A Survey of Current Balloon Trajectory Prediction Technology

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Introduction

Trajectory forecasting is an important part of safe high-altitude ballooning operations. FAA regulations and ethical considerations require balloon operators to avoid flying through and landing in certain areas. While some programs fly in sparsely-populated areas that largely avoid these concerns, others must rely on accurate trajectory predictions in order to operate safely. Moreover, trajectory forecasting benefits all programs by making chase and recovery operations more predictable.

Balloon Flight Dynamics

The trajectory of the balloon is dictated by the drag force on the canopy and the buoyant force of the lifting gas. Since the drag force varies with the balloon's velocity relative to the surrounding air, not its inertial velocity, drag tends to force the balloon's horizontal velocity to the local wind velocity (1, 2). In the vertical direction, the net lift of the balloon creates an upward acceleration that is opposed by drag. This causes a balloon to reach a terminal velocity at a particular altitude. However, since the local air density and the balloon's diameter are constantly changing with altitude, this equilibrium velocity is constantly being adjusted. Figure 1 shows this state of quasi-equilibrium.

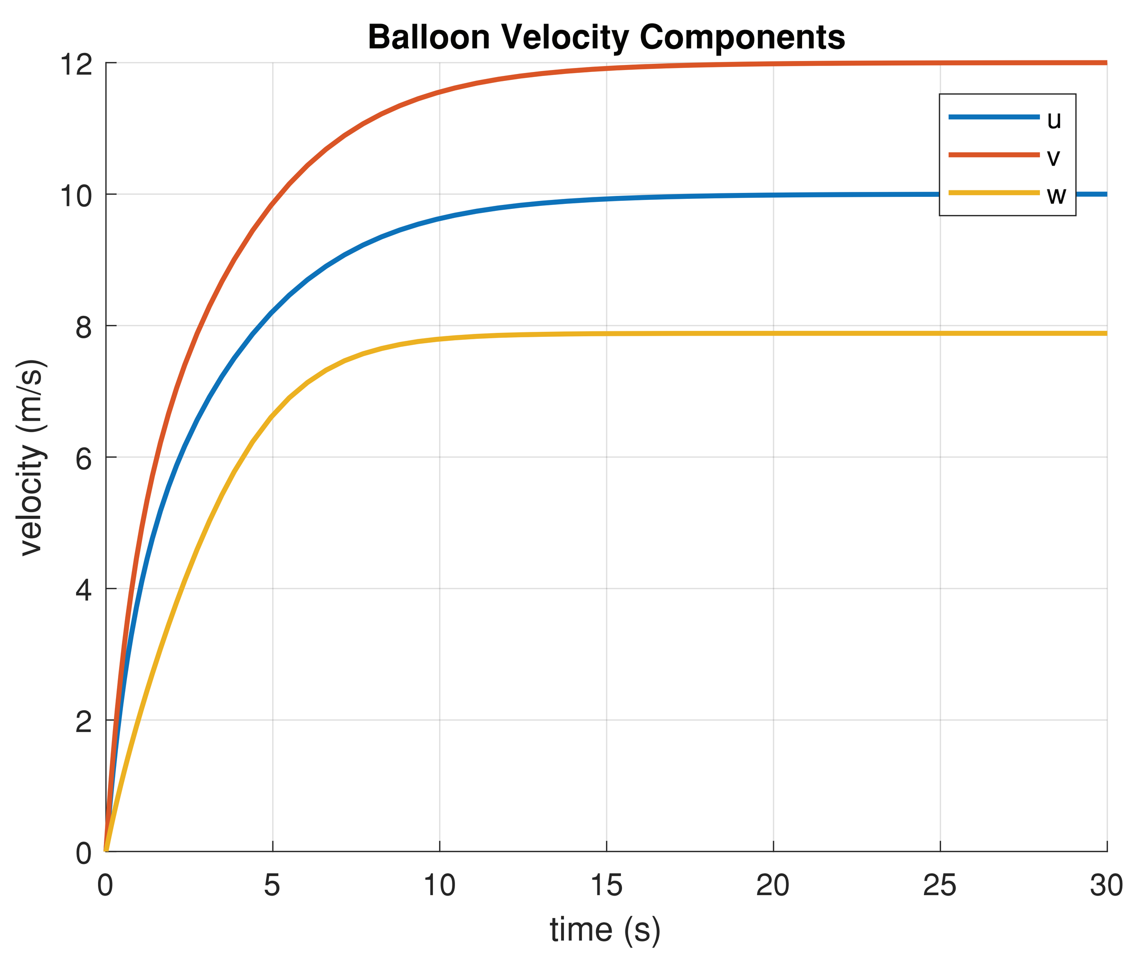

Fig. 1 The velocity components, computed from the governing equations, of a latex balloon starting from rest at sea level in wind. All three velocity components converge to their steady-state values within 15 seconds, suggesting that a reasonable simplifying assumption for many predictors is to ignore transient effects.

Because the governing equations of balloon trajectories are coupled with the ambient atmospheric conditions, it is effectively impossible to do balloon trajectory prediction analytically. Instead, the typical approach is to use numerical methods, such as a Runge-Kutta solver, to numerically integrate the equations of motion. This allows data from numerical weather forecasting models to be incorporated into the prediction.

Canopy Modeling

For latex balloon flights, the burst height of the balloon has a very significant impact on the trajectory. Good prediction of canopy burst height is thus critical to effective trajectory modeling.

As the balloon rises, the gas inside expands by the ideal gas law. The pressure inside the balloon is roughly equivalent to the ambient atmospheric, pressure, but the temperature can be off by several Kelvin (3, 4). Higher-fidelity models attempt to calculate solar flux and convection losses in order to more effectively model the thermal environment.

The burst diameter of the balloon is provided by the manufacturer, but is subject to significant uncertainty. There exists a model of this uncertainty based on NOAA 700 g balloon flights, but this model has not been validated for other balloon sizes (3).

ASTRA/Southampton Predictor

The online predictor hosted by Sóbester and Zapponi at Southampton University is the most comprehensive publicly available predictor for latex balloon flights. It includes extensive probabilistic models based on historical NOAA balloon flights (3), and is capable of running Monte Carlo ensemble simulations. Its principal limitation is that it does not allow for the specification of arbitrary balloon sizes and parachutes (5).

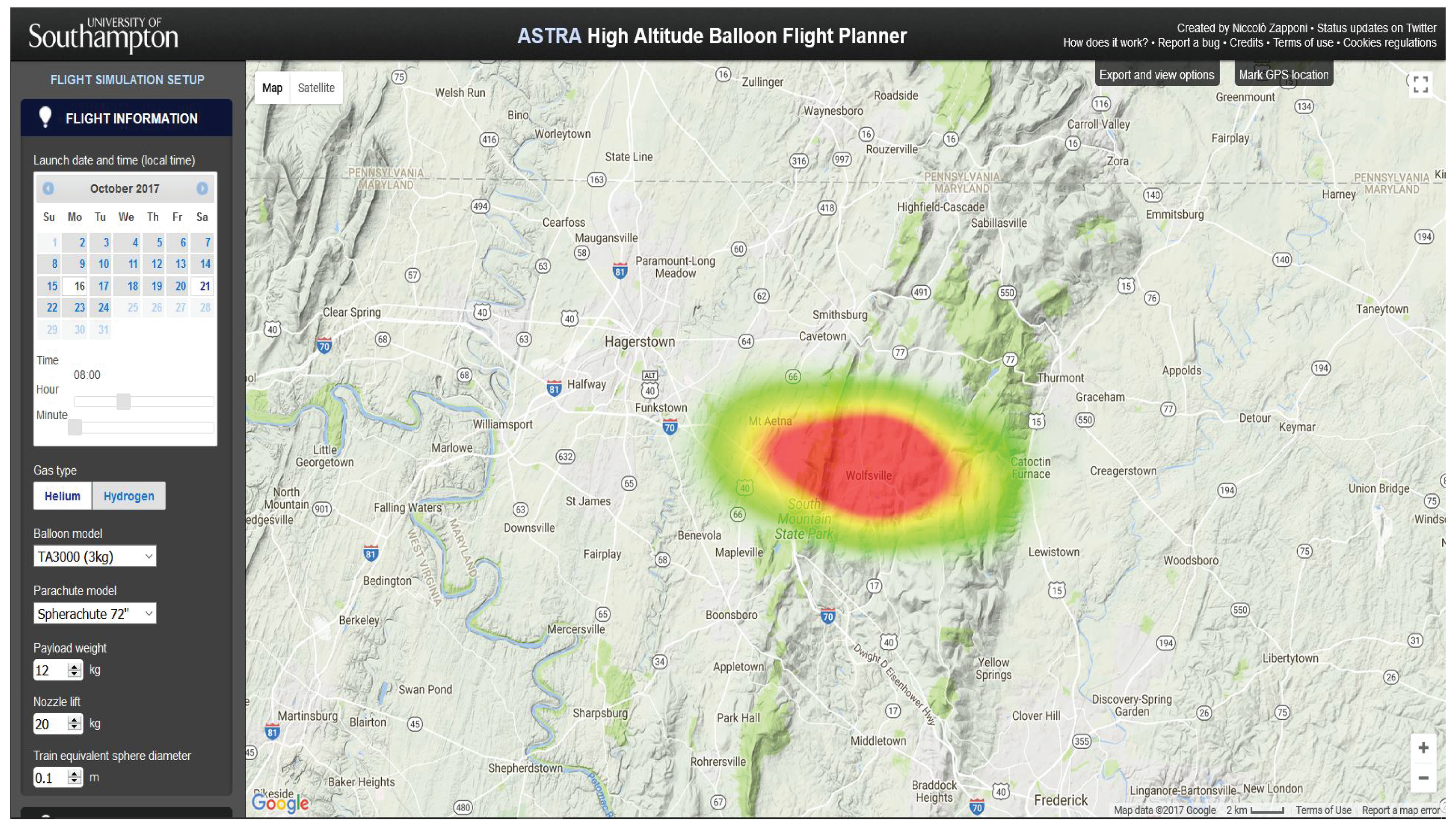

Fig. 2 A landing site heatmap produced by the ASTRA predictor (5). The predictor uses a large number of individual trajectory forecasts with randomly varied initial conditions to determine the most likely landing site of the balloon.

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CUSF Predictor

The Cambridge University Space Flight (CUSF) predictor is another web-based predictor commonly used by ballooning groups. Its main advantage is its simplicity. Unlike some other packages, it does not simulate the thermal profile or canopy size of the balloon as it ascends. Instead, it relies on the user to supply an ascent rate and burst height. While this may not yield the highest-fidelity simulations, it allows users with their own models of these phenomena to test them without having to write a full prediction suite. It also allows those with relatively little ballooning knowledge to run predictions without having to navigate too many configuration options.

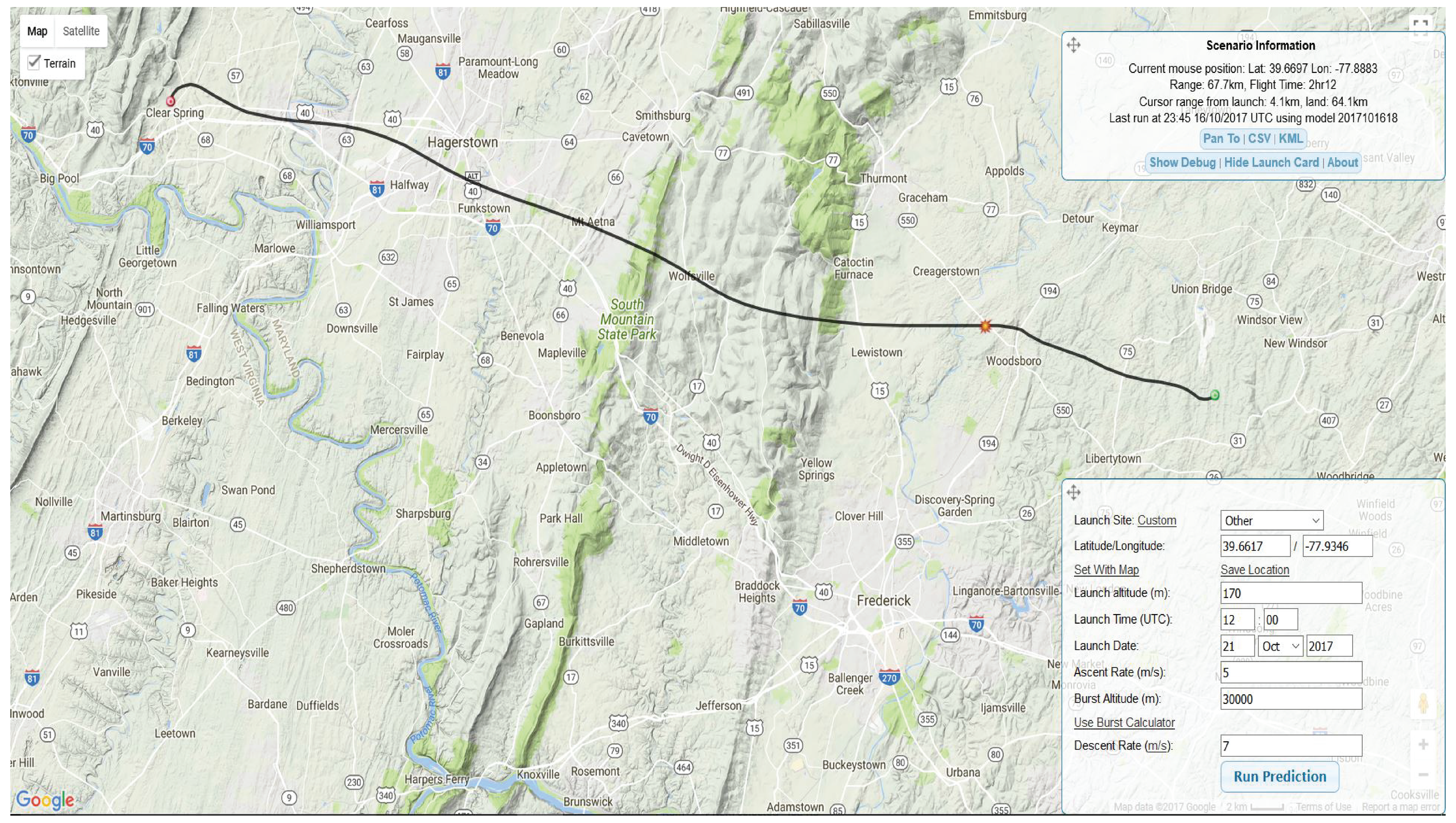

Fig. 3 A trajectory forecast produced by the CUSF predictor (6).

Future Work

Although several trajectory prediction software packages are available, there are a number of outstanding issues in the field that merit further investigation. Sóbester et al. (3) proposed a probabilistic model for balloon burst diameters, but it remains unvalidated for larger balloon sizes. Operationally, both the ASTRA and CUSF predictors, as well as some others, only consider wind data from NOAA's GFS model. If predictors were to take into account data from other numerical weather models, such as the ECMWF ensemble or NOAA's North American Mesoscale (NAM) model, it would provide useful information about uncertainties in the predicted wind and atmospheric state.

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