Cross-Agency Collaboration and Standards For Conjunction Assessment

Ground Systems Architecture Workshop 2011

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OBJECTIVES

- To describe collaborative development of the content, format, implementation, and operational use of timely information for mitigating the consequences of conjunctions among satellites.
- To encourage applying these advances in ground systems that support important space missions.

INTRODUCTION:

- The growing significance of close approaches among satellites demands greater accuracy and precision than Two Line Element Sets (TLE) can provide.
- Safe and collaborative space operations require greater information scope, accuracy, and precision than past operations.
- Civil, commercial, and governmental stakeholders are collaborating to develop essential exchange mechanisms.

BACKGROUND:

- There are many different approaches to perceiving conjunctions.
  - Close approach within a specified distance
  - Probability of collision
- There are many approaches to determining probability of collision
  - Covariance volume intersection
  - Heuristic
- Minimum information required
  - Force models used
  - Reference frame, coordinate system, time scale
  - Measurement Uncertainty
  - Probability of Collision and technique for determining the probability.

CONJUNCTION PHYSICS AND MATHEMATICS

- Satellites pass within a few kilometers of each other thousands of times each day.
  - Over 17,000 conjunctions within 5 km on 24 Jan 2011.
- Estimates based on even the most current and reliable data are very uncertain
  - Epoch of last orbit determination
  - Epoch and precision of reference frame
  - Frequency and distribution of underlying observations
  - Quality of observations

Trajectory Estimation

- Orbit determination is statistical hypothesis testing
  - Fitting a dynamic hypothesis (equations of motion) to redundant data sets
- Least Squares
  - Minimize sum square of residuals between the fit with free parameters and the observations.
  - Normal Equation (linear form)
    - $\boldsymbol{X} = (\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{A})^{-1}\,\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{b}$
  - For the orbit problem, it's non-linear
    - $\delta\boldsymbol{x} = (\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{A})^{-1}\,\boldsymbol{A}^T\boldsymbol{W}\underline{\boldsymbol{b}}$
    - $(\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{A})^{-1}$ – Covariance matrix
    - Corrections to the state ($\delta\boldsymbol{x}$) found through iteration

Least Squares Overview

Initial Orbit Determination

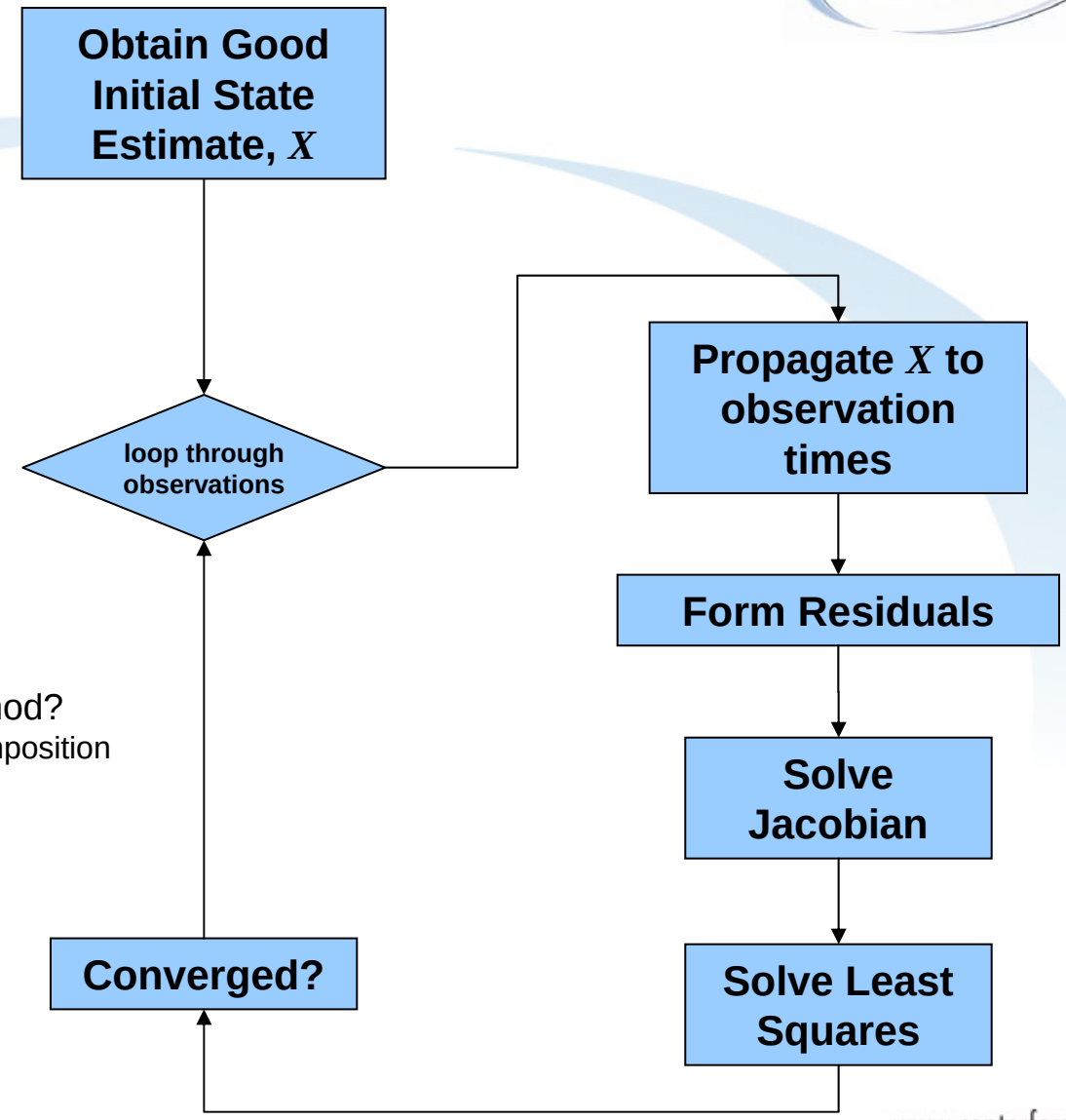
How good?
- Radius of Curvature

What state representation?
- Equinoctial, Keplerian, other

Orbit Determination

How to solve for Jacobian?
- Analytical, finite differencing

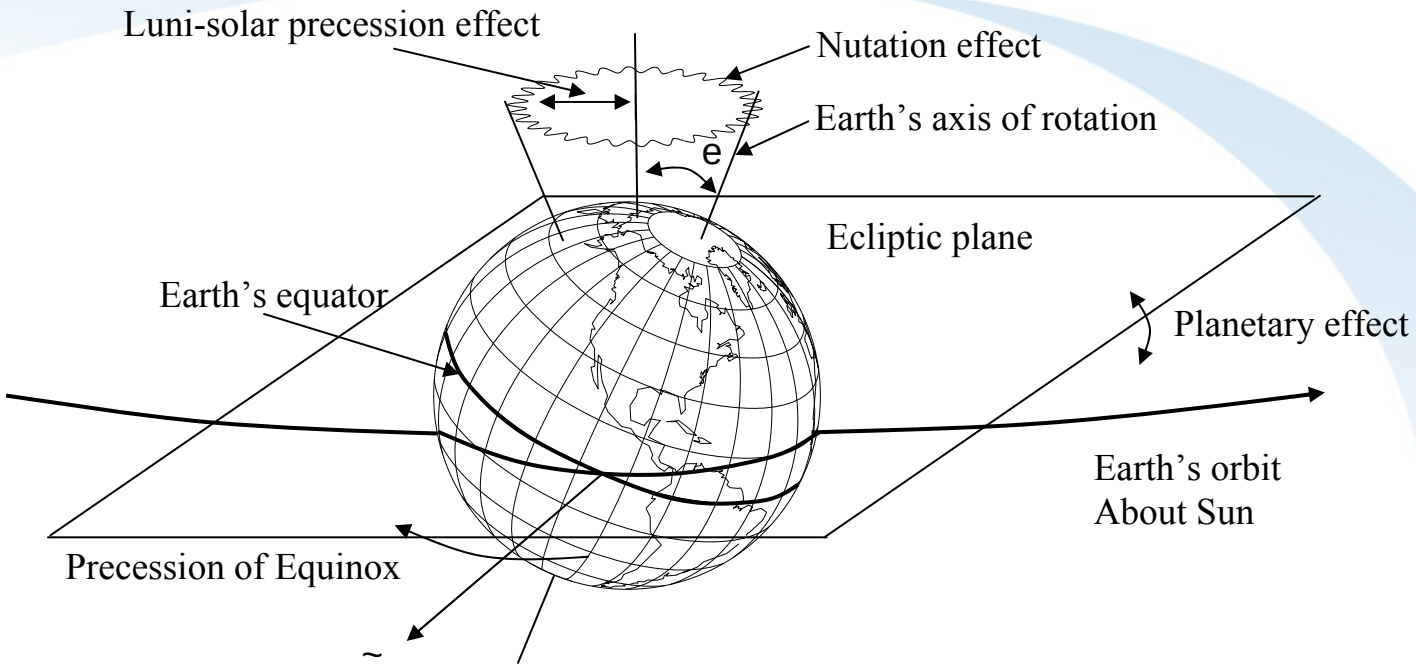
Least Squares Solution method?
- Classical, Single Value Decomposition



Data Alignment

- Data Alignment is arranging all of the observations in a common reference frame, coordinate system, and time scale.
  - Different reference frames are best for different applications.
  - The Earth is not a sphere, its axis is tilted, its orbit is not circular, and all of these change with time.
  - Time is measured in many different ways
    - Atomic time
    - UTC in atomic seconds
    - UT1 in Earth Rotations
    - Dynamical time relative to the barycenter of the Solar System

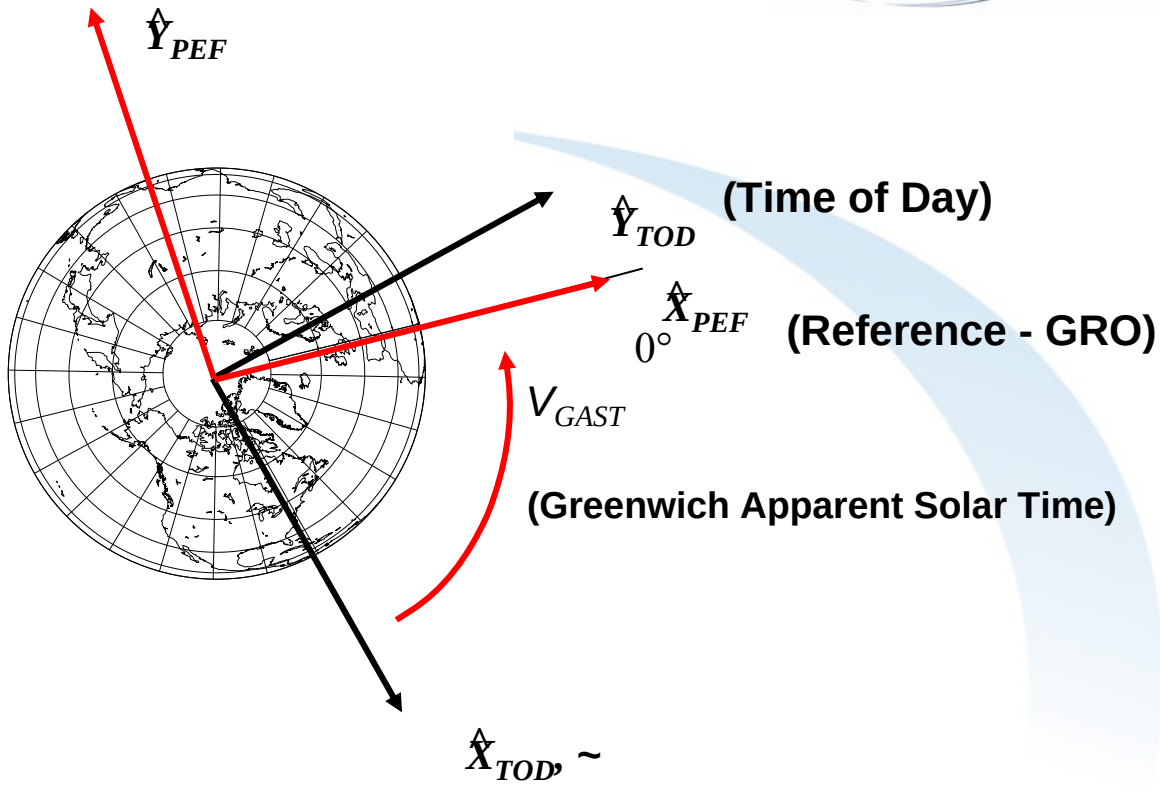
Precession and Nutation



The Tropic of Cancer (Longitude which equals the Earth's inclination) wanders hundreds of km in the course of a solar year.

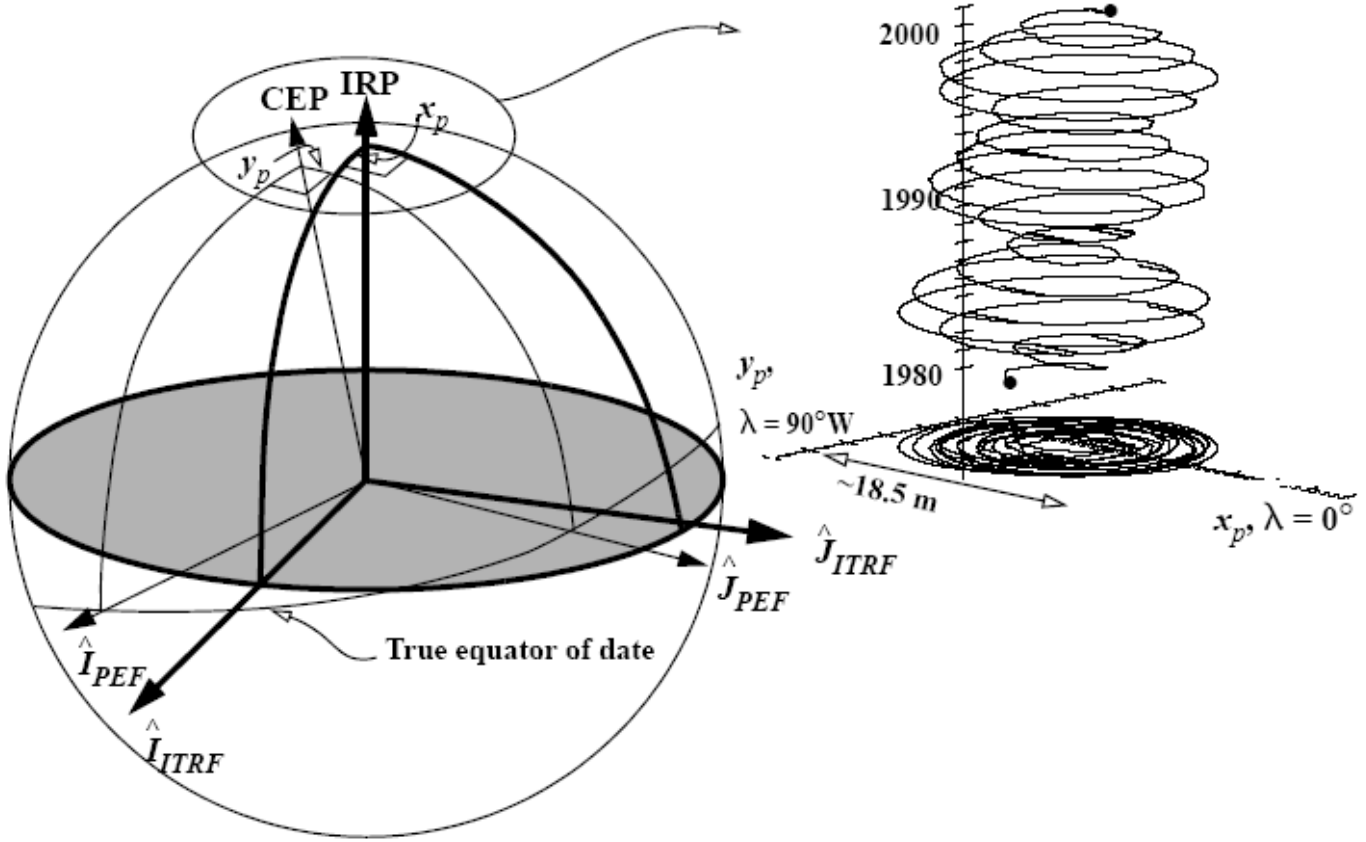
Many Different Time Scales

Many different kinds of seconds



Sideral time is accrued relative to the passage of a distant star
Solar time is accrued relative to the reappearance of the Sun each day and depends on your latitude.
Equinoctal time is accrued relative to the Equinox pointing in a given direction
Ephemeris time is accrued based on the Earth's orbit about the Sun

Polar Motion

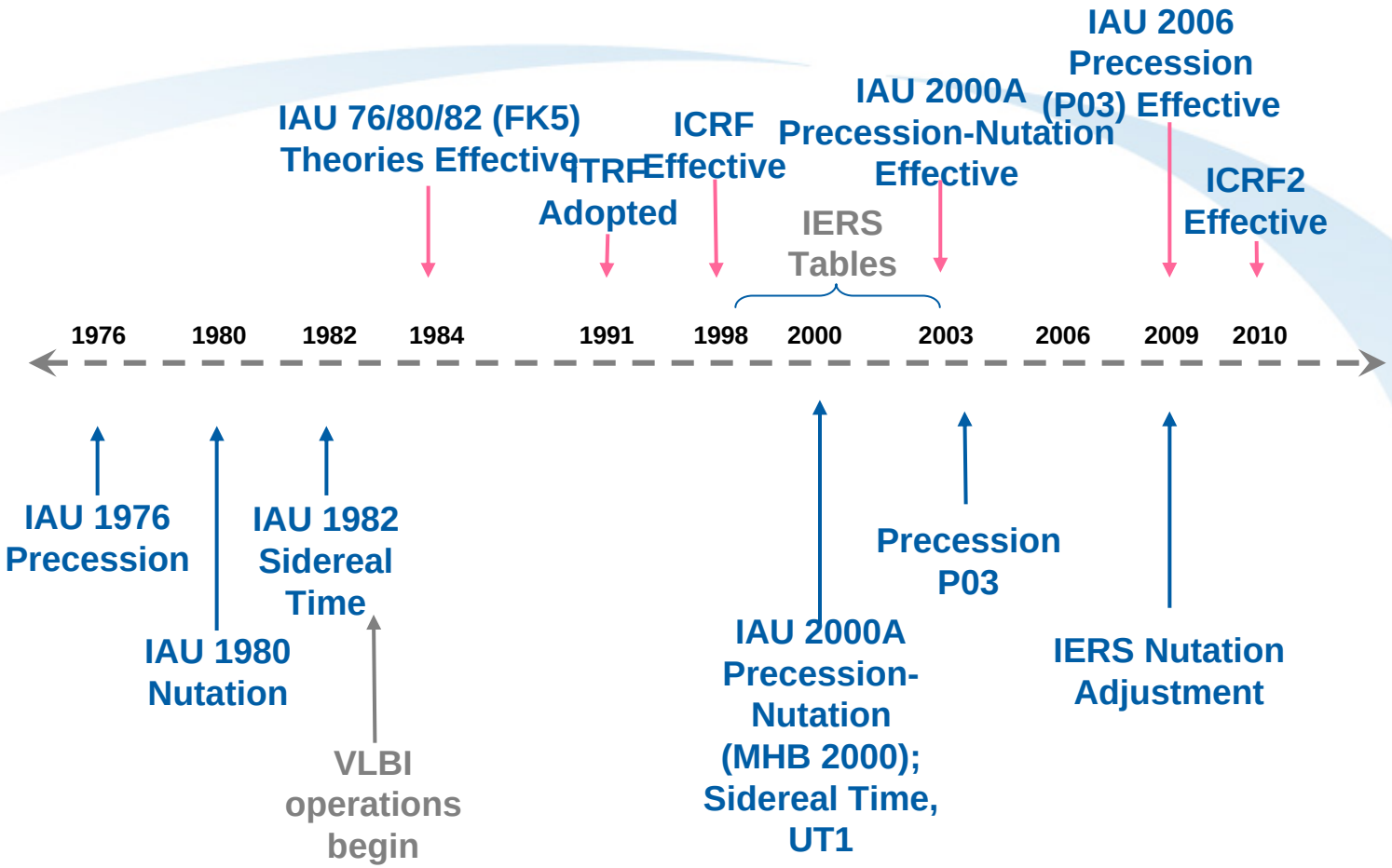


The Earth's geographic North Pole wanders by ten meters or more during the course of a solar year.

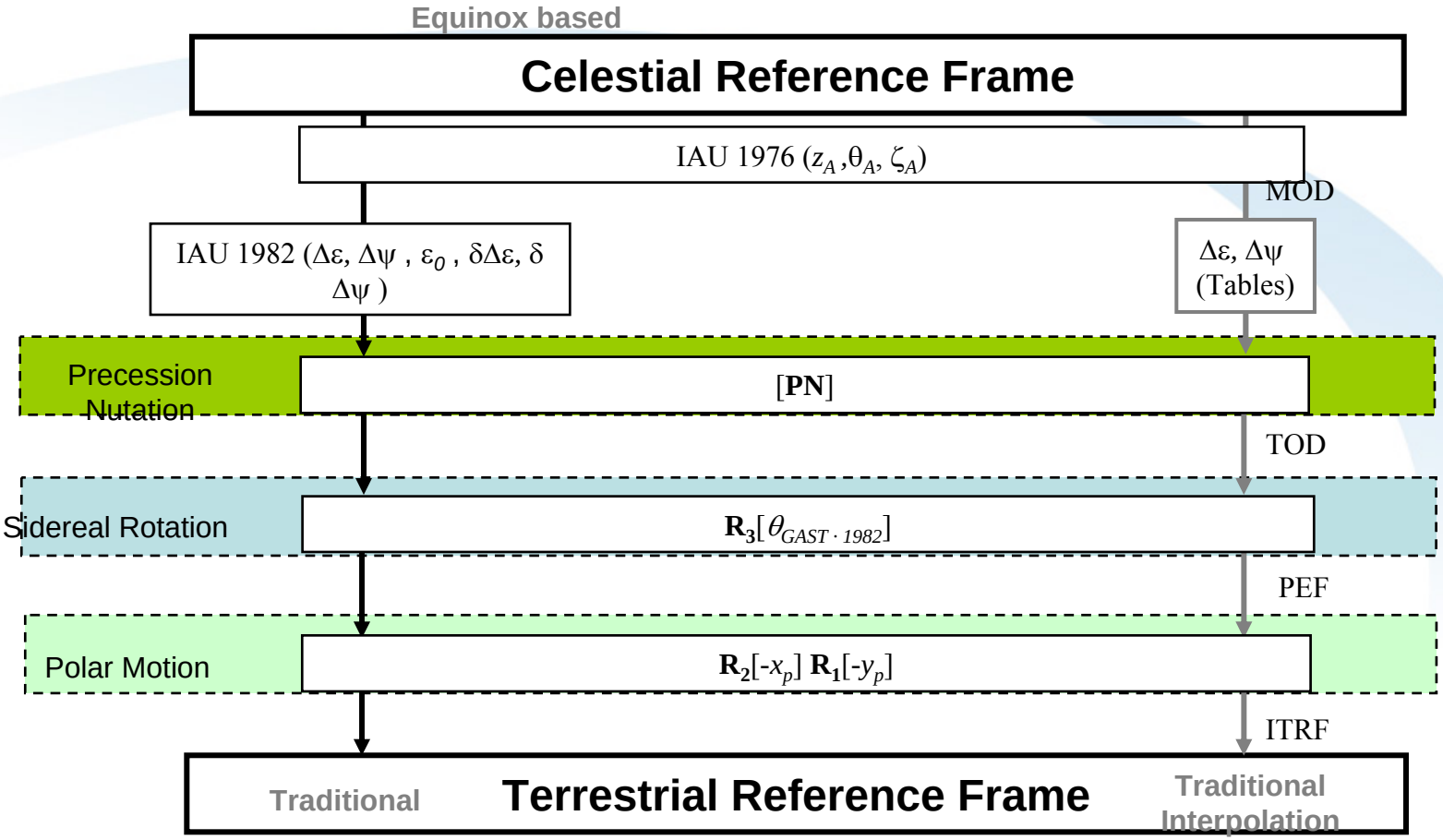
Transformation of Coordinates

- Motion of coordinate system implies many intermediate frames
- Primary use
  - Inertial (ECI) to Fixed (ECEF)
    - Numerical integration (ECI)
    - Apply Accelerations (ECEF)

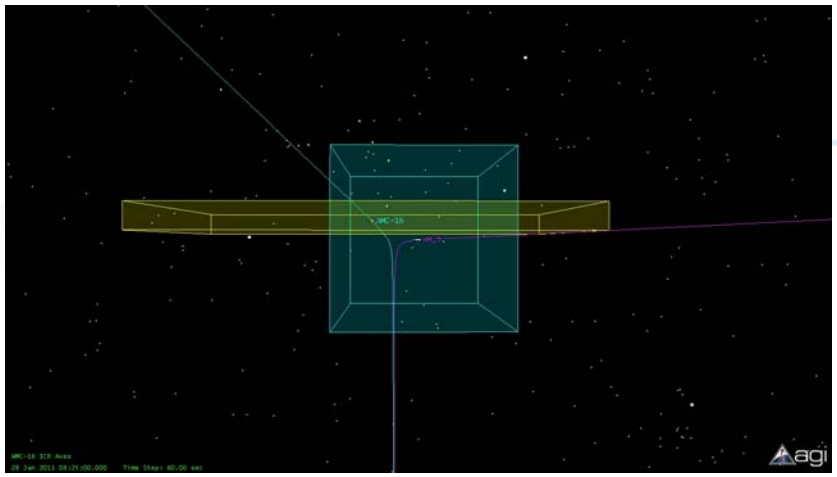
Reference Frame Chronology

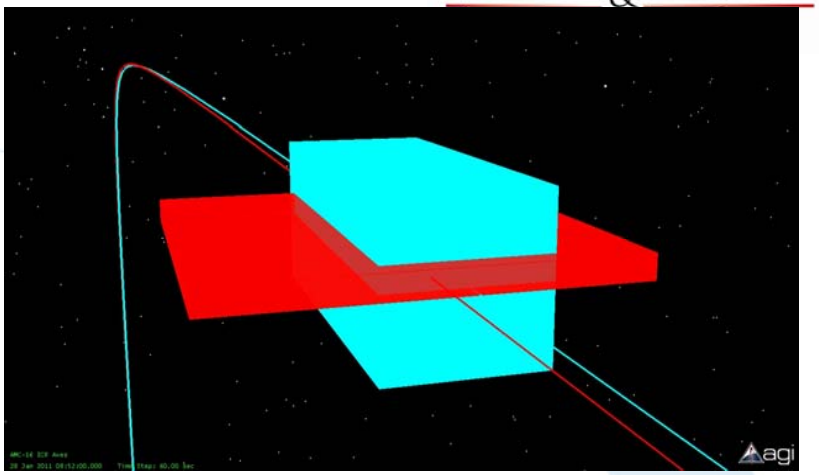


Operations Required to Rectify One Kind of Reference Frame to Another (IAU 76/FK5)

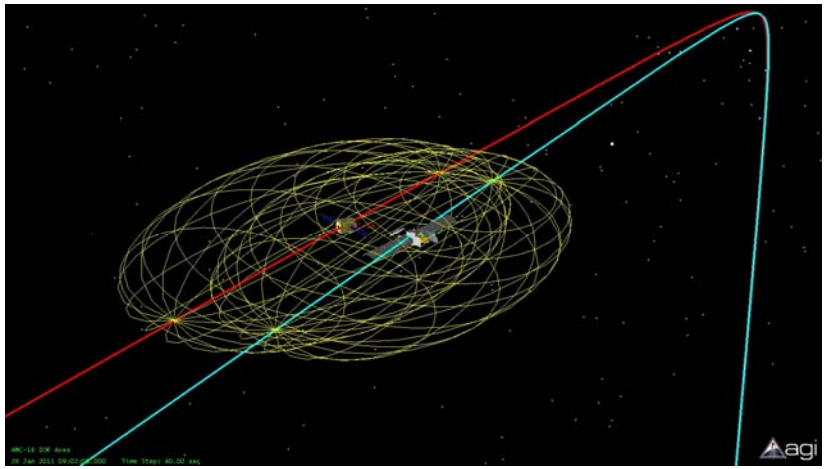


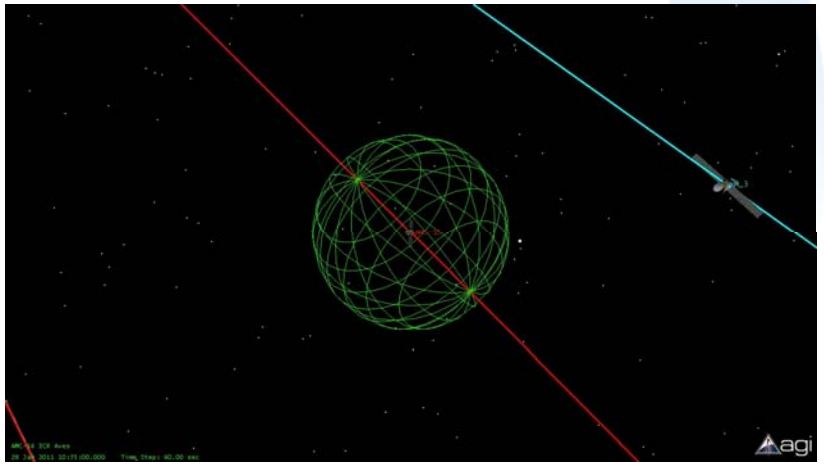
Collision Estimation Technique
(AMC-11 and XM-3, 29 Jan 2011, 10:35 UTC)





NASA 0.75x5x5 Pizza Box and 5x5x25 Parallelepiped





Intersecting Covariance Ellipsoids

3 Km Diameter Sphere

CONJUNCTION ASSESSMENT

- Identifying satellites that might collide, determining the likelihood of collision, and providing sufficient information for determining courses of action
- The Interagency Debris Coordinating Committee concludes that (47th Session of the COPUOS S&T Subcommittee, Feb 2010):
  - "actionable conjunction assessments require precision orbital trajectory information with quantified uncertainty values"
  - "Currently available mean general perturbation elements are insufficient"

CCSDS Orbit Data Message Standards enable more precise and interoperable exchange of trajectory information.

DEVELOPING A STANDARD

- Guiding principles
  - Each element of data and metadata must be directly traceable to an operational need
  - Fields must be formatted to include accuracy and precision adequate for the purpose
  - The message must be as concise as possible without compromising content
  - Collaboration is essential
    - Technical experts and intended users must be involved.

DATA AND METADATA REQUIREMENTS

- A Conjunction Data Message must include the content of Orbit Data Messages for each conjunction partner.
  - Whether included in the CDM or transmitted independently is a pertinent question
- Minimum Essential Information
  - Estimated time of conjunction within the provider's criteria
    - Knowing orbits of each conjunctor, the user should be able to infer everything else from the estimated time.
  - Criteria for a noteworthy conjunction
  - Required to understand the reaction time available.

Next Most Important Information

- Identities of the satellites and operational status (including avatars for protected identities)
  - Required to estimate consequences and collaborate.
- Closest approach between the satellites in a standard reference frame and coordinate system
  - Required to understand why one provider might have perceived a conjunction and another not perceive it.
- 3x3 Covariances for both objects in a well defined reference frame and coordinate system
  - Required to determine or confirm probability of collision

Required for Confidence and Courses of Action

- Kinematic state of each satellite at the time of closest approach expressed either as a state vector or ephemeris in a well defined orbit determination and propagation scheme.
  - Required to assess consequences and determine courses of action quickly
- Close approach threshold (provider's minimum safe separation criterion)
  - Required because each operator has a different risk tolerance.
- Relative Velocity at closest approach in the same reference frame and coordinate system as the close approach distance
  - Required for assessing consequences and developing maneuvers
- Probability that the conjunction might actually lead to lead to direct contact and metadata describing how the probability was estimated
  - Required by some recipients in order to judge the nature of operational action

STATUS AND PROGNOSIS

- First of a CDM White Book (ISO New Work Item Proposal) is available for comment
- White Book consensus expected in time for joint ISO SC14 – CCSDS meetings in Berlin in May 2011
- Promotion to full work item status in June 2011
- Coordination and comment within the affected community by Dec 2011
- “At risk” provisional use in 2012

CONCLUSION

- We have described collaborative development of the content, format, implementation, and operational use of timely information for mitigating the consequences of conjunctions among satellites.
- We encourage applying these advances in ground systems that support important space missions.

"In all … matters one must think of the range of parameters one has to … provide and the implicit assumptions others may be making about their relative significance."

Duncan Steel, ***MARKING TIME: THE EPIC QUEST FOR THE PERFECT CALENDAR****," Wiley, 2000, pg 283*