USV TEST FLIGHT BY STRATOSPHERIC BALLOON: PRELIMINARY MISSION ANALYSIS

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Abstract

The **U**nmanned **S**pace **V**ehicle test flights will use a 7 meters 1300 kg aircraft. The first three launches will take place at the **I**talian **S**pace **A**gency ASI base in Trapani-Milo, Sicily, through a stratospheric balloon that will drop the aircraft at a predefined height. After free fall acceleration to transonic velocities, the parachute deployment will allow a safe splash-down in the central Mediterranean Sea. The goal of this article is to show the preliminary analysis results for the first USV flight.

We carried out a statistical study for the year 2000÷2003, evaluating the typical summer and winter launch windows of the Trapani-Milo base.

First, in the center Mediterranean, we define safe recovery areas. They can't be reached during the balloon ascending phase so, after a sufficiently long floating part able to catch the open sea, the balloon will go down to the release height (24 km). The simulation foresees a 400,000 m^3 balloon and 3 valves for the altitude transfer.

A safe splash-down must occur far enough from the nearest coast: the minimum distance is considered around 25 km. The vehicle should be released at a distance, from the nearest coast, greater than this minimum amount plus the USV model maximum horizontal translation, during its own trajectory from balloon separation to splash-down. In this way we define safe release areas for some possible translations. Winter stratospheric winds are less stable. The winter average flight duration is 7 hours and it is probably too long for the diurnal recovery requirement and its scheduled procedures.

Comparing past stratospheric balloons flights and trajectories computed using measured meteorological data (analysis), with their predictions made using forecast models and soundings, we obtain the standard deviation of the trajectory forecast uncertainty at the balloon-aircraft separation. Two cases are taken into account: predictions made 24^h and 6^h before the launch.

Assuming a Gaussian latitudinal uncertainty distribution for the prediction 6^h before the launch, we are able to identify the forecast trajectories that have a probability greater than 97% to reach the safe release areas. Simulating the summer windows trajectories for the years from 2000 to 2003 and for the favorable ground wind days, we obtain the number of trajectories with the desired forecast probabilities.

1.Introduction and scope

The **U**nmanned **S**pace **V**ehicle project, conceived for the development of the future generations of spacecraft and new aerospace technologies, it is part of the Italian Aerospace Research Program (PRORA) managed by the Italian Aerospace Research Centre (CIRA). The program foresees, for the first three flight tests, the use of stratospheric balloons to drop the aircraft (7 meters aircraft of about 1300 kg) at a required height. Free fall acceleration will push the model to transonic region and, after aerodynamic measurements, the parachute will be deployed reducing the velocity before spash-down.

The purpose of this document is to show a preliminary mission analysis, in the case of launch performed by using the ASI's facilities in Trapani-Milo. The next sections will be focused on some important aspects of the analysis:

- Main requirements
- Wind properties
- Balloon's altitude profile

- Trajectory's properties and impacts on safety requirements
- Forecast trajectory uncertainties
- Release areas and confidence level
- Statistical results

2. Main Requirements

The following main requirements apply:

- Launch base: Trapani-Milo
- Launch windows: Summer or winter (June ÷ August or December ÷ January)
- Recovery operations: diurnal
- USV release height: 24 km
- Recovery: on sea
- Spash-down distance from costs   no less than 12 Nm

The launch site position does not allow the balloon to reach, during the ascending phase, a safe area having a distance from the coast no less than 12 Nm; the balloon flight must foresee an appropriate floating phase able to catch the release area at open sea.

The launch is assumed to be at 7-8 am local time, due to the ground wind statistical properties of the Trapani-Milo base and the requirement of diurnal recovery.

During summer the stratospheric winds are westward and the splash down will take place out to sea in front of the Algerian coast; in winter the eastward winds impose the balloon to go across the whole Sicily island and the recovery will be managed in the Ionian Sea, between the Italian and Greek coasts. The minimum distances between the launch site and the splash down area is 70 km for the summer window and about 250 km in winter.

3. Wind properties

The forecast simulation and the reconstruction of the balloon trajectories require the availability of the atmospheric data in the geographical area and at the epoch of interest. The same availabilities are still important to point out the statistical properties of the wind direction and intensity and its impact on the trajectory. The following sources have been used to retrieve the wind data:

- Sounding data, made from the Trapani-Birgi airport and the ASI Trapani-Milo Base
- Analysis (measured) data from the European Centre for Medium-Range Weather Forecasts
- Forecast data from ECMWF and MM5 (Fifth-generation Mesoscale Model) models

Fig.1 and Fig 2. show the probability distribution of wind directions and speeds for the float altitude (around 10 mb). The winter months have a bigger dispersion. In particular in that period the intensity could be very low, so the balloon will reach the release area few hours before sunset. This advance could be insufficient for the requested diurnal recovery.

4. Balloon's altitude profile

Fig.3 shows the balloon altitude as function of the mission elapsed time from launch to the USV release. The simulations have been performed by using:

- Balloon volume: 400,000 m^3
- Payload: 1500   Kg
- Other parts: 2500   Kg
- 3 (already used) valves type of 35 cm (Cardillo et al., 2001).

With reference to Fig.3:

• the balloon reaches the floating altitude after around 2.5^h;
• the differences in floating duration time (around 2^h) take into account the different locations of the release areas for the winter and the summer launch windows
• the height of 24 km is reached, from the floating altitude, in 1.5^h and it is kept until the balloon enters inside the release area.

5. *Trajectory's properties and impacts on safety requirements*

A database of days having meteorological conditions useful for launch is available in Trapani-Milo ASI base, for the past winter and summer balloons campaigns. Simulations have been performed according to the useful launch days from 2000 to 2003, considering 6 UTC as launch time.
In Fig.4 some balloons ground tracks are shown, reconstructed for the month of August 2000.
Analyzing the winter trajectories it is clear that the flight could last from 4 to 8 hours, due to high distance between launch and release points and big wind instability. As consequence the balloon could reach the release area at 3 pm local time and the interval time between splash-down and sunset could be less then 1.5^h. Because of no margin for diurnal recovery, the winter launch window could be critical and it will not be anymore taken into account.

6. *Forecast trajectory uncertainties*

The evaluation of the uncertainties, related to the forecast trajectory during the summer window, is calculated measuring the distances between the predicted and the actual ground traces for the stratospheric balloons flights of the ASI archive (Cosentino et al., 2004). Besides, in order to compute much more cases, we compared in addition couple of trajectories reconstructed by using forecast and analysis data.
Fig.5 shows, for some couples of simulations, the latitudinal distances between actual and predicted trajectories made by using the forecast wind data available 24^h before launch. Taking into account that the release area is around 10.5 degrees longitude, we obtain the following value for the latitudinal uncertainty's standard deviation at the balloon-aircraft separation point: $\sigma = 19$ Km.
Six hours before launch the trajectory is simulated using not only the forecast models but joining also just collected sounding data (Musso et al., 2003, 2004); this method reduces the latitude's uncertainty, as shown in Fig.6. Taking into account again 10.5 degrees as mean longitude of the release area, we obtain the following standard deviation for the latitudinal uncertainty: $\sigma = 11$ Km.

7. *Release areas and confidence level*

The safety conditions for the splash down impose not less than 12 Nm from the nearest coast (around 25 km). As consequence the release must take place from a minimum distance of 25 + x km, where x is the maximum horizontal translation of the Flying Test Bed USV during its own flight trajectory, from the release altitude to the sea level. For x we evaluated four cases with values of 30, 50, 70 and 90 km. The four corresponding areas are shown in Fig.7 together with their simplification by using rectangles (see also Fig.4). We considered that the launch must be done only if the last useful forecast trajectory, (made 6 hours before the flight), will allow the release area to be reached with a probability greater than 97%.
For the probability density of the latitudinal forecast uncertainty, a Gaussian distribution can be considered. The curve will be centered at the latitude where the prediction reaches the release area (Fig.8). The abort probability will be the integral of the curve outside the rectangle, representing the safe release area.
During the summer windows, the forecast trajectories are no less than 28 km south from the north side of the smallest rectangle (safe release area with x=90 km); so the integral of the latitudinal uncertainty function above the rectangles is negligible (always less than 0.007% considering $\sigma = 11$ Km). It means that to reach the required confidence level (97%), the forecast trajectories must be inside the considered rectangular release area, with a distance, from its south side, greater than 22 km (Fig.8).

8. Statistical results

Tab.1 shows, for each month of the summer windows for the years between 2000 and 2003, the number of trajectories reaching the release area with a confidence level greater than 97% over the total number of days useful for launch.

- For dispersion equal or greater than 90 km practically there are no cases with a confidence level greater than 97%.
- For a dispersion of 70 km, every month only 5% of trajectories reach the release area with a confidence level of 97%; in addition there could be months without launch opportunities
- For a dispersion of 50 km, every month the 20% of useful trajectories reach the release area with a confidence level of 97%;
- For a dispersion of 30 km, every month the 50% of trajectories reach the release area with a confidence level of 97%.

9. Acknowledgements

10. References

Cosentino, O.; Caballero, F.; Ibba, R.; Gerardi, G.; Cecchini, G.P.; Fernández Abad, A. Transmediterranean flights, in the edge of two centuries, Advanced Space Research, Elsevier, Vol 33, Issue 10, 2004, pp. 1594-1599

Musso, I.; Cardillo, A.; Cosentino, O.; Memmo, A balloon trajectory prediction system, Advanced Space Research, Elsevier, Vol 33, Issue 10, 2004, pp. 1722-1726

Musso I., A. Cardillo, O. Cosentino, Software and methodologies for stratospheric balloons' flight prediction, 3th AIAA Aviation Technology, Integration and Operations Technical Forum, Denver, Colorado, 17-19 November 2003, A03-46753 AIAA, Paper 2003-6820

Cardillo A., O. Cosentino, M.C. Falvella, R. Ibba, A. Leonardi, E. Morelli, A Computering Directional Drive for Stratospheric Balloons Using Wind Variation Versus Altitude, Prooceedings of 15th ESA Symposium on Rocket and Balloons Programmes and Related Research, ESA SP'471, ESA/ESTEC, Noordwijk (NL), August 2001, pp. 629-633

	30 km	50 km	70 km	90 km
Jun 00	40%	7%	0%	0%
Jul 00	61%	22%	6%	0%
Aug 00	41%	23%	9%	0%
Jun 01	39%	15%	8%	0%
Jul 01	44%	19%	13%	6%
Aug 01	47%	26%	0%	0%
Jun 02	38%	14%	5%	0%
Jul 02	75%	25%	8%	0%
Aug 02	58%	26%	11%	0%
Jun 03	50%	31%	6%	6%
Jul 03	45%	10%	0%	0%
Aug 03	48%	13%	0%	0%

Tab.1: Trajectories percentage (w.r.t. the number of days useful each month for launch) reaching the release area with a confidence level greater than 97%.

Fig.1: Stratospheric wind direction: Probability distribution for wind directions at floating altitude (10 mb).

Fig.2: Stratospheric wind intensity: Probability distribution of wind speed at an altitude of 10 mb.

Fig.3: Mission profile: winter (solid) and summer flight opportunities (dash)

Fig.4: Trajectories computation: August 2000, simulations approaching the release areas

Fig.5: 24^h Forecast uncertainty: latitudinal distances, as function of longitude, between actual and predicted trajectories 24^h before the launch

Fig.6: 6^h Forecast uncertainty: latitudinal distances, as function of longitude, between actual and predicted trajectories 6^h before the launch (forecast models + sounding)

Fig.7: Forecast confidence evaluation: considering a Gaussian distribution, the failure probability is function of the latitude of the predicted trajectory, while approaching the release area. For a 6^h prediction 22 km inside the rectangle, it is less than 2.14+0.135 +0.7=2.975%.

Fig.8: Safe release areas: starting from the lines at 25 km from the coasts and considering USV horizontal translations of 30, 50, 70 and 90 km, four release areas can be drown and, for each of them, one rectangle is identified.