Mem. S.A.It. Vol. 79, 841
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Meteorological conditions forecast and balloon trajectory estimations

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Abstract. In order to comply with the objectives of a balloon mission, it is usually necessary to forecast ground wind and weather conditions for launch operations and to predict, monitor and track the flight trajectory. In the framework of the PRORA-USV program, CIRA has developed several methodologies and tools useful to evaluate balloon mission feasibility, predict and optimize flight trajectory and assess on trajectory prediction errors. These methodologies are based on the characterization of the micrometeorological features of launch site, on weather and wind forecasts during the flight campaign, on meteorological data provision for trajectory computation and on the use of ACHAB a proprietary software for the prediction of flight trajectory and thermal behavior of high altitude zero-pressure balloons.

Key words. Scientific ballooning – Weather conditions forecast – Balloon trajectory prediction

1. Introduction

Scientific community is often relying on high-altitude zero pressure balloons to carry out different kinds of experiments in a near-space environment. Balloons are commonly used as observation platforms for atmospheric studies or as carrier systems of particular instruments for research purposes or even as drop towers for flight tests of specific payloads. In any case, balloon mission planning is a challenging problem. In fact launch operations demand particular weather and ground wind conditions, requiring the important task of forecasting the actual state of the atmosphere a few days or hours in advance (Morris 1975). In addition, mission objectives and safety constraints may also require specific flight trajectories making trajectory prediction an important, yet difficult, matter. Indeed after lift-off, a balloon can be considered as a *thermal and dynamical system* that is practically in free evolution inside a complex thermal environment and subject to atmospheric winds. Consequently, balloon mission preparation requires an accurate and reliable prediction methodology of both weather and trajectory, in order to accomplish the mission successfully. In the framework of the PRORA-USV project (Russo et al. 2007), the Italian Aerospace Research Center (CIRA) has developed several methodologies and tools in the fields of meteorological conditions forecast and balloon trajectory prediction and optimization. The objective of the USV project is to design and manufacture two unmanned vehicles (FTB1 for atmospheric flights and FTBX for reentry demonstrations), conceived as flying laboratories, in order to test and ver-

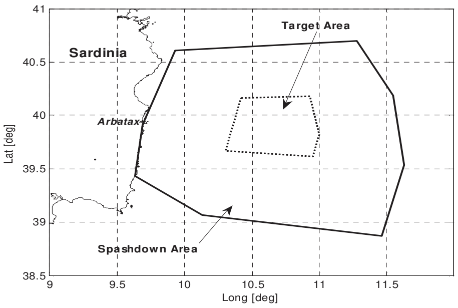

Fig. 1. USV Mission Splashdown and Target Areas.

ify advanced functionalities and critical operational aspects peculiar of the future Reusable Launch Vehicle. The nominal atmospheric mission profile (named DTFT) is based on a drop of the FTB1 vehicle from a stratospheric balloon at an altitude between 19 km and 21 km, inside a specific Target Area, lifting off from a launch base located in Arbatax, Sardinia, Italy (see Fig. 1). Therefore weather forecast considerations and balloon trajectory prediction are vital for mission operations and success.

In the following sections we will describe the methodologies and tools developed in the field of meteorological conditions forecast and we will deal with the trajectory prediction problem. The methodologies and tools described in this paper were all applied to the USV mission but, nevertheless, they are general and could be easily applied, with minor modifications, also to other balloon missions.

2. Meteorological methodologies and tools

The meteorological activities developed for the USV mission, may be subdivided into 4 parts: micrometeorological characterization of the launch site for the detection of the launch time window; daily micrometeorological characterization of the launch site obtained using meteorological instrumentation; meteorological forecast up to 72 hours over the area interested by the flight; meteorological data provision for trajectory forecast support. In addition, twice a day, meteorological forecast data were provided, thanks to a collaboration with the Italian Meteorology Office (CNMCA), allowing the prediction of the flight trajectory with an advance of 90 h.

2.1. Weather instrumentation

The instrumentation used by CIRA's meteorological team consisted of:

- two automatic weather stations: one with multi meteorological sensors (*sea side weather station*) while the other with an anemometric sensor only (*land side weather station*).
- a tethered balloon system with 4 probes between 20 and 220 m of altitude.
- a sounding system.

The instrumentation was properly set at the launch site. All the hardware was placed inside the mission control room: this was necessary both for instrumentation management and for meteorological data exchange between CIRA main site and the launch site.

2.1.1. Weather stations

The two weather stations represent a complete system for the micrometeorological characterization of the launch site. The most important features determined by the anemometers are: breeze regime, direction of the prevailing winds at sea level in stable weather conditions, the understanding of the weather configurations at the sea level determining the presence of calm or weak winds. The weather stations are equipped with sensors for different measurements, assembled at 2 m or 10 m of altitude. The two stations are powered by a solar panel and have a backup battery that can provide energy also during winter campaigns. The *sea side weather station* is equipped with a sensor for the wind intensity and direction (on the top of the 10 m pile) and with a sensor for the air pressure, rainfall, temperature and humidity (at 2 m of altitude). Sensors for net and global solar radiation are also available (at 2 m of altitude). The *land site weather station* is equipped only with a sensor to measure wind direction and intensity (on the top of the 10 m pile).

2.1.2. Tethered balloon system

The tethered balloon system allows the measurement of air pressure, relative humidity, temperature and wind intensity and direction at different altitudes along the same vertical profile in the planetary boundary layer and up to continuous 20 hours. It can be equipped with flags to allow visual assessment of wind shears during the minutes preceding the launch. The system purchased by CIRA can provide data up to 2 km of altitude and it can be equipped with up to 6 probes. For the USV mission, 4 probes were used. Two of them monitored the altitudes of interest for the launch team (20 and 220 m). The system can be used only if winds remain below 15 m/s.

2.1.3. Sounding system

The radiosonde is launched using a latex balloon. During the USV campaign a sounding was performed almost every day at the scheduled launch time, allowing measurement of the main weather parameters (temperature, pressure, humidity, wind) and real time verification of the predicted trajectory (Fig. 2). On the launch day, several soundings were made a few hours before the flight: this is useful to identify the ground area flown over by the balloon during the initial flight phase in order to verify that the flight takes place within the safety parameters established by ENAV (Ente Nazionale Assistenza Volo).

2.1.4. Meteorological forecast maps

An essential operative tool, necessary to forecast the optimal weather conditions for launch operations is the *interpretation* of the forecast maps and the definition of adequate *post processing tools*. Thanks to an agreement with CNMCA, CIRA has the access to the web interface prometeo.meteoam.it that allows accredited users to have access to all weather data previously agreed with CNMCA. In addition, the meteorological team developed several post-processing tools for a more precise evaluation of the surface winds. To this end the mesoscale COSMOMED meteorological

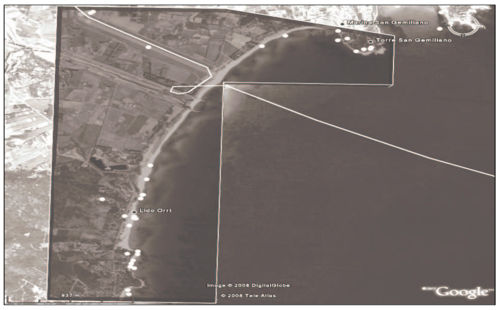

Fig. 2. Sounding trajectory during the initial flight phase displayed on Google Earth®.

model was used (Fig. 3). This model is developed by the consortium COSMO in which both CNMCA and CIRA are members. Finally CNMCA provided (in real time) the meteorological data for trajectory prediction, using the IFS model by ECMWF (European Centre for Medium-Range Weather Forecasts).

2.2. *PreOperative and operative meteorological activities*

The pre-operative meteorological activities are performed before the start of the flight campaign. In the case of the USV mission these activities included the statistical analysis of the observed ground wind at the launch site in a time span between 2001 and 2008 in order to study the feasibility of the launch operations from that site. In addition, the meteorological team provided IFS historical analysis data to carry out a statistical analysis of the flight trajectory in order to verify the feasibility of the flight. The operative meteorological activities are performed during the flight campaign and during launch operations. Each day a radiosounding was carried out, together with the analysis of the data acquired by the weather stations. Additionally, surface winds were monitored using the tethered balloon. Moreover, nowcasting activity (forecast from 0 to 6 hours) was performed in support of launch operations. Finally, in support of the launch decision-making process, a weather bulletin was issued daily reporting a detailed summary of the forecast activity.

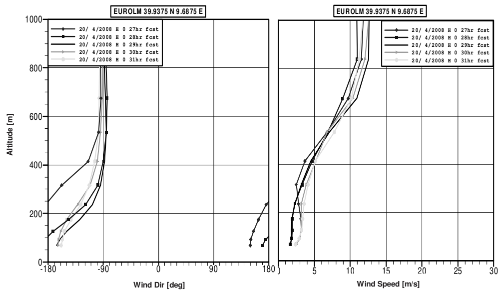

Fig. 3. Surface winds from COSMOMED model along a vertical profile starting from the two grid points nearer to the launch site. The forecast data span from 2 h before launch time to the following 2 h.

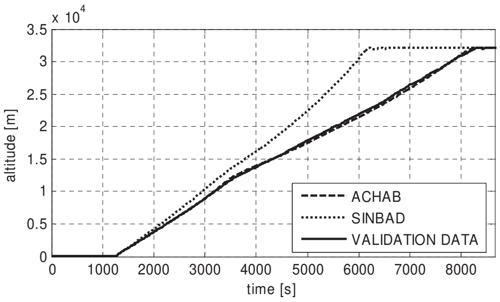

Fig. 4. Comparison between ACHAB and SINBAD with respect to real flight data.

3. Balloon trajectory prediction problem

We have stated in the Introduction that the DTFT mission profile is based on a drop of the FTB1 vehicle from a stratospheric balloon inside a specific Target Area. As a result it is extremely important to accurately forecast the trajectory of the balloon to achieve the mission objectives (i.e. reach the Target Area). To this end, CIRA has developed a specific simulation software named ACHAB: Analysis Code for High-Altitude Balloons (Palumbo et al. 2007).

3.1. ACHAB

ACHAB is a new software tool that is able 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 is basically made of several models:

– 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 assess on balloon performance and trajectory. The main inputs to the software are: the balloon characteristics, the atmospheric data and the date, time and location of launch. The atmospheric data can either be forecast, sounding or analysis data. As said, we use the IFS model by ECMWF for trajectory prediction. The ECMWF model allows us to have a trajectory forecast each 12 h, starting from 72 h before lift-off.

3.2. Code validation and flight results.

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. 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 good agreement with flight data, even better agreement than SINBAD. Figure 4 shows an example of a 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 first

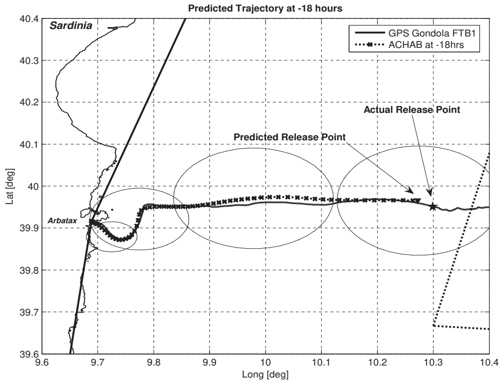

Fig. 5. Comparison between ACHAB's prediction and actual flight data.

USV flight test (Feb 24, 2007). Figure 5 shows the comparison between ACHAB's prediction at 18 h before lift-off and the actual flight data. Agreement between flight data and simulation is evident. We have also traced the dispersion ellipses on the trajectory prediction at -18 h. Indeed we have conducted an extensive analysis focused on the estimation of balloon trajectory uncertainties during the ascent portion of the flight, based on: *ECMWF wind forecast uncertainties*, *free lift uncertainties* and *simulation (ACHAB) uncertainties.*

3.3. Uncertainty characterization and trajectory optimization

ECMWF wind forecast uncertainty characterization has been carried out performing a statistical analysis. This analysis aimed at estimating the prediction error comparing a set of 370 trajectories obtained using ACHAB and ECMWF forecast and analysis data. The characterization is concerned with wind velocity error, averaged along the trajectory, between predicted and actual trajectories. It is important to remark that this error characterization is independent of the actual balloon ascent rate, making this approach more general and suitable for other balloon ascent applications. Indeed prediction errors are essential when evaluating mission success probability and especially when dealing with trajectory optimization problems. Taking advantage of this error characterization, we have developed a specific mission planning tool: a trajectory optimization facility that allows the determination of the optimal *free lift* and ballast, with respect to mission objectives and wind uncertainties. The optimization process, using wind forecast data, calls iteratively ACHAB with the objective of finding a trajectory solution in terms of nominal free lift to be transferred to the balloon at inflation. This solution maximizes the probability of mission success in the presence of wind 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.

4. Conclusions

In this paper we have briefly presented the methodologies and tools that CIRA has developed in support of scientific ballooning activities and in particular in the domains of meteorological conditions forecast and balloon trajectory estimation. These methodologies and tools were successfully applied to the case of the USV balloon flight and, being general, they could be easily applied, with minor modifications, also to other kinds of balloon missions.

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