# Results from the Radio Frequency Mass Gauge Technology Demonstration on the Intuitive Machines Nova-C Lunar Lander

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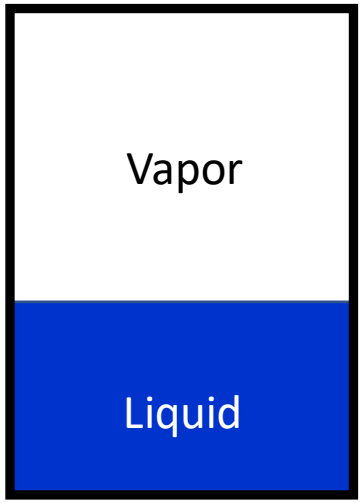
# IN-SPACE PROPELLANT GAUGING

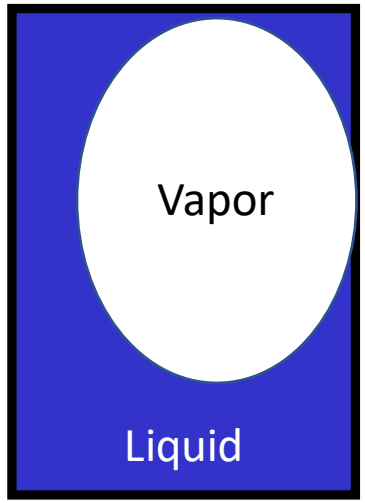
**Challenge: How to measure propellant quantity in spacecraft tanks during various phases of a mission**

**State of the art methods:**




Level sensors:
- Capacitance probe
- Wet-dry sensors
- Delta-P (pressure head)
- Ultrasonic liquid-level sensor

**Settled**



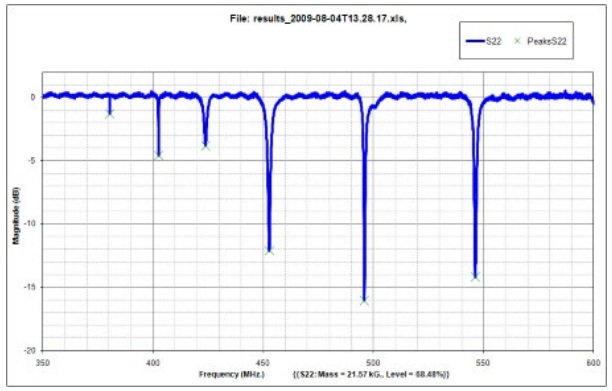

Unsettled methods:
- Bookkeeping (Burn Time Integration)
- Pressure-Volume-Temperature (PVT, requires helium; not used in-flight for cryos)
- Thermal pulse (storables, slow)
- **New: RFMG**

**0g - Unsettled**

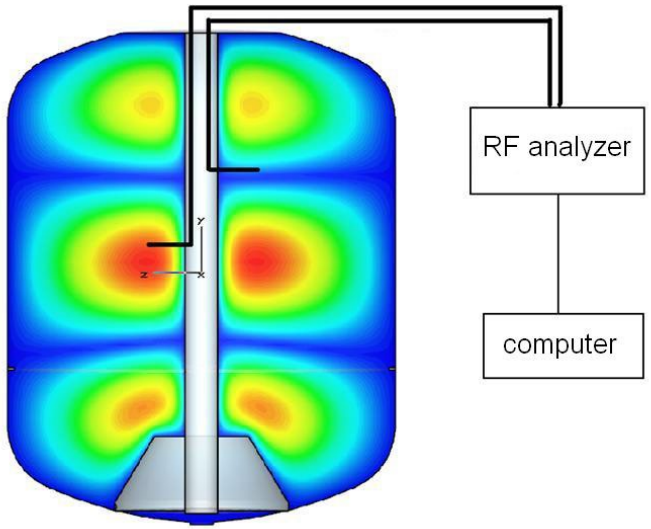
**For cryogenic propellants, settled measurements or bookkeeping is SOA**

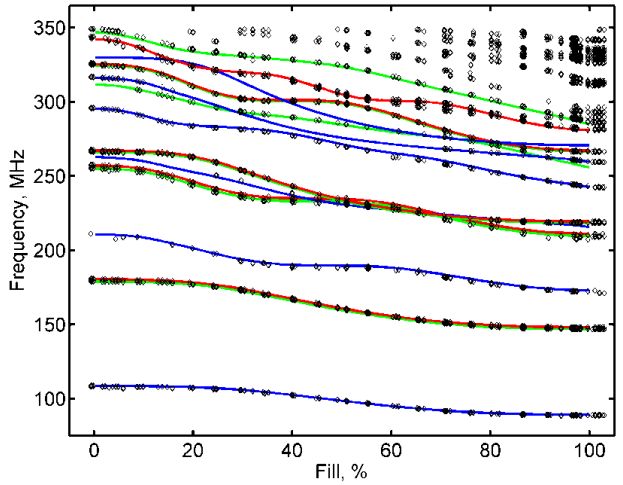
# RADIO FREQUENCY MASS GAUGE (RFMG) OVERVIEW

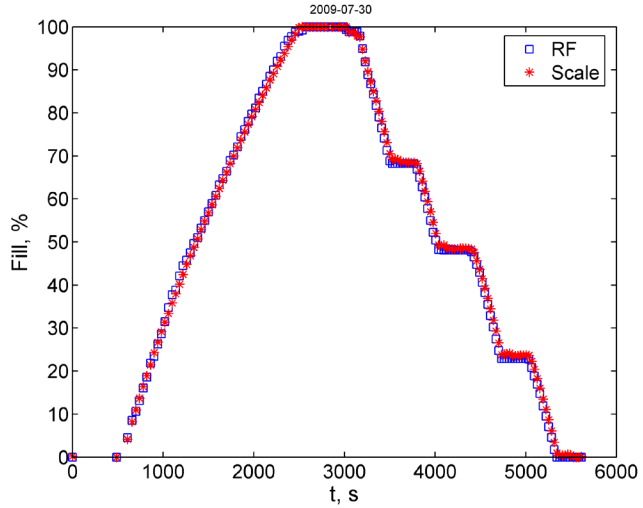
- Antenna sensor(s) located inside the tank transmit and reflect the incident RF signal
- Measure reflected RF spectrum; the spectrum changes with fill level, since the dielectric fluid (ε) slows the speed of light




- The basis of the RFMG is that these changes can be accurately predicted via RF/fluid simulations
- RFMG analysis software compares the measured tank spectra to a database of simulated spectra and returns the best match propellant mass information




(Data shown is not from IM tanks)

# RFMG DEMO ON INTUITIVE MACHINES NOVA-C LUNAR LANDER

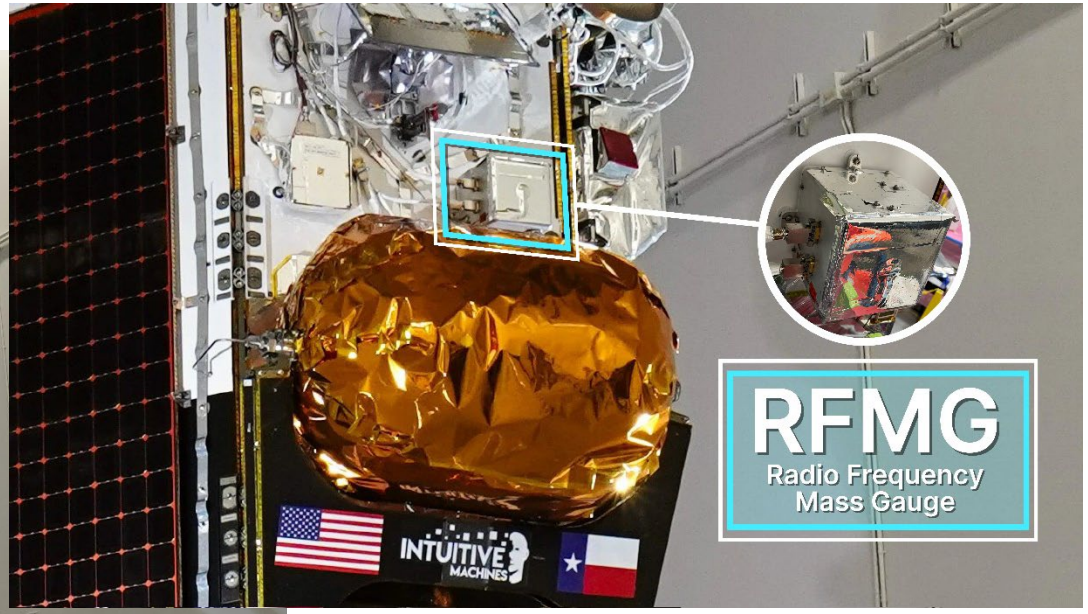




Image credit: Intuitive Machines

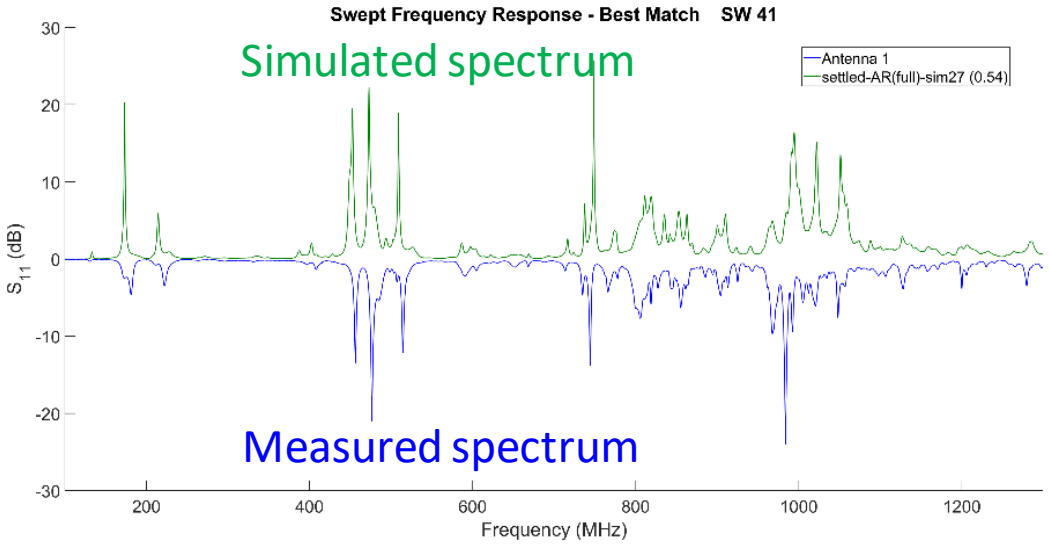
- Liquid oxygen – liquid methane
- One antenna sensor in each tank
- Carbon composite tanks
- Similar RFMG hardware & software as used on RRM3 mission
- RFMG data files downlinked to ground for analysis

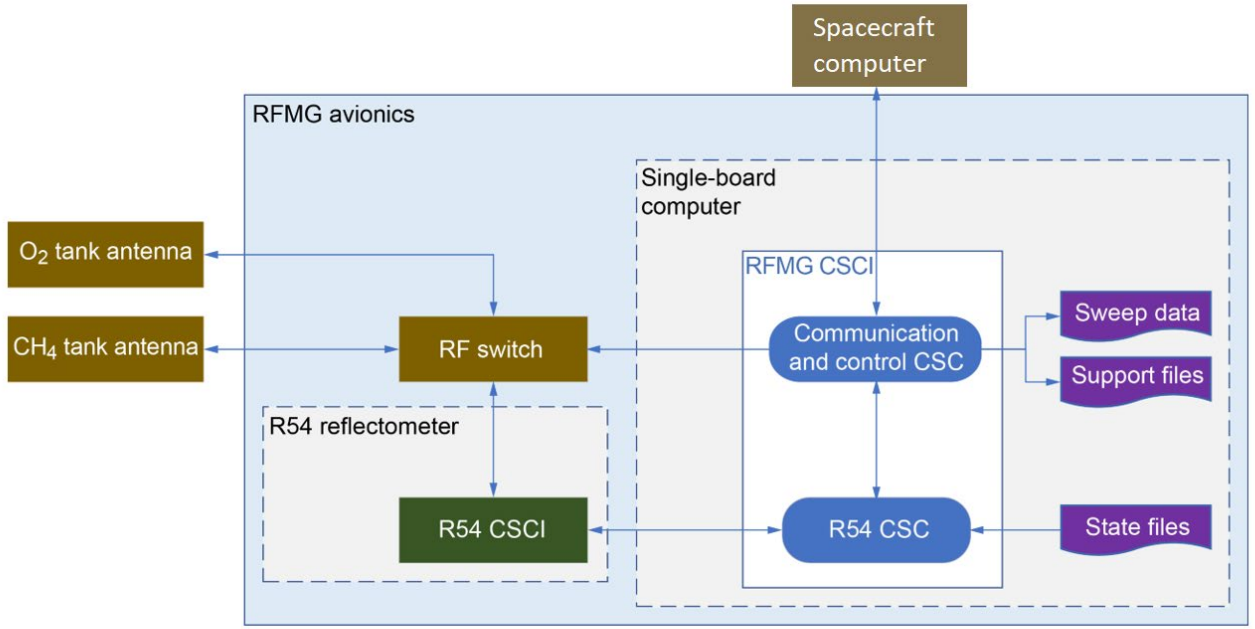
# RFMG MEASUREMENT

- Spacecraft computer sends command to conduct RF sweep
  - RF sweep is S11 reflection spectrum measurement from 100 - 1300 MHZ
  - RFMG avionics collects S11 sweep data from both tanks
- Sweep file data is sent to s/c computer and stored for downlink
- Sweep files sent to ground for analysis during favorable comm periods
- Data analyzed on the ground and results reported to IM

S11 (dB) = 10log(Pr/Pi)
Pr, reflected power
Pi, incident power

**Best spectral match (measured v. sim) at 54% liquid mass fraction (launch pad prop loading)**

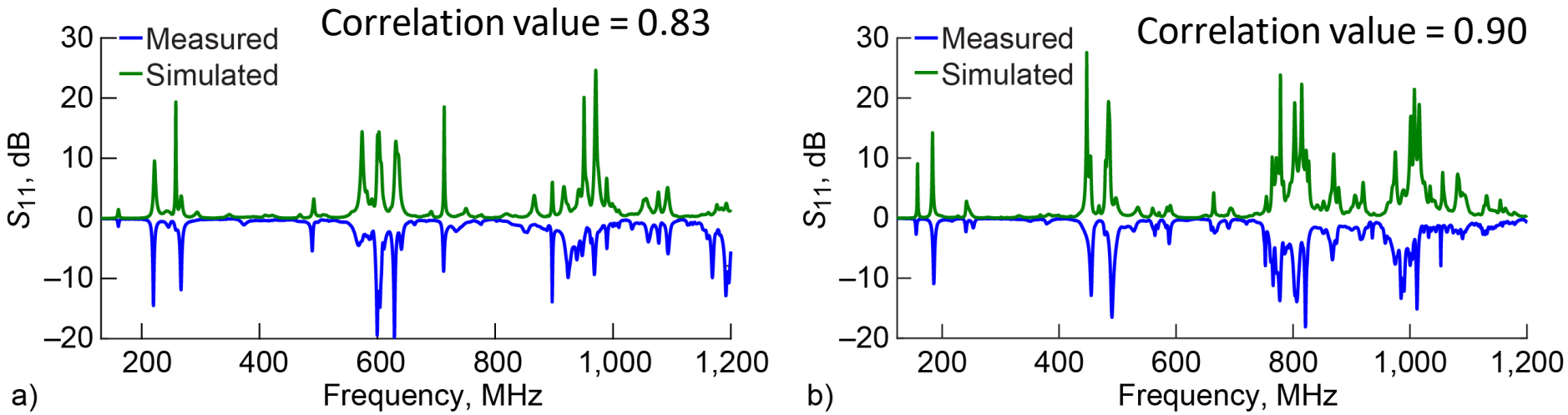



Copper Mountain R54 reflectometer is a one-port VNA

# RF MODELING TO CALCULATE SIMULATED SPECTRA

- Intuitive Machines provides CAD model of tank + internal hardware: Includes slosh baffles, PMD's, TVS HX tubing, pressurant diffuser, antenna & mounting bracket
- Build RF model of tank & simulate antenna sensor response using RF modeling software CST Studio Suite
- Adjust model as needed to achieve best correlation between measured and simulated spectra
- Methane tank has better match (higher correlation value), which generally results in higher accuracy

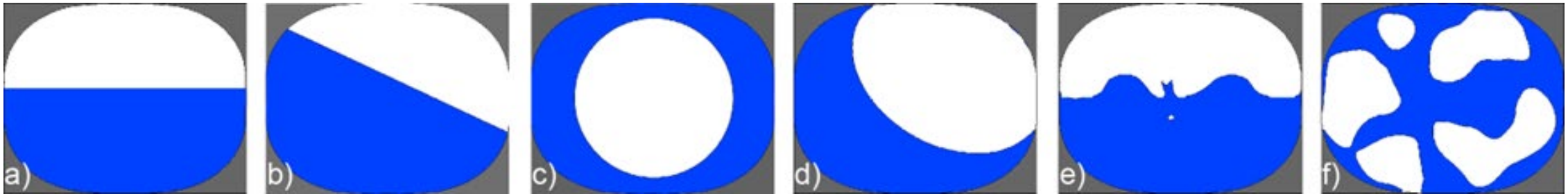



**Comparison of simulated and measured empty tank (no fluid) spectra for a) oxygen tank and b) methane tank. Simulated spectra are inverted for clarity.**

# FLUID CONFIGURATION MODELING

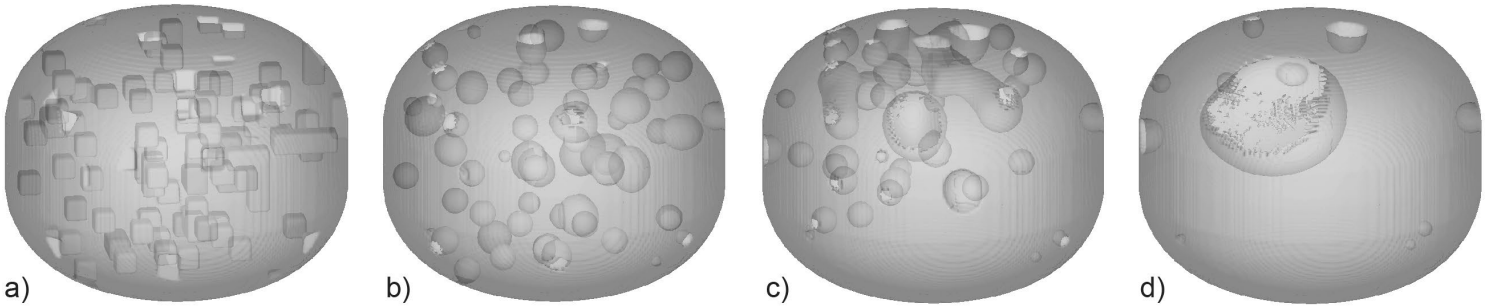
- Tank RF spectra change with propellant mass AND liquid configuration
- Conduct RF/fluid simulations at various fill levels and liquid configurations

Flow-3D sims

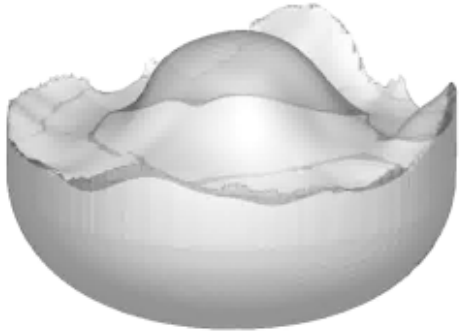



Settled | Tilt | Bubble | Low-g | Engine Burn | Random

Flow-3D simulation of Random fluid configuration




t = 0 s | 10 s | 60 s | 180 s



"Engine burn" CFD simulation

# RF/FLUID MODEL DATABASE

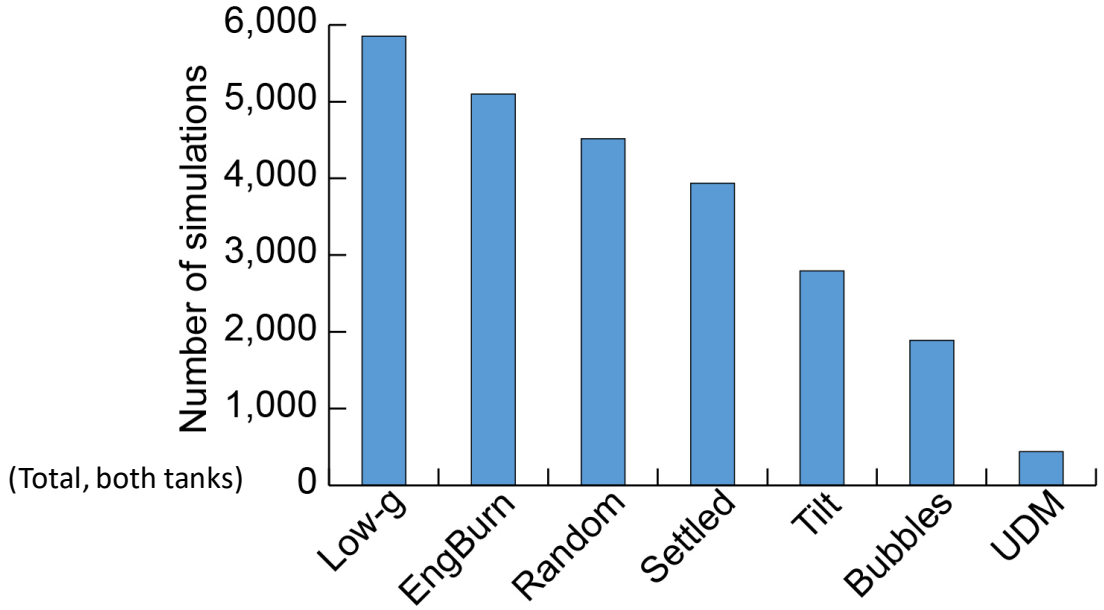
- CST Studio (RF modeling software) used to calculate S11 antenna response of combined tank/fluid model
  - Over 12,000 RF/fluid simulations were completed for each tank using 32 nodes on HPC cluster

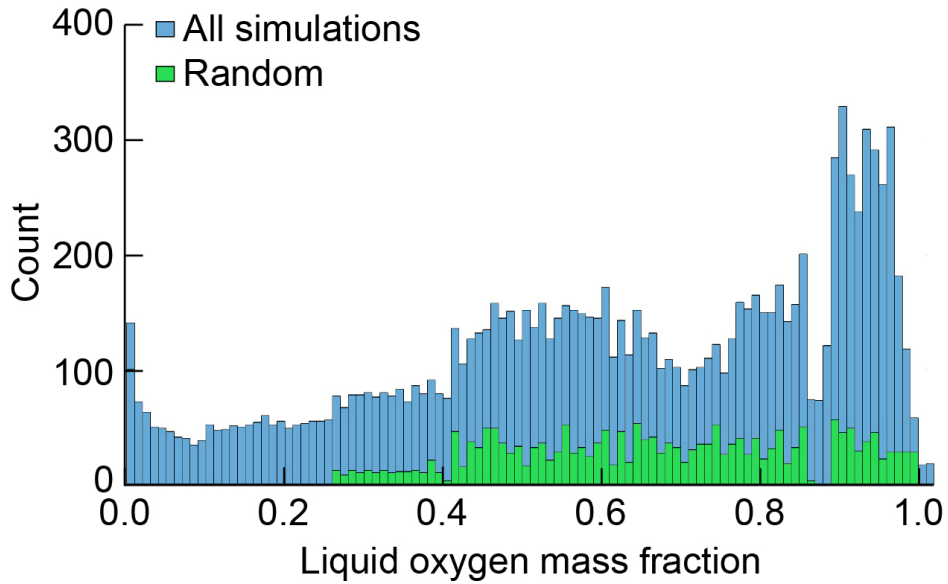
- The set of S11 antenna response simulations becomes the database against which measured S11 spectra are compared

- Gauging results are reported as a liquid mass fraction, $\phi_L$

$$\varphi_L = \frac{M_{LIQ}}{M_{REF}} \quad \text{where } M_{REF} = \rho_{LIQ} * V_{TANK}$$

$M_{REF}$ is the full tank liquid mass at 15 psi saturated vapor pressure



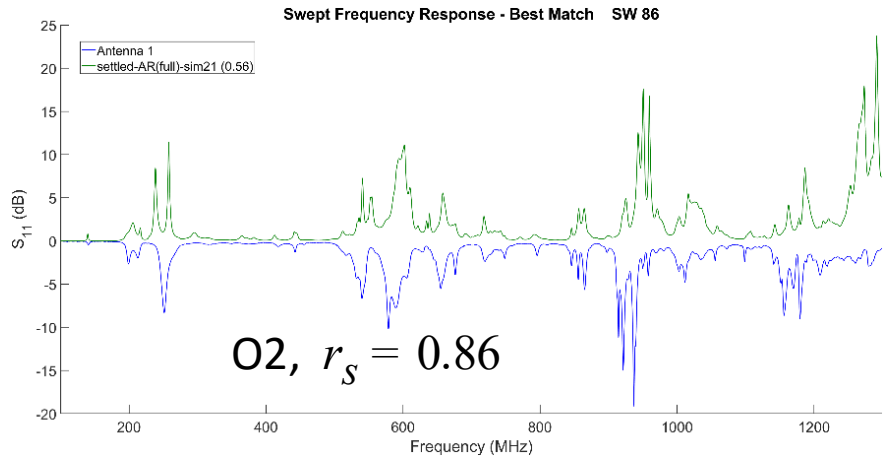



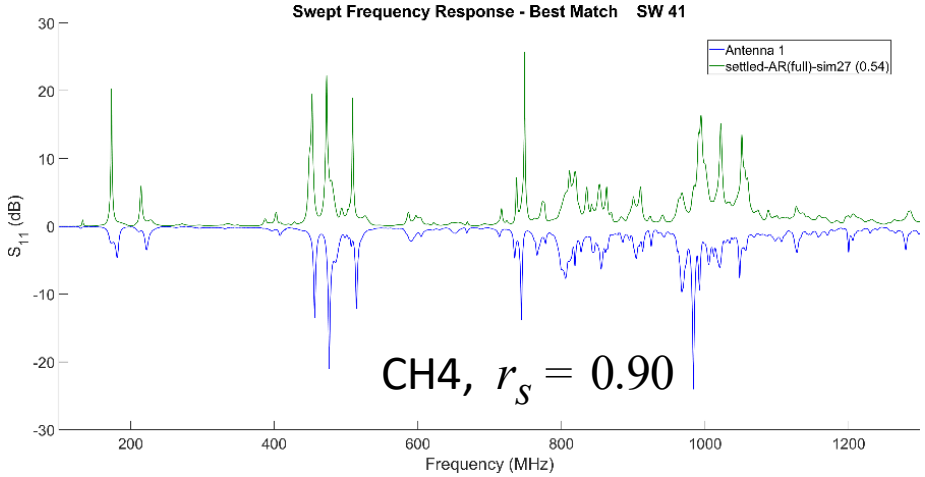
# GAUGING ALGORITHM

- Measured tank spectra are compared to the simulated spectra in the database
- The Spearman correlation coefficient ($r_s$) is computed for each pair of measured-simulated spectra
  - Spearman correlation is a rank-based correlation method

$$r_s = \frac{covariance(R_{exp}, R_{sim})}{\sigma(R_{exp})\,\sigma(R_{sim})}$$

- $R_{exp}, R_{sim}$ are the rank representations of experimentally measured and simulated S11 spectra
- $\sigma$ is the standard deviation of the rank representations

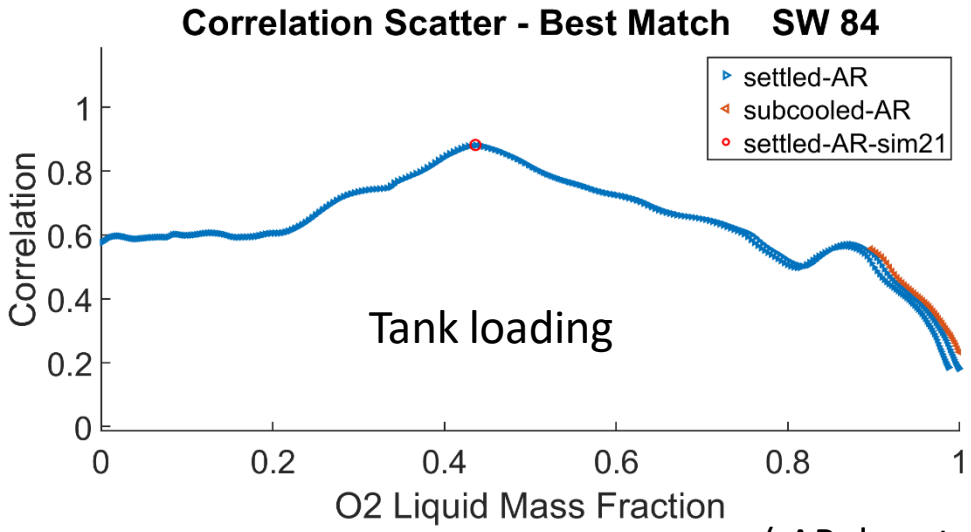


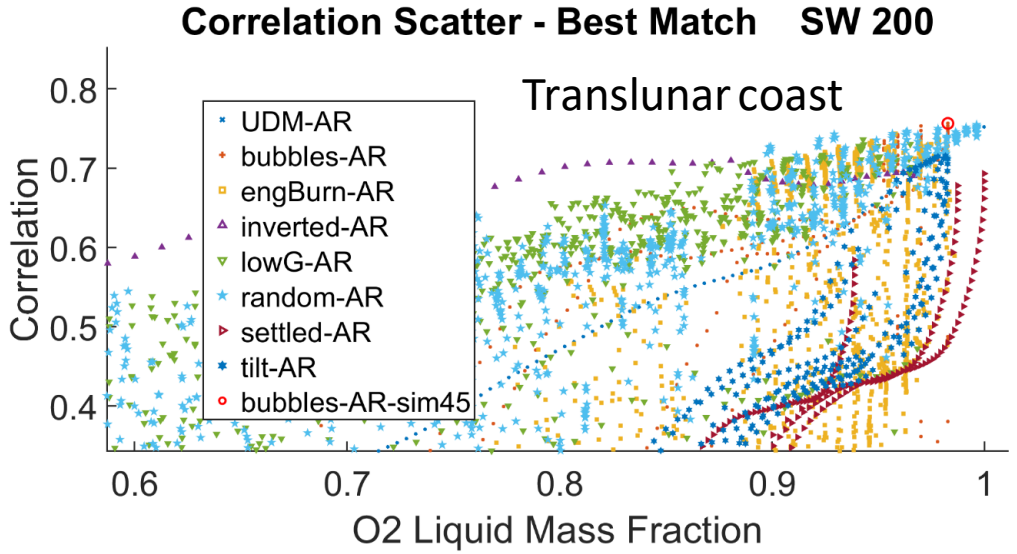




Best match spectra during propellant loading, near 55% fill

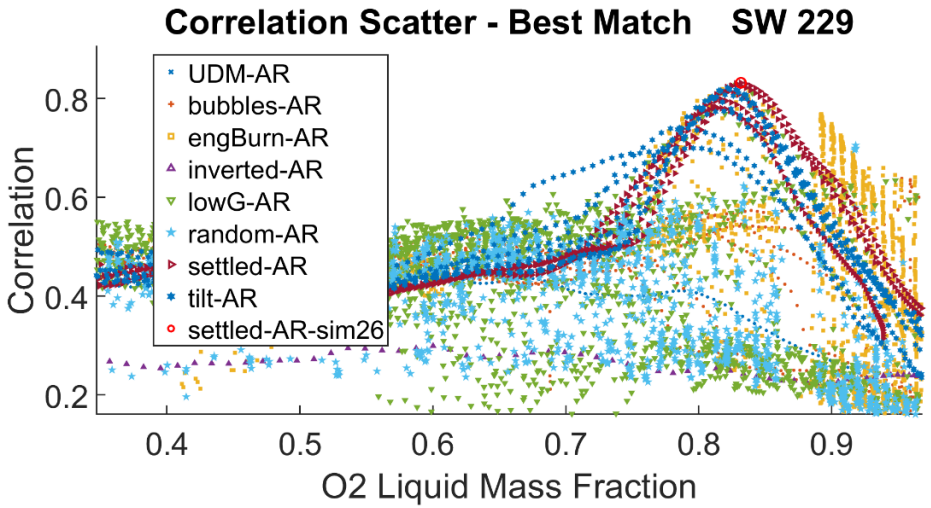
# EXAMPLE CORRELATION PLOTS

More examples in back-up charts

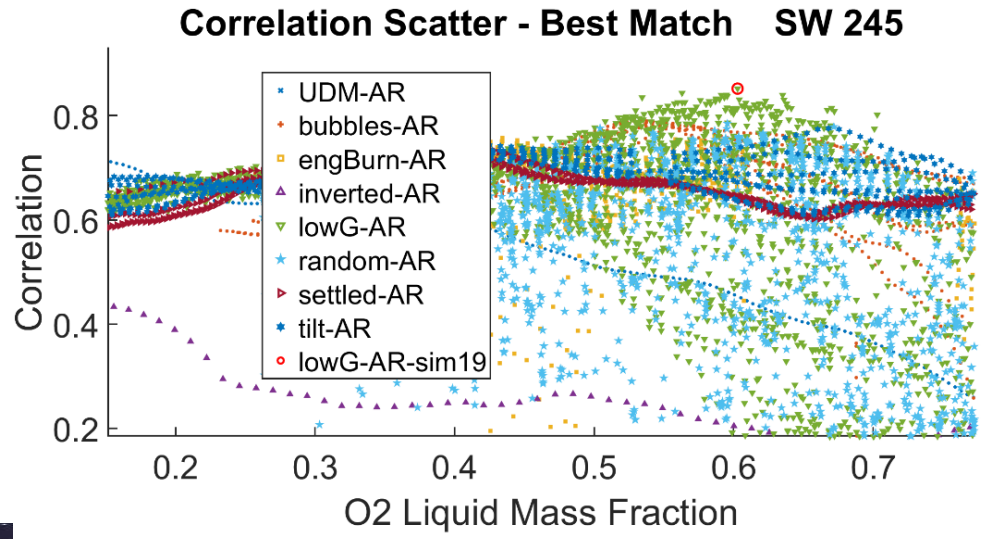



(-AR denotes antenna response simulations)



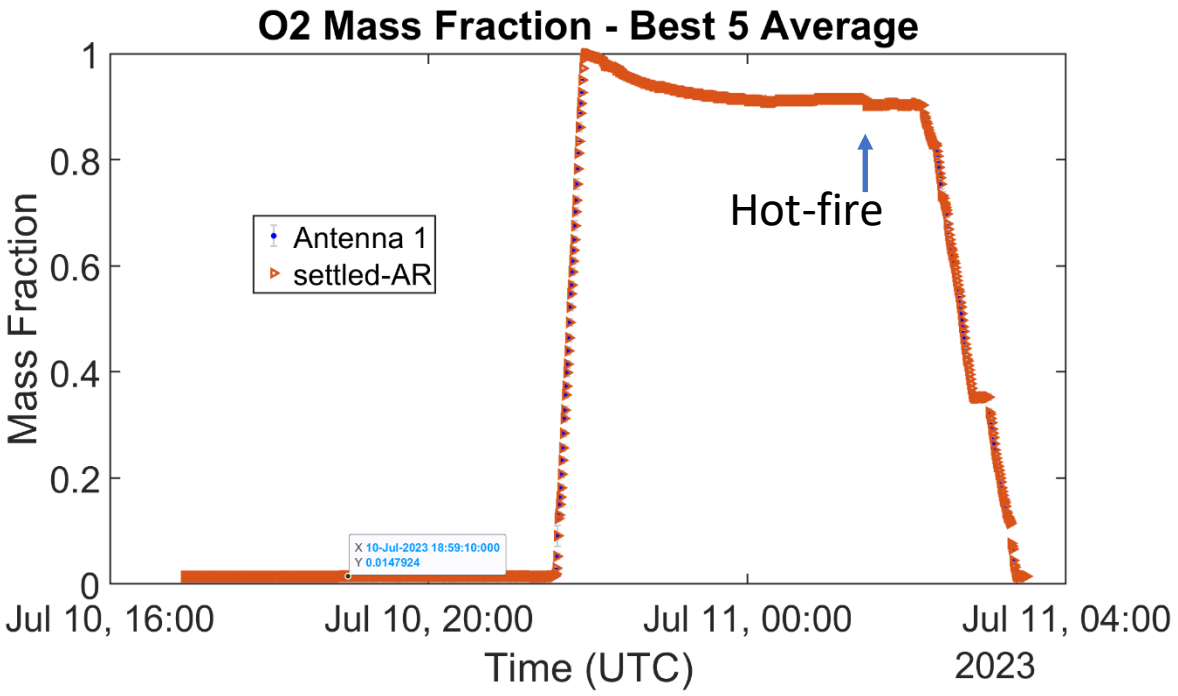

Lunar orbit insertion

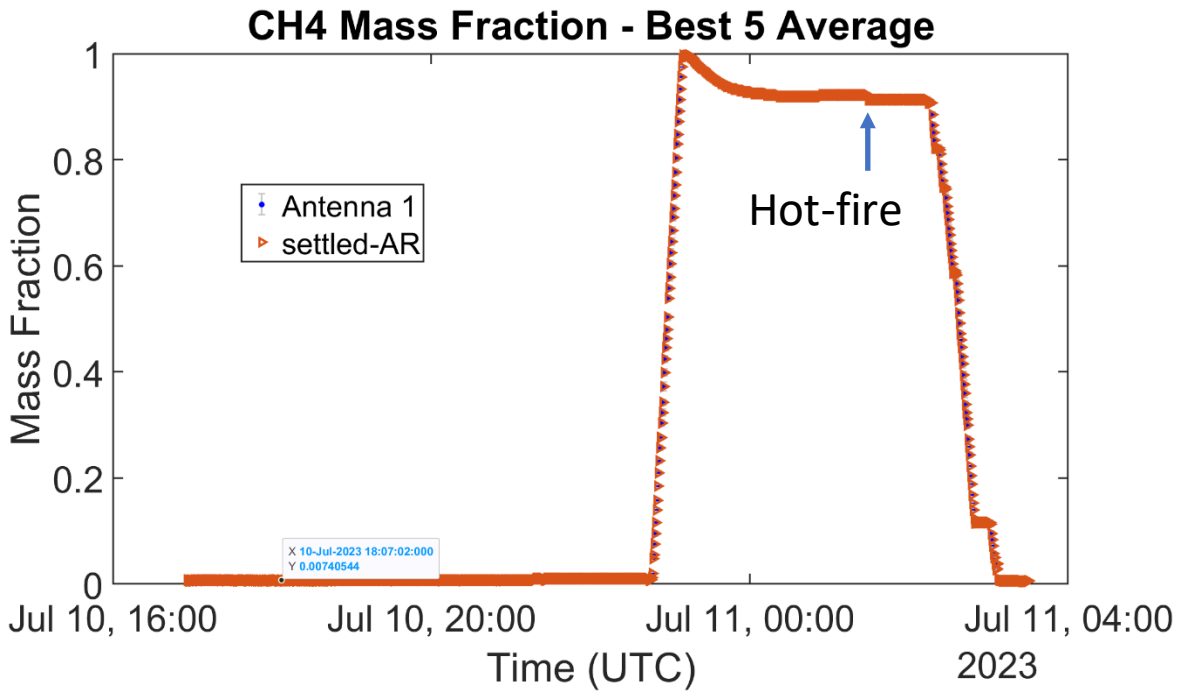



Low lunar orbit

# IM HOT-FIRE TEST: RFMG RESULTS

**Gauged liquid mass fraction, as a % of full-tank mass at 15 psi saturation**



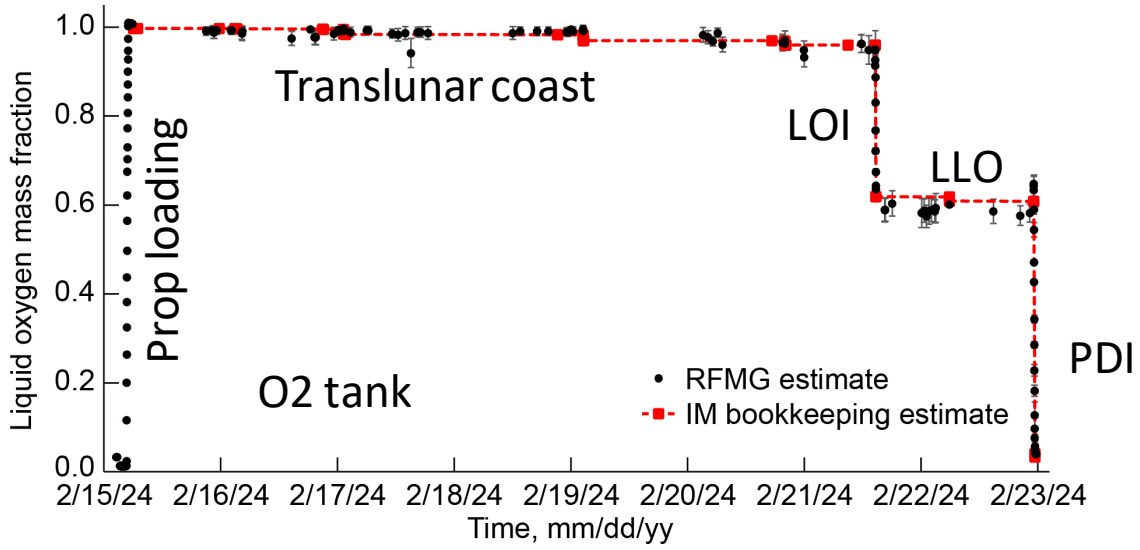



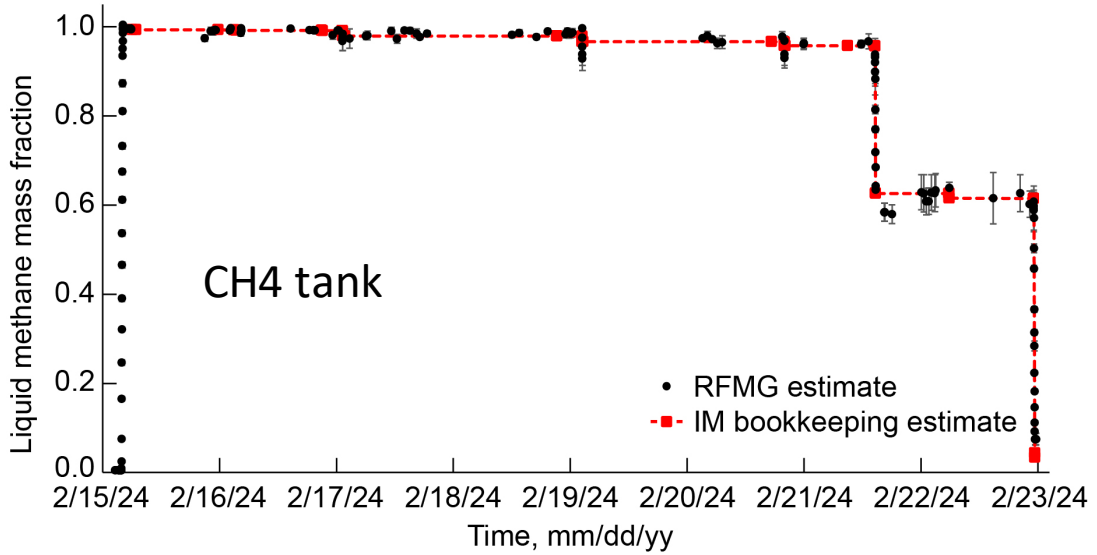

- Propellant depletion was detected by RFMG during the hot-fire test, which lasted a few seconds
- Delta-mass values in good agreement with IM estimate
- RFMG data compared with load cell data during tank loading
  - See back-up charts

| Tank | Mean err. ± Std.Dev. | 90th percentile O2 + CH4 |
|---|---|---|
| O2 | 1.5% ± 0.8% | 2.2% |
| CH4 | 1.0% ± 0.7% | |

# RFMG RESULTS FROM IM-1 MISSION

- RFMG data collected during all phases of the mission: Propellant loading on the launch pad; Translunar coast; Lunar orbit insertion (LOI); Low lunar orbit (LLO); Powered Descent Initiation (PDI) through post-touchdown.
- IM provided bookkeeping estimate of propellant mass and is indicated in the plots
- Error bars in the figures are not true error bars; they are the standard deviation of the best-5 (settled) or best-10 (unsettled) matches to the simulation database



# PRE-LAUNCH PROPELLANT LOADING

- RFMG was operated on the launch pad during prop loading
- SpaceX cooled the propellants below normal boiling point T
- RF sims included sub-cooled state
- Loaded mass in very good agreement with IM estimate

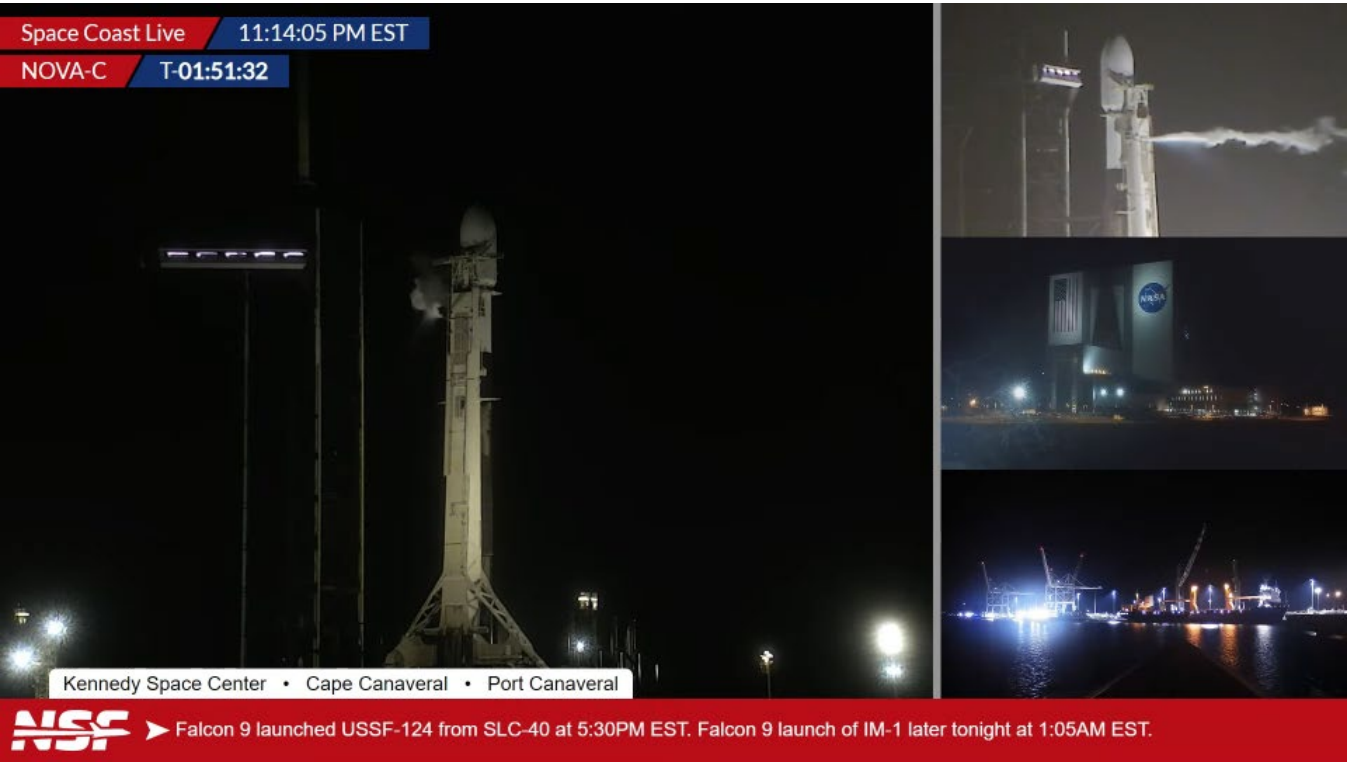
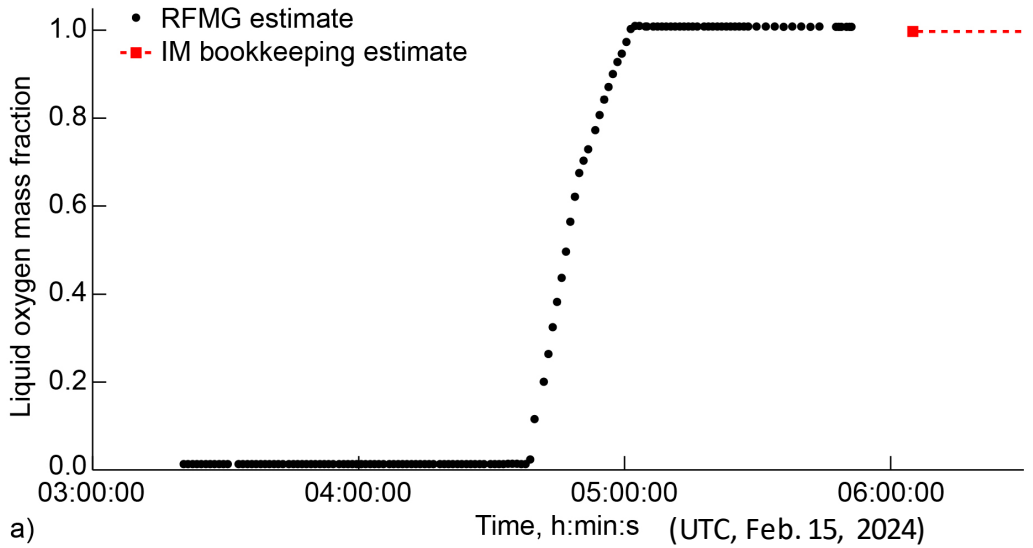
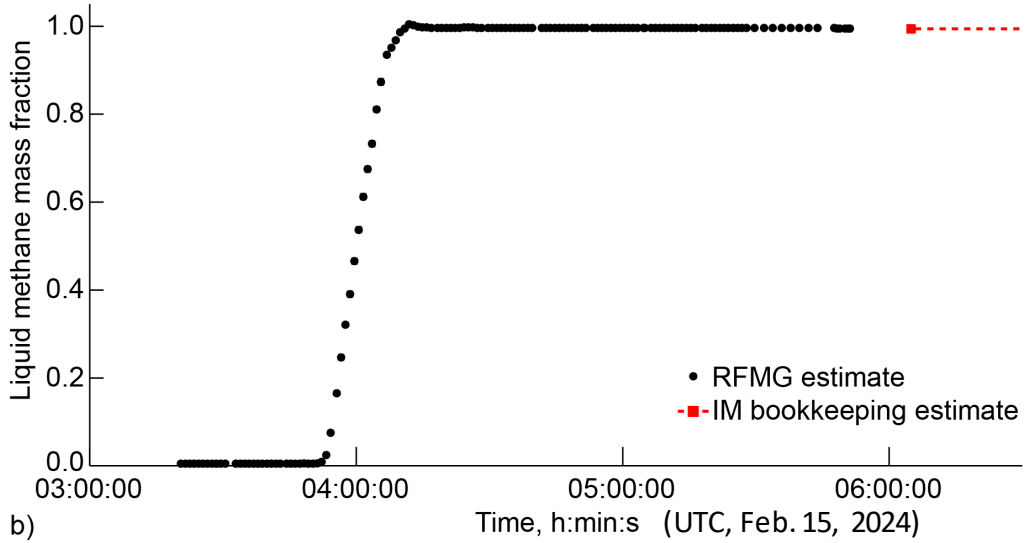


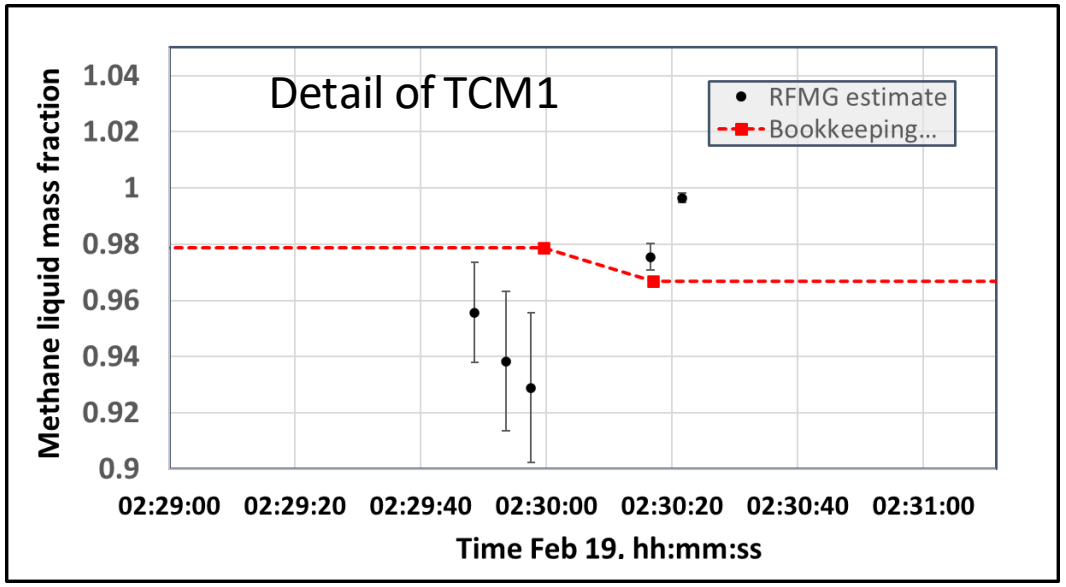

Image credit: nasaspaceflight.com (used with permission)



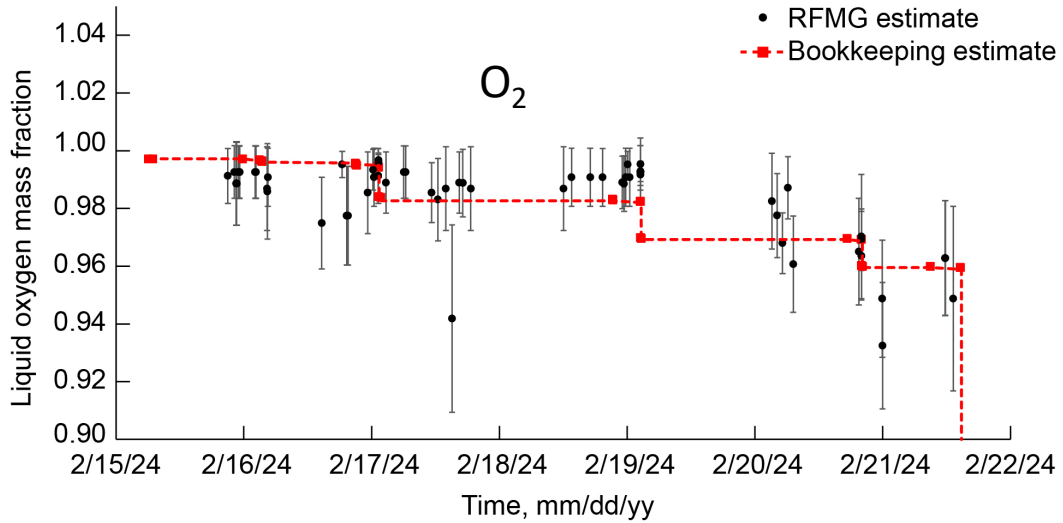
# TRANS-LUNAR COAST

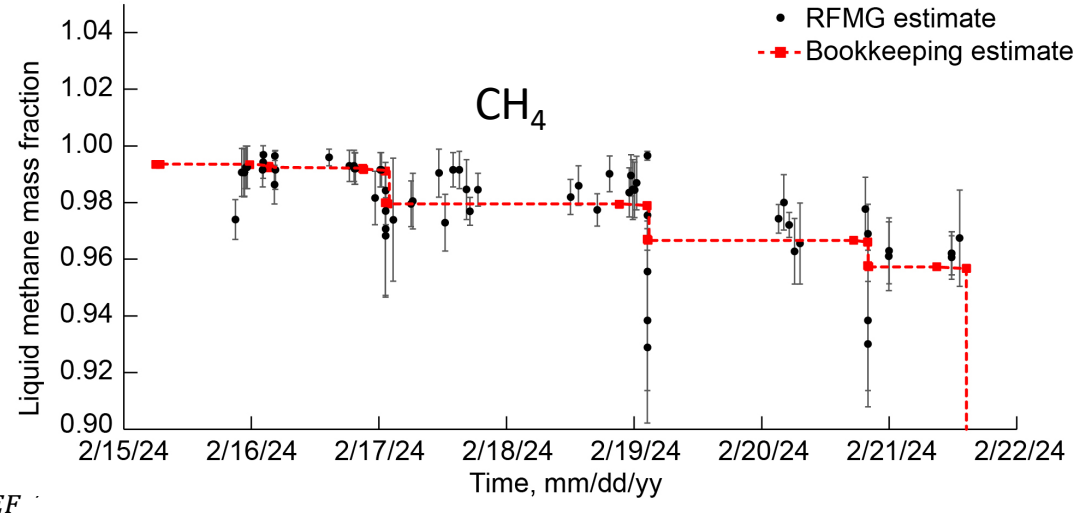
- RFMG powered-on 15 hr after launch
- Data collected during trans-lunar coast phase incudes three engine burns: Initial commissioning maneuver and two trajectory course maneuvers (TCM)




| Tank | Mean err. ± Std.Dev. | 90th percentile O2 + CH4 |
|---|---|---|
| O2 | 0.3% ± 1.1% | 1.8% |
| CH4 | 0.2% ± 1.3% | |

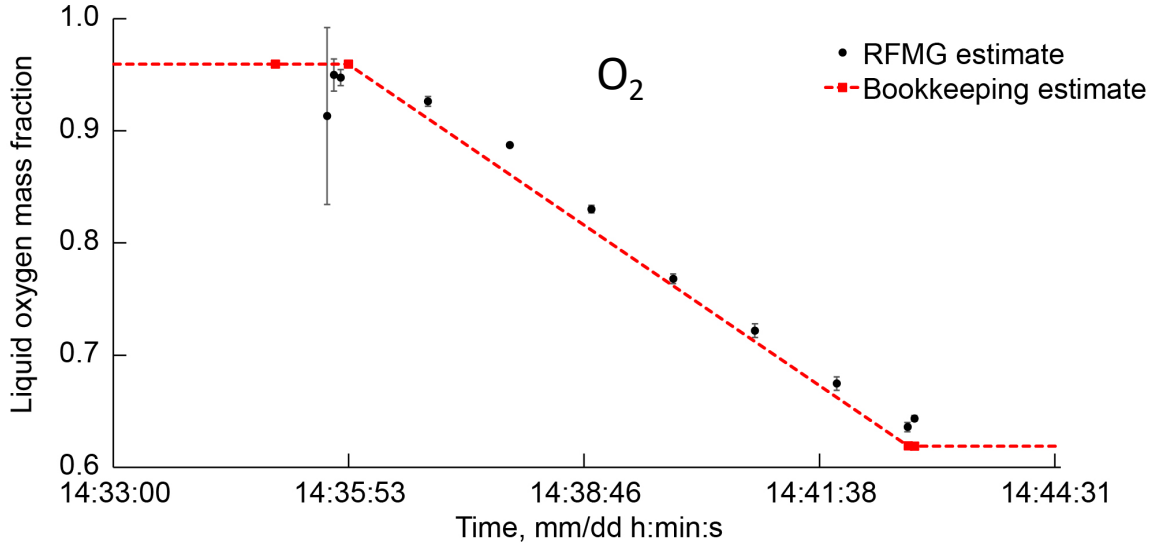
% value is with respect to $M_{REF}$

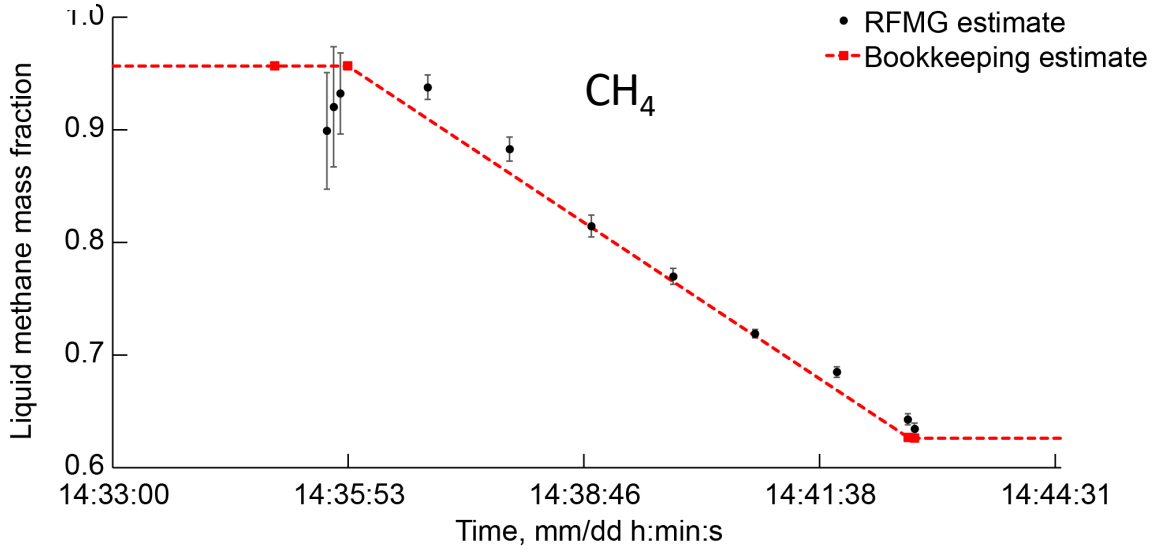


# LUNAR ORBIT INSERTION

- LOI burn on Feb 21
- Approximately 7-minute main engine burn period
- The three pre-Tig sweeps show variability, suggesting fluid motion during this period
- Overall good agreement with IM bookkeeping estimate
- RFMG data from LOI provided valuable information on engine performance



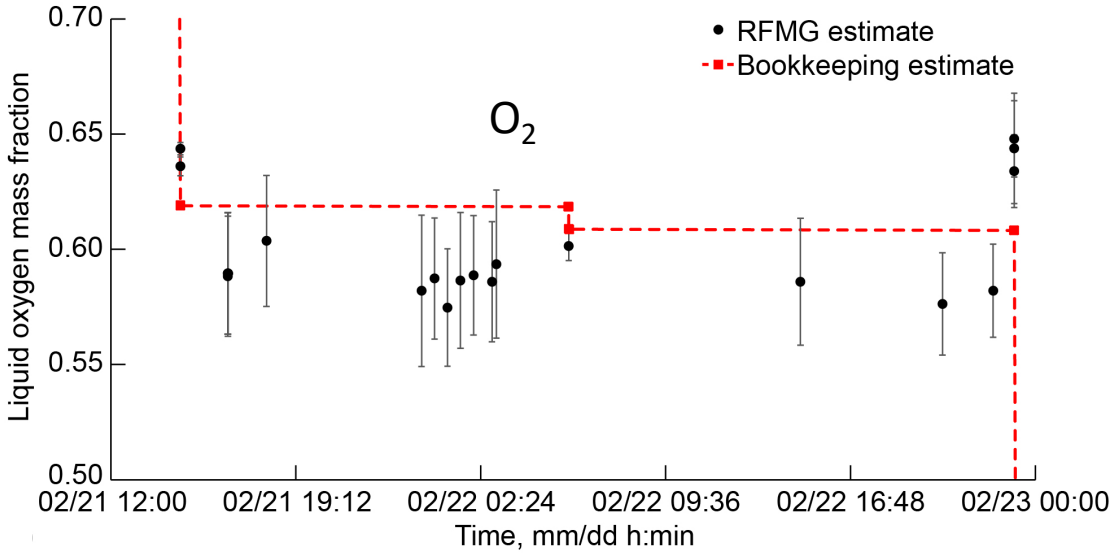



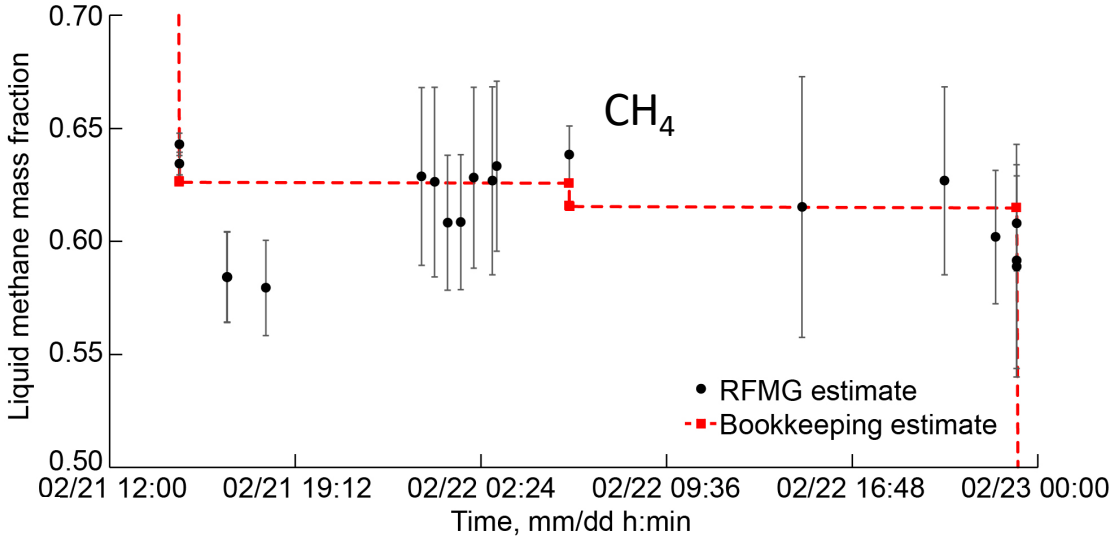
# LOW LUNAR ORBIT

- Approximately 35 hr in LLO, Feb 21-22
- One correction maneuver while in LLO
- First two RFMG data points in plot are just after LOI engine shutdown
- Except for data points on edge of LOI and PDI burns, gauged values in O2 tank are consistently low
  - Unclear why this is the case
  - Top 10 best matches for each point are all from the low-g simulation set

| Tank | Mean err. ± Std.Dev. | 90th percentile O2 + CH4 |
|---|---|---|
| O2 | -1.3% ± 2.8% | 4.0% |
| CH4 | -0.7% ± 1.9% | |

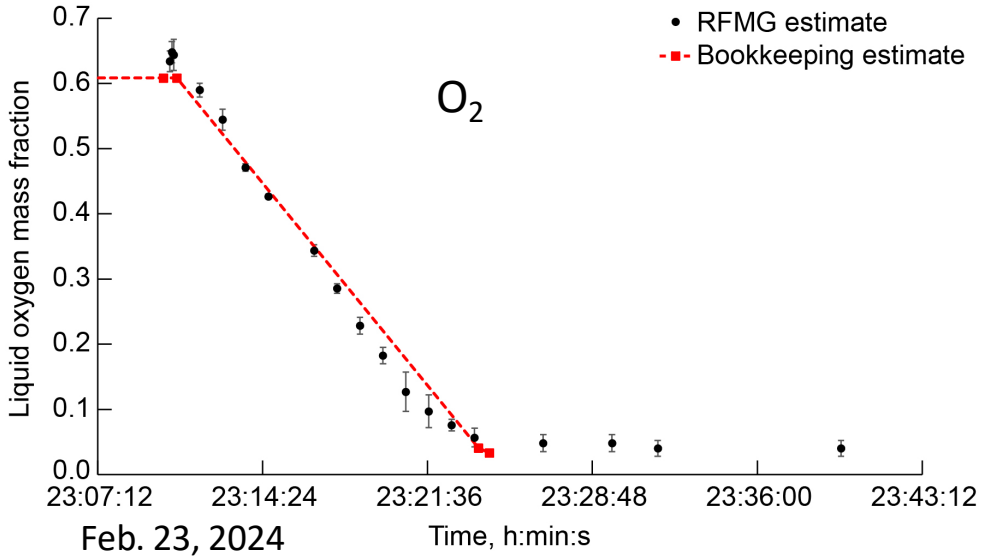
% value is with respect to $M_{REF}$

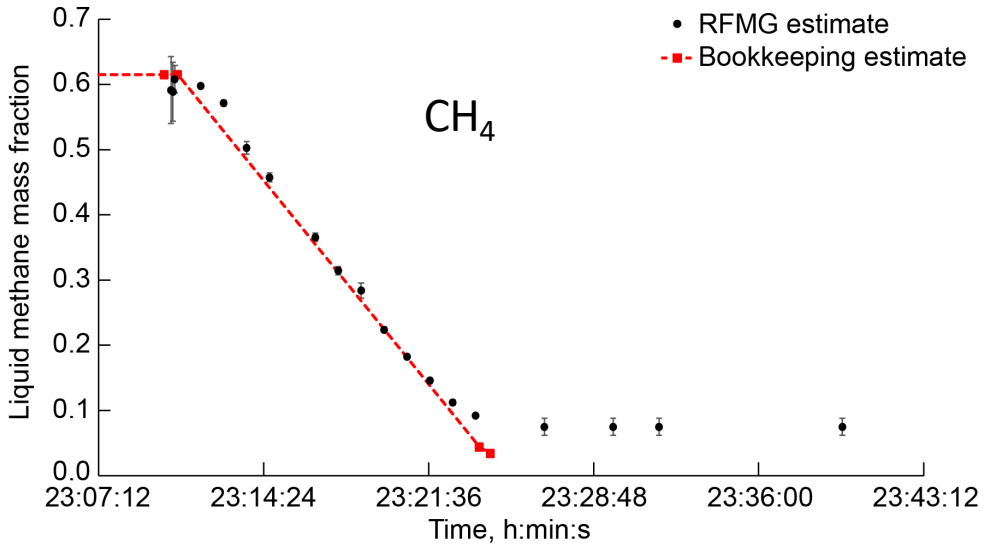


# POWERED DESCENT INITIATION – POST LANDING

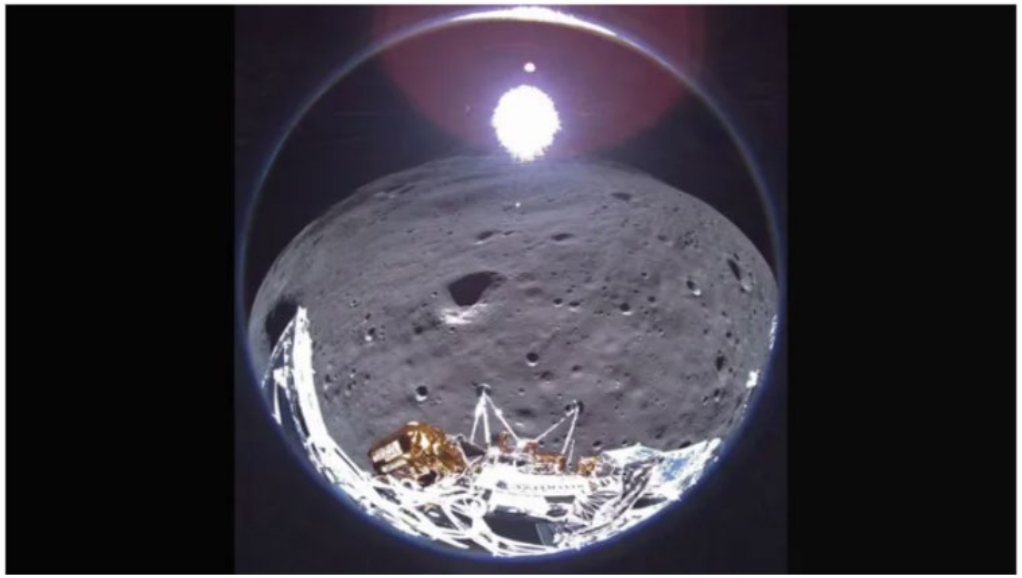
- RFMG data collected once/minute during PDI though touchdown and layover
- RFMG data files collected after landing had several missing data blocks. Two or more files were combined to create four complete data files.
- RFMG powered off ~ 2 hours after landing
- PDI through post landing data, as well as some other pre-PDI data was downlinked Feb. 26-28
- Post-mission RF/fluid simulations were run using 0-10% fill levels and several high tilt (layover) angles
  - Best matching sims had tilt angles in good agreement with IM's estimate of s/c orientation on lunar surface
- Surface ops ended on Feb. 29



# SUMMARY

- The RFMG instrument operated successfully on the IM-1 mission. It was operated as an instrument that was integrated into the IM Nova-C lander propulsion system.
  - It was not used for real-time gauging, but provided valuable information to the IM propulsion team throughout the mission
- The RFMG is the highest TRL technique for gauging cryogenic propellants in omni-g environments (TRL-8)
- The RFMG gauged results were generally within 2.2% of full-scale mass for 1g tests, and within 4% for low-g gauging measurements (90$^{th}$ percentile values)
- The minimum mission-success criteria for RFMG data was to downlink 100 files, we received 130.
- The complexity of the RF models certainly contributed to some of the gauging error/uncertainty



Odysseus' final farewell image of its landing site on the moon's south pole. (Image credit: Intuitive Machines)

| Event | O2, liq mass Error ± STDEV | CH4, liq mass Error ± STDEV | 90$^{th}$ percentile |
|---|---|---|---|
| 1g, Hot Fire test | 1.5% ± 0.8% | 1.0% ± 0.7% | 2.2% |
| Translunar coast | 0.3% ± 1.1% | 0.2% ± 1.3% | 1.8% |
| Low lunar orbit | -1.3% ± 2.8% | -0.7% ± 1.9% | 4.0% |

% value is with respect to $M_{REF}$

# ACKNOWLEDGEMENTS


- This work was supported by NASA through the Space Technology Mission Directorate through the Cryogenic Fluid Management Portfolio Program and the NASA Science Mission Directorate

- Thanks to the RFMG team at GRC and all the facility personnel that supported hardware build-up and testing

- Thanks to the NASA Commercial Lunar Payload Services (CLPS) program office for assisting in payload integration and mission operations logistics

- Special thanks to Intuitive Machines for successful integration and operation of the RFMG on the IM-1 mission

# Back-up charts

## *Mission Details*

- *Lander/ Launch Provider*: Nova-C / SpaceX Falcon 9
- *Launch Date:* Feb 15, 2024
- *Landing Date:* Feb 23, 2024
- *Surface Ops End:* Feb 29, 2024
- *Landing Site:* South Pole, Malapert A

## *NASA Manifest*

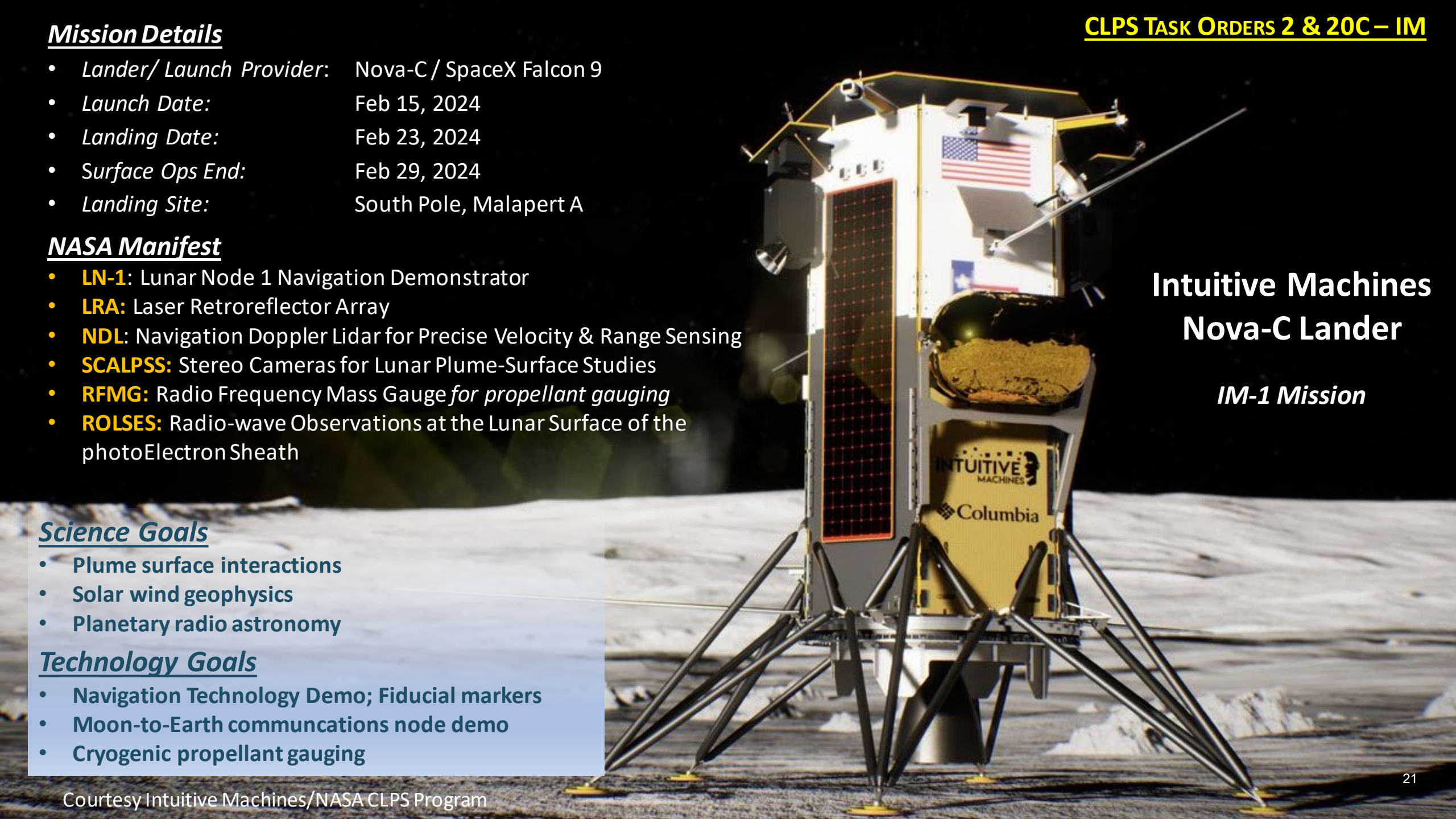
- **LN-1**: Lunar Node 1 Navigation Demonstrator
- **LRA:** Laser Retroreflector Array
- **NDL**: Navigation Doppler Lidar for Precise Velocity & Range Sensing
- **SCALPSS:** Stereo Cameras for Lunar Plume-Surface Studies
- **RFMG:** Radio Frequency Mass Gauge *for propellant gauging*
- **ROLSES:** Radio-wave Observations at the Lunar Surface of the photoElectron Sheath

## *Science Goals*

- **Plume surface interactions**
- **Solar wind geophysics**
- **Planetary radio astronomy**

## *Technology Goals*

- **Navigation Technology Demo; Fiducial markers**
- **Moon-to-Earth communcations node demo**
- **Cryogenic propellant gauging**




**Intuitive Machines Nova-C Lander**

***IM-1 Mission***

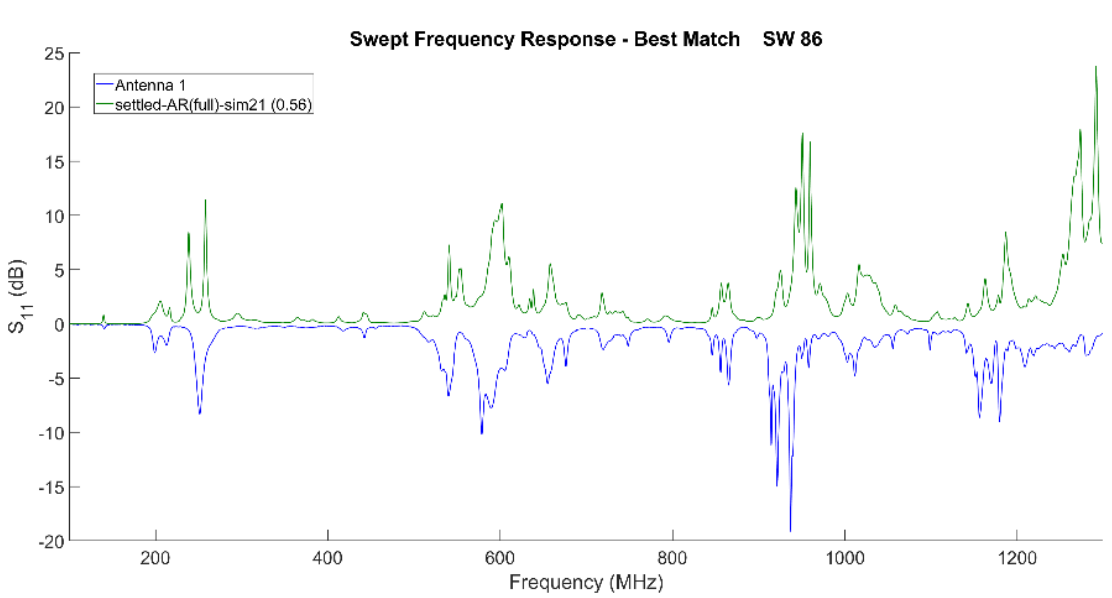
Courtesy Intuitive Machines/NASA CLPS Program

# MODEL ACCURACY

- **O2 Tank - Sweep spectra vs. best-match sim spectra at two fill levels during propellant loading:**

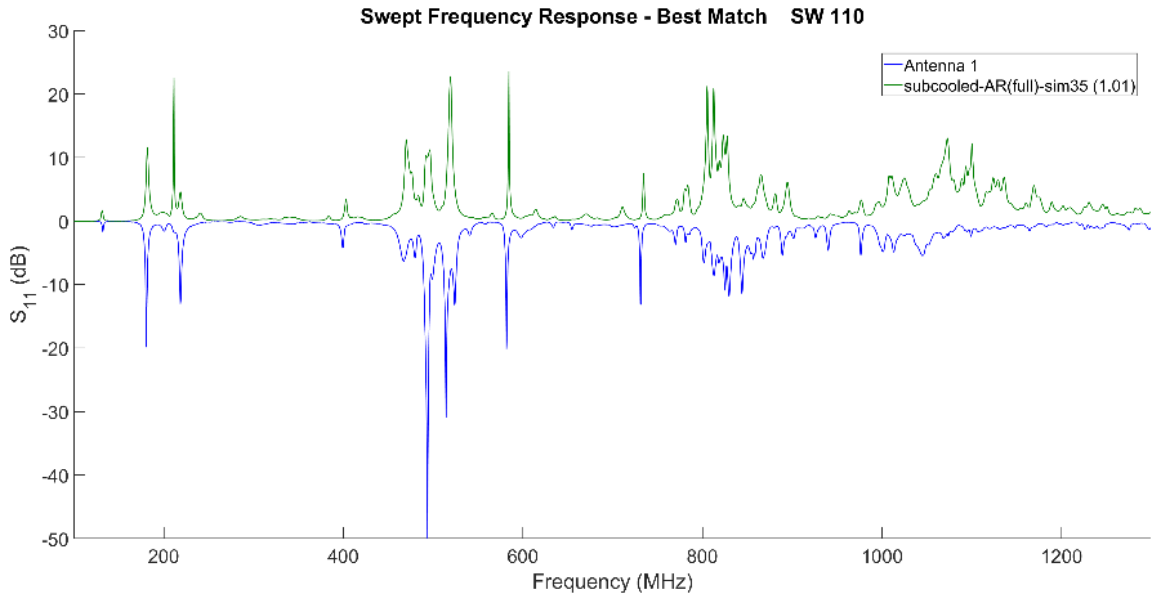
Liquid Mass Fraction = 0.56

Correlation = 0.86




Liquid Mass Fraction = 1.01

Correlation = 0.79

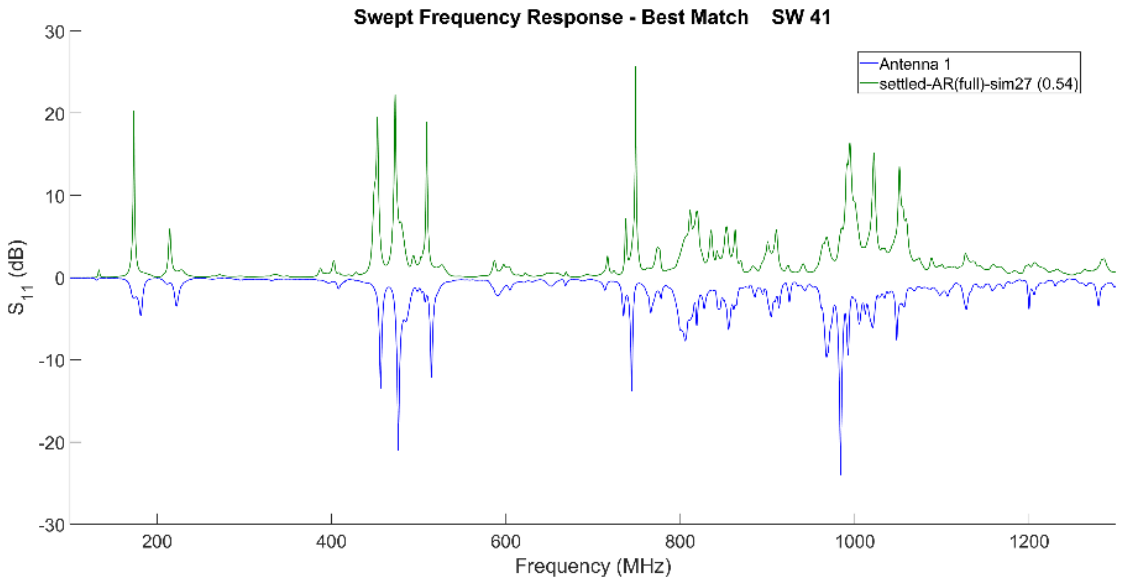


# MODEL ACCURACY

- **CH4 Tank - Sweep spectra vs. best-match sim spectra at two fill levels during launch pad propellant loading:**

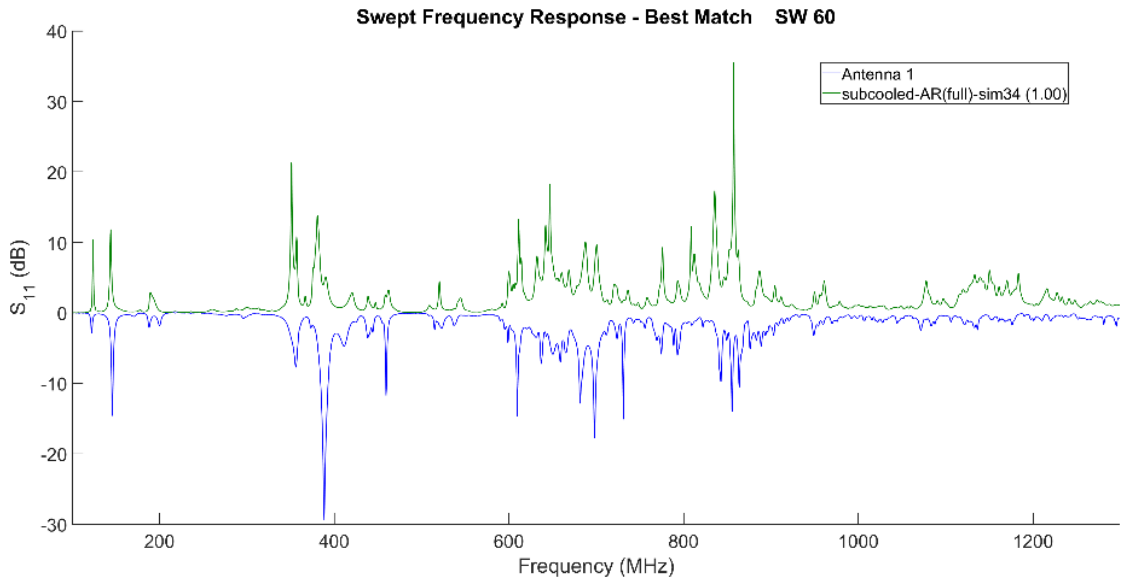
Liquid Mass Fraction = 0.54

Correlation = 0.90



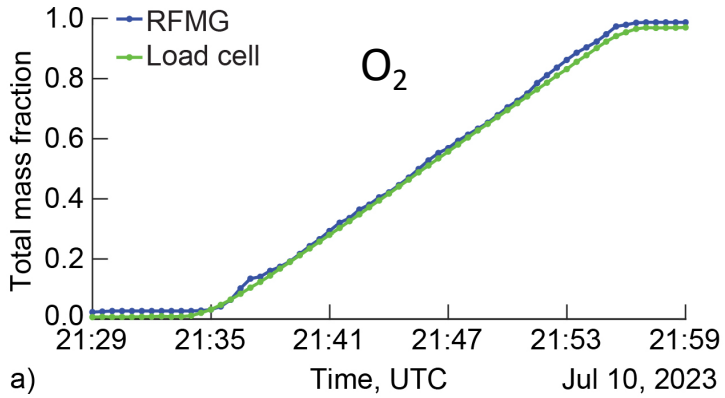

Liquid Mass Fraction = 1.00

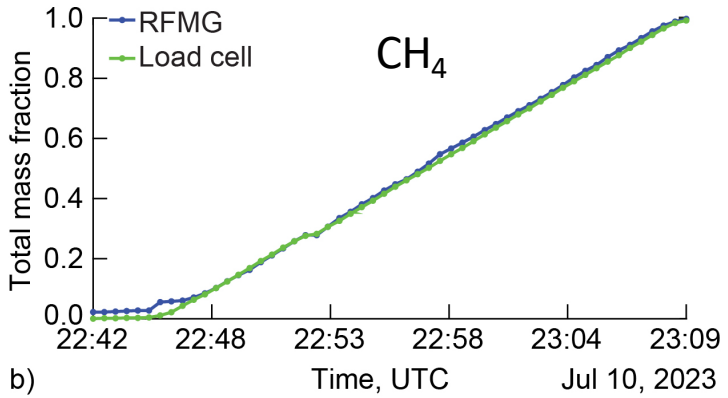
Correlation = 0.79

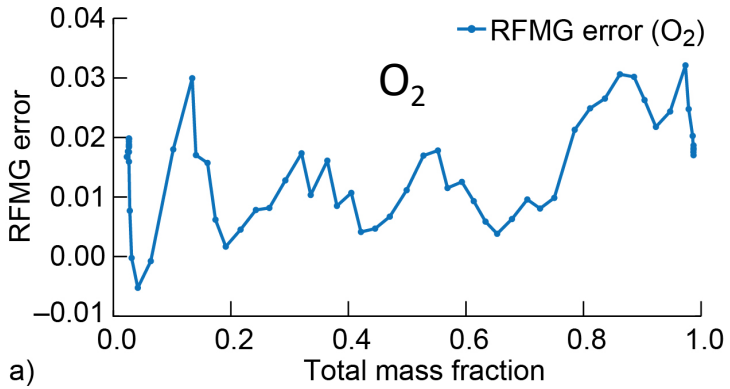


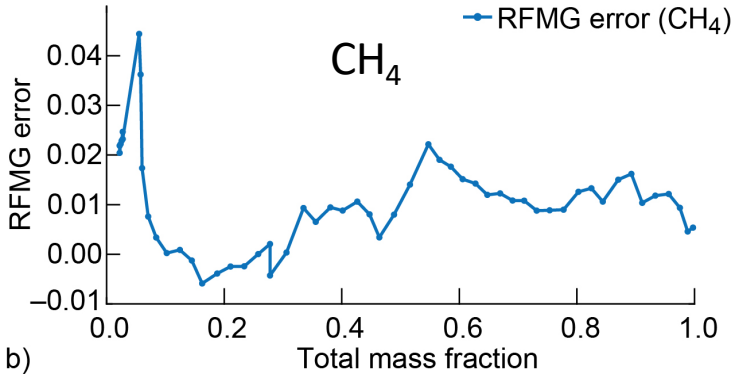
# IM HOT FIRE TEST – RFMG ERROR ANALYSIS

- Intuitive Machines collected load cell data during the test
- $O_2$ tank was filled first; $O_2$ boil-off during $CH_4$ tank fill was accounted for during $CH_4$ tank loading




$$RFMG\ error = \frac{RFMG_{mass} - LoadCell_{mass}}{M_{REF}}$$

$M_{REF}$ is the full tank liquid mass at 15 psi saturated vapor pressure

| Tank | Mean err. ± Std.Dev. | 90th percentile O2 + CH4 |
|---|---|---|
| O2 | 1.5% ± 0.8% | 2.2% |
| CH4 | 1.0% ± 0.7% | |

% value is with respect to $M_{REF}$

# MISSION OPERATIONS & ANALYSIS

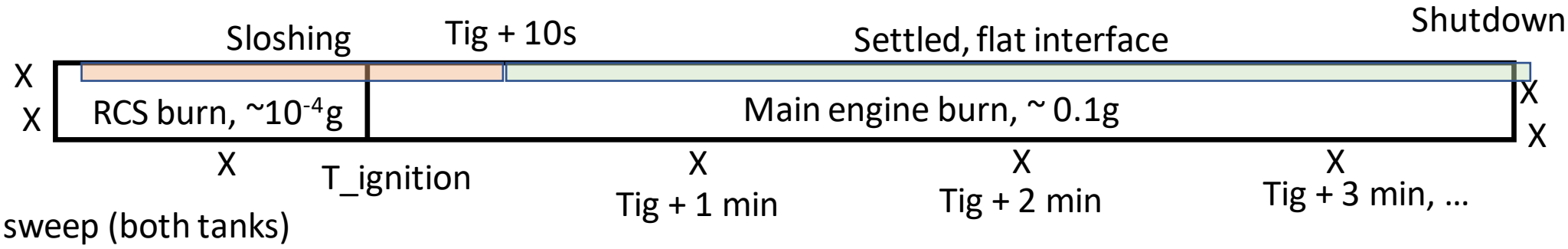
- RFMG data collected during all phases of the mission
- 35% of RFMG data collected was downlinked and analyzed
- The RFMG instrument functioned very well, though there was a clock drift relative to s/c clock (~ minutes)
  - RFMG clock data was corrected using Tig times as reference points

| Mission Phase | # RFMG files downlinked/collected | Notes |
|---|---|---|
| Pre-launch prop loading | 139/139 ` | 1g settled |
| Trans-lunar coast | 84/252 | Micro-g + TCM ~ 98% fill |
| Lunar Orbit Insertion | 11/11 | ~ 0.1 g settled |
| Low Lunar Orbit | 20/80 | Micro-g + TCM |
| Powered Descent | 12/12 | ~ 0.1 g settled |
| Post- landing | 4 (17 partial files)/105 | 1/6 g, tilted |
| Total in-space | 131/372 | 4.6 MB/12.3 MB |

# RFMG DATA COLLECTION DURING MAIN ENGINE BURNS

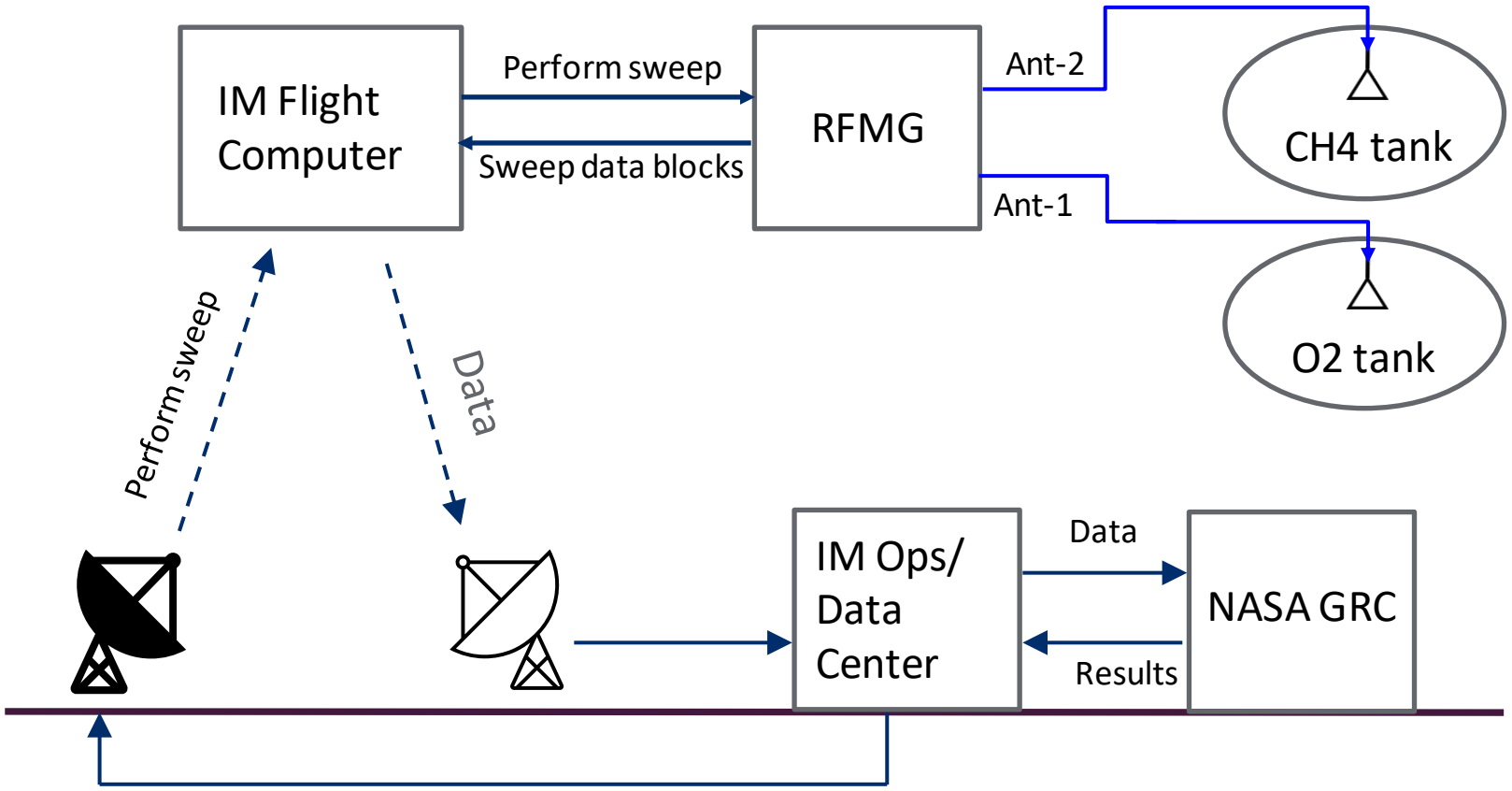
- A pre-programmed (s/c computer) sequence of RFMG sweeps takes place during main engine burns
- Prior to the main engine ignition, two RFMG sweep files are collected in the pre-settling phase
- Another RFMG measurement is made during or after the RCS burn
- After main engine ignition (Tig) RFMG data collection triggers are at 1-minute intervals
- Two RFMG measurements are made after engine shutdown (5 s apart)
- If the main engine burn is less than one minute, no RFMG data is collected during the burn, just at shutdown

- Flow-3D sims indicate RCS burn sloshing lasts until Tig + 10s, then the liquid is settled
- Flow-3D sims indicate that, after engine shutdown, the fluid transitions from settled to unsettled with 5-10 s



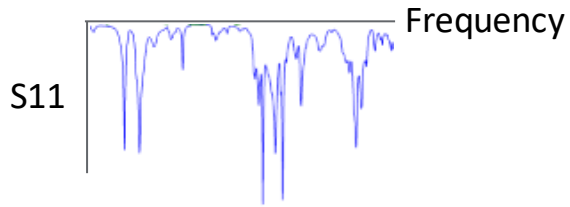

X = RF sweep (both tanks)

# RFMG MEASUREMENT




**RFMG Sweep File**

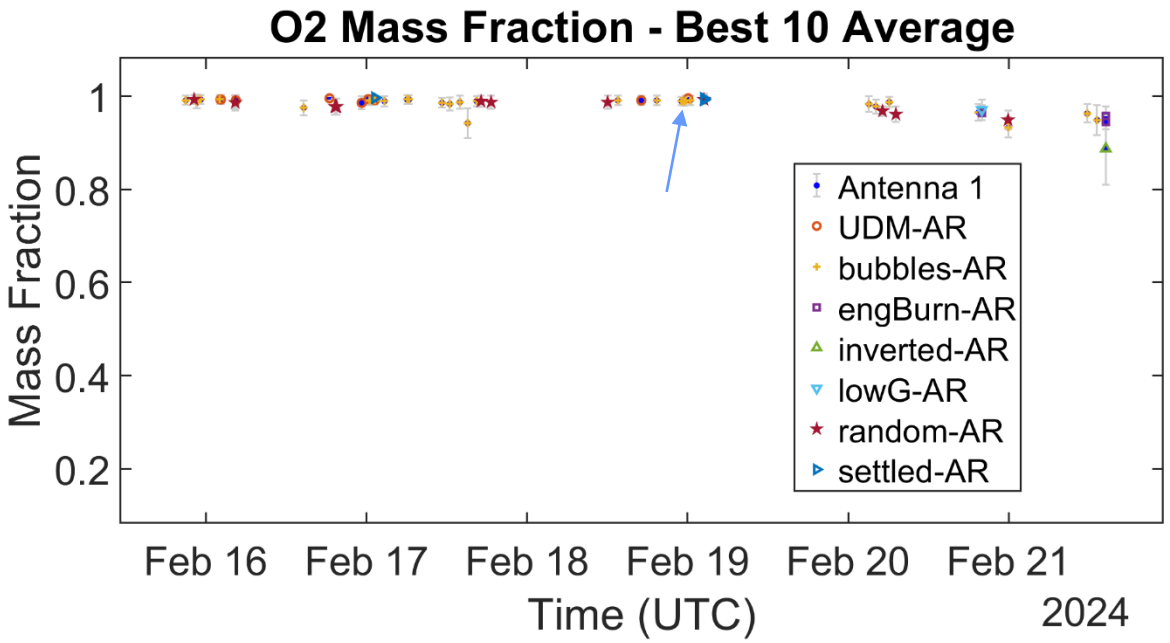
- 3,000 frequency points (100 – 1300 MHz)
- Each sweep file contains O2, CH4 tank spectrum



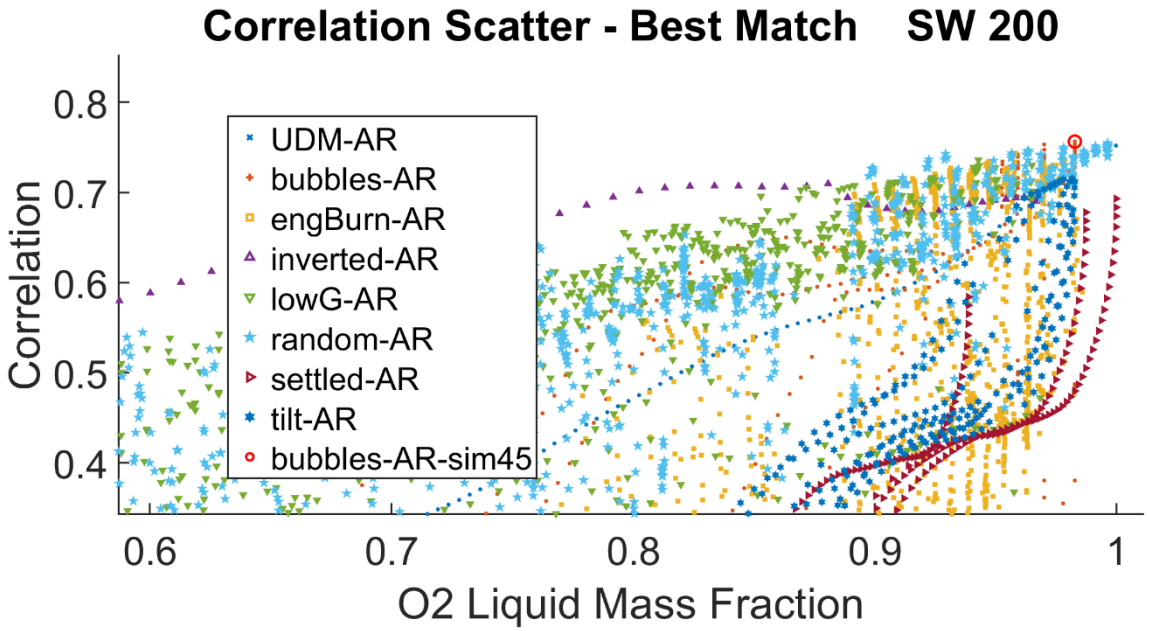

- Most RFMG sweep commands are issued from the ground
- During engine burns, the IM flight computer issued a predetermined sequence of RFMG sweeps

# O2 TANK- BEST MATCH SIM SETS

**Translunar coast**




Arrow indicates selected point(s) for correlation scatter plot(s)

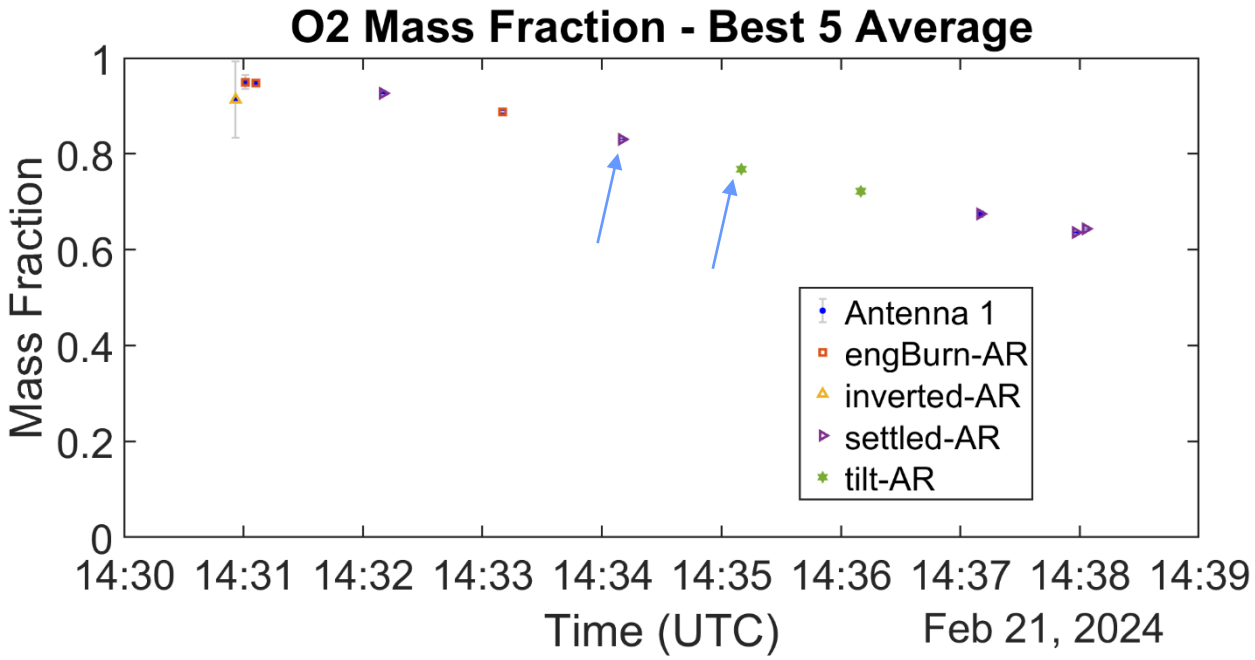



Red circled point indicates best match

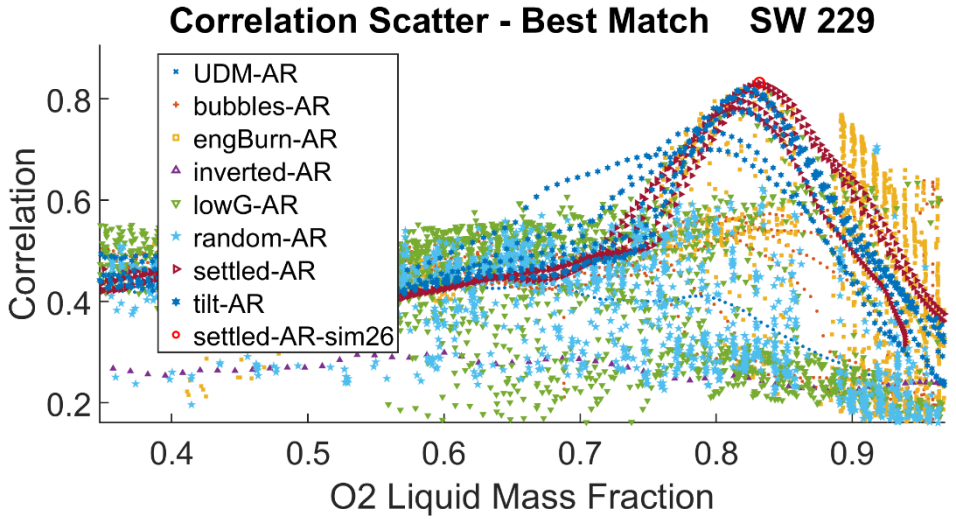
(-AR denotes antenna response simulations)

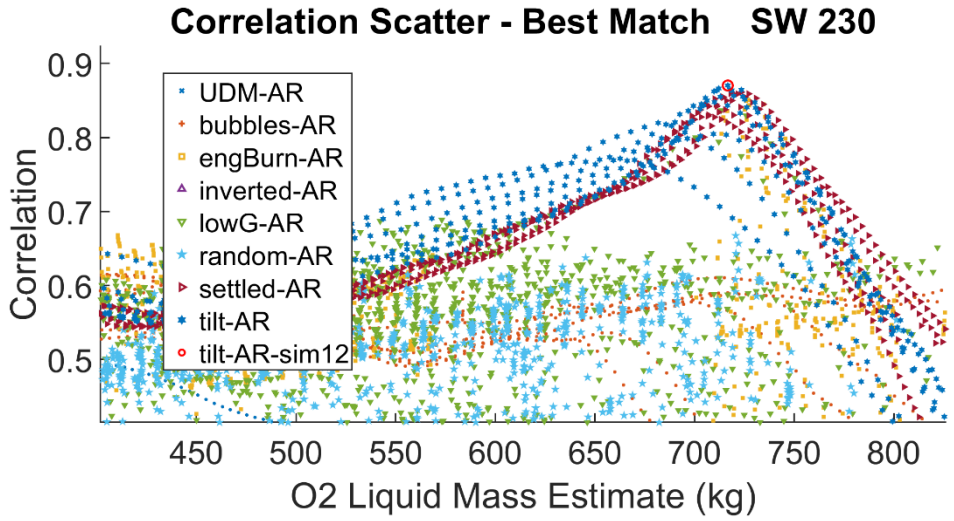
# O2 TANK- BEST MATCH SIM SETS

**Lunar orbit insertion**




Arrow indicates selected point(s) for correlation scatter plot(s)

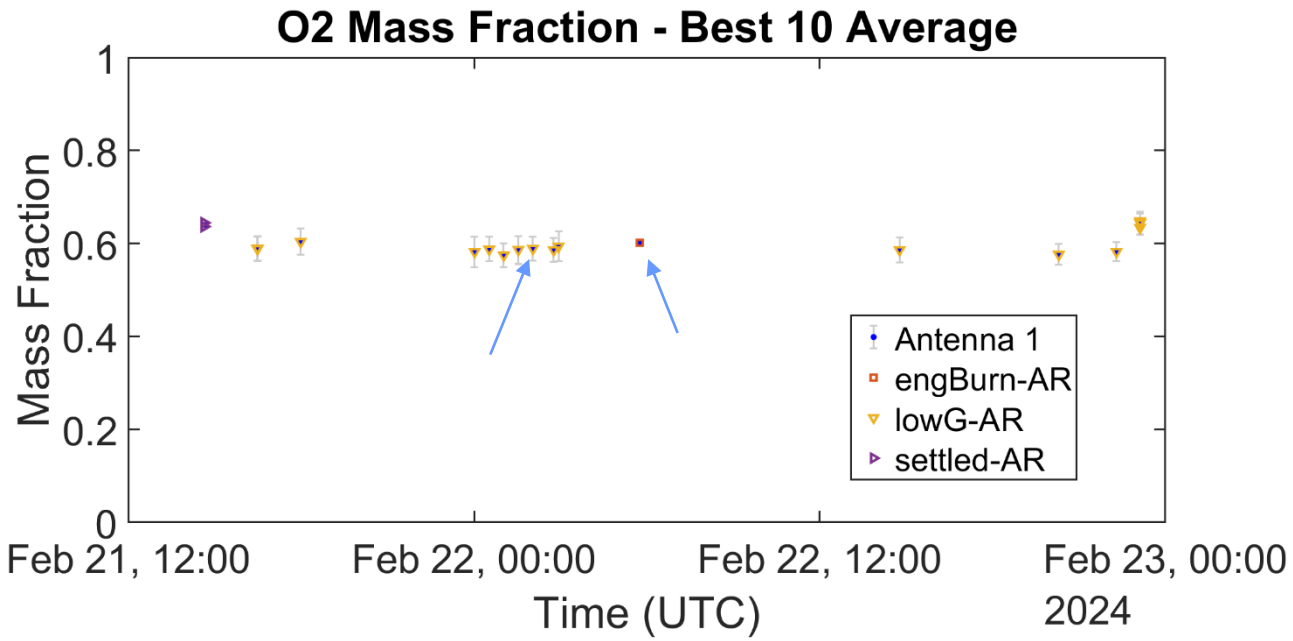


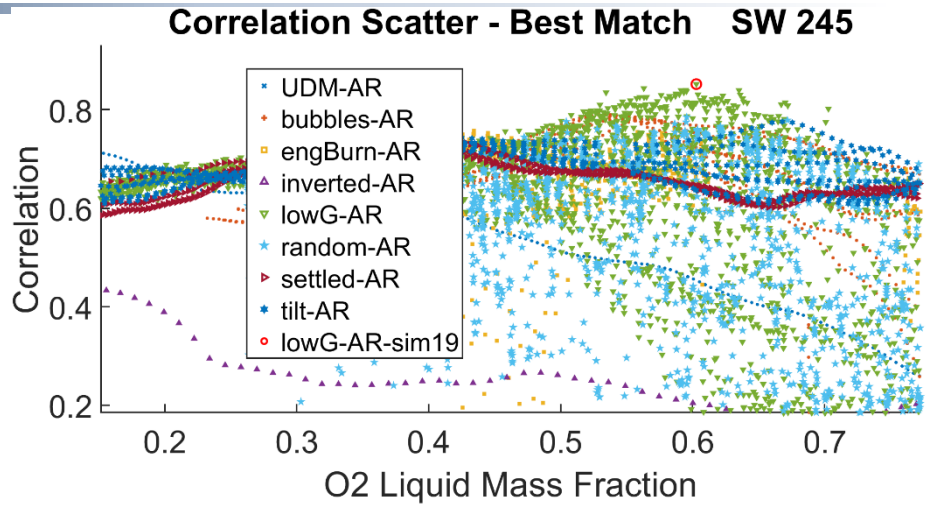

Red circled point indicates best match

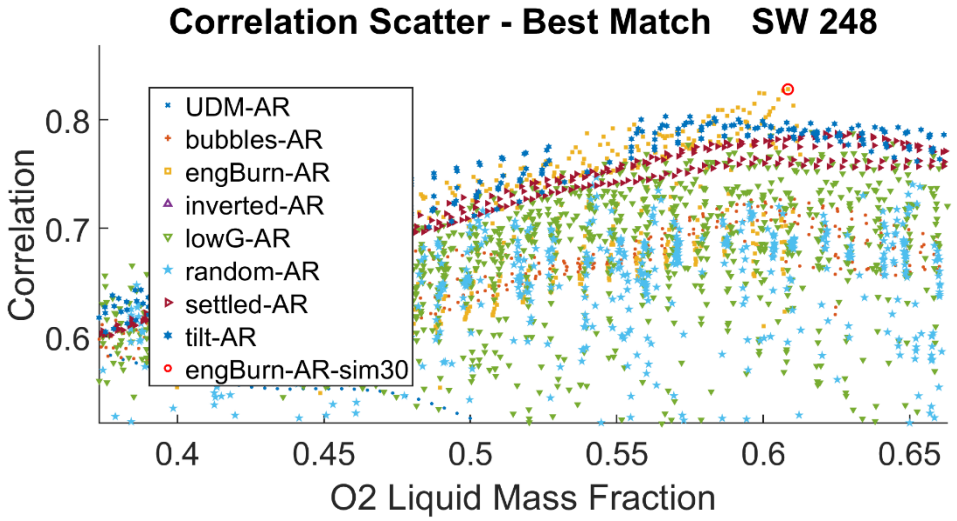
# O2 TANK- BEST MATCH SIM SETS

**Low lunar orbit**




Arrow indicates selected point(s) for correlation scatter plot(s)

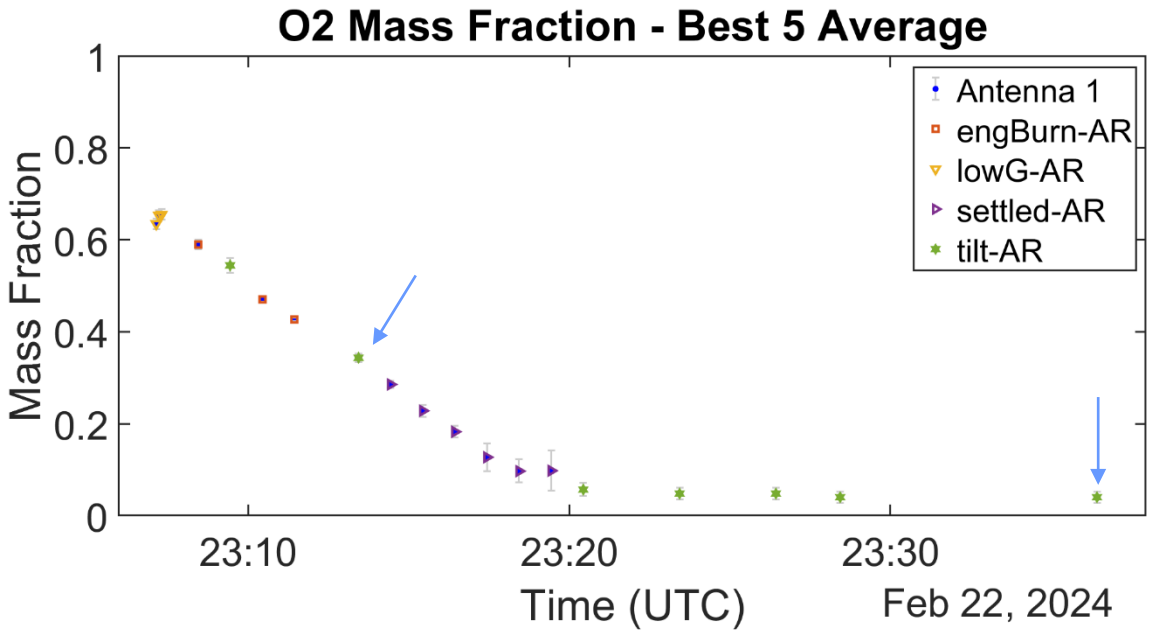


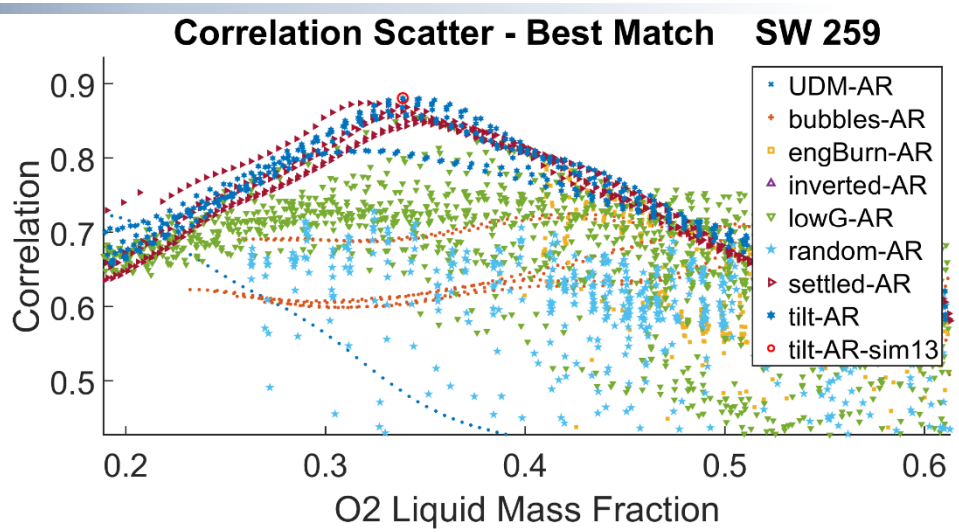

Red circled point indicates best match

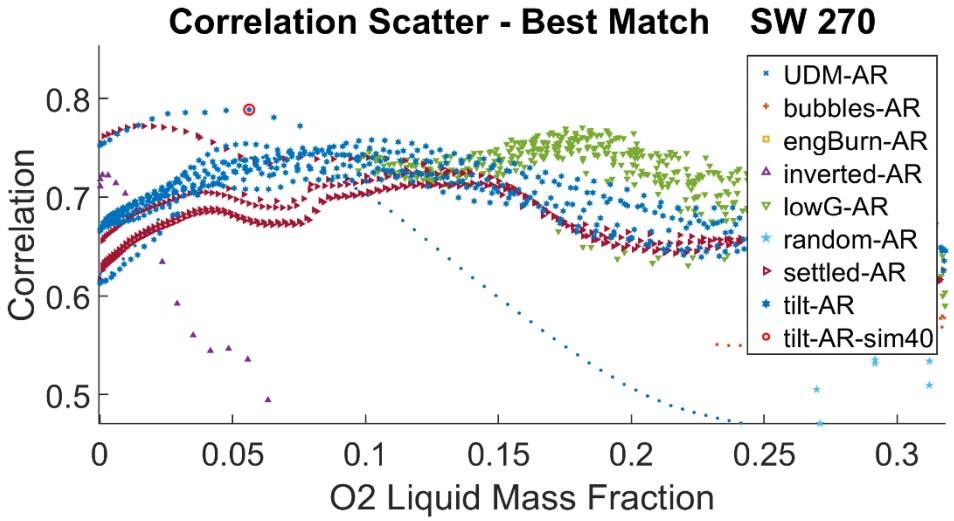
# O2 TANK- BEST MATCH SIM SETS

**Powered descent initiation through post-landing**




Arrow indicates selected point(s) for correlation scatter plot(s)

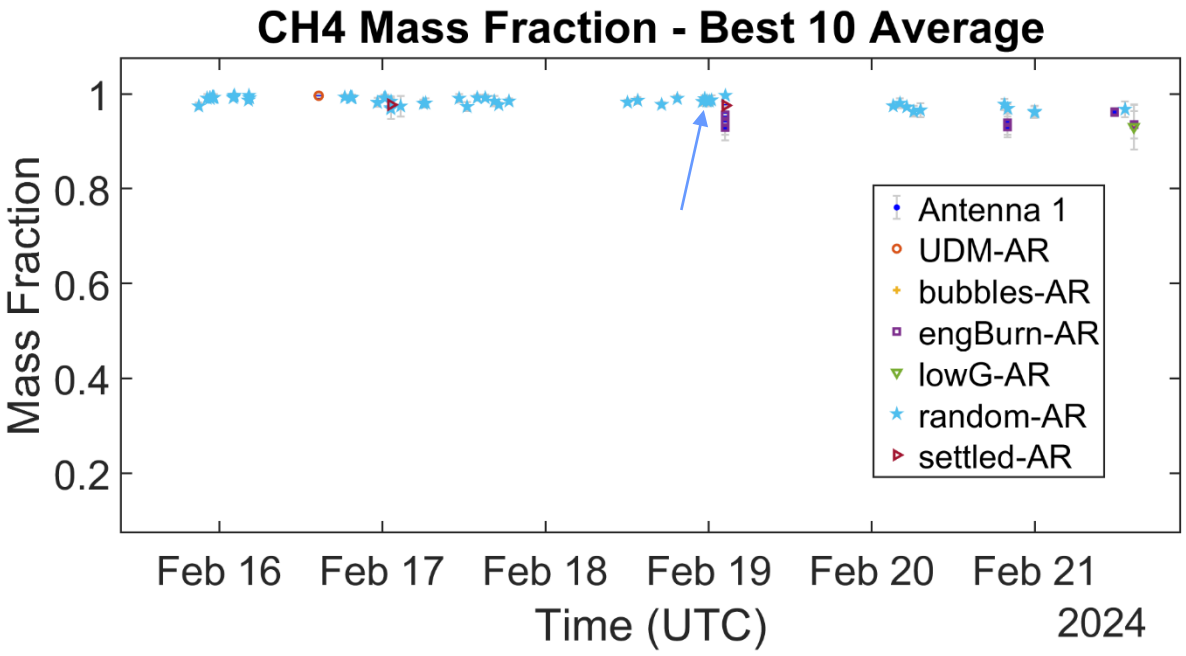


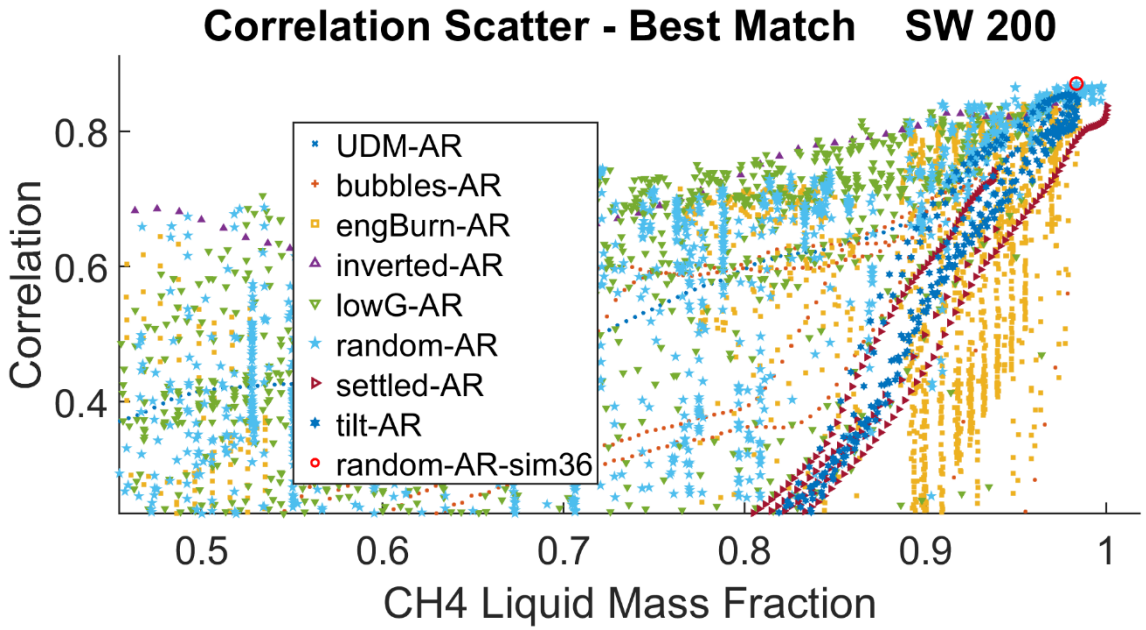




Red circled point indicates best match

# CH4 TANK- BEST MATCH SIM SETS

**Translunar coast**



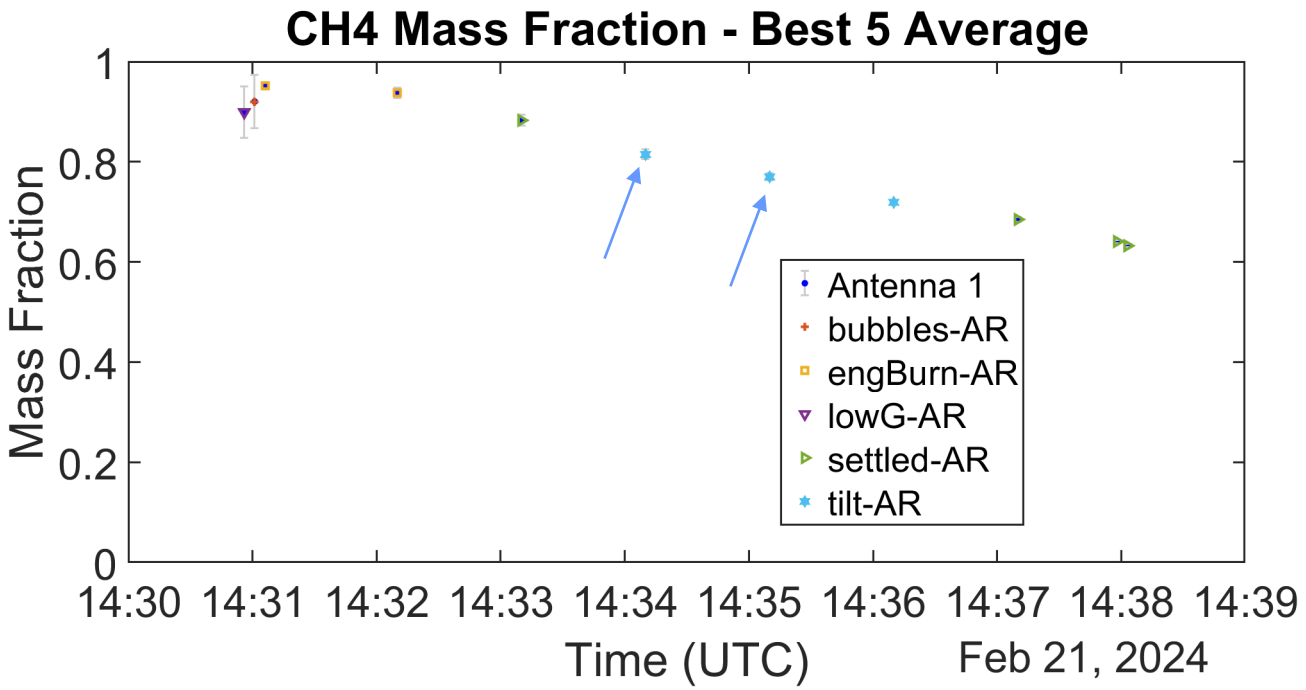




Arrow indicates selected point(s) for correlation scatter plot(s)

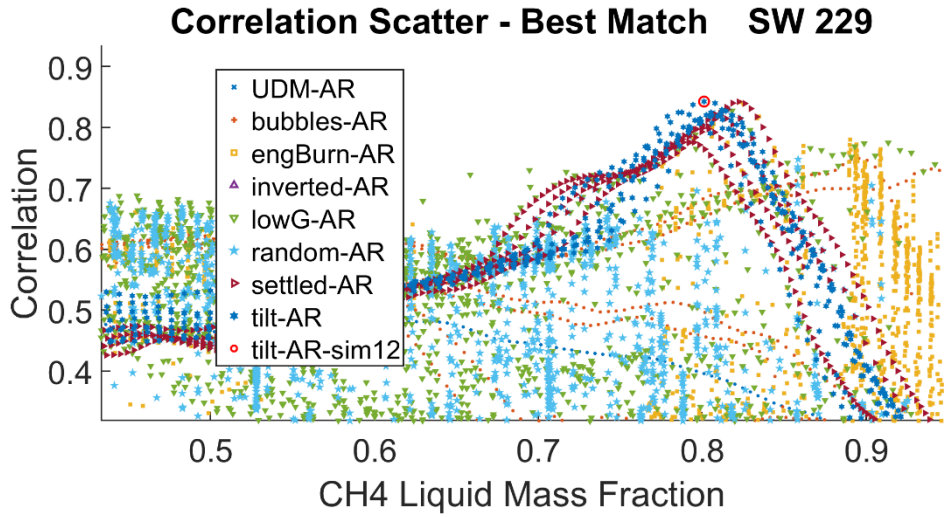
Red circled point indicates best match

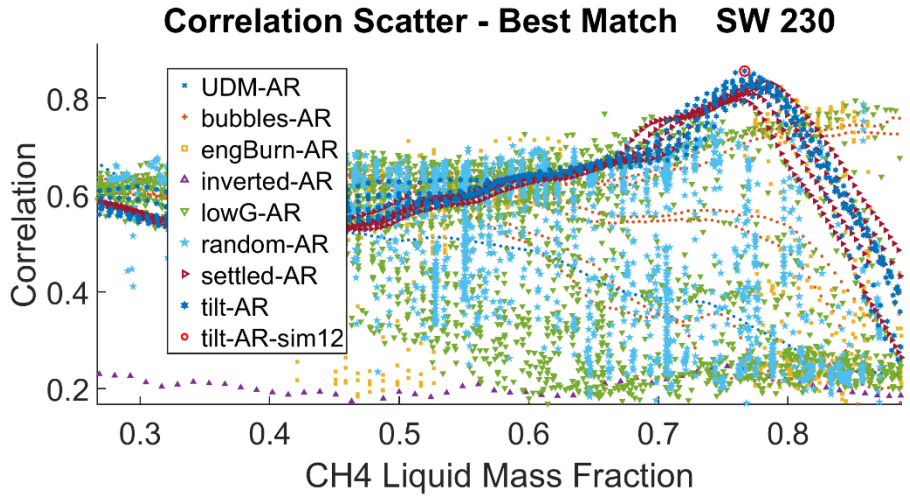
# CH4 TANK- BEST MATCH SIM SETS

**Lunar orbit insertion**




Arrow indicates selected point(s) for correlation scatter plot(s)

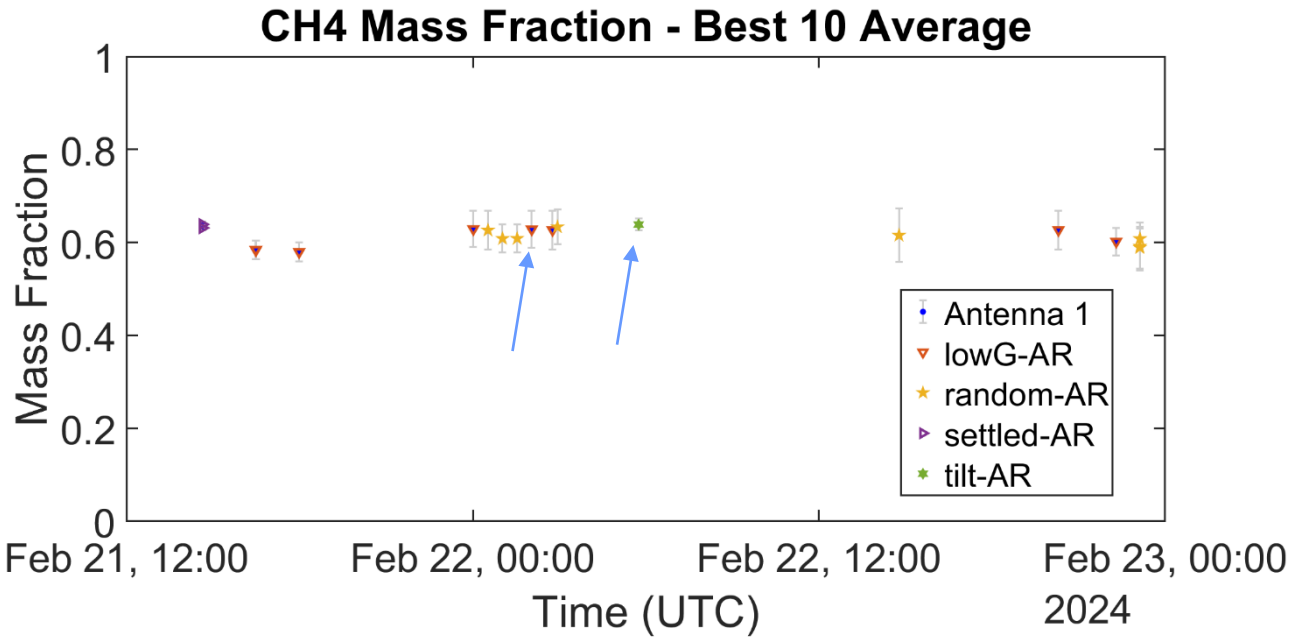


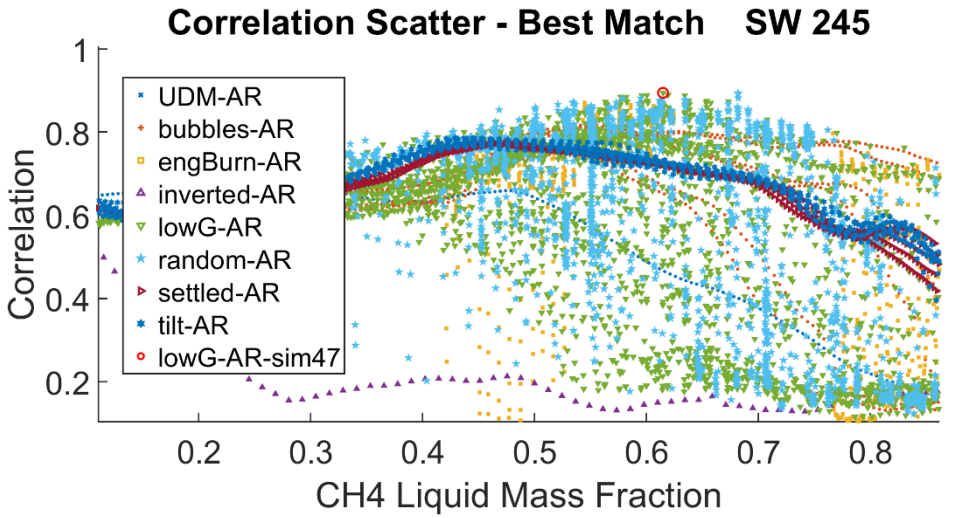

Red circled point indicates best match

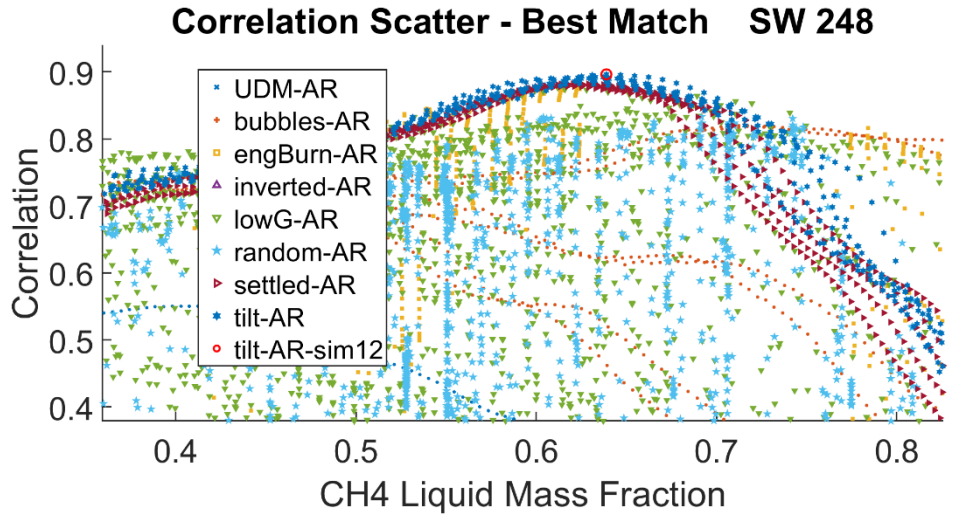
# CH4 TANK- BEST MATCH SIM SETS

**Low lunar orbit**




Arrow indicates selected point(s) for correlation scatter plot(s)

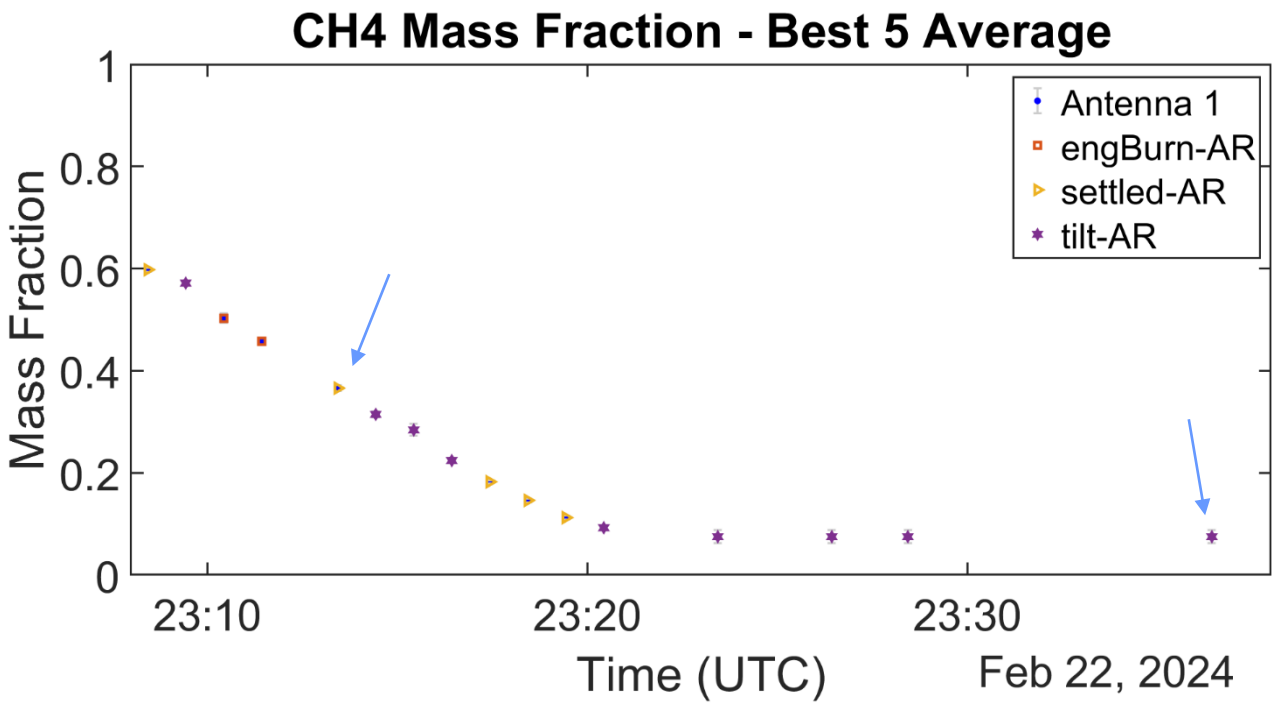


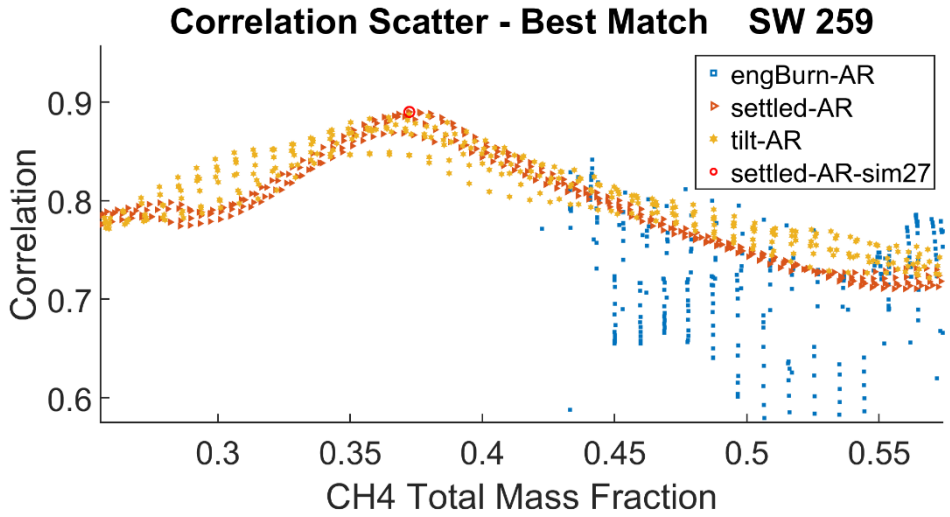

Red circled point indicates best match

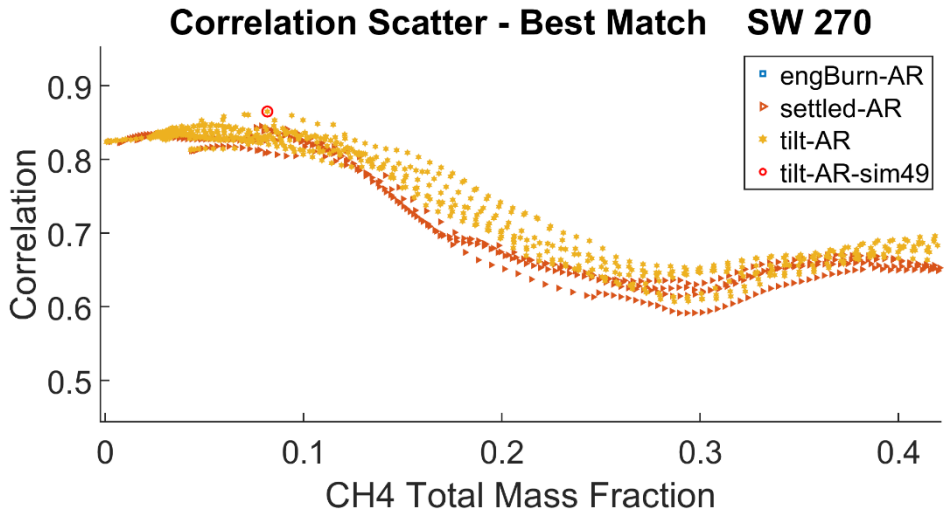
# CH4 TANK- BEST MATCH SIM SETS

**Powered descent initiation through post-landing**




Arrow indicates selected point(s) for correlation scatter plot(s)




Red circled point indicates best match

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