Summary of the 2014 IAC A6 – IAA Symposium on Space Debris

The 12th IAA Symposium on Space Debris was held during the 2014 IAC in Toronto, Canada. The Symposium addressed the complete spectrum of technical issues of space debris, ranging from measurements, modelling, risk assessment in space and on the ground, reentry, hypervelocity impacts and protection, mitigation and standards, to space situational awareness and surveillance. The Symposium consisted of nine oral sessions and one poster session, including more than 70 oral presentations and 40 posters. One of the sessions, A6.8, "Policy, Legal, Institutional and Economic Aspects of Space Debris Detection, Mitigation, and Removal" was a joint session with the Space Security Committee. The poster, "Ground-based Optical Observation System for LEO Objects" by Dr. T. Yanagisawa (JAXA) also won the Best Poster Award during the conference. Overall, the Symposium brought subject matter experts from academia, government, and industry around the world together for focused as well as cross-disciplinary presentations and discussions on various aspects of space debris. It was a very successful event. More than 20 high quality papers were selected and recommended for submission to *Acta Astronautica* by Session Chairs and Rapporteurs. Highlights from each session are summarized below.

A6.1 Measurements

The first session of the Space Debris Symposium was on measurements. Session attendance ranged from 73 to 95. Eight papers were presented during the session. The first one was the "Capability of a Space-based Space Surveillance System to Detect and Track Objects in GEO, MEO, and LEO Orbits" (Silha et al). This paper described an ESA study of LEO sensors in dawn-dusk sun-synch orbit. The sensors look roughly anti-sunward, at the sunlit sides of objects in LEO to GEO, with the main focus being GEO. The study found that design changes are needed to eliminate coverage gaps in GEO. The second paper addressed "A Telescope Payload for Optical Detection of Space Debris from Low Earth Orbit" (Middleton et al). It described an ESA-funded study at Rutherford Appleton Lab. Like the first paper, it studied a sensor in dawn-dusk sun-synch orbit, but the focus here was on optical system design and image sensor type, for a ~30 kg secondary payload. It recommended a 3-mirror off-axis optical design together with a custom CMOS imager. The 3rd paper, "EOP-1/EOP-2 Mini-Observatories for Space Debris Observations: Characteristics, Tasks, and First Results of Operation" (Molotov et al) described early results from several new dedicated Roscosmos-funded mini-observatories using 19-65 cm aperture telescopes. In the first 1.5 years, they acquired 2 million observations to allow for better GEO conjunction predictions. The paper, "Additional Optical Surveys for Space Debris on Highly Eccentric and Inclined MEO Orbits" (Silha et al) summarized 23 nights of observations by AIUB of objects in Molniya-type orbits, using ESA's 1-m telescope at Tenerife, Spain. Extrapolation suggested that there were at least 338 untracked objects brighter than 19th magnitude in Molniya-type orbits.

The 4th paper, "Further Observations and Analysis in the Thermal IR and Visible of Graveyard Orbit Objects" (Skinner et al) described the attitude dynamics and expected optical and thermal signals from a generic GEO satellite like the Boeing/Hughes 601. It showed good agreement with two actual GEO satellites, one stabilized and one uncontrolled. The paper on "High-Power Optical Phased Arrays for Space Debris Tracking and Maneuvering" (Roberts et al) discussed a new ability to control the frequency and phasing of multiple lasers, and the resulting ability to achieve coherent combining in the far field. This allowed higher power and tighter focus than single lasers. This would provide more accurate ranging and also possibly laser ablation. The 7th paper, "An Open-Access Visible Near-Infrared Spectra Reflectance Library of Spacecraft Materials" (Bédard et al) described the BDRF characterization of 4 common spacecraft surfaces over the 350-1100 nm range: triple-junction solar cells, aluminum, white paint, and aluminized polyimide. It argued for an open-access library of such data for a wider range of surface types. The final paper of the session, "Trajectory Detection of GEO Debris Utilizing Features of Image Motion" (Fujita et al) provided a summary of image processing of sequences of starfield images taken by an earth-fixed telescope, to automate detection of objects moving in GEO-like orbits. The technique used was able to detect bright objects easily, but worked less well with fainter objects.

A6.2 Modeling and Risk Analysis

This session included nine excellent papers, in terms of interest and presentation quality. All were confirmed well in advance, so the structure of the session was firmly established before the beginning of the IAC, with no last minute withdrawal.

The first paper, "Massive Collisions in LEO – A Catalyst to Initiate ADR" (McKnight), highlighted the importance of massive collisions in LEO, between clustered upper stages, as a potential source of rapid environment deterioration well before the environment becoming unstable. An initial ADR activity should then be targeted to such clustered upper stages. The second paper, " Discussions on the Necessity of Orbital Debris Removal in GEO" (Furuta), tried to assess if ADR were needed in GEO as well, based on a more accurate conjunction analysis in the geostationary region, in order to verify the adherence or not with the NASA Safety Standard. The first two papers then encouraged accelerating research and development on active debris removal and/or just-in-time collision avoidance. The next three papers investigated the uncertainties and sensitivity of orbital debris population projections in LEO in terms of overestimation/underestimation of collision activity, (too simplistic) modeling assumptions, and solar activity. "Sensitivity Analysis of the Long Term Evolution of the Space Debris Population in LEO" (Dolado Perez) made a wide and complete review of the problems at stake. The paper, "The Effect of Modeling Assumptions on Predictions of the Space Debris Environment" (Lewis), concentrated on the collision probability estimations. The paper "Influence of Solar Activity on Long-term Propagations" (Bastida Virgili) addressed the effects of long-term solar activity uncertainties. The following two papers, "Deriving the Spacecraft Environment Criticality from Monte Carlo Simulations of the Space Debris Environment" (Radtke) and " Evaluation Index for the Ranking of LEO Objects" (Alessi) built on parallel ESA funded studies and discussed new ideas on how to rank objects to be removed from the environment for safe and secure space activities.

The paper, "ORDEM 3.0 and MASTER-2009 Modeled Small Debris Population Comparison" (Flegel) presented preliminary comparisons of the small debris population between the ESA MASTER-2009 and NASA ORDEM 3.0 engineering models. The results were encouraging, but the analysis of further cases and new in-situ debris measurements were recommended. The last presentation, "Hypervelocity Impact Testing of DebriSat to Improve Satellite Breakup Models", given jointly by Edhlund and Rivero, briefly introduced a laboratory impact test using a small satellite fully equipped with emulated components, parts, and subsystems to establish a representative and high fidelity fragmentation model. This DebriSat experiment, funded by NASA and DoD, will produce a wealth of new data to refine the fragmentation models in the coming years.

A6.3 Hypervelocity Impacts and Protection

This session covered a variety of presentations on shielding against hypervelocity impacts from space debris, damage predictions from debris impacts, models for collisional induced break-up, impact detectors, and experimental methods for hypervelocity impact research. Related experimental, analytical and computational work was also presented.

A novel shielding configuration, "Influences of Impact Position and Angle on Shielding Performance of N-shape Configuration" (Wen et al), highlighted the effect of an oblique aluminium stuffing layer placed in a Whipple shield as observed in experiments and hydrocode simulations. Enhancement of shielding performance was especially achieved at certain oblique impact angles. The paper, "Effects of Temperature of Targets on Ejecta Size Distribution in Hypervelocity Impact" (Nishida et al), reported about a moderate temperature dependence on the ejecta sizes from hypervelocity impacts. Two presenters reported about new models concerning spacecraft disintegration upon hypervelocity impact. "A new Method to Predict the Catastrophic Disintegration of Spacecraft Upon Collision with Large Orbital

Debris" (Zaccariotto et al) presented a new method based on Statistical Energy Approach (SEA) to evaluate the impact energy that is transmitted from the impact location to other spacecraft parts. Based on the amount of transmitted energy in relation to the mass of the spacecraft part, the authors considers the location of the impact on the spacecraft in the breakup analysis. The paper, "CARDC-SBM Spacecraft Breakup Model and Its Application" (Liu et al) presented a new model for collision induced spacecraft breakups. The work was based on several impact tests on simplified spacecraft structures made from Aluminium. The test results provided the mass-, area-to-mass-, and velocity distributions of breakup fragments. They were compared against the NASA breakup model predictions.

Two presentations reported on new engineering models in the field of impact analysis. The first, "An Engineering Model to Describe Fragments Clouds Propagating Inside Spacecraft in Consequence of Space Debris Impact on Sandwich Panel Structures" (F. Feltrin on behalf of A. Francesconi) described a new engineering model for the description of fragment clouds emanating from the penetration of honeycomb sandwich panel structures. The model described debris clouds as cones, containing a very large number of finely fragmented particles which behaved like a jet of dust, and one single solid fragment in the center. The model calculated the sizes, ejection angles, and velocities of the cloud. The second, "Modelling of Damage Formation on a Front Wall of Shielded Composite Overwrapped Pressure Vessel Subjected to Space Debris Impact" (Cherniaev et al) developed a model to show that the winding pattern of filament-wound composite overwrapped pressure vessels affected the impact damage produced in the front wall through scattering of stress waves in the composite material.

New impact detectors were described by two presenters. "Experimental Verification of an Innovative Debris Detector" (Bauer et al) described an impact detector that was integrated in solar panels. The detector is called SOLID ("SOLar generator based Impact Detector"). It uses metal strips to detect penetrating impacts on solar panels. The detector function was experimentally verified by hypervelocity impact tests. "Measurement of Micro-debris Flux via TANPOPO Capture Panel Onboard the ISS Kibo Exposed Facility" (Takayanagi et al) showed results from laboratory impact tests and numerical simulations from particle impacts with sizes ranging from 100 to 400 µm on the aluminium capture panel of the "Tanpopo" detector. This detector is to be installed on the exposure facility of the Japanese "Kibo" module of the International Space Station. The data serve to calibrate the impact craters on retrieved detectors. In the field of experimental methods for hypervelocity impact research, "Improvement of the Two-stage Light-gas Accelerators Performance by Using the Photonic Doppler Velocimetry (PDV)" (Hupfer et al) presented a new diagnostic method for two-stage light gas accelerators. This method allows measuring precisely the velocity of the projectile during acceleration in the gun bore.

A6.4 Mitigation and Standards

Of the 10 papers originally scheduled for this session, 2 were withdrawn (A6.4.8 by Wolahan and A6.4.10 by Xu). They were replaced by 2 ad-hoc presentations adapted from the A6 poster session. The A6.4 session was attended by ~80 participants, who actively participated in the discussions following the presentations.

The first paper, "An Assessment of Cubesat Collision Risk" (Lewis), analyzed the significance of cubesat missions. The results indicated that within the next 10 years 1 in 10 conjunctions would involve cubesats (1 in 5 within 20 years). Out of the ~10 catastrophic collisions by 2043, ~2 could involve cubesats. "A Compact Storage Deorbiting Sail for Cubesat Applications" (Valdatta) explored the concept of a time-triggered solar sail deployment mechanism to reduce cubesat orbital lifetimes by a factor 5. A prototype will be flown on a 3U cubesat of the University of Rome. The 3rd paper, "Generic Model for the Space Debris Mitigation Analysis Procedure of Cubesats" (Azari), used estimates of collision probability, based on a MASTER-2009 population model, to define a generic model for cubesat mission analysis purposes. The next paper, "Analysis of Mitigation Guidelines Compliance at International Level in LEO" (Dolado

Perez) performed a global 25-year lifetime compliance analysis for operational LEO satellites, as listed by the Union of Concerned Scientists, excluding passive LRR satellites. The estimated orbit lifetimes were determined on the basis of ballistic parameter estimates from retro-fitting TLE data histories. About 35% of the spacecraft were compliant with the 25-year guideline. “Compliance of the Italian Satellites in LEO with End-of-life Disposal Guidelines for Space Debris Mitigation” (Anselmo) analyzed the level of compliance with 29 Italian LEO objects with respect to the 25-year rule, in light of evolving guidelines. Approximately 60% compliance was achieved for past missions, while current missions are compliant to almost 90%.

The paper on “New Insights into the Stability of the Space Debris Environment” (Finkleman) recalled Tallent’s “particles in a box” debris population model to identify problems in assuming linear systems when solving associated differential equations. The author concluded that ~100 launches per year could lead to a sustainable spacecraft population. “Debris Creation in GTO: A Review of Launch Practices 2004-2012” (Fisher) performed semi-deterministic and Monte-Carlo analyses of debris creation processes on GTO and HEO orbits for different launch systems. A significant number of these systems were not compliant with international debris mitigation guidelines. “Deriving a Priority List Based on the Environmental Criticality” (Kebschull) described the software tool SANE that is optimized for the LEO-dominating, high-inclination orbits to determine the break-up epoch related, long-term effect of fragmentation events by means of analytical approximations of a “criticality index”. The analysis indicated that SL-16 and SL-8 orbital stages constituted the highest risk potential to the LEO environment. The paper “Towards the Generation of Thermal Flux Data for the Improvement of Atmospheric Entry and Spacecraft Deorbiting Simulations” (Donaldson) explained a conceptual approach to a generalization of thermal flux data for the analysis of the survival to ground impact of re-entry objects, taking into account the varying conditions in free-molecular and continuum flow fields. “Additional Orbital Fragmentation Events” (Wiedemann) outlined necessary corrections to implementations of NASA’s break-up model, resulting in fewer meter-sized objects and more sub-cm-sized objects

A6.5 Space Debris Removal Technologies

A total of 9 papers were presented in this session, including 7 papers focused on capture systems and mechanisms and 3 papers about vision systems. Papers about capture systems were essentially focused on the removal of non-cooperative debris. The technologies presented cover a large spectrum of debris size, from the very small debris between 1 and 10 cm to ENVISAT-class debris.

Two papers dealed with net systems. “Net-based Payload on Board AVUM Enhanced Platform to Efficiently Remove Large Debris from LEO” (Lavagna et al) presented the design of a net-based payload derived from VEGA’s AVUM third stage. The study used a numerical simulator developed at Politecnico di Milano to model the net dynamics from its launch to its target wrapping. The target debris considered in the simulation was ENVISAT. The net technique was also the subject of the paper “Deployment Dynamics of Throw-net for Active Debris Removal” (Liu et al). Finally, the paper, “Analysis of the Concept of Non-cooperative Targets and Associated Tailored Active Debris Removal Methods” (Gao) presented a general framework for the analysis for ADR solutions for non-cooperative targets.

The paper, “Clamping Mechanism – A Tentacles Based Capture Mechanism for Active Debris Removal” (Janovsky et al), also targeted large ENVISAT-like debris but with a different concept using a tentacle-based clamping mechanism which follows a “capture before contact strategy.” This system was studied in the frame of the ESA-funded Phase-A system study called “e.Deorbit”. The paper detailed the design process of the clamping mechanism and the trade-off investigating a wide range of potential solutions. The baseline concept retained features two tentacles with two degrees of freedom each. The paper, “Deployable Mechanisms for Small to Medium-Sized Space Debris Removal” (St-Onge et al) focused on much smaller debris (1-10 cm) and proposed a variant of the "sweeper" concepts for LEO orbits based on a large deployable cupola (100-500 m diameter) supporting a membrane. It also focused on a deployable mechanism that allowed a high expansion ratio. Such mechanism might also be the basis for a drag-augmentation device.

The use of polyurethane foam for ADR was investigated in "Expanded Polyurethane Foam for ADR" (Pigliaru et al). Considered applications of foam spraying for ADR were drag augmentation and the creation of a rigid link between the debris. The study highlighted how the chemical properties of the polyurethane foam influenced its physical and mechanical characteristics.

Besides captures mechanisms and techniques, 3 papers dealt with vision and guidance systems – "Development of a Camera for Autonomous Visual Guidance for Space Debris Removal System" (Shoji et al) presented an autonomous visual guidance system based on a camera deployed on the small solar-electric power-sail demonstrator IKAROS, "IP-Based Pose Estimation for Space Debris Removal: Implementation and Results" (Rodrigálvarez et al) proposed an image processing technique for the estimation of the relative pose between the target and the chaser, and "LIDAR-based Autonomous Pose Determination for a Large Space Debris" (Opromolla et al) investigated the performance of a LIDAR-based system for pose determination of a known large debris.

A6.6 Space Debris Removal Concepts

In many ways, the removal concepts session serveed as the culmination of the technology concepts from the preceding sessions, addressing the integration of tracking, risk assessment, rendezvous, capture, and deorbit. Despite the array of concepts and approaches discussed, all of the proposals focused on direct rendezvous of a chaser spacecraft with a target and the subsequent deorbiting of the target, in general agreement with ADR concepts. There was a dearth of concepts addressing non-ADR approaches to debris removal.

Two problem areas continue to emerge as key challenge for ADR, and were reflected in the papers presented in this session. (1) Target interaction - The debate and trade between contact vs. contact-less methods continued. A positive step was noted in that several of the papers began to address the complexities associated with tumbling targets, either by de-spinning or by engineering a capture device indifferent to rotational motion. (2) Mission efficiency- Given system failure rates, launch costs, and necessary mass for ADR missions, many papers attempted to address how efficiency of the overall ADR approach might be increased. Concepts to address efficiency ranged from conducting multiple missions per launch to substantially decreasing the chaser mass and complexity, thus driving down launch costs.

The papers from this session broke down into three basic categories. (1) Theory - these papers dealt with nascent technologies that are being developed to address critical shortfalls in debris removal. (2) Design - these papers dealt with system engineering point designs of removal systems, including size, weight, and power, capture mechanism, and deorbit methodology. (3) Test - these papers dealt with laboratory or on-orbit testing designed to reduce risk or demonstrate techniques and technologies. Among the papers, three key papers are highlighted below.

The paper, "Eddy Currents Applied to De-tumbling of Space Debris: Analysis and Validation of Approximate Proposed Methods" (Ortiz Gomez), outlined a theoretical approach to address contactless capture. The author presented a mathematical treatment for employing magnetic currents from one chaser satellite to de-tumble a second, non-cooperative target prior to capture and deorbit. The conceptual implementation addressed the need to conduct multiple-aspect detumbling since the magnetic field could only damp motion perpendicular to the field. It also examined the complexities of shielding the chaser spacecraft from the strong magnetic fields required to detumble the target.

The paper, “Solar Electric Propulsion Orbital Debris Ferry, Vehicle Concept and Reference Missions (Duchek), outlined a parametric trade study on the use of solar-electric propulsion as a debris removal platform. The particular point design covered in the paper requires terminator flight for maximum efficiency (since constant propulsion would require constant solar access), which is not a severe limitation given that many inert debris are rocket bodies used to launch payloads into sun-sync. The key parametric trade upon which the analysis is based minimized mass per deorbit vs. number of missions per launch, given that traditional chemical propulsion (and its subsequent mass budget per operation) would be necessary for precision rendezvous (i.e. SWAP must be made for both forms of propulsion). One of the main challenges with this approach is that the electrically-driven chaser leads to a random reentry of the target, which may turn out to be potentially hazardous and violate international guidelines of a maximum of 1 in 10,000 probability of casualties. The paper, “RemoveDEBRIS: An EU Low Cost Demonstration Mission to Test ADR Technologies” (Lappas), outlined a Surrey-led design of a test satellite to demonstrate various ADR technologies. The satellite is low-cost ($18M) and will demonstrate a harpoon, a net, a drag sail, and orbital inspection. The test platform will carry its own targets, in the form of deployable microsats. The key issue impeding the test is launch cost and availability, and could be an issue that the IAF champions in order to ensure the program's fulfillment.

A6.7 Operations in Space Debris Environment, Situational Awareness

More than 70 participants attended this session. From the 10 presentations initially scheduled only 8 were actually given. The paper, “Sensor Simulation Supporting the Prototype Pilot Data Center for the ESA SSA Preparatory Program” (Sanchez-Ortiz), presented a system level simulator that could be used either to assess the capabilities of a given SSA system to fulfill its missions or to define the better steps to be given in order to enhance de capabilities of an existing SSA system.

Two highlight papers from this session were on quite different subjects. The paper entitled “An approach to Ground Based Space Surveillance of Geostationary On-Orbit-Servicing Operations” (Scott) dealed with the problem of identifying the position of the chaser relative to the target during GEO proximity operations with optical sensors. By the application of a technique coming from the “Binary-Star community” (cross-spectrum speckle interferometry) this papers presented a method to determine the presence of a chaser in the vicinity of a target as well as to estimate the relative motion of the chaser with respect to the target. In addition of the theoretical validation of the technique, it has been experimentally tested using real observations of co-located GEO Satellites. The paper entitled “The PEGASUS Incident: The Loss of the First Ecuadorian Satellite and Its Recovery” (T.S. Kelso on behalf of R. Nader) presented and analyzed the incident that drove to the loss of the first Ecuadorian satellite. This paper is quite interesting due to the fact that operators are not used to communicate about incidents arriving to their satellite during operations. Concerning the causes that have driven to the loss of NEE-01 PEGASUS satellite, the possibility of being hit by a space debris is considered but not confirmed, knowing that the probability of losing this satellite by a sub-system failure is more probable or have the same level of probability that losing the satellite by space debris.

A6.8 Policy, Legal, Institutional and Economic Aspects of Space Debris Detection, Mitigation, and Removal

This session focused on determining a potential economic framework sufficient to encourage more investment into remediation activities related to orbital debris. A general theme of this session was the constant struggle of trying to determine what dimension of the problem must lead the others (e.g. operational, legal, regulatory, technical, economic, etc.) or must they all be nurtured in parallel.

The paper, “How Can We Justify Debris Mitigation and Removal Cost?” (Yasaka), provided a valuable engineering examination of how growing on-orbit servicing capabilities might spur on development and deployment of debris remediation systems. The very tight linkage between the compliance with existing debris mitigation guidelines was highlighted – lack of compliance of existing mitigation rules actually increases the future remediation market (i.e. results in derelict objects that will have to be removed later). The other three papers provided comprehensive models of economics for debris remediation but each had a specific focus area. The paper, "Cost and Risk Assessment for Spacecraft Operation Decisions Caused by the Space Debris Environment" (Schaub) examined the economics for viable approaches to remediation. His paper identified the broad range of operational options that will need to be considered. Alternatively, "The Economics of Space Debris: Estimating the Costs and Benefits of Debris Mitigation" (Macauley) provided a construct for an economic model that required an assessment of how other space operators were materially liable to create a monetary foundation for action. Lastly, "Business and Economic Considerations for Service Oriented Active Debris Removal Missions" (Lappas) was a summary of a recently released research project conducted for the European Space Agency. It provided details of a very comprehensive business model which detailed necessary supply and demand issues.

At the completion of the technical presentations, a moderated debate was conducted focused on discussing what component of the community (e.g. environmental, legal, policy, business, regulatory, economic, technical, or operational) would need to lead the others in creating a situation where debris remediation activities would be initiated in earnest. While the spirited discussion raised more questions than it answered, one consistent theme throughout was the need for early on-orbit technology demonstrations to help calibrate just how difficult many of the remediation options being considered will be to implement. This insight will assist all components that must work together to execute such global remediation operations to prioritize the next most important steps. Currently, there is almost too much ambiguity for people to determine what aspect of each respective dimension needs to be resolved first (e.g. ownership vs liability or cost vs reliability).

A6.9 Modeling and Orbit Determination

This session covered many different and complex subjects, from orbit determination using bi-static radar, to re-entry simulation of CLUSTER-II. Members of the audience entered into engaging discussions with some authors, which increased the benefit to all those present. Many new results were presented, but several questions were also raised by these and there is great potential for future work in these areas. Of particular interest was the observations made of High Area-to-Mass Ratio (HAMR) objects and the modelling of the same. There is still much to understand about this particular family of objects, but good progress is being made and some understanding is being built. Of similar importance, was work presented on the attitude characterization of objects in GEO, which will be valuable information for any on-orbit servicing or removal operations. New results show some unique and challenging spin characteristics, and more information regarding the cause of these is required. The work presented on re-entry was of equal interest and quality, with considerable effort being expended to understand the uncertainty associated with the re-entry and possible demise of complex spacecraft configurations. Results from an analysis of CLUSTER-II, for example, demonstrate the importance of initial orbital states on the fragmentation and demise of re-entering vehicles. In summary, the session provided an interesting and valuable combination of real-world observations combined with modelling of the same phenomena. There are several challenges that exist at this interface, including the development of representative models that are efficient, but work in this area is allowing the knowledge gaps to be filled.

The highlight papers from this session include the following. "Observation and Analysis of the Apparent Spin Period Variation of Inactive Box-wing GEO Resident Space Objects" (Earl), presented data gathered over long time period on spin rate, angular acceleration, and spin period. "Results of Two Year Dedicated Molniya-type HEO Surveys" (Agapov) identified many UCTs and some of the objects appeared to have high area-to-mass ratios. The paper, "Orbit Determination of Space Debris Using a Bi-static Radar Configuration with a Multiple-beam Receivers" (Morselli), explained the bi-static radar configuration and how it applied to orbit determination. “Disposal Strategies for GEO orbits of Beidou Satellite System” (Tang) showed if satellites were left to drift freely, eccentricity could grow up to 0.8. Inclinations of some test cases went through several resonance zones that contributed to the eccentricity growth. There was strong dependence on initial argument of perigee and right ascension as well. The paper, “Reentry of Spacecraft on Highly Eccentric Orbits – Cluster-II” (Kanzler) showed high re-entry velocity increased heat load but could shorten reentry duration.