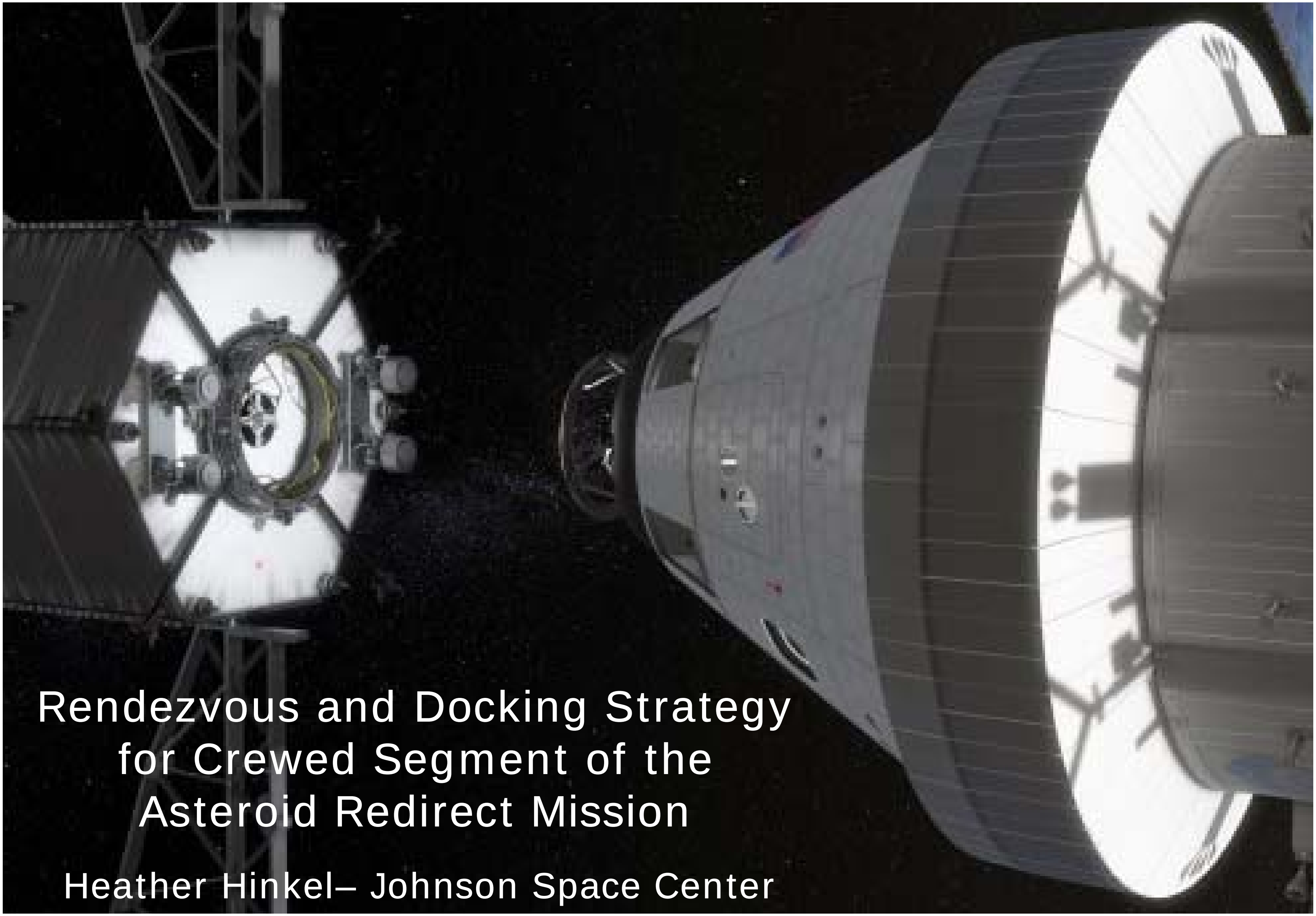


Rendezvous and Docking Strategy for Crewed Segment of the Asteroid Redirect Mission

Heather Hinkel– Johnson Space Center

Asteroid Redirect Mission (ARM) Rendezvous and Docking Overview

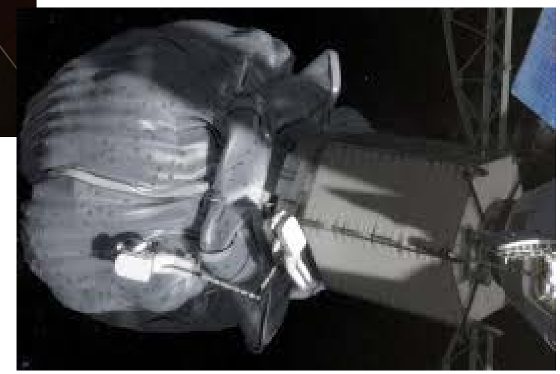
- Two mission concepts being considered:
  - Rendezvous with small (<10 meter mean diameter Near Earth Asteroid (NEA))
    - Capture <1000 metric ton rotating NEA
  - Rendezvous with a larger (~100+meter diameter) NEA
    - Collect ~2-4 meter diameter boulder (~10-70 metric tons)
- In either scenario, maneuver the asteroid material to stable, crew accessible lunar Distant Retrograde Orbit (DRO)
- Orion spacecraft launched on the Space Launch System (SLS) would rendezvous with the vehicle with the captured asteroid mass in lunar orbit and collect samples for return to Earth.

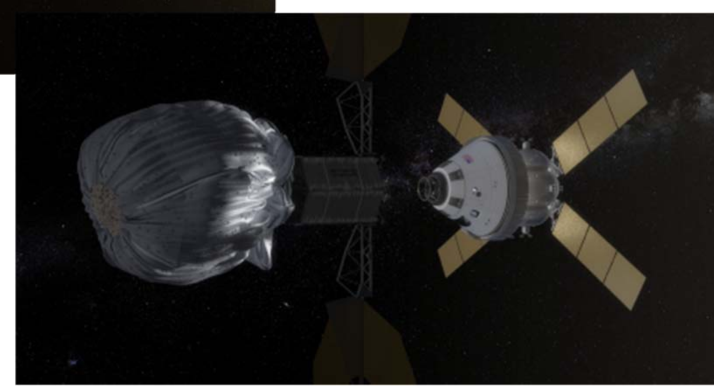
Asteroid Redirect Mission (ARM) Rendezvous and Docking Overview

- ARM Rendezvous requires a different paradigm than rendezvous in LEO
  - Potentially significant one-way light-time
  - Dynamics are very different than in LEO or LLO
    - No strong gravity field to offer ‘easy’ passive abort trajectories
    - Conversely with weak gravity, can perform rectilinear motion
      - Long time constants (one orbit = 14 days)
    - Can rendezvous as fast or as slow as desired
      - Determined by (crew) timeline and propellant
      - No ‘help’ from gravity in slowing you down (as in an R-bar approach)
      - Easier training
    - Lighting may be easier
      - Lighting will remain constant over the anticipated rendezvous
    - Can choose the direction of the approach (within reason) without any appreciable fuel penalty
- All of these offer unique charms and challenges

Orion Mission Design Overview

- ARRM
  - ARV - SEP/Chem.
  - Rendezvous/Redirect NEA
  - Delivers NEA to Earth-Moon vicinity: DRO
    - Stable
    - No maintenance
- ARCM
  - Orion rendezvous with ARV/NEA
  - 2 EVAs
  - Return
  - SLS launch
  - Min ΔV; 26 days

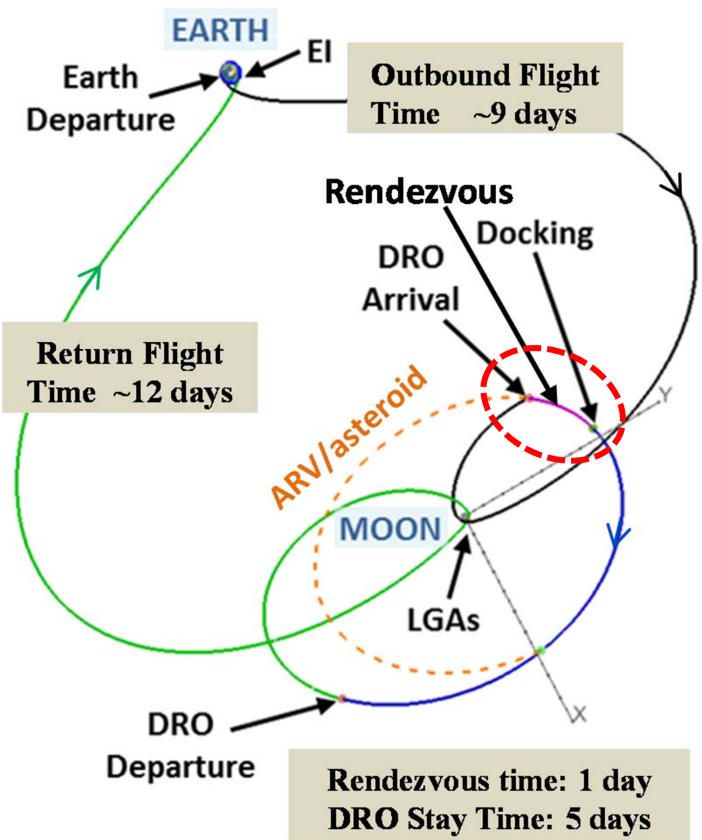


Orion Sensor Requirements

- Sensor performance requirements driven by GN&C.
  - LIDAR providing range & bearing measurements from at least 2km to docking contact, ~1m.
  - Visual camera original purpose was for crew piloting. Optical Navigation requirements dictating bearing accuracy of cameras in support of absolute and relative navigation.
- Reusability pushed sensor suite to interior.
  - Due to estimated high cost, it was deemed appropriate to not discard sensor after each flight, enabling sensor reuse.
  - Reduced thermal/pressure extremes since operating in shirt-sleeve environment.
- SWAP requirements driven by host vehicle limitations.
  - Package had to mount to the docking hatch, “looking” out the docking hatch window. Arrangement of sensors’ optics to have clear FOV paramount. Impacted the docking hatch design to accommodate mounting.
  - Had to be installed by crew prior to use in ARD. Sensors stowed after docking for hatch operations (crew egress/ingress).
- *Q: Should we reference the ARD Sensor BAA requirements?*

Orion Trajectory Design – Overall Trajectory

- SLS launch to MECO
- ICPS TLI with Orion TLI support
- Orion outbound LGA to DRO; 5-day stay; Return via LGA to EI target line (for splashdown off the coast of San Clemente, CA)

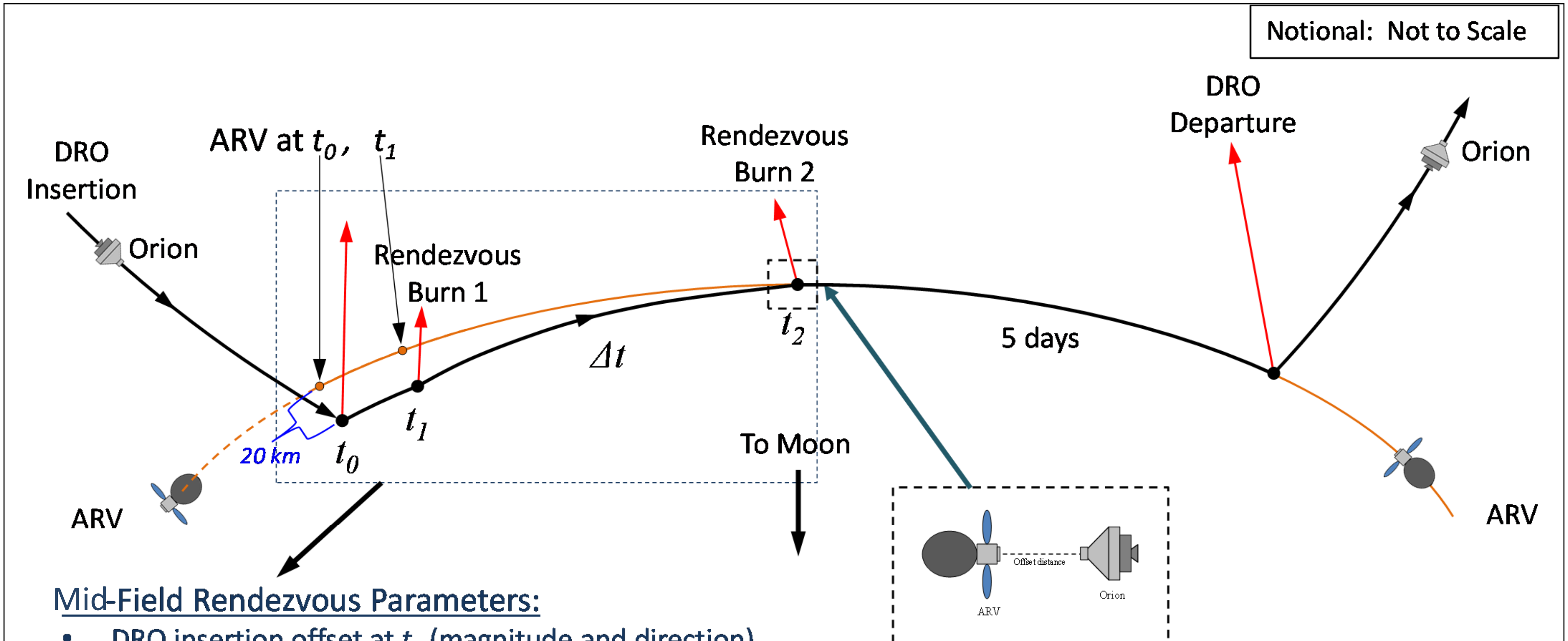


Earth-Moon rotating frame.

Flight Day	Event
1	Launch, Ascent, TLI
2-5	Outbound Translunar Cruise. Depress to 10.2 psi, suit checkout/EVA dry run, rendezvous/docking preparations
5	Lunar Gravity Assist and Lunar close approach
5-7	Lunar to DRO Cruise
8	Rendezvous and Docking
9	EVA 1
10	Suit refurbishment, EVA 2 prep
11	EVA 2
12	Contingency margin, Housekeeping, Departure Prep
13	Undock and Departure
13-19	DRO to Lunar Cruise
19	Lunar Gravity Assist maneuver
20-26	Inbound Translunar Cruise, cabin stow, repress to 14.7 psi
26	Entry, crew recovery

Orion Trajectory Design – Mid/Near-Field Rendezvous

- Far-field rendezvous – Launch to near DRO insertion
- Mid-field rendezvous – Near DRO insertion to 300 m prox-ops initiation
- Near-field rendezvous – prox -ops to docking



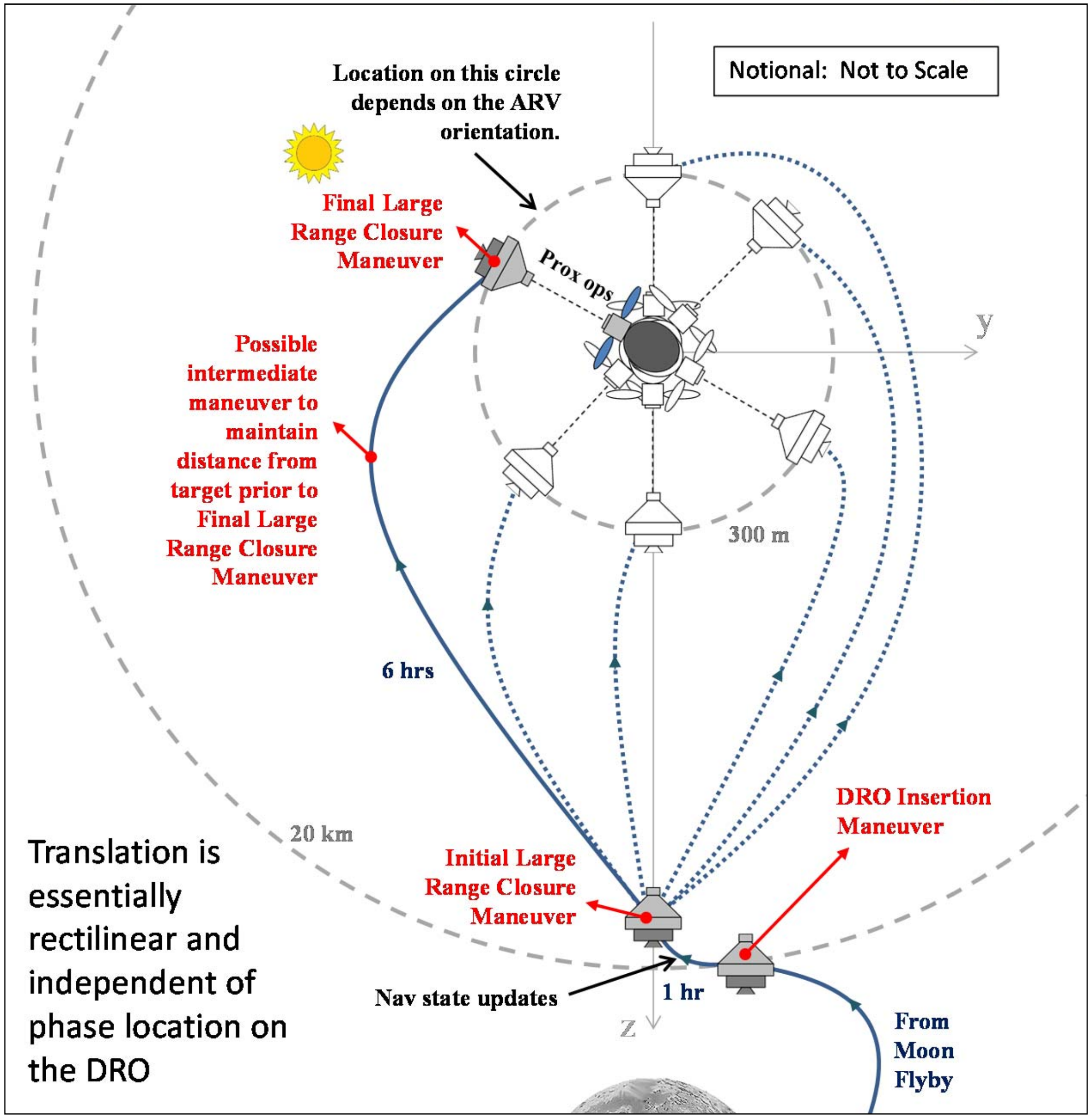
Mid-Field Rendezvous Parameters:

- DRO insertion offset at t_0 (magnitude and direction)
- Wait time before Rendez. 1 maneuver is performed
- Transfer time $\Delta t = t_2 - t_1$
- Final offset distance at t_2 (magnitude and direction)

Prox-ops to docking takes place after the mid-field rendezvous

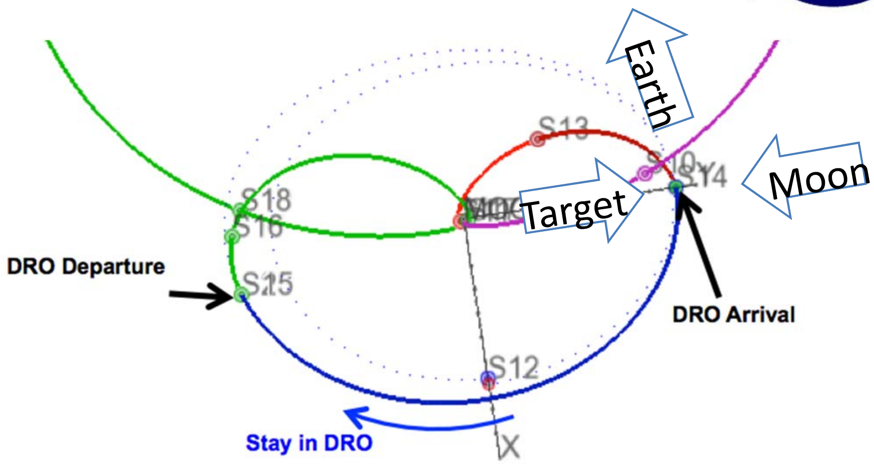
Orion Trajectory Design

- 200 m/s DRO insertion
- 1 day for entire mid/near-field rendezvous
  - 2 burn mid-field rendezvous closure (10 m/s) to 300 m prox-ops target offset position
  - Prox-Ops from 300 m to docking
- Near rectilinear motion
- Bent pipe maneuver sequence allows Orion to select prox-ops approach
  - Also a fail-safe for failed braking maneuvers



Orion Trajectory Design

- Initial approach is from inside DRO

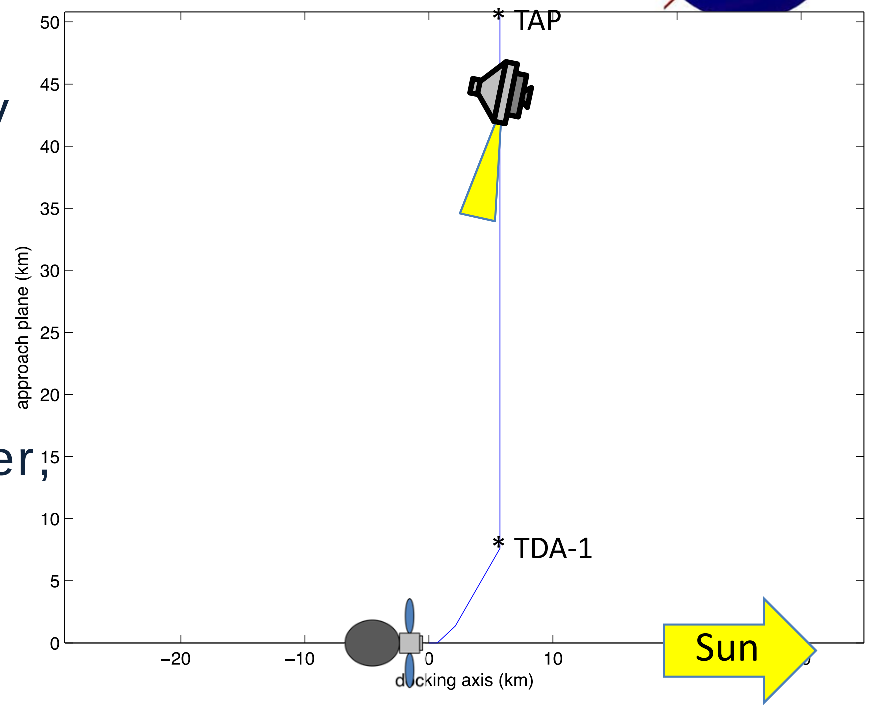


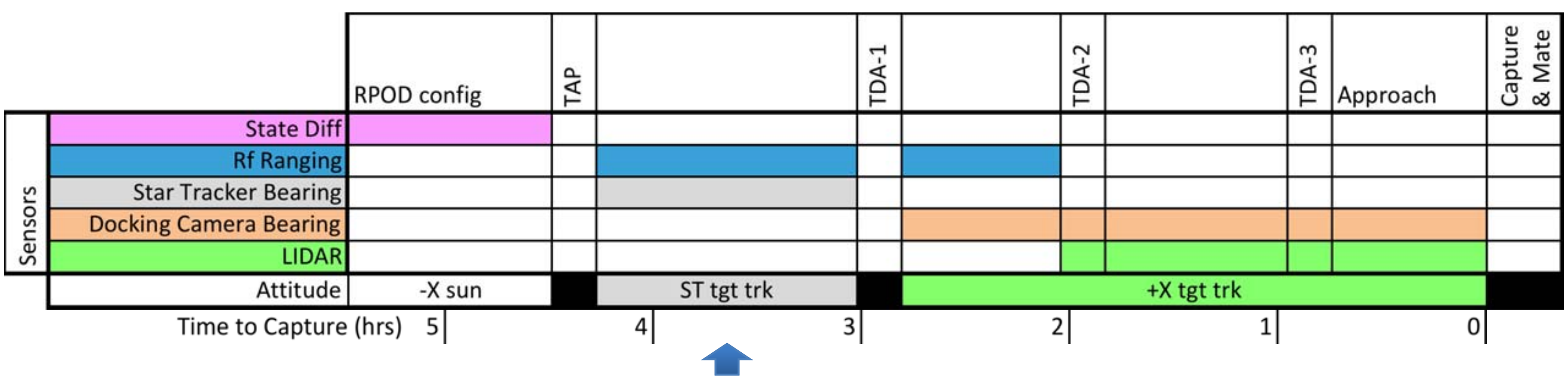
- Example sun location
- Initial trajectory offset ensures passive abort

- Orion performs a series of maneuvers to setup docking

Orion Trajectory Design

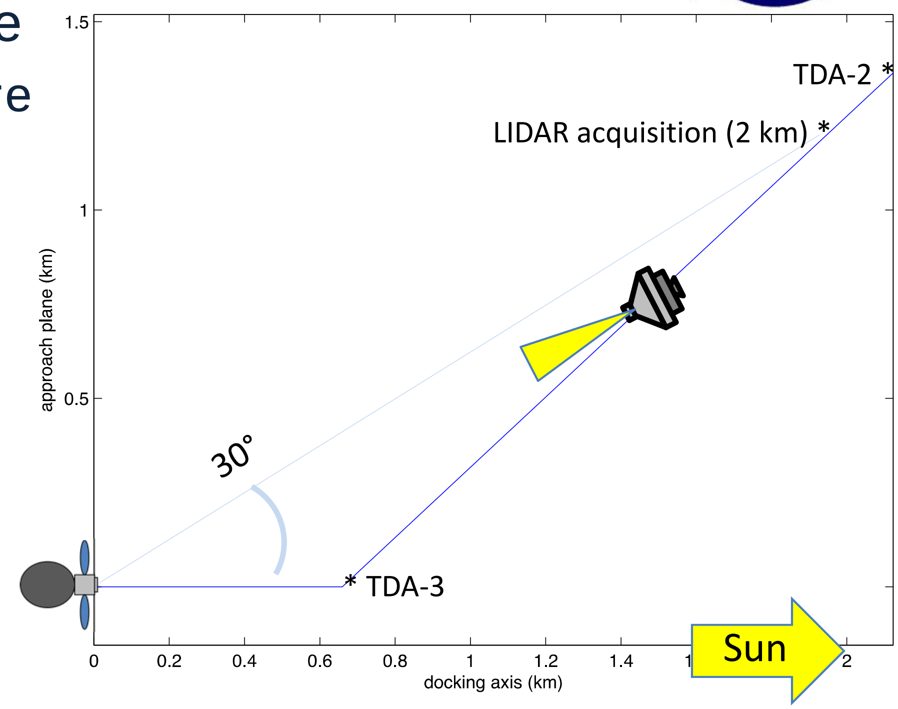
- Transition to Approach Plane
  - Large burn, slow relative velocity
- Transition to Docking Axis
  - Smaller burns to setup relative sensor observations
- Attitude
  - Sensor LOS to target (star tracker, camera, LIDAR)
  - Roll to optimize Orion power/thermal
- Midcourse maneuver(s) (not shown) after filter converges

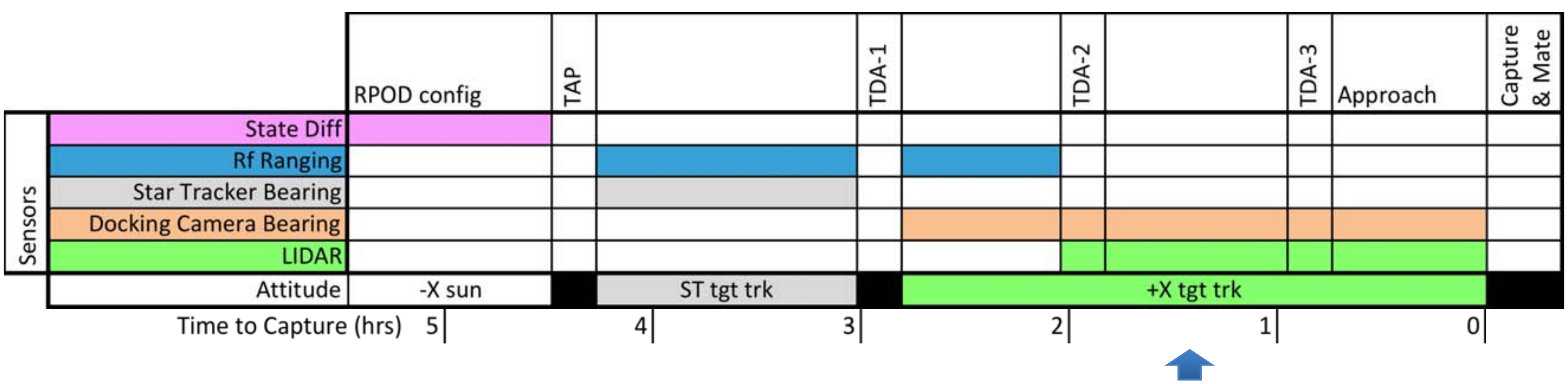




Orion Trajectory Design

- LIDAR acquisition at 2 km range
  - 17 min after TDA-2, 30° off bore sight of retro reflectors
- 50 minutes to process LIDAR
- Mid-course maneuvers after filter converges on LIDAR meas
- Prior to TDA-3, roll to align docking mechanisms
- TDA-3 starts proximity operations





Orion Proximity Operations

- TDA-3 places Orion on the docking axis at 660 m closing at -0.3 m/s
  - Docking will occur in about one hour
  - LIDAR continues to track the target vehicle and provides measurements to navigation filter
- Closure rate reduced as range decreases
- Hold at 10 m to allow for final systems checkout prior to docking
- Orion increases closure rate to -0.075 m/s and proceeds to docking

Range (m)	Brake to (m/s)	Time to Capture (min)	Note
660	-0.3	58.9	
300	-0.2	38.9	
100	-0.1	22.2	
10	0	7.2 (5 min hold)	Docking mechanism Dtemp, check Pose, GO
10	-0.075	2.2	
0	N/A	0	Capture

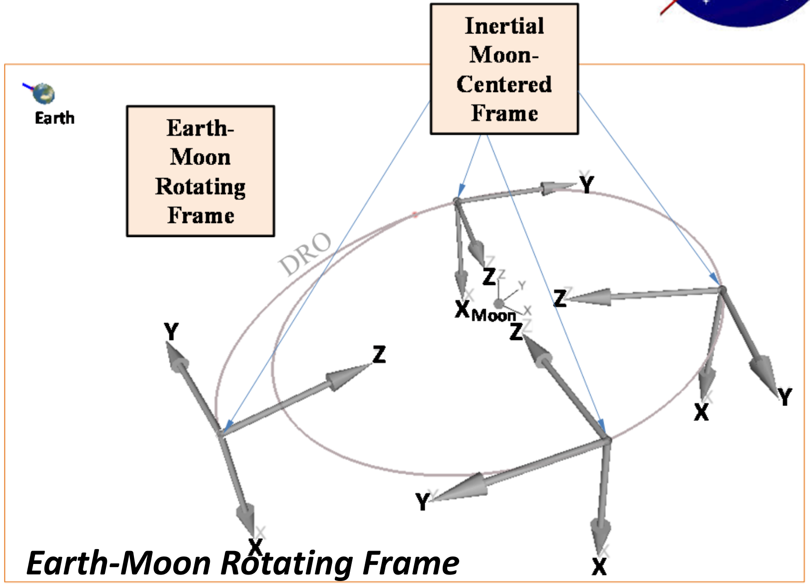
DRO Sub-studies - LVLH Frame

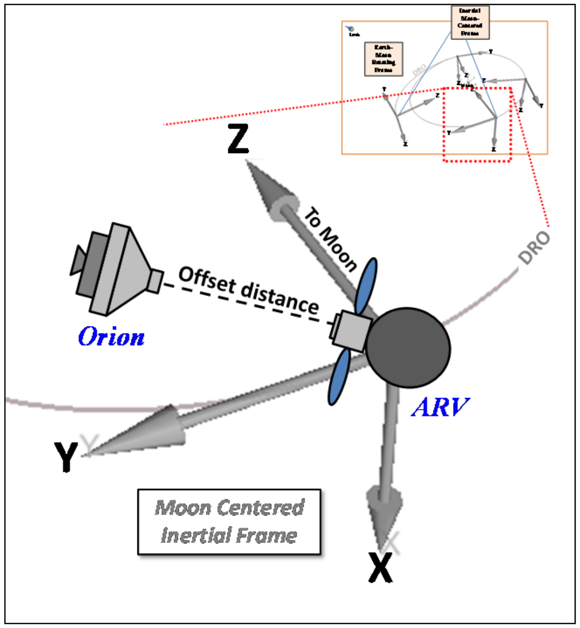
- A DRO LVLH Frame was constructed.
  - Used for rendezvous and prox-ops
  - Provides relative motion between a Target (ARV/asteroid) and a Chaser (Orion) in a DRO
- The Y-Z plane is the Earth-Moon (DRO) Plane.
- The LVLH unit vectors are computed (using the inertial Moon-centered state vector [$\underline{r}$,$\underline{v}$]) by:

$$\underline{\hat{x}} = \underline{\hat{h}}$$

$$\underline{\hat{z}} = -\underline{\hat{r}}$$

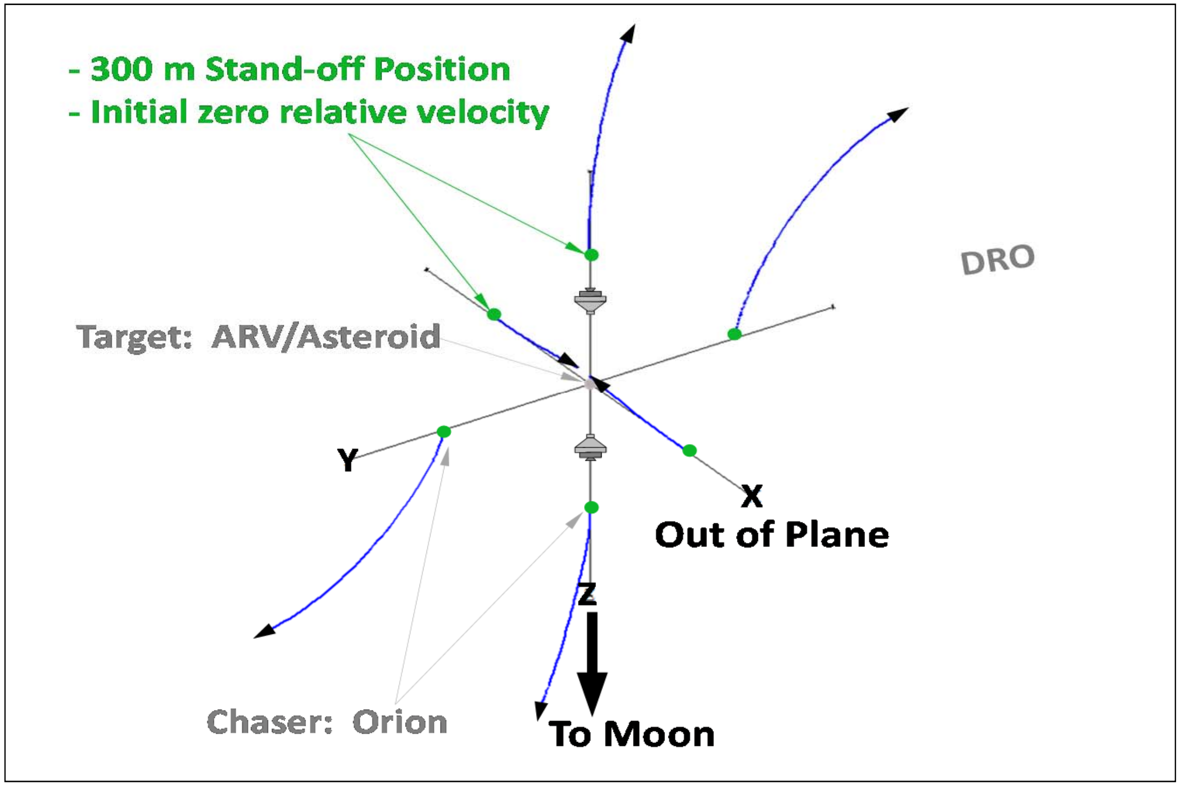
$$\underline{\hat{y}} = \underline{\hat{z}} \times \underline{\hat{x}}$$





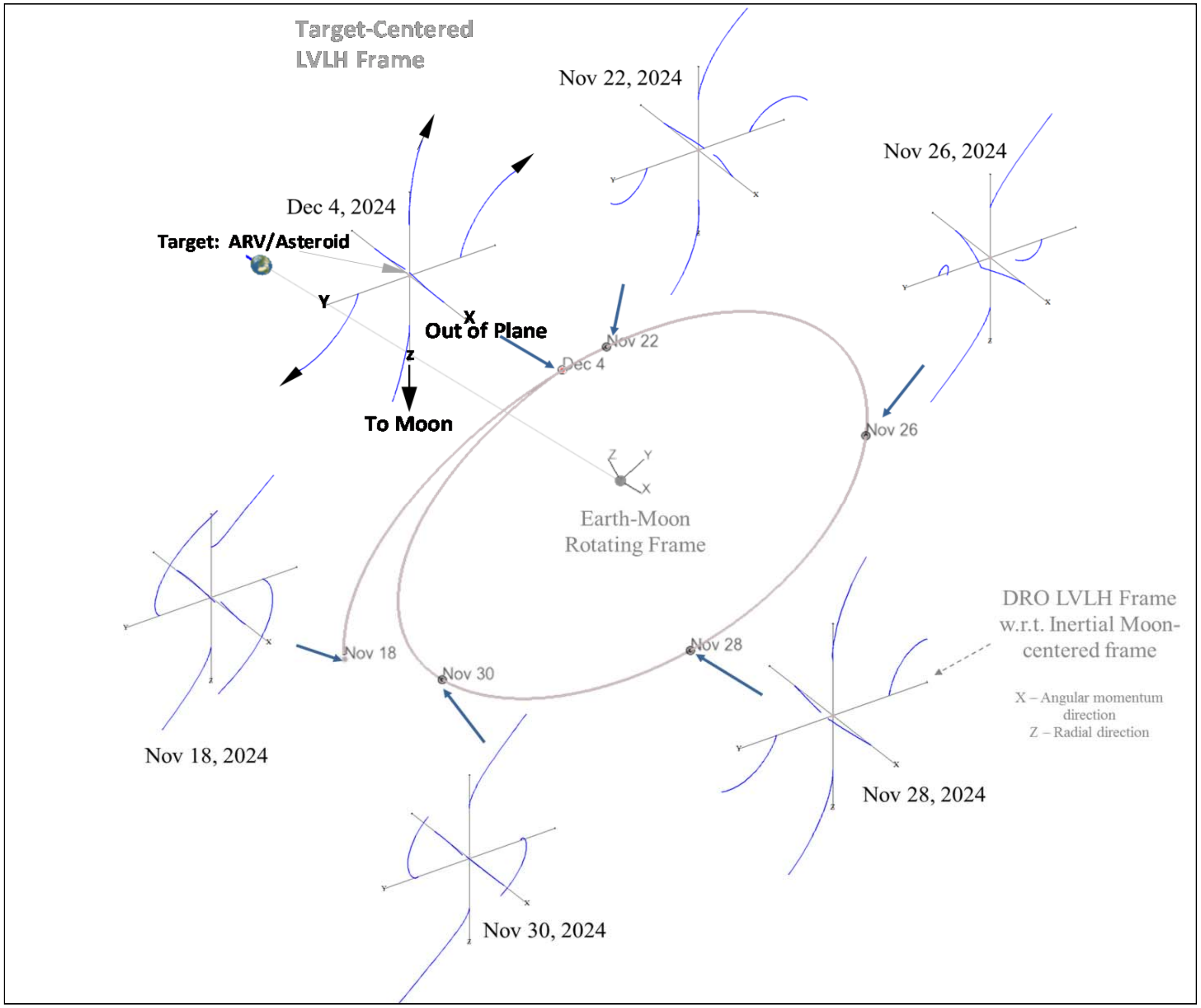
DRO Sub-studies – Prox-Ops Position Drift

- Sub-study conducted to gain insight as to natural drift of a spacecraft (Orion) relative to a target (ARV/asteroid), given initial axes positions with zero relative velocity
- Example 4 day drift propagation
- Z (radial) and Y (velocity) initial axes locations produced movement away from ARV; little or no threat of re-contact
- X (angular momentum, out of plane showed drift toward the ARV with possible collision issue



DRO Sub-studies – Prox-Ops Position Drift

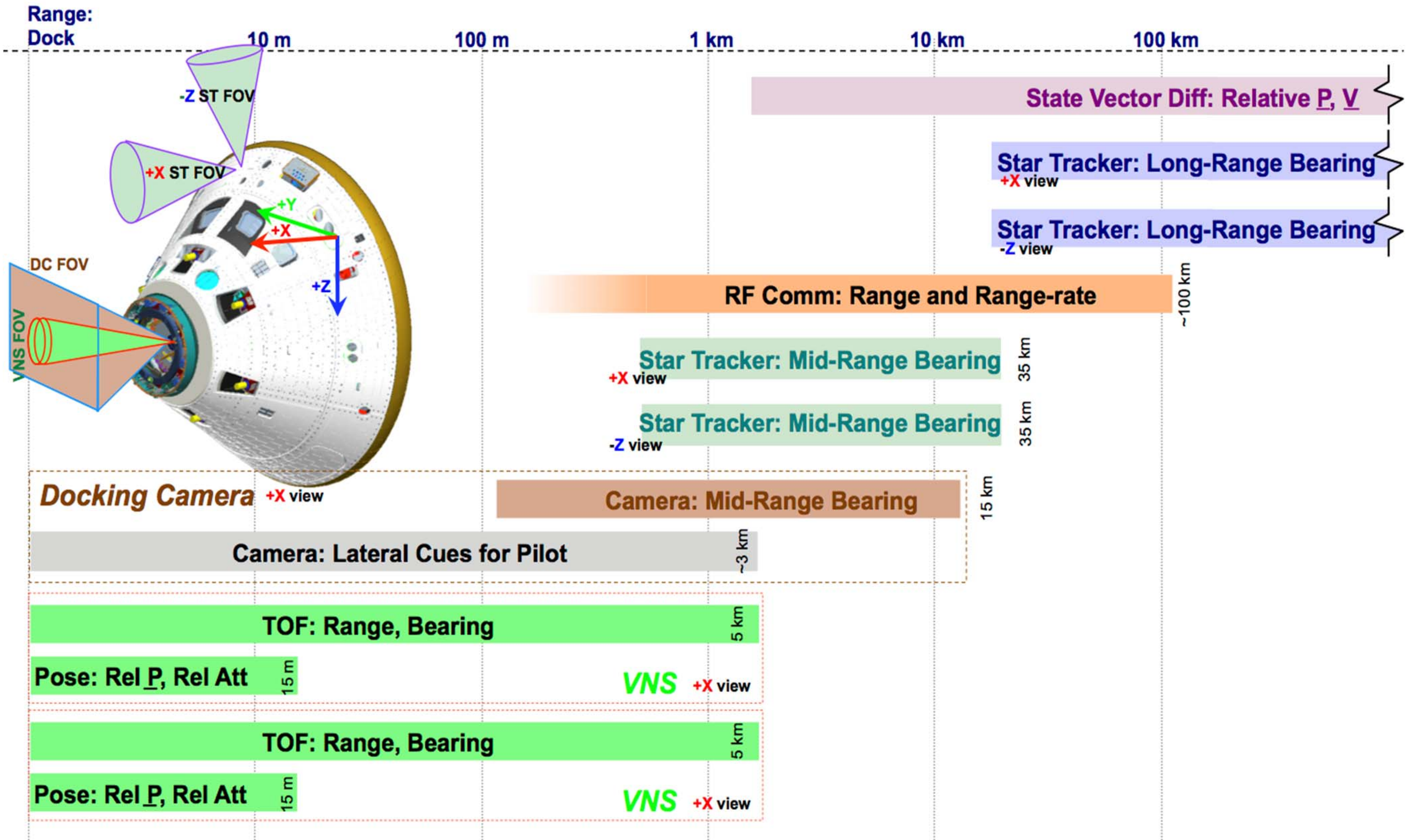
- The drift behavior appears consistent for the given 300 m relative target offset with varying insertion epochs or DRO phase angles.



Sensor Con Ops

- Orion's sensor suite comprised of two Vision Navigation Sensors (VNS) and two Docking Cameras (DC) in a package called LOCI
- State vector differencing based on uplinked target information and onboard state solution
- Star Tracker provide relative bearing measurements
- RF S-band communications provides range and range-rate from 100 km until accuracy degrades and VNS has acquired and tracks target.
- DC images target vehicle to supplement the star tracker relative bearing. Image processing of the DC imagery performed in the Vision Processing Unit (VPU).
- VNS portion of LOCI generates relative range and bearing around 2 to 3 km. Original Orion requirements had VNS acquisition at 5 km, but these are being relaxed under the NASA's common AR&D sensor action.
- Relative 6-DOF measurements output when relative range is 15m. Simultaneously, DC imagery provided to crew for piloting/docking cues.

MPCV/Orion Sensor Usage ConOps



Orion Navigation System Design

- The Orion Navigation Design includes Absolute Navigation and Relative Navigation functions
  - Absolute Navigation
    - Sensors
      - 2 GPS Receivers (derived from the Navigator GPSR)
      - 3 Orion IMUs (Derived from Honeywell MIMU)
      - 2 Star Trackers
      - 3 Baro-altimeters
    - 3 35-state Multiplicative Extended Kalman Filters
      - Each one tied to a single IMU
      - Includes 3 Inertial Navigation Propagators
  - Relative Navigation System
    - Sensors
      - 2 Lidars
      - 2 Docking cameras
      - STs provide bearing
    - Vision Processing Unit
    - Relative Navigation Filter

Relative Navigation System

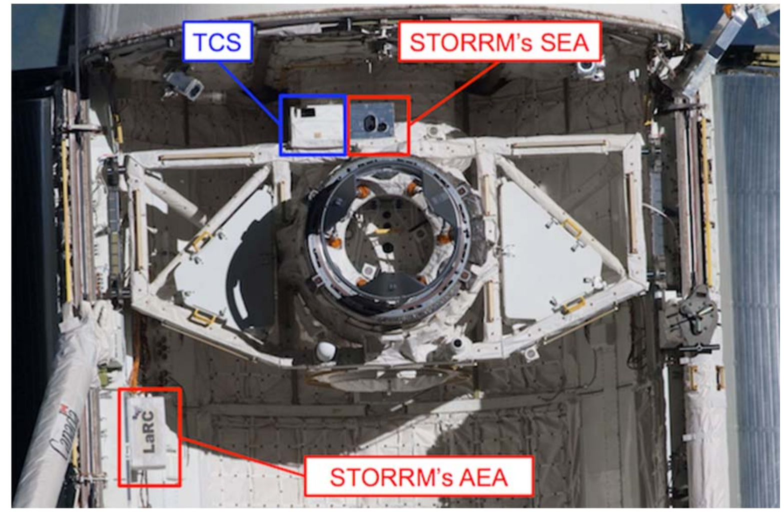
- Lidar provides time-tagged 30 Hz range and intensity images
- Vision Processing Unit Produces Pose Measurements to be used in the Relative Navigation System
  - Centroiding Function
    - Uses range and intensity images to centroid the target reflectors on the image plane
  - Reflector Identification function
    - Identifies the reflectors by means of (unique) inter-reflector distances
  - Pose function
    - Computes pose (relative position and relative attitude)
- Relative Navigation Filter in VMC
  - Single 23-state relative navigation filter
  - Includes a target ‘prop’ state in case of filter performance issue
    - Backup target state
    - Backup Orion state is in Absolute Navigation Filter

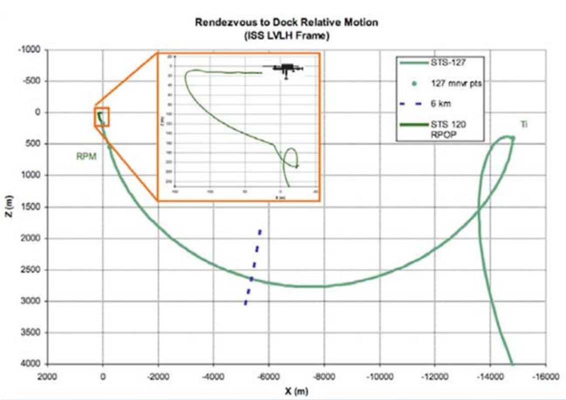
Relative Navigation Design

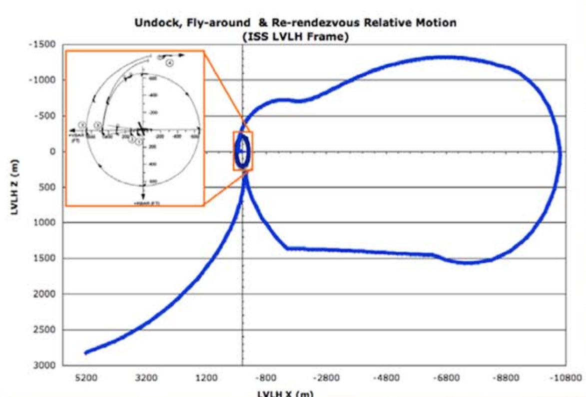
- The Relative Navigation Translation Filter is a dual inertial state filter design
  - Includes both the Orion and target inertial states
    - Position and Velocity
  - Includes Gravity of Sun, Earth, and Moon
  - Orion Attitude State is included
  - Sensor Bias States are modeled as First-order Gauss-Markov states
- Relative Attitude Filter
  - Orion IMU Delta-theta is used as a reference
  - Processes Pose (relative attitude) measurements from Lidar/image processing
  - Target attitude rate is modeled as a Gauss-Markov process

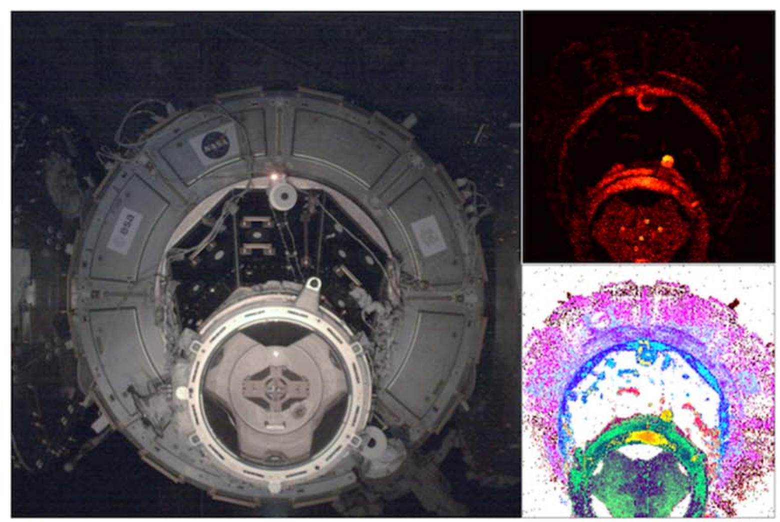
Rendezvous Testing – STORRM

- STORRM flew on STS-134 as DTO-703.
- Objective was to mitigate risk on Orion's first AR&D flight.
- VNS and DC in single enclosure (SEA)
- Data recorded in AEA
- Collected data on FD-03 (rendezvous and docking) and FD-15 (undocking)
- Total of 361 GB of VNS data, and 160 GB of DC data collected on-orbit
- DTO had looser requirements than Orion spec'ed VNS.
- Successful DTO!









Rendezvous Testing – SOSC

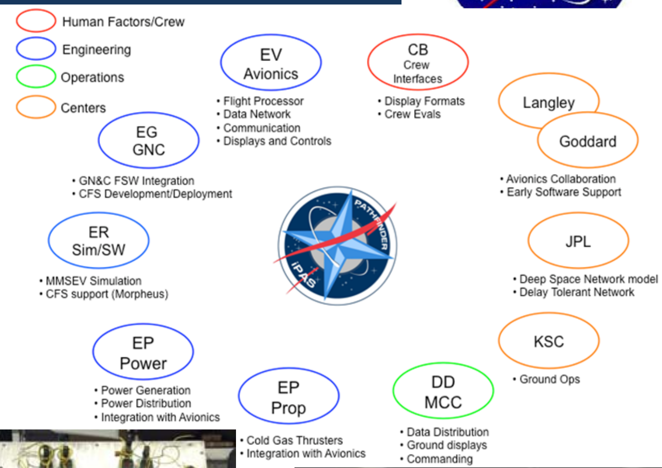
- To date, Orion has conducted three testing campaigns in the LM SOSC (Space Operations Simulation Center) in Denver, CO
  - 55m facility
  - ISS PMA mockup
  - The most recent tests were conducted in January 2014
- Orion has used the STORRM VNS with the designed Orion Relative Navigation system to conduct open and closed-loop tests
  - VPU functions (centroiding, reflector ID, pose)
  - VMC flight software functions (relative translation and attitude filter)
- These tests were carried out from 55 m to 2 m
  - Stationkeeping at 15 m
  - Various approach geometries (dispersions)
- Tests were very successful and demonstated the robustness of the relative navigation system
- A set of open-loop and static tests were conducted to test the performance at ranges longer than 55 m and at extreme angles

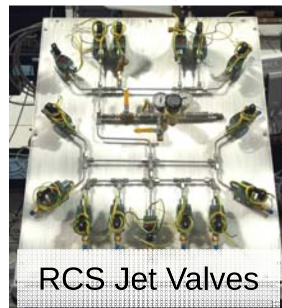
Rendezvous Testing – SOSC

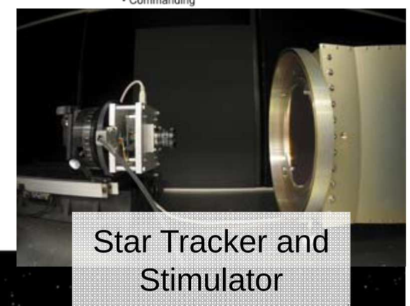
- Several AR&D and VNS test campaigns conducted over last few years at LM SOSC facility
- Objectives:
  - Characterize facility as a space-like environment for future Orion testing
  - Develop capability to execute closed-loop Orion rendezvous and docking with hardware-in-the-loop
  - Characterize VNS performance under different dynamics conditions and ranges
- Test results have demonstrated Orion’s closed-loop docking capability and increased confidence in the performance and robustness of the design

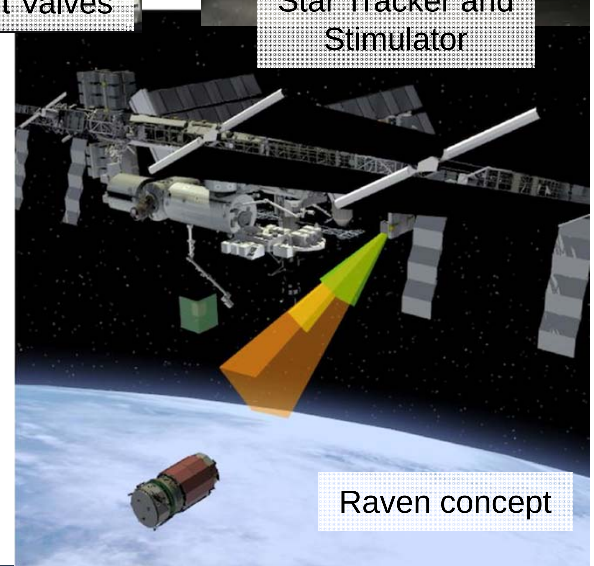
Rendezvous Testing – iPAS/Raven

- Integrated Power, Avionics and Software (iPAS) developed at JSC, with multiple center and organization participation.
  - Utilized Core Flight Software (CFS)
  - Sensor models, GNC algorithms implemented on a common testbed framework.
  - Performed MCPV-ARV simulations, utilizing developing MPCV AR&D FSW.
  - Sensor hardware and stimulators being incorporated.
- Raven is a sensor payload to be installed on ISS via the STP-H5 pallet (launch Sep 2016).
  - Consists of visible camera, IR camera and VNS
  - Raven on a gimbaled platform to track incoming ISS Visiting Vehicles
  - Image processing and relative navigation algorithms to be tested on a dedicated, real-time processor (part of Raven).




RCS Jet Valves


Star Tracker and Stimulator


Raven concept

Rendezvous Design Forward Work

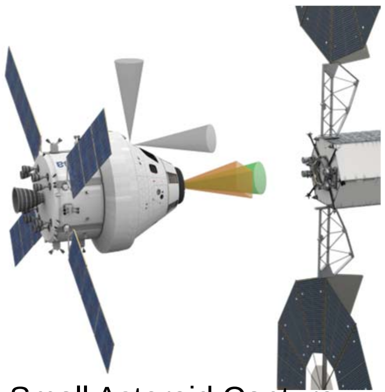
- NASA needs automated rendezvous and docking/capture (AR&D) sensors for both the robotic and crewed segments of the Asteroid Redirect Mission

- NASA is pursuing a common suite of AR&D sensors to apply across all asteroid missions
  - Visible cameras
    - Medium resolution paired with selectable lenses per mission needs
    - High resolution paired with selectable lenses per mission needs
  - 3D LIDAR
  - Infrared camera

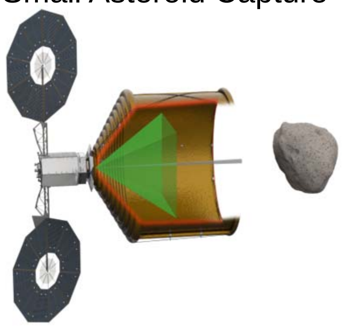
- NASA created a common specification for environment and performance for each sensor which will fulfill each mission's AR&D needs

Rendezvous Design Forward Work (cont'd)

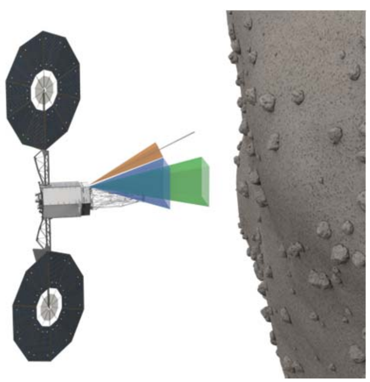
Crewed Asteroid Mission



Small Asteroid Capture



Robotic Boulder Capture



	Long Range	Medium Range	Close Range	Application of Common Suite
Crewed Asteroid Mission	S-Band Transponder for Range/Range Rate to reduce timeline; Star Tracker for bearing High Resolution Camera for bearing		3D LIDAR for precise alignment for docking High Resolution Camera for secondary pose	High Resolution Camera 3D LIDAR
Small Asteroid Capture	Medium Resolution Camera for asteroid acquisition, spin rate and bearing to the asteroid		3D LIDAR for asteroid characterization and alignment for bag capture	Medium Resolution Camera 3D LIDAR
Robotic Boulder Capture	Medium Resolution Camera for bearing to the asteroid	Medium and High Resolution Cameras for spin rate, 3D map of the surface and boulder identification	3D LIDAR for 3D range images to the target boulder Medium and High Resolution Cameras for spacecraft pose and images of boulder collection areas	High Resolution Camera Medium Resolution Camera 3D LIDAR

* Addition of infrared camera on asteroid missions for robustness is being assessed