Apollo Onboard Navigation Techniques
Objectives

- Review basic navigation concepts
- Describe coordinate systems
- Identify attitude determination techniques
  - Prime: PGNCS IMU Management
  - Backup: CSM SCS/LM AGS Attitude Management
- Identify state vector determination techniques
  - Prime: PGNCS Coasting Flight Navigation
  - Prime: PGNCS Powered Flight Navigation
  - Backup: LM AGS Navigation
Review of Basic Navigation Concepts

- Navigation: “Where am I?”
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- Vehicle maintains internal representation of where it is with respect to some external reference (coordinate system)
  - State vector (position and velocity vectors)
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  - State vector (position and velocity vectors)
  - Attitude
Review of Basic Navigation Concepts

- Navigation: “Where am I?”
- Vehicle maintains internal representation of where it is with respect to some external reference (coordinate system)
  - State vector (position and velocity vectors)
  - Attitude
- To maintain accuracy, this internal representation must be updated periodically using some source of external “truth data” (sensor measurements)
Basic Reference Coordinate System

• Inertial coordinate system
  – All nav stars and lunar/solar ephemerides were referenced to this system
  – All vehicle state vectors referenced to this system except during Lunar Module (LM) powered flight

• Epoch at nearest beginning of year
  – Simplified inertial-to-Earth-fixed computations
Basic Reference Coordinate System

- Origin at center of Earth or center of moon
Basic Reference Coordinate System

- Origin at center of Earth or center of moon
  - Command and Service Module (CSM) navigation automatically transformed between Earth and moon centered when crossing the moon’s Sphere of Influence (SOI)

Lunar Sphere of Influence
(r=64373.76 km, 34759.05 nmi)
Basic Reference Coordinate System

- Origin at center of Earth or center of moon
  - Command and Service Module (CSM) navigation automatically transformed between Earth and moon centered when crossing the moon’s Sphere of Influence (SOI)
- Axes:
  - X-axis pointed to First Point of Aries
Basic Reference Coordinate System

- **Origin at center of Earth or center of moon**
  - Command and Service Module (CSM) navigation automatically transforms between Earth and moon centered when crossing the moon’s Sphere of Influence (SOI)

- **Axes:**
  - X-axis pointed to First Point of Aries
  - Z axis parallel to Earth mean north pole
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  – Command and Service Module (CSM) navigation automatically transforms between Earth and moon centered when crossing the moon’s Sphere of Influence (SOI)

• Axes:
  – X-axis pointed to First Point of Aries
  – Z axis parallel to Earth mean north pole
  – Y axis completed right-handed system
IMU Stable Member Coordinate System

- Inertial coordinate system
- Defined relative to BRCS by REFerence to Stable Member MATrix (REFSMMAT)
- Many possible alignments during a mission (discussed later)
CSM Vehicle Coordinate System

- Rotating coordinate system, fixed to CSM body
- Origin along vehicle centerline, 25.4 m (1000 in) behind Command Module (CM) heat shield
- Axes:
  - +X “forward” along longitudinal axis
CSM Vehicle Coordinate System

- Rotating coordinate system, fixed to CSM body
- Origin along vehicle centerline, 25.4 m (1000 in) behind Command Module (CM) heat shield
- Axes:
  - +X “forward” along longitudinal axis
  - +Z “down” along crew’s feet when in couches
CSM Vehicle Coordinate System

- Rotating coordinate system, fixed to CSM body
- Origin along vehicle centerline, 25.4 m (1000 in) behind Command Module (CM) heat shield
- Axes:
  - +X “forward” along longitudinal axis
  - +Z “down” along crew’s feet when in couches
  - +Y “starboard” completed right-handed system
LM Vehicle Coordinate System

- Rotating coordinate system, fixed to LM body
- Origin along vehicle centerline, 5.08 m (200 in) below LM ascent stage base
- Axes:
  - +X “up” through top hatch
LM Vehicle Coordinate System

- Rotating coordinate system, fixed to LM body
- Origin along vehicle centerline, 5.08 m (200 in) below LM ascent stage base
- Axes:
  - +X “up” through top hatch
  - +Z “forward” through egress hatch
LM Vehicle Coordinate System

- Rotating coordinate system, fixed to LM body
- Origin along vehicle centerline, 5.08 m (200 in) below LM ascent stage base
- Axes:
  - +X “up” through top hatch
  - +Z “forward” through egress hatch
  - +Y “starboard” completed right-handed system
CSM/LM Body Coordinate Systems

- Axes parallel to vehicle coordinate system
- Origin at vehicle center of mass
Navigation Base Coordinate System

- Rotating coordinate system, fixed to navigation base
  - IMU gimbal angles define the transformation between stable member coordinates and nav base coordinates
- Origin at center of navigation base
- Axes parallel to vehicle body axes
Earth-fixed Coordinate System

• Rotating coordinate system, fixed to Earth
  – All Earth landmarks, including launch site vector, referenced to this system
• Origin at center of Earth
• Axes:
  – +Z along true north pole
Earth-fixed Coordinate System

- Rotating coordinate system, fixed to Earth
  - All Earth landmarks, including launch site vector, referenced to this system
- Origin at center of Earth
- Axes:
  - \(+Z\) along true north pole
  - \(+X\) along true Greenwich meridian at equator
Earth-fixed Coordinate System

- Rotating coordinate system, fixed to Earth
  - All Earth landmarks, including launch site vector, referenced to this system
- Origin at center of Earth
- Axes:
  - $+Z$ along true north pole
  - $+X$ along true Greenwich meridian at equator
  - $+Y$ in equatorial plane, completed right-handed system
Moon-fixed Coordinate System

- Rotating coordinate system, fixed to moon
  - All lunar landmarks, including landing site vector, referenced to this system
- Origin at center of moon
- Axes:
  - +Z along true north pole
Moon-fixed Coordinate System

- Rotating coordinate system, fixed to moon
  - All lunar landmarks, including landing site vector, referenced to this system
- Origin at center of moon
- Axes:
  - +Z along true north pole
  - +X along zero longitude at equator (center of moon visible disc)
Moon-fixed Coordinate System

- Rotating coordinate system, fixed to moon
  - All lunar landmarks, including landing site vector, referenced to this system
- Origin at center of moon
- Axes:
  - +Z along true north pole
  - +X along zero longitude at equator (center of moon visible disc)
  - +Y completed right-handed system (“trailing” moon in its orbit around the Earth)
Objectives

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• Identify state vector determination techniques
  – Prime: PGNCS Coasting Flight Navigation
  – Prime: PGNCS Powered Flight Navigation
  – Backup: LM AGS Navigation
Apollo used three-gimbal IMU
- Lighter and less complex than four-gimbal IMU, but vulnerable to gimbal lock when all three gimbals in same plane
- Spacecraft attitudes operationally constrained to avoid gimbal lock

Apollo Flight Director Attitude Indicator (FDAI) driven directly by IMU gimbal angles rather than computer
- Allowed IMU to operate independently of computer
- Allowed gimbal lock region to be graphically depicted as red circles on FDAI ball

Periodic IMU aligns to different REFSSMMATs required to:
- Accommodate variety of mission attitudes while avoiding gimbal lock
- Provide meaningful FDAI attitude display to crew
Common REF SMMATs

- Preferred
- Nominal (LVLH)
- Launch Pad (CSM only)
- Landing Site
- Liftoff
- Passive Thermal Control (PTC)
- Entry (CM only)
• Used for major burns
• +X aligned with $\Delta V$ vector at Time of Ignition (TIG)
Preferred REFSMMAT

- Used for major burns
- $+X$ aligned with $\Delta V$ vector at Time of Ignition (TIG)
- $+Y$ perpendicular to both $\Delta V$ vector and position vector at TIG
  - Direction could be defined to provide either “heads-up” or “heads-down” burn attitude

+Y into screen ("heads-up")
out of screen ("heads-down")
• Used for major burns
• +X aligned with $\Delta V$ vector at Time of Ignition (TIG)
• +Y perpendicular to both $\Delta V$ vector and position vector at TIG
  – Direction could be defined to provide either “heads-up” or “heads-down” burn attitude
• +Z completed right handed system
• FDAI read 0,0,0 when in burn attitude at TIG
• Aligned with Local Vertical/Local Horizontal (LVLH) coordinates at time of alignment
• Used for coasting orbital flight
• +Z aligned with radius vector (+Rbar) at time of align
Nominal REFSMMAT

- Aligned with Local Vertical/Local Horizontal (LVLH) coordinates at time of alignment
- Used for coasting orbital flight
- +Z aligned with radius vector (+Rbar) at time of align
- +Y aligned with negative orbital momentum vector (-Hbar) at time of align
- Aligned with Local Vertical/Local Horizontal (LVLH) coordinates at time of alignment
- Used for coasting orbital flight
- +Z aligned with radius vector (+Rbar) at time of align
- +Y aligned with negative orbital momentum vector (-Hbar) at time of align
- +X in orbit plane in direction of velocity (+Vbar)
- FDAI read 0,0,0 when in “airplane attitude” at time of align
- Note that this was an inertial orientation aligned with LVLH only at one point in time
  - Inertial pitch angle diverged from LVLH pitch angle at orbital rate
  - Crew used Orbital Rate Display – Earth and Lunar (ORDEAL) to bias FDAI pitch angle to display LVLH attitude
Launch Pad REFSMMAT

- CSM only
- +Z aligned with radius vector (+Rbar) at liftoff time
• CSM only
• +Z aligned with radius vector (+Rbar) at liftoff time
• +X aligned with flight azimuth at liftoff time
- CSM only
- +Z aligned with radius vector (+Rbar) at liftoff time
- +X aligned with flight azimuth at liftoff time
- +Y completed right-handed system
- At liftoff, FDAI read pitch 90, yaw 0, roll 90 plus flight azimuth
Landing Site and Liftoff REFSMMATs

- $+X$ aligned with position vector at planned landing time
Landing Site and Liftoff REFSMMATs

- +X aligned with position vector at planned landing time
- +Z pointed “forward” (parallel to CSM orbit plane)
Landing Site and Liftoff REFSMMATs

- +X aligned with position vector at planned landing time
- +Z pointed “forward” (parallel to CSM orbit plane)
- +Y completed right-handed system
- LM FDAI read 0,0,0 at landing
- Liftoff REFSMMAT identical except defined at planned lunar liftoff time
• Used for passive thermal control ("barbecue roll") during translunar/transearth coast
• +X in ecliptic plane perpendicular to Earth-moon line
• Used for passive thermal control (“barbecue roll”) during translunar/transeearth coast
• +X in ecliptic plane perpendicular to Earth-moon line
• +Z perpendicular to ecliptic plane directed south
• Used for passive thermal control (“barbecue roll”) during translunar/transearth coast
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• +Z perpendicular to ecliptic plane directed south
• +Y completed right-handed system
• PTC roll initiated from 90 deg pitch attitude to place CSM/LM stack perpendicular to ecliptic (and hence, line of sight to sun)
• Aligned with LVLH at predicted time of Entry Interface (EI), 122 km (400 kft) altitude
• FDAI read pitch 180, 0, 0 in heads-down heat-shield forward attitude at EI
• Note that nominal EI attitude pitched 20 degrees above local horizontal
IMU Alignment Techniques

• Two vectors required to uniquely define orientation of one frame with respect to another
  – First vector fixes a line of sight (LOS) but leaves one degree of freedom (rotation about LOS)
IMU Alignment Techniques

• Two vectors required to uniquely define orientation of one frame with respect to another
  – First vector fixes a line of sight (LOS) but leaves one degree of freedom (rotation about LOS)
  – Second vector fixes rotation about LOS
• Crew marked on two stars (or other known celestial bodies) using the sextant (SXT) or scanning telescope (SCT)
• Auto optics modes allowed SXT/SCT shaft and trunnion to be pointed directly at stars selected by the computer
• Manual optics modes allowed tweaking of SXT/SCT shaft/trunnion using optics controller
• Minimum Impulse Controller (MIC) could be used to tweak CSM attitude
• Crewman Optical Alignment Sight (COAS) could be used as backup alignment device if optics failed
  – Not attached to navigation base – calibration required prior to use
LM Docked IMU Alignment

- Initial coarse alignment used CM gimbal angles
- Docking mechanism did not tightly constrain relative roll
  - Crew recorded docking angle ($R_c$) from index marks on tunnel during initial LM activation
- Required LM gimbal angles computed manually from CM gimbal angles as follows:
  \[
  \begin{align*}
  OGA_{LM} &= 300° + R_c - OGA_{CM} \\
  IGA_{LM} &= 180° + IGA_{CM} \\
  MGA_{LM} &= 360° - MGA_{CM}
  \end{align*}
  \]
LM Orbital IMU Alignment

- Crew marked on two stars (or other known celestial bodies) using the alignment optical telescope (AOT)
- AOT had six detent positions; however, only forward position could be used while docked to CSM
- Rendezvous Radar (RR) antenna required to be positioned out of AOT field-of-view
- Crew entered detent position code and star code manually into computer
- COAS could be used as backup (same calibration restrictions as CSM)
• X-line and Y-line on AOT reticle used for in-flight alignment
• Crew allowed star to drift across AOT field-of-view
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• Crew allowed star to drift across AOT field-of-view
• Crew pressed [MARK Y] when star crossed Y-line
LM AOT Usage

• X-line and Y-line on AOT reticle used for in-flight alignment
• Crew allowed star to drift across AOT field-of-view
• Crew pressed [MARK Y] when star crossed Y-line
• Crew pressed [MARK X] when star crossed X-line
• Marks could be taken in either order
• Crew pressed [MARK REJECT] if bad mark
• Not always possible to sight on two stars while on surface
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• For first surface alignment, local gravity vector (as measured by IMU accelerometers) could be substituted for one of the star sightings
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• For first surface alignment, local gravity vector (as measured by IMU accelerometers) could be substituted for one of the star sightings
• Present orientation of LM Y and Z axes stored in moon-fixed coordinates at conclusion of each alignment
LM Lunar Surface IMU Alignment

- Not always possible to sight on two stars while on surface
- For first surface alignment, local gravity vector (as measured by IMU accelerometers) could be substituted for one of the star sightings
- Present orientation of LM Y and Z axes stored in moon-fixed coordinates at conclusion of each alignment
- For second and subsequent alignments, could use either gravity vector and present Z axis, or present Y and Z axes
• Stars may never cross AOT X or Y lines while on surface
  – LM in fixed attitude
  – Moon rotates very slowly
  – Different marking technique required
• AOT reticle had two additional markings
  – Radial “cursor”
  – Archimedean “spiral” (radius increases linearly with angle)
• AOT reticle rotated to allow cursor or spiral to be superimposed on star
  – Reticle angle displayed on counter, manually entered via DSKY
LM AOT Surface Usage

- Stars may never cross AOT X or Y lines while on surface
  - LM in fixed attitude
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- LM in fixed attitude
- Moon rotates very slowly
- Different marking technique required

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- Radial “cursor”
- Archimedean “spiral” (radius increases linearly with angle)

AOT reticle rotated to allow cursor or spiral to be superimposed on star:
- Angle displayed on counter, manually entered via DSKY
CSM SCS Attitude Management

- Stabilization and Control System (SCS) served as backup control system for the Primary Guidance, Navigation, and Control System (PGNCS)
- Attitude reference provided by two Gyro Assemblies (GAs), each of which contained three Body Mounted Attitude Gyros (BMAGs)
- GA2 BMAGs measure attitude rate
- GA1 BMAGs nominally measure attitude change from reference attitude but could be configured to measure rates as backup to GA2
CSM SCS Attitude Management

- Gyro Display Coupler (GDC) combined GA1 attitude difference with reference attitude to produce total attitude for display to crew
- Reference attitude set to current IMU attitude on Attitude Set Control Panel (ASCP), then GDC aligned to reference
- BMAGs were more “drifty” than IMU
LM AGS Attitude Management

• Abort Sensor Assembly (ASA) was strapdown inertial navigation system for the Abort Guidance System (AGS)
• AGS had access to PGNS downlist data via telemetry link
• Crew had capability to command AGS to align ASA to IMU
• AGS could also calibrate ASA gyro/accelerometer biases using IMU as reference
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Coasting Integration

- Encke’s Method
  - Use current state vector and gravity of primary body to compute a reference conic
Coasting Integration

- **Encke’s Method**
  - Use current state vector and gravity of primary body to compute a reference conic
  - Sum all other accelerations to propagate a position/velocity deviance from the reference conic
Coasting Integration

• Encke’s Method
  – Use current state vector and gravity of primary body to compute a reference conic
  – Sum all other accelerations to propagate a position/velocity deviance from the reference conic
  – When deviances exceed threshold, compute new reference conic and zero the deviations (rectification)
Coasting Integration

• Compare to Cowell’s Method (shuttle):
  – Sum all accelerations on vehicle (including primary body gravity) and propagate directly to advance the state vector

• Cowell’s advantage: simpler, brute-force algorithm

• Encke’s advantages:
  – Maintains more precision at larger stepsizes
  – More suitable for slow computers with limited precision (i.e. Apollo Guidance Computer)
Perturbing Accelerations

• Depended on phase of mission
• Earth or lunar orbit: non-spherical gravity of primary body (up to fourth order terms)
• Translunar/transearth coast: Earth, lunar, and solar gravity (spherical terms only)
• No drag
• No IMU acceleration
• Several different programs available, not all on both vehicles

• MCC prime for most forms of navigation; onboard capability intended as loss-of-comm backup

<table>
<thead>
<tr>
<th>Program</th>
<th>CSM</th>
<th>LM</th>
<th>Prime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rendezvous</td>
<td>✓</td>
<td>✓</td>
<td>Onboard</td>
</tr>
<tr>
<td>Orbital</td>
<td>✓</td>
<td></td>
<td>MCC</td>
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<tr>
<td>Cislunar-midcourse</td>
<td>✓</td>
<td></td>
<td>MCC</td>
</tr>
<tr>
<td>Lunar Surface</td>
<td></td>
<td>✓</td>
<td>MCC</td>
</tr>
</tbody>
</table>
- The state vectors for both vehicles are propagated to the current time.
LM Rendezvous Navigation

- The LM RR takes a measurement (range, range rate, shaft, or trunnion angle) of the CSM
• The navigation software computes an estimate of the RR measurement based on the current state vectors, and a measurement geometry vector.
• The navigation software computes the difference (residual) between the actual RR measurement and the estimated measurement.
The navigation software computes a weighting vector based on the current states, the measurement geometry vector, and predefined sensor variances.
LM Rendezvous Navigation

- The navigation software computes an update to the state vector and the estimated RR biases using the weighting vector and the measurement residual.
LM Rendezvous Navigation

- The state vector update is tested against a predefined threshold
- If the test passes, the state vector and RR biases are updated
- Otherwise, alarm annunciated and crew either accepts or rejects the update
State vector update can be applied to either vehicle (usually the active vehicle, LM)

- If CSM performs maneuver, maneuver $\Delta V$ should be externally applied to CSM vector in the LM to prevent excessive RR updates and improve state vector convergence
If it quacks like one...

- Apollo navigation software initial development by Battin was concurrent with (and independent of) Kalman’s work on recursive estimators (later named Kalman filters)
  - Early Apollo documents didn’t use Kalman’s nomenclature
  - Battin discovered Kalman’s work during development
- Apollo navigation software contained several simplifications/differences from “orthodox” Kalman filter
  - W-matrix instead of error covariance matrix
    - Square root of covariance: \([E] = [W][W]^{T}\)
    - Eliminating negative numbers from matrix improved convergence
  - One measurement incorporation at a time
    - Reduced a lot of matrix-vector math to vector-scalar math
  - Measurement edit test used state vector update rather than ratio
    - Ratio test incorporates covariance, becomes more stringent as state vector converges
• CSM rendezvous measurements are performed using VHF (range) and SXT (shaft and trunnion angles)
• Sensor biases are not propagated
The LM vehicle state is stored in Moon-Fixed Coordinates and updated by transforming to inertial coordinates.

- The CSM state vector is updated using LM RR data.
- Only RR range and range rate are incorporated, not angles.
- RR biases are not propagated.
CSM Orbital Navigation

- Only the CSM state vector is propagated
- Measurements are SCT shaft and trunnion angles on a landmark on the Earth or lunar surface
- All updates must be accepted or rejected by the crew
- Landmark may be known (update CSM state vector) or unknown (update landmark position)
- Sensor biases are not propagated
CSM Cislunar-Midcourse Navigation

- Only the CSM state vector is propagated
- Measurements are SXT marks on a star and either a landmark or Earth/moon horizon
- All updates must be accepted or rejected by the crew
- Sensor biases are not propagated
Powered Flight Navigation

- Both CSM and LM used Average-G algorithm for state vector propagation during powered flight
  - Used IMU accumulated $\Delta V$ over one guidance cycle (2 seconds)
  - Used average gravitational acceleration over one cycle, primary body only
    - Earth gravity model: spherical and J2 (equatorial bulge) terms only
    - Lunar gravity model: spherical term only
  - Estimated vehicle mass updated based on IMU sensed $\Delta V$
- No measurement incorporation for CSM
- LM Average-G incorporated Landing Radar (LR) measurements only
  - Slant range data available starting at 12.2 km (40 kft) altitude
  - Velocity data available starting at 10.6 km (35 kft) altitude
  - Both range and velocity subjected to simple independent reasonableness checks
  - All data inhibited at 15.2 m (50 ft) altitude
- LM state vector propagated in Stable Member coordinates (rather than Basic Reference coordinates) during powered descent, ascent, and aborts
  - Since IMU aligned to landing/liftoff REFSMMAT, sometimes referred to as landing site coordinates
  - Average-G output transformed back to BRCS for downlink
LM AGS Navigation

- AGS state vectors initialized from PGNS telemetry link upon crew command
- AGS state vectors could also be initialized via manual keyboard entries of vectors voiced up from MCC
- AGS propagated CSM/LM state vectors from last initialized data using acceleration data from ASA
- If LM under PGNS control, AGS acquired rendezvous radar (RR) data (range, range rate, and angles) automatically from PGNS
- If LM under AGS control, AGS acquired rendezvous radar data via manual DEDA entries
  - Range and range rate only
  - Crew manually pointed LM +Z axis at CSM to zero RR angles
Summary

• Review of Basic Navigation Concepts
• Coordinate Systems
• Attitude Determination
  – Prime: PGNCS IMU Management
  – Backup: CSM SCS/LM AGS Attitude Management
• State Vector Determination
  – Prime: PGNCS Coasting Flight Navigation
  – Prime: PGNCS Powered Flight Navigation
  – Backup: LM AGS Navigation
References

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- Apollo Guidance Computer History Project, Interview with R. Battin, MIT, 30 September 2002 (http://authors.library.caltech.edu/5456/01/hrst.mit.edu/hrs/apollo/public/interviews/battin.htm).