Federal Aviation Administration

COE CST Second Annual Technical Meeting:

Space Situational Awareness

D.J. Scheeres

October 31, 2012

Overview

- Team Members
- Purpose of Task
- Research Methodology
- Results or Schedule & Milestones
- Next Steps
- Contact Information

SSA Team Members

Direct Current / Past Support from the FAA COE

- Dan Scheeres, CU Professor, PI
- George Born, CU Professor, Co-I
- Bob Culp, CU Professor Emeritus, Co-I
- Brandon Jones, CU Research Scientist
- Kohei Fujimoto, CU PhD Candidate

Related Research from Fellowship Students

- Aaron Rosengren, CU Graduate Student, NSF Fellow
- Antonella Albuja, CU Graduate Student, NSF Fellow
- Ddard Ko, CU Graduate Student, Korean Government grant

Government and Industry Partners

- AFRL Kirtland and Maui
- NASA Orbit Debris Program Office
- Analytical Graphics, Incorporated
- Orbital Sciences Corporation

Purpose of Task

- ***Space Situational Awareness***

  SSA = Cognizance of Resident Space Objects (RSO) and activities in orbital regions of interest, both now and in the short and long-range future.

- **Objectives**: Improve SSA abilities in regions of interest to the FAA for space-based activities.
- **Current regions of focus**: LEO-*down* and GEO-*up*
- **Goals are to improve**: uncertainty modeling and propagation, precision long-term orbit propagation, non-gravitational model prediction and estimation, orbit estimation techniques.

Schedule/Milestones

- Past:
  - Presented 12 papers at 8 international conferences
  - Published 2 papers in peer-reviewed journals
- Future:
  - Will present 2 papers in February 2013 at AAS/ AIAA conference
    - Debris rotation
    - Maneuver reconstruction
  - Total of 7 journal papers in development, for submission by May 2013

Results since commencement of funding

- ## Journal Papers:

- K. Fujimoto and D.J. Scheeres. 2012. "Correlation of Optical Observations of Earth-Orbiting Objects and Initial Orbit Determination," Journal of Guidance, Control and Dynamics 35(1): 208-221.
- K. Fujimoto, D.J. Scheeres and K.T. Alfriend. 2012. "Analytical Non-Linear Propagation of Uncertainty in the Two-Body Problem," Journal of Guidance, Control and Dynamics 35(2): 497-509.

- ## Conference Papers:

- K. Fujimoto, D.J. Scheeres , and K.T. Alfriend. "Analytical Non-Linear Propagation of Uncertainty in the Two-Body Problem," paper presented at the 2011 **AAS/AIAA Spaceflight Mechanics Meeting**, New Orleans, February 2011. Paper AAS 11-202.
- A. Rosengren and D.J. Scheeres. "Averaged Dynamics of HAMR Objects: Effects of Attitude and Earth Oblateness," paper presented at the 2011 **AAS/AIAA Astrodynamics Specialist Meeting**, Girdwood, Alaska, August 2011. Paper AAS 11-594.
- D.J. Scheeres and A. Rosengren. "Closed Form Solutions for the Averaged Dynamics of HAMR Objects," paper presented at the **62nd International Astronautical Congress**, Cape Town, South Africa, October 2011.
- K. Fujimoto and D.J. Scheeres. "Non-Linear Propagation of Uncertainty With Non-Conservative Effects," paper presented at the 2012 **AAS/AIAA Spaceflight Mechanics Meeting**, Charleston, SC, Jan/Feb 2012.
- S. Gehly, B. A. Jones, P. Axelrad, G. H. Born, "Minimum L1 Norm Orbit Determination Using a Sequential Processing Algorithm", paper presented at the 2012 **AAS/AIAA Spaceflight Mechanics Meeting**, Charleston, SC, Jan/Feb 2012.
- K. Fujimoto and D.J. Scheeres. "Non-Linear Bayesian Orbit Determination Based on the Generalized Admissible Region," paper presented at Fusion 2012, the 15th International Conference on Information Fusion, Singapore, July 2012.
- D.J. Scheeres, M.A. de Gosson, and J. Maruskin. "Fundamental Limits on Orbit Uncertainty," paper presented at Fusion 2012, the 15th International Conference on Information Fusion, Singapore, July 2012.
- A.J. Rosengren and D.J. Scheeres. "Long-term Dynamics of HAMR Objects in HEO," paper presented at the AIAA/AAS Astrodynamics Specialist Meeting, Minneapolis, August 2012.
- A.J. Rosengren and D.J. Scheeres. "Prediction of HAMR Debris Population Distribution Released from GEO Space," paper presented at the 2012 AMOS Meeting, Maui, September 2012.
- K. Fujimoto and D.J. Scheeres. "Rapid Non-Linear Uncertainty Propagation via Analytical Techniques," paper presented at the 2012 AMOS Meeting, Maui, September 2012.
- A.J. Rosengren and D.J. Scheeres. "Long-Term Dynamics of High Area-to-Mass Ration Space Debris in GEO," paper presented at the 63rd International Astronautical Congress, Naples, Italy, October 2012. Paper IAC-12, A6.2.5.
- K. Fujimoto and D.J. Scheeres. "Non-Linear Bayesian Orbit Determination: Angle Measurements," paper presented at the 63rd International Astronautical Congress, Naples, Italy, October 2012. Paper IAC-12-C1.6.11.

- ## Industry Interactions:

- Exchanges of simulated data with AFRL Maui research personnel.
- Interactions with NASA Orbit Debris Program Office and the Center for Space Standards & Innovation (AGI).
- Dissemination of orbit determination tools to Aerospace Corp. researchers for analysis and testing.
- Visiting positions and collaborations at IHI Corporation (Japan) and the University of Bern (Switzerland), applying orbit determination research to real data and observations.

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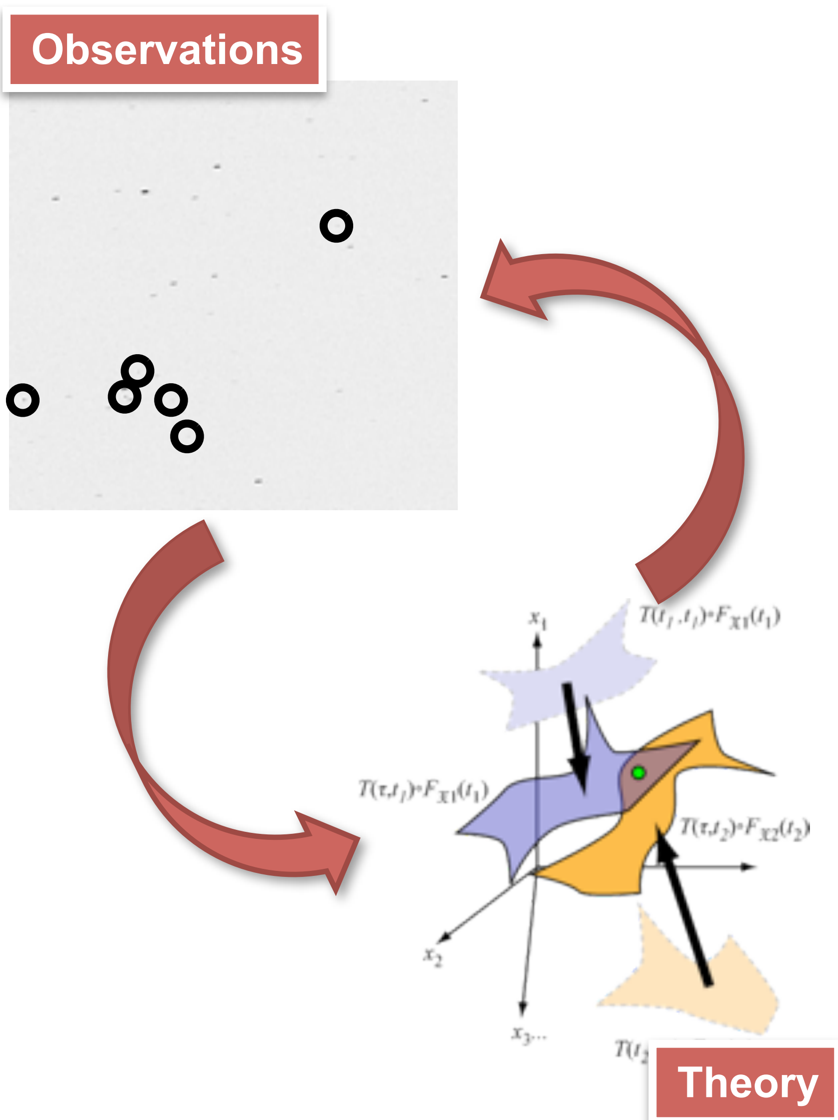
Research in SSA

- Current and future areas of research identified:
  - Rapid uncertainty propagation and conjunction analysis (Fujimoto)
  - Hypothesis-free optical observation correlation and initial orbit determination (Fujimoto)
  - Long-term dynamics of objects in GEO and identification of safe graveyard orbits (Rosengren)
  - Rotational dynamics of debris objects (Albuja)
  - Representation of unobserved maneuvers (Ko)

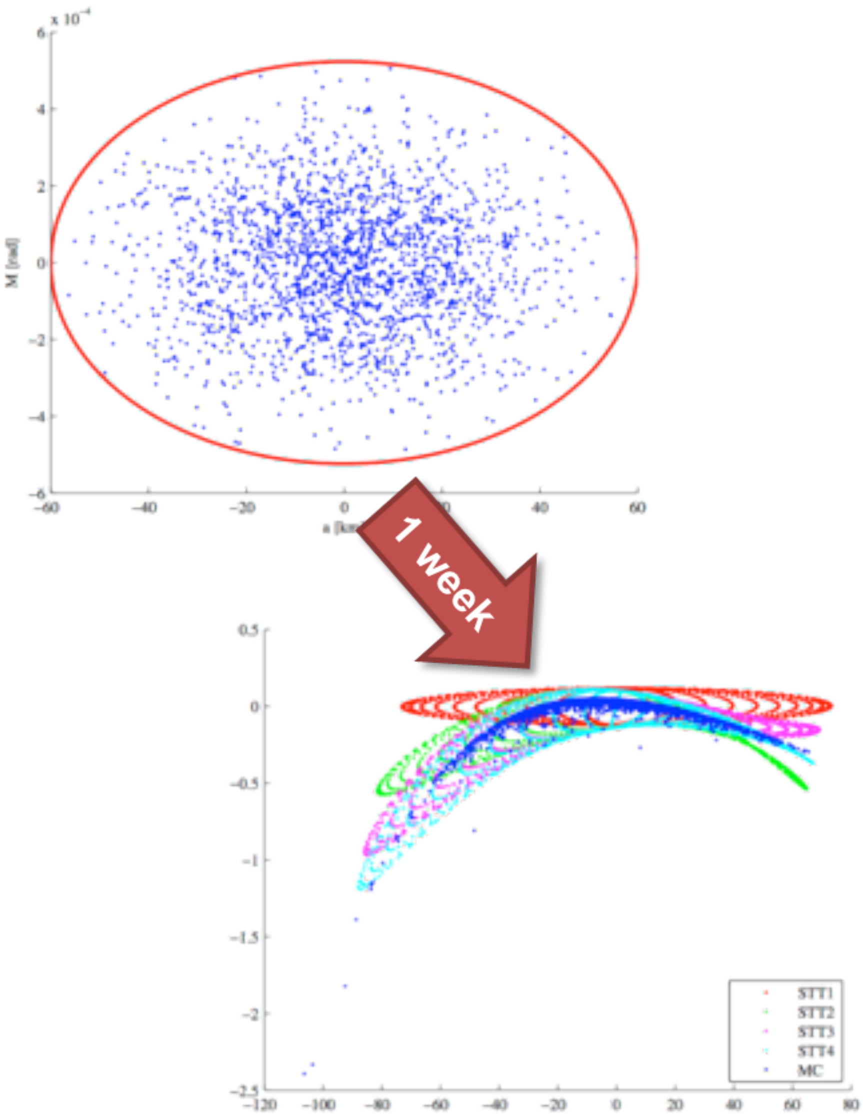
Association of Optical Observations



Credit: IHI Corp., Hamane, T. (GAO), Fujimoto, K.

- Direct Bayesian approach to observation association
  - Exploits sparseness of the estimation problem
  - Robust with little tuning
  - Presented at IAC 2012
- Experimentation with real-world observations
  - Collaboration with IHI Corp., University of Bern
  - Developed techniques to take into account measurement error
  - To be submitted to ISTS 2013
- “Closing the loop” on the too-short-arc problem

Analytic Propagation of Uncertainty



- Rapid non-linear uncertainty propagation
  - Special soln. to the Fokker-Planck eqn. for deterministic systems
  - State transition tensor description of the solution flow
- Added effects due to atm. drag
  - Classical results (King-Hele) applied to a modern problem
  - Up to 10^6X faster but comparable results to numerical simulation with realistic drag model
- “Consistent” representation of uncertainty key to SSA
  - Conjunction assessment, track correlation, etc.

Averaged Model for GEO Objects

- Perturbations in vector form (Milankovitch elements):

$$\boldsymbol{h} = \sqrt{1-e^2}\hat{\boldsymbol{h}}, \quad \boldsymbol{e} = e\hat{\boldsymbol{e}}$$

$$\boldsymbol{h}\cdot\boldsymbol{e} = 0, \quad \boldsymbol{h}\cdot\boldsymbol{h} + \boldsymbol{e}\cdot\boldsymbol{e} = 1$$

$$\dot{\boldsymbol{h}} = \tilde{\boldsymbol{h}} \cdot \left(\frac{\partial \mathcal{R}^*}{\partial \boldsymbol{h}}\right)^T + \tilde{\boldsymbol{e}} \cdot \left(\frac{\partial \mathcal{R}^*}{\partial \boldsymbol{e}}\right)^T$$

$$\dot{\boldsymbol{e}} = \tilde{\boldsymbol{e}} \cdot \left(\frac{\partial \mathcal{R}^*}{\partial \boldsymbol{h}}\right)^T + \tilde{\boldsymbol{h}} \cdot \left(\frac{\partial \mathcal{R}^*}{\partial \boldsymbol{e}}\right)^T$$

	SRP	J_2	Third-body
$\dot{\bar{\boldsymbol{h}}}$	$-\frac{3}{2}\sqrt{\frac{a}{\mu}}\frac{\beta}{d_s^2}\tilde{\hat{\boldsymbol{d}}}_s\cdot\boldsymbol{e}$	$\frac{3nC_{20}}{2a^2h^5}(\boldsymbol{h}\cdot\hat{\boldsymbol{p}})\tilde{\hat{\boldsymbol{p}}}\cdot\boldsymbol{h}$	$\frac{3\mu_p}{2nd_p^3}\hat{\boldsymbol{d}}_p\cdot[5\boldsymbol{e}\boldsymbol{e}-\boldsymbol{h}\boldsymbol{h}]\cdot\tilde{\hat{\boldsymbol{d}}}_p$
$\dot{\bar{\boldsymbol{e}}}$	$-\frac{3}{2}\sqrt{\frac{a}{\mu}}\frac{\beta}{d_s^2}\tilde{\hat{\boldsymbol{d}}}_s\cdot\boldsymbol{h}$	$\frac{3nC_{20}}{4a^2h^5}\left[\left(1-\frac{5}{h^2}(\boldsymbol{h}\cdot\hat{\boldsymbol{p}})^2\right)\tilde{\boldsymbol{h}}+2(\boldsymbol{h}\cdot\hat{\boldsymbol{p}})\tilde{\hat{\boldsymbol{p}}}\right]\cdot\boldsymbol{e}$	$\frac{3\mu_p}{2nd_p^3}\left\{4(\boldsymbol{e}\cdot\hat{\boldsymbol{d}}_p)\tilde{\boldsymbol{h}}\cdot\hat{\boldsymbol{d}}_p-\tilde{\boldsymbol{h}}\cdot\boldsymbol{e}-\hat{\boldsymbol{d}}_p\hat{\boldsymbol{d}}_p\cdot\tilde{\boldsymbol{h}}\cdot\boldsymbol{e}\right\}$

$\mathcal{R}^* = \mathcal{R}/\sqrt{\mu a}, \mathcal{R} = \text{force potential}, a = \text{semi-major axis}$

$n = \sqrt{\mu}/a^{3/2} = \text{mean motion}$

$\beta = (1+\rho)(A/m)P_\Phi$

$\rho = \text{reflectivity}, A/m = \text{area-to-mass}, P_\Phi = \text{SRP constant}$

$C_{20} = \text{oblateness gravity field coefficient}$

$\hat{\boldsymbol{p}} = \text{unit vector aligned with Earth's rotation pole}$

$\boldsymbol{d}_p = d_p\hat{\boldsymbol{d}}_p = \text{position vector of disturbing body}$

Assumptions and approximations:

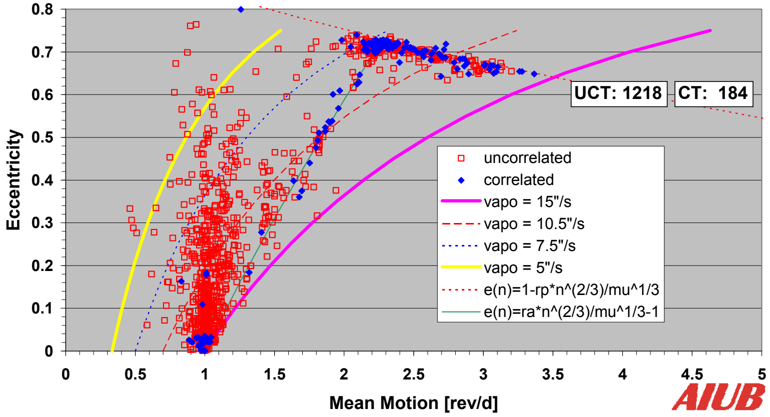
- perturbations come from force potential (semi-major axis = constant of motion)
- SRP modeled using cannonball model
- Hill's approximation for lunisolar third-body perturbations

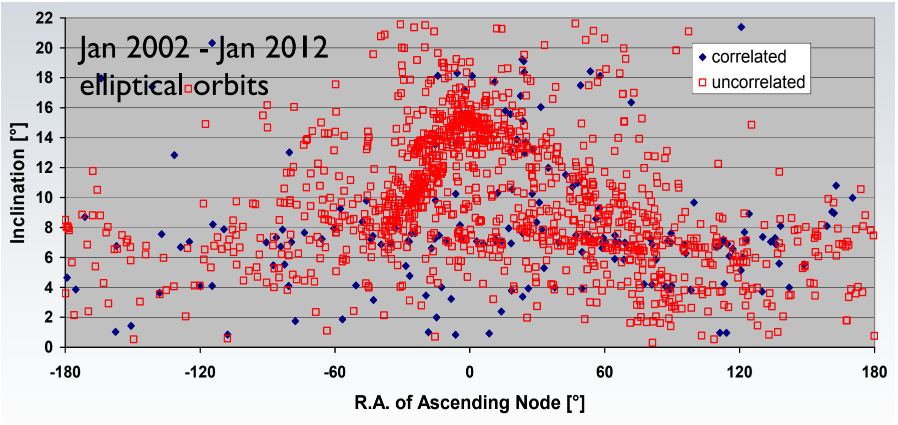
HAMRs: A New Class of Debris

- Discovery (Schildknecht et al. 2004)
  - mean motion suggest release near GEO
  - orbital evolution indicates they are HAMRs
- Recent studies focusing on long-term orbit dynamics:
  - analytical, semi-analytical, and numerical investigations

    Liou & Weaver (2004, 2005), Anselmo & Pardini (2005-2010),

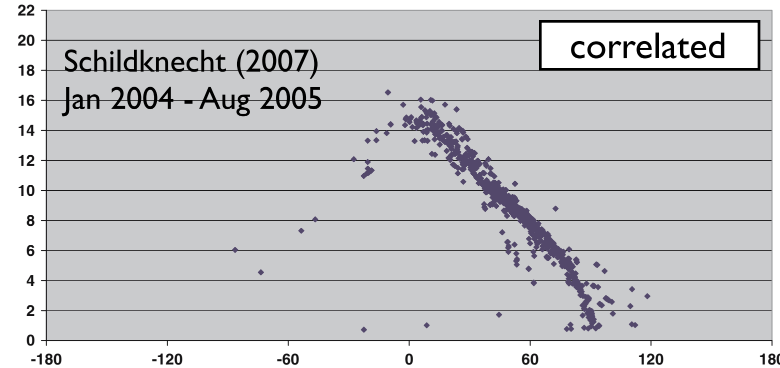
    Chao (2006), Valk et al. (2007-2009), Rosengren & Scheeres (2010-2012)
- Distribution of observed objects (Schildknecht et al. 2012)

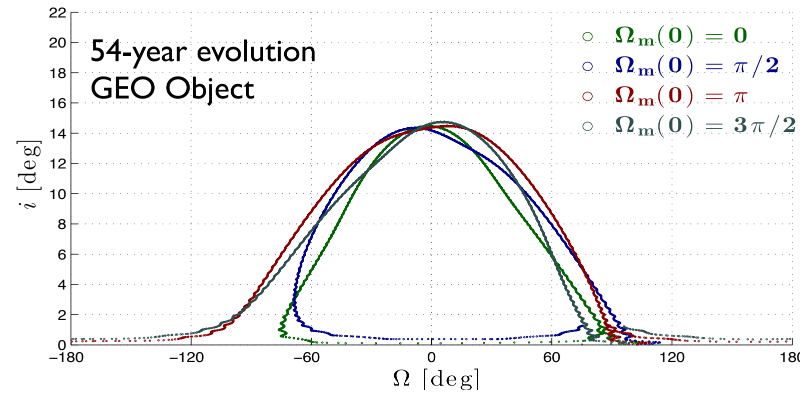


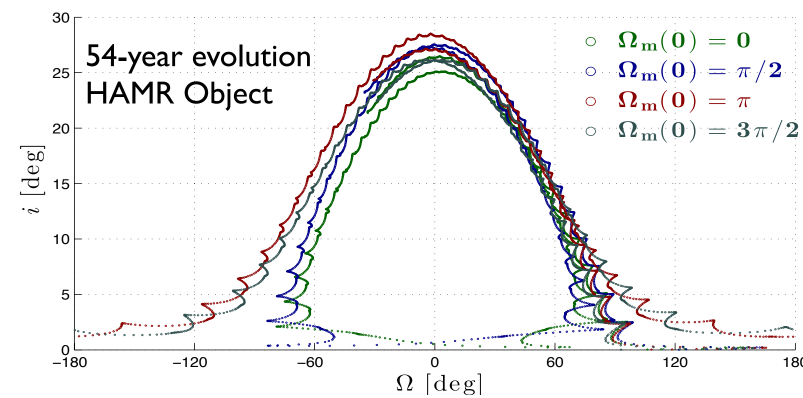


Long-term Behavior of GEO Orbits

- Almost fifty years have elapsed since satellites were first launched into GEO
- The motion of uncontrolled GEO satellite:
  - precession about the Earth's rotational axis (J2 effect)
  - precession about pole of the ecliptic (solar third-body)
  - precession about pole of the Moon's orbit (lunar third-body)
- Structure in (i, Ω) phase space
- What about HAMRs?

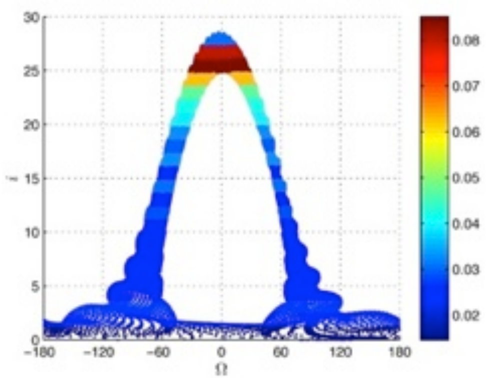


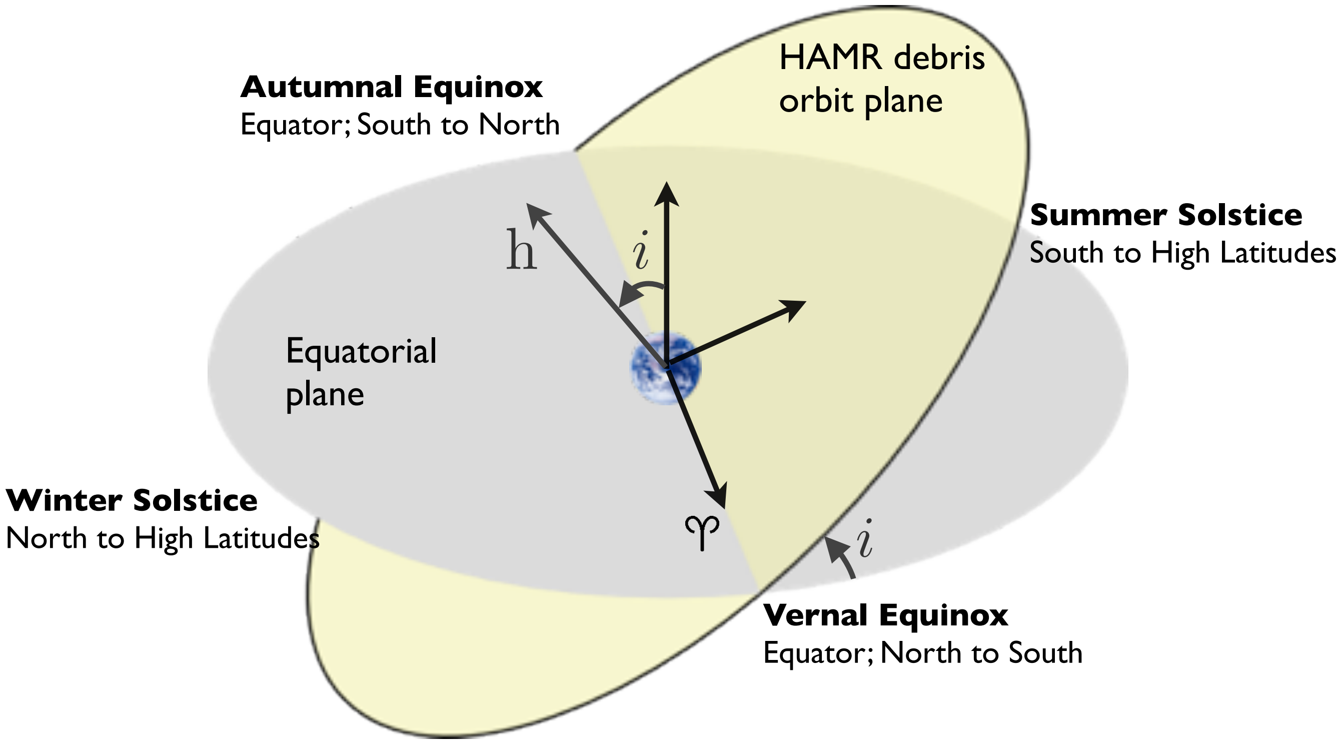




Implications for Space Surveillance

- Inclination and ascending node of HAMRs evolve in predictable ways
- Where should observers point their telescopes?
  - Spring, Fall: anti-solar survey, concentrate near equator
  - Summer, Winter: look at high latitudes





Conclusions

- Progress being made on the following fronts:
  - Object correlation and initial orbit determination
  - Rapid and accurate propagation of uncertainty
  - Long-term dynamics of objects in Earth orbit
- Future work will focus on:
  - Continuing above achievements
  - Identification of robust, long-term GEO disposal orbits
  - Modeling of debris rotational motion
  - Modeling of unobserved maneuvers

Contact Information

- Questions:
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  - <scheeres@colorado.edu>
  - 1-720-544-1260

TASK 187. Space Situational Awareness Improvements

MAJOR MILESTONES - PAST	MAJOR MILESTONES - FUTURE
• Recruitment of student research team • Presentation of research results at international conferences 2011: 3 conference papers 2012: 9 conference papers • Documentation through publication of research papers in high-impact journals 2012: 2 published papers	• Continue presentation of FAA supported and related research at international conferences February 2013: 2 conference papers • Submission of additional conference papers expected (AAS, IAA, AMOS) • Submission of 7 journal papers expected by May 2013, all in progress
SCHEDULE	**BUDGET**

• February 2013: presentation of conference papers at AAS/AIAA Spaceflight Mechanics Meeting
• February/March/April 2013: submission of abstracts to the IAA, AAS/AIAA, and AMOS conferences
• May 2013: submission of journal papers currently being written
	• FY13 - FY14 - FY15 - FY16 - FY17
	• $190K - $220K - $220K - $0K - $0K
	• Notes
	  • FY13 $67K allocated to date, through 5/2013
	  • FY13 Total assumes continuation of funding level + 1 GSRA
	  • FY14/15 assumes continuation

Funding Requirements – Five Years

- Gross received thru October 31, 2012
  - $157,000 + $67,000 for FY13
- Gross requested for five total years broken out by year, based on 2011 forecasts
  - FY11: $77,000
  - FY12: $80,000
  - FY13: $190,000
  - FY14: $220,000
  - FY15: $220,000