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

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Background

- **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

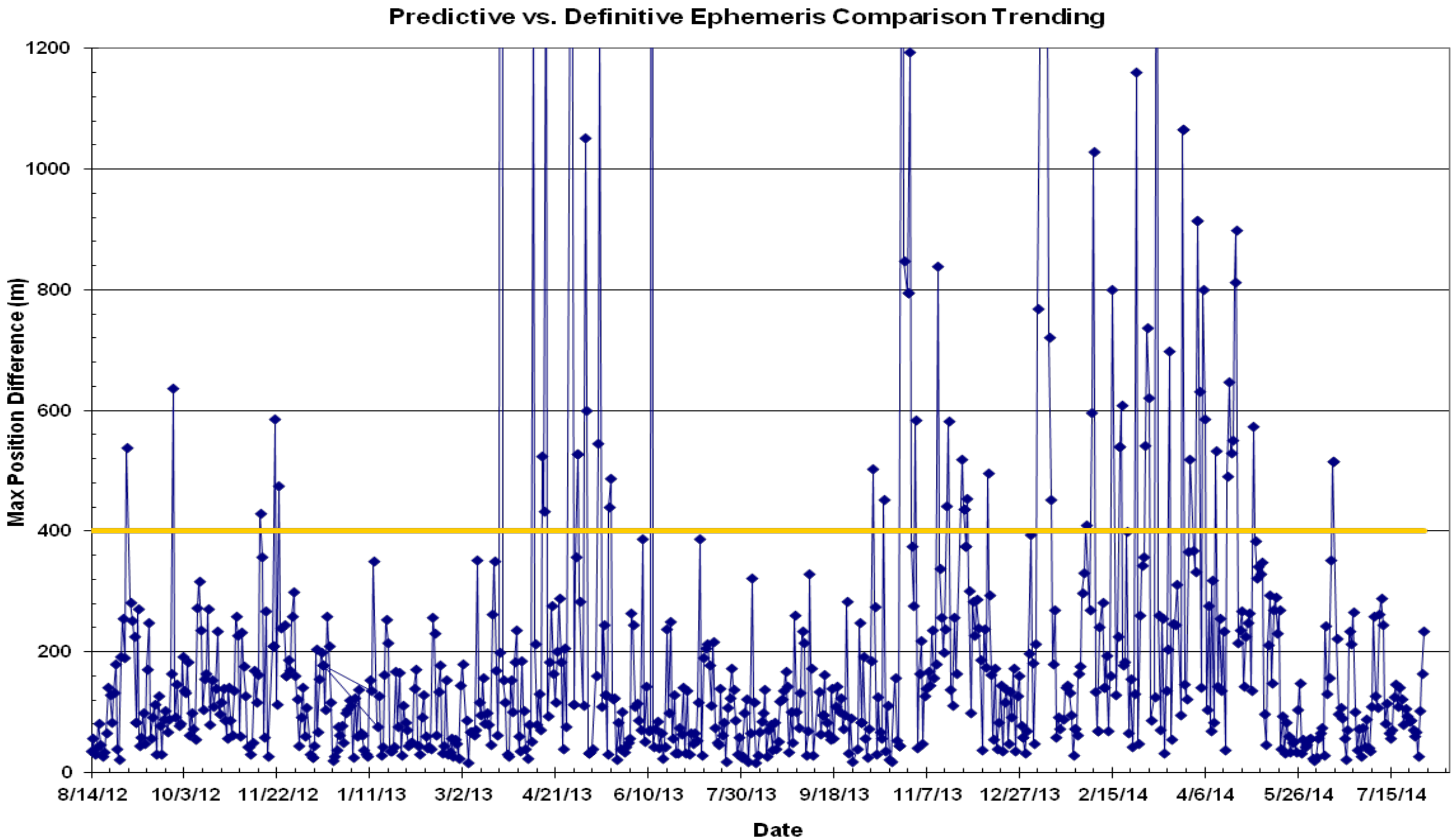
EOS Mission Orbit (Aqua)

- **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)**

Aqua Flight Dynamics Team Routine Operations

- **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



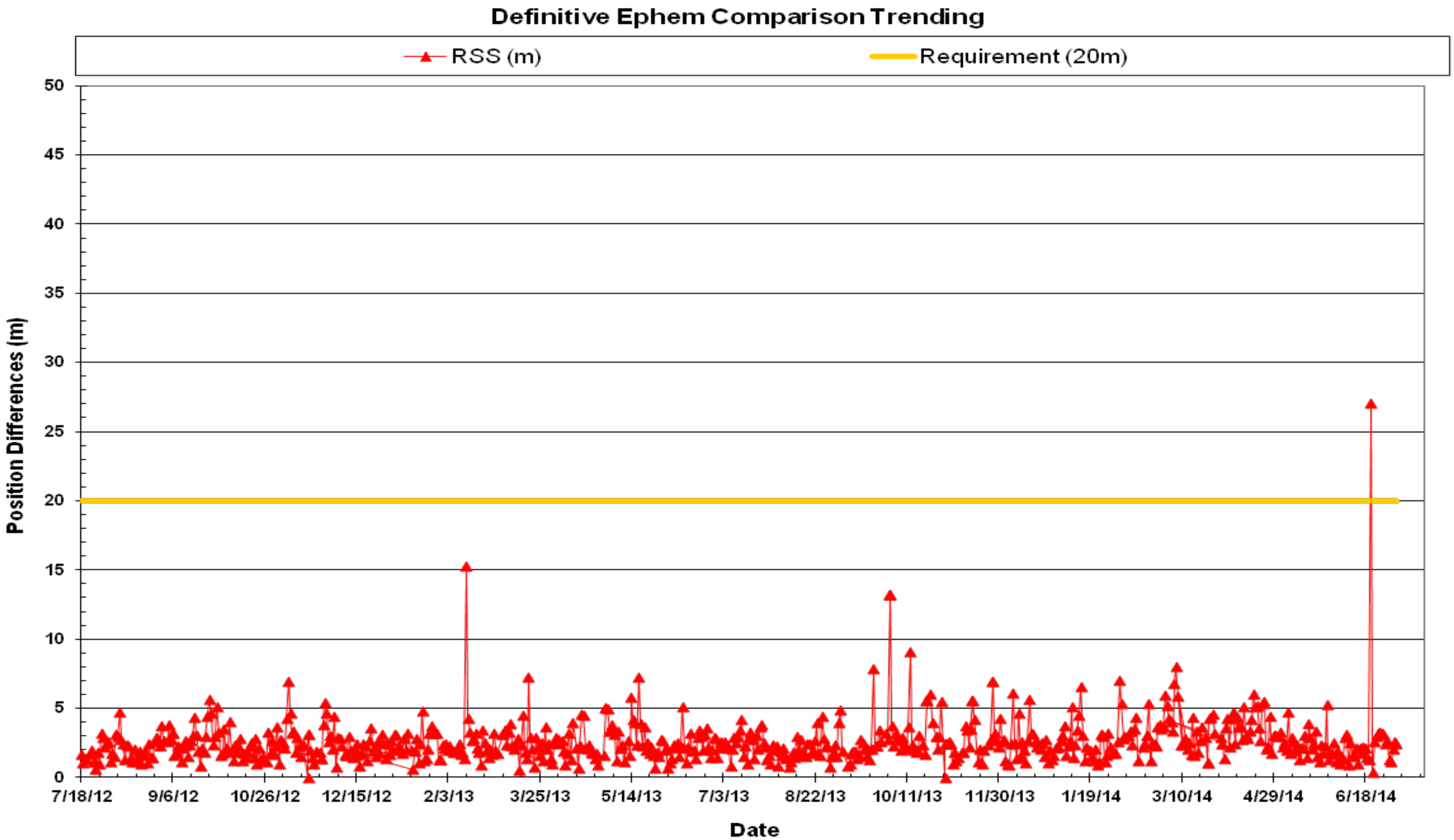
Aqua Flight Dynamics Team Routine Operations

- **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**

Flight Dynamics Facility (FDF) - GSFC

- **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**

Definitive FDF Ephem RSS Position Differences



FDF: Quick Refresher on Drag

$$\vec{a}_{\text{drag}} = -\frac{1}{2}\rho\frac{C_D A}{m} v_{\text{rel}}\vec{v}_{\text{rel}}$$

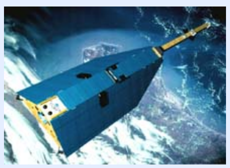
- ρ = density
- C_D = drag coef. (note: "fitted" vs. "physical")
- A = cross-sectional area
- m = mass
- $\vec{v}_{\text{rel}}$ = atmosphere-relative velocity

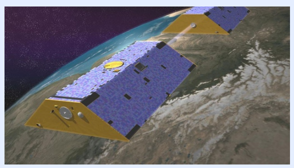
Fitted C_D:
- estimated parameter that is solved for during orbit estimation process

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)

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 coef. ($\beta = C_D A/m$) and corrections to density
    - Both modeled as Gauss-Markov processes with different half-lives
    - Ballistic coef. allowed to vary more slowly than density
    - C_D delivered to FDT is extracted from β 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?**

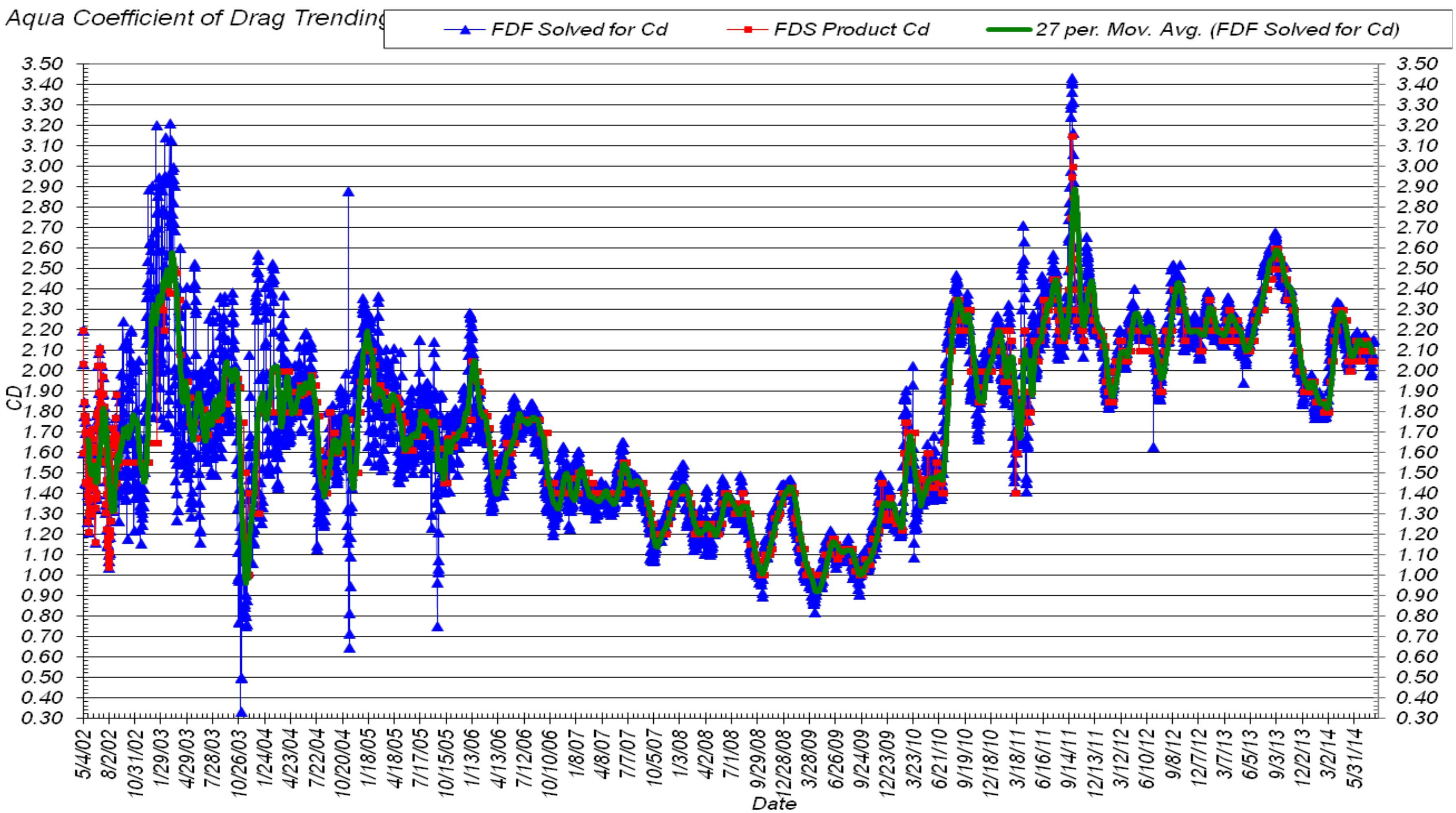
Also:

- **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 ~0.5 to ~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



EOS FD - Proposed Analysis Approach

- **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.**

EOS Mission Magnetic Field Information

- 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)

EOS Magnetic Field Information

- **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**

Solar Flux History and Planetary A Index