LOON™

Hammerhead (aka “Blimp”) Design and Sizing

Balloon Business Fundamentals

We have competing objectives:

- Highest service availability to end user
- Lowest cost vehicle
- Fewest vehicles needed (lowest fleet cost)

But these can be traded against each other. Examples:

- More expensive vehicles can navigate better ==> fewer vehicles needed
- Higher availability requires better navigation ==> more expensive vehicles, or more vehicles

Major Design Variables

Navigation-affecting design variables: For all, “better station-keeping” = “higher cost”

- Altitude Floor : *how low during normal operations*
- Altitude Ceiling : *how high*
- Speed of altitude variation : *how fast up and down*
- Amount of altitude variation / day : *how far down per day*
- Average (sustained) lateral speed : *how fast horizontally*

Important Performance Metrics

- TWR : time-within-range
  - How well vehicle can “station-keep” within a certain service distance?
- Availability vs Fleet-Size (Over-Provisioning)
  - How many extra balloons needed to hit specific availability? Includes blown-away + return time.
- And, of course: Cost

Architecture and Sizing Objective

Vehicle Design Objective: Minimum cost/month/footprint =

Cost per month to cover a specific spot of ground

= num_vehicles * vehicle_cost / vehicle_lifetime_months

How:

- We have built a full Hammerhead design parameter and sizing optimizer that optimizes for:
  - lowest cost / month / footprint
- We have spreadsheets and other tools for maximizing fleet-wide cost / GB

Valuing Altitude Range

Altitude Range Impacts

- Higher ceiling = much larger balloons = higher cost = slower horizontally, *but,*
- Higher ceiling = more wind directions to choose from = better altitude steering
- *Higher ceiling = better altitude steering but worse lateral steering*

Following slides are a small part of our analysis of min wind speed layers for several regions:

- Inputs: different locations, vehicle floor and ceiling
- Outputs: what is minimum wind speed, for different percentiles of time
  - Eg: At indicated speed, what percentage of time could we station-keep for that floor+ceiling+location?

How to Read

Red block covers our existing vehicles:

- v1.6 = upper left corner
- v1.4 = lower right corner

V1.3/vN1 assumed values:

- 15.3 to 21 km (50.2 to 69 kft)
- 11,500 to 4,700 Pa (115 to 47 hPa)

v1.4 assumed values:

- 15.8km to 20km (50.8 to 65.6kft)
- 10,700 to 5,500 Pa

Blue box is raising ceiling to

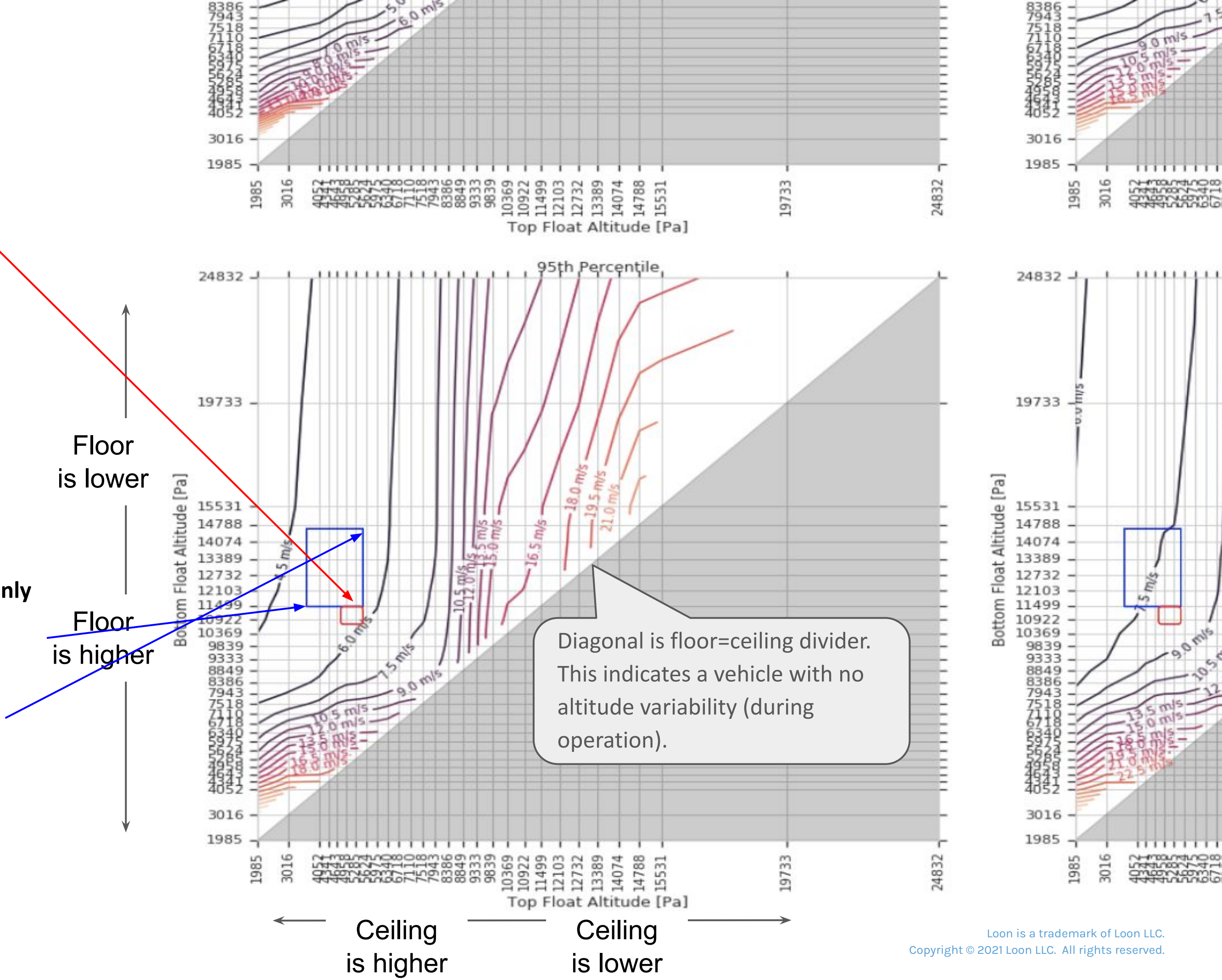
- 22.9km (75kft) = 3,500 Pa (mv left)

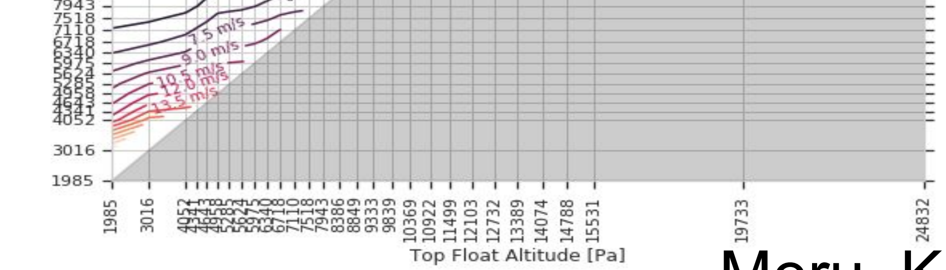
and lowering floor down (to

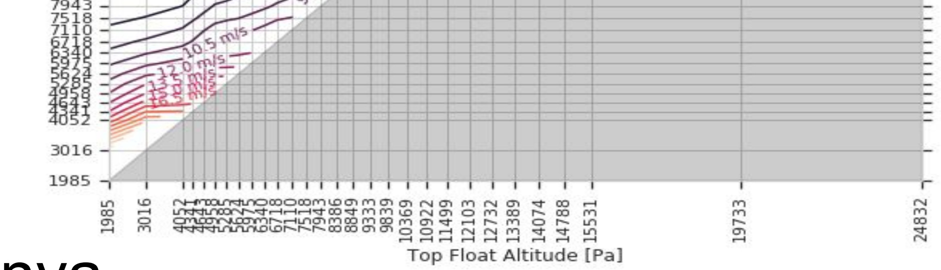
- 13.7km (45kft) = 14,700 Pa (move up)

So,

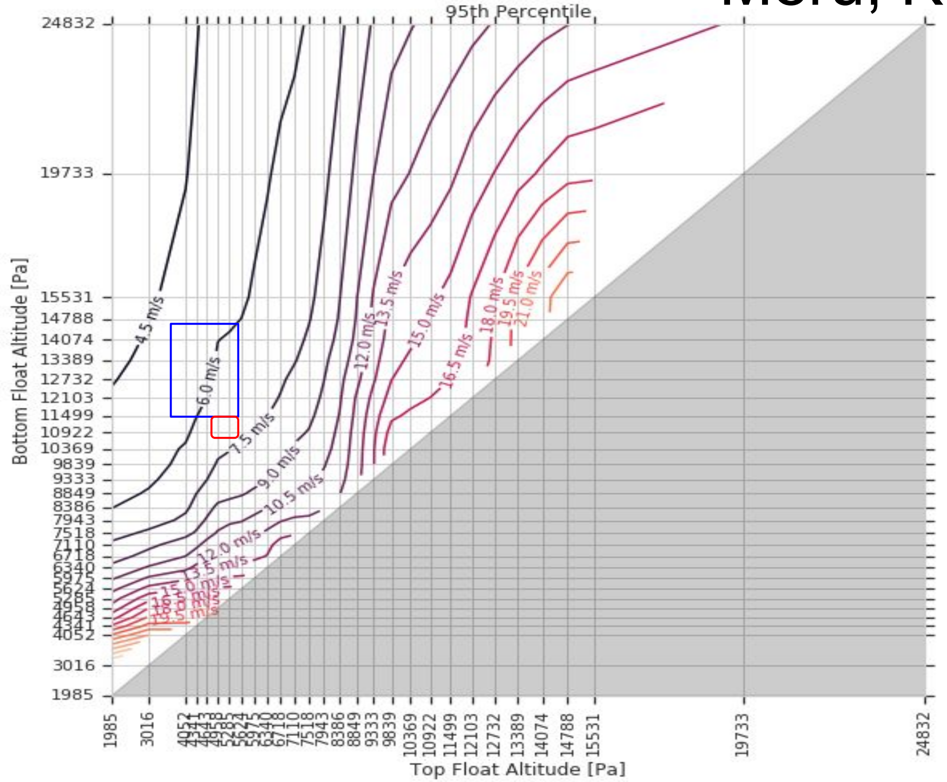
- **Lower left of Blue box is ceiling raise only vs v1.6 (most possible)**
- Upper right is floor drop only (vs v1.4)
- Upper left corner is both extensions

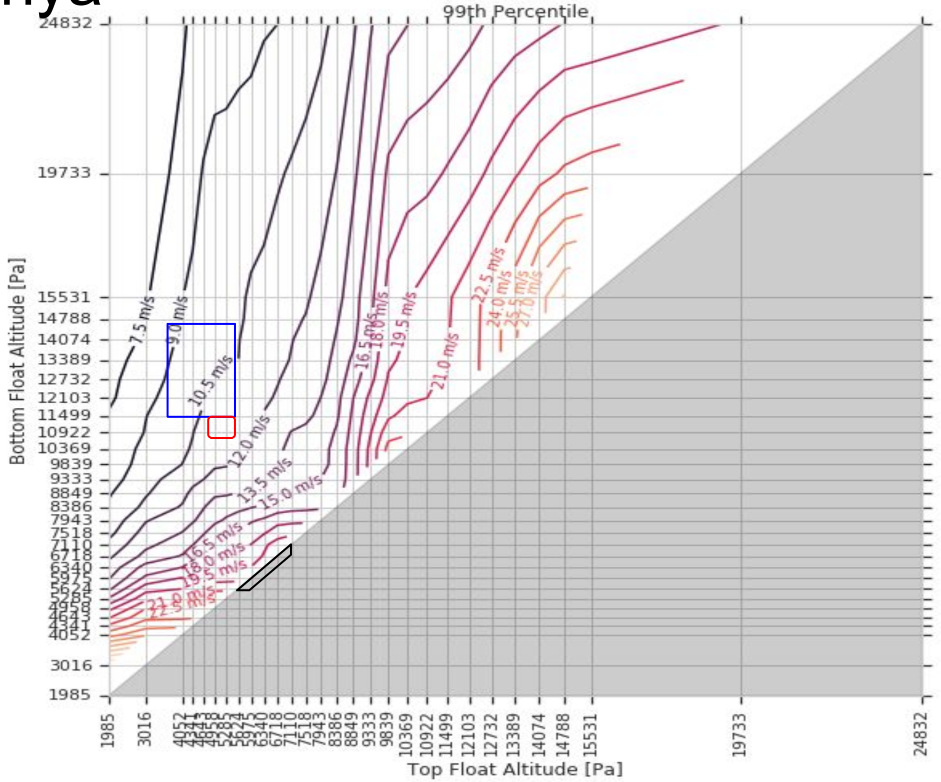


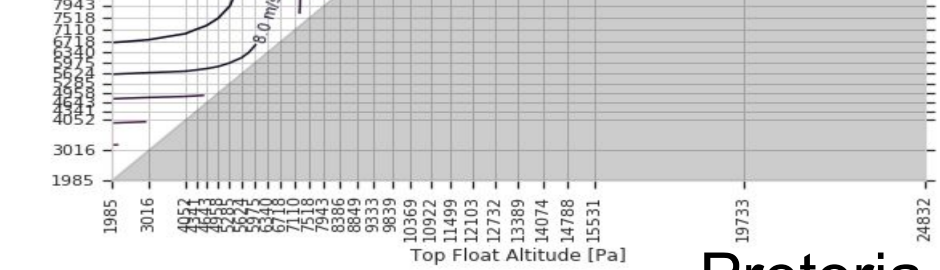

Top Float Altitude [Pa]

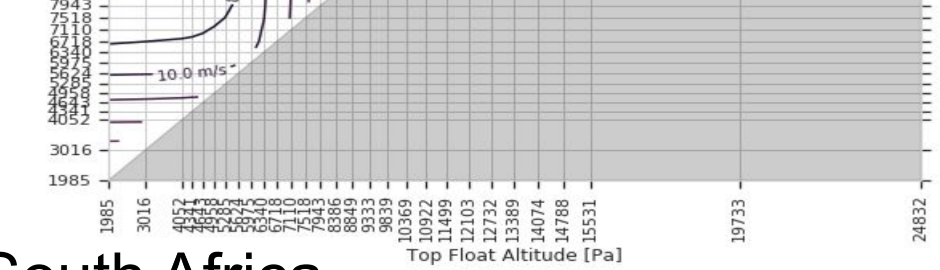

Top Float Altitude [Pa]

Meru, Kenya

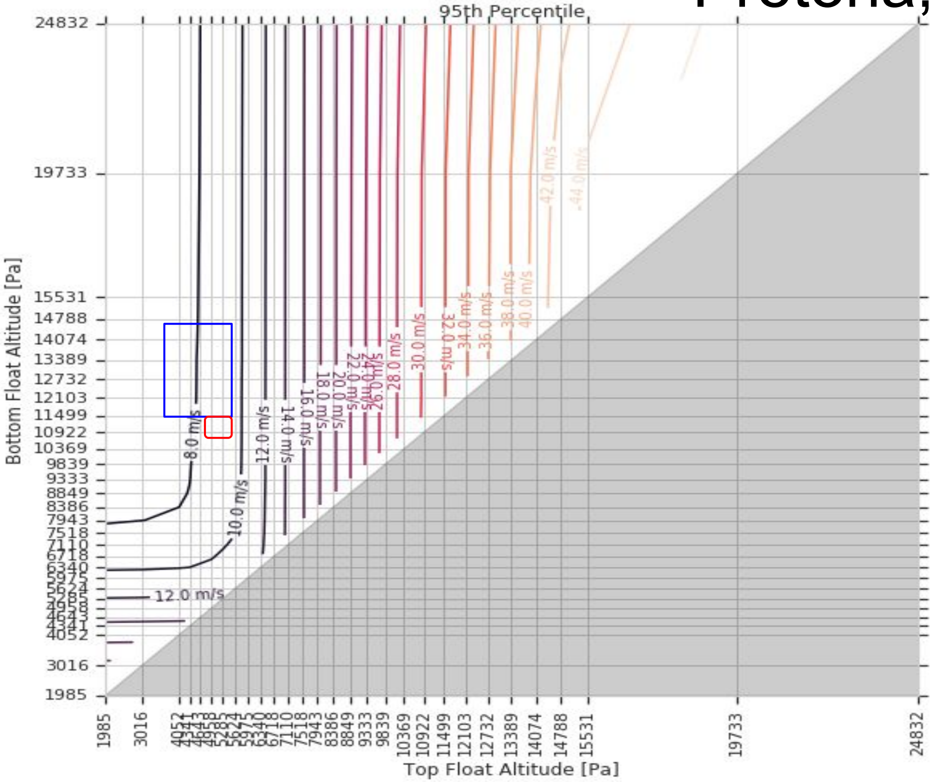

95th Percentile
Bottom Float Altitude [Pa]
Top Float Altitude [Pa]
4.5 m/s
6.0 m/s
7.5 m/s
9.0 m/s
10.5 m/s
12.0 m/s
13.5 m/s
15.0 m/s
16.5 m/s
18.0 m/s
19.5 m/s
21.0 m/s

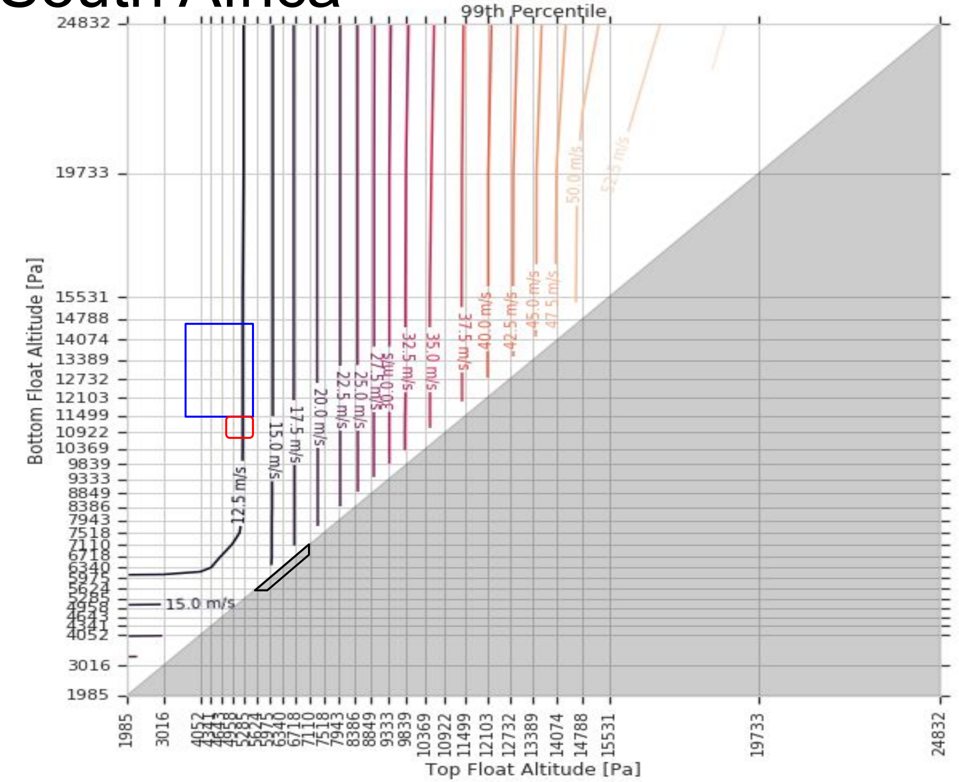

99th Percentile
Bottom Float Altitude [Pa]
Top Float Altitude [Pa]
7.5 m/s
9.0 m/s
10.5 m/s
12.0 m/s
13.5 m/s
15.0 m/s
16.5 m/s
18.0 m/s
19.5 m/s
21.0 m/s
22.5 m/s
24.0 m/s
25.5 m/s
27.0 m/s

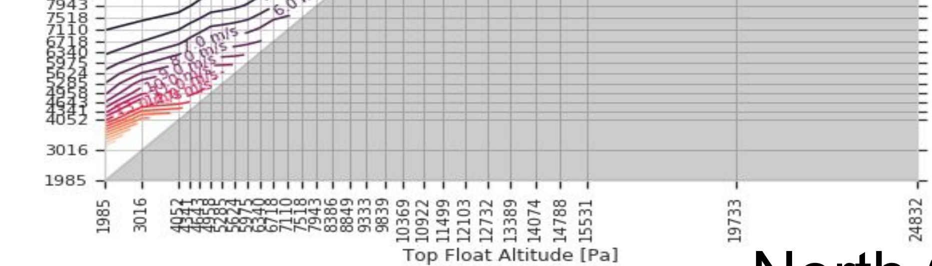


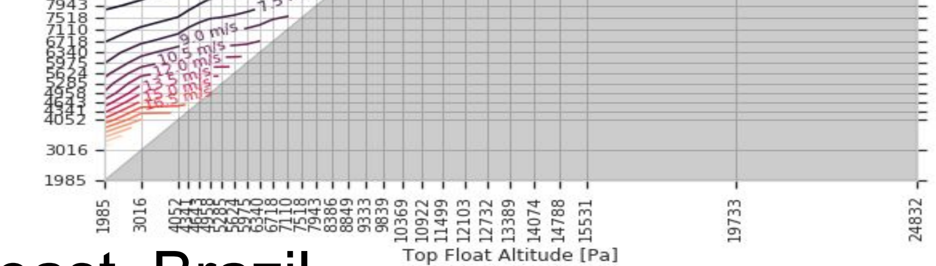


Pretoria, South Africa

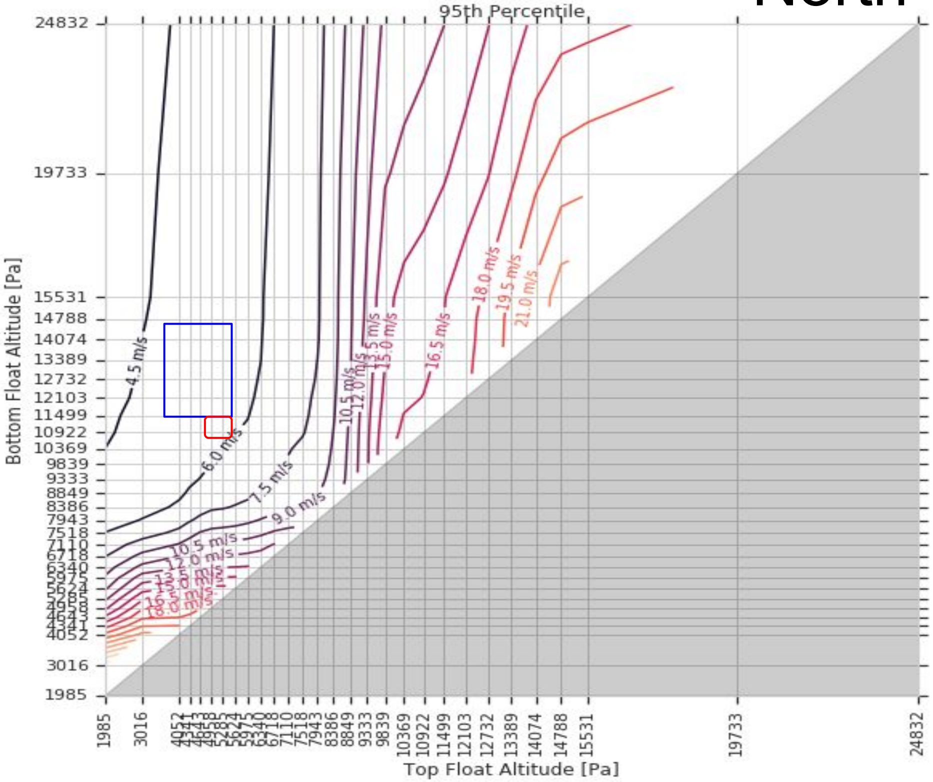


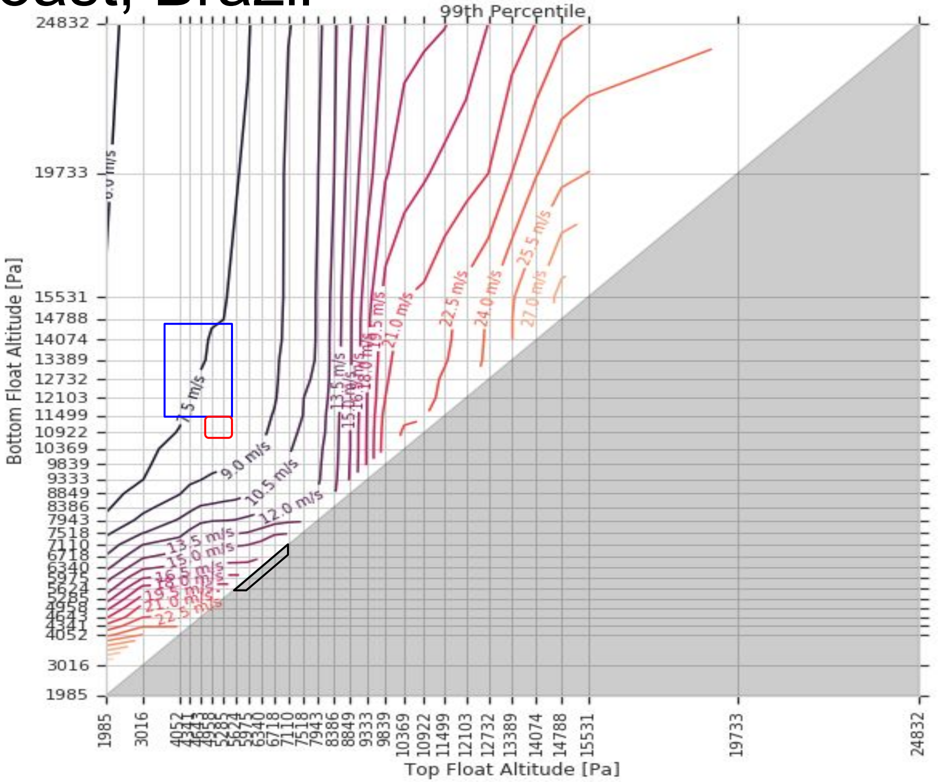


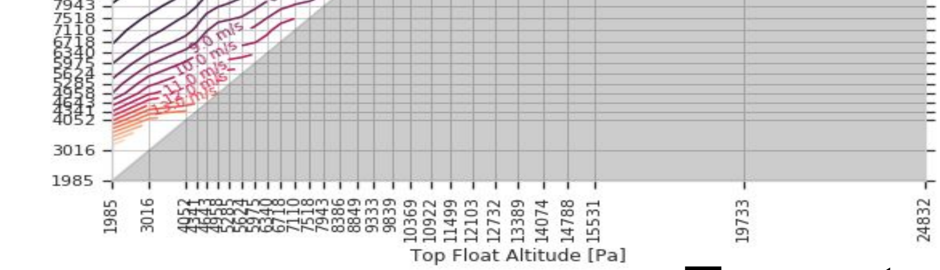


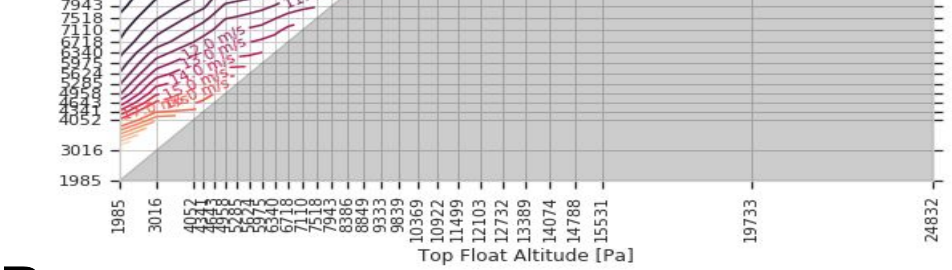


North Coast, Brazil

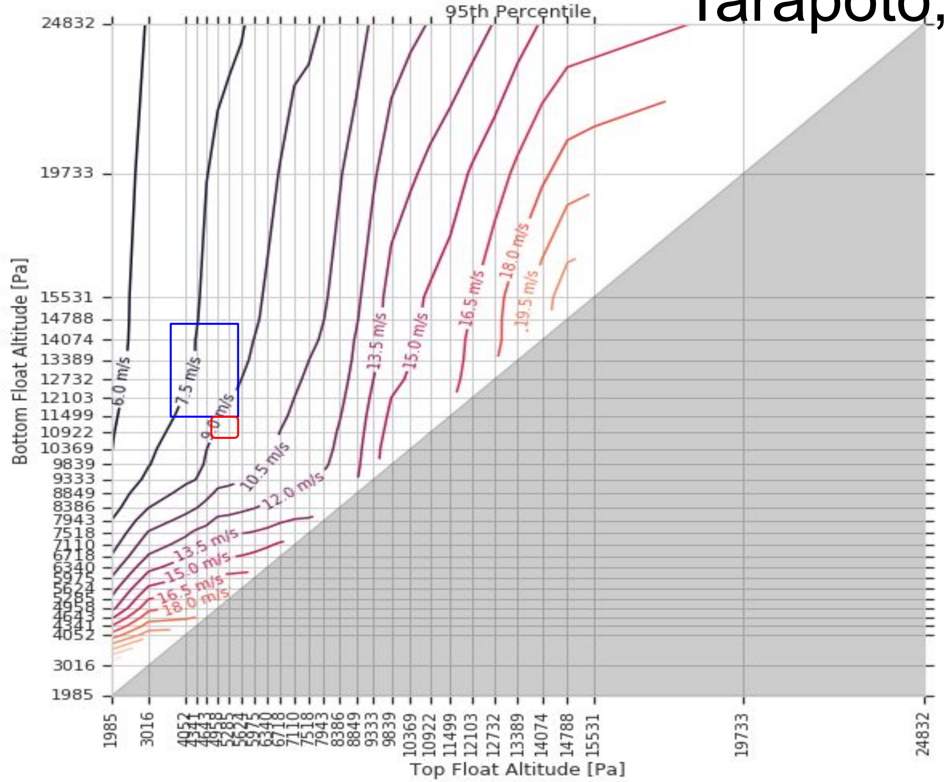


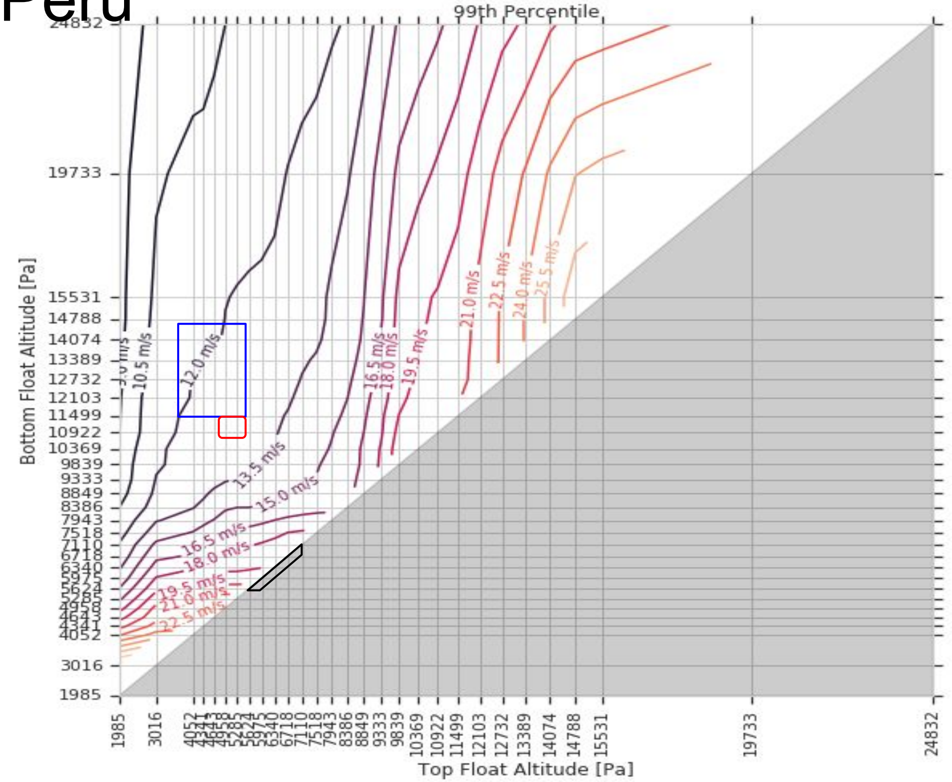


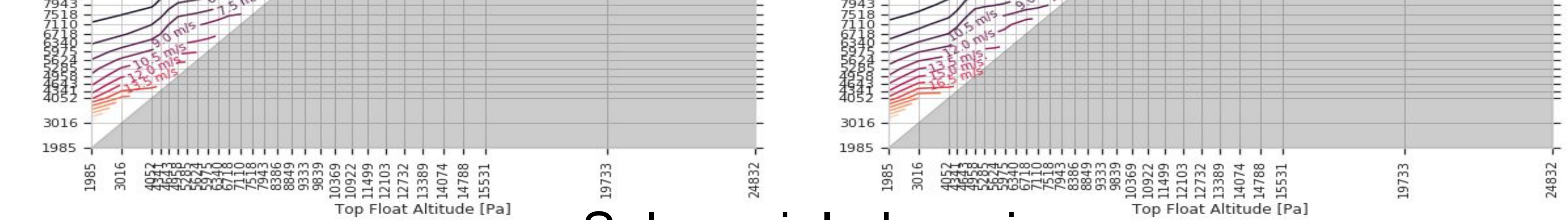




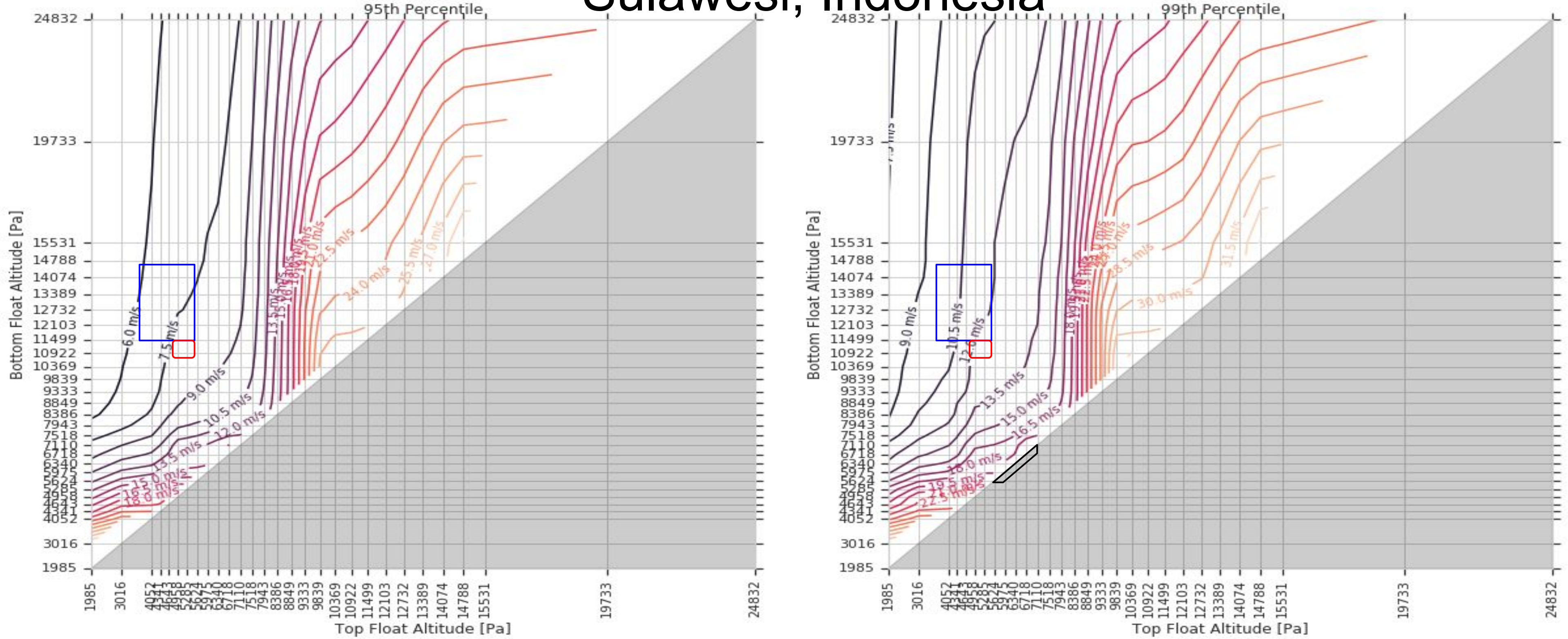
Tarapoto, Peru

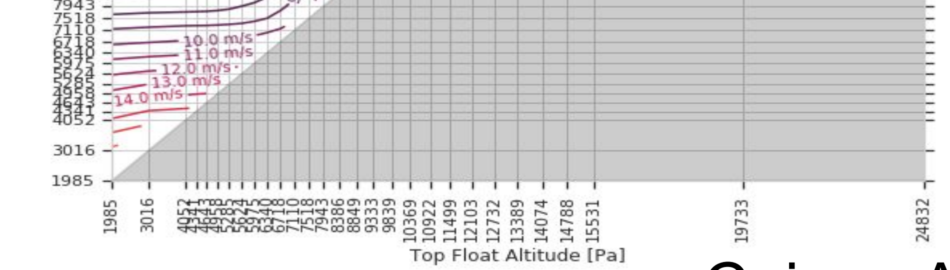


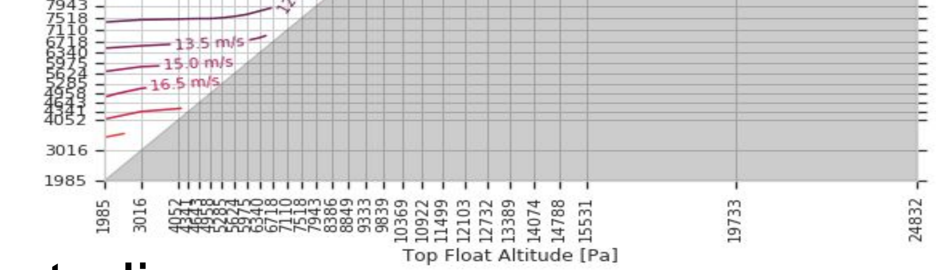




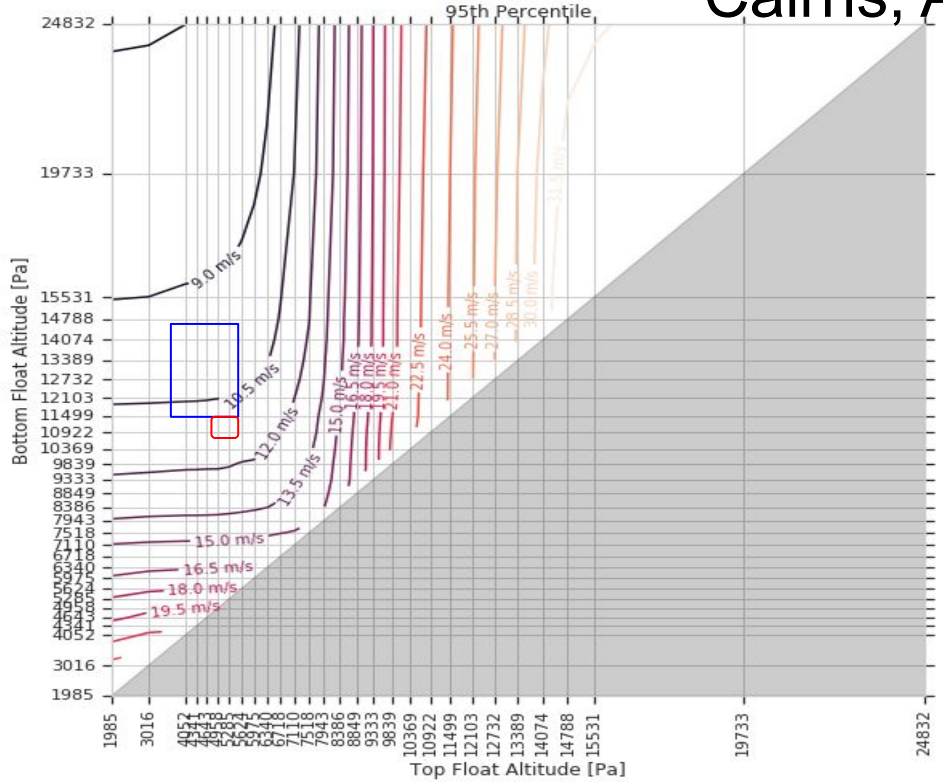
Sulawesi, Indonesia

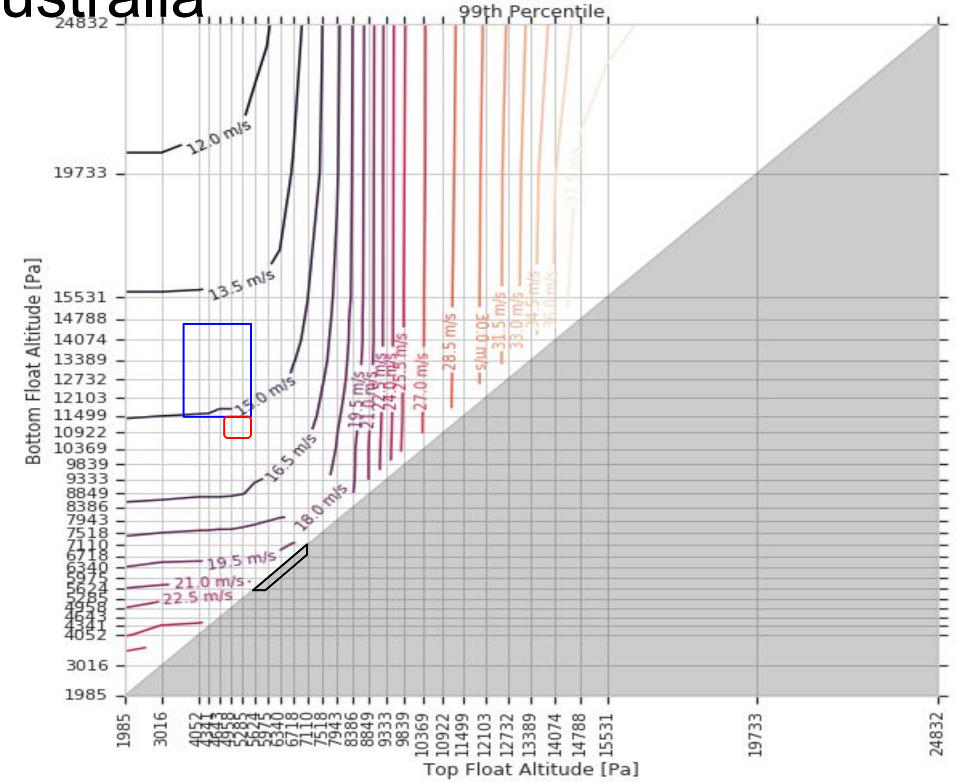


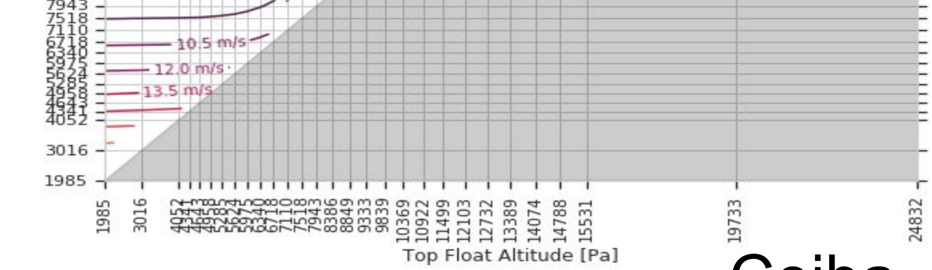


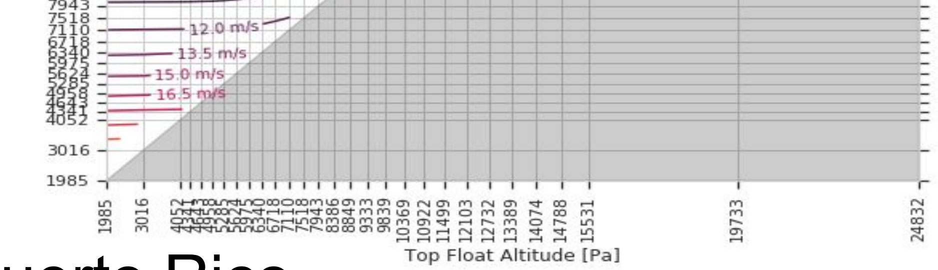


Cairns, Australia

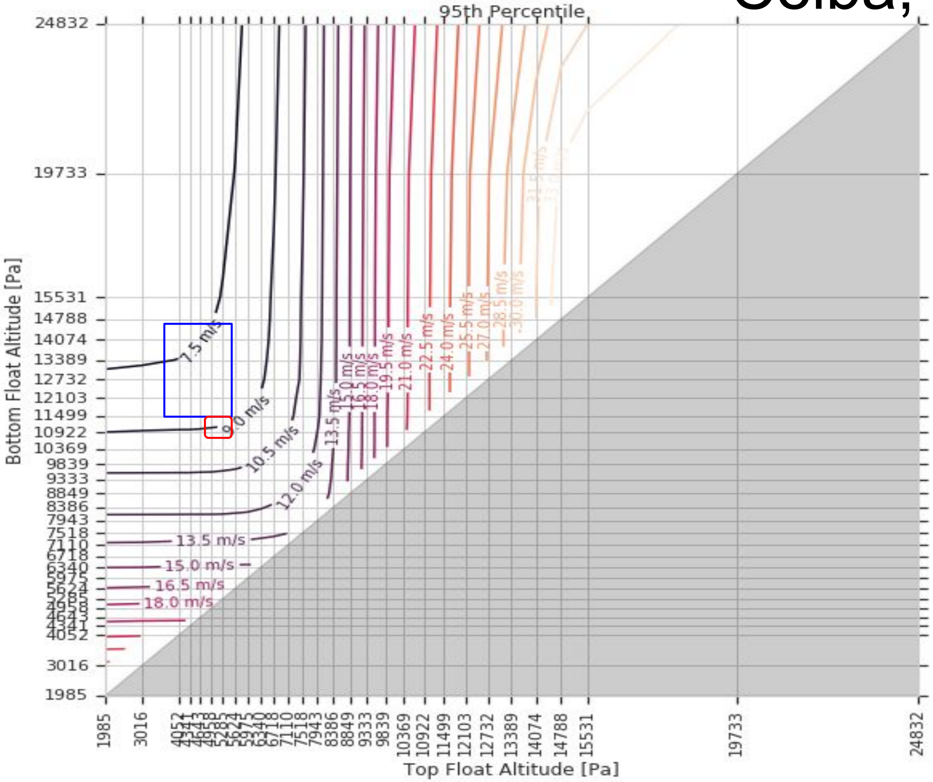


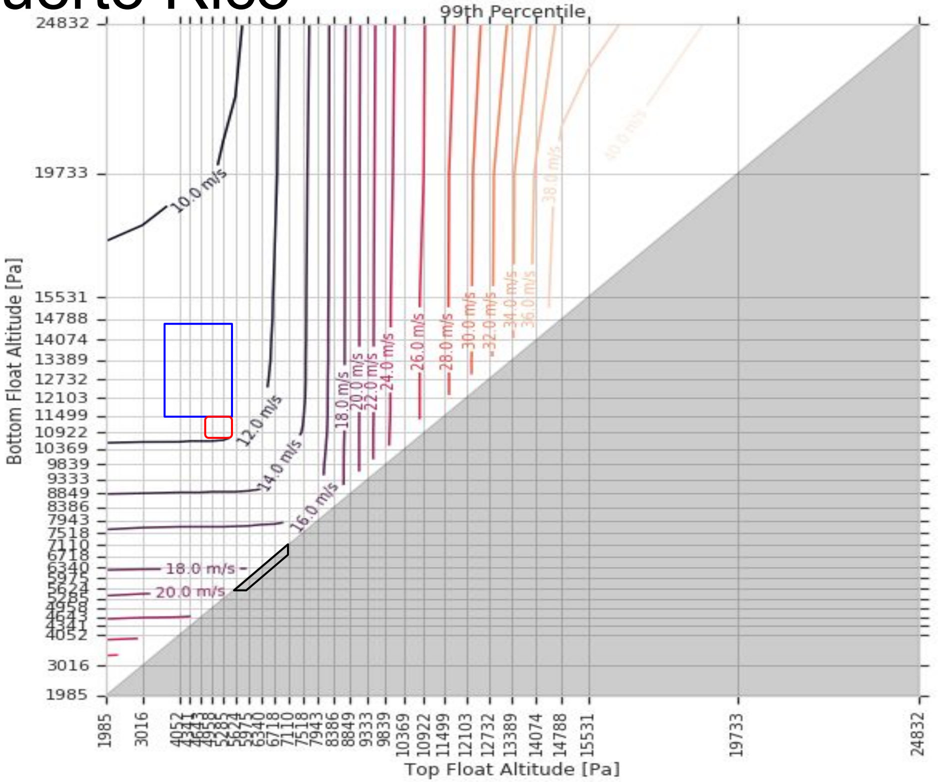


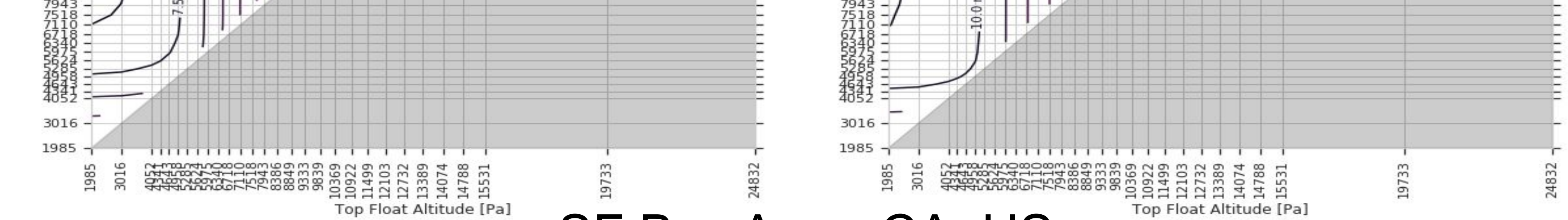




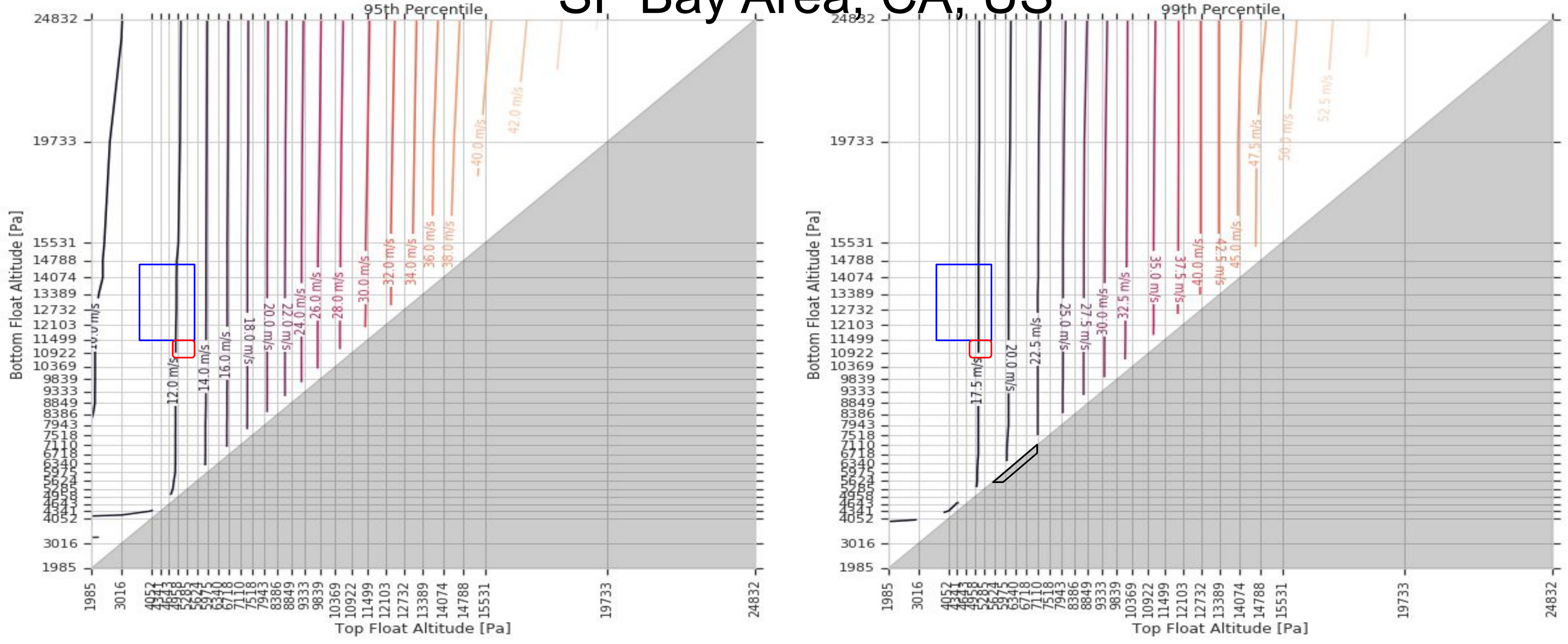
Ceiba, Puerto Rico







SF Bay Area, CA, US



MinWind Analysis

Conclusions

- High variability of required lateral speed across regions
- High variability of required lateral speed across altitude ranges
- Assuming medium altitude range of vehicle:
  - Africa, South America, tropics
    - “OK” availability: ~2-5 m/s
    - “Good” availability: ~5-8 m/s
    - “Excellent” availability: ~8-12 m/s
  - Australia
    - “OK” availability: ~6 m/s
    - “Good” availability: ~10 m/s
    - “Excellent” availability: ~15 m/s

- We will *not* need ~25 m/s (common for HAPS/HALE vehicles) to reach Excellent availability
  - Flexible altitude range vehicle can save large cost

Lateral Propulsion

Lateral Propulsion Impact

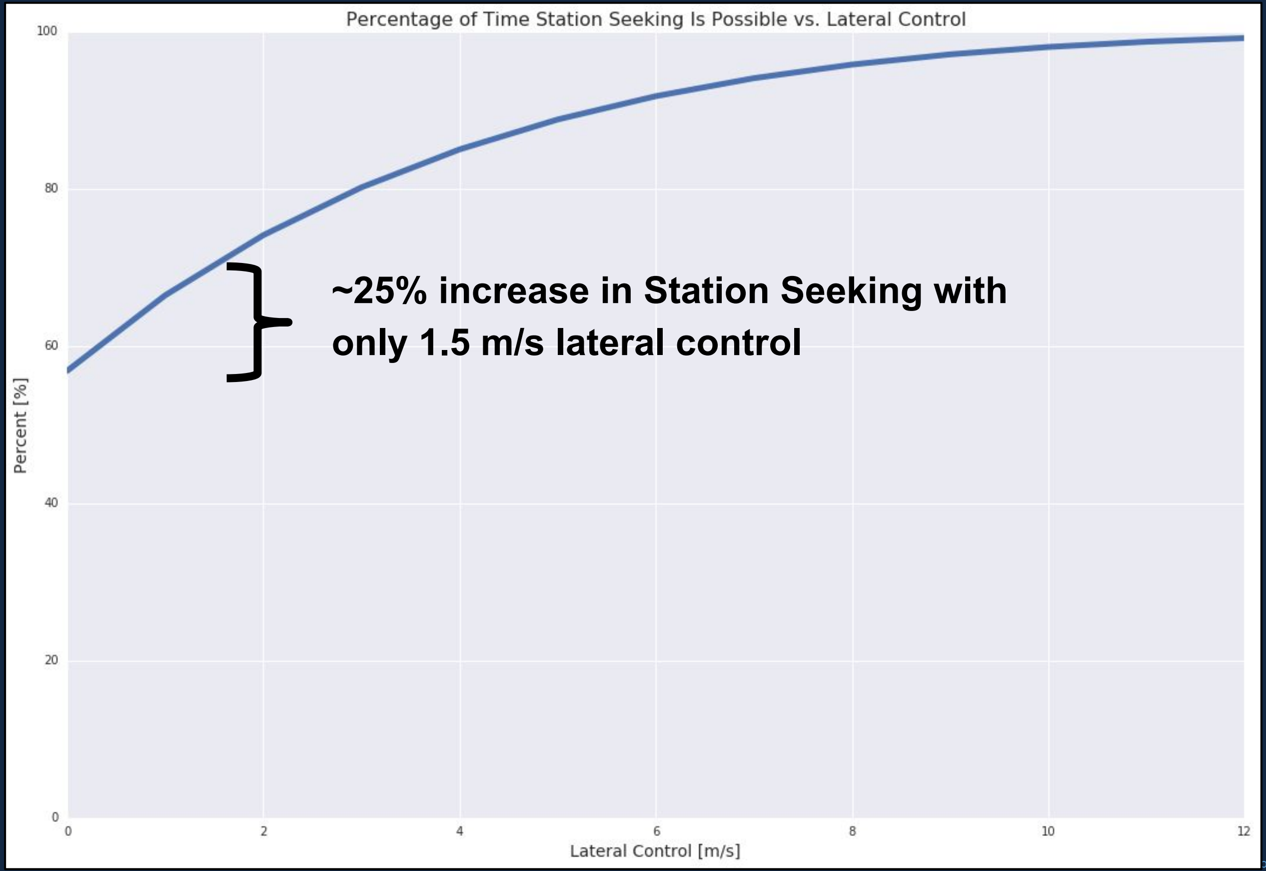
Two primary types of navigation:

- Station-Seeking
  - Balloon stays close to target
- Fly-Around
  - Balloon gets blown away from target but flies around loop to get back to target

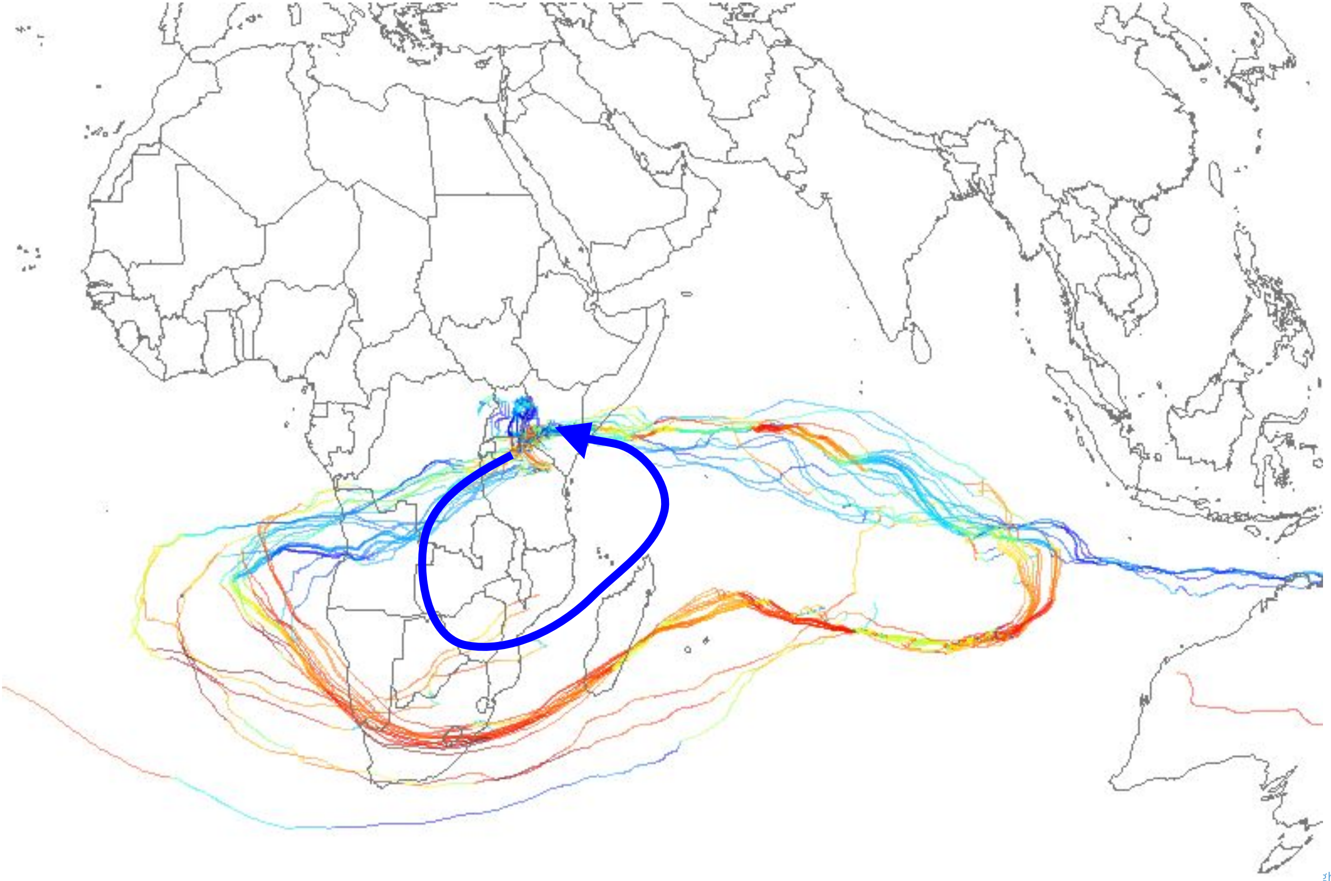
Improving lateral propulsion improves both:

- Station-Seeking
  - Better able to stay closer to target, higher percentage of time
- Fly-Around
  - Can get back to target more quickly

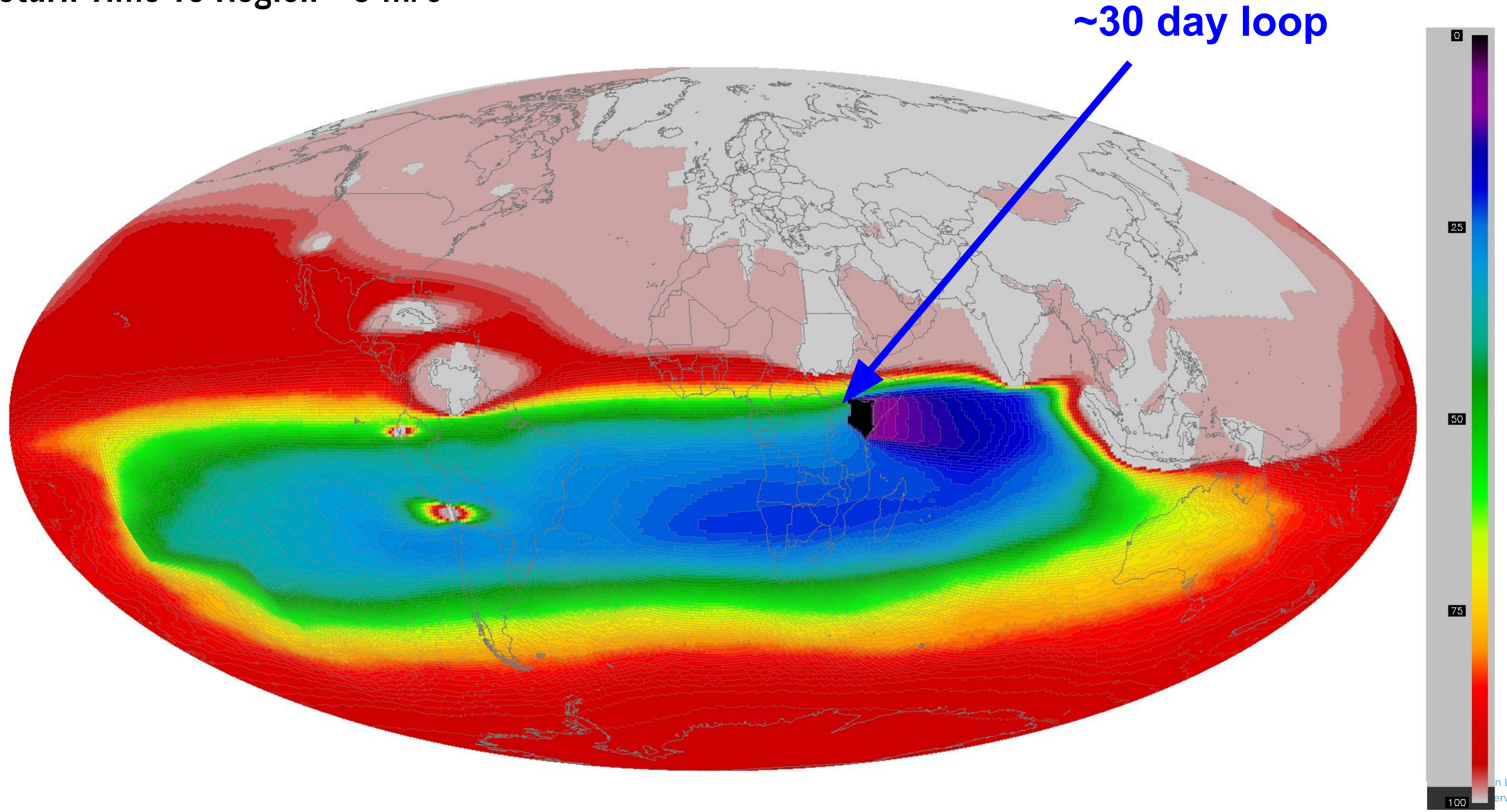
Station Seeking vs. Lateral Control



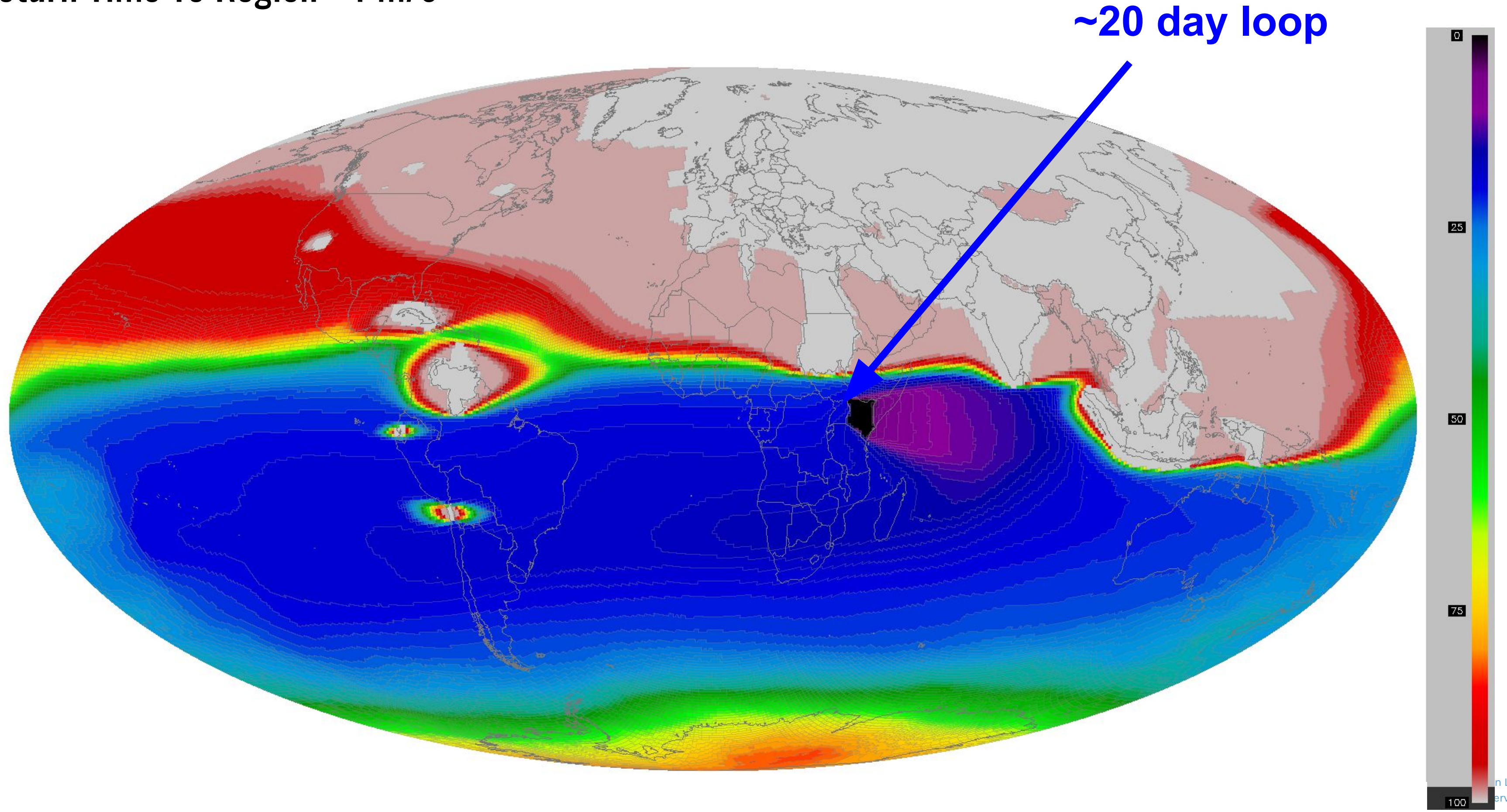
Faster Return Time To Region



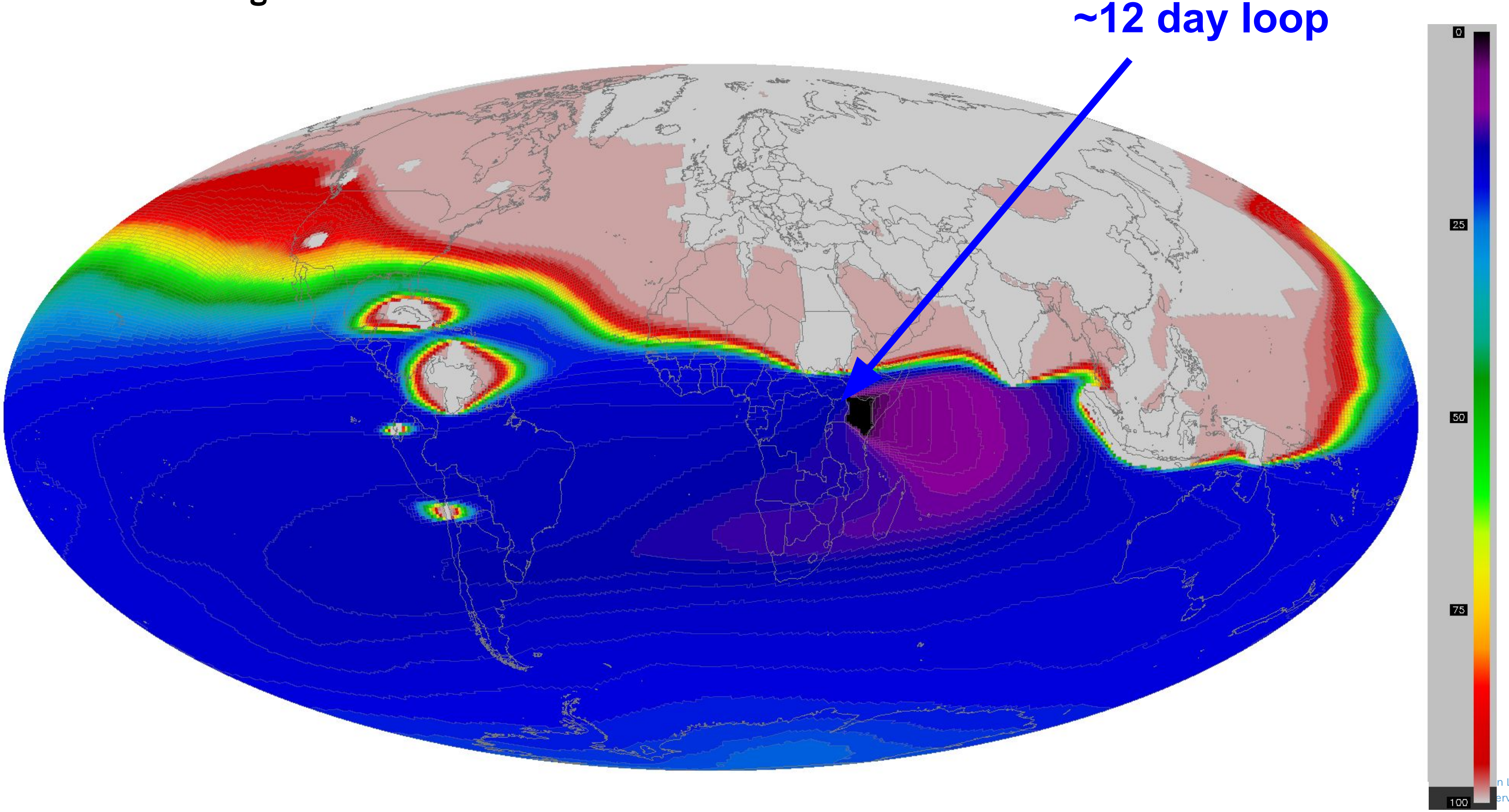
Return Time To Region - 0 m/s



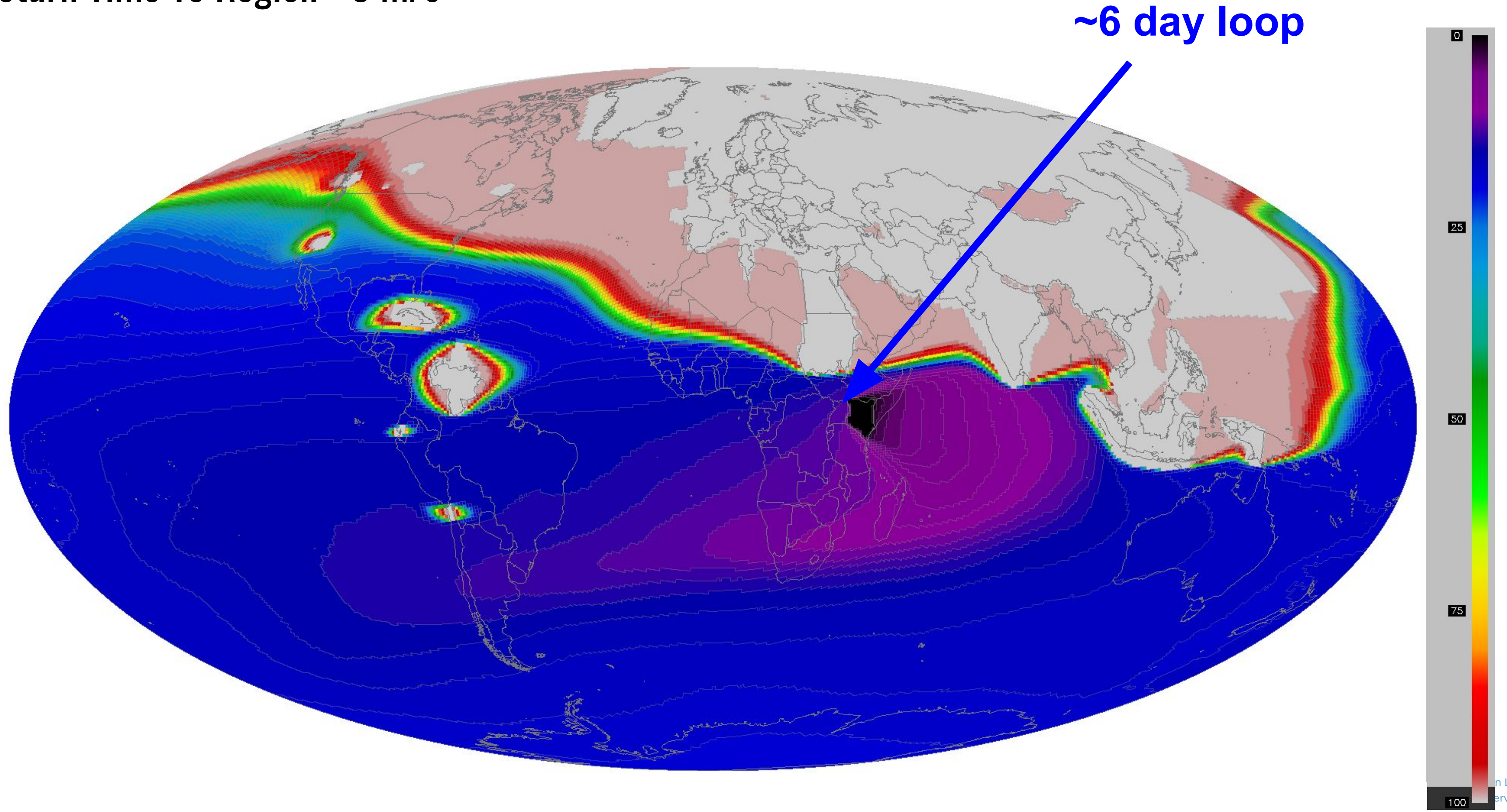
Return Time To Region - 1 m/s



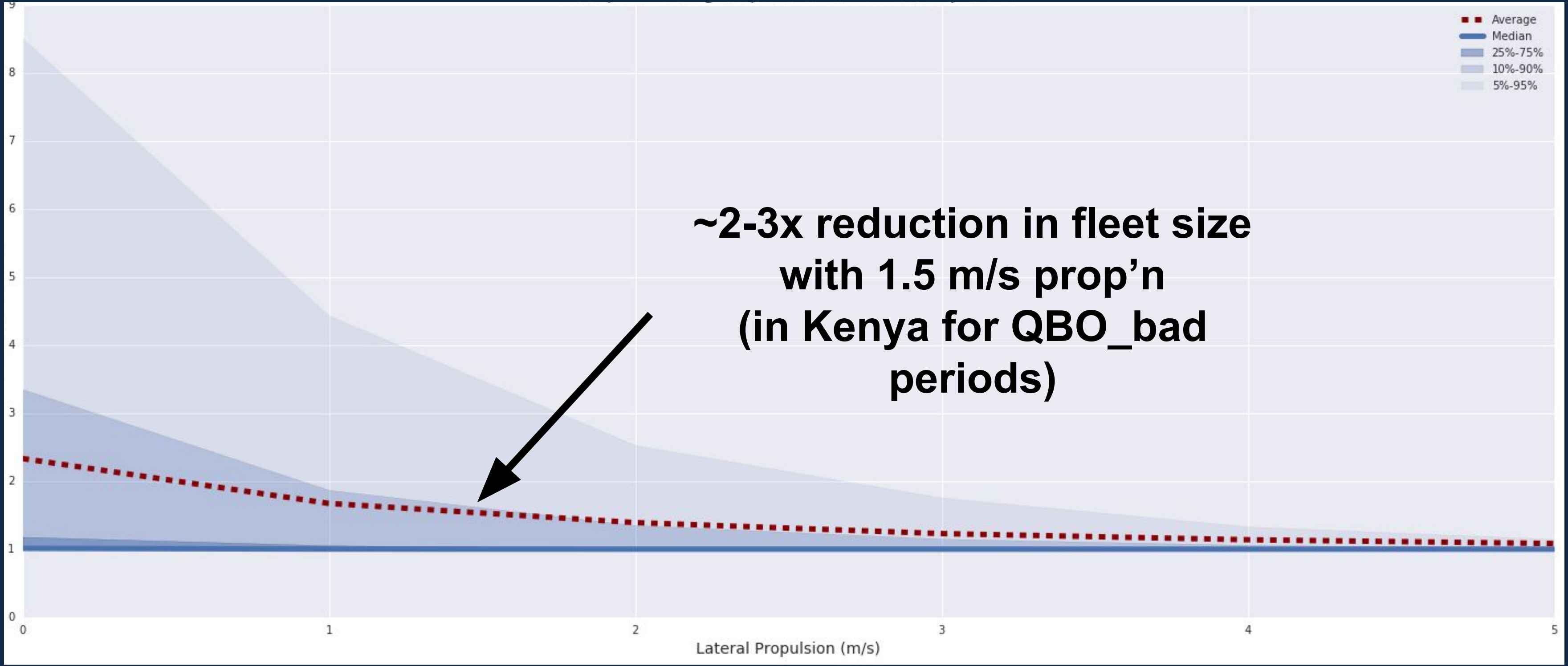
Return Time To Region - 2 m/s



Return Time To Region - 3 m/s



Reduced Fly-Around Time (vs Time in service region)

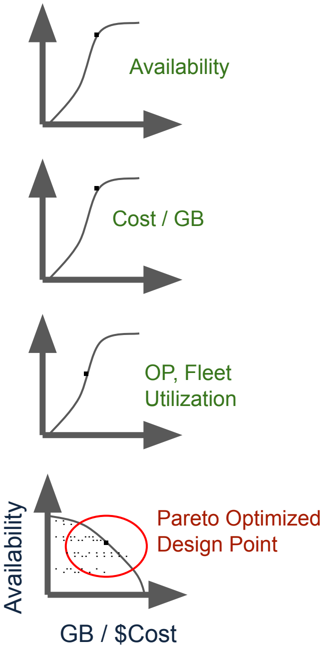


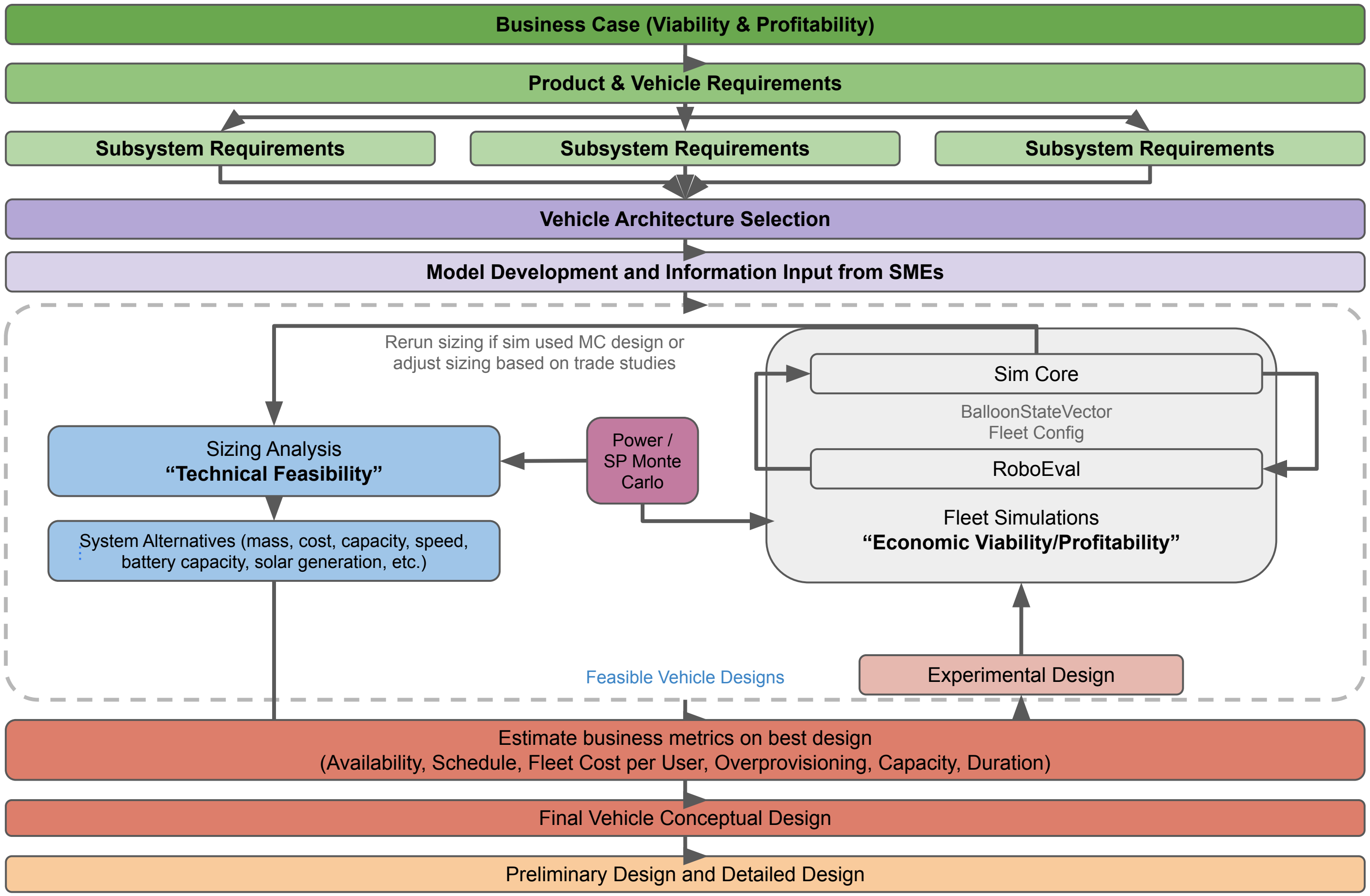
Hammerhead Design Process

SysE

Process Overview

Some Top Level Metrics:





Sizing

Roadmap | PRD Review and Agreement | **Conceptual Design** | Preliminary Design | Detailed Design & Testing and Verification | Production & Operations

Vehicle sizing optimizes the many design parameters of the vehicle and estimates cost and performance.

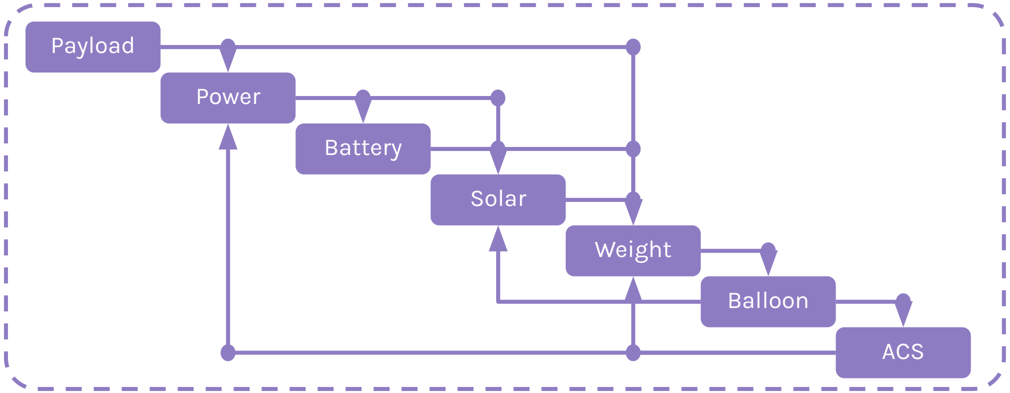
Sizing tool is organized into modules. A module contains all relevant equations/data to estimate the size of a particular subsystem. (e.g. the battery module estimates all parameters relevant to batteries)

The tool uses modules to construct a nonlinear system of equations with inequalities

- Inequalities represent constraints that must be met

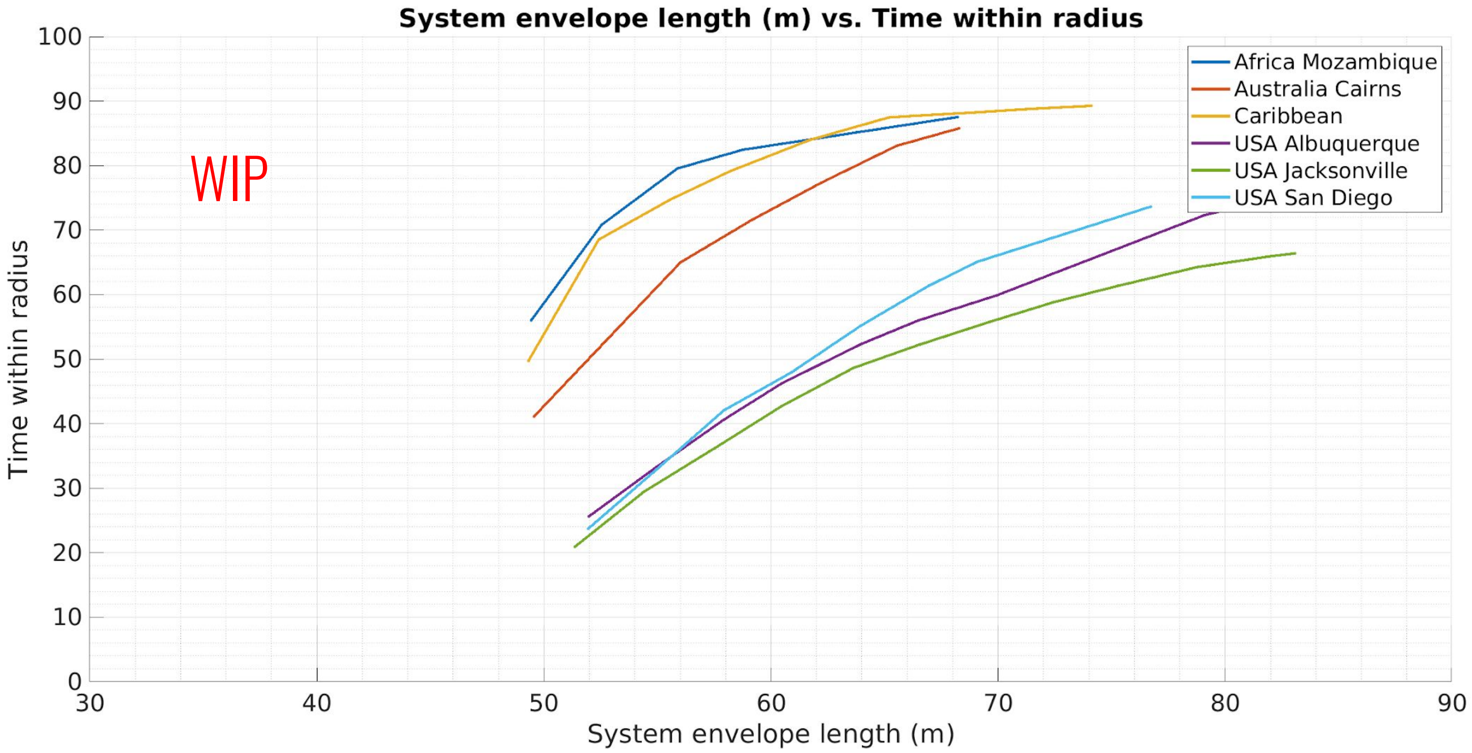
Sizing tool iterates to converge on a vehicle design:

- Iterates to meet inequality constraints
- Iterates to minimize user-defined objective function (e.g. max altitude, lateral speed, etc.)

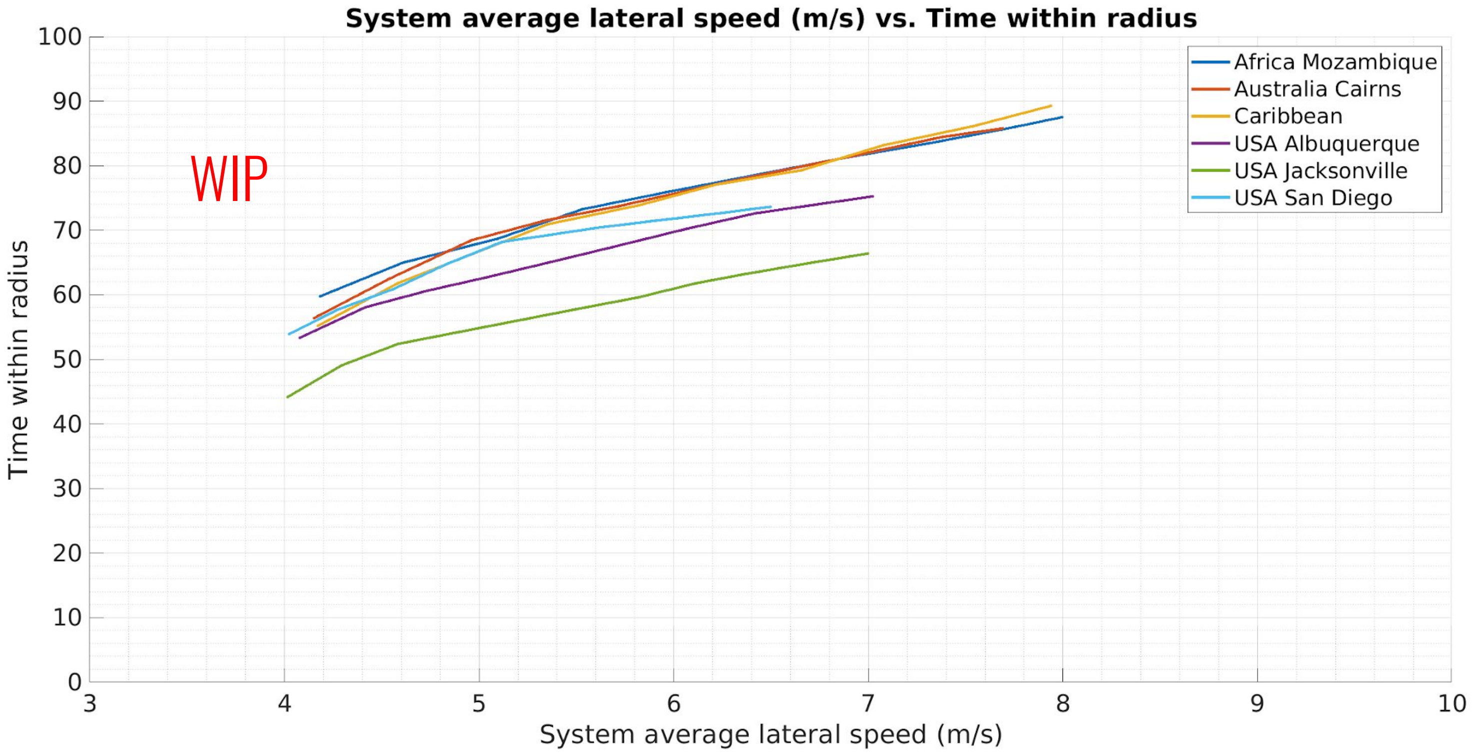


Sizing Environment

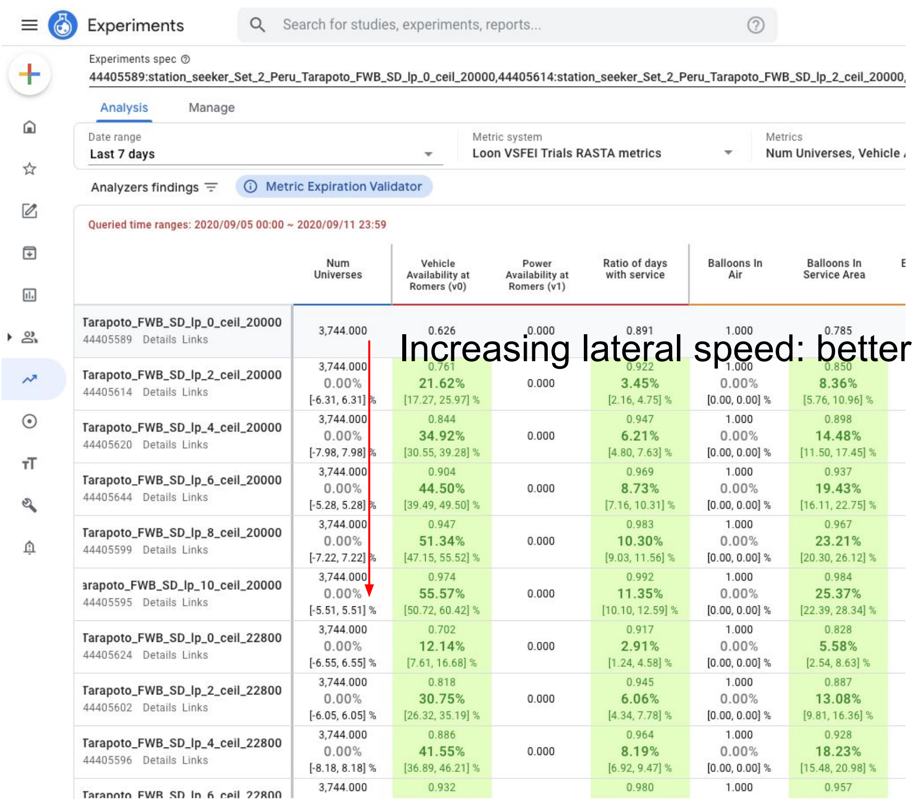
Tradespace Exploration - Envelope Length (Comms ‘a’) - Updated - 4/28/2020



Tradespace Exploration - Speed (Comms ‘a’) - Updated 4/28/2020



Example Analysis Outputs



	Num Universes	Vehicle Availability at Romers (v0)	Power Availability at Romers (v1)	Ratio of days with service	Balloons In Air	Balloons In Service Area
Tarapoto_FWB_SD_lp_0_ceil_20000 44405589 Details Links	3,744.000	0.626	0.000	0.891	1.000	0.785
Tarapoto_FWB_SD_lp_2_ceil_20000 44405614 Details Links	3,744.000 0.00% [-6.31, 6.31] %	0.761 21.62% [17.27, 25.97] %	0.000	0.922 3.45% [2.16, 4.75] %	1.000 0.00% [0.00, 0.00] %	0.850 8.36% [5.76, 10.96] %
Tarapoto_FWB_SD_lp_4_ceil_20000 44405620 Details Links	3,744.000 0.00% [-7.98, 7.98] %	0.844 34.92% [30.55, 39.28] %	0.000	0.947 6.21% [4.80, 7.63] %	1.000 0.00% [0.00, 0.00] %	0.898 14.48% [11.50, 17.45] %
Tarapoto_FWB_SD_lp_6_ceil_20000 44405644 Details Links	3,744.000 0.00% [-5.28, 5.28] %	0.904 44.50% [39.49, 49.50] %	0.000	0.969 8.73% [7.16, 10.31] %	1.000 0.00% [0.00, 0.00] %	0.937 19.43% [16.11, 22.75] %
Tarapoto_FWB_SD_lp_8_ceil_20000 44405599 Details Links	3,744.000 0.00% [-7.22, 7.22] %	0.947 51.34% [47.15, 55.52] %	0.000	0.983 10.30% [9.03, 11.56] %	1.000 0.00% [0.00, 0.00] %	0.967 23.21% [20.30, 26.12] %
arapoto_FWB_SD_lp_10_ceil_20000 44405595 Details Links	3,744.000 0.00% [-5.51, 5.51] %	0.974 55.57% [50.72, 60.42] %	0.000	0.992 11.35% [10.10, 12.59] %	1.000 0.00% [0.00, 0.00] %	0.984 25.37% [22.39, 28.34] %
Tarapoto_FWB_SD_lp_0_ceil_22800 44405624 Details Links	3,744.000 0.00% [-6.55, 6.55] %	0.702 12.14% [7.61, 16.68] %	0.000	0.917 2.91% [1.24, 4.58] %	1.000 0.00% [0.00, 0.00] %	0.828 5.58% [2.54, 8.63] %
Tarapoto_FWB_SD_lp_2_ceil_22800 44405602 Details Links	3,744.000 0.00% [-6.05, 6.05] %	0.818 30.75% [26.32, 35.19] %	0.000	0.945 6.06% [4.34, 7.78] %	1.000 0.00% [0.00, 0.00] %	0.887 13.08% [9.81, 16.36] %
Tarapoto_FWB_SD_lp_4_ceil_22800 44405596 Details Links	3,744.000 0.00% [-8.18, 8.18] %	0.886 41.55% [36.89, 46.21] %	0.000	0.964 8.19% [6.92, 9.47] %	1.000 0.00% [0.00, 0.00] %	0.928 18.23% [15.48, 20.98] %
Tarapoto_FWB_SD_lp_6_ceil_22800	3,744.000	0.932		0.980	1.000	0.957

Hammerhead Design - Conclusions

Tools and Process

- We've built tools to simulate, analyze and optimize future flight systems.
- With these, we can forecast the nominal and rare performance of these vehicles for all of-interest markets around the world
- We are narrowing down the size and capabilities of each evolution of Hammerhead, starting with the prototypes, then first commercial vehicle, then even higher performance variants following.

Current Expectation

- Initial prototype vehicle sizing works for our current markets (tropical, Africa, Central+South America).
- First commercial vehicle extends beyond current markets.
- Subsequent vehicles can reach high revenue markets with higher winds.