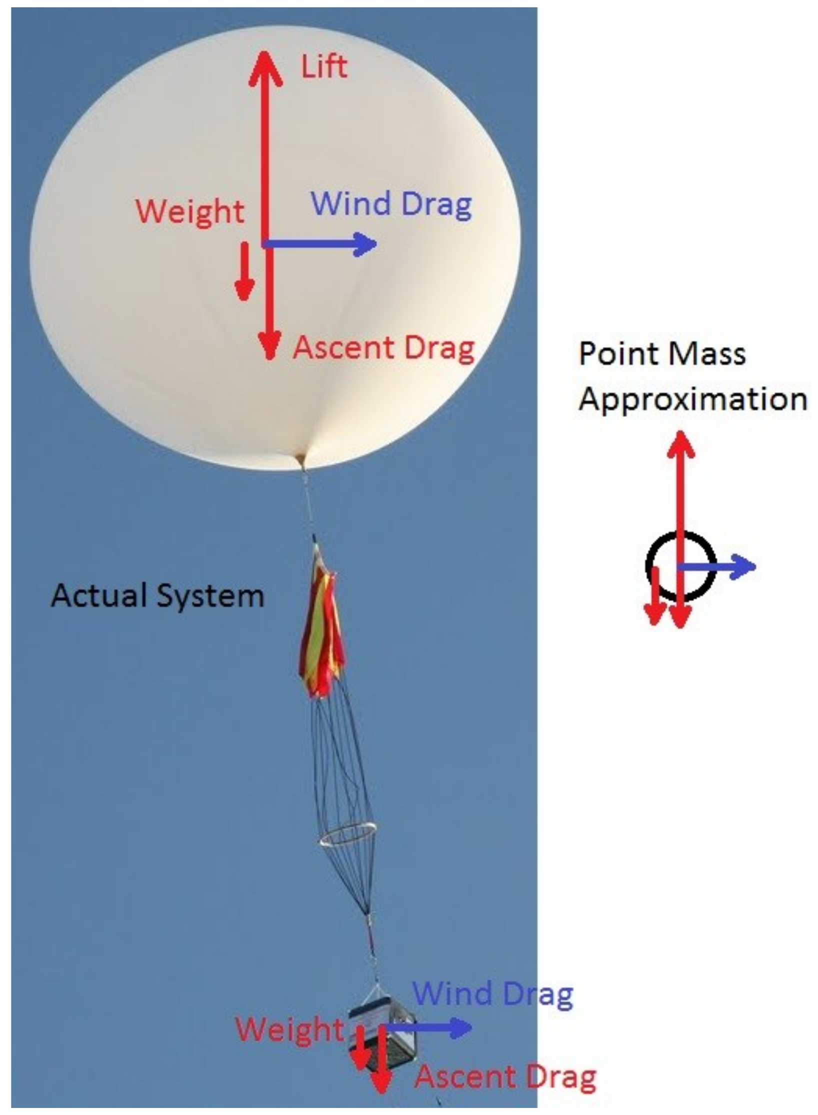
Analysis of HAB Flight Prediction Methods

Abstract:

Accurate flight predictions are crucial for the success of many HAB flights. A payload landing in a city center or large body of water may have been avoided by scrubbing a flight due to prediction results. Many of the assumptions made by prediction algorithms were made to save computational resources and are no longer needed and certainly not valid. This poster examines some of the most common assumptions in an attempt to categorize the error created.

System Dynamics



The balloon/payload system shown above is too dynamically complex for a simple simulation. However, under normal conditions, several simplifications can be made. If you assume the system does not invert, you can treat the system as a point mass for the balloon and a point mass for the payload with a rigid l ink between them. By recognizing that z-axis rotation does not affect the dynamics and that the mass of the payload provides a restoring force to keep x and y rotations small, the system can be further reduced to a single point mass with 3 degrees of freedom.

The primary forces that act on the system are Lift, Drag and Weight. Lift and weight only act along the local gravitational normal (assumed to be z-axis) and are given below.

$$W = mg$$

$$L = V_b\left(\rho - \rho_g\right)g$$

Drag acts in all directions and is given by

$$D = 0.5\rho v^2 S C_D$$

With the assumption that wind acts in a direction parallel with the Earth's surface, the problem can be decomposed into the solution of the balloon's ascent and the solution of the balloon's drift.

Altitude (km)	Rise Time (s)	Error (m)
0.3	60	20
15	18	6
33	65	20

Static Assumption

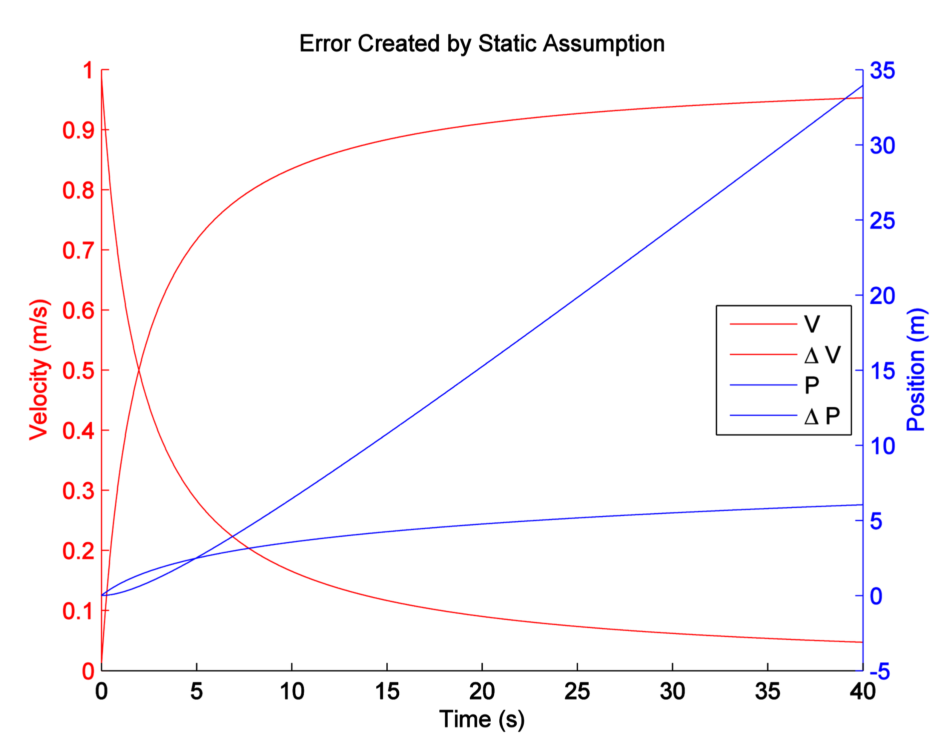
Most current balloon simulations make the assumption that the balloon is always in equilibrium with the atmosphere. This means that the system instantly accelerates to match velocities exactly with the atmosphere. There are two important results of this, the payload drifts at the same velocity as the wind and the ascent rate is the velocity that balances the lift, drag and weight forces.

The static assumption allows ascent rate to be solved as below.

$$v_z = \sqrt{\frac{2(L - mg)}{\rho S C_D}}$$

The static assumption for the vertical case is close enough to reality under normal conditions to be treated as fact.

The horizontal case allows the simulation to assume that the payload always moves at the same velocity as the wind. Therefore no equations need to be solved. The real life situation is the wind causes a drag force on the system which then accelerates the system to match the wind velocity. An analysis of the error caused by this assumption with a mismatch of 1m/s is presented below for



the case of the balloon at 15km altitude.

This case actually represents the worst case velocity mismatch as it is the altitude the jet stream is typically found at. An error of only 6m is irrelevant and can safely be ignored. The error is larger at the lower and upper extremities of the flight profile, but the wind speed is usually much lower in those regions. Typically the error created by these effects is much lower than the inaccuracies of the predicted wind profile. Therefore, the static assumption holds fore most HAB flights.

Ascent Rate

A standard assumption made for flight prediction is that the ascent rate is constant. This is based on the (correct) assumption that lift is constant and the incorrect assumption that drag is constant. Both the ambient pressure and density decrease with altitude. This causes the balloon to expand proportionally which causes an increase in drag area proportional to the 2/3 power of density. This increase in area is not enough to balance the reduction in density, causing a reduction of drag and therefore an increase in ascent rate (shown as green line in ascent rate graph to left).

This is not the whole story however. Drag varies as a function of Reynolds number which is given below and the relation is shown to the right.

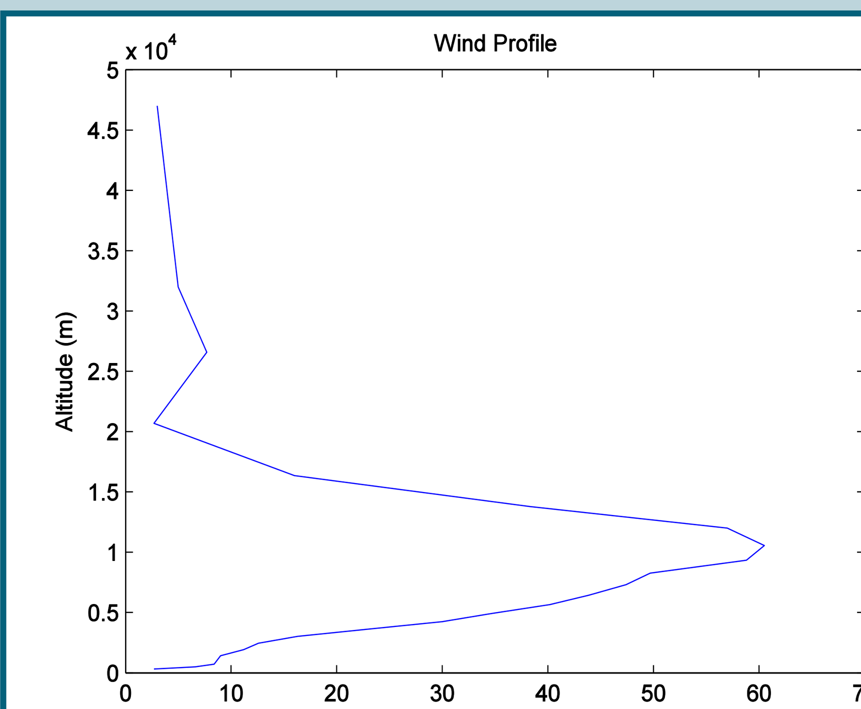
$$Re = \frac{\rho v L}{\mu} \qquad C_D = \frac{24}{Re} + \frac{2.6\left(\frac{Re}{5.0}\right)}{1+\left(\frac{Re}{5.0}\right)^{1.52}} + \frac{0.411\left(\frac{Re}{263,00}\right)^{-7.94}}{1+\left(\frac{Re}{263,000}\right)^{-8.00}} + \left(\frac{Re^{0.80}}{461,000}\right)$$

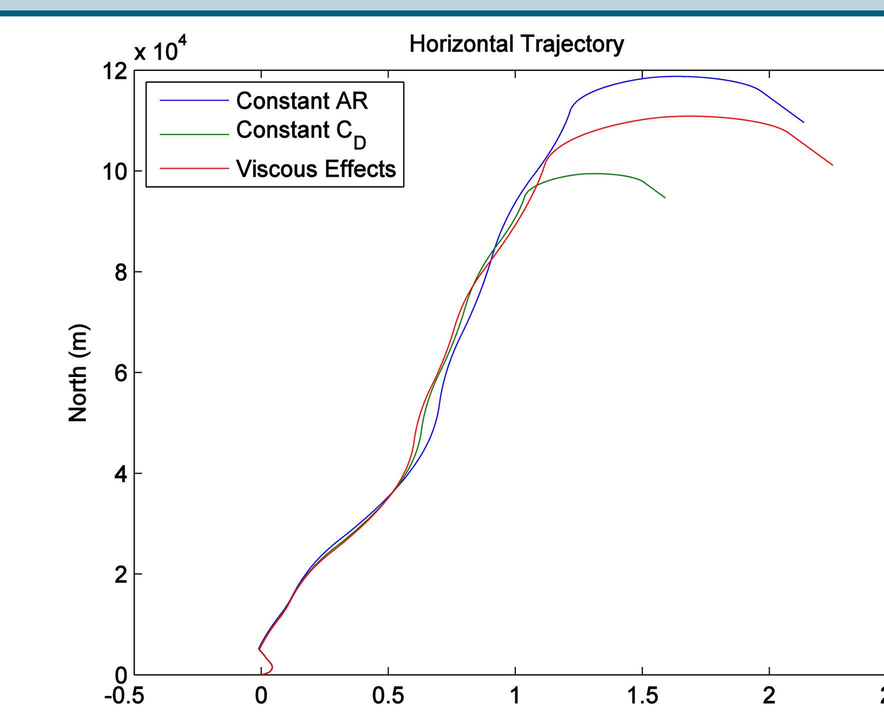
Most balloons have a Reynolds number that falls in the critical region between 10e5 and 10e6. This can cause a dramatic change in drag coefficient due to the turbulent transition reducing the wake area behind the balloon. This is shown in the graph to the right. The ascent rate that results from the modeling of Reynolds number effects is shown in the graph on top right.

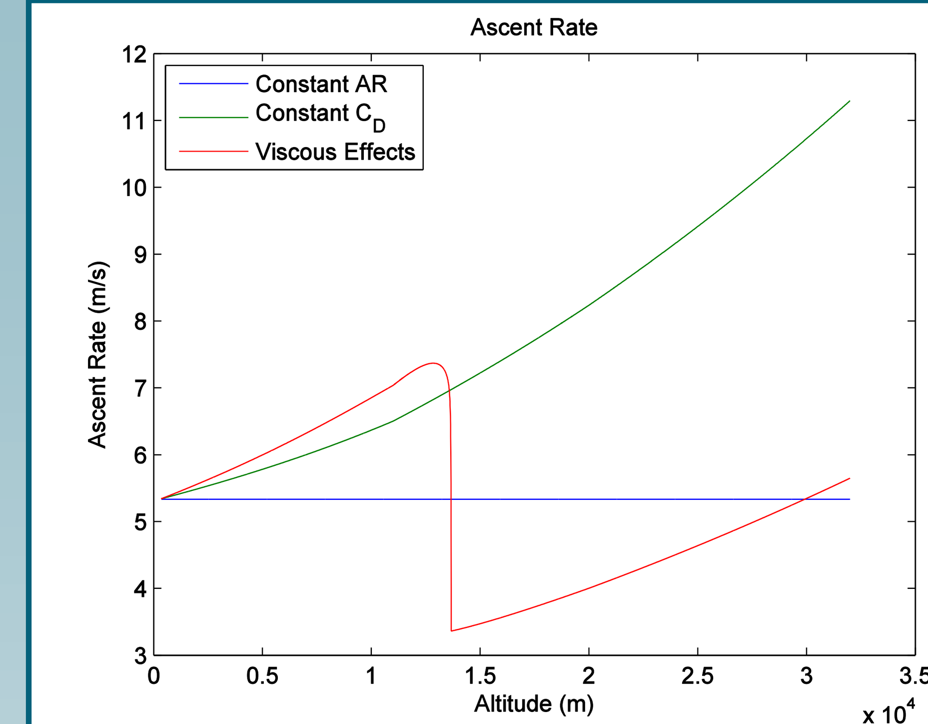
A simulation was run with the sample wind profile, shown below, for the various ascent rate models discussed. The resulting ascent section flight profile is seen below. The effects discussed above also pertain to the descent portion of flight and cause similar results.

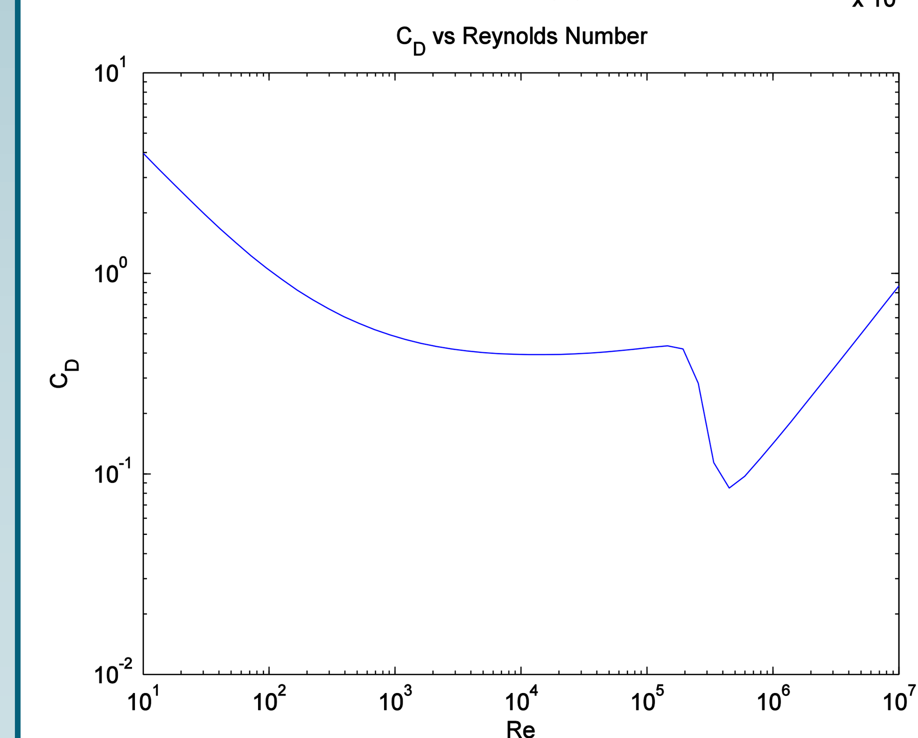
Conclusions

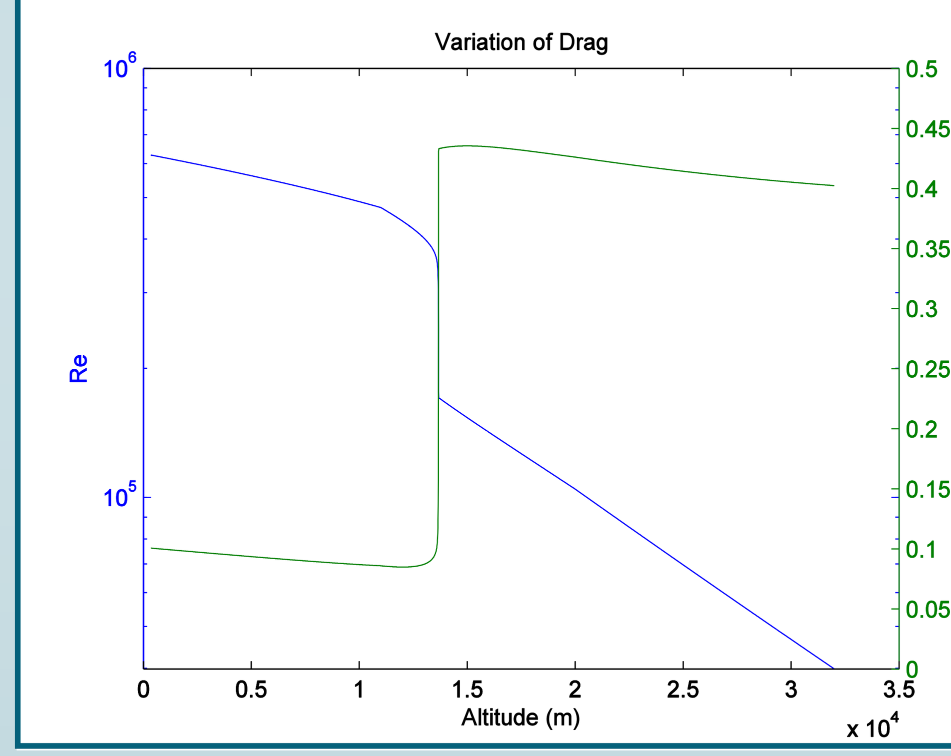
Constant ascent and descent rates are not accurate and the error compounds over longer durations. The effects of Reynolds number can be magnified by humidity or abnormal density gradients not accounted for in the standard atmosphere model used for these simulations. Further errors can be created by balloon pressure gradients, Kutta-Joukowski and Bernoulli effects, and changes in gravitational potential. These effects will be studied further in future papers.











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