Jet Propulsion Laboratory
California Institute of Technology

SWARMS

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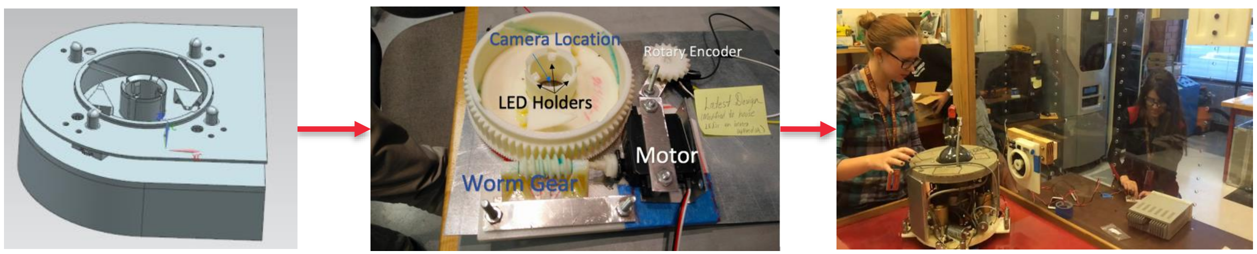
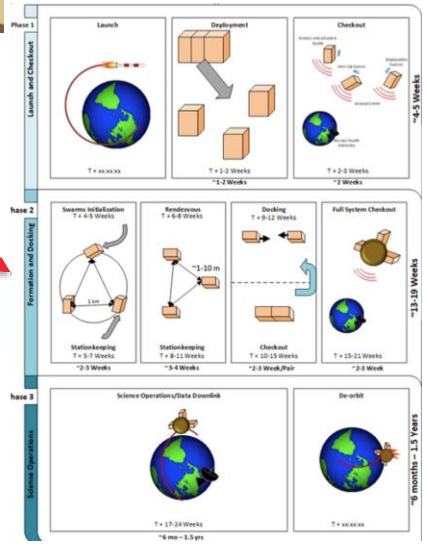
Progress to date

- Establishment of baseline performance requirements: A science workshop was arranged and conducted by **Paul Scowen** of ASU. The SWARMS team and ASU earth science faculty participated in the workshop to brainstorm and narrow down options for a compelling mission architecture that demonstrates all the key SWARMS technologies.
- Workshop preparation included an in depth review of the recently released Earth Science decadal survey to ensure SWARMS is responsive to the needs of that community. Three possible science missions were considered and finally a down select to a weather satellite model was chosen. A Science Traceability Matrix has been developed to provide context for a mission baseline.

USC



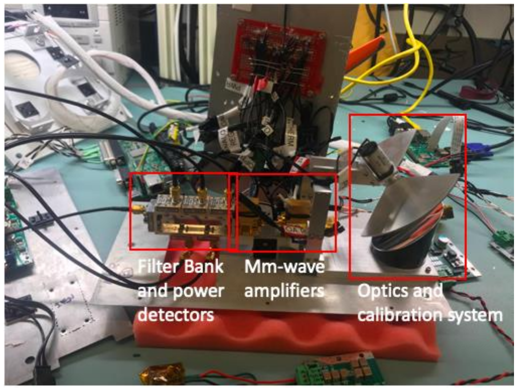
- Georgia Tech – PhD Student **Andrew Fear** developed the L1 / L2 systems level requirements for the 3x 6U CubeSats configuration. Current configuration will be a L-Shaped integrated satellite.
- ASU – **Sean Bryan** with professor Chris Groppi did an antenna reflector design.
- USC students have developed a working prototype of CLING.
- Under USC prof. **David Barnhart,** students have contributed via CAPstone projects

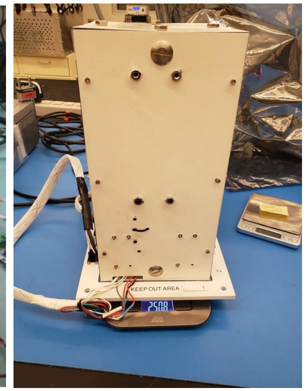


Jet Propulsion Laboratory

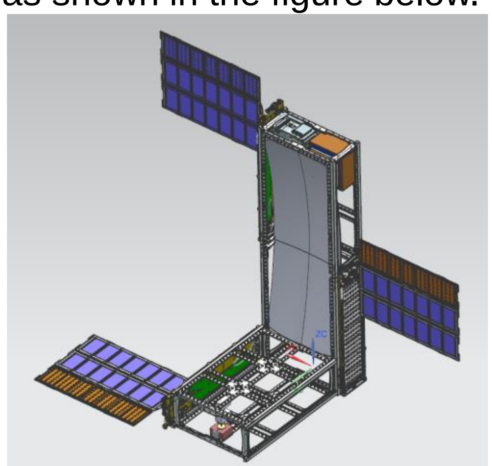
Progress to date

- After the establishment of baseline performance requirements from a science workshop that was arranged and conducted by **Paul Scowen** of ASU, ASU has developed a prototype science payload as shown in the figure below:

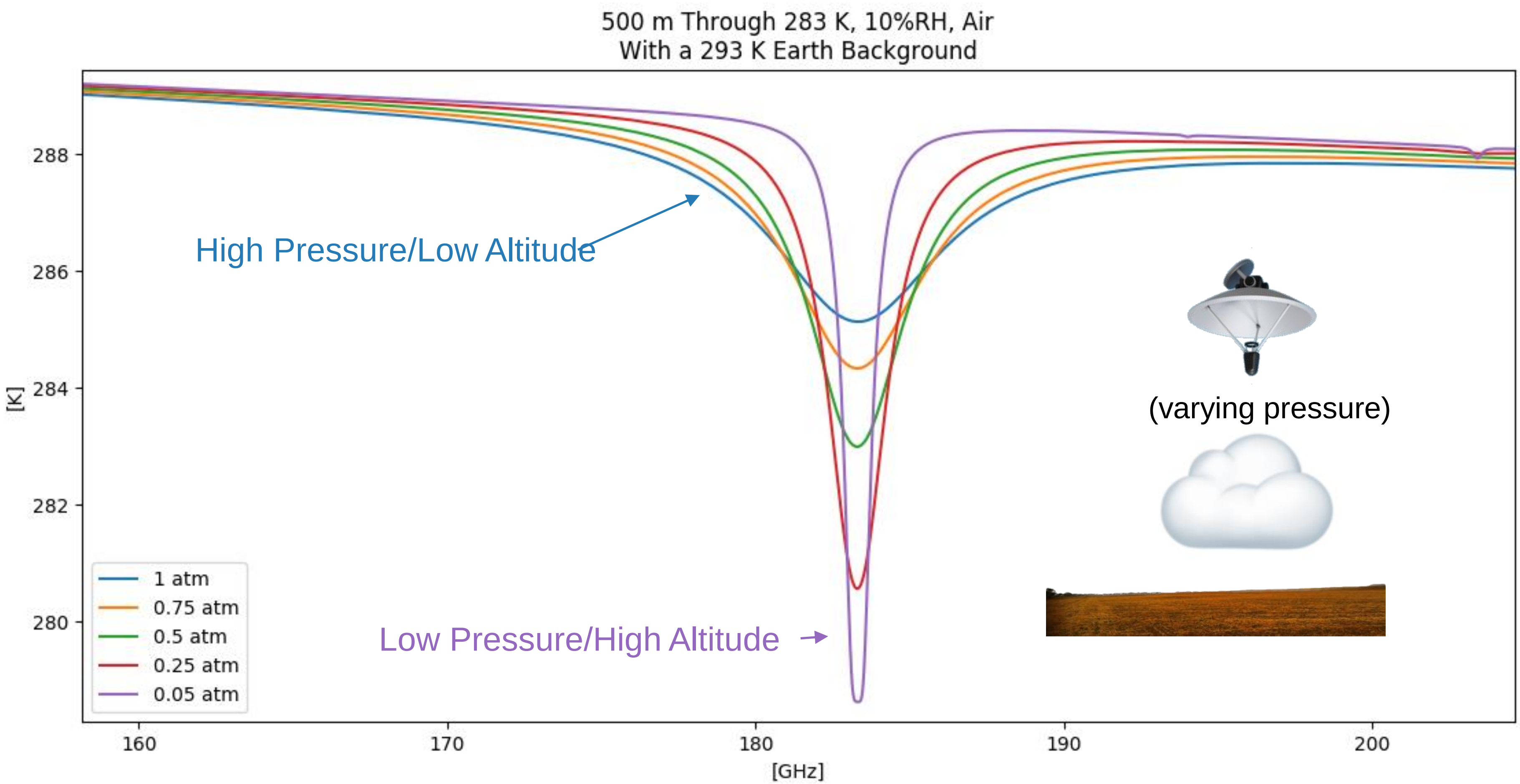




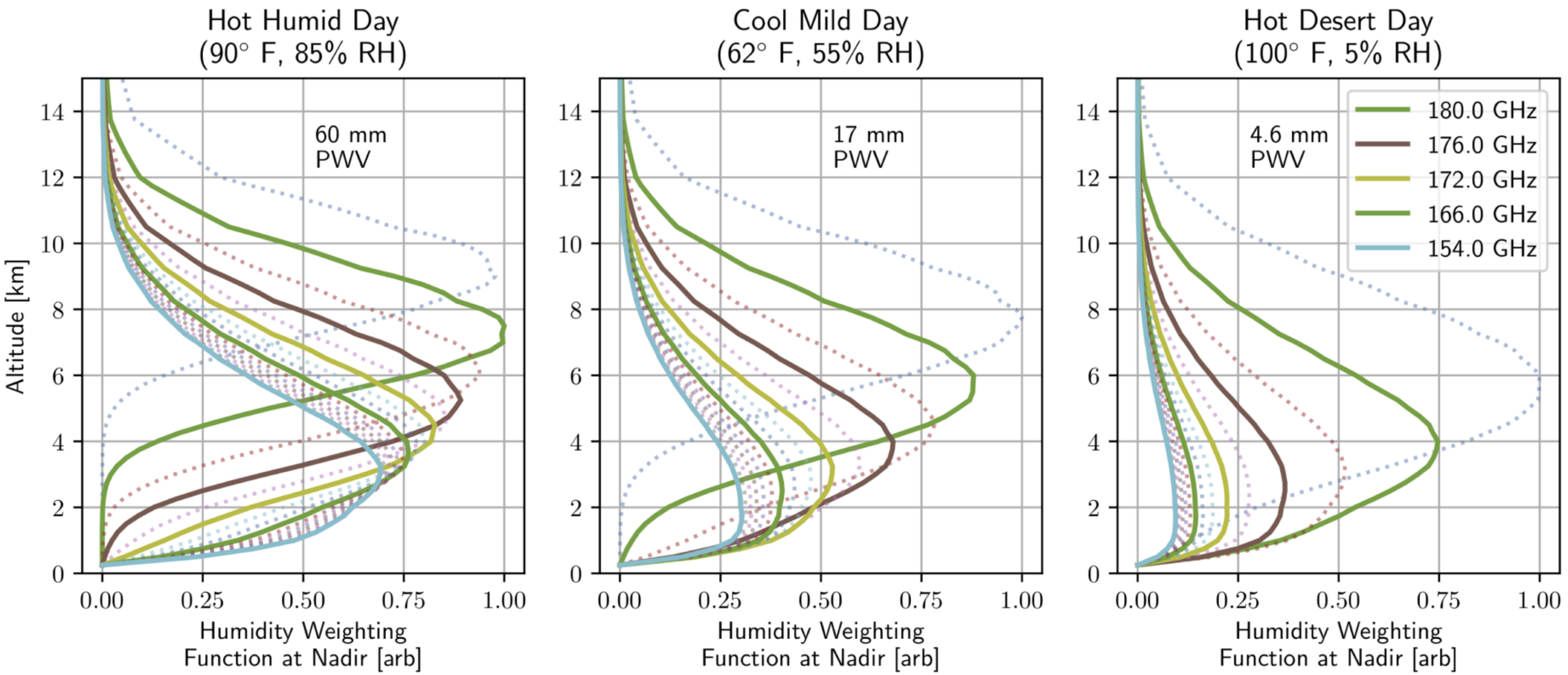
- The payload (prototype radiometer) was tested in NASA's High Altitude Student Project (HASP) Stratospheric Balloon. NASA High Altitude Student Project (HASP) hosted 12 student-built payloads, approximately CubeSat sized which, was a competitive process to get ride. Balloon flew at 125kft. Atmospheric pressure 0.3 mbar. Above 99.7% of atmosphere.
- ASU, USC and JPL worked together to develop a configuration model for the integrated 3x 6U CubeSats in orbit as shown in the figure below.



- USC continued further development of the docking mechanism prototype as shown in the adjacent figure



500 m Through 283 K, 10%RH, Air
With a 293 K Earth Background
288
286
284
282
280
[K]
160
170
180
190
200
[GHz]
High Pressure/Low Altitude
Low Pressure/High Altitude
(varying pressure)
1 atm
0.75 atm
0.5 atm
0.25 atm
0.05 atm



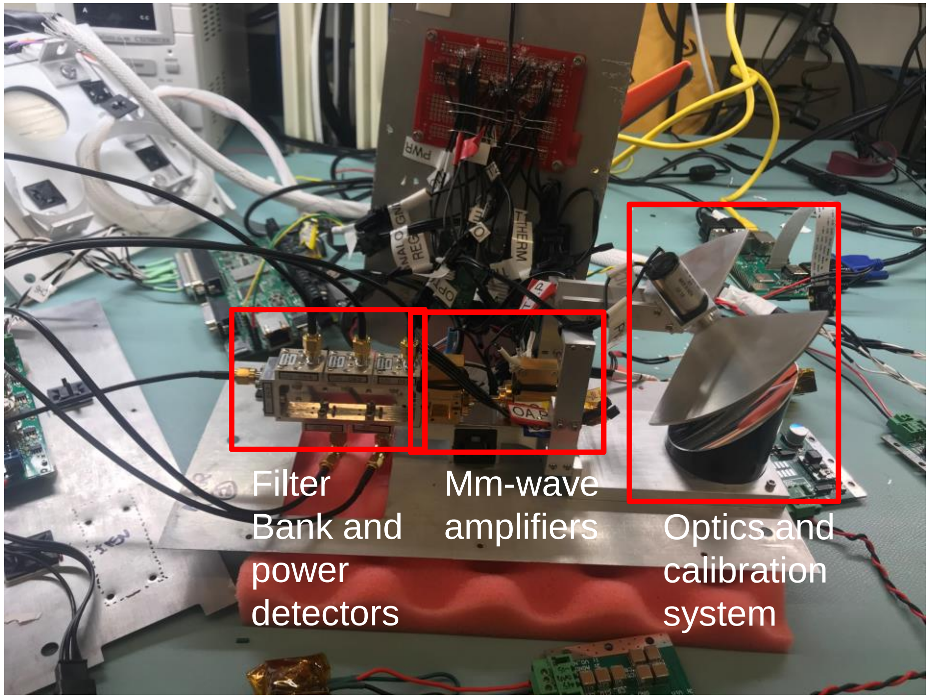
Hot Humid Day
(90° F, 85% RH)
60 mm
PWV
Cool Mild Day
(62° F, 55% RH)
17 mm
PWV
Hot Desert Day
(100° F, 5% RH)
4.6 mm
PWV
180.0 GHz
176.0 GHz
172.0 GHz
166.0 GHz
154.0 GHz
Altitude [km]
0
2
4
6
8
10
12
14
0.00
0.25
0.50
0.75
1.00
Humidity Weighting
Function at Nadir [arb]

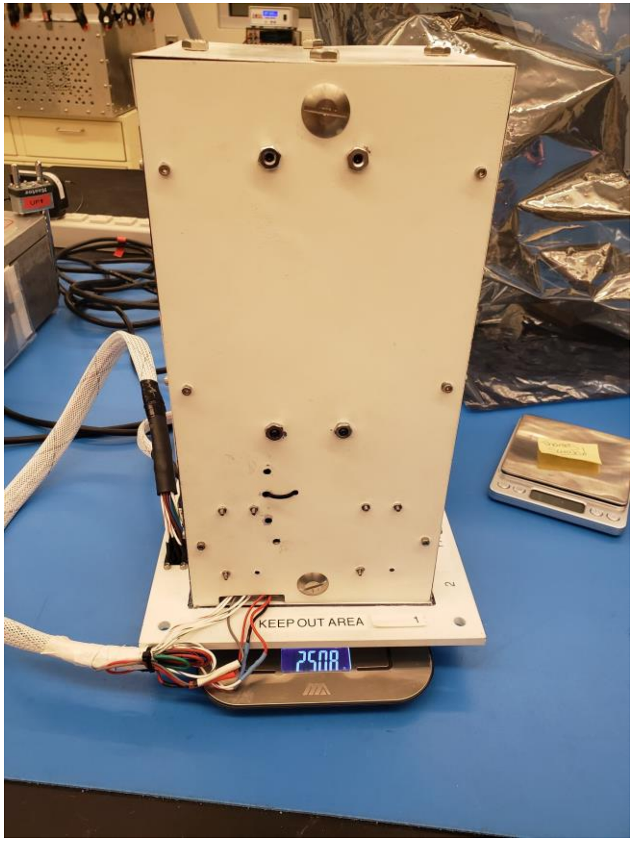
NASA High Altitude Student Project (HASP)

- Stratospheric balloon payload.
- Hosts 12 student-built payloads, approximately Cubesat sized.
- Competitive process to get ride
- ASU team is flying SWARMS prototype radiometer.
- Balloon flies at 125kft. Atmospheric pressure 0.3 mbar.
- Above 99.7% of atmosphere.

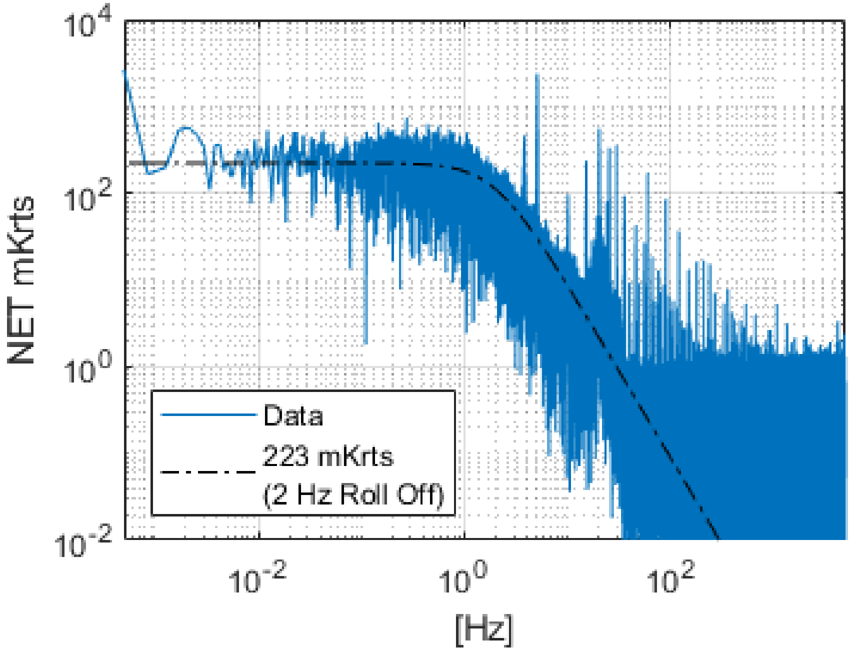
ASU SWARMS Prototype Science Payload

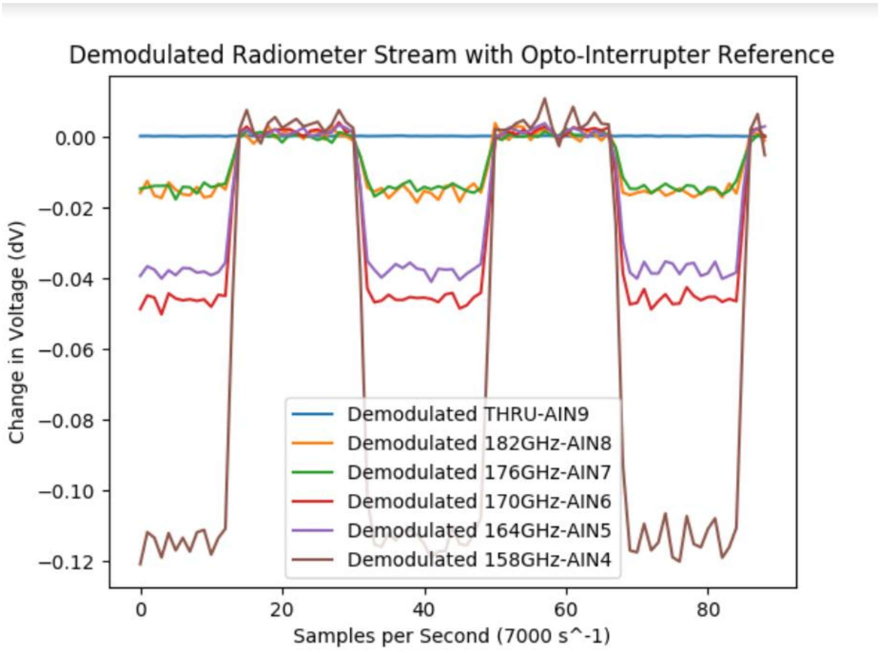
Built for NASA High Altitude Student Project (HASP) Stratospheric balloon

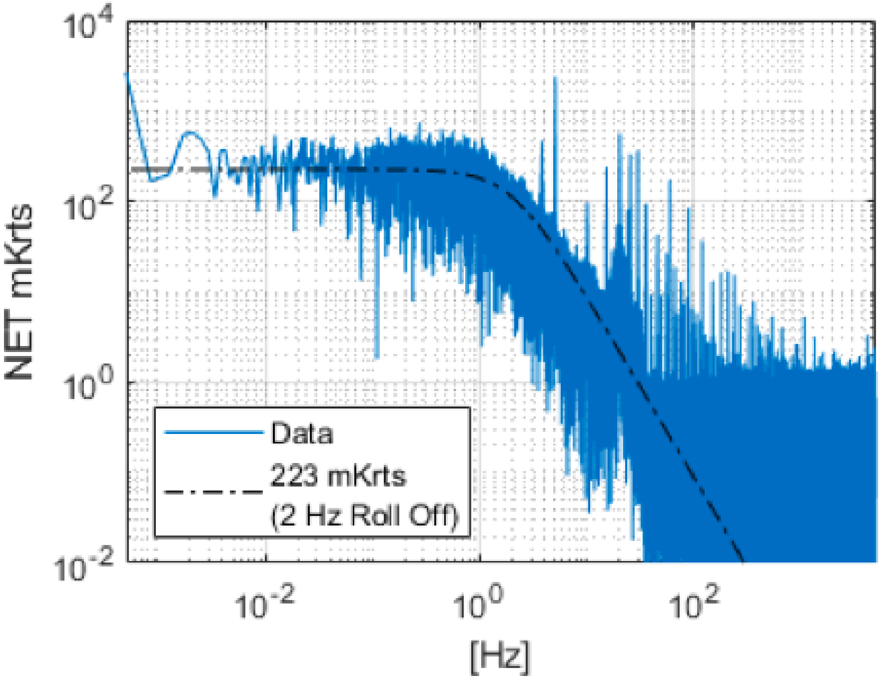




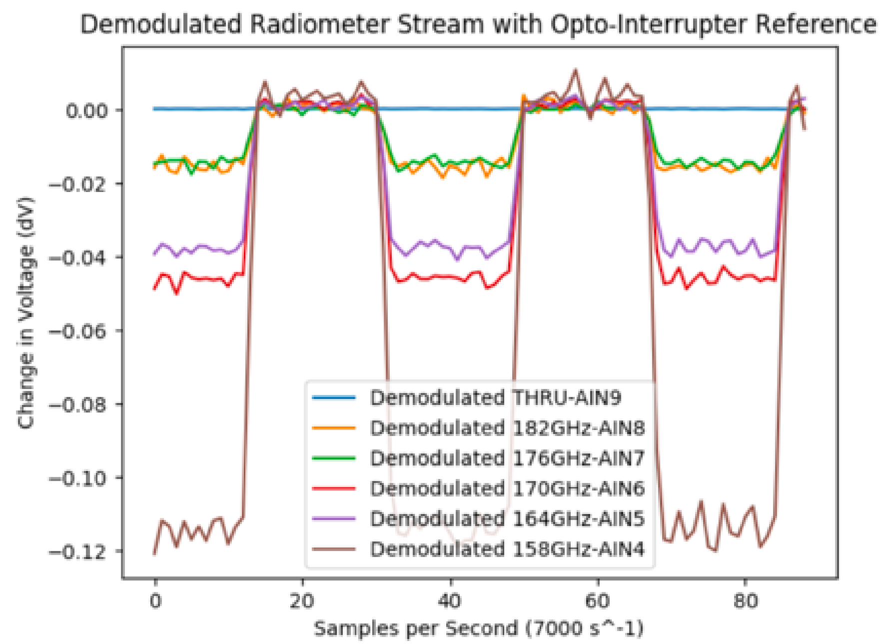
Measured performance







NET mKrts
[Hz]
Data
223 mKrts
(2 Hz Roll Off)



Demodulated Radiometer Stream with Opto-Interrupter Reference
Change in Voltage (dV)
Samples per Second (7000 s^-1)
Demodulated THRU-AIN9
Demodulated 182GHz-AIN8
Demodulated 176GHz-AIN7
Demodulated 170GHz-AIN6
Demodulated 164GHz-AIN5
Demodulated 158GHz-AIN4

ASU SWARMS Team

Rendezvous Parameters

- Preliminary Delta-V values
  - Initial rendezvous approach (~2 km – 10 m)
  - Terminal Phase
  - Station keeping

- Implemented Model Predictive Control (MPC) for AR&D
  - Based off of paper by Weiss, et al.
    - https://ieeexplore.ieee.org/document/7012053
  - Handles nonlinear constraints (line of sight, obstacle avoidance)
  - Robust as control is recalculated over control horizon at each step

MPC Formulation

Set up as a QP solver

- Comparable to LQR control
- Ensure local stability with solution to Ricatti equation
- Smoother control than LP

$$J = \min \left[\sum_{k=0}^{N-1} \left(X_k^T Q X_k + U_k^T R U_k \right) + X_N^T Q_f X_N \right]$$

s.t.

$$X_{k+1} = AX_k + BU_k$$

$$\|U_k\|_\infty < u_{max}$$

Where A is discretized CW equations and $B = A \begin{bmatrix} \mathbf{0} \\ \boldsymbol{I} \end{bmatrix}$.

Q_f is the solution to the discrete Ricatti equation.

Rendezvous Constraints

- Thrusting Direction Limits

$$\Delta \dot{y}_k \leq \mu e^{-\beta k}$$

- Overshoot constraint (for V-bar approach)

$$y_k \geq 0$$

- Obstacle Avoidance

- Line-of-sight (stay within a designated cone)

$$\sum_{k=1}^{N} \lambda \mathbf{1}^T (A_{cone} X_k - b_{cone})$$

This is augmented to MPC cost function to be a penalty

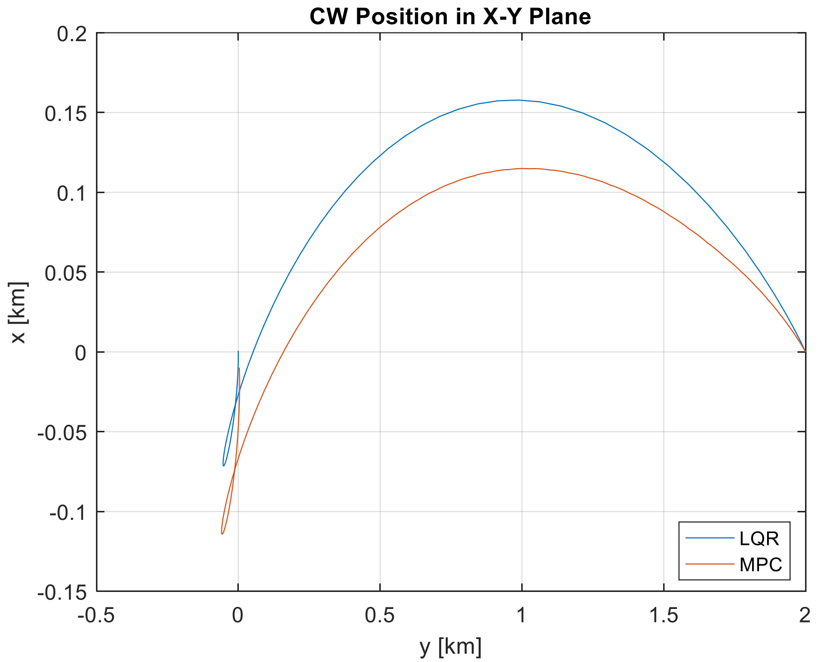
- Thrust Direction Changes

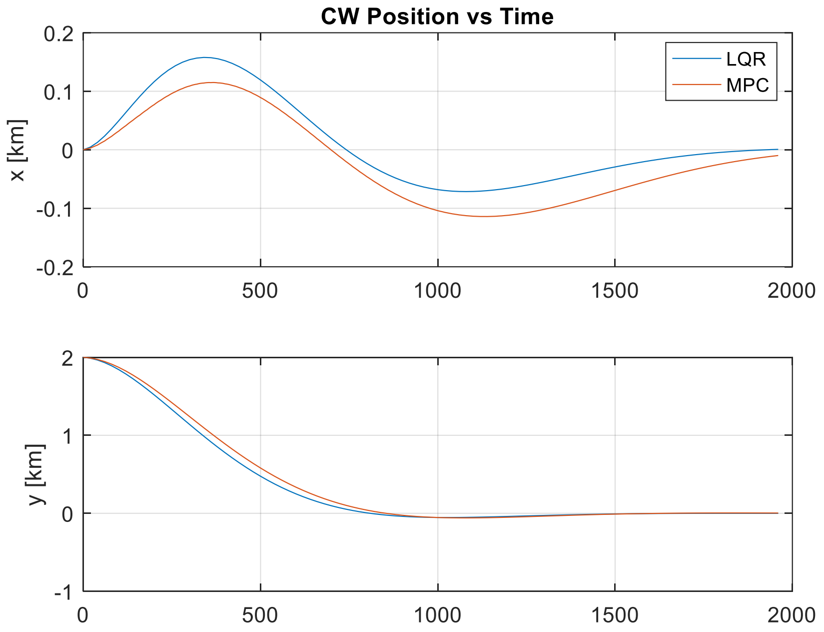
$$\sum_{k=0}^{N} (U_k - U_{k-1})^T R^{attitude} (U_k - U_{k-1})$$

Comparing MPC to LQR

Rendezvous Phase (2 km – 10 km)

Using same Q and R weighting





LQR DV = 8.59 m/s
MPC DV = 8.45 m/s
Time to box of < 10 m = 1960s

MPC Simulations

This was originally done before adding in overshoot (v-bar direction) constraint.

Varying position weighting of matrix Q, σ_r

Varying control horizon time, Ts

T_s (s)	σ_r (m)	Δv (m/s)	T_f (s)
1	1	52.20	102
5	1	26.59	505
30	1	10.50	1410
60	1	7.34	2400
5	10	38.42	140
5	0.1	15.67	880
5	0.01	9.35	1610