Orbital Debris Research in the United States

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Growth of the Satellite Population

1960
1965
1970
2005
1975
1980
1985
January 2009
1990
1995
2000

94% of Tracked Object Population are Debris
National Aeronautics and Space Administration

US Space Surveillance Network

LSSC = Lincoln Space Surveillance Center
(Millstone, Haystack, HAX)
AMOS = AFRL Maui Optical & Super-computing Site
AFSSS = Air Force Space Surveillance System
MOSS = Moron Optical Space Surveillance
MSX/SBV = Mid-Course Space Experiment/Space Based Visible
The US Department of Defense maintains a worldwide network of sensors which catalogs and tracks man-made orbital debris

- Although some cataloged debris is as small as 5 cm diameter, the nominal size of debris in the catalog is 10 cm in low earth orbit and 1 m at geosynchronous altitudes
- Catalog currently has approximately 14,000 objects in orbit

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Objects</th>
<th>Fragmentation Debris</th>
<th>Spacecraft</th>
<th>Mission-related Debris</th>
<th>Rocket Bodies</th>
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Haystack and HAX Radars

• Orbital Debris Radar Observations – Objective

  – Haystack and HAX are the prime sources of data for orbital debris smaller than 10cm. Haystack and HAX collect debris data in the critical size region between 1cm and 10cm.
  – Both radars annually collect between 500 hours to 700 hours of debris observation data which provides enough statistics for developing orbital debris models.

• Radar Description

  – Collocated in Tygsboro, Massachusetts at a latitude of 42.6°.
  – The main reflector of the Haystack and HAX radars are 36.6m and 12.2m diameter, respectively.
  – A pulsed continuous wave (CW) single frequency waveform is used for debris detection. Haystack transmits X-band and HAX transmits K-band.
  – Both radars observe a range window of ~ 300 to 1900 km.
  – Haystack can observe debris down to 5 mm and HAX can observe down to 2cm for LEO observations.

• Data Collection and Processing

  – NASA conducted the Orbital DEbris RAdar Calibration Spheres (ORDERACS) experiments on two space shuttle missions in 1994 and 1995 to validate data processing at NASA JSC.
  – The experiments showed that the Haystack radar is calibrated within nominal limits, with measured RCS values accurate to ±1.5dB.
• **Goldstone Radar Overview**
  – The NASA Jet Propulsion Laboratory Goldstone radar is used on a limited basis to supplement orbital debris observations made by Haystack and HAX.
  – Collects nearly 100 hours of data annually
  – Goldstone provides a measurement of the debris environment between 2 mm and 1 cm.

• **Radar Description**
  – Collocated in southern California’s Mojave desert at a latitude of 35.2°.
  – Pairs of up chirp and down chirp X-band pulses are used for debris detection.
  – Observable range window of ~ 350 to 3300km.
  – Observable range rates of 0.85km/s.
    • This dictates a staring observation mode near the zenith which makes Doppler inclination measurements unreliable.
    • Upgrades to the data acquisition system are currently being tested to increase the observable range rates. This would allow pointing away from the zenith and hence a reliable Doppler inclination measurement.
  – The radar cross section measurements have greater uncertainties than that of Haystack or HAX since the Goldstone radar:
    • does not calibrate using a calibration satellite
    • does not have a monopulse system to determine the position of the debris within the radar beam.

• **Data Collection and Processing**
  – The data collected at the radar is processed at JSC using software supplied by JPL.
  – The processed data is thoroughly inspected at JSC for quality control before subsequent extensive analysis.
Michigan Orbital Debris Survey Telescope (MODEST)

- GEO debris survey telescope (0.6/0.9 Schmidt Telescope)
- Located near La Serena, Chile at the Cerro Tololo Inter-American Observatory (CTIO)
- Collecting data since 2002
- Data used in modeling of the future environment (sample data shown middle right)
- Limiting Magnitude ~ 19 $M_v$ in R (corresponding to a size of 30 cm if you assume 0.13 albedo)
- Figure (bottom right) shows a probability map of where we have looked and the detections seen
  - Red shows the orbit planes that were the most visible, while blue shows the orbit planes that were the least visible
  - Solid diamonds are correlated targets and the open circles are uncorrelated targets

**Status of Survey Project**
- Collecting survey data every observing run
- Collecting light curve data in specific photometric bands on uncorrelated targets
- Use of two telescopes to refine orbits and the orbit determination process

**Special Projects – High Area-to-Mass (A/m)**
- Joint project through IADC for objects of high A/m
- Following IADC high A/m objects at sites around the world for a more complete orbit
- Efforts being made to determine source and material of these objects
Spacecraft Surface Examinations

- HST
- Mir
- ISS
- MPLM
Sample Space Shuttle Impacts

STS-92 Window Impact
~0.1 mm Aluminum Debris
2 mm diameter crater

STS-90 Radiator Penetration
~0.3 mm Paint Particle
1 mm diameter hole
STS-115 Radiator Impact

Outer Face Sheet Damage

- Entry hole, 0.108"
- Core damaged across ~ 5 cells (1" diameter x 0.5" deep)

Inner Face Sheet Damage

- Hole, 0.031"
- Crack, 0.267"
- Bonded Al Strip (0.011" H x 0.4" W x 15" L)
- 0.005" Silver-Teflon Tape
- F21 Tube

- 0.011" Facesheet
  3/16" Cell 3.1 Pcf Al Core
- AFT Rad (Typ.)
  28 Tubes/Pnl
  15.1 ft x 10.5 ft/Pnl
  4 Pnls/eh
GEO/LEO Observations from Kwajalein Atoll

• GEO
  - Comprehensive assessment of debris environment
    • High A/m debris
    • Determination of orbital parameters as inputs to NASA's environment model
  - Current capability
    • Broadband color photometry of targets to 16th magnitude (~50 cm diameter) via an autonomous 0.35 m telescope (an element of the AFRL High Accuracy Network Determination System – HANDS).
  - Planned capability
    • Designing a 1.3 m, 0.96 deg FOV autonomous survey telescope (Meter Class Autonomous Telescope - MCAT to be installed 3Q 2010) for detection and multi-spectral (Optical/NIR) photometry of targets to 20th magnitude (10 cm diameter)

• LEO
  • MCAT will detect new LEO debris and enable a statistical assessment of the low-inclination (0-20 deg) debris environment in the 1-10 cm diameter size regime
• The ORDEM series of models is in the process of an upgrade to ORDEM2008
  – Time range – 1995 to 2035
  – Altitude range – 200 km to 38000 km
  – Size range – 10 µm to 1 m

• Main Datasets and complementary Models
  – SSN, Haystack, STS window impacts, MODEST
  – LEGEND, NaKModule, SRMSlag, Degradation/Ejecta

• Statistical estimation of ORDEM2007 OD populations
  – The Bayesian algorithm developed in the statistical size estimation model (SSEM) is used throughout
    • Particularly suitable for data in the form of counts
    • Allows propagation of uncertainties
  – Based on reference populations such as LEGEND, NaK Module, SRM slag model …
  – Populations estimated for each year from 1995 to 2035

Haystack Detections:
Fragments size ≥ 1 cm
FY2003

Estimated Population:
(orbital distribution)
Fragments size ≥ 1 cm
FY2003
LEGEND
(A LEO-to-GEO Environment Debris Model)

- A state-of-the-art orbital debris evolutionary model
  - Can mimic the historical environment, and project it into the future (based on user-selected scenarios)
  - Has a fast pair-wise comparison algorithm to estimate $P_{\text{col}}$ among orbiting objects
  - Includes two reliable orbit propagators for GEO and LEO/GTO objects
  - Uses the NASA Standard Breakup Model to create simulated breakup fragments
  - Is the tool for the study published in *Science*, and the latest active debris removal analysis
Debris Assessment Software (DAS) 2.0

- NASA’s DAS 2.0 is designed to assist NASA programs in performing orbital debris assessments.
  - Assessment requirements are described in NASA-STD 8719.14 “Process for Limiting Orbital Debris”
  - DAS 2.0 addresses most requirements point-by-point

- Recent upgrades to DAS for the 2.0 version include:
  - Improvements to the orbit propagators and debris environment model
  - Improvements to the reentry survivability model and casualty estimation method
  - Improvements to the user interface and documentation
  - Recommendations from users of the current DAS (1.5.3)
  - Changes in the debris mitigation guidelines
Spacecraft Configuration (I-DEAS Finite Element Model)
- Describes spatial relationships of spacecraft components
- Defines spacecraft orientation (velocity and zenith directions)
- Defines M/OD shield regions

- Approximately 120,000 elements in ISS assembly complete mated configuration FEM

Meteoroid & Debris Environments (GEOMETRY)
- Threat directions
- Velocity distribution
- Shadowing

- 90 debris threat cases and 149 meteoroid threat cases assessed for each element in the FEM

Critical Particle Diameter Calculation (RESPONSE)
- Protection capability

Whipple Shield Ballistic Limit (failure above lines)

Computation of Penetrating Flux and PNP (SHIELD)
Graphical Interpretation of Results (EXCEL & I-DEAS)

<table>
<thead>
<tr>
<th>Station Region</th>
<th>Impact Risk from 1mm Ø Debris</th>
<th>Debris Penetration Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Probability No Impact</td>
<td>Odds of Impact</td>
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<tr>
<td>FG3</td>
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<td>CRV</td>
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<td>1/391</td>
</tr>
</tbody>
</table>

TOTALS: 0.934622 | 1/15 | 0.999132 | 1/148
Object Reentry Survivability Analysis Tool (ORSAT)

- This code is used to generate trajectory, atmosphere, aerodynamics, aeroheating, thermal, and ablation response of objects during a simulated Earth reentry
  - Predict demise altitude of objects which burn-up during reentry
  - Computes footprint and debris casualty area of items which do not burn up

- ORSAT Debris Assessments of note
  - Hubble Space Telescope
  - Atlas V and Delta IV Rocket Bodies
  - Tropical Rainfall Measuring Mission (TRMM)
  - National Polar-orbiting Operational Environment Satellite System (NPOESS)
  - Compton Gamma Ray Observatory (CGRO)
  - Early Ammonia Servicer (EAS) (ISS Jettison)
Optical Size and Shape Determination

• Goal
  – To develop an optical size estimation model comparable to the existing radar size estimation model.
  – To look for differences in the optical probability distributions of different classes of objects.

• Current work
  – Complex 3-D shapes cannot be easily described mathematically although they can be grouped into broad categories such as nuggets, flakes, etc.
  – Scanner can take many realistic shapes which can be grouped into these shape classes.
  – Characteristic length of each sample is measured, where X, Y, Z are the three orthogonal projections of an object as seen in the top figure.
    • \( L_c = \frac{1}{3}(X+Y+Z) \)

• Future work
  – Shapes can be manipulated in software to produce photometric response as a function of viewing geometry for all orientations of the object.
  – Calibration of the photometric response and the specular, diffuse ratio can be calibrated in the laboratory.
Work on More Complicated Fragments
Spectral Studies

- Use reflectance spectroscopy in the visible and near-infrared to determine the surface material of space objects
  - Knowledge of material yields better size estimation data

- Each material has specific absorption features that make it unique
  - Using those features, as well as slope, creates a model for materials that best fits the spectrum taken of the object in space

- Results
  - Placed objects into categories based on spectral response
    - See example on top right, where the object was thought to be either an asteroid or a human-made object
    - Determined to be human-made due to spectral signature of white paint
  - Measured pristine spacecraft prior to launch and looked at space weathering of materials
    - See example at the bottom right, where the model is based on pre-flight measurements showing great agreement in slope and absorption features
  - Received first data on debris objects (all large pieces)

- Status of the project – Work in Progress
  - Continued material modeling
  - Determine cause of the unexpected increase in slope for remote measurements as compared to laboratory measurements
  - Taking ground truth data on spacecraft prior to launch to get better idea of changes in material spectra
  - Obtain more remote measurements of cataloged objects and debris