Navigation Concepts for NASA's Constellation Program and Human Missions to the Moon

Michael C. Moreau, Ph.D.
Constellation Program Office

National Aeronautics & Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

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CHARLIE PAYNE

NASA
Vision For Space Exploration

- Complete the International Space Station
- Safely fly the Space Shuttle until 2010
- Develop and fly the Crew Exploration Vehicle no later than 2014
- Return to the Moon no later than 2020
- Extend human presence across the solar system and beyond
- Implement a sustained and affordable human and robotic program
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration

NASA Authorization Act of 2005
The Administrator shall establish a program to develop a sustained human presence on the Moon, including a robust precursor program to promote exploration, science, commerce and U.S. preeminence in space, and as a stepping stone to future exploration of Mars and other destinations.
The Moon – the First Step to Mars and Beyond....

- Gain significant experience in operating away from Earth’s environment
  - Space will no longer be a destination visited briefly and tentatively
  - “Living off the land”
  - Human support systems
- Developing technologies needed for opening the space frontier
  - Crew and cargo launch vehicles (125 metric ton class)
  - Earth ascent/entry system – Crew Exploration Vehicle
- Preparing for human exploration of Mars
- Conduct fundamental science

Next Step in Fulfilling Our Destiny As Explorers
How We Plan to Return to the Moon
Components of Constellation Program

Earth Departure Stage

Orion - Crew Exploration Vehicle

Heavy Lift Launch Vehicle

Crew Launch Vehicle

Lunar Lander
How We Plan to Return to the Moon
Orion - Crew Exploration Vehicle

♦ A blunt body capsule is the safest, most affordable and fastest approach
  ♦ Vehicle designed for lunar missions with 4 crew
    – Can accommodate up to 6 crew for Mars and Space Station missions

♦ 5 meter diameter capsule scaled from Apollo
  ♦ Significant increase in volume
  ♦ Reduced development time and risk
  ♦ Reduced reentry loads, increased landing stability and better crew visibility
Orion will initially be used to support space station missions

- Transport up to 6 crew members on Orion for crew rotation
- 210 day stay time at ISS
- Emergency lifeboat for entire ISS crew
- Deliver pressurized cargo for ISS re-supply
Serves as the long term crew launch capability for the U.S.

5 Segment Shuttle Solid Rocket Booster

New liquid oxygen / liquid hydrogen upperstage
  - J2X engine

Large payload capability
Ares V – Heavy Cargo Launch Vehicle

- 5 Segment Shuttle Solid Rocket Boosters
- Liquid Oxygen / liquid hydrogen core stage
  - Heritage from the Shuttle External Tank
  - RS68 Main Engines
- Payload Capability
  - 106 metric tons to low Earth orbit
  - 125 Metric tons to low Earth orbit using Earth departure stage
  - 55 metric tons trans-lunar injection capability using Earth departure stage
- Can be certified for crew if needed
Foundation of Proven Technologies
Launch Vehicle Comparisons

Space Shuttle
- Height: 56.1 m
- Gross Liftoff Mass: 2041 mT
- 25 metric tons LEO

Ares I
- Height: 97.8 m
- Gross Liftoff Mass: 907 mT
- 22 metric tons to LEO

Ares V
- Height: 109 m
- Gross Liftoff Mass: 3311 mT
- 53 metric tons to TLI
- 65 metric tons to TLI in Dual-Launch Mode with Ares I
- 132 metric tons to LEO

Saturn V
- Height: 111 m
- Gross Liftoff Mass: 2948 mT
- 45 metric tons to TLI
- 119 metric tons to LEO
Lunar Lander

- Transports 4 crew to and from the surface
  - Seven days on the surface
  - Lunar outpost crew rotation
- Global access capability
- Anytime return to Earth
- Capability to land 20 metric tons of dedicated cargo
- Airlock for surface activities
- Descent stage:
  - Liquid oxygen / liquid hydrogen propulsion
- Ascent stage:
  - Storable Propellants
## Comparison of Constellation and Apollo

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Apollo</th>
<th>Constellation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch architecture</td>
<td>Single launch, Lunar orbit rendezvous</td>
<td>Dual Launch, Earth-orbit/Lunar Orbit rendezvous</td>
</tr>
<tr>
<td>Landing location</td>
<td>Near side; equatorial to mid-latitude; 1 time visits</td>
<td>Global including poles &amp; far side; 1 time &amp; return to site</td>
</tr>
<tr>
<td>Crew</td>
<td>2 crew to surface</td>
<td>4 crew to surface</td>
</tr>
<tr>
<td></td>
<td>All missions piloted</td>
<td>Piloted &amp; robotic missions</td>
</tr>
<tr>
<td>Lighting condition</td>
<td>All missions during lunar day</td>
<td>Missions in lunar day &amp; night</td>
</tr>
<tr>
<td>Rover Range</td>
<td>Range: 57 mi (92 km); 6 mi (9.7 km) range from LM per EVA</td>
<td>100 km &lt; range &lt; 1000 km; no limit due to EVAs</td>
</tr>
<tr>
<td>Earth tracking network</td>
<td>Apollo 17: ~12 sites</td>
<td>3 DSN sites + up to 3 secondary sites</td>
</tr>
<tr>
<td>In-situ tracking network</td>
<td>none</td>
<td>Range and Doppler tracking from 2-satellite lunar relay constellation</td>
</tr>
<tr>
<td>Resulting landing accuracy</td>
<td>Reqt: 3000 ft radius; Actual: Computer controlled accuracy (no piloting effects) ~1500 ft, 1 σ</td>
<td>Goal: 100 m unaided (1st landing at a site); &lt;10 m aided (return to Outpost)</td>
</tr>
<tr>
<td>Surface navigation aids</td>
<td>None</td>
<td>Deployable sensors (UWB, WiMax, RFID), landing aids</td>
</tr>
<tr>
<td>Re-entry/landing</td>
<td>Direct-entry, water landing</td>
<td>Skip-entry, CONUS or coastal water landing zone</td>
</tr>
<tr>
<td>EVA navigation equipment</td>
<td>Maps; mission checklist</td>
<td>MEMS IMUs, LRS/LCT/DSN S-band tracking, hand-held optical</td>
</tr>
</tbody>
</table>
Navigation Challenges for Lunar Missions

- Perturbations from vehicle venting, thruster firings, even waste dumps a significant error source for “crewed” missions
  - Estimated to contribute approx 500 m per hour of error growth in navigation state
- Observability of lunar vehicle from Earth
- Compressed timelines require rapid convergence of navigation solution
- Lunar Gravity Model Uncertainty
  - A dominant error source today, but expected to improve dramatically due to missions such as Selene and GRAIL
Navigation and Tracking Architecture for Lunar Mission

- TDRS
- GPS
- Ground Tracking
- Onboard Sensors
- Lunar Relay Satellite
- Surface RF Beacon

Earth-based Ground Station Tracking
- GPS
- TDRSS
- Lunar Relay

Onboard Sensors/Inertial Nav

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Onboard Navigation System Architecture
Optical Navigation and other Onboard Sensors

Images of stars and other celestial objects

IMU

Images of lunar landmarks for lunar-approach nav

Images of Orion for rendezvous nav

Range and Doppler from RF proximity link

Images of lunar surface for landing and Hazard avoidance
Primary Navigation Sources
- Radar tracking data
- Vehicle’s inertial solution
- GPS solution

Secondary Navigation Sources
- TDRSS Doppler tracking

Changes:
- No s-band tracking from ground stations
- Reduced radar tracking data
- Possibly no radar tracking coverage downrange for lunar launches
Navigation Sources in Low-Earth Orbit

Primary Navigation Sources
- Two-way Range and two-way Doppler tracking from TDRSS
- GPS
- Inertial Navigation Solution

Changes:
- No routine s-band or radar tracking for ground stations
Relative Navigation Sensors and Operational Range for Orion Crew Exploration Vehicle

- State Vector Diff: Relative P, V
- Star Tracker: Long-Range Bearing
- Star Tracker: Long-Range Bearing
- Star Tracker: Mid-Range Bearing
- Star Tracker: Mid-Range Bearing
- RF Comm (1): Range, Range rate
- TOF: Range, Bearing
- VNS
- TOF: Range, Bearing
- VNS
- Camera (1): Lateral Cues for Pilot

Legend: Primary, Secondary, Degraded, Functional

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Critical Lunar Mission Events from a Navigation Perspective

- Trans-lunar navigation targeting Lunar Orbit Insertion (LOI)
- Update to navigation state in lunar orbit prior to initiation of powered descent
- Powered descent/landing
- Trans-Earth Injection targeting an Earth-entry interface point
- Skip entry, chute deployments
Primary tracking from 3 DSN Sites
Up to three additional secondary sites
Navigation Sources In Lunar Vicinity

Earth-based ground tracking augmented by in-situ tracking and onboard sensors

TDRS

GPS

2-way Range and Doppler

3-way Doppler

Lunar Relay Satellites

Ground Tracking Stations

Inertial Nav Soln

2-way Range 2-way Doppler
Lunar Surface Operations

- Communications through combination of lunar comm terminal (cell tower) and lunar relay satellite
- Range and Doppler tracking from both comm terminal and relay satellite
- Inertial and optical nav systems for use with rovers and EVA systems
GPS Navigation Updates During Lunar Return

- Weak GPS signal tracking technology enables tracking of GPS signals well beyond the GPS constellation sphere.
- GPS can potentially improve navigation accuracy in the 12-24 hours preceding Earth entry interface.

### Periods or 2 or more SVs available
- 35 dB-Hz sensitivity
- EL – 2 hrs

### GPS altitude
- EL – 1.2 hrs

### Ground Updates

### Final TCM

### Periods 2 or more SVs available
- 25 dB-Hz sensitivity
- EL – 12 hrs
Skip-Entry Targeting
Coastal Landing Zone

- Skip entry capability enables return to CONUS (or coastal waters) for all potential Earth-Moon geometries
  - Reduces entry loads on crew
  - Increases cross-range capability
  - Enables entry from Mars Return
- Ground navigation solution during Earth-return is used to target the initial skip-entry interface point (Flight Path angle error <0.1 degrees 3-sigma)
- GPS required to perform chute deployment to achieve 5 km landing accuracy
Elements of Navigation and Tracking Architecture and Navigation Data Types

TDRS
- 2-way Range
- 2-way Doppler

GPS
- GPS pseudorange
- GPS carrier phase

Onboard Sensors:
- Inertial Measurements
- Celestial object measurements
- Optical/landmark tracking
- Active ranging (RF or optical)

Radar Tracking
- 2-way Range
- 2-way Doppler

Ground Tracking Stations
- 2-way Range and Doppler
- 3-way Doppler

Lunar Relay Satellites
New Navigation Techniques to Enable Exploration Beyond the Moon

♦ Laser communications
  - For Mars missions, RF communications will likely only support uplink data rates on the order of 10 kb/sec – inadequate to support human missions
  - Laser communications and tracking will be used for Mars-Earth trunk links

♦ X-Ray Pulsar Navigation
  - Widely available – in locations where traditional tracking sources are not
    - Earth-Sun libration point orbiters
    - Interplanetary navigation

♦ Advanced Onboard Navigation Techniques
CONSTELLATION
Acknowledgements

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