Ascent trajectory of sounding balloons: dynamical models and mission data reconstruction

C. Bettanini[1,2] *, M. Bartolomei[2], A. Aboudan[2] and L. Olivieri[2]

[1] Department of Industrial Engineering, University of Padova, via Venezia 1, Padova (Italy)

[2] CISAS - Center for Studies and Activities for Space "Giuseppe Colombo", University of Padova, via Venezia 15, Padova (Italy)

carlo.bettanini@unipd.it

Keywords: Sounding Balloon Dynamics; Trajectory Reconstruction, Linear Quadratic Estimation Method

Abstract. Small sounding balloons are a fast and cost-effective transport system to lift up scientific payloads up to stratospheric burst altitudes below 40 kilometres; during ascent and descent phase dedicated instruments may be operated to monitor atmospheric parameters and optical payloads may be used for remote observation. This work will focus on the reconstruction of the trajectory of the ascent phase, which is the longest and dynamically less perturbed part of the flight; in this section the dynamics of the flight system is determined by the lift of the balloon guiding the vertical motion and the local winds controlling the horizontal motion. The presented reconstruction algorithm is based on a linear quadratic estimation predictor corrector using the standard equations of motions in ECEF system to propagate the simulation and the measurement of the on-board sensors (triaxial accelerometer, GPS, pressure and temperature sensors) to correct the estimation and reduce the uncertainty in the reconstruction, which is mainly related to the value of balloon canopy drag coefficient Cd, the lifting gas volume and local wind perturbations. Two different balloon flights, both launched within a joint effort between teams by University of Padova and University of Pisa, are considered: one conducted during daytime, the other in night time. The different environmental conditions and in particular the different temperature evolution within the lifting balloon in the day flight due to Sun heating provide a good proving ground to investigate sensitivity of algorithm to environmental conditions. The prediction of flight dynamic models implementing horizontal and vertical equations of motion are compared with real mission data acquired by on board systems, highlighting the influence of local perturbations on the foreseen ascent trajectory.

Introduction

Stratospheric sounding balloons are small high-altitude balloons that can reach altitudes below 40 kilometres before burst; to date thanks to the availability of powerful low-cost command and data acquisition systems it is possible to carry scientific instruments, experiments or complex autonomous systems with an overall payloads mass below 3 kilograms to high altitudes and conduct in situ research and remote observation of ground targets. [1] [2].

One of the key challenges associated with stratospheric balloon flights is the accurate prediction and reconstruction of the balloon's trajectory; an accurate prediction is needed since launch decisions must be based on the likelihood of landing in a desirable location for safety issues and recovery; post flight reconstruction is both used to tune the parameters of the prediction algorithms and to provide along with attitude data georeferentiation for remote sensing data.

The simplest dynamic model utilised in the simulation of balloon trajectory is a lumped mass 3 DOF system and is the one applied in several freely available trajectory prediction software tools [3][4] or in the more complex Monte Carlo based simulation codes[5].

Several factors may affect the accuracy of these prediction algorithms: environmental conditions and atmosphere layering above the launch site may differ from the nominal standard atmosphere profile and the ascent profile depends strongly on the temperature reversal near the tropopause (about 15 km) [6]. Wind variations and atmospheric turbulence, along with cloud presence and changing ground albedo can affect also the accuracy of the prediction; the last two contributions affect lifting gas equilibrium temperature inside the canopy [7] [8] and ,as a consequence, the temperature inside the balloon may differ from surrounding atmosphere of more than 30 K due to balloon radiative heating both from the Sun and from the Earth's surface[5].

During daytime launches it is therefore critical to develop a thermal model for the balloon to investigate internal temperature variation and consequently calculate balloon volume and shape along ascent trajectory. [9] For the typical size of latex balloons temperature and pressure gradients can be disregarded and density considered constant over the volume of the balloon.

Furthermore, although helium gas mass at launch may be inferred by measuring the lift at the hook, the value is usually not accurate since is calculated by reaching the floating condition using a ballast mass; this requires to reconstruct the correct ascent velocity by mission data. Finally flight Reynolds numbers span within the so called "drag crisis" zone and accurate modelling of the balloon's ascent rate requires that the Cd be treated as a function of Reynolds number and therefore iteratively calculated depending on altitude and ascent velocity [10]. Adjustments and corrections are therefore needed to improve the accuracy of the dynamical model and due to the variability of the environmental conditions a reconstruction process is usually performed relying on mission data from a variety of sensors and instruments, including GPS receivers, accelerometers, magnetometers and external temperature sensors. Such exercise is particularly important when optical systems are part of the payload and no active control is present to guarantee platform's stability; an accurate trajectory reconstruction along with the elaboration of inertial attitude may minimise the error on pointing and therefore on the data extracted for targeted areas on ground.

Equations of motion for balloon ascent phase

The balloon ascent dynamic is a result of the lift, drag and gravitational forces on the flight train. The balloon's motion is mainly driven by the atmosphere winds governing the horizontal motion and the net lift force of the balloon determining the variation of altitude versus time and so the vertical motion. Usually the horizontal velocity of the balloon can be assumed as equal to the atmospheric wind so the drag created by relative motion between the atmosphere and the balloon system may be limited to the vertical motion into the atmosphere.

This assumption is essentially correct for lightly loaded balloons, especially at lower altitudes, but becomes less accurate at higher altitudes where inertia of the accelerated balloon must be taken into consideration. [11]

During the motion into the atmosphere, surrounding air is assumed to behave like a perfect gas in hydrostatic equilibrium. This assumption in the Earth's atmosphere is justified by the fact that the deviation from the perfect gas equation of state is negligible within the range of density and temperature conditions between the ground and a 40 km maximum altitude

The free lift force , also called net buoyancy of the balloon, is a function of the density of the lifting gas and the volume of the balloon and can be expressed as

$$\overrightarrow{F_{FL}} = \left(\rho_A V - m_{tot}\right)\vec{g} \quad (1)$$

where ρ_A is ambient air density, V is the volume of the balloon, g is the gravitational acceleration vector and m_{tot} is the total mass for lift. Total mass m_{tot} is the sum of the flight train mass (payload mass, harness mass and balloon fabric mass), helium mass and the added mass which is the inertia of the mass of fluid displaced by the body, since the balloon must shift some volume of surrounding fluid as it moves through it

$$m_{ftrain} = m_{pay} + m_{harness} + m_{ball} \; ; \quad m_{tot} = m_{ftrain} + m_{gas} + m_{add} \quad (2)$$

The added mass for the sounding balloon may is typically approximated as 40% of the mass of the displaced air volume of the balloon [12][13]

$$m_{add} = 0.4\, \rho_A V \quad (3)$$

It can be noted that due to added mass contribution, effective mass of the balloon system varies with altitude and must be properly updated especially if high volume balloons are considered.
In zero pressure balloons (like the sounding balloons) the elastic latex canopy does slightly compress the lifting gas, but internal and external pressure remain within 1% of each other on average over the course of the flight, so treating the interior and exterior pressures as equal is reasonable and treating the lifting gas as an ideal gas, the density may be solved for by using the ideal gas law for balloon volume calculation.

The drag force of the aerostat is a function of the relative velocity of the balloon and atmosphere, the ambient density, the size of the balloon, and the drag coefficient. It can be calculated as F_D using:

$$\overrightarrow{F_D} = \frac{1}{2} \rho_A S\, v_{rel}^2\, C_D \overrightarrow{u_{vrel}} \quad (4)$$

where S is the top projected area of the balloon, and C_D is the drag coefficient representative of the balloon flight train and can be considered as the one related to balloon canopy.

The C_D may be then assumed to be close to the one of a sphere and is a function of Reynolds number; Reynolds number must be therefore calculated using balloon diameter as reference dimension following the classical expression

$$Re = \frac{\rho_A v_{rel} D_{ball}}{\mu_{dyn}} \quad (5)$$

It may be underlined than velocity is given relative to the atmosphere, so a balloon's horizontal movement which is supposed to be similar to the horizontal wind does not affect the Reynolds number. As already mentioned balloon flight Reynolds numbers span the region where the coefficient of drag of the sphere decreases from 0.4-0.5 to 0.1; for the present work Conner's model was selected, as it is based on experimental data from latex balloon flights.[5]

Linear quadratic estimation model for Ascent trajectory reconstruction

The implemented model simulates the evolution of the balloon system considered as a point mass using a linear dynamic system of 12 variables (state) and considers the measures of on-board sensors as corrector building 7 observation parameters. The list of the variables is shown in listed the following equations (6)

The State is constituted by position (Rx, Ry, Rz) and velocity (Vx, Vy, Vz) of balloon system in ECEF Earth reference; Wind velocity (Wx, Wy, Wz) also expressed in ECEF is needed to calculate the vector expression for velocity relative to atmosphere as the difference of balloon velocity and local wind velocity and afterwards used in drag force evaluation. Atmospheric pressure and temperature are the last two parameters of the state and used to calculate balloon pressure and to estimate balloon temperature using a simplified thermal model for balloon canopy energy balance. [11]

The prediction of the system state at every time step performs the evaluation of total force on the balloon system (equations (2) and (4)) and calculates acceleration components (velocity time derivatives) for the trajectory.

$$State = (Rx|Ry|Rz\,|Vx|Vy|Vz|Wx|Wy|Wz|Pa|Ta)$$

$$Observation = \left(Rx_{GPS}\middle|Ry_{GPS}\middle|Rz_{GPS}\,\middle|Alt_{GPS/BARO}\middle|Ext\_T\middle|Ext\_P\middle|Acc\_tot\right) \quad (6)$$

Standard Atmosphere models for atmospheric pressure (Pa) and temperature (Ta) are used to predict evolution depending on vertical velocity. The correction of the prediction is performed using GPS data acquired at 1 Hz sampling rate during the flight and transforming latitude and longitude data in cartesian coordinates in ECEF reference. Depending on flight altitude, the altitude measurement from GPS or inferred from IMU barometer is used as observation. At altitudes near 25 km ambient pressure falls close to barometer resolution so increases variance in the model is assigned to barometer readings forcing the algorithm to disregard the data. Atmospheric temperature and pressure observation are obtained by data from external sensors although as previously described pressure data need to be disregarded above a certain altitude. The module of total acceleration measured by IMU Triaxial accelerometer is used to estimate vertical accelerations linked to vertical turbulence. [14]

Flight data analysis

The data of two different sounding balloon flight have been analysed. The MINLU flight was launched on July 7th 2020 in an astronomical night condition with no Moon to investigate light polluting sources on ground. AREO flight was launched in day time on October 20th 2021 to provide remote observation with high resolution of crop fields providing calculation of vegetation indexes.

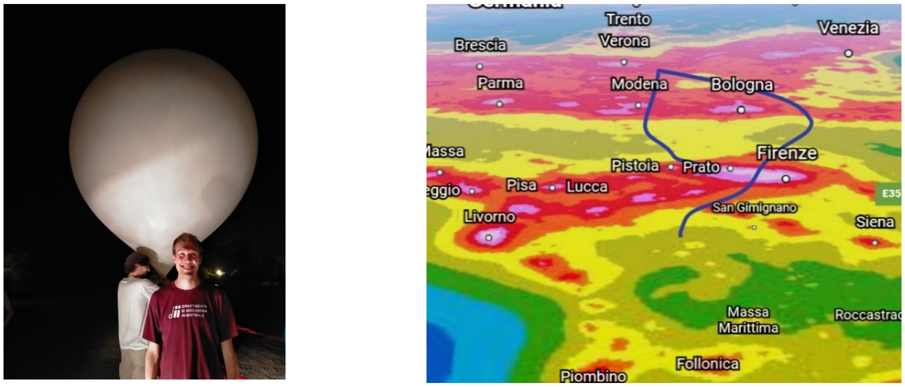

Figure 1 – MINLU night flight in the night of July 7th 2020 - Burst altitude 32104 m (3D trajectory reconstructed on satellite-based ground light pollution map)

Figure 2 – AREO flight on October 20th 2021 - Burst altitude 36907.9 m (3D trajectory reconstructed on Google Earth)

The elaboration of trajectory profiles and vertical velocities are reported in following figures 3 and 4 showing the ability of LQE model to predict system dynamic to fit real mission data.

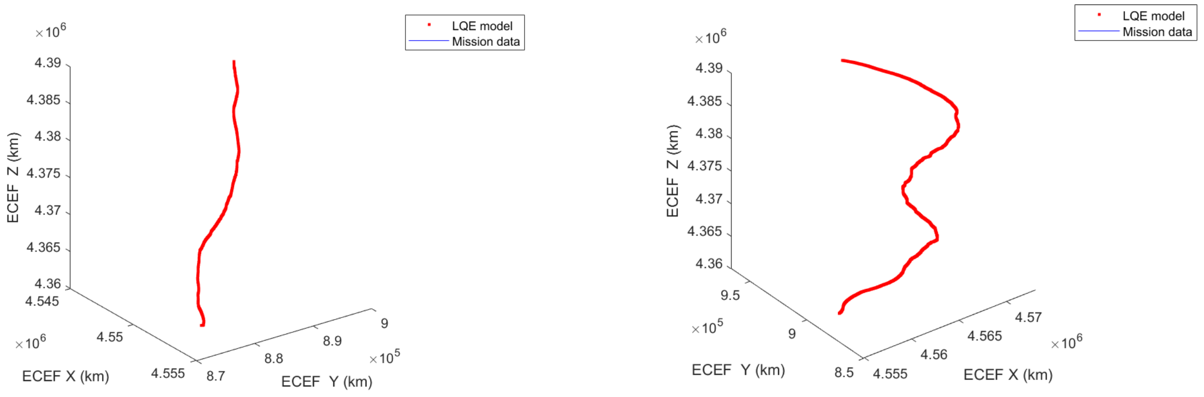

Figure 3 – Reconstructed trajectory from LQE model compared with GPS vertical velocity from mission data (left MINLU flight, right AREO flight)

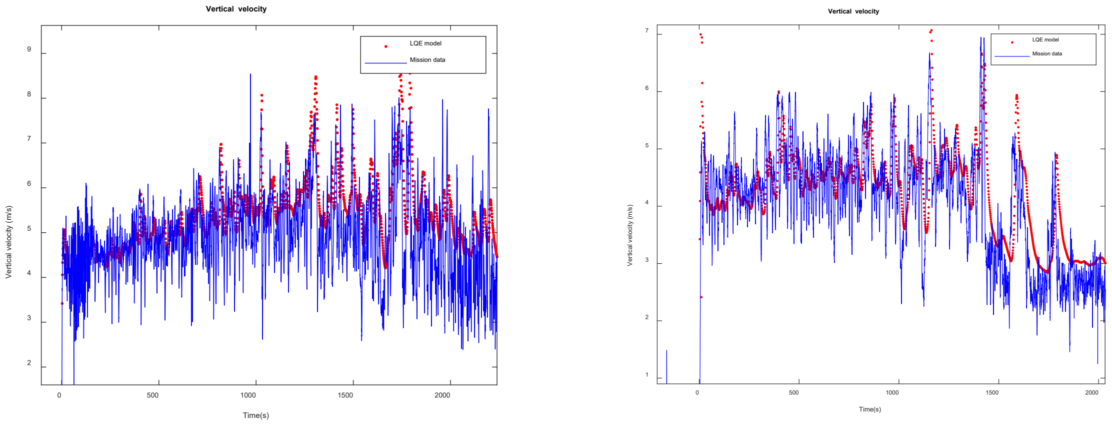

Figure 4 – Vertical ascent velocity from LQE model compared with GPS vertical velocity from mission data (left MINLU flight, right AREO flight)

LQE model is designed to adjust at every time step the parameters with higher uncertainty and no measured mission data (local Wind vector and Balloon drag coefficient Cd) allowing to estimate their time evolution

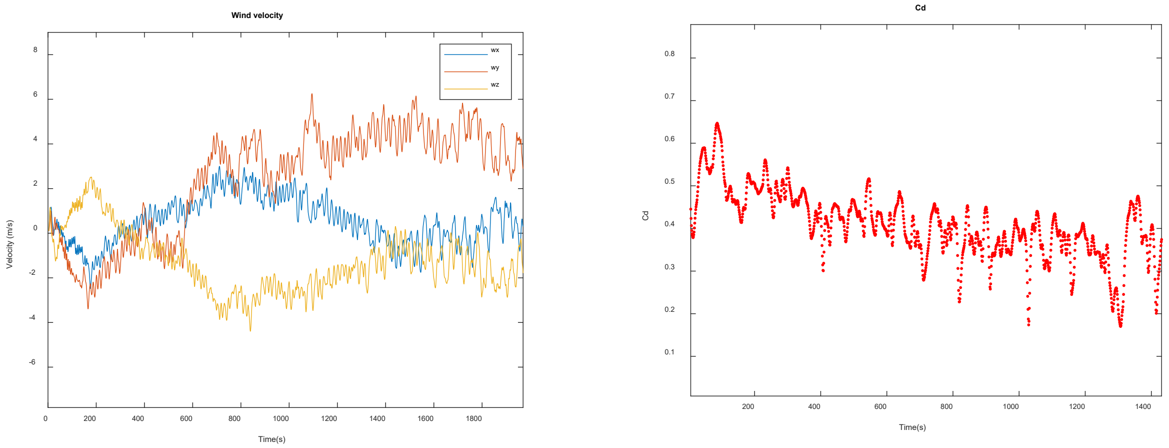

Figure 5 –LQE model estimation of local wind velocity and balloon Cd values (AREO flight)

Conclusions

LQE algorithms for trajectory reconstruction of ascent phase of high-altitude balloons have been developed to increase the accuracy of mission predictors and tested using real mission data. Post flight analysis has been conducted on two balloon-launched Earth observation payloads, one dedicated to the determination of ground sources of Artificial Light at Night, the other to the analysis of vegetation Indexes. Although the presented results are preliminary and further validtions shall be conducted , the algorithm allows to limit sudden changes in trajectory due to temperature variation and wind turbulences and improves the correct correlation of position and pointing direction needed to provide georeferentiation of images acquired during the balloon flights.

References

[1] C. Bettanini, M. Bartolomei, P. Fiorentin, A. Aboudan and S. Cavazzani, “Evaluation of Sources of Artificial Light at Night With an Autonomous Payload in a Sounding Balloon Flight,” *IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING,* vol. 16, pp. 2318-2326, 2023. https://doi.org/10.1109/JSTARS.2023.3245190

[2] F. Toson, M. Pulice, M. Furiato, M. Pavan, S. Sandon, D. Sandu and R. Giovanni, “Launch of an Innovative Air Pollutant Sampler up to 27,000 Metres Using a Stratospheric Balloon,” *Aerotecnica Missili & Spazio,* vol. 102, no. 2, pp. 127-138, June 2023. https://doi.org/10.1007/s42496-023-00151-y

[3] L. W. Renegar, “A Survey of Current Balloon Trajectory Prediction Technology”. https://via.library.depaul.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1125&context=ahac

[4] A. Gallice, F.G. Wienhold, C.R. Hoyle, F. Immler and T. Peter "Modeling the ascent of sounding balloons: derivation of the vertical air motion", Atmos. Meas. Tech., 4, 2235–2253, 201. https://doi.org/10.5194/amt-4-2235-2011

[5] Luke W. Renegar “Development of a Probabilistic Trajectory Model for High-Altitude Scientific Balloons”, University of Maryland, College Park

[6] H.D. Voss, N.A. Ramm and J. Dailey “Understanding High-Altitude Balloon Flight Fundamentals” , Proceedings of 3rd Annual Academic High-Altitude Conference

[7] C. Olsson,”Sensitivity Analysis for Ascending Zero Pressure Balloons”, Master thesis ,2019, Luleå tekniska universitet

[8] Q. Dai, X. Fang , X. Li, L. Tian, “Performance simulation of high altitude scientific balloons”, Advances in Space Research 49 (2012), 1045–1052. https://doi.org/10.1016/j.asr.2011.12.026

[9] F. Kreith , J.F. Kreider “Numerical Prediction of the Performance of High Altitude Balloons”, National Center for Atmospheric Research, Technical Note NCAR-TN/STR-65

[10] J. Söder, M. Gerding, A. Schneider, A. Dörnbrack, H. Wilms, J. Wagner and F. Lübken “Evaluation of wake influence on high-resolution balloon-sonde measurements”, Atmos. Meas. Tech., 12, 4191–4210, 2019. https://doi.org/10.5194/amt-12-4191-2019

[11] F.P. Camara, “Flight Dynamics of a High-Altitude Balloon,” Master Thesis , 2018, Universidad Carlos III, Madrid

[12] M. Tuveri, A. Ceruti, "Added masses computation for unconventional airships and aerostats through geometric shape evaluation and meshing"

[13] W.J. Anderson, G.N. Shah, J. Park "Added Mass of High-Altitude Balloons", JOURNAL OF AIRCRAFT Vol. 32, No. 2, March-April 1995. https://doi.org/10.2514/3.46714

[14] G. J. Marlton “On the development, characterisation and applications of a balloon-borne atmospheric turbulence sensor" , Thesis Work, University of Reading, Department of Meteorology