# BALLOON TRAJECTORY PREDICTION METHODOLOGIES FOR THE UNMANNED SPACE VEHICLES PROGRAMME

**Roberto Palumbo, Gianfranco Morani, Federico Corraro**

*CIRA – Italian Aerospace Research Centre, via Maiorise, 81043 Capua (CE), Italy*
*Email: r.palumbo@cira.it; g.morani@cira.it; f.corraro@cira.it*

## ABSTRACT

Within the framework of the Unmanned Space Vehicles (USV) Programme, CIRA has developed several methodologies and tools for balloon trajectory prediction and optimization. As a matter of fact, the two experimental flights planned as part of the USV Programme were carried out using stratospheric balloons as drop towers. To this end, a specific simulation software named ACHAB (Analysis Code for High-Altitude Balloons) was developed from scratch to fulfil the need for an accurate forecast of balloon ascent trajectories. In addition starting from wind and atmospheric forecast data provided by the European Centre for Medium Range Weather Forecast (ECMWF) an extensive characterization of the forecast errors was carried out, leading to a methodology for the computation of dispersion regions around the predicted balloon trajectories and to the implementation of a trajectory optimization tool.

## 1. INTRODUCTION

Balloon trajectory prediction is of primary importance when planning a scientific balloon mission. Often mission objectives and safety constraints require an accurate knowledge of the flight trajectory. In fact a stratospheric balloon can be seen as a thermal and dynamical system in free evolution inside a complex thermal environment and subject to atmospheric winds. As a result, balloon trajectory forecast poses several challenging problems since the subject is both complex and multidisciplinary. In the past, few authors have extensively dealt with balloon modelling and simulation [1][2]. Despite the good results, their work was primarily focused on long-duration flights with less attention on the ascent portion of the balloon flight. Besides, the use of standard atmospheric models and/or of sounding data for wind computation generally made the predictions rather inaccurate. In addition, the lack of an effective characterization of the trajectory prediction error did not allow to identify meaningful trajectory dispersion regions around the predicted trajectory of the balloon. Consequently trajectories computed in this way ended up giving only qualitative indications on the actual trajectory without any quantitative information to be used for mission planning. In recent years several and more quantitative approaches have been proposed [3][4]. However, the methodologies developed in these works are mostly based on a non-optimal consideration of the uncertainties that characterize a balloon flight leading to results that are often heavily dependent on the reference altitude profile chosen for the analysis.

In this paper we will describe an alternative approach taken by the authors to develop several methodologies and tools useful to plan and execute scientific balloon missions within the framework of the Unmanned Space Vehicles (USV) Programme currently carried out by the Italian Aerospace Research Centre (CIRA).

## 2. THE USV PROGRAMME

Recently, CIRA has been carrying out a national programme named Unmanned Space Vehicles (USV) [5]. The main objective of the USV project is the development of enabling technologies for future reusable launch vehicles through the production of fully autonomous crafts conceived as flying laboratories designed to acquire important flight data for the study of the final phase of an atmospheric re-entry. Up to now, two experimental transonic flights have been performed, the Dropped Transonic Flight Tests 1 and 2 (DTFT1, DTFT2), using, respectively, two twin autonomous and unpowered test vehicles named Castore and Polluce (both also called FTB1). Both Castore and Polluce were dropped from a stratospheric balloon at altitudes between 20 km and 25 km, inside a specific target area located in the Tyrrhenian Sea, lifting off from a launch base located in Arbatax, Sardinia, Italy (see Fig. 1). For this reason, it is clear how balloon trajectory prediction and wind estimations are vital for mission operations and success. Thanks to the DTFT flight experiments, CIRA has acquired valuable experience in the field of scientific ballooning and much effort was given to the development of effective methodologies and tools for balloon trajectory prediction and optimization.

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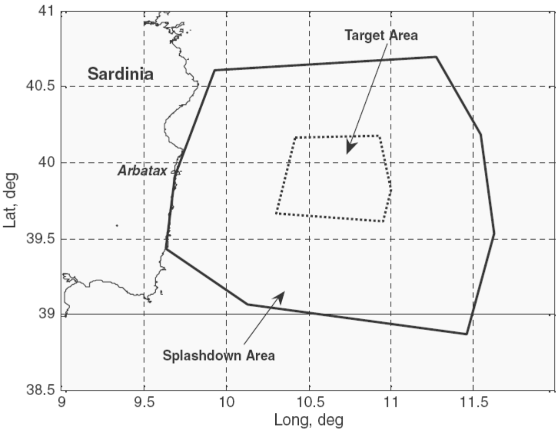


*Figure 1. Target area/Safe Splashdown area.*

## 3. ACHAB

As stated in the previous paragraph, the mission profile of the DTFT missions is based on the drop of FTB1 from a stratospheric balloon inside a specific area. As a result it is extremely important to accurately forecast the trajectory of the balloon to achieve the mission objectives while ensuring flight safety. To this end, CIRA has developed from scratch a specific simulation software named ACHAB: Analysis Code for High-Altitude Balloons [6]. ACHAB is a simulation tool specifically developed to predict flight trajectory and thermal behaviour of high-altitude zero-pressure balloons. Its features include: 3D trajectory prediction, ascent rate prediction, ballasting and valving management, gas and balloon film temperature prediction.

ACHAB was developed starting from specific mathematical models found in open literature [7][8] and taking advantage of several engineering formulations to take into account the various atmospheric and thermal effects given the time varying shape and volume of the balloon. Particular attention was given to the simulation of the ascent phase of the balloon flight in order to fulfil the needs of the DTFT mission objectives.

ACHAB is basically made of several submodels [6][9]:

- a thermal model, that takes into account the thermal interaction between the balloon and its environment;
- a flight dynamics model, that relates the forces that act on the balloon;
- a geometric model, that gives a geometric description of the balloon system;
- a drag coefficient model, that accounts for $C_D$ variations with altitude;
- a ballast and valve manager.

These models work together in order to determine the evolution of the buoyancy force and assess the trajectory of the balloon and its flight performance given the atmospheric winds and weather data.

Some basic assumptions are necessary [6][8]:

- the balloon is considered a 3 degree-of-freedom point mass;
- lifting gas and air are assumed to follow the perfect gas law;
- effects of humidity on atmospheric pressure are neglected;
- lifting gas density and pressure are considered uniform inside the balloon (except when considering valving or venting);
- lifting gas temperature is uniform inside the balloon volume;
- balloon film temperature is uniform along the surface;

The main inputs to the software are: the characteristics of the balloon and of the lifting gas, the atmospheric data and the date, time and location of launch.

Indeed accurate atmospheric data are extremely important for the computation of the spatial trajectory. To this end we have chosen to use the deterministic data of the Integrated Forecast System (IFS) model by the European Centre for Medium Range Weather Forecast (ECMWF) for trajectory prediction. The ECMWF produces both forecast data and analysis data. Analysis data are outputs of the IFS model corrected using the related wind and atmospheric observations. The dispatch of the ECMWF data allows to have a trajectory forecast each 12 h, starting from 72 h before lift-off. It is important to point out that uncertainties on wind predictions as well as uncertainties on atmospheric pressure and atmospheric temperature may significantly affect the trajectory prediction. Therefore these uncertainties must be taken into consideration when planning the balloon mission.

Moreover it is very important to carefully consider the surrounding thermal environment in which the balloon moves. The vertical motion of balloons depends critically on the heat transfer to and from the gas inside, because the temperature and the density of the gas determine the lift of the balloon. The balloon film plays an important role in this heat transfer mechanism, therefore its radiation properties significantly influence the performance and the vertical flight of the balloon. As a consequence, optical properties of both the atmosphere and the balloon film are necessary to determine the thermal fluxes and to evaluate the heat exchange of the system. It is assumed that the lifting gas is completely transparent so it does not emit nor absorb. Therefore the temperature of the lifting gas (helium) may change only as a result of the internal free convection and volume expansion. The internal free convection depends on the difference between the temperature of the gas and the temperature of the film. The variation of the film temperature is the result of the environmental heat loads acting on the balloon film (absorbed visible radiation, absorbed/emitted thermal radiation, free and forced convection). Engineering formulations, involving the use of total absorptivity and total transmissivity coefficients, were considered for the determination of the heat loads. These coefficients are generally function of the type of irradiance. Therefore shortwave radiation (visible light) and longwave radiation (thermal infrared) must be taken into account separately.

Another important aspect is the formulation of a variation law for the aerodynamic drag coefficient. Our studies, supported by considerations found in open literature [10][11], have suggested the use of a drag coefficient model in which the $C_D$ is a function of the Reynolds number, the Froude number and another dimensionless parameter that accounts for shape variations:

$$C_D = f(Re, Fr, L) \tag{1}$$

Indeed a zero-pressure balloon experiences a remarkable shape variation from lift-off up to the attainment of the float altitude and consequently it appears reasonable that the drag coefficient should be considered variable.

### 3.1. Code Validation

The reliability of the trajectory simulation is an important matter. For this reason ACHAB has been validated comparing its results to GPS data of different balloon flights and to the outputs of a reference code, SINBAD v3.1G [12]. Obviously input parameters in the two codes are not the same. An effort was made in order to derive correct conversion rules with the purpose of ensuring the use of same simulation inputs. During the validation process we have observed that in most cases ACHAB showed very good agreement with flight data, even better agreement than SINBAD. Fig. 2 shows an example of a comparison between ACHAB and SINBAD with respect to real flight data.

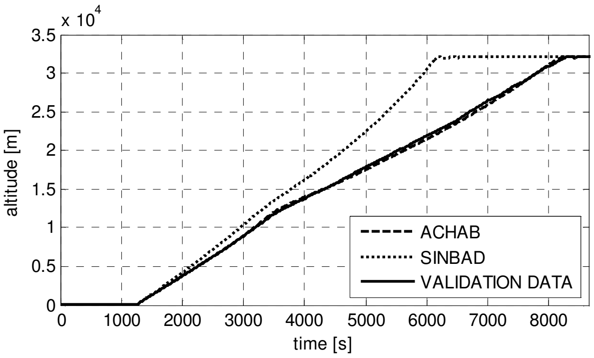


*Figure 2. Comparison between ACHAB and SINBAD with respect to real flight data.*

At the end of the validation process, ACHAB was considered suitable for flight prediction and was used for trajectory prediction of the balloon flights for the DTFT missions. Actually, after DTFT1, some fine-tuning and modifications were implemented concerning especially minor bug fixes and the addition of a cloud cover management system to take into account the effects of cloud cover on the overall thermal environment.

A validation process was also carried out in order to evaluate the effective use and the reliability of the ECMWF weather forecast data. Several past approaches to trajectory prediction [3][4] heavily rely on the soundings carried out some hours before the launch, considering these data more reliable than the forecast ones. Our analysis, however, showed the poor reliability of the sounding-based predictions with respect to the forecast-based ones (ECMWF data). This fact is not surprising because, although sounding data guarantee better accuracy on wind status than the forecast data, they refer to an atmospheric condition (some hours before lift-off) which may be significantly different from the one at the actual hour of flight [13].

*Figure 3. Arbatax airport runway with balloon, launch crane and FTB1.*

Finally ACHAB was used to assess the feasibility of the DTFT mission from the selected launch site (Arbatax, Italy) [9]. A specific statistical analysis was carried out considering ECMWF analysis data and observed ground wind in a time span between 2001 and 2008. The results of this analysis concluded that in spite of the limited number of days per month offering a suitable trajectory for the achievement of the mission objectives, nonetheless the balloon flight was feasible and safe. The most limiting factor was certainly the requirement on the wind direction at lift-off. Indeed the Arbatax launch base is essentially an airport and therefore a circular launch pad could not be used, but only the runway, which allowed a very narrow manoeuvring area for a balloon dynamic launch (Fig. 3).

## 4. UNCERTAINTY CHARACTERIZATION

As pointed out earlier, trajectory prediction is strongly dependent on the knowledge of both wind and atmospheric data (which are inputs to ACHAB). In any case, these data are affected by a given amount of uncertainty that may have a significant effect on the overall trajectory prediction.

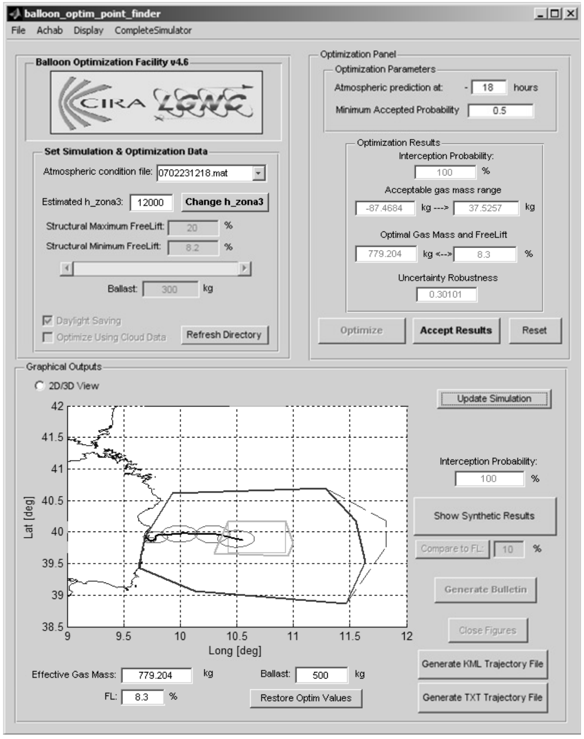
An extensive study has been conducted to deal with the problem of estimating the balloon trajectory uncertainties during the ascent portion of the flight [14]. To this end, a general approach has been developed to estimate the error on the prediction of the balloon's position, starting from the different sources of uncertainty, namely uncertainties on wind, air temperature and air pressure forecast (as predicted by the ECMWF model) and gas mass uncertainties (due to inflation procedures). The characterization of these uncertainties was carried out using the atmospheric data only (without relying on simulated trajectories), and the trajectory prediction error was computed analytically starting from this uncertainty characterization. This allows reducing the computational effort and, at the same time, it gives a more reliable dispersion along the predicted ascent trajectory.

ECMWF forecast uncertainty characterization in terms of wind, air temperature, and pressure has been carried out performing a statistical analysis based on a set of ECMWF forecast and analysis data relative to the area of Arbatax (DTFT mission launch base) during the years 2004–2008. The forecast data have been compared to the analysis data (which are assumed to be the true atmospheric and wind data) in order to perform a statistical characterization of the ECMWF forecast error at 6, 18, 30, 42, 54, and 66 h before a given reference time (launch time).

The uncertainty on the amount of gas mass transferred to the balloon during inflation, strictly depends on the inflation procedure that aims at giving the balloon a desired nominal *free lift*. This procedure is affected by several measurement errors and model approximations that lead to an uncertainty on the gas mass in the range of 1 to 2% [11]. This error is assumed to be a zero-mean Gaussian random variable, with a maximum error of 2% with respect to the nominal mass of gas.

## 5. TRAJECTORY OPTIMIZATION

Indeed prediction errors are essential when evaluating mission success probability and especially when dealing with trajectory optimization problems. In fact, taking advantage of this error characterization, we have developed a specific mission planning tool [13]: a trajectory optimization facility that allows the determination of the optimal *free lift* and ballast, while taking into account mission objectives and trajectory prediction uncertainties. The optimization process, using wind forecast and atmospheric data, calls iteratively ACHAB with the objective of finding the optimal trajectory solution in terms of nominal free lift to be transferred to the balloon at inflation [13]. Since each trajectory has its own prediction error (expressed through uncertainty bounds on the balloon position), the optimal trajectory is the one maximizing the probability of mission success (i.e. the reaching of the target area) in the presence of such uncertainties. Obviously the optimization process takes into account the structural limitations on the allowable values of free lift. It is worth to note that this approach significantly reduces ballast drops during the ascent phase, thus increasing the amount of available ballast for float altitude control purposes. Furthermore, the above described approach may be also used to evaluate the maximum allowable error in the balloon inflation. In fact, for each amount of free lift at inflation, a related probability of mission success exists and, as a consequence, the maximum allowable displacement from optimum free lift can be computed once that a minimum allowable probability of mission success has been defined. Fig. 4 shows the graphical user interface of the optimization tool.



Atmospheric condition file: 0702231218.mat
Estimated h_zona3: 12000
Structural Maximum FreeLift: 20 %
Structural Minimum FreeLift: 8.2 %
Ballast: 300 kg
☑ Daylight Saving
☐ Optimize Using Cloud Data
Atmospheric prediction at: - 18 hours
Minimum Accepted Probability 0.5
Interception Probability: 100 %
Acceptable gas mass range -87.4684 kg ---> 37.5257 kg
Optimal Gas Mass and FreeLift 779.204 kg <--> 8.3 %
Uncertainty Robustness 0.30101
Interception Probability: 100 %
Compare to FL: 10 %
Effective Gas Mass: 779.204 kg
Ballast: 500 kg
FL: 8.3 %

*Figure 4. Graphical User Interface of the optimization tool.*

## 6. BALLOON NAVIGATION FACILITY

To support the balloon flight operations during the DTFT missions, a real-time online balloon navigation facility was also developed. The System for Augmented

Navigation of BAlloon missions (SANBA) is a real-time navigation facility that integrates several prediction and decision-making tools extremely useful during balloon missions. It is able to acquire the GPS data coming from the gondola and display the trajectory and the current position on a map. Using ACHAB, it can also display the predicted trajectory starting from the current position. SANBA has different modules with several additional features and functionalities that make it a unique navigation tool. Among these tools, SANBA includes:

- an optimization module that allows finding (by iteratively calling ACHAB) optimal ballast drop manoeuvres in order to maximize the probability to reach the target area;
- an identification tool, that aims at finding the "exact" value for relevant balloon flight parameters that are usually known with some uncertainty (i.e. inflated mass of gas, balloon drag coefficient), in order to improve the online trajectory prediction.

Fig. 5 shows a global view of SANBA graphical user interface. Further details can be found in [15].

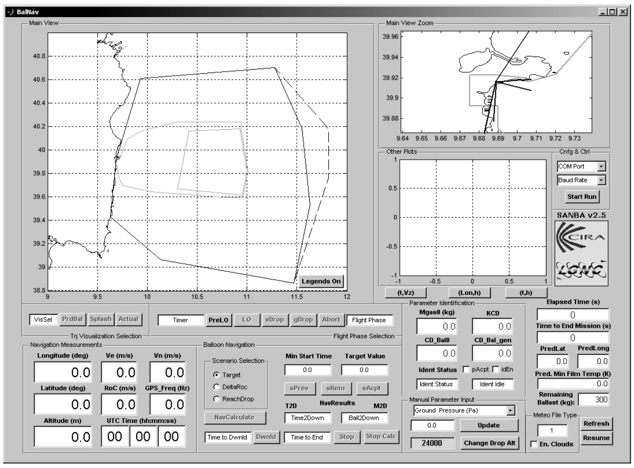


*Figure 5. SANBA graphical user interface.*

## 7. FLIGHT RESULTS

In this Section we will briefly present the results of the balloon flights and we will show the effectiveness of the described prediction methodologies.

### 7.1. System Description

In both DTFT1 and DTFT2, the system was composed of: a 334711 m$^3$ scientific balloon, a recovery parachute, the flight chain, a specifically designed gondola (carrying some avionics and ballast) and the FTB1 vehicle (Castore/Polluce) (see Fig. 6). The total system mass (without the lifting gas) was 4489 kg for DTFT1 and 4247 kg for DTFT2, the difference being essentially on the amount of ballast carried on the gondola.

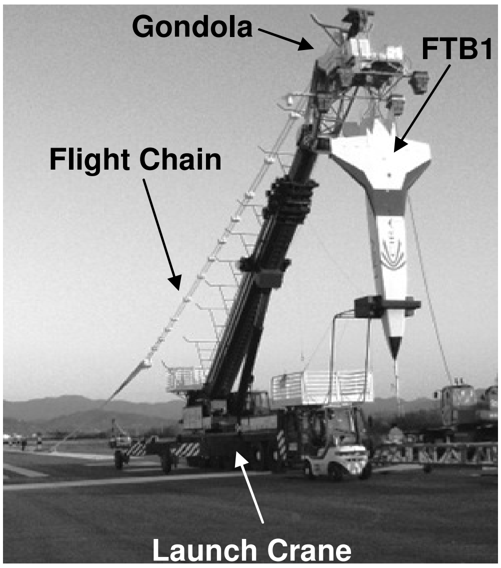


*Figure 6. System configuration.*

### 7.2. Flight Data

The DTFT1 mission took place on 24 February 2007 at 07:30 UTC. The balloon was inflated with 793 kg of helium corresponding to 10% nominal free lift. This free lift value was chosen in accordance with the results of the optimization process. Indeed the optimization tool yielded the lowest possible free lift value because of the extremely moderate eastbound winds. In this way, the low vertical speed generated by the low free lift value allowed the balloon to reach the prefixed drop altitude in an area as close as possible to target area (thus maximizing the probability of reaching it). Fig. 7 shows the comparison between the actual trajectory and the predicted trajectory at -18 h before lift-off.

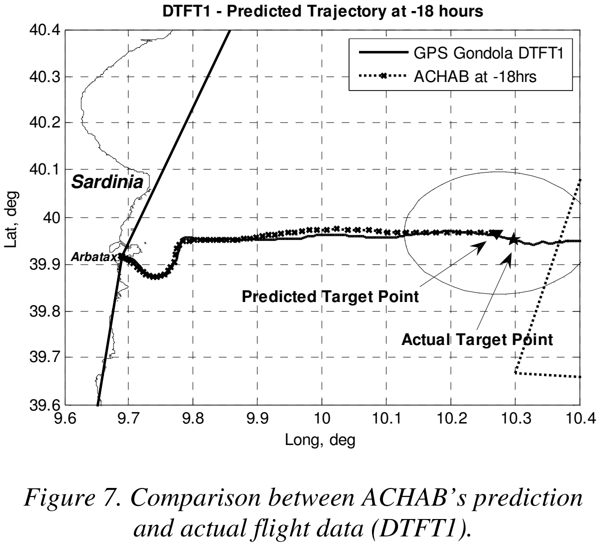


*Figure 7. Comparison between ACHAB's prediction and actual flight data (DTFT1).*

The DTFT2 mission took place on 11 April 2010 at 06:44 UTC. The balloon was inflated with 763 kg of helium corresponding to 12% nominal free lift. Again this free lift value was the result of the optimization process computed using the described methodology and it maximized the probability to reach the target area. Fig. 8 shows the comparison between the actual trajectory and the predicted trajectory at -18 h before lift-off.

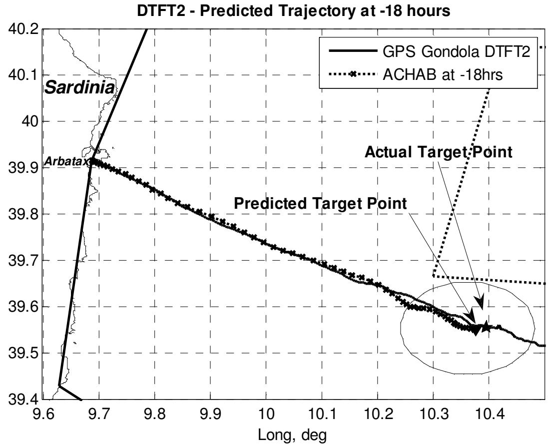


*Figure 8. Comparison between ACHAB's prediction and actual flight data (DTFT2).*

As it can be seen from Fig. 7 and Fig. 8 in both missions the drop point was outside the target area. It must be pointed out that the target area is merely a reference area in which mission objectives and splashdown requirements are automatically guaranteed without any further analyses. However, since on both launch dates, ground wind conditions were ok for both inflation and lift-off, and the overall weather conditions were stable, it was decided to launch anyway after carrying out several additional safety considerations on the balloon flight for that particular trajectory.

Fig. 7 and Fig. 8 show the good agreement between the predicted trajectories and the actual trajectories in both missions. In a more quantitative way, integral error and root-mean-square (*rms*) error between the *actual vertical velocity* and the *predicted vertical velocity* were evaluated. Table 1 and Table 2 show the error analysis for the prediction at -18h for both the DTFT1 and the DTFT2 balloon flight. The errors were evaluated separately along the tropospheric segment of the flight and the stratospheric segment of the flight. A global evaluation is also reported.

| ***DTFT1*** | | |
|---|---|---|
| | **Prediction at -18h** | |
| | $\bar{e}$ [m/s] | *rms* [m/s] |
| **Tropospheric** | 0.02 | 1.30 |
| **Stratospheric** | 0.25 | 2.28 |
| **Global** | 0.16 | 1.96 |

*Table 1. System configuration.*

| ***DTFT2*** | | |
|---|---|---|
| | **Prediction at -18h** | |
| | $\bar{e}$ [m/s] | *rms* [m/s] |
| **Tropospheric** | 0.16 | 0.98 |
| **Stratospheric** | 0.22 | 0.80 |
| **Global** | 0.07 | 0.87 |

*Table 2. System configuration.*

## 8. CONCLUSIONS

In this paper the methodologies and tools, that CIRA has developed over the years in support of scientific ballooning activities and in particular in the domain of balloon trajectory prediction and optimization, have been briefly presented. These methodologies and tools were successfully applied to the case of the DTFT balloon flights demonstrating their effectiveness and their reliability. These methodologies, being general, could be easily applied, with minor modifications, also to other types of balloon missions.

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