Space Debris Re-entries and Aviation Safety

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Space debris as re-entry risk

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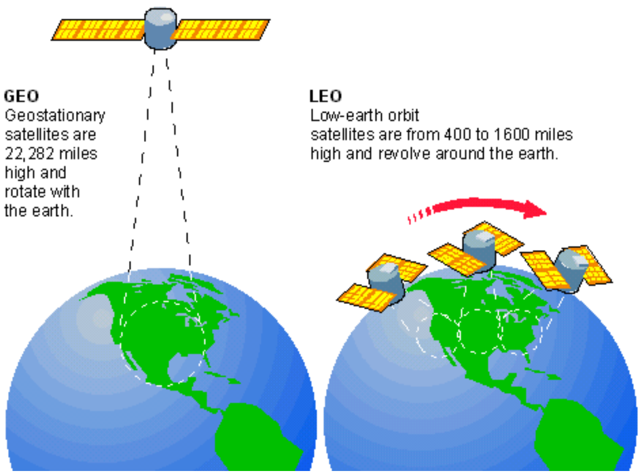
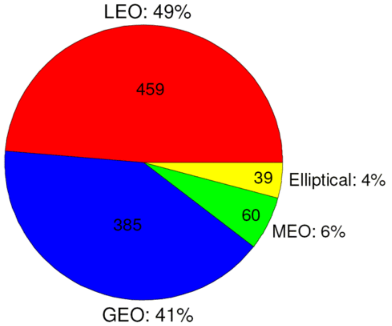
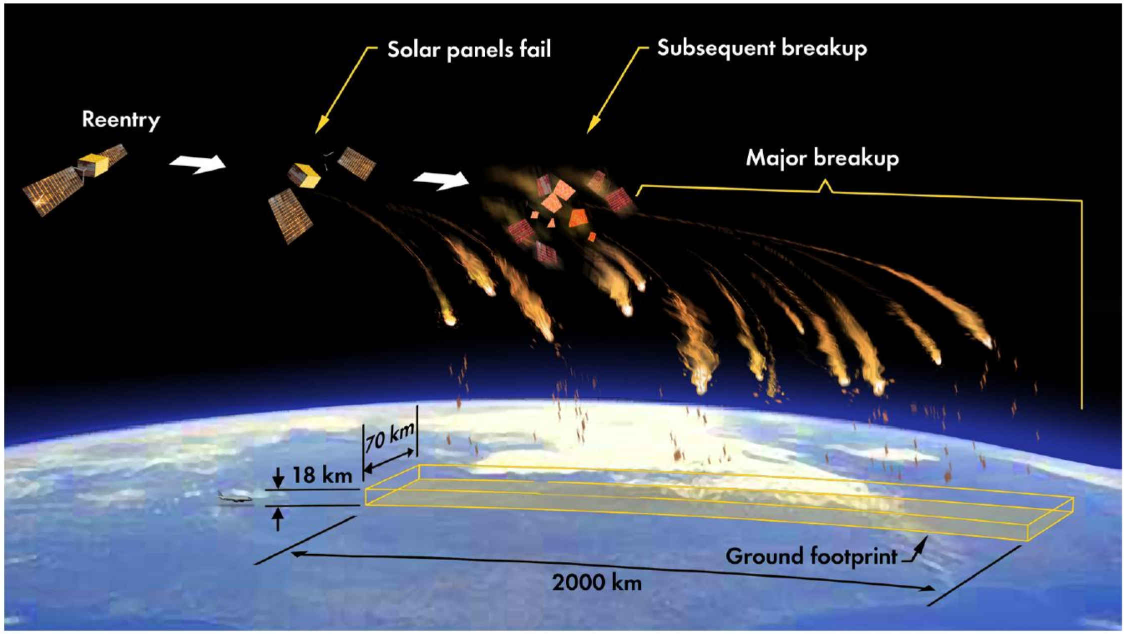


- Over 20000 tracked objects
  (objects larger than 10 cm diameter),
  of which about 1000 are operating satellites
- Over 13000 tracked objects are in
  Low Earth Orbit (LEO) of which about 500 are operating satellites
- Re-entry of objects from LEO happens due to natural decay. The drag force that such objects experience is due to their interaction with the few air molecules that are present at those altitudes. The density of the atmosphere at LEO heights is controlled by solar X-ray flux and particle precipitation from the magnetosphere and so varies with the current space weather conditions.
- Reentry within 25 years is recommended end-of-mission disposal option for LEO objects to mitigate the (debris) orbital pollution
  - Controlled reentry to safe oceanic area for objects with casualty expectation exceeding defined limit ($1x10^{-4}$ for US, $2x10^{-5}$ for France)
  - Random reentry acceptable in US (exceptionally acceptable in France) for objects with risk lower than $1x10^{-4}$

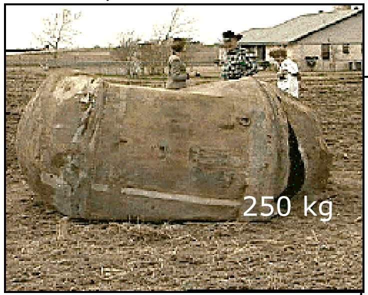


Re-entry breakup basics

- Space systems in LEO reenter naturally at very shallow angle (<1 degree).
- Location of uncontrolled reentries is unpredictable
- Major breakup at ~78 km
- 10 to 40% of mass survives reentry and impacts the Earth's surface posing hazard to people and property (e.g. of the ATV-1 mass of 12.3 tons about 3.5 tons in 183 fragments survived re-entry, 28.4% of mass)
- Debris spread over long, thin ground footprint (e.g. for ATV ~ 817km by 30km)



Texas, 1997



South Africa, 2000

250 kg

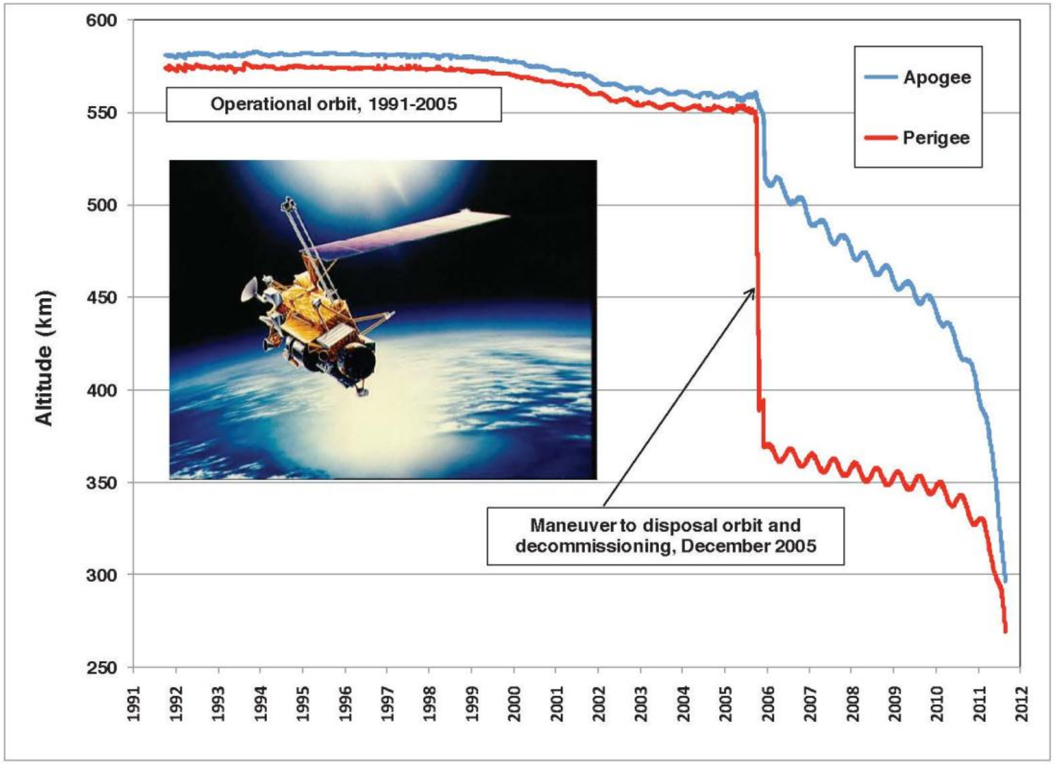
Saudi Arabia, 2001

Mongolia, 2010

Brazil, 2012

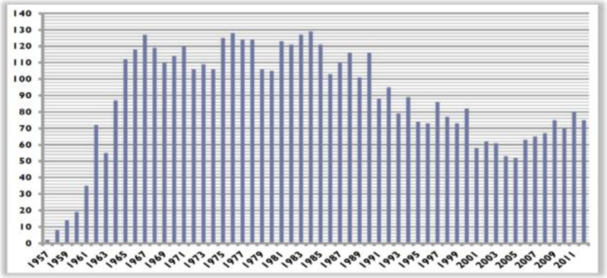
Space debris as re-entry safety risk

- Currently most large objects in LEO exceed the $1x10^{-4}$ risk limit but lack the capability to perform a controlled reentry (e.g. UARS estimated risk was 1 in 3200)

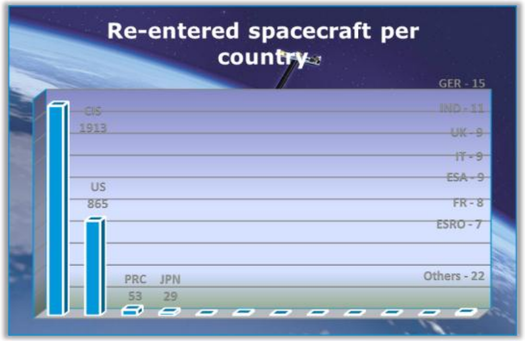


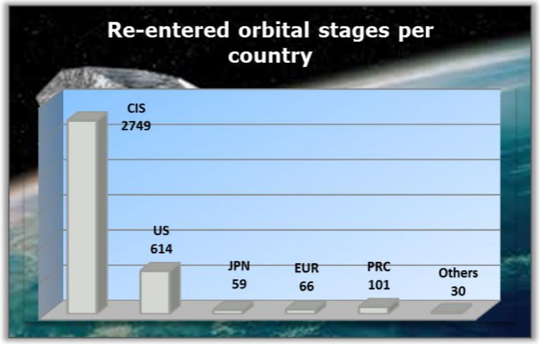
Re-entry statistics

- As of 3 April 2013, and since the decay of the Sputnik 1 launch vehicle core stage on 1 December 1957, **22,142** cataloged orbiting objects have re-entered the Earth’s atmosphere
- **7112 intact objects** (i.e. spacecraft, rocket bodies)
- Currently, approximately 70% of re-entries of intact orbital objects are uncontrolled, corresponding to about 50% of the returning mass, (i.e. **100 metric tons per year**)



- **On average, there is one spacecraft or rocket body uncontrolled re-entry every week, with an average mass around 2000 kg**

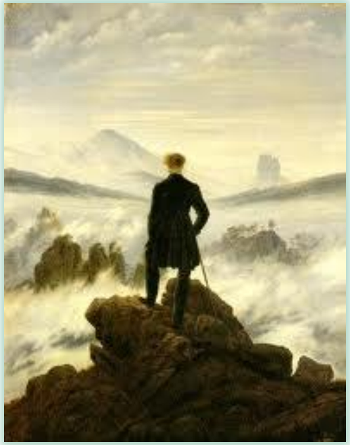




Re-entry risk evaluation

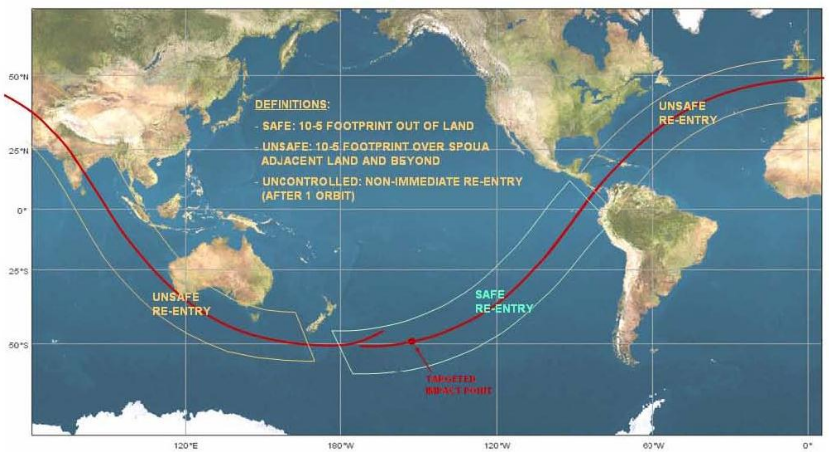
The human casualty risk associated with an uncontrolled re-entry can be subdivided in **primary** and **secondary**

- The **primary risk** derives from the possibility of a direct hit of people in the open by a falling fragment. It can be evaluated using Eqs. 1 and 2, taking into account that the debris kinetic energy threshold for any injury to the human body is 15 J, while a probability of fatality of 50% corresponds to a kinetic energy of 103 J



- The **secondary risk** is associated with a potential debris impact on a building, a shelter, a high risk industrial plant (e.g. chemical or nuclear) or a vehicle (e.g. aircraft, ship, or train), possibly leading to indirect human casualties. Unfortunately there is no easy way to compute the secondary risk globally

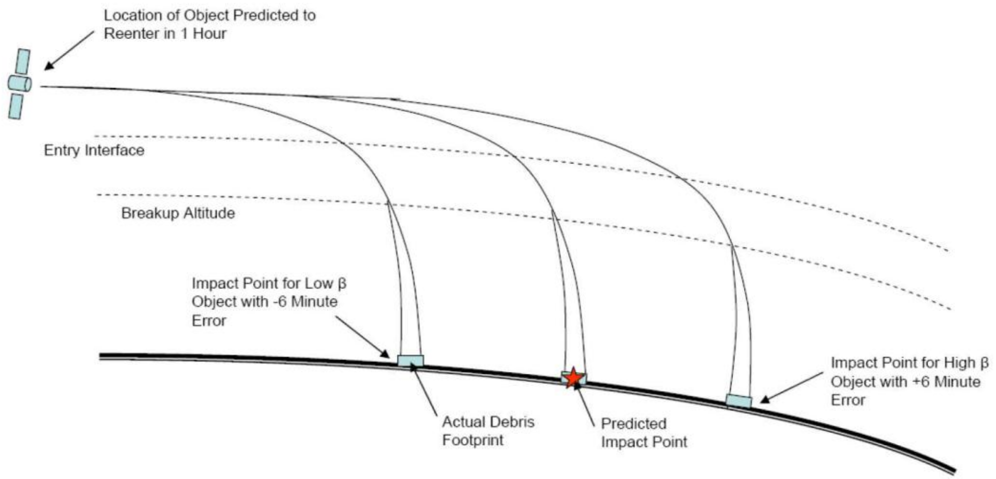
Estimating safety risk



- Models predict number, size, mass of surviving debris
- Debris will fall in latitude band defined by orbit inclination
- Risk estimated for objects with enough kinetic energy to cause injury or death on ground (> 15 Joules in U.S.)
- Risk estimated based on population density within latitude band
- Currently no estimate is performed of risk for aviation

Like a skipping pebble

- Precise location of space debris reentry point (defined altitude prior to breakup) impossible to predict for uncontrolled reentries
- At very shallow angle of reentry a spacecraft behavior when approaching the upper layers of the atmosphere is similar to a pebble skipping across the surface of a pond. (in 1930s Eugen Sänger proposed using such skipping effect to increase the range of a suborbital bomber)
- There is considerable uncertainty in the estimation of the re-entry epoch due to:
  - ✓ sometimes sparse and inaccurate tracking data
  - ✓ complicate shape and unknown attitude evolution of the re-entering object
  - ✓ biases and stochastic inaccuracies affecting the computation of the atmospheric density at the altitudes of interest
  - ✓ magnitude, variability and prediction errors of solar and geomagnetic activity mismodeling of gas-surface interactions and drag coefficient



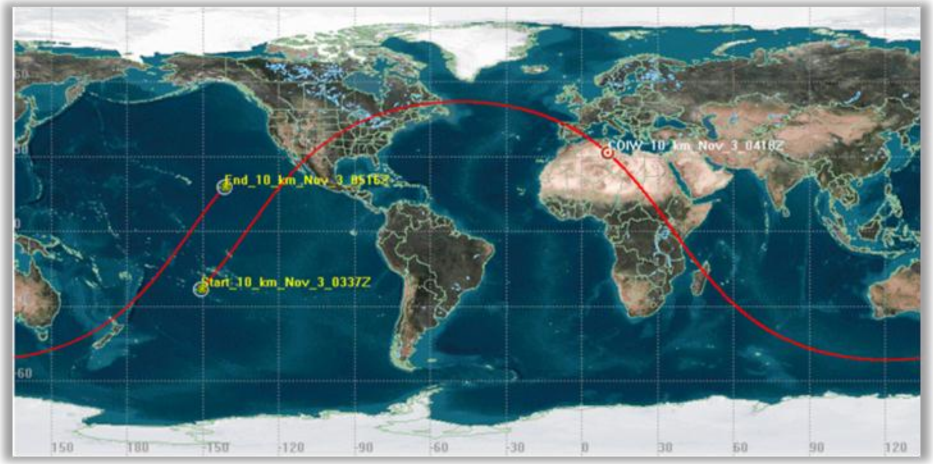
Current re-entry predictions capability

- Generally assume ±10-25% error in time of reentry due to atmospheric and drag uncertainties
  Example:
  - *Prediction made with tracking data 1 orbit revolution (90 minutes) from reentry has ±9 minute error*
  - *Object travelling at 7.5 km/sec x ±9 minutes → ±4050 km uncertainty in reentry location*

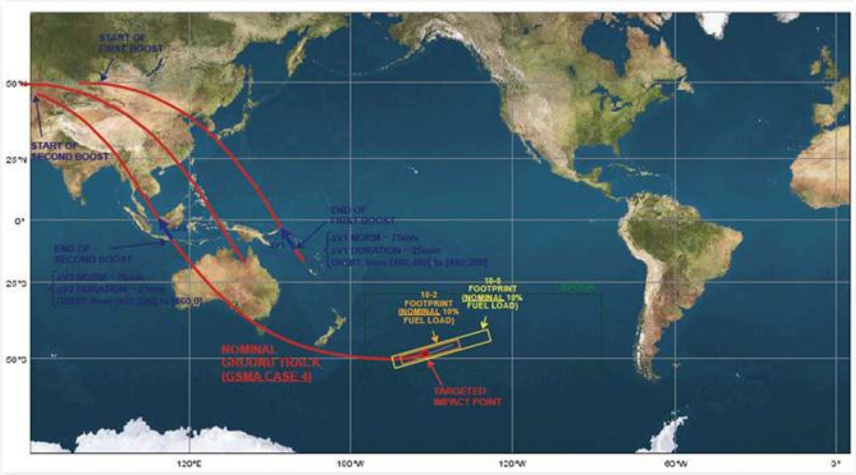
- The US official source of reentry predictions for uncontrolled reentry is USSTRATCOM's Joint Space Operations Center (JSpOC).TIP (Tracking and Impact Prediction) messages released at intervals (T-4 days, T-3 days, T-2 days, T-1 day, T-12 hrs, T-6 hrs,T-2hours)

- The IADC (Inter-Agency Space Debris Coordination Committee) performs annually reentry predictions exercises. Results are not released to the public

Uncertainty window computed from an orbit determined around 6 hours before re-entry by varying by +/- 20% the drag perturbation



Where will fragments land?

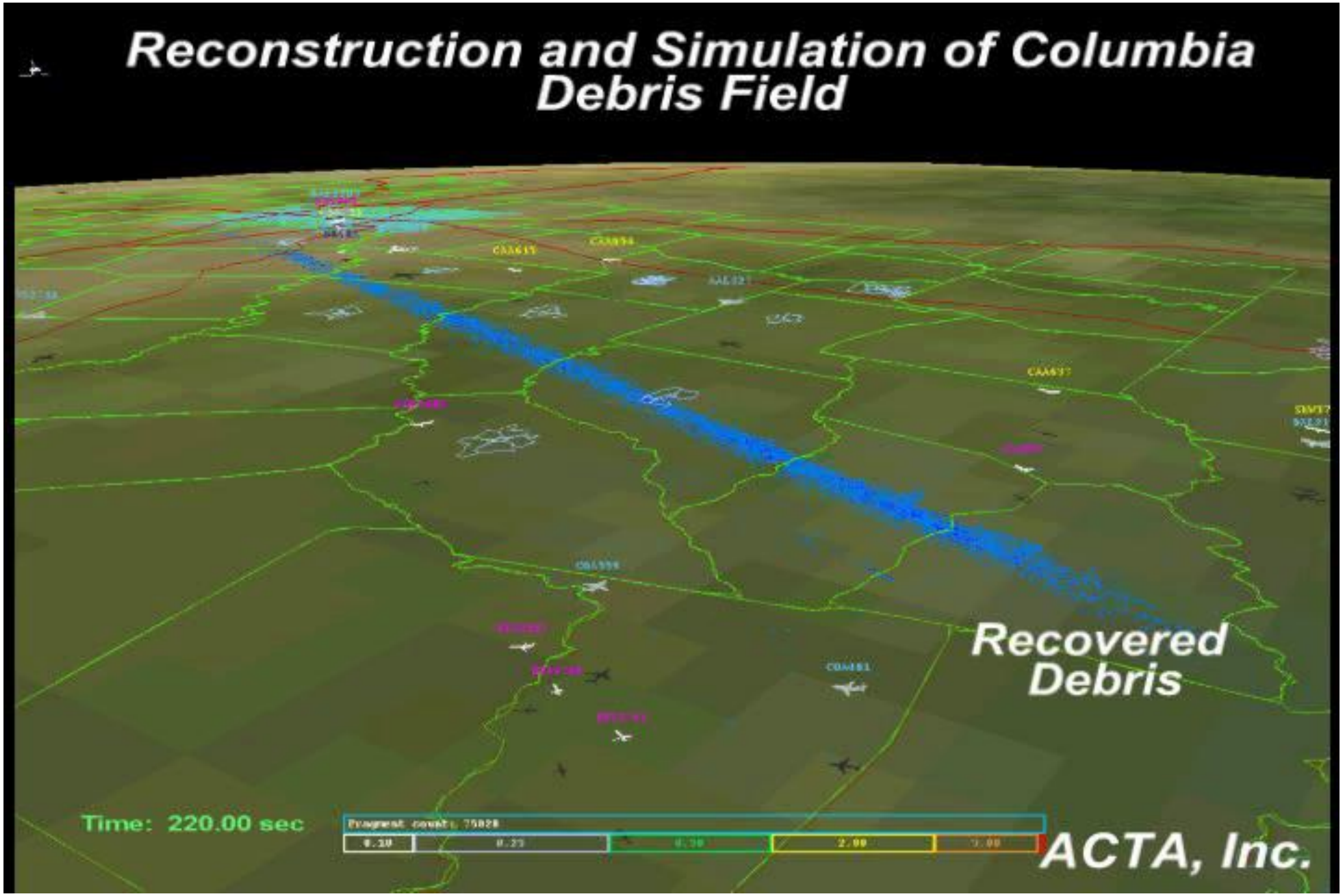


- Impact point for surviving fragments also impossible to predict
  - ✓ *Spread of fragments will depend on where fragments released, flight characteristics of each fragment*
  - ✓ *Fragments impact many kilometers from each other*
  - ✓ *Local wind can be significant factor*

- Uncertainties are addressed by “footprint probability boxes” (e.g. $1x10^{-5}$, and $1x10^{-2}$)

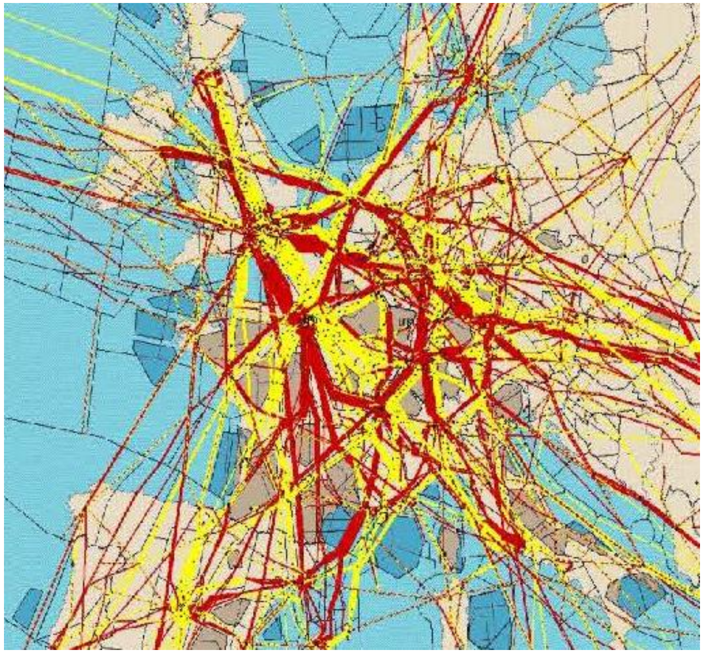
- “Footprint probability boxes” are routinely used to determine re-entry maneuvers for controlled re-entries (e.g. ATV)

Risk for aviation (video clip not for public distribution)



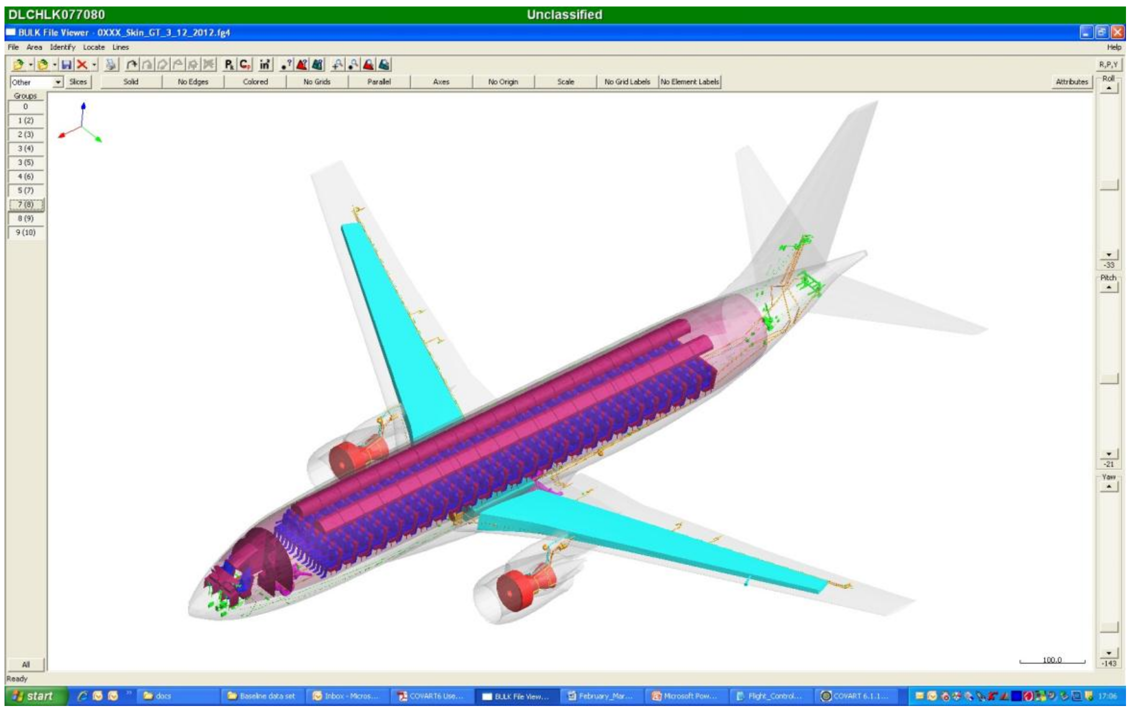
Risk for aviation

- Casualty expectations for people in commercial aircraft exposed to the risk of falling fragments from Shuttle Columbia disintegration was 1 in 1000 (1 in 100 for general aviation)
- On average >27 fragments from random re-entry exceeds specified limit for aircraft in hazard area
- The core area of Europe has one of the highest air traffic density in the world
- On Sunday 15 January 2012, in the middle of the Russian Phobos-Grunt uncontrolled re-entry window, the EUROCONTROL Network Management Operations Centre received an international NOTAM from Russian authorities, requesting European States to close their airspace for two hours



Risk for aviation

The US Federal Aviation Administration (FAA) Office of Commercial Space Transportation (AST) and the US Department of Defence co-sponsored the development of Aircraft Vulnerability Models (AVMs) to quantify the areas of aircraft susceptible to catastrophic or emergency outcome (e.g. fuselage penetration, fuel tank rupture) following impact with falling space debris. A fragment > 300gm is generally considered catastrophic.



Re-entry risk for aviation

- According to a study of R.P. Patera (The Aerospace Corporation, AIAA, 2008), the annual world wide risk of a commercial aircraft being struck with a piece of re-entering space debris is on the order of **3 x 10-4**. The associated mean time between occurrences is about 3,300 years. The probability of reentering space debris striking a commercial aircraft will increase as the number of commercial airline flights increases and as the debris population in low Earth orbit increases. This study did not use actual space traffic density data, but assumed proportionality with ground population density

- A study on the likelihood of a meteorite striking an aircraft concluded that the probability is between 1.3 x 10-5 and 1.7 x 10-5. Thus it is more likely that an aircraft is struck by reentering space debris than by meteorite

- The IAASS is launching a study to develop an advanced aviation risk assessment tool for debris and meteorites, which will take into account the actual air traffic density data for five regions: Europe, United States (East-Central, West), Far East (Japan and East China). It is expected that the highest regional risk will be that of Europe

R&D to reduce re-entry hazards

Reentry Breakup Recorder assembly
(recorder is inside heat shield)

Reentry Breakup Recorder during
pre-flight testing

- The Aerospace Corporation with NASA, ESA and JAXA is promoting operational testing and use of new instruments recording what happens during breakup and providing precise information on debris impact locations
  - *Reentry Breakup Recorder (REBR) developed by collected data on re-entry breakup of JAXA's HTV-2 and -3 and on ESA's ATV-3 cargo vehicles*
  - *REBR provided data on its trajectory and impact location*

- REBR data are meant for scientific purpose of helping to improve breakup and hazard prediction models

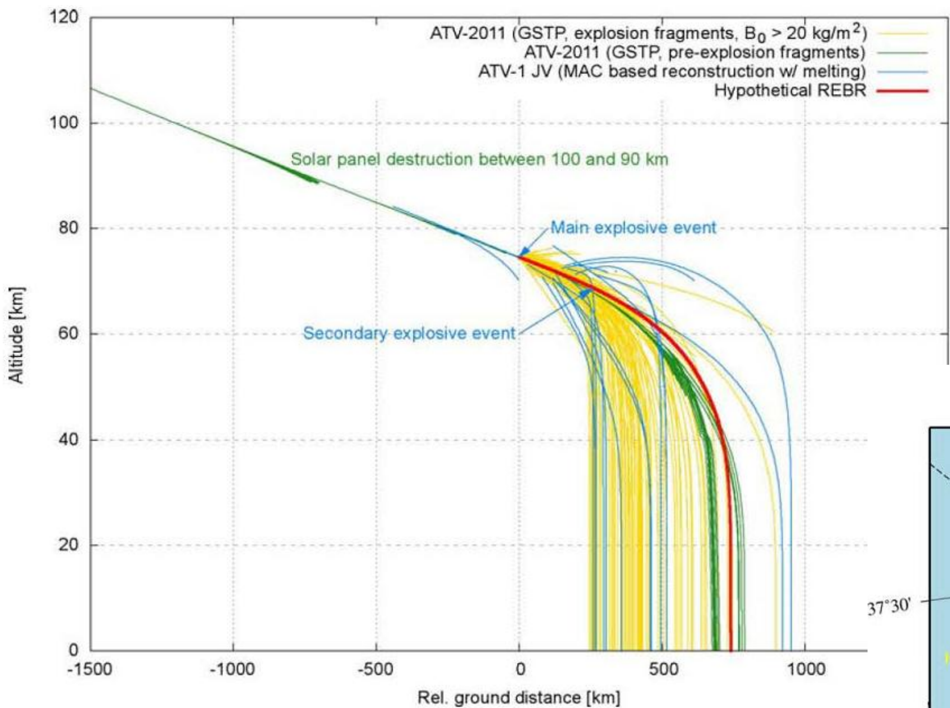
- Data from sensors (accelerometers, gyro rate, temperature, GPS receiver) are collected and recorded for several minutes during re-entry, then an Iridium modem is activated which makes a satellite phone call and downloads recorded data

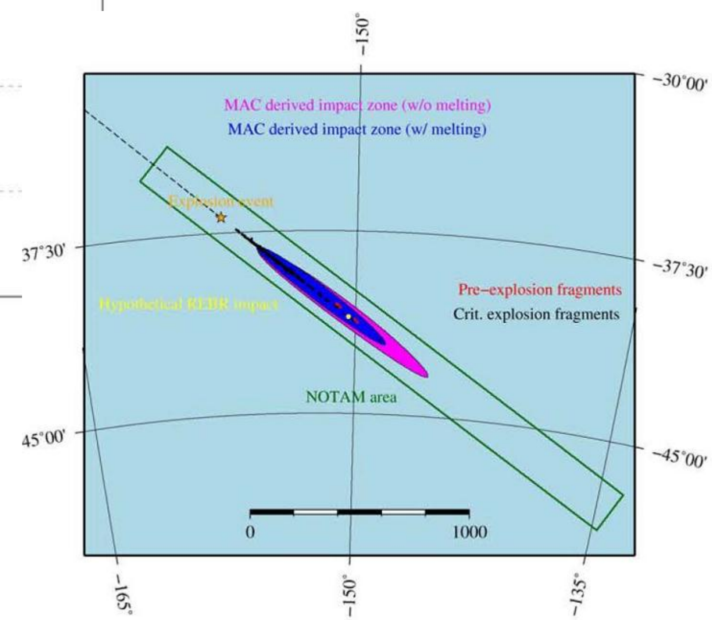
Re-entry observation campaigns

- The destructive re-entry of the ESA ATV-1 Jules Verne occurred on the 29th September 2008. ESA organized with NASA the first ever multi-aircraft re-entry observation campaign aiming at:
  - ✓ characterizing fragmentation and explosive events, including altitude of explosion
  - ✓ identification of likely cause (e.g. fuel tank rupture) and resulting fragments; characterizing ablation products and demise
  - ✓ reconstructing fragments trajectories and impact points

- A series of observation campaigns are currently being discussed by NASA with the ISS international partners in view of preparing the ISS end-of-life disposal by controlled by controlled re-entry (420 tons)!

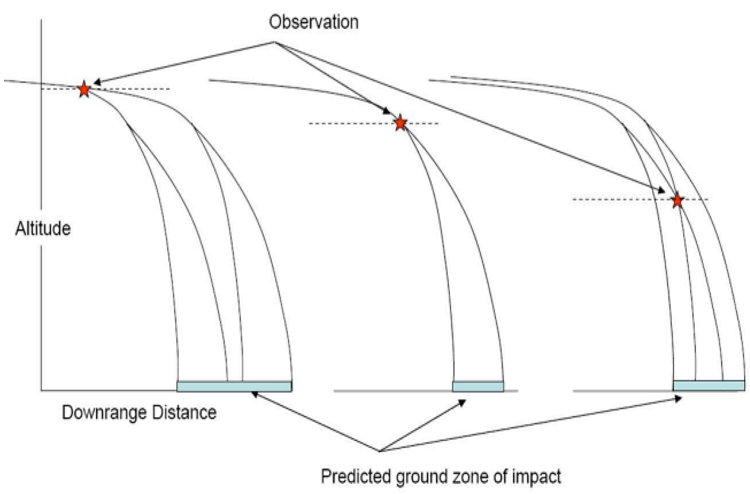
Localizing the footprint





Alerting

- Length of predicted impact zone depends on observation altitude
- Most accurate prediction for observation at primary breakup altitude



- On average, first fragment reaches the airspace (i.e. 18km) ~10 minutes after breakup
- Last fragment reaches ground ~26 minutes after breakup

Re-entry Direct Broadcasting Alert System

- The Re-entry Direct Broadcasting Alert System (R-DBAS) (Patent Pending, inventor: T. Sgobba) works as a "smart fragment" which can autonomously determine its own position during re-entry, and which knows its relative location in the projected hazard area (footprint probability box), which has been pre-computed on ground.

- The R-DBAS allows to directly broadcast related alerts to potential users within the time falling fragments take to reach altitudes used by aviation or to reach Earth surface.

- The Re-entry Direct Broadcasting Alert System (R-DBAS) consists of an On-board Unit and a Receiver-Display Unit
  - The On-Board Unit consists essentially of a Global Positioning System (GPS) tracking device, a central processing unit (CPU), memories and software, transmitter, and antennas.
    The On-board Unit includes also an aerodynamically shaped housing and related heat shield, power storage/distribution unit, and switching device.
  - The Receiver-Display Unit consists of receiver device, antenna, and display system.

Conclusions

- Currently, approximately 70% of re-entries of intact orbital objects are uncontrolled, corresponding to about 50% of the returning mass, (i.e. 100 metric tons per year). On average, there is one spacecraft or rocket body uncontrolled re-entry every week, with an average mass around 2000 kg. Between 10 and 40% of such mass will reach ground

- The annual risk for aviation due to uncontrolled re-entry has been approximately quantified as 3x10-4. An advanced risk estimation tool is being developed to account for actual (regional) air traffic density and more precise airplane vulnerability models

- During the Columbia accident the probability of fragments hitting an airplane was 1/1000 for commercial airliners in the area and 1/100 for general aviation. Operational (alert) procedures were later putted in place for subsequent Shuttle missions

- The European Space Agency is developing an experimental device (Re-entry Direct Broadcast Alert System) for directly communicate to airplanes dangerous areas due to falling space debris (First tests expected in 2014)

- According to the space Liability Treaty the “launching state” of the re-entering object is liable for damages