# Human Spaceflight Conjunction Operations

## *History, Lessons Learned, and Future Improvements for ISS Debris Avoidance*

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*Lark Howworth*
*Lead, Space Station Trajectory Operations Group*
*Mission Operations Directorate, Johnson Space Center*

# Evolution of Conjunction Assessment

## Initial Operations: Space Shuttle

- Before 1986 Challenger accident, no Shuttle mitigation actions were taken for conjunctions based on assumption that predictions were too imprecise
- After Challenger, analysis led to a “box” method for Shuttle protection

## Preparation for ISS operations: the Probability Method

- The 24/7/365 nature of ISS operations meant the box method from Shuttle could not be an option
  - Work began at NASA/JSC in early 1990’s to develop infrastructure for “Pc” method
  - NASA provided support to USSPACECOM to develop covariances, computing capability, and “JSpOC” staffing for conjunction detection
- NASA started trial conjunction assessment operations with Russia in 1996 on Mir (“Phase I” program, upon arrival of Americans onboard)
  - Box method always used as trigger to notify Moscow during Mir, and no Russian avoidance maneuver was expected or performed

# Evolution of Conjunction Assessment: ISS Operations

**Maneuver thresholds determined for ISS**

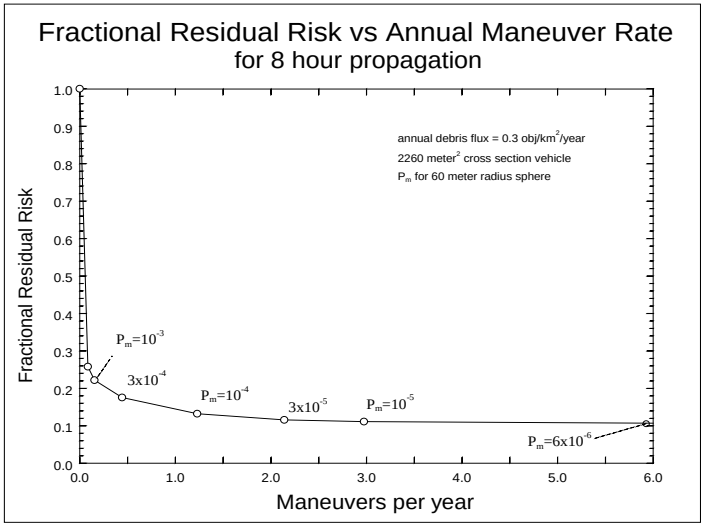
- Balance safety with minimum of operations disruption
- Red threshold of 1-in-10,000: Always maneuver if possible; place crew in Soyuz if maneuver not possible
- Yellow threshold of 1-in-100,000: Maneuver if convenient

**Invented Orbital Conjunction Message (OCM) format with USSTRATCOM**

**Developed "validity criteria" on OCMs to ensure maneuver decisions based on good data**

- Requires multiple updates, with prediction variations within expected bounds

**Shuttle program and Goddard later adopted probability method for conjunctions**




*Example of risk evaluations used to determine ISS maneuver thresholds*

# Developing ISS Operations

## International coordination required to establish ISS DAM capability

- ISS has had 6 different vehicles to act as propulsion module, each requiring varying kinds of coordination:
  - *FGB (Zarya) until SM arrival*
  - *Service Module (Zvezda)*
  - *Progress:  aft and nadir*
  - *ESA's Automated Transfer Vehicle (ATV)*
  - *Soyuz (contingency; never used)*
  - *Shuttle*
- **Each method (except Shuttle) relies on a planning template requiring >28 hours**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# ISS Debris Avoidance Maneuver History

| Date | Debris Object | Vehicle | Notes |
|---|---|---|---|
| 06/03/99 | 1844 (SL-3 R/B) | FGB | Maneuver Execution FAILED. Two PC violations (1E-2 and 1E-3) early in event based on bad data |
| 10/26/99 | 25422 (Pegasus R/B) | FGB | First successful ISS DAM and only DAM performed by FGB. Highest PC = 1E-03. |
| 09/29/00 | 5143 (SL-3 R/B) | Progress 1P | Maneuver on Yellow threshold violation |
| 02/10/01 | 87610 (Unknown Debris) | STS-98 (5A) | Shuttle Box method used |
| 12/15/01 | 5730 (SL-8 R/B) | STS-108 (UF-1) | Shuttle PC method used |
| 05/15/02 | 23279 (SL-8 R/B) | Progress 7P | $P_c$ = 1E-03 (red threshold violation) |
| 05/30/03 | 25722 (MEGSAT) | Progress 10P | $P_c$ = 9E-04 (red threshold violation) |
| 08/27/08 | 33246 (COSMOS 2421 Debris) | ATV-1 | $P_c$ =2E-02 (red threshold violation) and largest PC calculated to date |
| 03/22/09 | 26264 (CZ-4 Debris) | STS-119 (15A) | Red threshold violations on a multi-repeating conjunction. TCAs were during an EVA, so a Retrograde DAM was executed early by having orbiter hold attitude. |
| 07/18/09 | 84180 (Unknown Debris) | STS-127 (2 JA) | TCA occurred 15 hours after STS-127 docking (during crew sleep). Due to the docking perturbations, a red threshold violation was computed and a reboost was performed by the Shuttle before the crew went to sleep. |
| 10/26/10 | 37195 (UARS Debris) | Progress 39P | $P_c$ = 5E-03 (red threshold violation). Probabilities were yellow & red threshold violations throughout the event. |
| 4/2/11 | 34443 (Cosmos 2251 Debris) | ATV-2 | Conjunction with dozens of repeating passes, high drag. Prime TCA shifted later during event |

**12 ISS debris avoidance maneuvers attempted**

**7 performed by ISS**

**1 attempted by ISS, but failed (ISS's first attempt)**

**4 performed by Shuttle during mated operations**

# Visiting Vehicle Protection

**The Trajectory Operations group (TOPO) at MCC-Houston integrates the trajectories of ISS and all vehicles coming to ISS**

**In recent years, the TOPO office began implementing debris avoidance support for the operators of these visiting vehicles**

- ESA's ATV (1 mission per year)
- JAXA's HTV (1 mission per year)
- Russia's Soyuz and Progress (approximately 7 missions per year)
- Commercial vehicles (SpaceX Dragon and Orbital Cygnus) (1-2 missions per year each)
- *This protects not only the vehicles in rendezvous, but keeps the ISS environment safe as well.*

**TOPOs use close relationship with JSpOC to help provide the highest-quality data for use in protecting these vehicles**

- Maintain single human spaceflight point of contact with JSpOC to provide data for partners to assess risk
- As with ISS, all visiting vehicles screen their planned maneuvers against debris catalog
- In development of conjunction operations, TOPO has provided expertise in
  - Negotiating ephemeris formats and notification thresholds with JSpOC on behalf of partners
  - Providing primary or backup collision probability calculations during mission
  - *Currently, operational responses are still the responsibility of the operating partner and vary for each vehicle*
- With high levels of vehicle traffic expected for many years, ops standardization might become more important

# Implemented Conjunction Improvements for ISS

- ✓Russian pre-maneuver command verification improved
- ✓Developed “validity criteria” to ensure good Pc calculations so unnecessary actions aren’t taken
- ✓Improvements in notification criteria to reduce false alarms
- ✓Implementation of capability to cancel a DAM almost up to the time of ignition
- ✓Crew Soyuz “shelter in place” capability for late notifications where DAM not possible
- ✓Ongoing improvements in orbit determination capabilities at USSTRATCOM/JSpOC

# ISS Lessons Learned

- "1844 Incident" (1999) proved the need for a very well-defined process, well-trained people, and software adequate to the task
  - A sequence of errors occurred among all parties, from conjunction identification, to "debris clearing" of the DAM, to failed execution of the maneuver. Actions taken:
    - Ground processes between Houston and Moscow made clearer
    - Russian maneuver command testing implemented
    - NASA and USSTRATCOM began routine familiarization cross-training
- Constant improvements to balance safety and mission viability are beneficial
  - Excessive conjunction notifications from Houston to Moscow early in ISS program caused personnel overwork
  - In response, partners implemented smarter conjunction notification criteria
- Flexibility in planning avoidance maneuvers is key in reducing the likelihood of needing to execute them

# ISS vs. Cosmos 2251 Debris

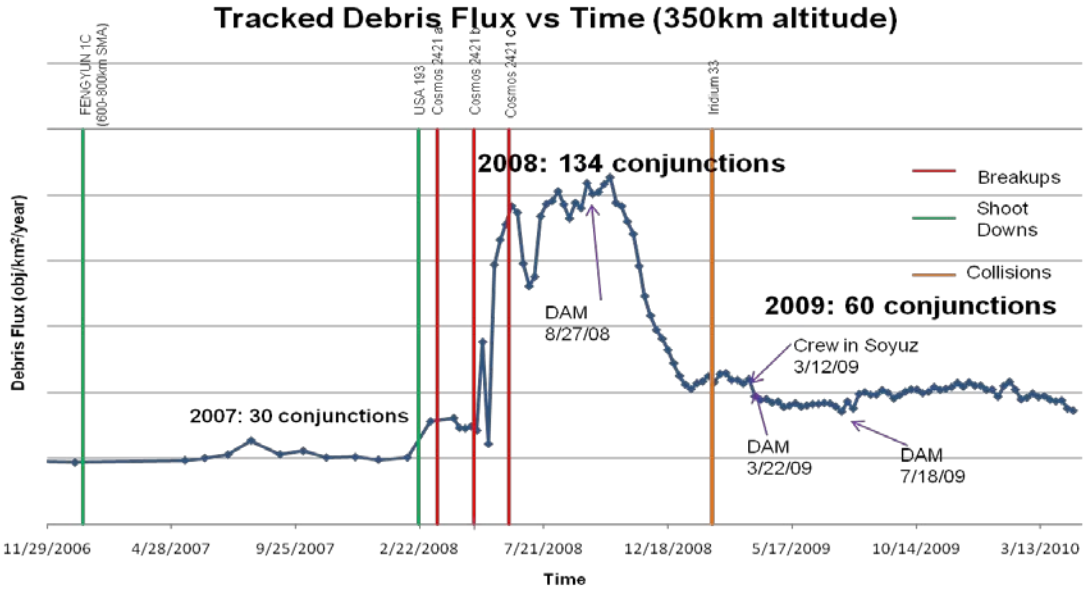
- April 2011 conjunctions with Cosmos 2251 had over 40 registered close passes
- Highest concern TCA changed over time
- 0.5 m/s DAM was executed to protect highest Pc cases
- Scenario shows value of flexible maneuvering capability
- There may be better ways to assess risk for repeaters in the future

| TCA (GMT) | TCA-30 (CDT) | U | V | W | R | Time to TCA | Pc |
|---|---|---|---|---|---|---|---|
| 2011 091 (Fri, 01 Apr) 03:41:59.541 | 2011 089 (Wed, 30 Mar) 04:42 PM CDT | 2.6 | 29.5 | -7.7 | 30.6 | 44.7 | 3.54E-13 |
| 2011 091 (Fri, 01 Apr) 04:27:40.973 | 2011 089 (Wed, 30 Mar) 05:27 PM CDT | -2.1 | 133.1 | 34.2 | 137.4 | 25.9 | 0.00E+00 |
| 2011 091 (Fri, 01 Apr) 05:13:39.612 | 2011 089 (Wed, 30 Mar) 06:13 PM CDT | 2.5 | -64.4 | 16.6 | 66.5 | 15.7 | 0.00E+00 |
| 2011 091 (Fri, 01 Apr) 05:59:18.063 | 2011 089 (Wed, 30 Mar) 06:59 PM CDT | -1.5 | 106.0 | 27.1 | 109.4 | 27.4 | 1.90E-10 |
| 2011 091 (Fri, 01 Apr) 06:45:16.485 | 2011 089 (Wed, 30 Mar) 07:45 PM CDT | 1.7 | -87.4 | 22.4 | 90.2 | 17.2 | 1.23E-19 |
| 2011 091 (Fri, 01 Apr) 07:30:52.375 | 2011 089 (Wed, 30 Mar) 08:30 PM CDT | -2.7 | 121.0 | 30.8 | 124.9 | 22 | 9.61E-06 |
| 2011 091 (Fri, 01 Apr) 08:16:51.811 | 2011 089 (Wed, 30 Mar) 09:16 PM CDT | 1.1 | -90.9 | 23.3 | 93.9 | 24.2 | 5.77E-15 |
| 2011 091 (Fri, 01 Apr) 09:02:30.236 | 2011 089 (Wed, 30 Mar) 10:02 PM CDT | -2.1 | 85.9 | 21.8 | 88.6 | 19.5 | 2.16E-06 |
| 2011 091 (Fri, 01 Apr) 09:48:28.154 | 2011 089 (Wed, 30 Mar) 10:48 PM CDT | 0.4 | -107.5 | 27.4 | 110.9 | 25.7 | 9.66E-08 |
| 2011 091 (Fri, 01 Apr) 10:34:06.606 | 2011 089 (Wed, 30 Mar) 11:34 PM CDT | -1.9 | 68.5 | 17.3 | 70.7 | 21 | 1.85E-12 |
| 2011 091 (Fri, 01 Apr) 11:20:05.111 | 2011 090 (Thu, 31 Mar) 12:20 AM CDT | -0.5 | -135.5 | 34.4 | 139.8 | 30 | 0.00E+00 |
| 2011 091 (Fri, 01 Apr) 12:05:42.765 | 2011 090 (Thu, 31 Mar) 01:05 AM CDT | -1.6 | 53.1 | 13.4 | 54.8 | 22.6 | 4.96E-17 |
| 2011 091 (Fri, 01 Apr) 12:51:41.170 | 2011 090 (Thu, 31 Mar) 01:51 AM CDT | -1.3 | -149.8 | 37.9 | 154.5 | 31.5 | 0.00E+00 |
| 2011 091 (Fri, 01 Apr) 13:37:18.883 | 2011 090 (Thu, 31 Mar) 02:37 AM CDT | -1.4 | 39.3 | 9.9 | 40.5 | 24.1 | 0.00E+00 |
| 2011 091 (Fri, 01 Apr) 15:08:54.994 | 2011 090 (Thu, 31 Mar) 04:08 AM CDT | -1.3 | 27.0 | 6.8 | 27.9 | 25.6 | 0.00E+00 |
| 2011 091 (Fri, 01 Apr) 16:40:30.795 | 2011 090 (Thu, 31 Mar) 05:40 AM CDT | -1.3 | 17.3 | 4.3 | 17.9 | 27.2 | 0.00E+00 |
| 2011 091 (Fri, 01 Apr) 18:12:06.496 | 2011 090 (Thu, 31 Mar) 07:12 AM CDT | -1.3 | 8.4 | 2.1 | 8.7 | 28.7 | 0.00E+00 |
| 2011 091 (Fri, 01 Apr) 19:43:42.272 | 2011 090 (Thu, 31 Mar) 08:43 AM CDT | -1.3 | 2.0 | 0.5 | 2.5 | 30.2 | 0.00E+00 |
| 2011 091 (Fri, 01 Apr) 21:15:17.857 | 2011 090 (Thu, 31 Mar) 10:15 AM CDT | -1.2 | -1.8 | -0.4 | 2.2 | 31.7 | 0.00E+00 |
| 2011 091 (Fri, 01 Apr) 22:46:53.255 | 2011 090 (Thu, 31 Mar) 11:46 AM CDT | -1.1 | -3.7 | -0.9 | 4.0 | 33.3 | 0.00E+00 |
| 2011 092 (Sat, 02 Apr) 00:18:28.483 | 2011 090 (Thu, 31 Mar) 01:18 PM CDT | -1.0 | -3.3 | -0.8 | 3.5 | 34.8 | 0.00E+00 |
| 2011 092 (Sat, 02 Apr) 01:50:03.495 | 2011 090 (Thu, 31 Mar) 02:50 PM CDT | -0.8 | -1.1 | -0.3 | 1.4 | 36.3 | 8.96E-20 |
| 2011 092 (Sat, 02 Apr) 03:21:38.420 | 2011 090 (Thu, 31 Mar) 04:21 PM CDT | -0.5 | 2.5 | 0.6 | 2.6 | 37.8 | 4.28E-09 |
| 2011 092 (Sat, 02 Apr) 04:53:13.332 | 2011 090 (Thu, 31 Mar) 05:53 PM CDT | -0.2 | 7.5 | 1.8 | 7.7 | 39.4 | 8.58E-05 |
| 2011 092 (Sat, 02 Apr) 06:24:48.222 | 2011 090 (Thu, 31 Mar) 07:24 PM CDT | -0.2 | 15.2 | 3.7 | 15.7 | 40.9 | 1.31E-04 |
| 2011 092 (Sat, 02 Apr) 07:56:22.833 | 2011 090 (Thu, 31 Mar) 08:56 PM CDT | -0.3 | 25.9 | 6.3 | 26.7 | 42.4 | 7.54E-05 |
| 2011 092 (Sat, 02 Apr) 09:27:57.249 | 2011 090 (Thu, 31 Mar) 10:27 PM CDT | -0.3 | 38.5 | 9.3 | 39.6 | 43.9 | 1.44E-04 |
| 2011 092 (Sat, 02 Apr) 10:59:31.460 | 2011 090 (Thu, 31 Mar) 11:59 PM CDT | -0.2 | 53.6 | 12.9 | 55.1 | 45.5 | 2.25E-06 |
| 2011 092 (Sat, 02 Apr) 11:45:25.418 | 2011 091 (Fri, 01 Apr) 12:45 AM CDT | -8.6 | -19.7 | 4.8 | 22.0 | 76.7 | 3.54E-13 |
| 2011 092 (Sat, 02 Apr) 12:31:05.538 | 2011 091 (Fri, 01 Apr) 01:31 AM CDT | -0.1 | 70.4 | 16.9 | 72.4 | 47 | 7.01E-14 |
| 2011 092 (Sat, 02 Apr) 14:02:39.616 | 2011 091 (Fri, 01 Apr) 03:02 AM CDT | -0.2 | 88.9 | 21.2 | 91.4 | 48.5 | 0.00E+00 |

*Summary of ISS conjunctions with object 34443*

# Lesson: Conjunction Frequency vs. Debris Flux

- Frequency of notifications varies substantially depending on debris population at vehicle altitude. Number of ISS conjunctions:
  - 390 from ISS first element launch through July 2008 (~0.8 conjunctions per week)
  - 200 from August 2008 through April 2009 (~5 per week)
    - *COSMOS 2421 – Three breakup events in 2008: 14-March, 28-April, 9-June*
    - *COSMOS 2251 / Iridium 33 collision 10-February-2009*
  - 191 from May 2009 through present (~2 conjunctions/week)
- As ISS raises permanent altitude from 350 km to 410 km this year, conjunction frequency may increase



# Conjunction Operations Considerations for ISS

- Maximum consequences if we fail
- Size of vehicle: 140 meters between farthest points of solar arrays
- Low altitude, high-drag environment means making assessments for "correct" operations difficult
  - Late-notifications ("false negatives")
  - Unnecessary concern for some objects
  - Highly erratic predictions for small debris
  - High Pc for objects very far away (>100 km)
- Many requirements on ISS orbit to satisfy visiting vehicle success
  - Space Shuttle rendezvous on flight day 3
  - Space Shuttle maximum rendezvous altitude
  - Soyuz/Progress rendezvous on FD3; daylight landing in Russian zone
  - HTV perigee limits
  - ATV mission design limits
  - Future vehicle requirements?
  - *All of these must be considered when designing a DAM for safety*

# Improvements for the Future

- Improving covariance realism
- Implementing late-notification DAM capabilities
  - Allows critical decisions to be made when uncertainties are small
- Solving the repeating conjunction problem
- Developing covariances for perturbing events on ISS
  - Docking/undocking
  - Reboost
  - Propulsive attitude maneuver
- Adapting operations/resources to an increasing debris population
  - Future collisions, satellite breakups
  - Improved tracking capability may find more, and smaller, objects
- Overhaul criteria to determine if a Pc is valid
- Investigate using covariance-based debris screening (instead of fixed volumes)