Investigating the Feasibility of Obtaining RO Measurements of a Meteorological Phenomena Using Loon Balloons

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Study Objectives

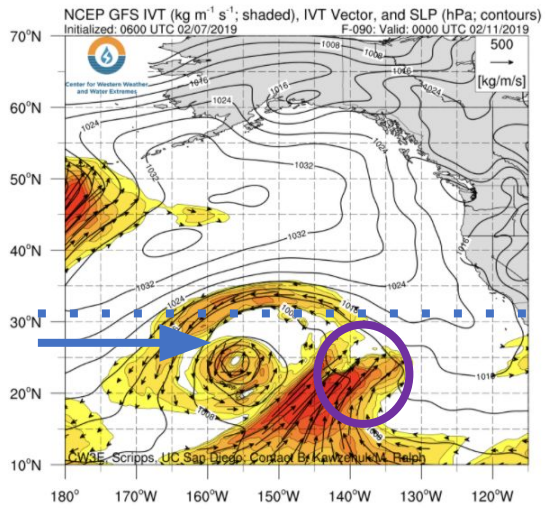
- Simulate the coverage of observations that would be produced if commercial Loon balloons were equipped with radio occultation (RO) profiling capability.
- Investigate the capability of the balloon to log necessary fields for RO profiling of the atmosphere.
- This study focuses on 2 cases:
  - Atmospheric River in the northeastern Pacific
    - Simulate an increase in the spatial and temporal extent of observations to improve precipitation forecasts for flooding and water resource management in the western US
  - Moist convection in the deep tropics (Kenya)
    - Exploratory study from a flight of opportunity over equatorial eastern Africa

Loon, LLC

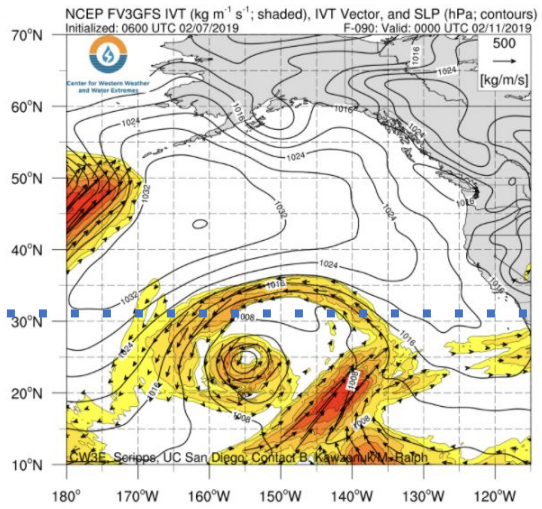
- Loon is a stratospheric balloon company that provided internet connectivity to people in areas without robust ground communication infrastructure.
- The balloons utilize a Global Navigation Satellite System (GNSS) receiver to navigate during flights, and AI algorithms to adjust altitude to maneuver with favorable winds.
- The longest recorded flight for a single balloon was 312 days in the stratosphere and the most balloons in the air at one time was 35 providing service to Kenya.
- However, the commercial enterprise was not sustainable and the difficult decision to cease operations was made in early 2021.

Mid-latitude AR Forecast Uncertainty

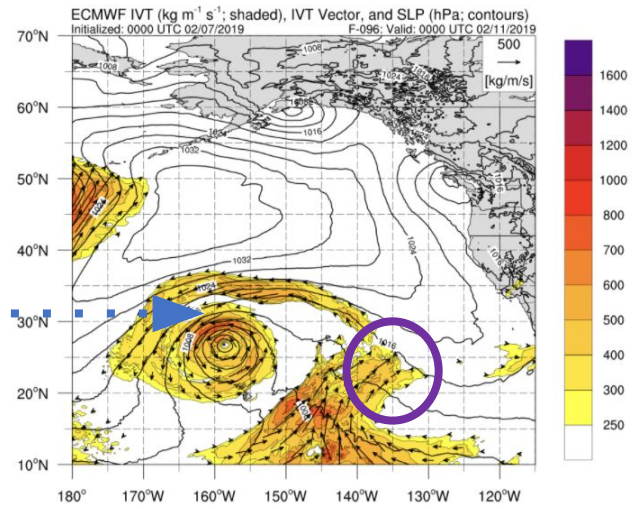
GFS



FV3



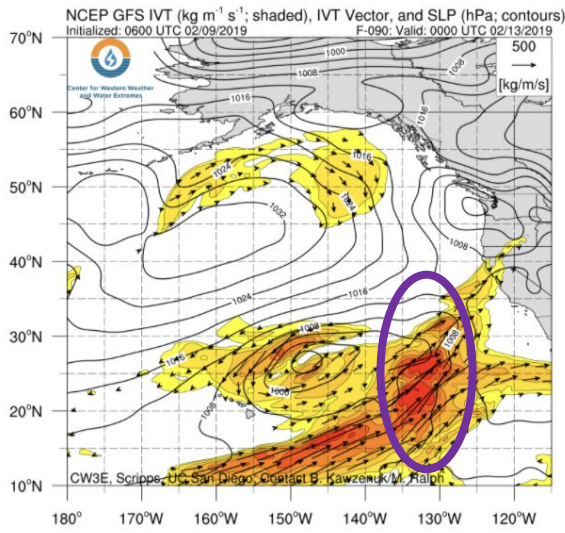
ECMWF



- Comparison of 4-day forecast (initialized 7 Feb) valid at 00Z 11 Feb 2019.
- Decent agreement between models, but with a difference in IVT values.
  - Suggests different days for when the AR will make landfall.
  - Potentially different intensity at landfall.
- GFS shows larger IVT values, GFS FV3 moderate strength, and ECMWF shows weaker IVT
- GFS location of cutoff Kona low is further south

- Comparison of 4-day forecast (init 6Z 9 Feb) valid at 00Z 13 Feb 2019.
- Decent agreement between the models, however higher IVT values for the ECMWF.
- AR had a high impact on Southern California, heavy rainfall on Feb. 14 2019.

GFS



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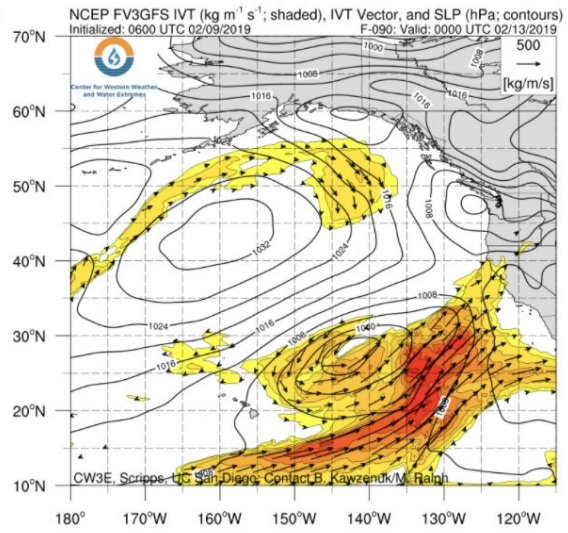

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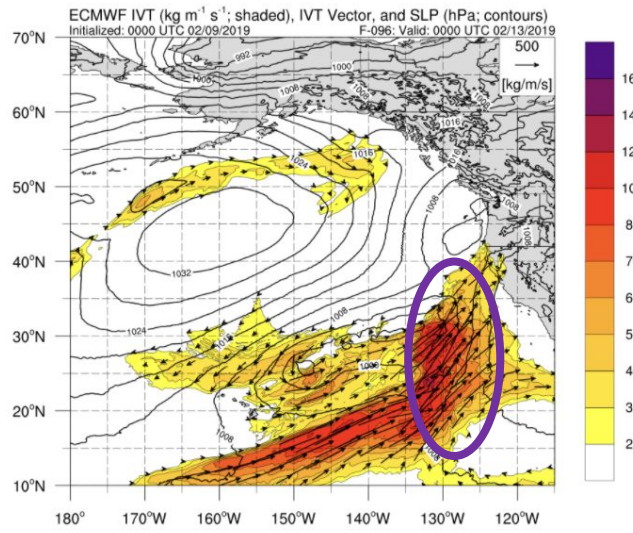
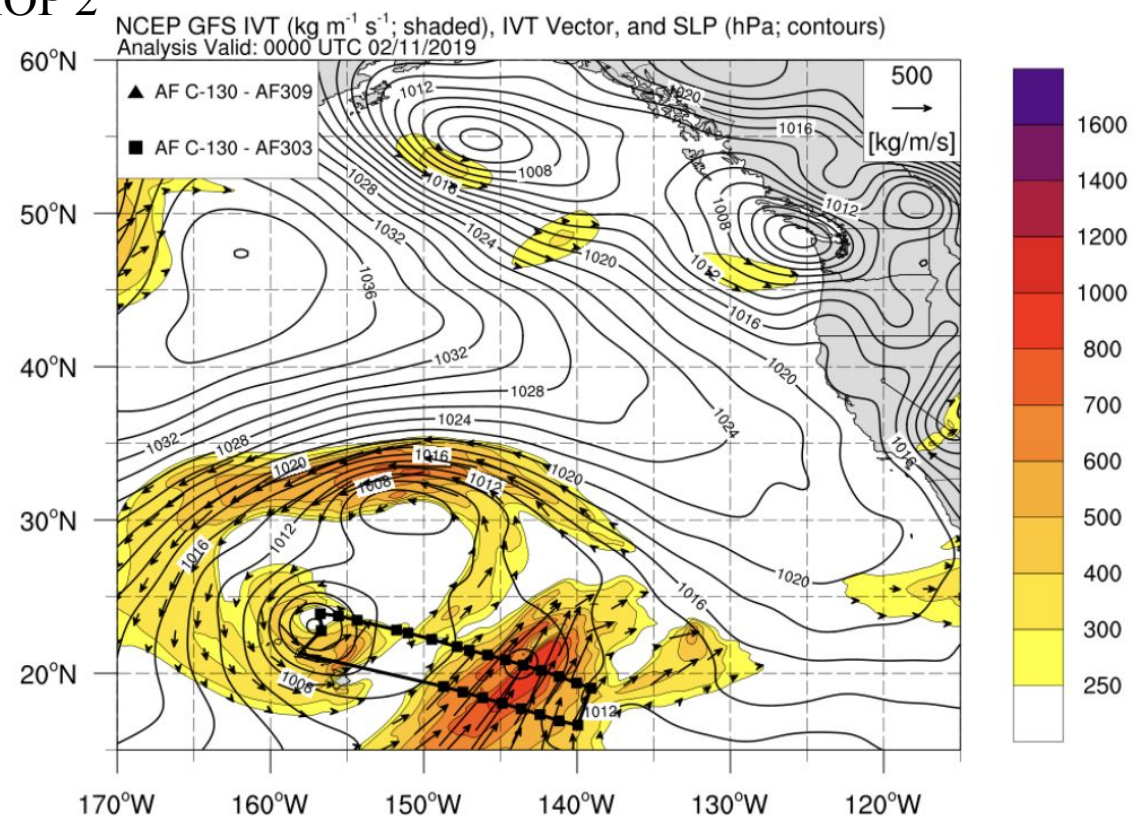
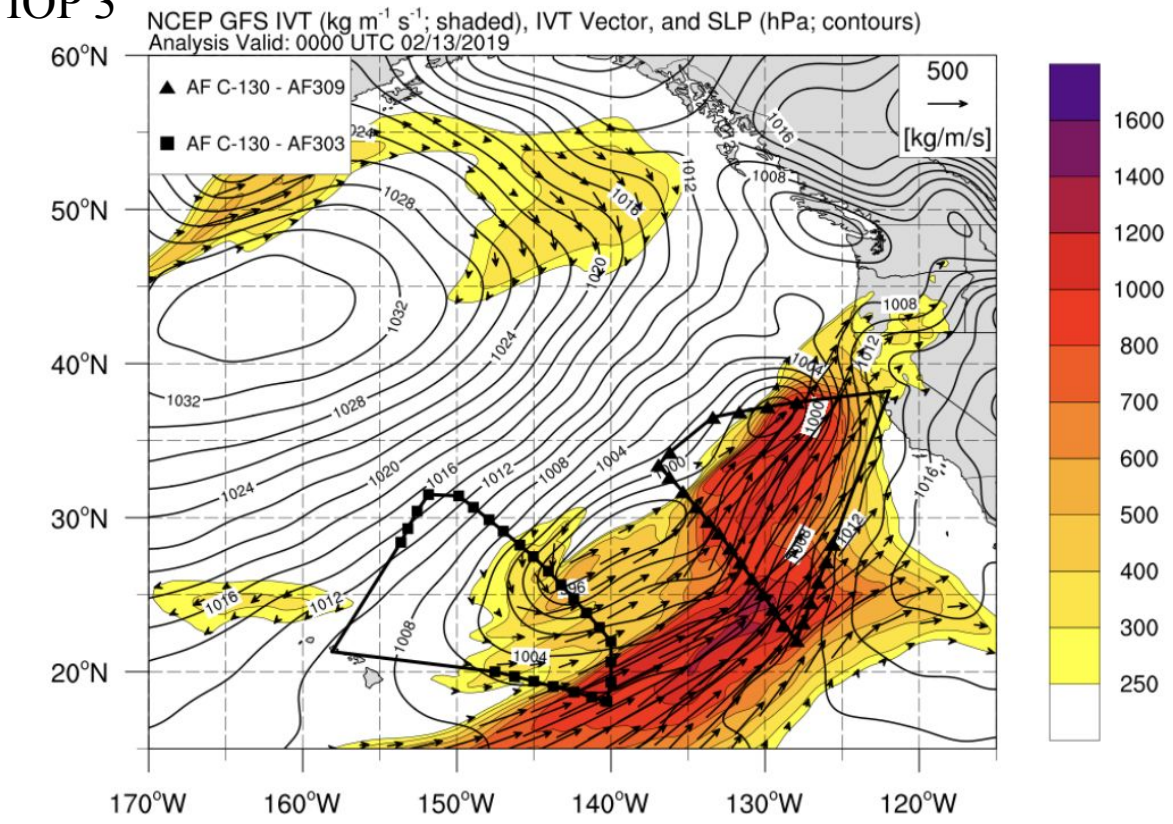


Possible Complementary Balloon Flights to Aircraft

IOP 2



IOP 3

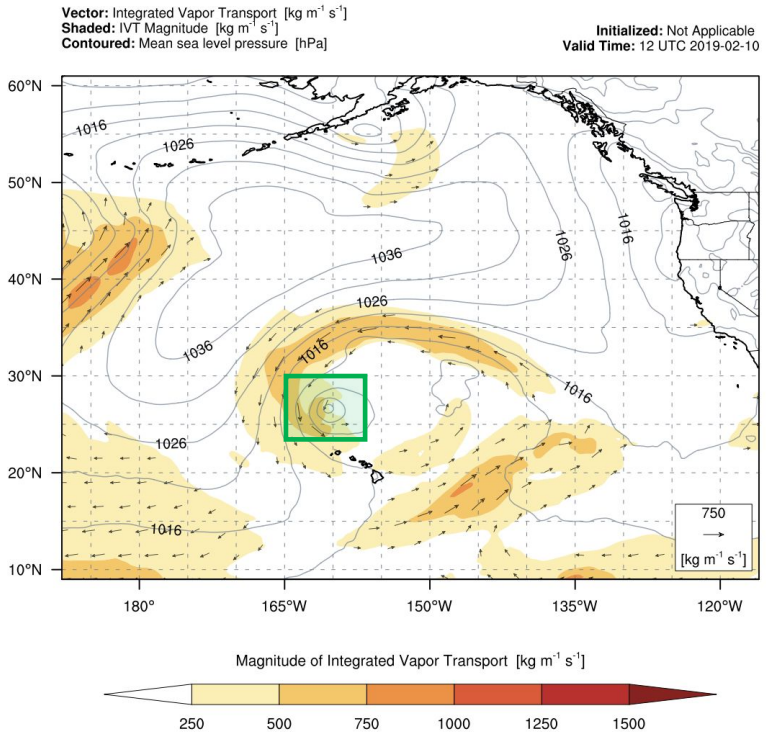


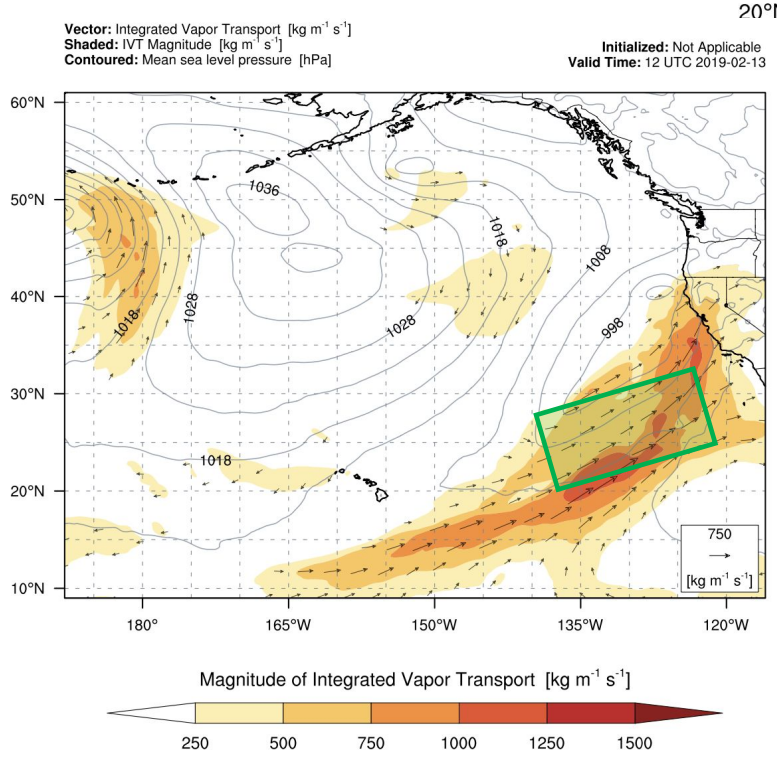
The scenario for the flights poses the questions:

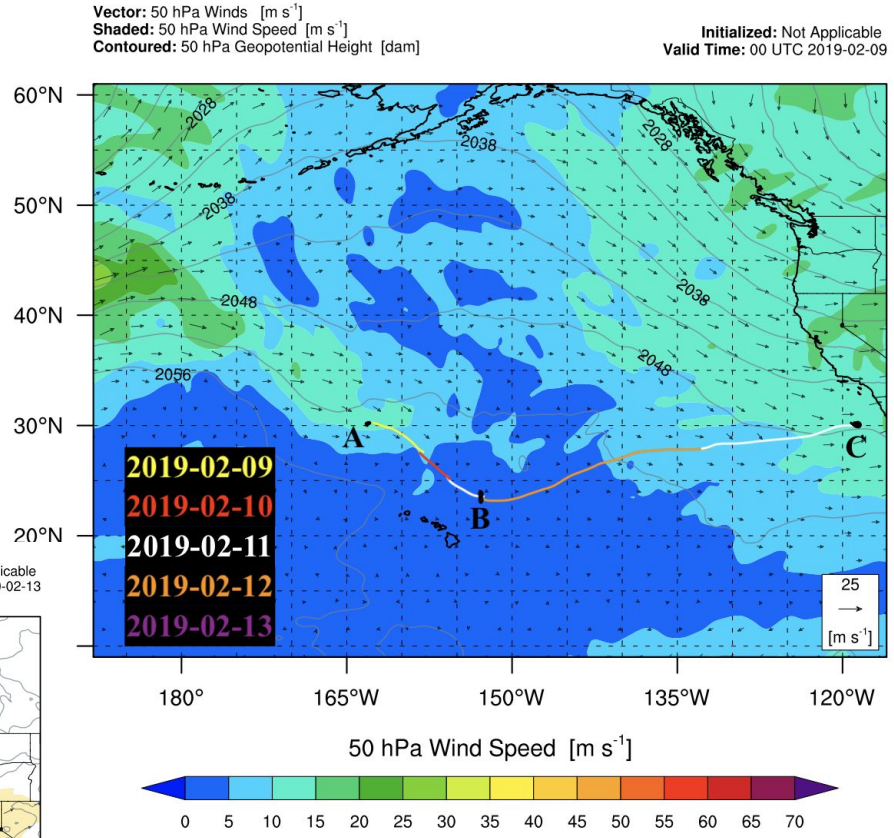
1. Is it possible to use a balloon to sample the system the day before the first aircraft flight into the storm (2019-02-11) to contribute to improving longer lead time predictions?
2. Is it possible to use a balloon to sample the system on the day between IOP2 and IOP3 when there were no aircraft available, because it has been shown that dropsonde sampling on consecutive days improves the impact (Zheng et al., 2021 submitted)?
3. Could a flight be designed to accomplish both these objectives?

Potential Balloon Trajectory

- Simulation Focus:
  - On 2019-02-10, 26N -160W, the balloon would be sampling the developing Extra-Tropical Cyclone (ETC) off the northern coast of Hawai'i.
  - On 2019-02-13, the balloon would be flying closely to the northwestern side of the AR core and traversing the AR.

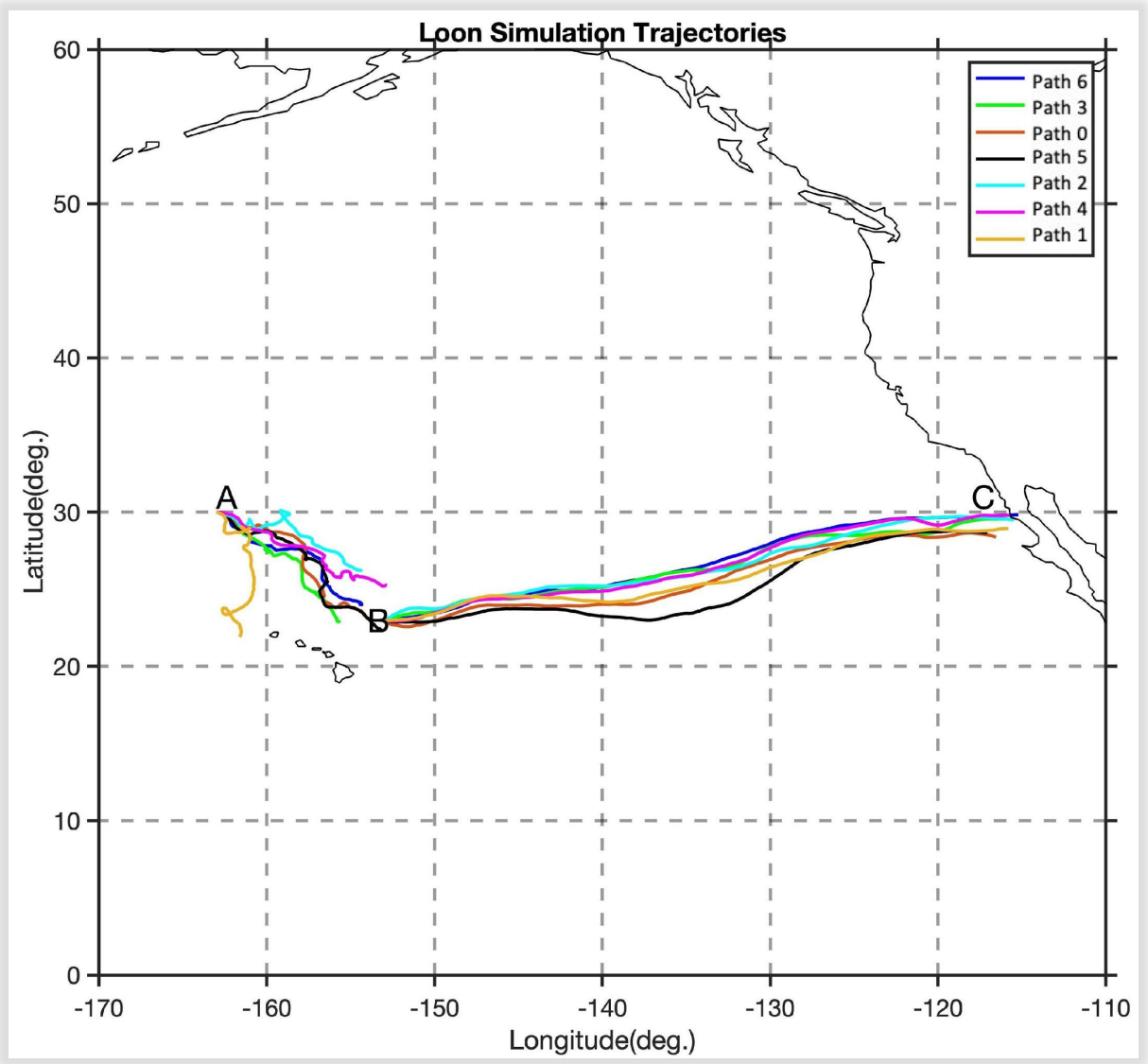






- To increase the likelihood of the simulated balloon trajectory to travel over the Kona Low and traverse the AR, points A, B, and C were used as guiding markers.

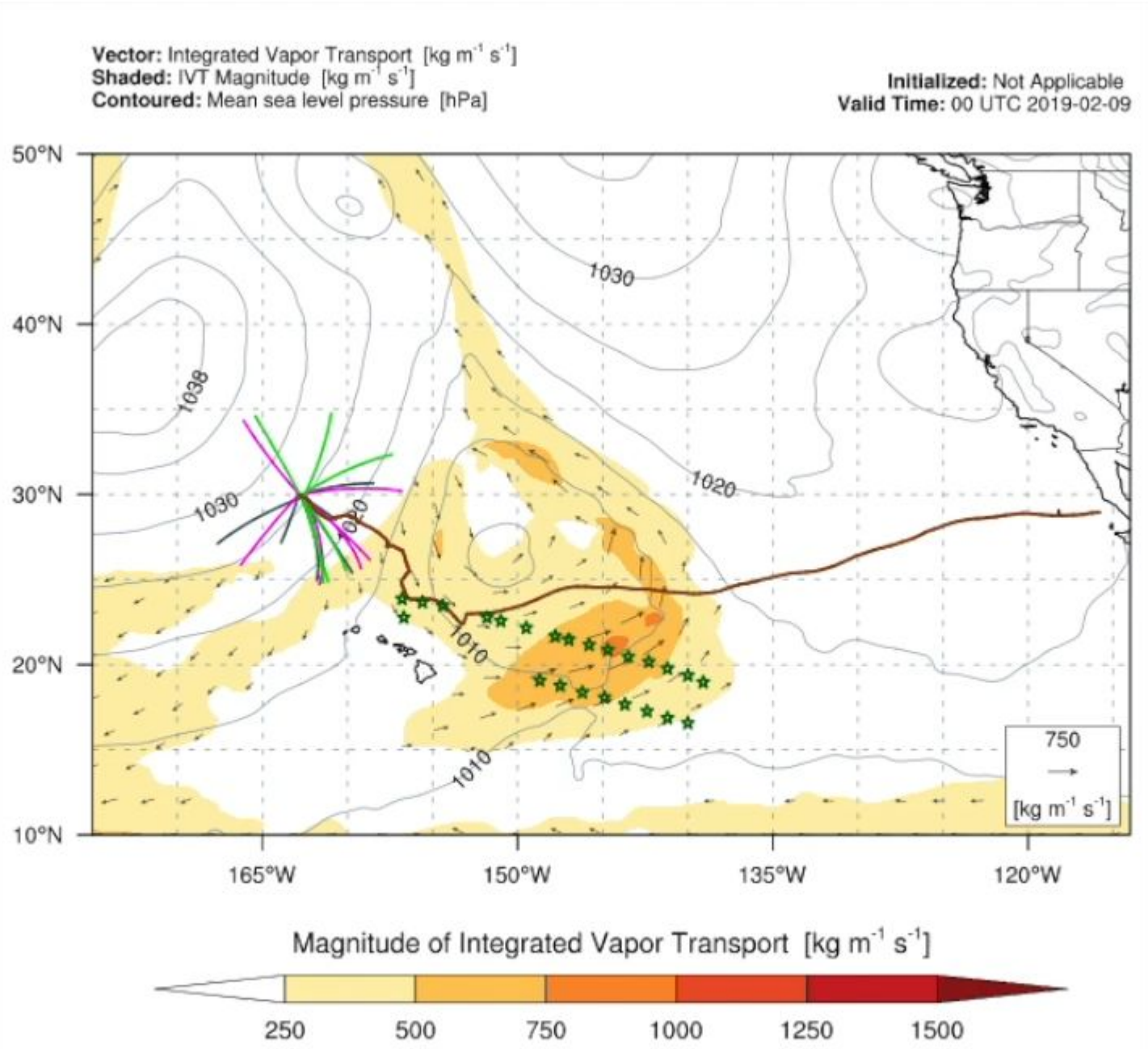
Simulated Trajectories

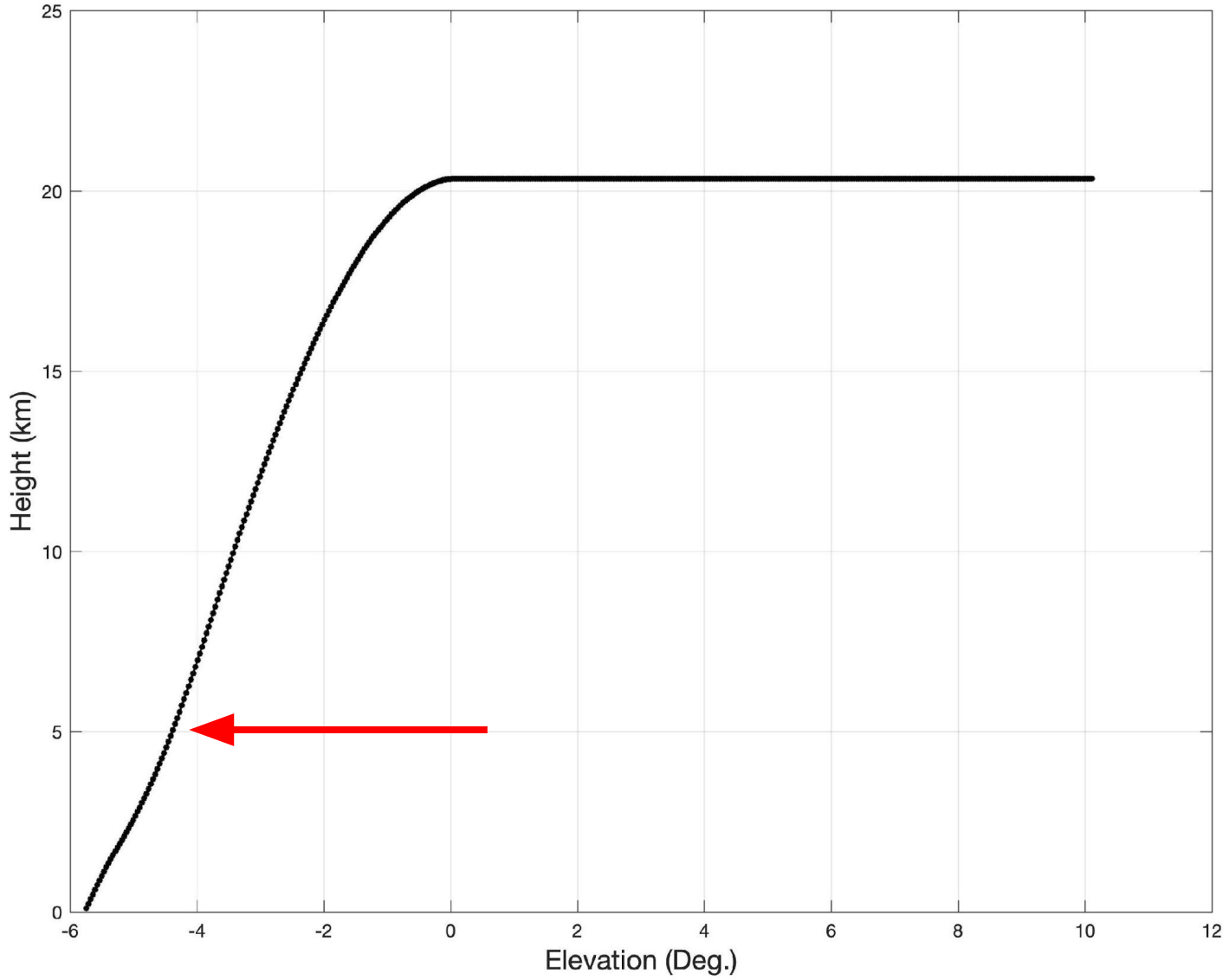


- With respect to our points A, B, and C, Loon created 2 simulations with 7 possible trajectories.
- Path #5 was was chosen to run RO using 3 satellite constellations. (GPS, Galileo, GLONASS)
  - It was chosen because it closely resembled the desired initial trajectory.
- The different ensemble members illustrate there is some uncertainty in achieving exactly the desired sampling.

Results

- Daily average number of occultations for this simulation was 211 occultations.
  - Galileo: 50-60 occultations per day
  - GPS: 80-90 occultations per day
  - GLONASS: 70-80 occultations per day
- The path closely follows the northern side of the developing ETC through 2019-02-10.
- The balloon travels on the northwestern side of the AR before crossing over the AR on 2019-02-13
- Typical successful retrieval rate is ~60% of the possible predicted occultations.



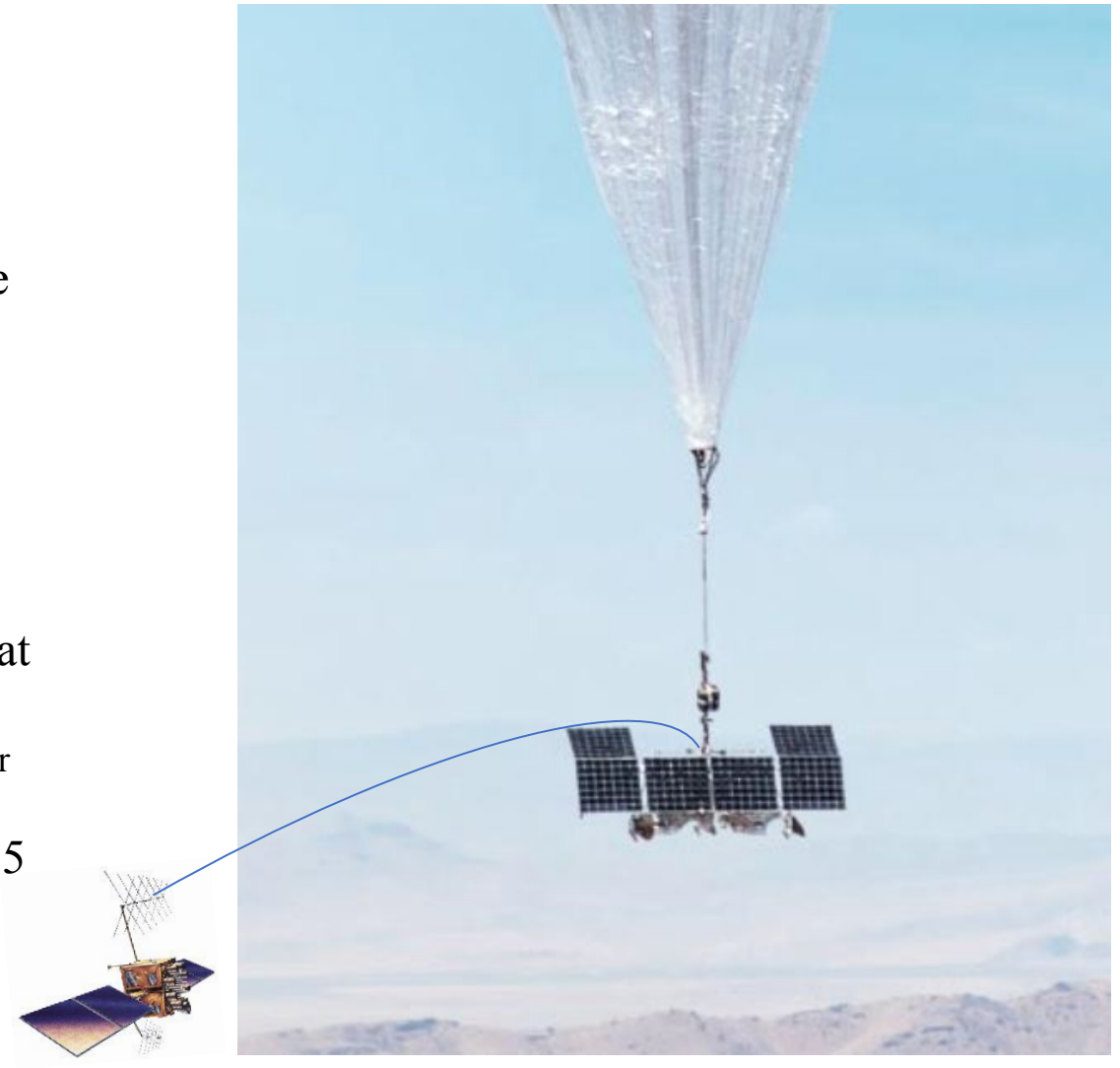


Elevation Angle of Simulated RO

- The simulated data shows that if the recorded data descends to, for example, -4^{o} below the horizon, that the lowest expected tangent point height would be about 5 km above the surface.

Current Loon GPS Configuration Evaluation

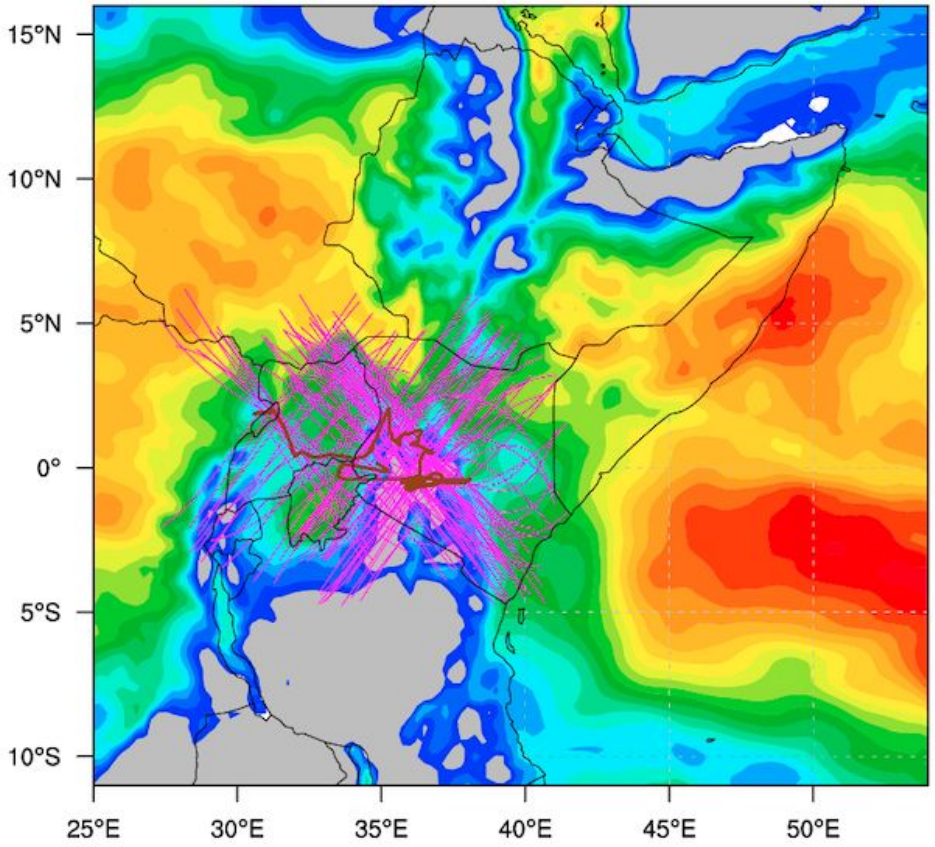
- Current configuration capabilities:
  - In addition to the information currently recorded for navigation, the current configuration can continuously record GNSS observations of satellite-to-receiver range.
  - Capable of recording at a 5 sec interval or less and has the bandwidth to transmit the data back to the control center.
  - Can capture signals from elevation angles below the horizon.
- Disadvantages of current configuration:
  - Limited visibility of antenna to the horizon.
  - Solar panels are likely to produce multipath reflections that degrade data quality.
    - A higher quality GNSS antenna is desired for higher SNR and lower profiles
  - Altitude variations during flight are sometimes > 700 m/15 min, which can impact retrieval accuracy.



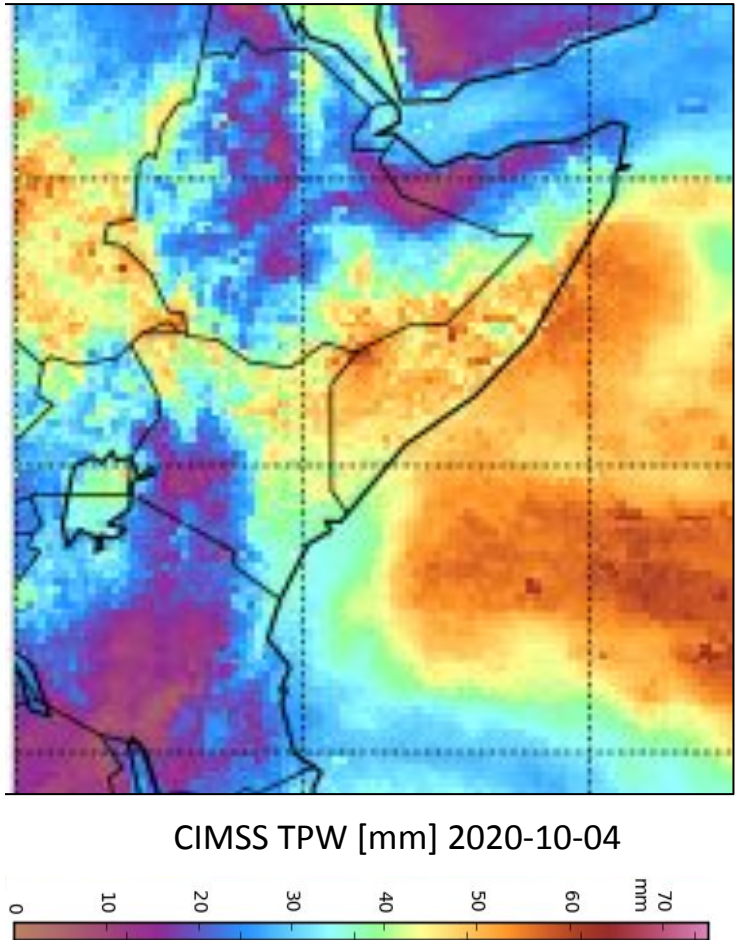
Current Experiments with Loon Balloons

- During Loon's service mission in Kenya, 3 balloons were dedicated to collect data in the desired configuration.
  - From this mission we collected 4 days worth of data to analyze.
    - The trajectory for HBAL263 (red line) is about 7 hours of continuous flight.
  - We investigated whether the quality is adequate for RO profiling using existing navigation receivers or whether we need to deploy our specialized RO receivers.

Predicted Occultation Locations for HBAL263



ERA5 integrated water vapor [mm] 2020-10-04

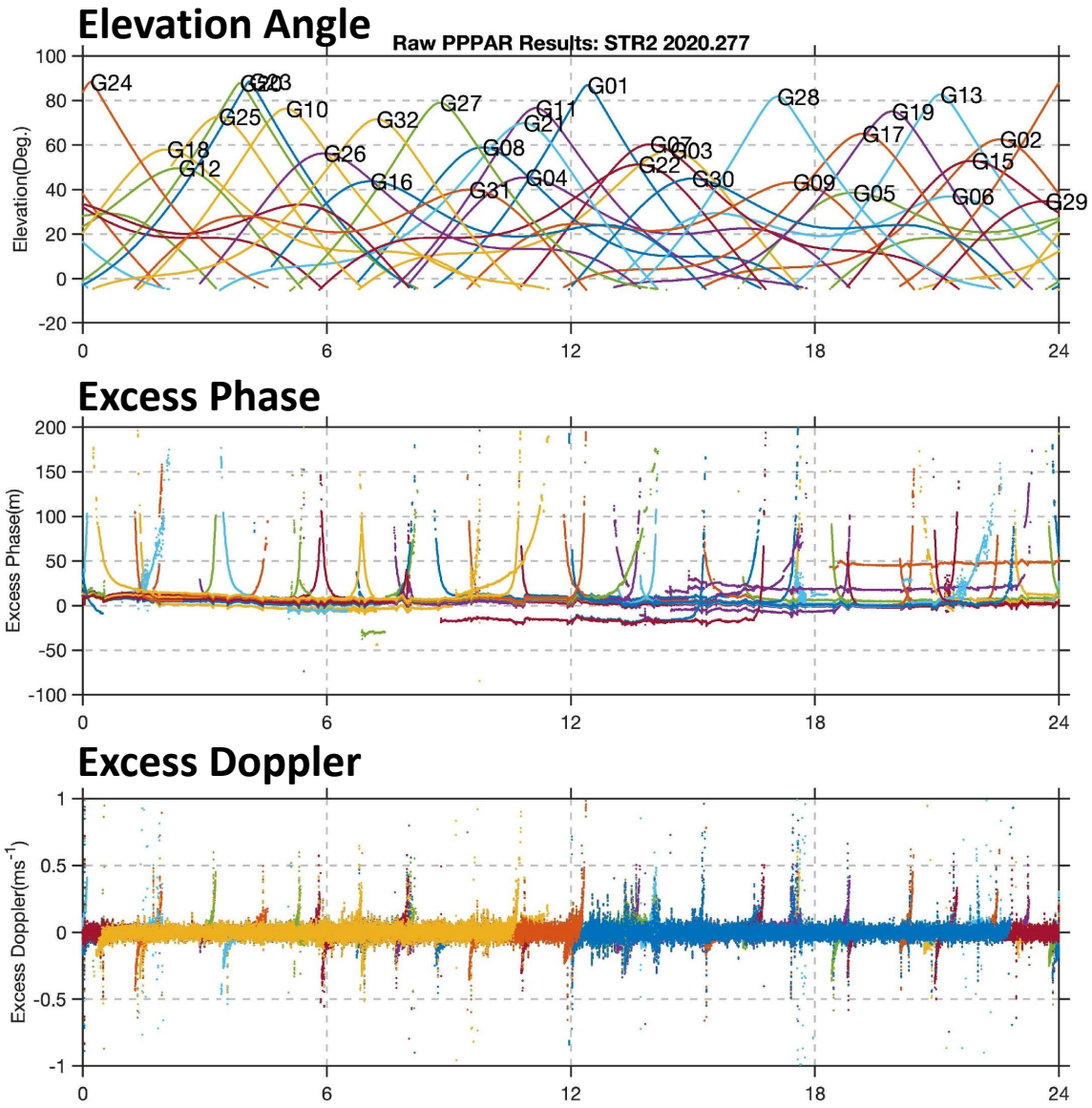


CIMSS TPW [mm] 2020-10-04

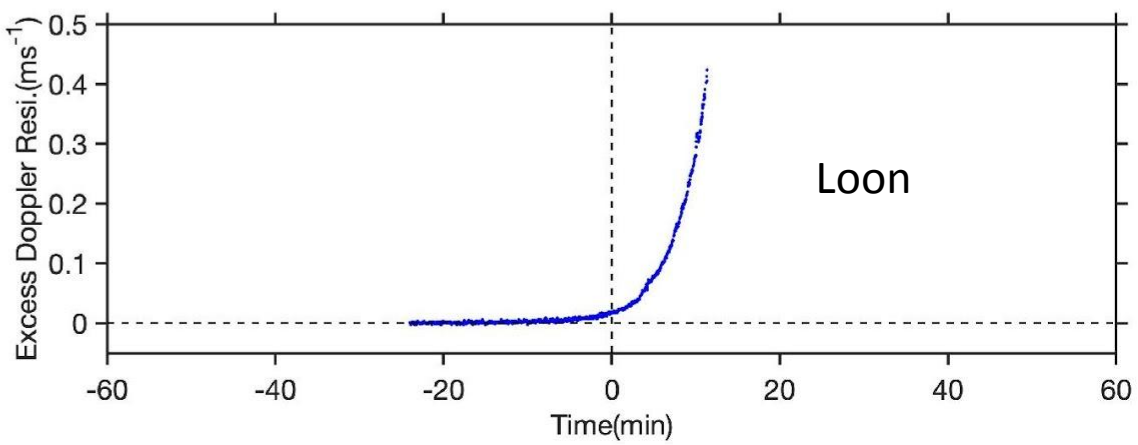
- The raytracing simulation predicts 209 possible GPS RO profiles (pink lines) over eastern Africa over 3.4 days.
  - They are dense around the balloon track and continuous in space and time.
  - They provide additional observations in poorly sampled region of high water vapor variability.
- The slanted tangent point profiles have the lowest point up to 500-km away from the balloon path.
- The profiles are aligned in 4 primary directions, forming an orthogonal pattern.

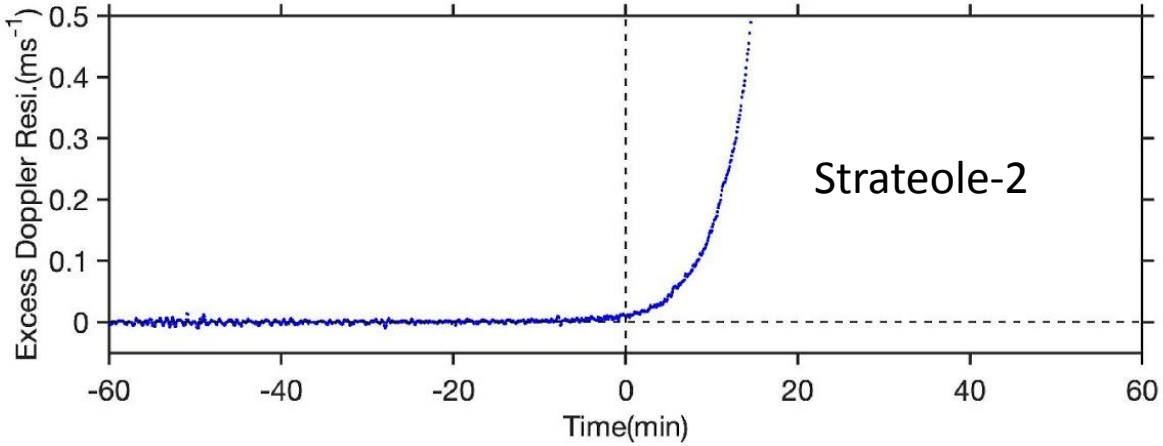
Preliminary Analysis of Data Quality: Elevation Angle/Excess Phase/ Excess Doppler

- Precise point positioning with ambiguity resolution is used to recalculate the precise balloon positions and retrieve the excess phase and Doppler.
- GPS satellites are tracked down to 4^{o} below the horizon (straight line elevation angle).
- Excess phase and Doppler reach about 100 m and 0.5 m/s.
- There are about 45 possible good occultations recovered in one day, slightly more setting ones than rising ones, 76% of predicted occultations.
- Further refractivity retrieval is underway.



Excess Doppler comparison Loon and Strateole-2*





Loon (Novtel OEM718D receiver+ GPS only antenna)

Strateole2 (Septentrio AsteRx-4 receiver+ multi-GNSS antenna).

- Similar excess Doppler was retrieved compared to Strateole-2 RO-dedicated multi-GNSS receiver.
- Doppler of 0.41 ms^{-1} corresponds to approximately 6 km tangent point height.
- It was possible to use the existing Loon navigation receiver/antenna to do RO profiling, without extra investment.
- Enabling the GLONASS and Galileo options would provide more profiles.

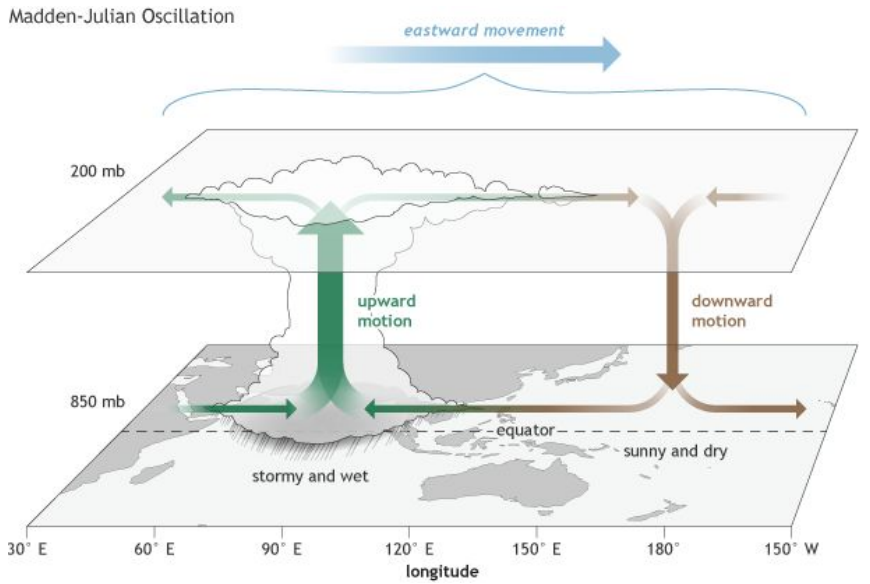
**See poster Cao et al., "Tropical waves observed by balloon-borne GPS Radio Occultation during the equatorial Strateole-2 super-pressure balloon campaign".*

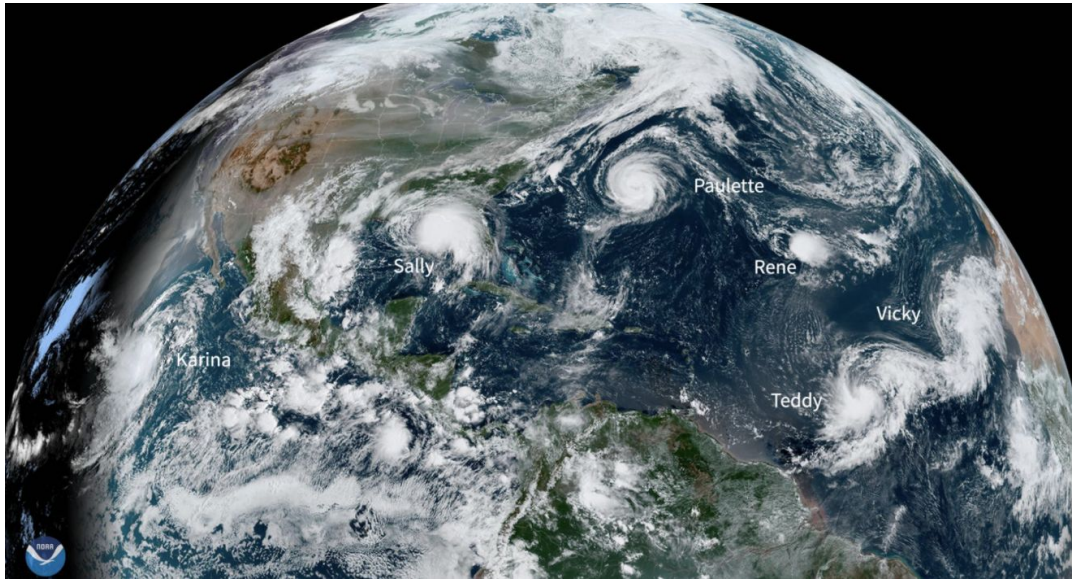
Summary

- Simulated RO Observations in Atmospheric Rivers
  - The balloon would provide dense and continuous sampling of the Kona low over the time period of its development.
  - The ARO tangent point trajectories from the balloon samples into the core of the AR continuously over 12 February when there were no aircraft available.
  - The balloon ARO sampling continues after the last aircraft flight and follows the AR to the coastline.
  - We conclude dedicated balloons could be useful to complement reconnaissance flights.
- Kenya Flight
  - Loon balloons are capable of recording satellites below the horizon and the existing navigation receivers are adequate for RO profiling.
  - There is some variation in the lowest angle reached below the horizon for the different satellites, but this may be attributed to blockage of the signal or multipath from the structure, or atmospheric conditions limiting the penetration from simple GNSS receivers.
  - Flights of opportunity during operational service could provide valuable data in undersampled regions.

Future Endeavors

- Equatorial Observations - MJO
  - Measuring the poorly understood intraseasonal tropical climate variability to improve climate models.
- Year-round observations of weather occurring in the southwestern US.
- Long-term marine coverage
  - Hurricanes





Acknowledgements

Funding Provided by:

- Loon, LLC(a subsidiary of Google Alphabet)
- CW3E
- NSF Grant AGS-1642650 and NASA grant NNX15AU

Data Provided by:

- ECMWF

Special thanks for assistance:

- Chad Hecht
- F. Martin Ralph, Mike Sierks, Will Chapman, & rest of the CW3E summer intern cohort

Center for Western Weather and Water Extremes

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