we can write:

$$R^2_{j+1}(V) = m_c / (\rho_{j+1}\, l_{pj+1}\, ((C_D S)_j + C_c S_c)) \qquad (21)$$

3.1 Optimum area of drag parachute

Having taken the system total mass m_s from (18) as the optimization criteria we can determine optimum X_{opt} value of the system which guarantees m_{smin}. Then X_{opt} is the root of the equation:

$$dm_s^* / dX = 0 \qquad (22)$$

When the area of the main parachute is given we can write :

$$m_s^* = \Sigma\, R_j^2(V)\, K_j(S)\, K_{mj}\, R_{Rj} + \text{const} \qquad (23)$$

Taking (11), (21) and (23) for non-reefed drag and main parachutes from (18) we have:

$$m_s^* = R_j^2(V)\, K_{mj}\, C_{kj}\, \rho_j (C_D S)_j^{3/2} / m_c + K_{j+1}(S)\, K_{mj+1} m_c / (\rho_{j+1}\, l_{pj+1} ((C_D S)_j + C_c S_c)) + \text{const} \qquad (24)$$

Let us take for the first step of drag area $(C_D S)_j$ optimization the value of $C_{kj} = C_{xj}$ as for drag parachute and $(C_D S)_j >> C_c S_c$ as for a relative small capsule. Then from (22) and (24):

$$dm_s^* / d(C_D S)_j = 3 C_{xj}\, K_{mj}\, R_j^2(V)\, \rho_{j+1} (C_D S)_j^{1/2} / 2 m_c - K_{mj+1}\, K_{j+1}(S)\, m_c / (\rho_{j+1}\, l_{pj+1}\, (C_D S)_j) \qquad (25)$$

$$(C_D S)_{jopt1} = ((2\, (K_{mj+1} / K_{mj})\, m_c\, K_{j+1}(S)) / (3\, C_{xj}\, \rho_j\, R_j^2(V)\, \rho_{j+1}\, l_{pj+1}))^{2/5} \qquad (26)$$

If $K_{mj} = K_{mj+1}$, $l_{pj} = l_{pj+1}$ and $K_{j+1}(S) = 0.25$ (for main parachute, see Table 1) we have:

$$(C_D S)_{jopt1} = (m_c^2\, g / (3\, C_{xj}\, \rho_j\, V_o^2\, \rho_{j+1}))^{2/5} \qquad (27)$$

For the second step of drag area optimization we can determine $C_{kj+1} = f(R_m, C_x)$. Then:

$$(C_D S)_{jopt2} = (C_D S)_{jopt1}\, (C_{kj+1}\, (1 + C_c S_c / (C_D S)_{jopt1}))^{-2/5} \qquad (28)$$

3.2 Optimum sea-level rate of system descent

When the drag area of the drag parachute $(C_D S)_j$ is known we can write from (18):

$$m_s^* = (w_{cj+1}\, S_{j+1} / m_c + V_e^2\, f_{sa} / (g\, l_a\, (\eta_a - 1/G)))(1 + K_b) + \text{const}' \qquad (29)$$

Taking $V_e^2 = X$ and area of main parachute S_{j+1} from (19) if $(C_DS)_{j+1} >> C_cS_c$ we have:

$$S_{j+1} = 2\, m_c\, g\, /(C_{Dj+1}\ \rho_o V_e^2) \qquad (30)$$

$$m_s^* = (w_{cj+1}\ 2\ g\ /(C_{Dj+1}\ \rho_o\, X) + X\ f_{sa}\ /(g\ l_a\ (\eta_a\text{-}1/G)))(1+K_b) + \text{const'} \qquad (31)$$

Let us define $V_{eopt}^2 = X_{opt}$ as the root of the equation (22). Then from (31) we have:

$$-2\ X^{-2}\ w_{cj+1}\ g\ /(C_{Dj+1}\ \rho_o) + f_{sa}\ /(g\ l_a\ (\eta_a\text{-}1/G)) = 0 \qquad (32)$$

$$X_{opt} = (w_{cj+1}\ g\ /(C_{Dj+1}\ \rho_o)\ /\ (2\ f_{sa}\ /(g\ l_a\ (\eta_a\text{-}1/G)))^{1/2} \qquad (33)$$

$$V_{eopt} = (w_{cj+1}\ g^2\ l_a\ (\eta_a\text{-}1/G)/(2\ f_{sa}\ C_{Dj+1}\ \ \rho_o))^{1/4} \qquad (34)$$

3.3 Necessity of parachute reefing

Let us make the convention to evaluate reefing necessity by comparison of the system mass gain with, inevitable for reefing, complication of construction and possible decrease of the reliability of the system. Within this, each non-reefed parachute of the system being developed should have a certain mass increase barrier, the excess of which would mean the reefing necessity. The gain in system mass due to use of the parachute reefing can be calculated as:

$$\Delta m = m_f - m_f^R - m_R \qquad (35)$$

where Δm mass gain, kg
m_f mass of parachutes framework without reefing, kg
m_f^R mass of parachutes framework with reefing, kg
m_R mass of reefing equipment, kg.

From (7) the parachute framework masses with and without reefing are:

$$m_f = m_c\ K_m\ R^2(V)\ K(S) = K_m\ \rho\ V_o^2\ (C_DS)^{3/2}\ C_k\ /(2g\ l_p) \qquad (36)$$

$$m_f^R = K_m\ R^2(V)\ K^R(S) = K_m\ \rho\ V_o^2\ (R_R\ C_DS)^{3/2}\ C_k^R \qquad (37)$$

$$\Delta m = m_f\ (1 - R_R^{3/2}\ C_k^R\ /\ C_k) - m_R \qquad (38)$$

4. CALCULATIONS FOR SARA RECOVERY SYSTEM

Let us take the following system parameters and requirements for recovered from orbit SARA capsule (Moraes, 1999):

Capsule mass, m_c	215 kg
Capsule drag area, C_cS_c	0,4 m^2
Capsule speed at moment of the system inflation, V_o	135 m/s
Air density at altitude of drag parachute inflation, ρ_6	0.67 kg/m^3 (H = 6 km)
Air density at altitude of main parachute inflation, ρ_2	1.0 kg/m^3 (H = 2 km)
Load factor (capsule maximum acceleration), G	8 g.

4.1 Calculations for basic system

Let us consider the system, which guarantees the sea-level rate of descent of 6 m/s, as the basic one. Taking index j for the drag parachute and index (j+1) for the main parachute, coefficients C_{kj} = 1.2, C_{Dj} = 0.55 for ribbon drag parachute and C_{Dj+1} = 0.8 for cross main parachute we can determine maximum force and required parachutes areas from (5) and (30):

$$F_{xj} = C_{kj} C_{Dj} S_j \rho_6 V_o^2 / 2 \leq G\, m_c\, g = 8 \;\; 215 \;\; 9.81 = 16900 \text{ N} \tag{39}$$

$$S_j \leq G\, m_c\, g /(C_{kj} C_{Dj} \rho_6 V_o^2 / 2) = 8 \;\; 215 \;\; 9.81 \;\; 2/(1.2 \;\; 0.55 \;\; 0.67 \;\; 135^2) = 4.19 \text{ m}^2 \tag{40}$$

$$S_{j+1} \geq 2\, m_c\, g /(C_{Dj+1} \;\; \rho_o V_e^2) = 2 \;\; 215 \;\; 9.81 / (0.8 \;\; 1.225 \;\; 6^2) = 120 \text{ m}^2 \tag{41}$$

Taking drag area $(C_D S)_j$ = 4.19 0.55 = 2.3 m^2 the initial velocity V_{oj+1} from (20) is:

$$V_{oj+1} = (2\, m_c\, g /\rho_2 /((C_D S)_j + C_c S_c))^{1/2} = (2 \;\; 215 \;\; 9.81 / 1.0 / (2.3 + 0.4))^{1/2} = 40 \text{ m/s} \tag{42}$$

It is necessary to use the reefing because within the ratio V_{oj+1}/V_e = 40 / 6 = 6.7 > 5 the apparent air recontact is possible (Koldaev, Guimaraes & Moraes, 1999). Taking reefing ratio R_{Rj} = 0.2 and $(C_D S)_{Rj}$ = 2.3 m^2, from (6) the value $(C_D S)_j$ = 2.3/0.2 = 11.5 m^2. For parameters K_b = 0.75, l_p = 30 km, K_m = 10 (Table 2), w_c = 0,065 kg/m^2 (MIL-C-7350I), f_{sa}= 2.5, l_a = 20 km, m_R = 0.3 kg, η_a = 0.65, and $R_{j+1}(V)$ from (21) the basic system mass from (18) is:

$$m_{sbas} = (V_o^2 C_{xj} \;\rho_6 (C_D S)_j^{3/2} R_{Rj} K_m /(2g\, l_p) + 0.25\, K_m m_c^2 /(\rho_2\, l_p\, ((C_D S)_j + C_c S_c)) + \tag{43}$$

$$+ S_{j+1} w_c + N_R m_R + V_e^2 f_{as}\; m_c / (g\, l_a(\eta_a - 1/G))) \,(1 + K_b) =$$

$$= (135^2\, 1.2 \;\; 0.67 \;\; 11.5^{3/2}\; 10\; 0.2/(2\; 9.81\; 30000) + 0.25 \;\; 10 \;\; 215^2 /(1 \;\; 30000\; (11.5 +0.4)) +$$

$$+ 120 \;\; 0.065 + 0.3 + 6^2 \;\; 2.5 \;\; 215 \;\; /(9.81 \;\; 20000\; (0.65 - 1/8)))(1 + 0.75) = 18.4 \text{ kg.}$$

4.1 Calculations of optimum system values

Taking the requirements equal to basic system for the optimum sea-level rate of capsule descent from (34), the drag and main parachute optimum areas from (27) and (30), we have:

$$V_{eopt} = (w_c\, g^2\; l_a\, (\eta_a - 1/G) / (2\, f_{sa}\, C_{Dj+1}\, \rho_o))^{1/4} = \tag{44}$$

$$= (0.065 \;\; 9.81^2 \;\; 20000\; (0.65\text{-}1/8)/(2 \;\; 2.5 \;\; 0.8 \;\; 1.225))^{1/4} = 10.8 \text{ m/s}$$

$$(C_D S)_{jopt} = (m_c^2\, g/(3\, C_{xj}\, \rho_j\, V_o^2\, \rho_{j+1}))^{2/5} = (215^2\; 9.81/(3 \;\; 1.2 \;\; 0.67 \;\; 135^2\; 1))^{2/5} = 2.5 \text{ m}^2 \tag{45}$$

$$S_{j+1opt} \geq 2\, m_c\, g /(C_{Dj+1} \;\; \rho_o\, V_{eopt}^2) = 2 \;\; 215 \;\; 9.81 /(0.8 \;\; 1.225 \;\; 10.8^2) = 37 \text{ m}^2 \tag{46}$$

Taking $(C_D S)_j$ = 2.3 m^2 the parachute mass gain due reefing use from (36) and (38) is:

$$\Delta m_j = K_m\, \rho_j\, V_o^2 (C_D S)_j^{\;3/2} (C_{kj} - R_{Rj}^{\;3/2}\, C_{kj}^{\;R}) / (2g\, l_p) - m_R = 0.56 \text{ kg} \tag{47}$$

It is not necessary to use the parachutes reefing as the mass gain Δm_j is small and the ratio V_{oj+1} / V_e = 40 / 10.8 = 3.7 < 5. Then the mass of optimum recovery system from (43) is:

$$m_{sopt} = (135^2\ 1.2\ \ 0.67\ \ 2.3^{3/2}\ 10/(2\ \ 9.81\ \ 30000) + 0.25\ \ 10\ \ 215^2\ /(1\ \ 30000\ (2.3 + 0.4)) +$$

$$+\ 37\ \ 0.065 + 10.8^2\ \ 2.5\ \ 215\ /\ (9.81\ \ 20000\ (0.65 - 1/8)))(1 + 0.75) = 8.94\ \text{kg}.$$

5. CONCLUSIONS

Preliminary design features of a high performance ground recovery system for small orbital payloads based on parachutes with an air bag for impact attenuation have been analyzed and discussed. A method for determination of system optimum values for the parachute recovery systems was proposed. With the use of this method to design the recovery system of the orbital platform SARA, the areas of drag and main parachutes have been determined, which guarantee minimum system mass and volume. Compared with the basic system, the so optimized system has approximately two times less mass (see Figure 1), more simple construction and higher reliability of function due to exclusion of the parachute reefing with equal load during parachutes opening and landing impact.

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6. REFERENCES

- Deweese, J.H., Shultz, E.R., Nutt, A.B., 1978, “Recovery System Design Guide”, Technical Report AFFDL-TR-78-151, California.
- Knacke, T.W., 1992, “Parachute Recovery Systems Design Manual”, 1st ed., Para Publishing, Santa Barbara, California.
- Koldaev, V., 1989, “Optimization of Parachute Construction Characteristics”, The Reports Collection of NIIAUS Scientific Conference, Moscow.
- Koldaev, V., Moraes, P.Jr., 1997, “Analytical Method for Optimization of Recovery System Parameters and its Application”, Nota Técnica NT-132/ASE-N/97, CTA/IAE, São José dos Campos-SP.
- Koldaev, V., Moraes, P.Jr., 1998, “Design of Impact Attenuators for Ground Recovery of Small Space Capsules”, V Congresso Brasileiro de Engenharia Mecânica Norte-Nordeste, Fortaleza-CE.
- Koldaev, V., Guimarães, M., Moraes, P.Jr., 1999, “Simmulation of Parachute Dynamics”, XV Congresso Brazileiro de Engenharia Mecânica, COBEM'99, Águas Lindoia-SP.
- Lobanov, N.A, 1975, “Calculation and Dsign of Parachutes”, Mashinostroenie, Moscow.
- Moraes, P.Jr., 1998, “Design Aspects of the Recoverable Orbital Platform SARA”, 8º Congreso Chileno de Ingenieria Mecánica, Concepción, Chile.
- Moraes, P.Jr., 1999, “Proposta para Ensaios em Vôo Suborbital do SARA com Veículo VS-40”, Nota Técnica NT-166/ASE-N/99, CTA/IAE, São José dos Campos-SP.
- Peterson, C.W., 1990, “High Performance Parachutes”, Scientific American Journal of Aircraft, pp. 108-116.