Derived Atmospheric Density Corrections from Historical EOS Mission(s) Ephemeris Data for Space Weather Model Validation

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• An unpredicted, post-maneuver close approach between Aqua and a piece of orbital debris required a quick response Risk Mitigation Maneuver (RMM)-10/25/2013
  • RMM required two days after a routine orbit maintenance maneuver was performed
    - Caused an unplanned control box violation (mission CB not science CB)
• This activity resulted in an Earth Science Mission Operations (ESMO) review board which included representatives from the Space Weather group
  • Follow-on discussions with Space Weather representatives resulted in a proposal to investigate the possible use of derived Aqua atmospheric density data for use in space weather model validation
Agenda

- Aqua Mission Background
- Routine Flight Dynamics Operations
- Definitive Ephemerides
- GSFC Flight Dynamics Facility
- Proposed Approaches for Derivation of Atmospheric Density
- Aqua Magnetometer Data
EOS Mission Orbit (Aqua)

- Aqua was launched on May 4, 2002
- Ascended into a polar, sun-synchronous, frozen orbit
  - 98.2 degree inclination
  - 705 km semi-major axis (SMA)
  - 16 day repeat cycle
  - Mean Local Time (MLT) range: 1:36:30 +/- 45 seconds
- Maintains World Reference System-2 (WRS-2) ground track to +/-10km (mission goal)
  - WRS-2 was originally established by USGS for cataloging Landsat data
  - 20km is the Aqua ground track maintenance science requirement
- EOS Flight Dynamics team (FDT) receives a daily Aqua definitive ephemeris from GSFC-Flight Dynamics Facility (FDF)
• FDT propagates the Aqua predicted orbit from the end of the definitive ephemeris for both short- and long-term duration predicted product generation
  • Generate daily Aqua on-board computer (OBC) ephemeris upload
    - Predicted OBC ephemeris accuracy requirement is 400 meters (RSS) after 32 hours
  • Predicted Aqua OBC ephemeris accuracy requirement (400 m RSS) is occasionally exceeded due to errors in predicted solar flux
    - Predicted ephemeris accuracy depends on the NOAA 27-day solar flux prediction
    - Flux predictions are less reliable during peaks of solar cycle
  • Determine if orbit maintenance maneuvers are necessary to meet mission constraints using predicted ephemeris
    - Plan orbit maintenance maneuvers
      > Drag make-up (DMU) maneuvers – solar flux level dependent (density)
      > Inclination maneuvers – compensate for solar/lunar effects on inclination
Predictive vs. Definitive RSS Position Differences

Predictive vs. Definitive Ephemeris Comparison Trending

Max Position Difference (m)

Date

8/14/12 10/3/12 11/22/12 1/11/13 3/2/13 4/21/13 6/10/13 9/18/13 11/7/13 12/27/13 2/15/14 4/6/14 5/26/14 7/15/14
Aqua Flight Dynamics
Team Routine Operations

• Predicted ephemeris is also used to plan risk mitigation maneuvers (RMMs)

• PROBLEM: Predicted miss distances depend on the accuracy of the predicted solar activity and modeling the effects of density changes on each object
  • Each object has unique physical properties resulting in differential drag effects
  • Improvements in space weather predictions and the effects on atmospheric density would be beneficial for routine maneuver/RMM planning and could also improve predicted ephemeris accuracy
    - RMM planning is based on short-term (<1 week) predictions of the orbits of a primary and a secondary object
    - If the solar flux prediction is not accurate, the predicted miss distance between objects is not accurate either
• FDF provides a daily definitive ephemeris for the Aqua (and Aura) missions
  • Nominal tracking schedule for Aqua orbit determination (OD)
    - One ground station pass per orbit (~14/day)
    - 4-6 TDRS passes per day
  • 24 hour tracking arc is used for daily OD
  • 20 meters (RSS) is the required definitive OD accuracy
    - OD accuracy requirement defined as the maximum error over the 24 hour overlap segments in successive FDF definitive products
      > i.e., today’s definitive vs. yesterday’s prediction at end of filter run
    - Most of that error is in the along track direction

• The FDF/EOS FDT maintain a historical ephemeris record (since launch) of the definitive orbit solutions and concatenates them into yearly segments
FDF: Quick Refresher on Drag

\[ \vec{a}_{\text{drag}} = -\frac{1}{2} \rho \frac{C_D A}{m} \nu_{\text{rel}} \vec{v}_{\text{rel}} \]

- \( \rho \) = density
- \( C_D \) = drag coef.
- \( A \) = cross-sectional area
- \( m \) = mass
- \( \vec{v}_{\text{rel}} \) = atmosphere-relative velocity

Physical \( C_D \):
- determined by energy and momentum exchange of atmospheric particles with surface
- depends on geometry, orientation, gas-surface interaction (GSI) model, atmosphere chemical composition, relative velocity, gas temperature, wall temperature
- closed-form solutions exist for simple shapes, but complex shapes need numerical solutions, e.g. Direct Simulation Monte Carlo (DSMC)

Fitted \( C_D \):
- estimated parameter that is solved for during orbit estimation process
FDF: Relation to Other Density Estimation Efforts?

Things like CHAMP, GRACE, GOCE:
- Precision measurements (accelerometers, GPS) on small number of satellites
- High-fidelity force modeling (required)
- High temporal resolution (~sec), local to orbit
- Low altitude (<450 km)

Things like Aqua (and other EOS):
- Pretty good measurements
- Medium-fidelity force modeling
- Medium temporal resolution (~per orbit?), local to orbit
- Upper thermosphere (~700 km)

Things like HASDM (High Accuracy Satellite Drag Model) from USAF:
- Radiometric tracking of ~100 targets (e.g. rocket bodies) throughout thermosphere.
- Somewhat well-known drag properties.
- Dynamic Calibration of the Atmosphere (DCA)
  - Spatially-resolved (global correction)
  - Low temporal resolution (~3 hrs).
FDF: OD of Aqua

- Uses AGI’s Orbit Determination Tool Kit (ODTK)
  - Filter-Smoother processes past 24-hrs of tracking data
  - Solves simultaneously for operational TDRS, Aqua, Aura, Terra, TRMM
  - Estimate simultaneously ballistic coeff. \( \beta = \frac{C_D A}{m} \) and corrections to density
    - Both modeled as Gauss-Markov processes with different half-lives
    - Ballistic coeff. allowed to vary more slowly than density
    - \( C_D \) delivered to FDT is extracted from \( \beta \) using agreed-upon area (orbit average) and mass.
  - Also estimate a SN transponder Doppler bias, again as Gauss-Markov process
  - Do not estimate correction to solar radiation pressure (SRP) coefficient.
    - SRP modeled as cannonball, constant coefficient
FDF: A Proposed Strategy

Simple approach:

• Estimate only a density correction, where $C_D$ is calculated from ODTK’s box-and-wing model.
• In parallel, estimate both density correction and $C_D$ correction simultaneously, as done now.
• Cross-validate the results from the above two.
  • Also, validate using predictive vs. definitive ephemeris comparisons.

Expanded approach:

• Compare density estimate with other models?

Also:

• Investigate higher-fidelity SRP modeling.
EOS FD - Proposed Analysis Approach

• Initial Concept:
  • Aqua drag area is repeatable on an orbital basis
    - Daily FDF solved-for $C_D$ variation ranges from $\sim 0.5$ to $\sim 3.0$ over mission life
  • Identify “small” predicted vs. definitive compares (e.g. <50m over the predicted interval)
  • Look for consistency in the $C_D$ value(s) used in the predicted ephemeris when the compares were <50m
    - If the predicted vs. definitive compare was small, that implies that the $C_D$ value used to generate the predicted ephemeris was correct for the atmospheric model used
    - If the $C_D$ values were consistent for the small compares, then use this value as the true $C_D$ value for correcting the predicted atmospheric density model used by the FDT
  • FDF can output definitive OD solutions at orbital frequency to 20 meter accuracy
    - FDF can also output the solved-for $C_D$, predicted density, and solved-for density
Aqua Solved for $C_D$

Aqua Coefficient of Drag Trending

- FDF Solved for $C_d$
- FDS Product $C_d$
- 27 per. Mov. Avg. (FDF Solved for $C_d$)

Date

5/4/02 8/29/02 11/3/02 11/10/02 11/17/02 11/24/02 12/1/02 12/8/02 12/15/02 12/22/02 12/29/02 1/5/03 1/12/03 1/19/03 1/26/03 2/2/03 2/9/03 2/16/03 2/23/03 3/1/03 3/8/03 3/15/03 3/22/03 3/29/03 4/5/03 4/12/03 4/19/03 4/26/03 5/3/03 5/10/03 5/17/03 5/24/03 5/31/03 6/7/03 6/14/03 6/21/03 6/28/03 7/5/03 7/12/03 7/19/03 7/26/03 8/2/03 8/9/03 8/16/03 8/23/03 8/30/03 9/6/03 9/13/03 9/20/03 9/27/03 10/4/03 10/11/03 10/18/03 10/25/03 11/1/03 11/8/03 11/15/03 11/22/03 11/29/03 12/6/03 12/13/03 12/20/03 12/27/03 1/3/04 1/10/04 1/17/04 1/24/04 1/31/04 2/7/04 2/14/04 2/21/04 2/28/04 3/6/04 3/13/04 3/20/04 3/27/04 4/3/04 4/10/04 4/17/04 4/24/04 5/1/04 5/8/04 5/15/04 5/22/04 5/29/04 6/5/04 6/12/04 6/19/04 6/26/04 7/3/04 7/10/04 7/17/04 7/24/04 8/1/04 8/8/04 8/15/04 8/22/04 8/29/04
The FDT analysis started out looking for small definitive vs. definitive overlap compares, but no \( C_D \) consistency was immediately obvious. Other task activities have precluded working on this analysis recently, but it will continue, as time permits.
Aqua (and Aura) use three-axis magnetometers (TAM) for coarse attitude determination/control and for momentum management.

- Post-calibration magnetometer accuracy should be within a few milli-gauss per axis.
- Magnetic field strength and direction at 705 km can be derived from this information:
  - Total magnetic field strength is ~ 300 milliGauss at 705 km.
  - 16-day repeat cycle over WRS-2 grid.
  - <20 meter spacecraft position accuracy available when using definitive ephemeris.
  - TAM output available at 32 second intervals.

- Historical magnetometer record is available (with effort by the Flight Operations Team [FOT]) from near launch for both Aqua and Aura.
  - Sample Aqua TAM data were provided by John Nidhiry (Aqua FOT GN&C Lead).
• TAM data are potentially useful for Space Weather model validation/enhancement
  • Historical data are available from other EOS missions, if Aqua magnetometer data are shown to be useful

• Aura Location
  • Aura crosses the ascending node ~8 minutes behind Aqua
    - Same WRS-2 path as Aqua, but offset ~18 km East of Aqua
      > To facilitate coincident observations between CALIPSO CALIOP and Aura MLS instruments