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

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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

Lunar Lander

Crew Launch 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
- Upper Stage
  - (1 J-2X)
  - LOx/LH₂
- 5-Segment reusable solid rocket booster (RSRB)

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
- Core Stage
  - (5 RS-68 Engines)
  - LOx/LH₂
- 5-Segment 2 RSRB’s

Saturn V
- Height: 111 m
- Gross Liftoff Mass: 2948 mT
- 45 metric tons to TLI
- 119 metric tons to LEO
- Crew
- Lander
- S-IIB
  - (1 J-2 engine)
  - LOx/LH₂
- S-II
  - (5 J-2 engines)
  - LOx/LH₂
- S-IC
  - (5 F-1)
  - LOx/RP
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
Typical Lunar Reference Mission

Vehicles are not to scale.

100 km Low Lunar Orbit

LSAM Performs LOI

Earth Departure Stage Expended

Ascent Stage Expended

Service Module Expended

Direct Entry Land Landing
## Comparison of Constellation and Apollo

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Apollo</th>
<th>Constellation</th>
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</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</td>
<td>Global including poles &amp; far side; 1 time &amp; return to site</td>
</tr>
<tr>
<td></td>
<td>time visits</td>
<td></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</td>
<td>100 km &lt; range &lt; 1000 km; no limit due to EVAs</td>
</tr>
<tr>
<td></td>
<td>from LM per EVA</td>
<td></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</td>
<td>Goal: 100 m unaided (1st landing at a site); &lt;10 m aided (return to Outpost)</td>
</tr>
<tr>
<td></td>
<td>controlled accuracy (no piloting effects)</td>
<td></td>
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<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
- Onboard Sensors
- Lunar Relay Satellite
- Ground Tracking
- Lunar Relay
- Earth-based Ground Station Tracking
- Surface RF Beacon
- Onboard Sensors/Inertial Nav
Onboard Navigation System Architecture

Optical Navigation and other Onboard Sensors

Images of stars and other celestial objects

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
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
Constellation Ground Tracking Capability
Comparison to Apollo Tracking Network

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

Inertial Nav Soln

2-way Range
2-way Doppler

3-way Doppler

2-way Range
and Doppler

Lunar Relay
Satellites

Ground Tracking
Stations
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

**Final TCM**

**Ground Updates**

**Periods 2 or more SVs available**

- 25 dB-Hz sensitivity
- EL = 12 hrs

**TCM**
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

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

TDRS
- 2-way Range
- 2-way Doppler

GPS
- GPS pseudorange
- GPS carrier phase

Radar Tracking

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

Lunar Relay Satellites
- 2-way Range
- 2-way Doppler
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
Parts of this presentation were adapted from original material developed by John Connaly of the Altair (lunar lander) Project Office at Johnson Space Center