Computational Fluid Dynamics Study of Balloon System Tethered to a Stratosail

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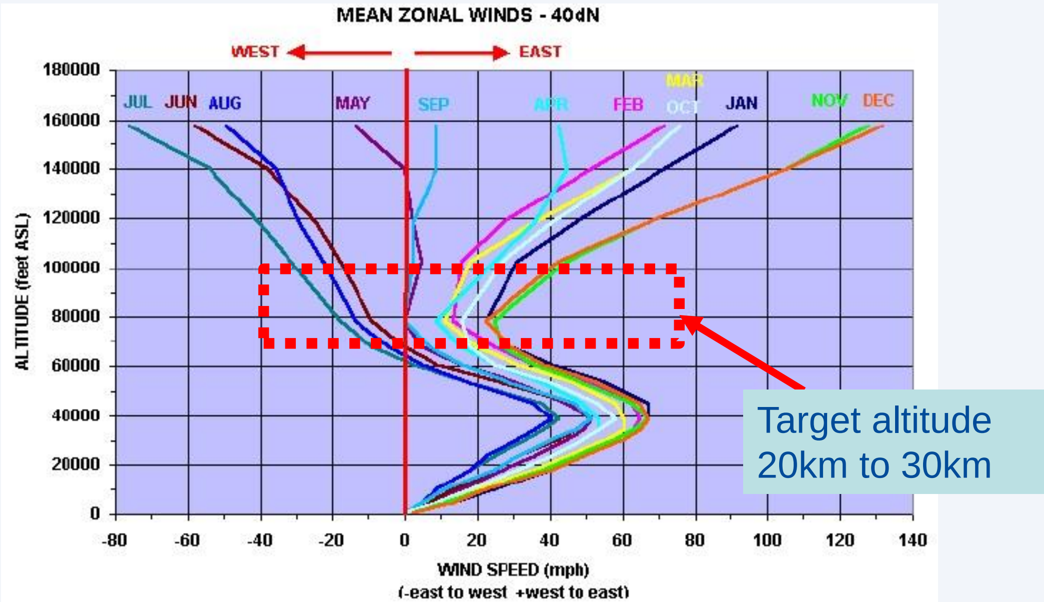
Outline

- **Introduction of StratoSail**
- **Computational Modeling of Balloon-StratoSail System**
- **Results on Drift Velocity and Tether Length**
- **Conclusion and Future Work**

Station-Keeping of Stratospheric Balloon

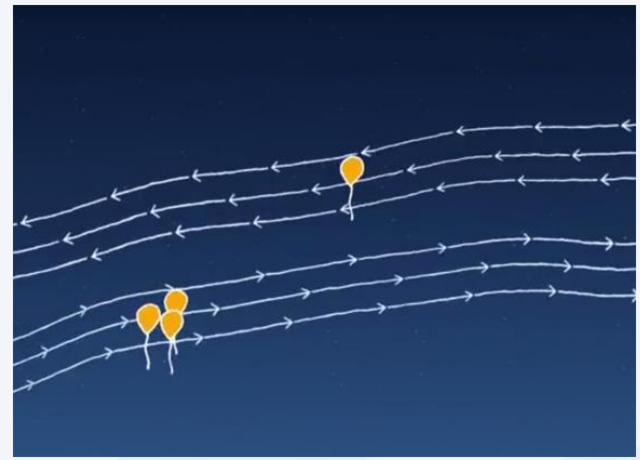
- Within 2 km horizontal radius
- Over a one-week duration
- Altitude of between 20 km and 30 km
- A minimum payload capacity of 200 kg

Wind Speed at Various Altitudes



The wind speed vs altitude [Cees Bil, 2014]

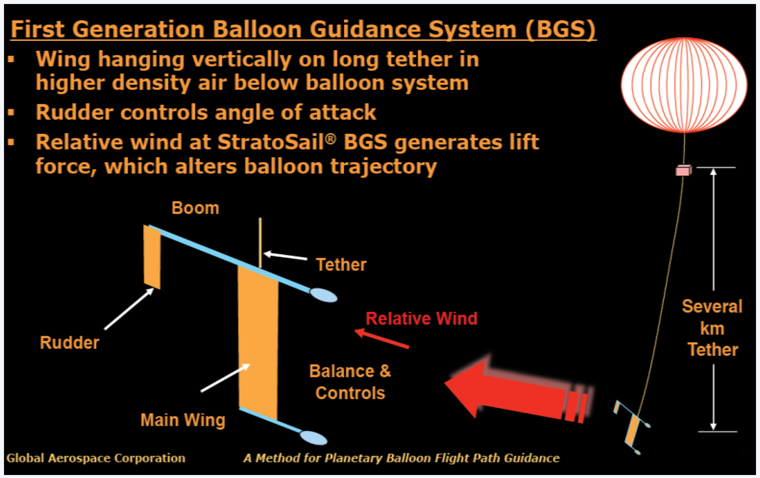
1.0 feet=0.3048 m, 1.0 mph=0.447m/s

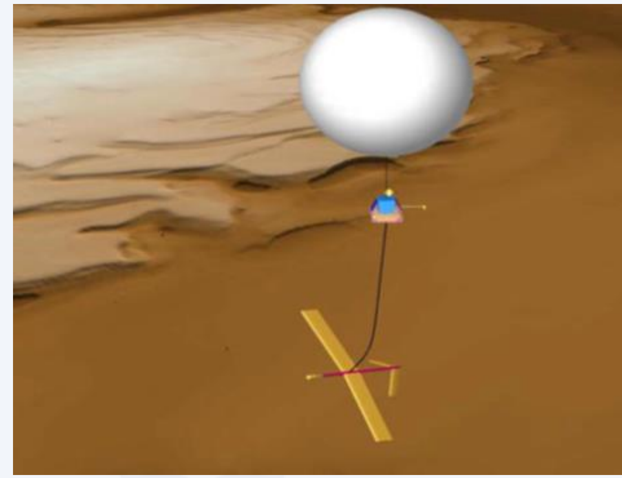


Google loon control

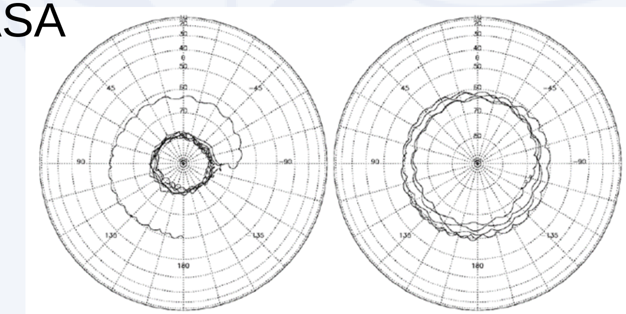
- ✓ Balloons drift with local wind.
- ✓ Wind direction changes with altitude.
- ✓ Indirect trajectory control through altitude control.

NASA StratoSail – Horizontal Motion Control





- ✓ Developed by Global Aerospace Corporation (GAC)
- ✓ Used as Balloon Guidance System (BGS) for NASA
- ✓ Wing, rudder, boom, 15 km-tether
- ✓ Generate horizontal lift or drag
- ✓ 1m/s velocity correction capability
- ✓ Successful ¼ scale ground test in 1999



(a) Trajectory of the Free-Floating Balloon. (b) Trajectory of the DARE Platform.

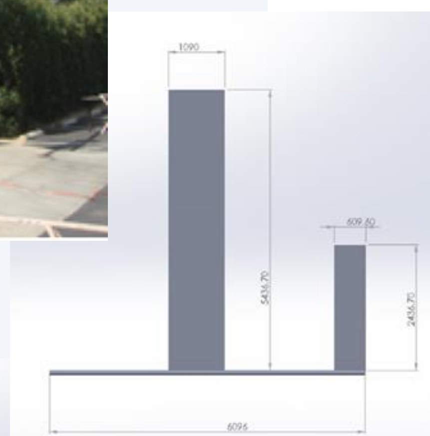
FIGURE 2. Trajectories of the Free-Floating Balloon and the DARE Platform at Mars.

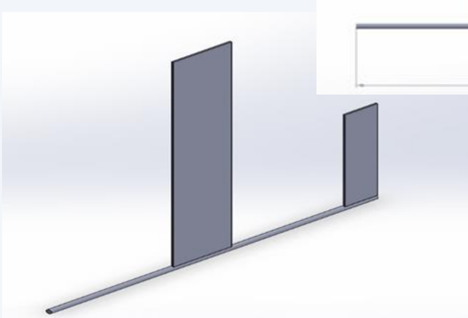
Objectives and Scope

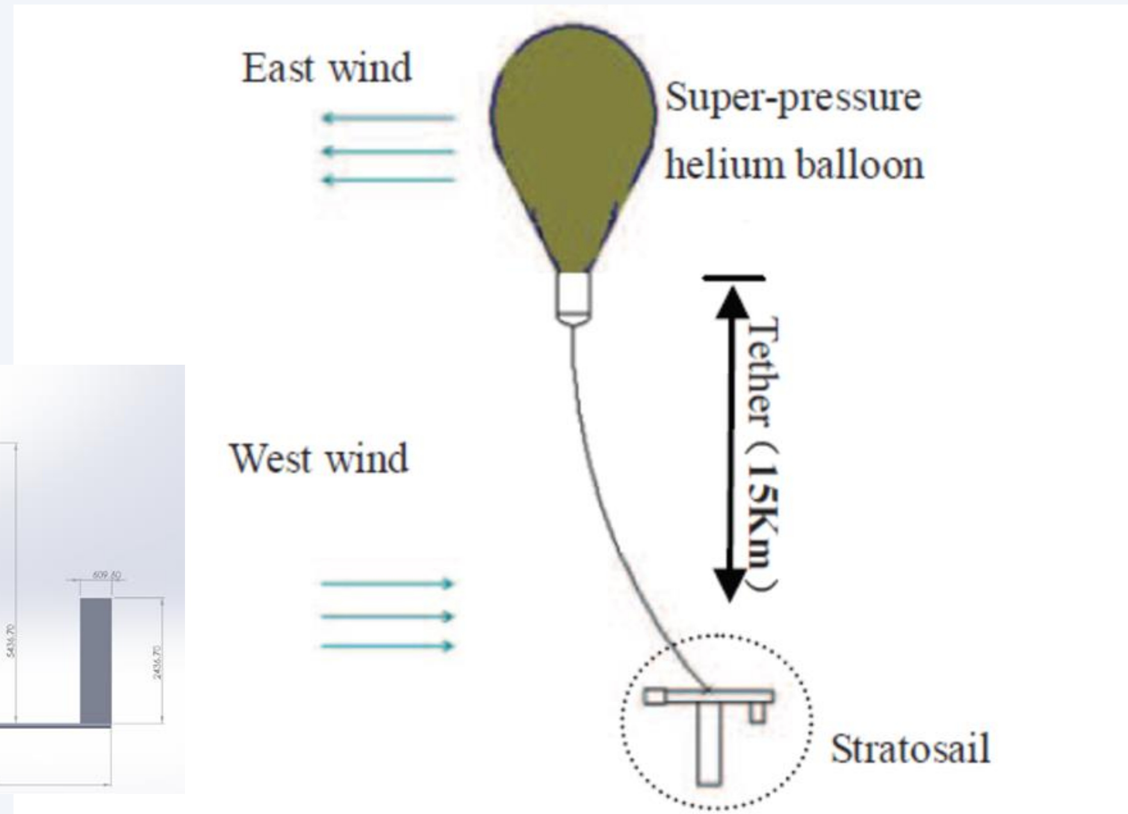
- **To develop a computational model**
  - Calculate the drag force on stratosail
  - Determine the drift velocity of balloon-stratosail system
  - Parametric study on balloon size, angle of attack, and altitudes
  - Determine the tether length

- **Simplifications**
  - 2D analysis
  - Steady-state: dynamic equilibrium
  - Best case scenario of opposing winds

Our Numerical Model

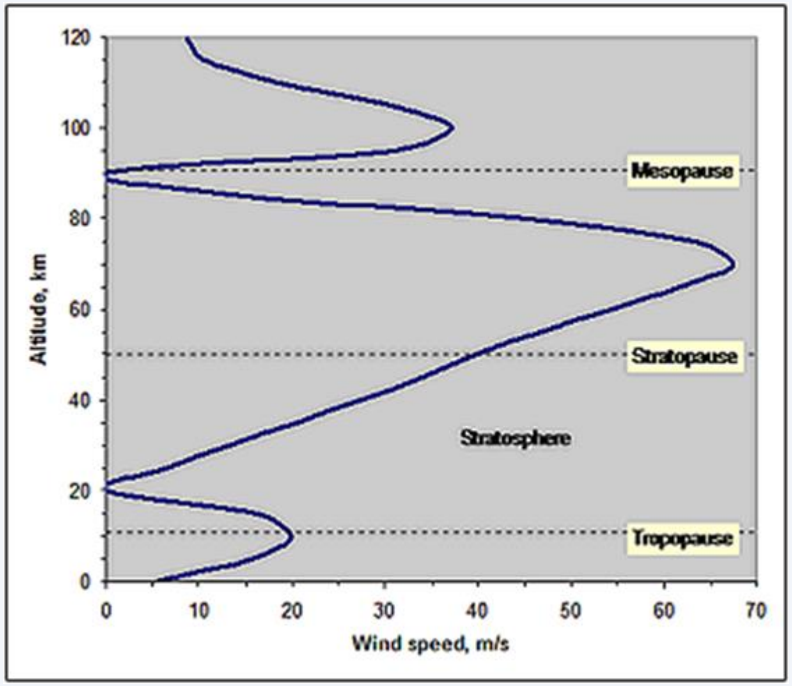






Rudder : 8ft by 2 ft
Wing : 18ft by 3.6 ft
Aluminium boom : 20 ft

Atmospheric Properties

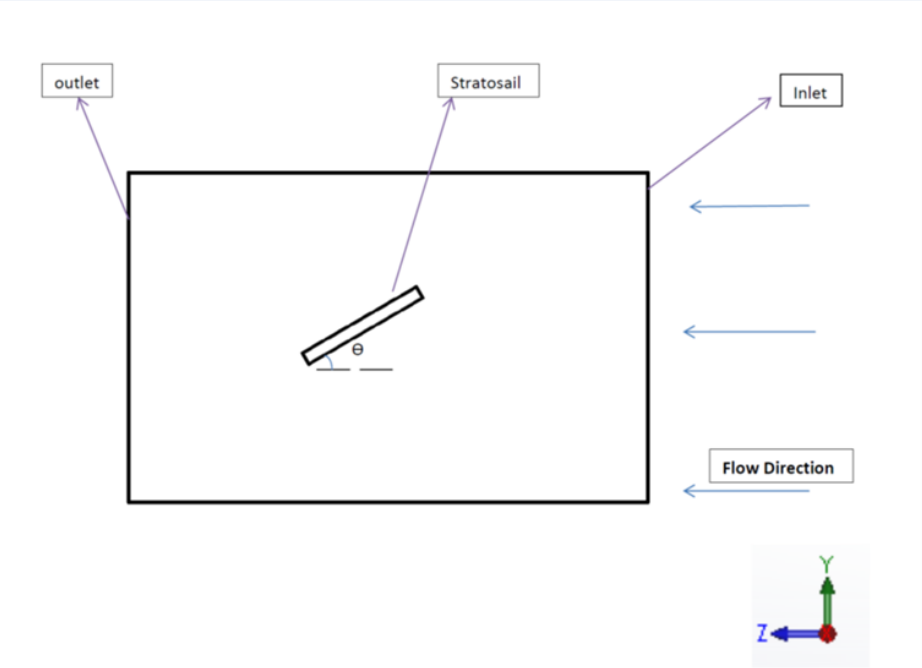


Plot of altitude (km) against Wind Speed (m/s) (Struzak, 2003)

Physical Properties of U.S Standard Atmosphere, 1976 in SI Units (Braeunig).

Height Of Stratosphere (km)	45	40	30	15
Temperature of air (K)	265.05	251.05	226.65	216.65
Air Density (kg/m^3)	1.88E-03	3.85E-03	1.80E-02	1.94E-01
Wind Speed (m/s)	33	26	11	15
Kinematic Viscosity (N.s)	1.69E-05	1.62E-05	1.49E-05	1.43E-05

Computational Domain

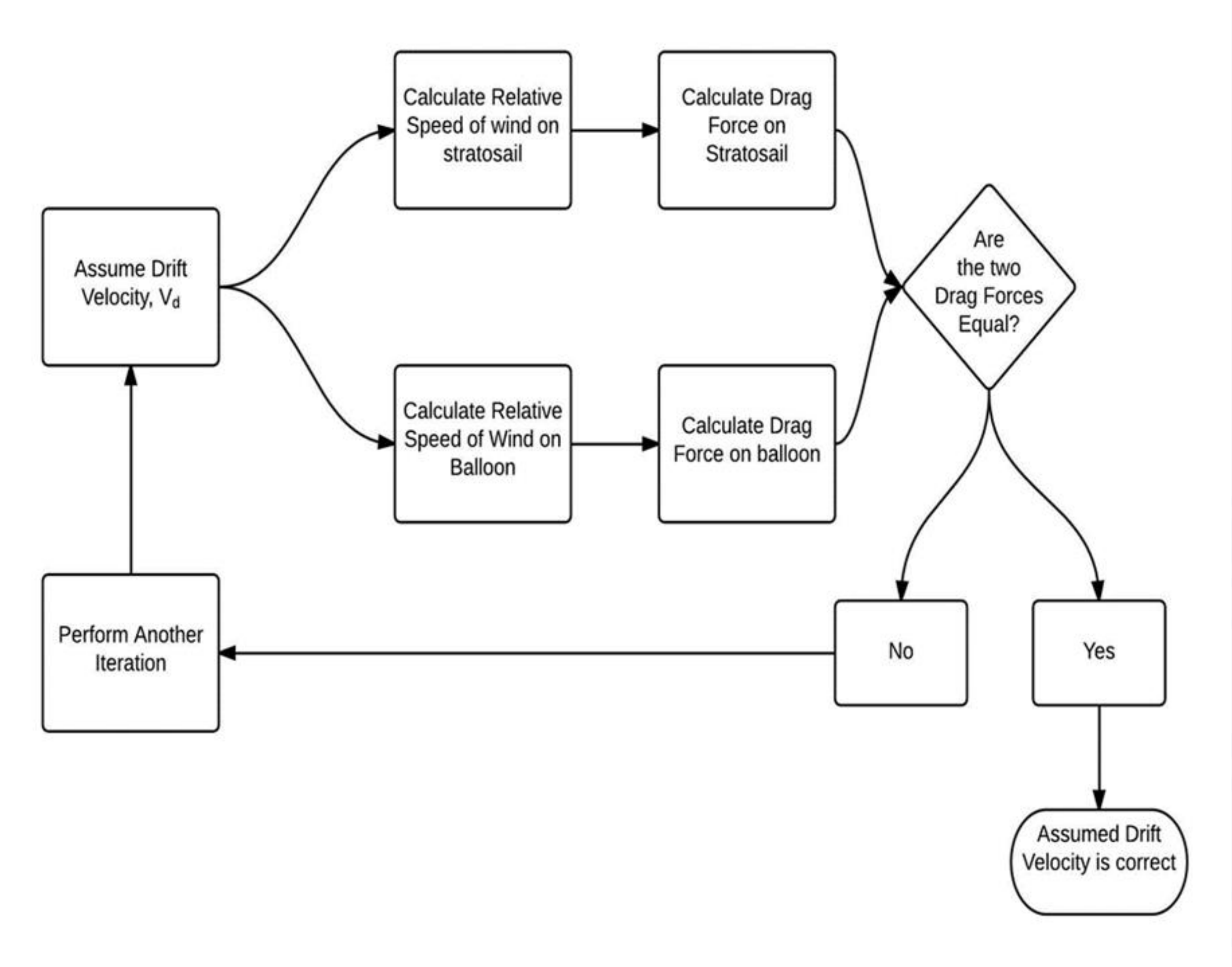


Fluent Settings	
Viscous Model	SST K-Omega
Stratosail Boundary Condition	No-Slip Wall Condition
Inlet Boundary Condition	Velocity-Inlet
Outlet Boundary Condition	Outflow
Surrounding Walls	Gauge Pressure=0
Inflation Option	Smooth Transition

Domain Setttings	
Dimensions of Domain	200m x 100m x 300m
Volume of Stratosail	0.267m^3
Ratio of Volume of Domian over Volume of Stratosail	2.25E+07

Angle of Attack	Nodes	Elements
0 degrees	77208	403512
30 degrees	77329	403376
60 degrees	76948	401424
90 degrees	78130	406841

Solve for Drift Velocity by Iteration

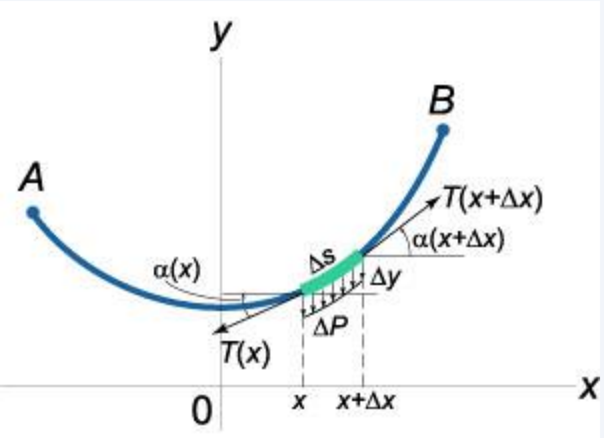


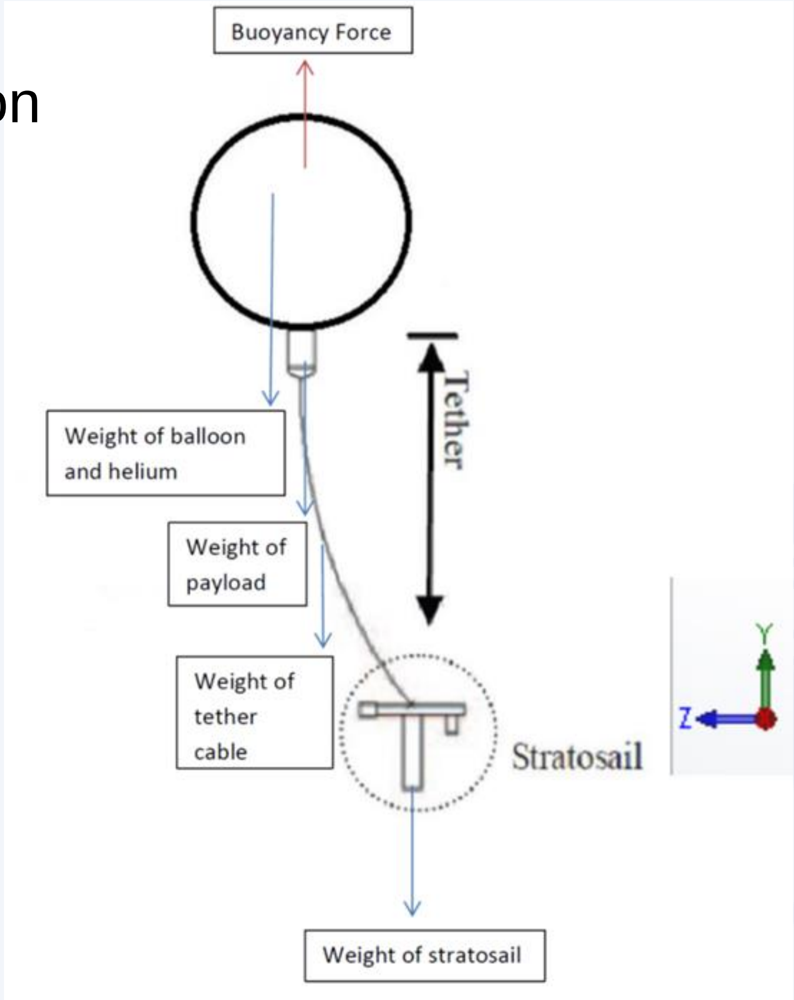
Centenary Cable

Calculate the tether length to maintain steady-state drift motion at fixed altitudes.

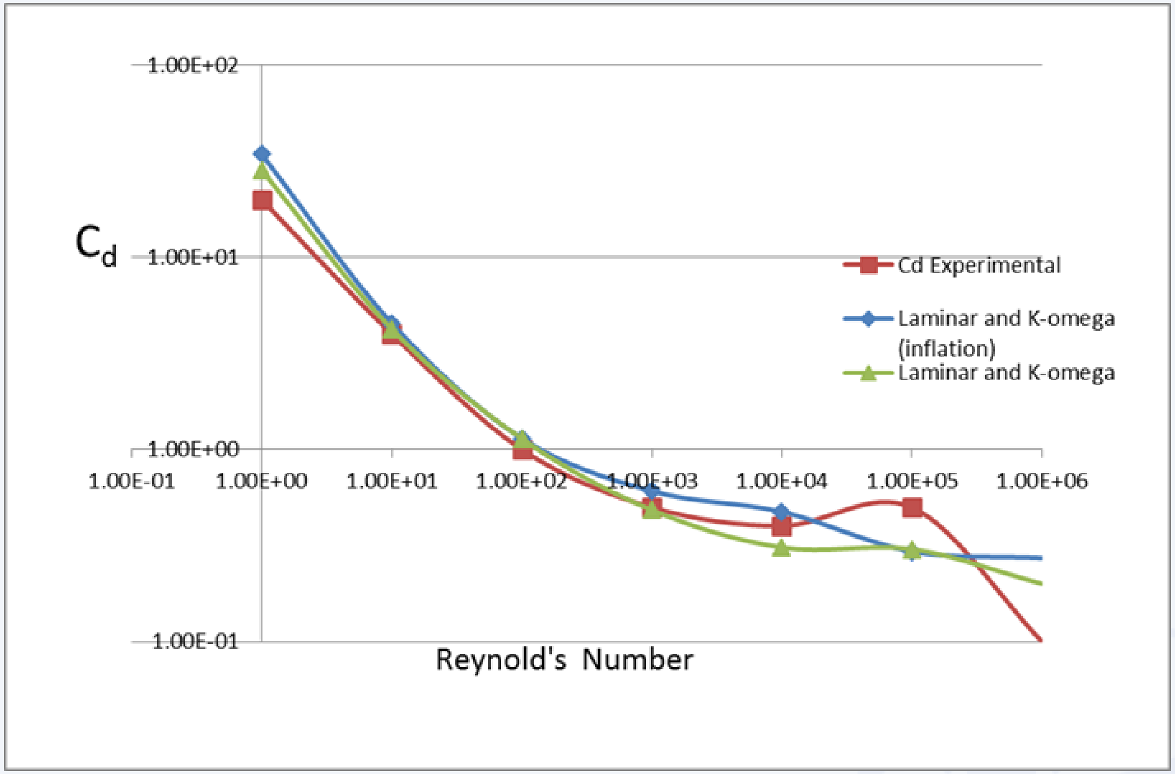
$$y = \frac{T_0}{w} cosh\left(\frac{wz}{T_0}\right)$$

$$s = \frac{T_0}{w} sinh\left(\frac{wz}{T_0}\right)$$



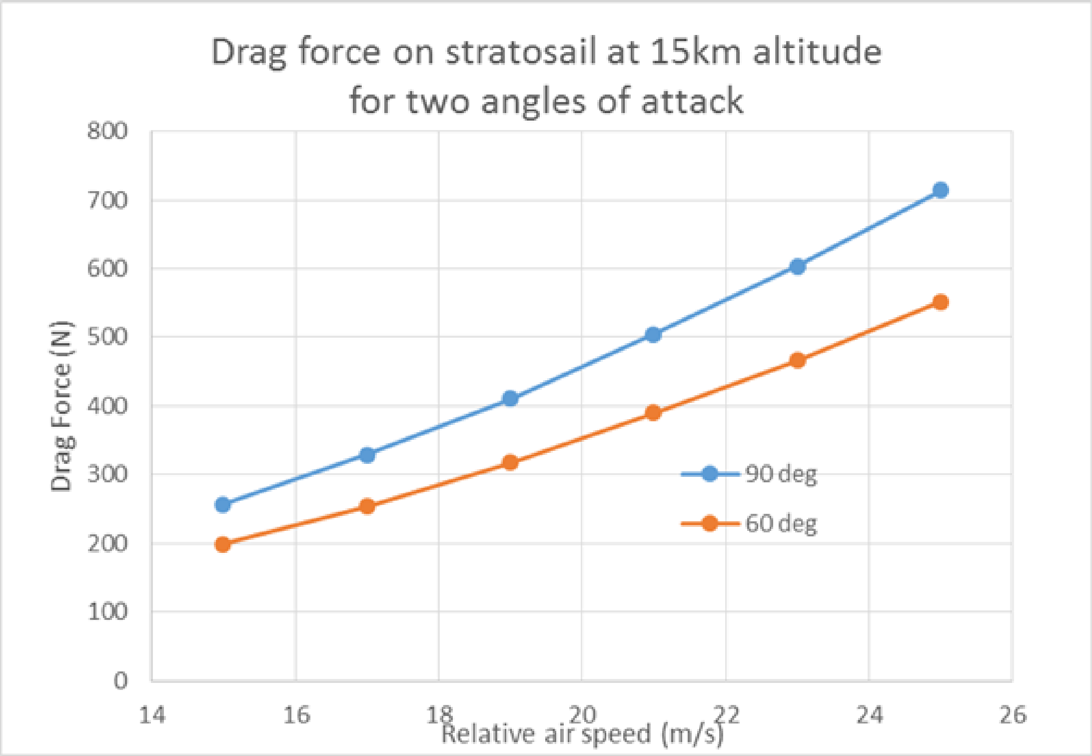


Validation of CFD simulation



- Drag force/coefficient on a sphere at various speeds (Reynold's No.)
- Fluent software simulation close to reported data
- Small differences noticed with inflation option turned on to smoothen the transition of elements

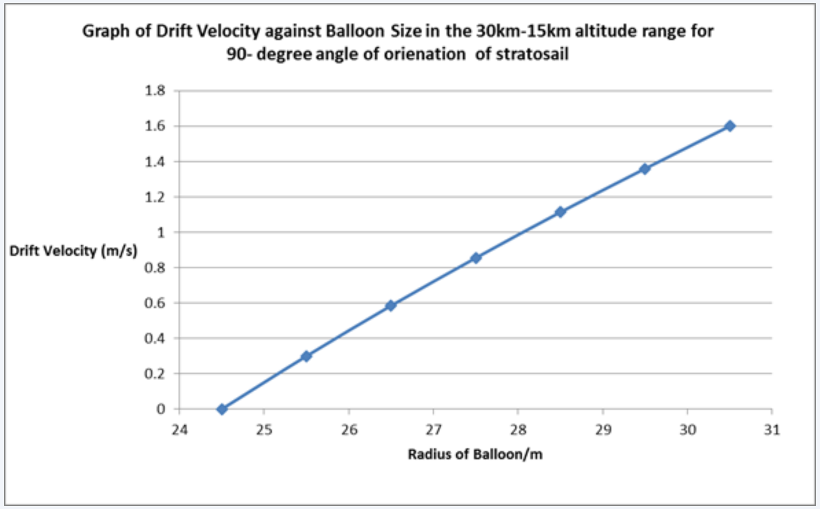
Drag Force on Stratosail



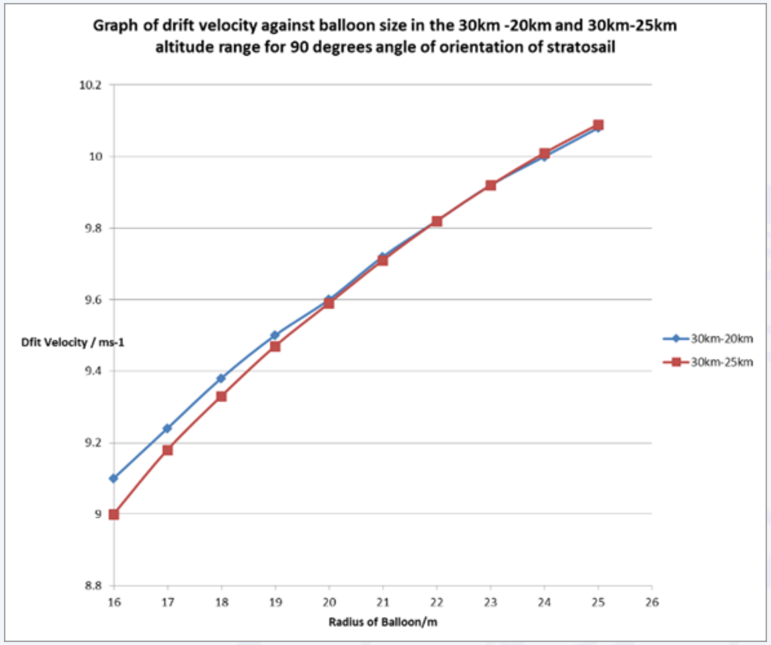
- Stratosail at 15 km altitude
- Drag force is larger at angle of attack of 90° compared to 60°
- Frontal area decreases with angle of attack

Drift velocity of Balloon-Stratosail System

- Wind speed at balloon altitude 30km: 12.5 m/s
- Drift velocity: less than 2 m/s for various sizes of the balloon for stratosail at 15km
- Drift velocity increases with balloon size

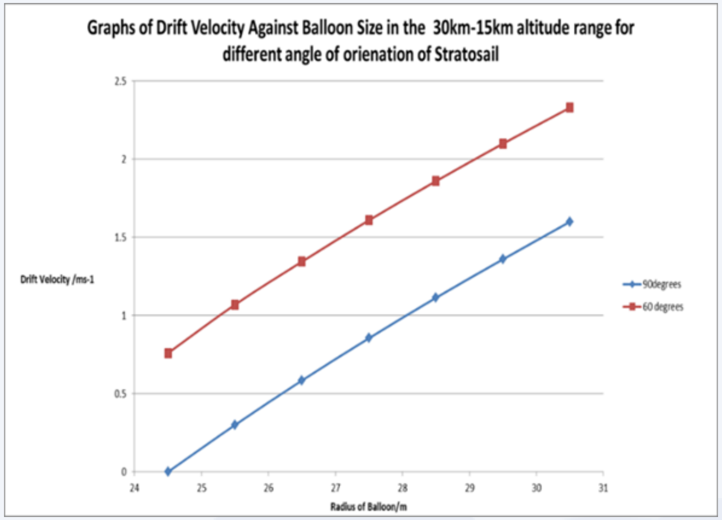


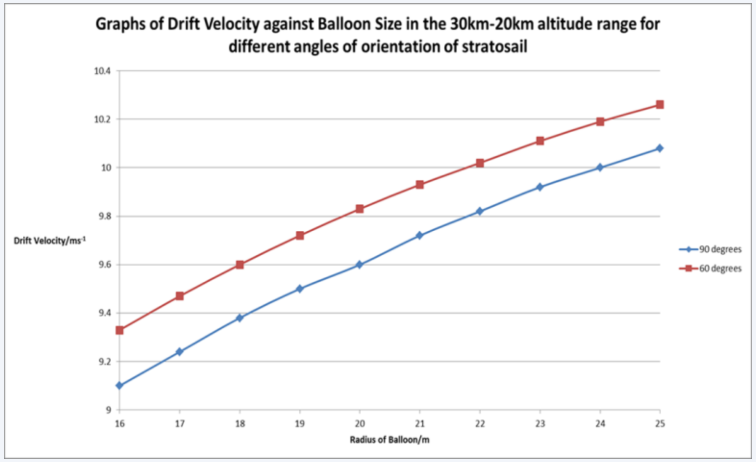
- Drift velocity increases to about 10 m/s with stratosail moved to 20 km and 25 km due to lower wind speed at those altitudes.

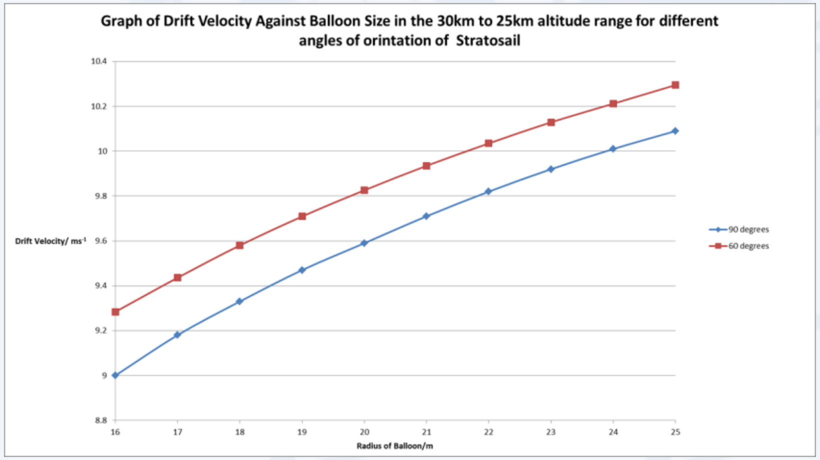


Drift Velocity with Angle of Attack

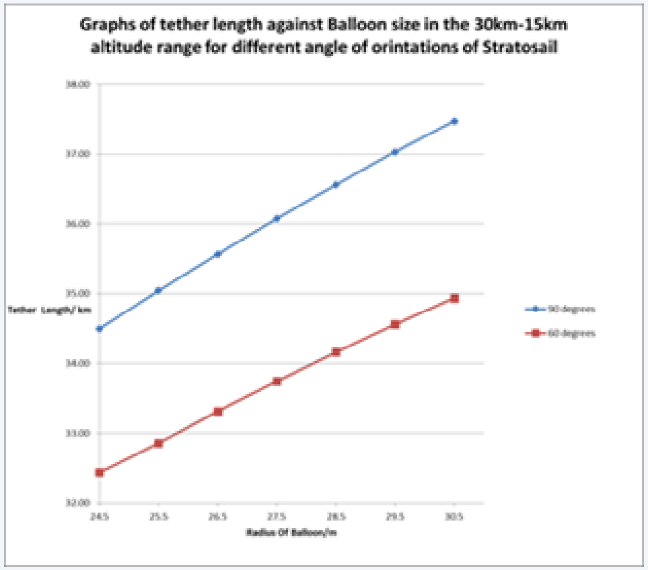
Drift velocity decreases when the angle of attack is reduced from 90° to 60° due to the reduction in drag force.

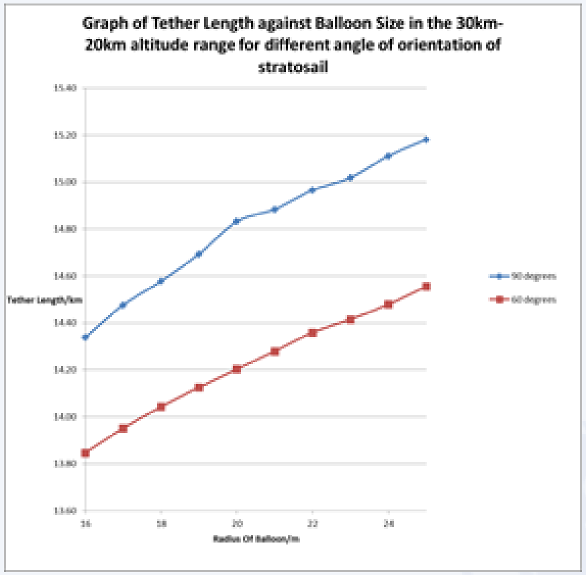


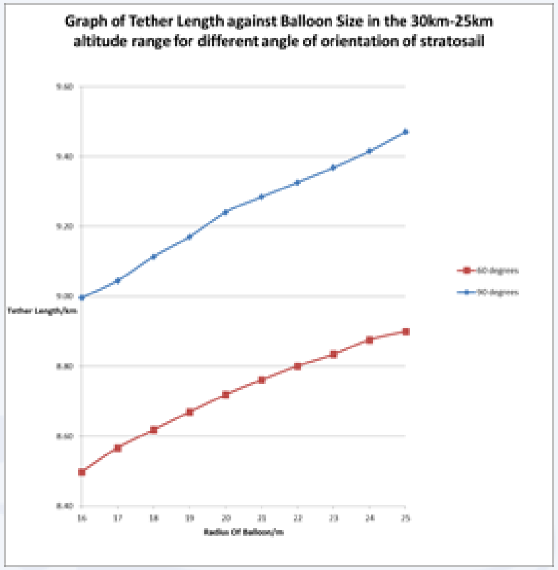




Tether Length for Various Cases







- Length of tether for various cases of altitudes and angle of attack
- Length increases with size of balloon due to larger drag force (parameter T_0)
- Angle of attack at 90° gives larger tether length than 60°
- Changing the tether length will change the dynamics of the system

Conclusion and Future Work

- **Preliminary work on simulation of balloon-stratosail system**
- **Drift velocity: Feasibility of station-keeping**
- **Future work**
  - Full 3D and transient motion simulation
  - Use of more realistic wind-speed data, especially wind directions
  - Change of tether length and stratosail angle of attack as control parameters
  - Evaluate control strategies for station-keeping by using the stratosail (or with other active means)

THE END