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?”
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)
Review of Basic Navigation Concepts

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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)
  - 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)
Coordinate Systems

Planet-Fixed Coordinates
- Moon-Fixed Coordinates
- Earth-Fixed Coordinates

Basic Reference Coordinates
- Lunar ephemeris
- Earth rotation

Stable Member Coordinates
- REFSSMMAT
- IMU gimbal angles

Navigation Base Coordinates
- Nav base location

Vehicle Coordinates
- c.m. location

Body Coordinates

Vehicle-Fixed Coordinates
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)
**Basic Reference Coordinate System**

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- **Axes:**
  - X-axis pointed to First Point of Aries
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- Axes:
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  - Z axis parallel to Earth mean north pole
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
  - Y axis completed right-handed 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)
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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 REFSMMATs required to:
- Accommodate variety of mission attitudes while avoiding gimbal lock
- Provide meaningful FDAI attitude display to crew
Common REFSMMATs

- 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)
• 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
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
- $+Z$ 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 ($+R_{bar}$) 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

+Y “out of screen” +Z
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
- 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 REFSMMA Ts

- +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/transearth 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
• +X in ecliptic plane perpendicular to Earth-moon line
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• +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
• FDAO 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

Optics Controller
Minimum Impulse Controller (MIC)
MARK and MARK REJECT pushbuttons
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:
  $$\text{OGA}_{LM} = 300° + R_c - \text{OGA}_{CM}$$
  $$\text{IGA}_{LM} = 180° + \text{IGA}_{CM}$$
  $$\text{MGA}_{LM} = 360° - \text{MGA}_{CM}$$
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
• 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
• 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
LM Lunar Surface IMU Alignment

- 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

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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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  – Prime: PGNCS Powered Flight Navigation
  – Backup: LM AGS Navigation
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
• 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>
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</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>
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</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
LM Rendezvous Navigation

- 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
LM Rendezvous Navigation

- 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
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.
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
• 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 REFSSMMAT, 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).