Development of a Probabilistic Trajectory Model for High-Altitude Scientific Balloons

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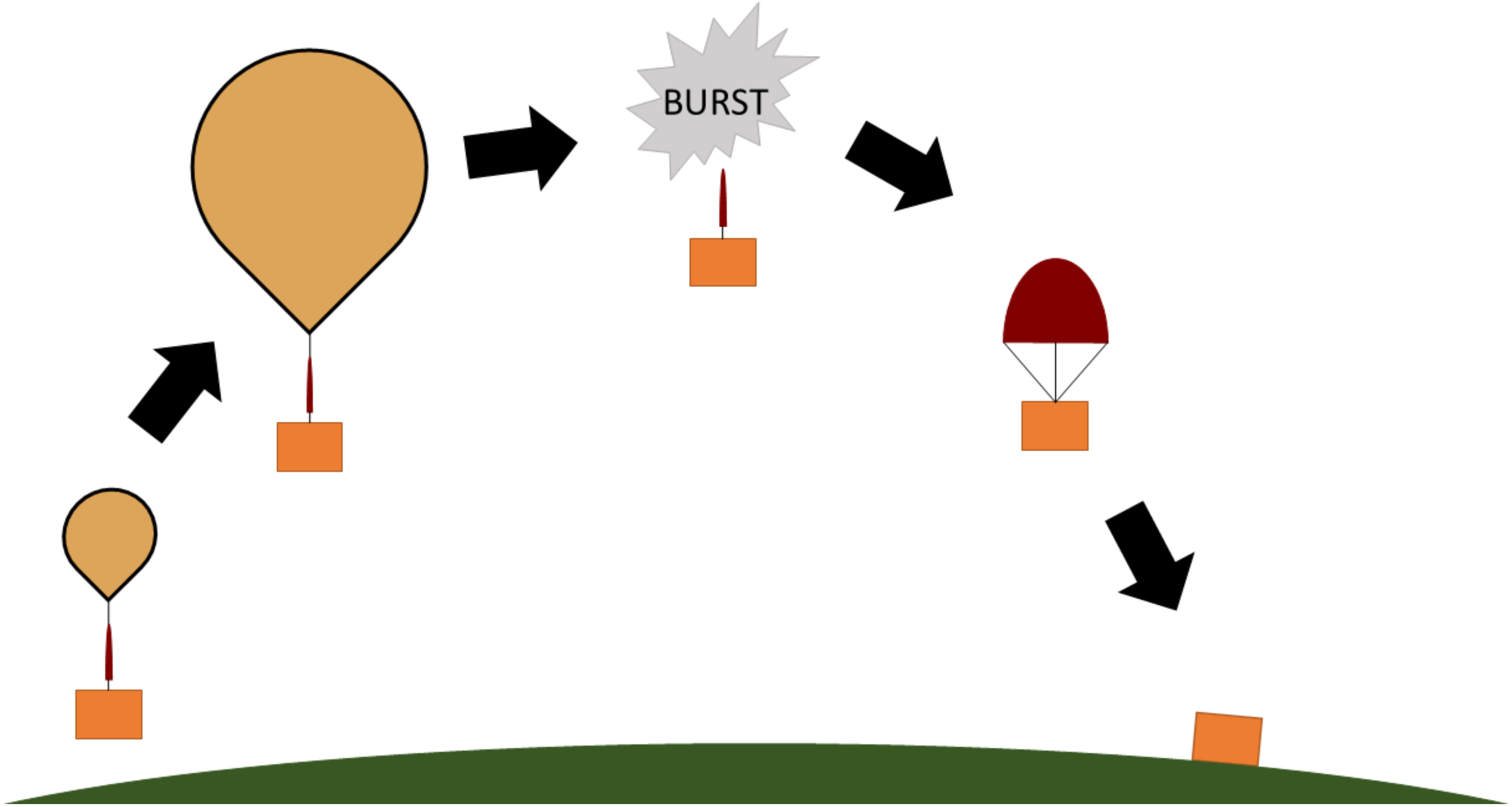
Background on Scientific Ballooning

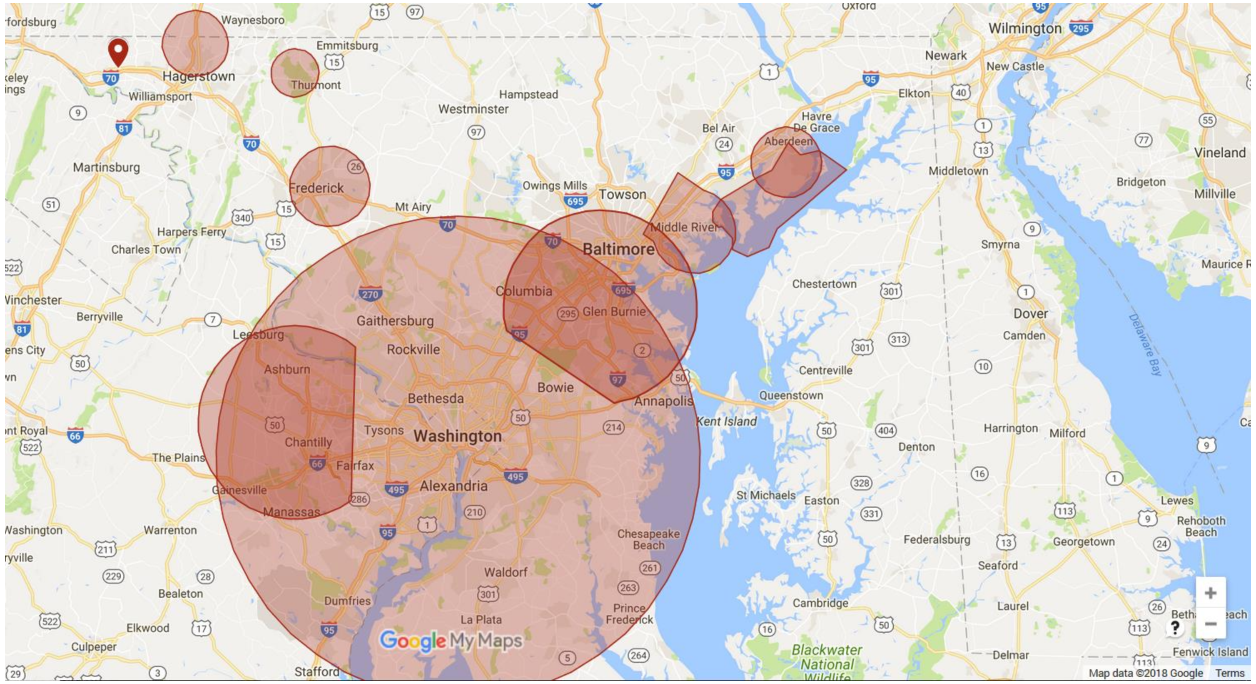
- Provides inexpensive, long-duration access to upper atmosphere
  - 80-120 kft (25-36 km)
- Payloads range from <1 kg to 3500 kg
- Typically made out of latex/substitute or polyethylene
- Latex balloons burst; polyethylene balloons float and must be terminated

Phases of a Latex Balloon Flight



Importance of Trajectory

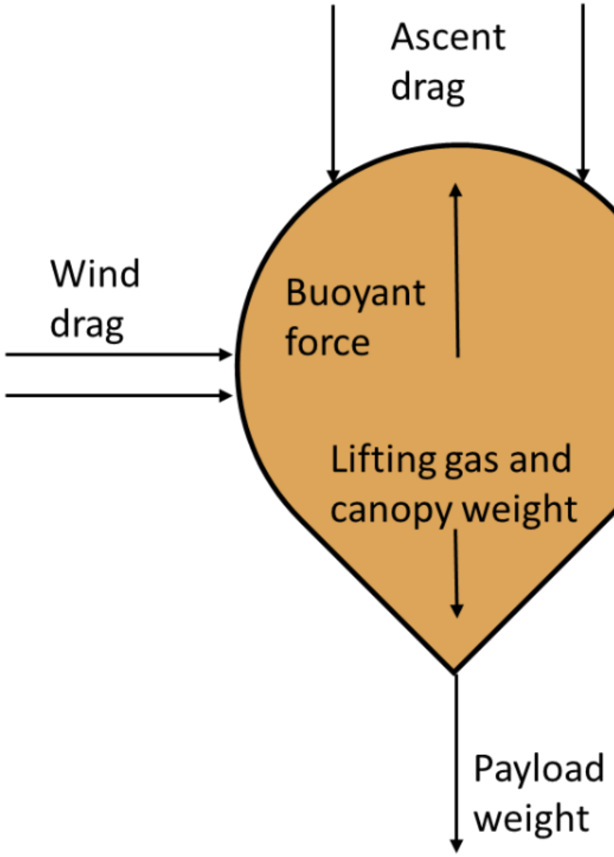
- FAA requires that balloons not "create [...] a hazard to persons or property not associated with the operation", nor penetrate restricted airspace (14 C.F.R. 101)
  - Can't land in urban areas, near airports or national security sites
- Want to recover equipment
  - No water landings
- Need to know where to send recovery team



How to predict trajectory?

- Initial value problem
- Find forces on balloon
- Integrate kinematic equations

Forces on a balloon



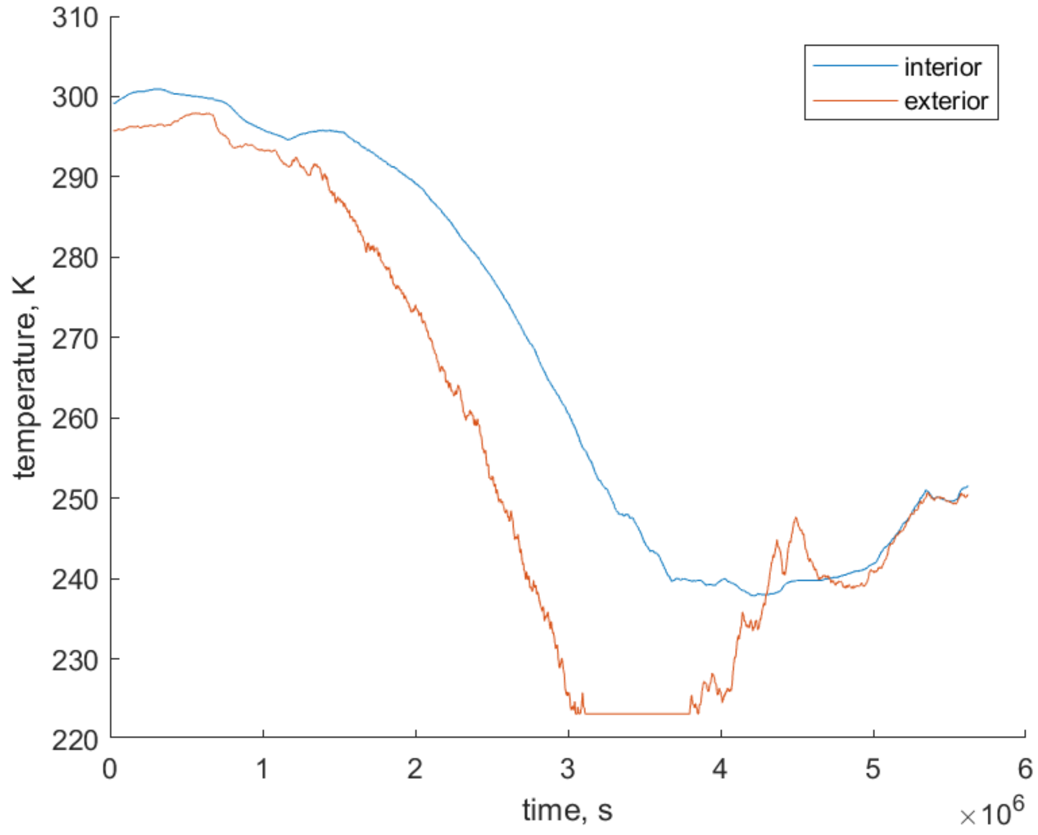
$$\overrightarrow{F_B} = \rho_{He} V g \hat{z}$$

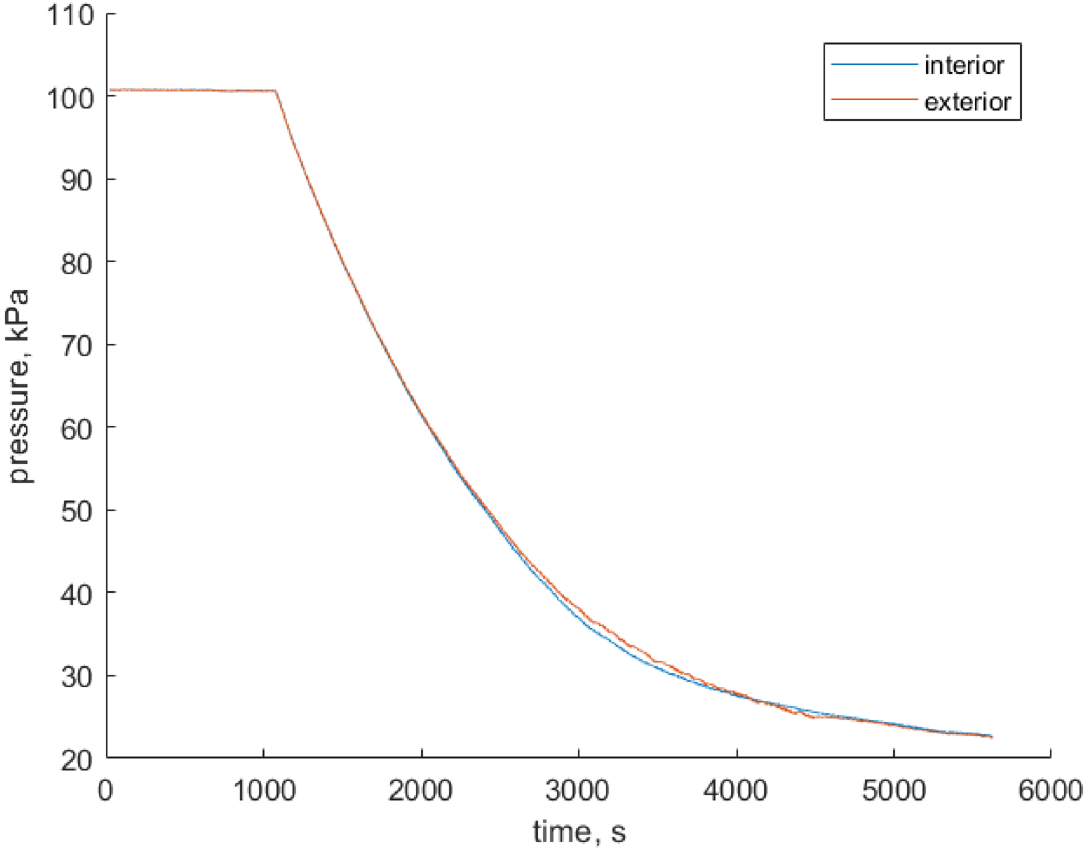
$$\overrightarrow{F_D} = -\frac{1}{2}\rho_{air} C_D A_{proj} \left|\overrightarrow{V_{rel}}\right| \overrightarrow{V_{rel}}$$

$$\overrightarrow{F_W} = -m_{sys} g \hat{z}$$

$$m_{sys} = m_{He} + m_{canopy} + m_{payload}$$

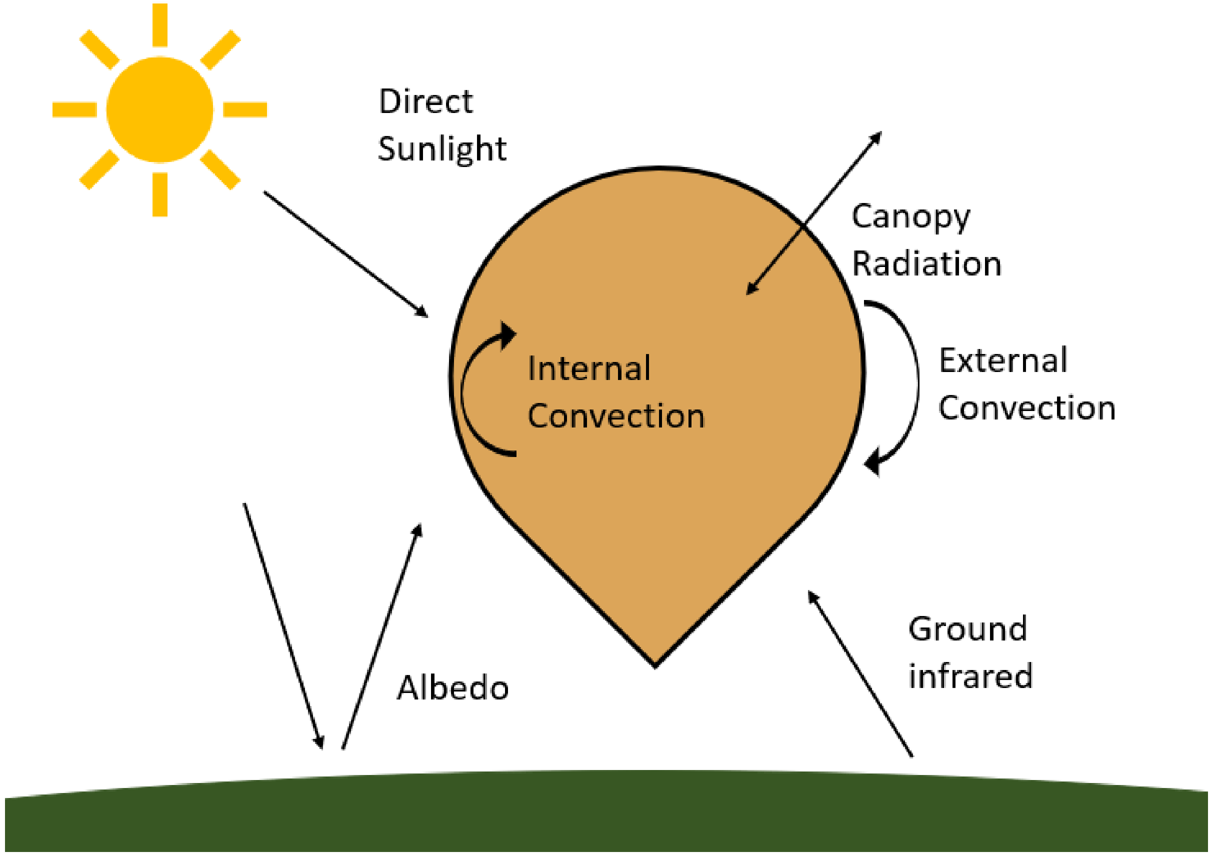
Internal Temperature and Pressure





Data credit: UMDBPP/J. Breeden and C. Bernard

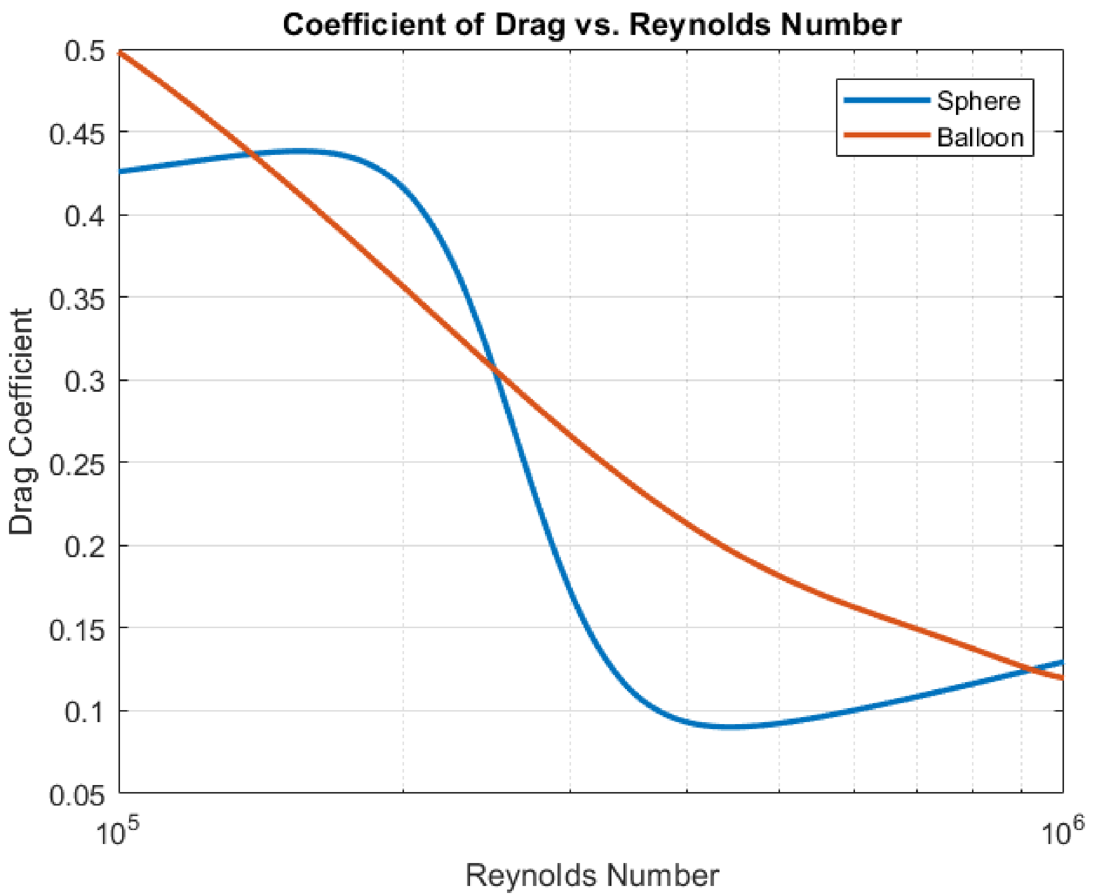
Thermal Loads on the Balloon



$$\frac{dT_c}{\mathrm{dt}} = \frac{\dot{Q}_{sun} + \dot{Q}_{alb} + \dot{Q}_{ground} + \dot{Q}_{atm} - \dot{Q}_{He} - \dot{Q}_{IR}}{\mathrm{c_c m_c}}$$

$$\frac{dT_{He}}{\mathrm{dt}} = \frac{\dot{Q}_{He}}{c_v \mathrm{m_{He}}} + (\gamma - 1)\frac{T_{\mathrm{He}}}{\rho_{\mathrm{He}}}\frac{d\rho_{\mathrm{He}}}{dt}$$

Effect of Reynolds Number on C_D



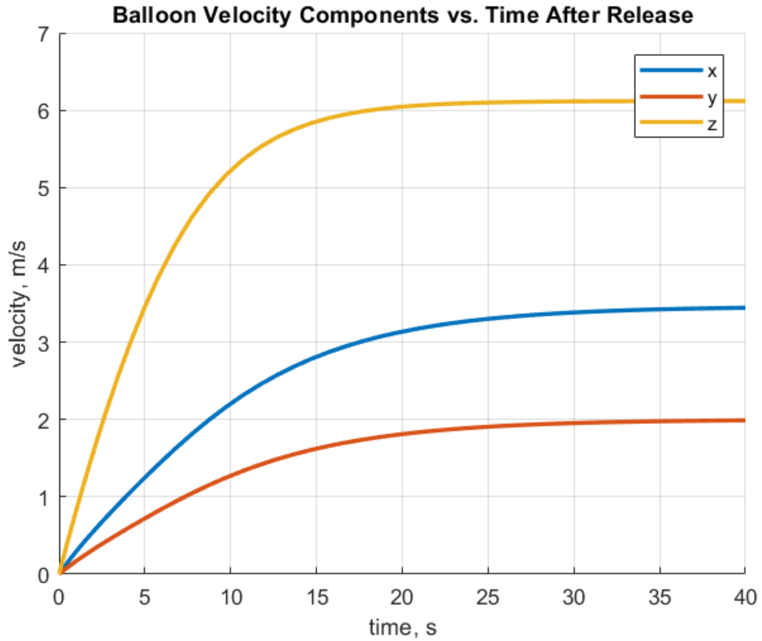
Models: Conner, Morrison

Obtaining Atmospheric Data

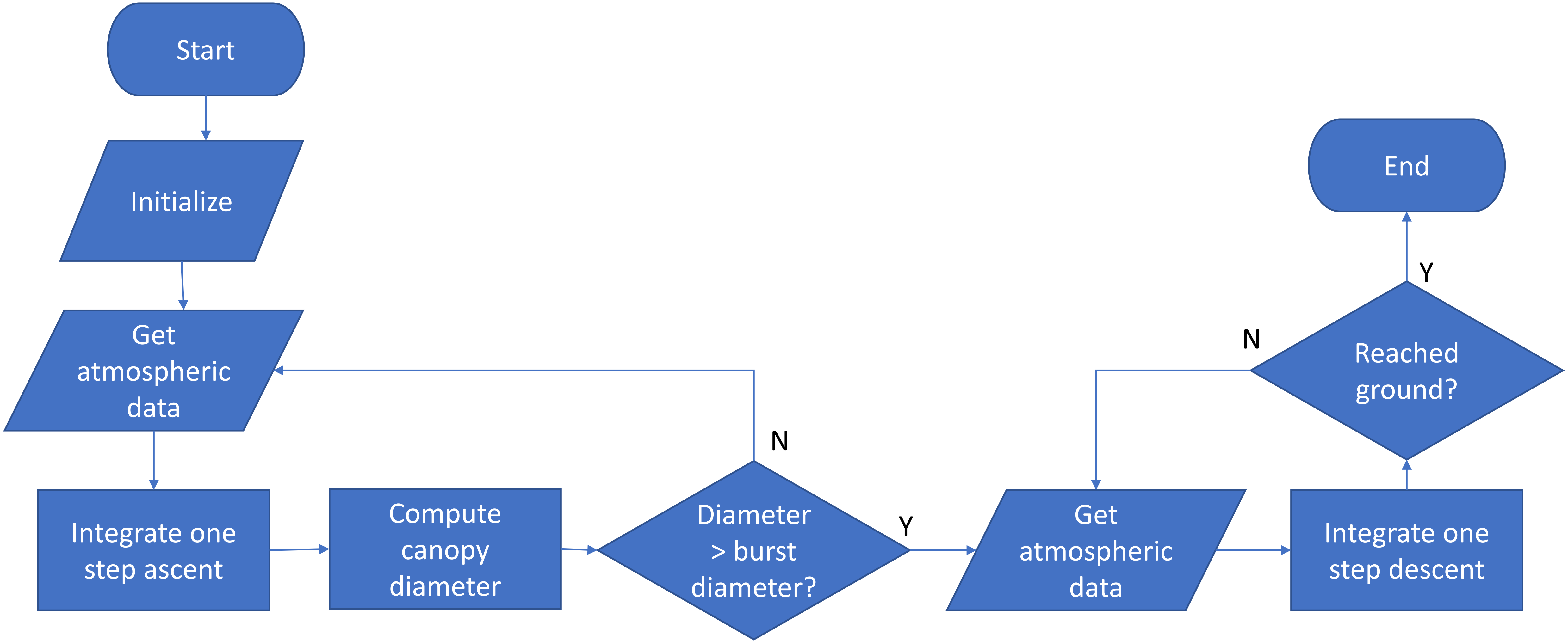
- Atmospheric state, especially wind, critically influences trajectory
- Obtained from NOAA’s Global Forecast System (GFS) model
  - 0.5° x 0.5° x 2.5 kPa spatial resolution
  - 3-hour temporal resolution
  - Run every 6 hours
- Parameters obtained:
  - Wind (u and v)
  - Temperature
  - Pressure
  - Albedo
  - Ground temperature

First-Order Simplifications

- Wind will rapidly drive horizontal velocity to wind velocity
- Balloon ascends at a “terminal velocity” determined by drag
  - Altitude-dependent, but changes slowly
- Compute velocity directly, rather than integrating acceleration
  - Reduces number of states from 8 to 5



Model steps



Start
Initialize
Get atmospheric data
Integrate one step ascent
Compute canopy diameter
Diameter > burst diameter?
N
Y
Get atmospheric data
Integrate one step descent
Reached ground?
N
Y
End

Estimating Uncertainty

- The prediction process is deterministic
- Trajectory predictions are necessarily uncertain
  - Environmental parameters are only predictions
  - Burst diameter varies between balloons
- Process is stochastic
- Randomly vary inputs to estimate most probable landing site

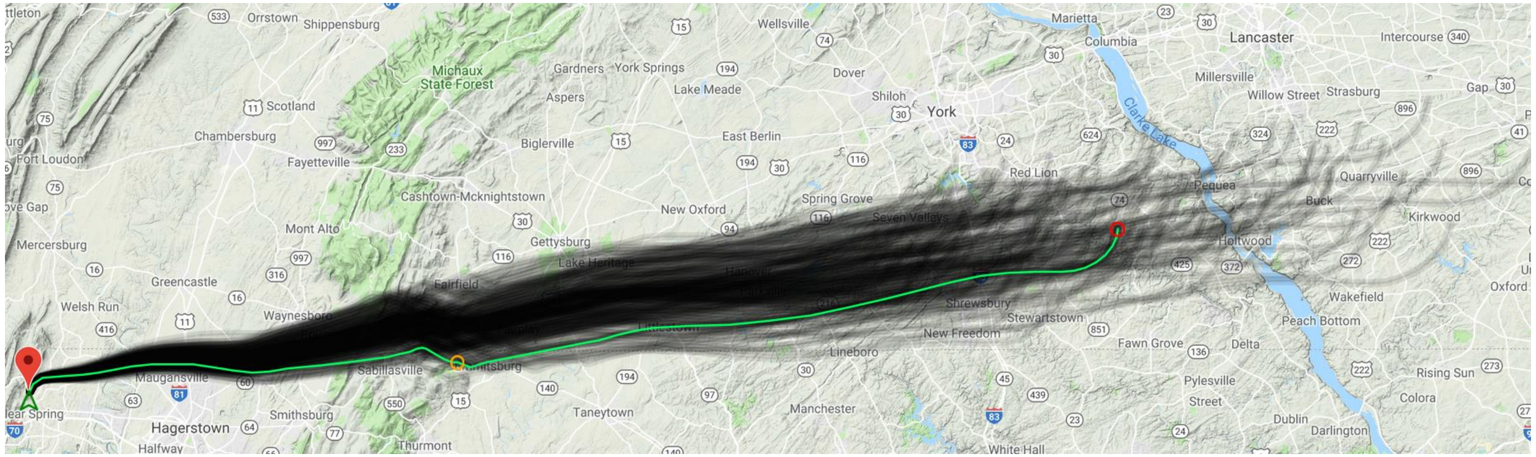
Ascent Rate and Burst Uncertainty

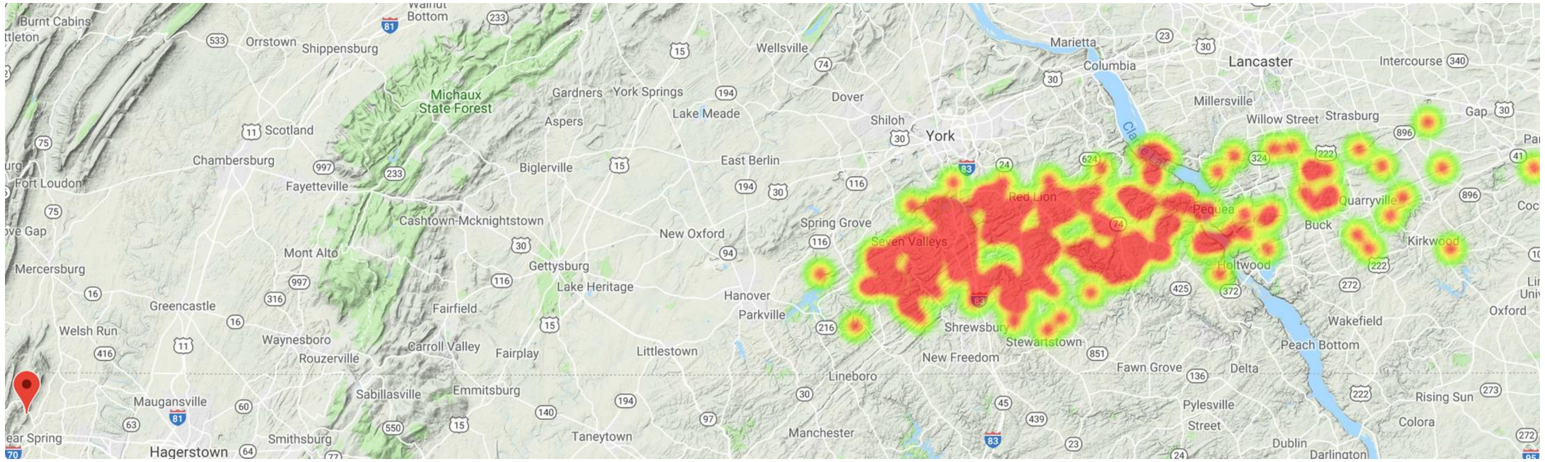
- Dominant factors in ascent rate are helium mass, C_D
- Normally distribute helium mass about nominal value
  - Helium mass is measured at launch
- Multiply C_D by a unity-mean normal deviate
- Burst diameter affects overall length of track
- Treat burst diameter as a Weibull variable
  - Burst diameter is a measure of lifetime

Wind Uncertainty

- Wind exhibits strong correlation across altitudes
  - Vary wind as a function of latitude, longitude only
- Wind is a vector quantity
  - Can’t treat components independently
  - Vary direction normally
  - Multiply magnitude by unity-mean normal deviate

Model Output





Future work

- Model validation with flight data
- Development of a payload drag coefficient model
    - Current model underestimates vehicle drag coefficient

Citations

- “14 C.F.R. 101,” Code of Federal Regulations, n.d.
- Breeden, J., “High Altitude Weather Balloon Venting and Balloon Dynamics,” Region I Student Conference, AIAA, 2017.
- Conner, J. P., and Arena, A. S., “"Near Space Balloon Performance Predictions",” AIAA Aerospace Sciences Meeting, Vol. 48, AIAA, 2010. doi:10.2514/6.2010-37.
- Morrison, F. A., “"Data Correlation for Drag Coefficient for Sphere",” Tech. rep., 2016. URL www.chem.mtu.edu/~fmorriso/DataCorrelationForSphereDrag2016.pdf.

Questions?