



# Navigation Challenges for Exploration Missions

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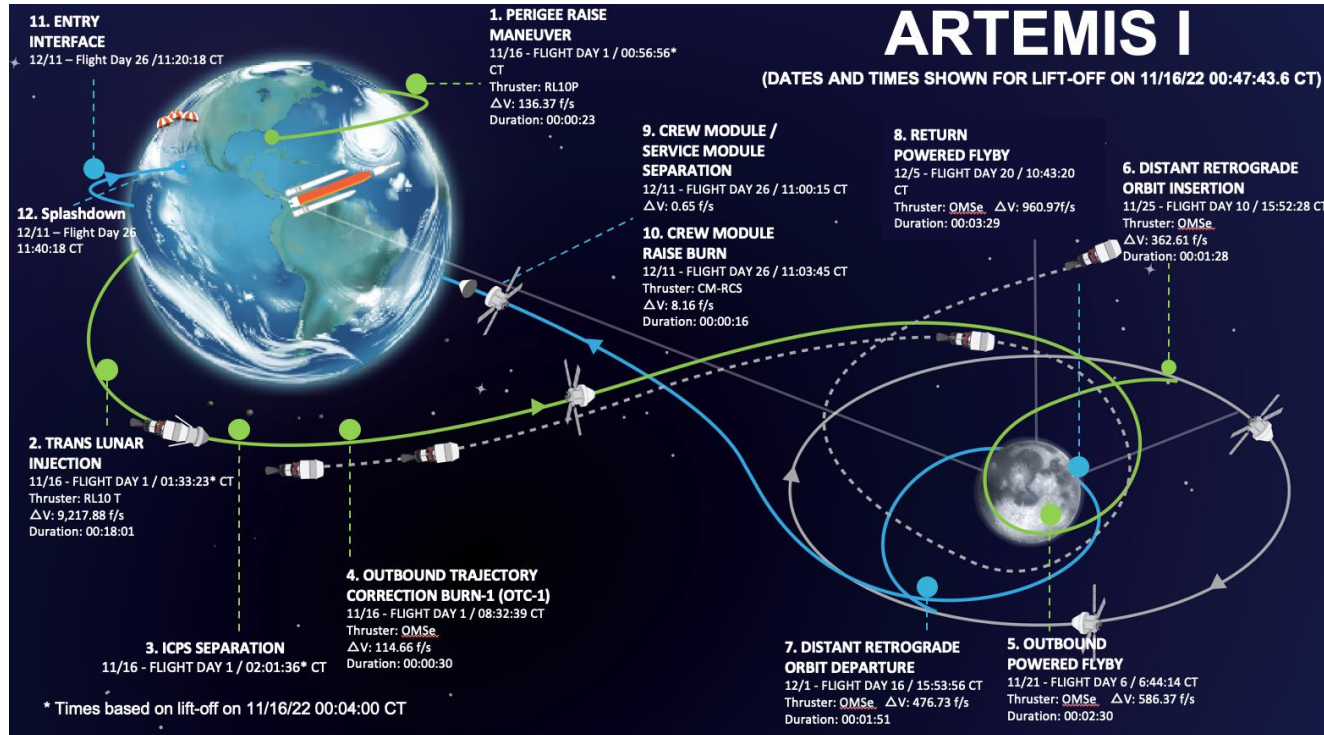
Dr. Christopher D'Souza is the NASA Technical Fellow for Guidance, Navigation and Control (since 2023). He joined the NASA/Johnson Space Center in 2005. In 2009 he started serving as the Deputy Branch Chief of the GNC Autonomous Flight Systems Branch where he led a group of 22 engineers responsible for the onboard Guidance, Navigation and Targeting of crewed vehicles. In 2014, he was selected to the the Navigation Technical Discipline Lead for Human Spaceflight.

Prior to joining NASA, he worked at the Charles Stark Draper Laboratory in Cambridge, MA. He has worked for the US Air Force Research Laboratory (AFRL) at Eglin AFB, FL. He also worked at the Jet Propulsion Laboratory on the Magellan and Galileo missions.



- Autonomous Navigation for Human-Rated Missions
- Autonomous Guidance and Navigation for Landing Missions

# Artemis I Mission Overview



# Artemis II Mission Overview



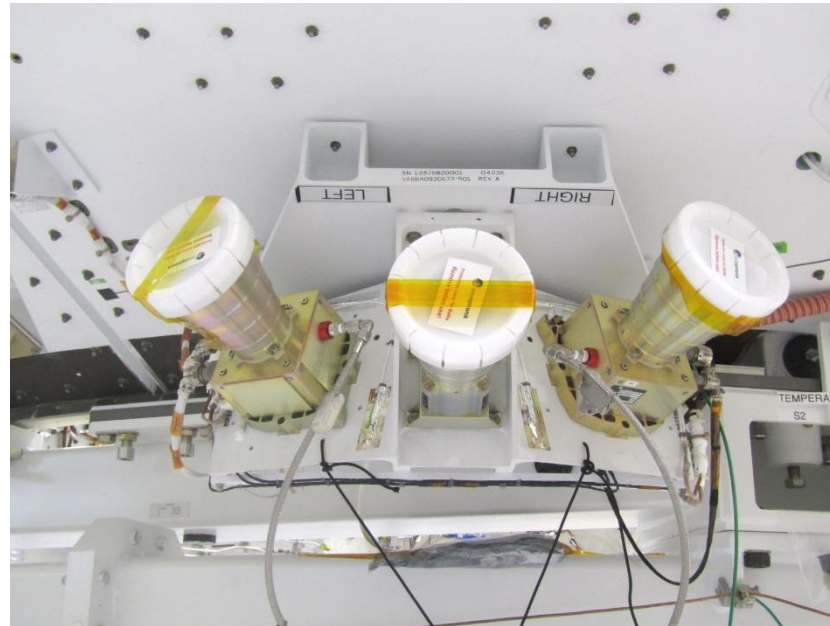


# The Role of Navigation on Artemis

- Running Pre-launch to Post-splashdown (*Never don't navigate!*)
- 4 instantiations of Multiplicative Extended Kalman Filter (MEKF)
  - Atmospheric Extended Kalman Filter (ATMEKF)
    - Prelaunch, Ascent, Entry
  - Earth Orbit Extended Kalman Filter (EOEKF)
    - Outbound/Inbound (within GPS constellation)
  - Cislunar Extended Kalman Filter (CLEKF)
    - Translation beyond GPS constellation
  - Attitude Extended Kalman Filter (ATTEKF)
    - Exo-atmospheric flight
- Split design allows for different filters to process different sensors
  - Pad position, GPS, star tracker, ground update, optical navigation...
  - Reduce software complexity and allow re-use of algorithms



## Orion Optical Base





# What was different on Artemis II than for Artemis I

- ECLSS (Environmental Control and Life Support System)
  - CO<sub>2</sub> and Humidity control via Pressure Swing Adsorption (PSA)
  - Waste Water
- Both of these were vented off-board
  - The PSA vents were continuous and had a frequency depending on the activity of the astronauts (awake, exercise, sleep)
  - The WW vents were periodic (every 8 hours or so)
- The biggest concern was the PSA vents (10X larger than WW)
- The strength of these two types of vents had large uncertainties
  - This had a significant impact on the trajectory



## How did the Navigation Perform on Artemis II?

- The four onboard navigation filters performed spectacularly
  - More than a million measurements processed by the four filters
  - Only two rejected measurements (Optical Navigation)
- The IMUs were able to pick up various crew activities
  - Exercising
  - Sleep
  - Toilet flushes
- Over all there were no surprises – it was a spectacularly boring flight from a GNC perspective – just the way we wanted it!
  - The Polaris console had to find things to keep themselves entertained



## Lunar Landing Guidance and Navigation

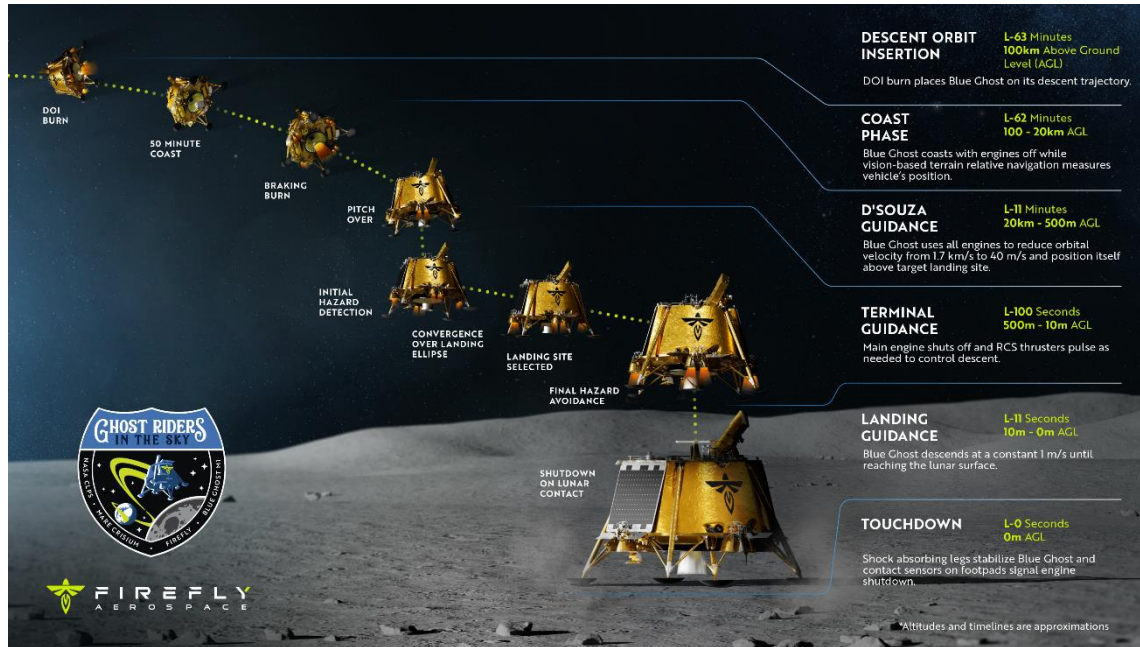
- Recently there has been a great deal of activity with respect to landing on the Moon
  - The Artemis Program
    - Human Landers
    - CLPS
- The NASA Commercial Lunar Payload Services (CLPS) is a program to facilitate commercial companies to delivery payloads to the surface of the Moon
  - Technology Demonstrations
  - Scientific Payloads
  - Tight funding constraints and tight schedules



## Lunar Landing Challenges

- The Navigation challenges are daunting, particularly for the autonomous landers
  - Unforgiving Lighting
    - Shadows
  - Harsh Environment
    - Temperature swings
    - No atmosphere
- Commercial providers have struggled
  - 3 out of 4 attempts have been unsuccessful or partly successful
  - Only one mission has been an unqualified success

# The Unqualified Success – Firefly Aerospace





## Why is there a problem?

- The tight funding constraints have necessitated the use of COTS (Commercial Off-the-Shelf) sensors
  - Lower cost IMUs and Star Trackers
  - Terrestrial grade laser range finders (LRFs)
    - Low TRL
    - Getting a good altitude measurement is vital for a safe landing
  - There is a tendency to treat these sensors as 'black boxes'
  - Reduced sensor testing campaigns
    - Sensors not tested over the entire operational envelope
    - Limited system-level testing
  - Systems Engineering is not well-practiced
- Very limited NASA oversight
  - Contractual constraints
- GNC is treated as a 'known' commodity
  - The propulsion system gets the most attention



## Addressing the Challenge -- Navigation

- Optical sensors are ready for prime-time
  - TRN
    - Craters
    - Feature-based
  - Optical Flow
    - Change in position of features from one frame to the next
- Active TRN
  - Optical and active sensors
- Laser Range Finders
  - Eye-safe lasers have lower operational range
  - The link-margins are tight
- Lidars
  - Scanning Lidars
  - Is Flash ready for prime-time?
  - Combination of the two?
- What about the performance of these sensors in a vibro-acoustic environment?



## Addressing the Challenge II

- Hazards are a particular challenge at the lunar South Pole
  - Shadows are a particular challenge at the lunar South Pole
  - Identifying safe sites in the presence of hazards is key
  - Identifying hazards in the field of view of the sensors is vital
- Precision Landing is the goal of future lunar landing missions
  - Hazard Relative Navigation (HRN) is a necessity (in all lighting conditions)
    - Scanning or Flash lidars
- Algorithms that can reliably process the HRN and TRN-type sensors are non-negotiables
  - Nonlinear estimation techniques are of absolute necessity
  - We need to go past the old-time EKFs
  - But be sensitive to computational constraints
- Being able to guide and control to the surface in the presence of hazards is a challenge



## Conclusions

- Whereas much has been accomplished in cislunar exploration with Artemis I and Artemis II, the challenges of landing on the Moon, particularly at the Lunar South Pole are daunting
  - Lighting (shadows)
  - Hazards
  - Thermal Environments (-280 F to 260 F)
- The Schedules and the Cost Constraints are tight
- There is a tremendous amount of collaboration among countries (Artemis Accords) and competition among 'new space' providers
  - The Artemis Service Module is provided by ESA

## Wellbore Positioning Technical Section

