LEO Constellations – Quo Vadis After End-of-Mission?

Kay-Uwe Hörl[(1)], Rüdiger Jehn[(2)], Claudia Sarrocco[(3)]

[(1)]Astrium GmbH Telecommunication & Navigation, 81663 Munich Germany, Kay.Uwe.Hoerl@astrium-space.com
[(2)]ESA/ESOC, Robert Bosch Str. 5, 64293 Darmstadt, Germany, Ruediger.Jehn@esa.int
[(3)]McGill University, Institute of Air & Space Law, 3661 Peel Street, Montreal, Canada, ClaudiaSarrocco@libero.it

ABSTRACT

Constellations in low-Earth orbit (LEO) will increase the number of debris objects if they are not removed from their orbit after end of mission. This paper addresses two issues: the technical aspects dealing with the collision risk during de-orbiting (calculated with the MASTER model) and the political and legal aspects covering the liability question.

Prerequisites for a code of conduct are outlined that could be agreed upon internationally to encourage spacecraft operators to de-orbit their spacecraft. If such measures were to be taken, a mass accumulation could be prevented at disposal orbits above 2000 km, thus preserving these regions useful for future generations.

1. INTRODUCTION

By the beginning of the year 2001 close to 9000 catalogued objects have accumulated in space, only about 600 of them being operational satellites and the rest being space debris. The launch of LEO constellations will even aggravate the debris problem if the spacecraft are not brought back to Earth (*i. e.* de-orbited) after end of mission. Some LEO constellations already exist, *e.g.* Globalstar and Iridium. Unfortunately Globalstar was not designed to perform de-orbit manouevres, whereas the de-orbiting of the Iridium constellation was foreseen from the very beginning. For new constellations, especially at altitudes between 1200 and 1600 km, a trade-off between re-orbiting to higher altitudes and de-orbiting has to be made. In this paper the technical and legal implications of the de-orbiting of LEO constellations are discussed using the example of the planned Skybridge constellation.

The Skybridge constellation consists of 80 satellites arranged in a 80/20/15 Walker constellation at an operational altitude of 1470 km and an orbital inclination of 53º [1]. Each satellite is equipped with 2 wings of rigid solar arrays spanning about 15 m in total and providing a power of 3750 W at end-of-life. The electrical propulsion system consists of stationary plasma thrusters (SPT 100) with a total thrust of 80 mN and a specific impulse of 1500 s. These SPT can be used to either re-orbit the spacecraft at end-of-life to a disposal orbit or to move the spacecraft to an orbit inside the denser atmosphere to cause a quick re-entry. Both options, re-orbiting and de-orbiting, would comply with the space debris mitigation standards currently drafted by the Inter-Agency Space Debris Coordination Committee (IADC).

2. THE COLLISION RISK DURING DE-ORBITING

From an operational and cost point-of-view there is only a small difference between the re-orbiting and de-orbiting option. To manoeuvre a 1300 kg spacecraft from 1470 km to 2500 km (the re-orbit altitude under consideration) using the SPT 100 motors requires 37 kg of propellant (Xenon) corresponding to a total ΔV of 426 m/s. The transfer is performed within 79 days. In order to de-orbit to an altitude of 600 km where a satellite with a typical area-to-mass ratio has a residual lifetime of about 25 years it requires less than 2 % more propellant (and also transfer time). This would be in compliance with the NASA Safety Standard 1740.14 [2] as well as the draft European Space Debris Mitigation Standards [3]. However, it would not make sense to stop de-orbiting at 600 km, but at least to continue 20 days more to arrive at an altitude of 400 km or even 40 days longer to reach an orbit with a lifetime of less than a day. Table 1 shows the cost of the various end-of-life disposition options:

Disposal Altitude (km)	Delta-V required (m/s)	Propellant (kg)	Transfer duration (days)	Residual lifetime (years)
2500	426	37.1	79	> 10000
600	432	37.6	80	25-30
400	542	47.0	100	0.1-0.5
200	652	56.4	120	0.01

Table 1. Comparison of propellant consumption, transfer time and residual lifetime for different options of Skybridge disposal altitudes.

The major difference between re-orbiting and de-orbiting is the associated risk to other spacecraft and on ground. Whereas the re-orbiting to a higher altitude forwards the risk to generations in some distant future, in the de-orbiting option the risk has to be dealt with immediately. In this paper only the on-orbit collision risk will be addressed, since it is assumed that the Skybridge satellite will completely burn up in the atmosphere during re-entry. As a rule of thumb, objects less than 5 tons in mass are assumed to burn up during re-entry except for especially heat resistant parts like titanium vessels [4].

The on-orbit collision risk is calculated with the MASTER model [5]. In Fig. 1 the space debris flux on a Skybridge satellite is shown during the 100 days of de-orbiting from 1470 km to 400 km altitude. The highest risk is encountered after about 50 days when the spacecraft crosses the most densely populated area in space at an altitude of 900 km. Yet, the probability of impact is below 1 over 10000 per square meter and year for debris larger than 1 cm. Fig. 2 gives the flux integrated over the time it takes to de-orbit down to 200 km.

The probability of an impact of an object larger than 10 cm (which has the potential to destroy a satellite) is $7 \cdot 10^{-7}$ per square meter. Assuming 80 satellites with a surface of 50 m^2 each, the total collision risk is 0.28 %. And considering that only about 300 out of the 7000 catalogued objects of this size in low-Earth orbit are operational satellites, then the collision risk that one of the 80 Skybridge satellites will collide with an operational spacecraft during the total de-orbiting phase is 0.012 %. Howbeit a collision cannot be ruled out completely if no collision avoidance procedures are undertaken.

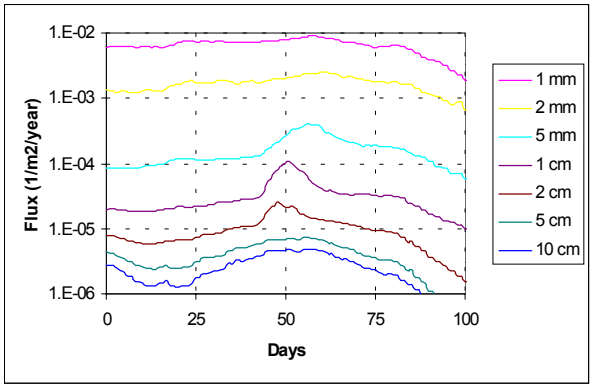

Figure 1. Space debris flux for various sizes onto a Skybridge satellite during de-orbiting from 1470 km to 400 km altitude based on the MASTER model.

3. FRAMEWORK DE LEGE LATA

Questions of space debris are by their very nature of international magnitude so that, from a legal point on

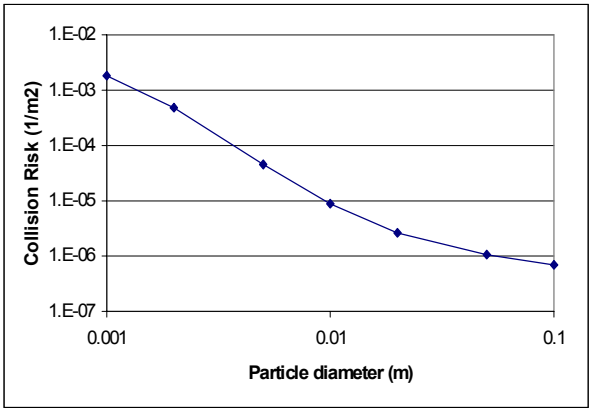

Figure 2. Collision risk of a Skybridge satellite during de-orbiting as function of debris size (calculated with the MASTER model).

view, one can look at the international body of law in the quest for answers. It is apparent that present international space law is based on the assumption that only States deploy space activities. Moreover, international space law does not contain explicit provisions dealing with space debris. Sources of this branch of international law refer to orbital debris in other terms.

A major legal challenge may then be, as the example of Skybridge demonstrates, that not only States but also private enterprises invest in space-activities, such as telecommunication, thereby potentially producing debris. A comprehensive discussion of space debris as it relates to public international law is beyond the scope of this paper. It only concentrates on the potential for legal issues with regard to private undertakings. Skybridge is used as an example to illustrate a point, but the problems are the same for other spacecraft operators and especially serious in cases of constellations.

Between the two legal issues of responsibility for creating space debris on the one hand and liability in case of a collision on the other hand, this paper addresses only the latter problem. Some of the initial question arising are (1) who has jurisdiction over private activities and (2) which norms of law apply to liability in case of on-orbit collisions? In this second category, both international and some national legal norms are discussed.

3.1 Jurisdiction

Jurisdiction constitutes a particular aspect of the general legal competence of States often referred to as sovereignty [6]. It is a tool used to achieve legal control over a given activity. While the concept of jurisdiction as an expression of States' sovereignty was initially territorial, the actions of nations in outer space required expansion of jurisdiction. According to Art. II Outer

Space Treaty [7] outer space is not subject to territorial application of sovereign laws but States are to register space objects.

In a sense, such registration can be seen as a link to the nationality of the space object that allows the State to extend the scope of any national law. However, a true concept of nationality does not exist in space law but rather that of "jurisdiction and control" according to Art. VIII s. 1 Outer Space Treaty. Its Art. VI s.1 provides that

> States Parties to the treaty shall bear international responsibility for national activities in outer space … whether such activities are carried on by governmental agencies or by non-governmental entities, and for ensuring that national activities are carried out in conformity with the provisions set forth in the present Treaty.

Since "[t]he activities of non-governmental entities in outer space … shall require authorization and continuing supervision by the appropriate State Party to the Treaty" (*ibid.* s. 2), States establish license requirements for such private undertakings. In the case of Skybridge, which was formed in Delaware, US, in 1997 [8], the US has jurisdiction over the company and subjects it to the administration of various US agencies. Thus, it becomes imperative to look at both international and national legal provisions.

3.2 Sources of law

National law that applies to space debris issues is often an implementation of States' international obligations under the space treaties. The latter are therefore examined at this point.

3.2.1. International law

Once decided who has authority over space activities, the question of applicable law for responsibility and liability issues needs to be settled. As to the sources of law, Art. 38(1) of the International Court of Justice (ICJ) Statute [9] provides for the ICJ to apply "international conventions … international custom … and general principles of law recognised by civilised nations".

The latter two sources are not directly relevant to the space debris issue. They may be used to support specific treaty provisions and be reflected in national legislation. Irrespective of a source of law, it is important to have a definition of space debris. As a popular term it includes all artificial Earth-orbiting objects that are no longer functional and are thus beyond control, and which therefore cannot serve a useful purpose. But do the international space treaties cover space debris?

The Outer Space Treaty establishes the main legal principles governing outer space activities. Also called the Magna Carter of international space law, it provides that State parties shall bear international responsibility for national activities. The term "responsibility" thus describes the obligations imposed on States.

If damage arises from a particular activity there is the question of liability. Art. VII Outer Space Treaty holds that

> [e]ach State Party to the treaty that launches or procures the launching of an object into outer space … is internationally liable for damage to another State Party … by such objects or its component parts on the Earth, in air space or in outer space.

In the absence of a legal definition of space debris, it has been suggested that debris be included in the definition of "space object".

By way of an extensive interpretation, it is concluded that the Outer Space Treaty applies to space debris since non-functional satellites and other spacecraft can legally be considered "objects" or their "component parts." By differentiating the two terms it is argued that the Treaty addresses possible failures and separation of space objects. Moreover, there is no reason why space debris that originates from a functional space object, should be considered something else once it becomes non-functional.

Liability in the context of the Outer Space Treaty is fault-based and requires wrongful intent or some form of negligence on the part of the launching State [10]. The launching State can not only be the State that launches or procures the launching but also the State from whose territory or facility an object is launched. In the present case, at least the US and France can be considered launching States as they license Skybridge's activities. Depending on the launcher chosen, other States may qualify as additional launching States and thus be potentially liable under public international law.

The problem remains that the fault standard in the Outer Space Treaty lacks a definition. While the intentional explosion of a satellite would qualify as fault, merely de-orbiting a satellite at the end of its lifetime would probably not. Thus, the Outer Space Treaty does not hold sufficient solutions.

The Liability Convention [11] elaborates on the issue of damage caused by space objects and becomes the

primary basis for claims. According to its preamble, the Convention takes into consideration that, notwithstanding the precautionary measures to be taken by States and inter-governmental organisations involved in the launching of space objects, such objects may on occasion cause damage. For liability to arise under the Convention, it becomes crucial that a "space object" causes damage.

De-orbiting satellites can be subsumed under Art. 1(d) Liability Convention, which states that the "term 'space object' includes component parts of a space object as well as its launch vehicle and parts thereof." The launching State's liability then extends beyond the functional status of space object and the Liability Convention therefore applies to space debris.

To establish liability under the Convention one has to differentiate between damage occurring on the surface of the Earth or to aircraft in flight and damage caused elsewhere. The liability is two-fold. Arts. III and IV (b) Liability Convention provide that liability for damage caused in outer space by space objects, launch vehicles, or components thereof is fault-based. A launching State shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the Earth or to aircraft in flight. The issue under study is whether or not Skybridge may be liable for collisions during de-orbiting so that for such activities the fault standard would apply to damages in outer space. Similar to the situation under the Outer Space Treaty, however, this standard is not defined.

In this context, it is important to know where other space objects are located in order to avoid such incidents. *De jure* intended to help in identifying space objects, the Registration Convention [12] is little help for de-orbiting manoeuvres. This is mainly because an obligation to provide limited data to the greatest extent feasible and as soon as practicable exists only with regard to the launch of a space object and when it has been but no longer is in Earth orbit, according to Art. IV (3).

Not only public international law applies to the present issue. Since international space law addresses space debris, States are obliged to ensure that these rules are reflected in their national laws.

3.2.2. National law

Under public international law, a plaintiff would have to use diplomatic channels of his respective government to have his claim presented to the launching State. This will certainly be a lengthy process and may not be too successful at the end. However, the petitioner could chose to sue the operator under national law. For the purpose of the present paper, and by way of example, only American law is mentioned.

Should a collision occur in space, a plaintiff could address a court in the US. A likely cause of action would be "negligence". Assuming it could be proven that this collision was caused by the negligent conduct of Skybridge, a positive outcome may still be unlikely due to issues of foreseeability of damage and assumption of risk. Without an in-depth discussion, it should become clear that substantiating a claim would be extremely difficult by the damaged petitioner.

The space debris issue is also addressed during licensing by national authorities such as the Federal Communications Commission (FCC) in the US. Skybridge is in the process of obtaining FCC authority to construct, launch, and operate their constellation under the Communications Act of 1934, as amended [13]. So far, the FCC has not imposed post-mission requirements on LEO constellation operators. Disposal methods have been left to operators' discretion. Moreover, Skybridge is not subject to other US reviews by the Federal Aviation Administration as the payload is exempt due to FCC jurisdiction [13]. The FCC will eventually adopt the US Government Orbital Debris Mitigation Standards for its licensing procedure.

Existing national standards and those to be implemented focus on space debris prevention. There is no doubt about it that prevention is better than cure. But what if a collision occurs in spite of precautionary measures?

3.3 Liability

The result with regard to liability occurring from an on-orbit collision is essentially the same under international and national law. Substantiating a claim necessitates the demonstration of fault. There are no legally binding standards with regard to collision avoidance. Fault requires breaching a duty of care. With no comprehensive duty to avoid the creation of debris in the first place, there can be no breach of duty in merely leaving inactive satellites in outer space. Nor can there be a duty established for avoiding collisions between those uncontrollable satellites and functioning space objects during de-orbiting. A claimant would thus have difficulties proving the fault standard as long as a collision was not intentional. The legal situation would be different if real time monitoring was technically feasible and legally required.

3.4 Available collision avoidance support

Collisions during de-orbiting can be avoided by relying on collision avoidance support. It is a service already offered. For instance, the European Space Operations

Centre and the Center for Orbital and Re-entry Debris Studies at Aerospace Corporation offer commercial collision warning. The Aerospace Corporation warrants that its services will be performed in accordance with the degree of skill and judgement usually exercised by generally recognised professional engineering firms. At the same time, however, the company includes the typical limitation of liability and indemnification clauses in its service contracts. Users of such services, however, mainly act out of self-interest. But the demand for, and provision of, this technical assistance is a prerequisite for a code of conduct, which could develop into mandatory procedures.

4. LEX FERENDA

A legal framework *de lege ferenda* should strongly encourage all operators to minimise space debris by de-orbiting LEO satellites at end of life. This is especially important in times of multi number satellite constellations for telecommunication, navigation and other applications. It would also be in line with UNISPACE III recommendations [15] and the Technical Report on Space Debris [16]. Unfortunately, the positive effects are visible only in the long term. Therefore they are not of interest for commercially operating entities, which have to answer to their shareholders' short-term interests.

4.1. A de-orbiting proposal

It is proposed to consider a legal obligation for spacecraft operators to de-orbit spacecraft from low Earth orbit after end of mission. For spacecraft equipped with solar electric propulsion a de-orbiting requirement without a simultaneous procedure for collision avoidance would increase the potential for collisions and liability of launching States. Therefore, it is also proposed to require spacecraft operators to continuously perform a proximity analysis to avoid collisions with catalogued space objects.

How realistic is this proposal? Part of it is already included in the draft of the European Space Debris Safety and Mitigation Standard [3]. The standard, which is drafted by ASI, BNSC, CNES, DLR and ESA and which is not yet approved, gives "priority" to performing a direct re-entry of the vehicle. Nevertheless, it does not explicitly oblige operators to de-orbit their spacecraft. In chapter 7.3.2 it is stated that the "space project should assess the [collision] risk and implement manoeuvres if necessary."
Once these standards are implemented nationally, this may become a significant contribution towards reducing space debris.

On the international level the Inter-Agency Space Debris Coordination Committee has been active to draft international standards. Its current draft foresees de-orbiting as one disposal option. However, a re-orbiting above 2000 km altitude is equally allowed. If the IADC can agree on the European proposal to set a time limit for the re-orbiting option (*i.e.* re-orbiting would only be allowed for spacecraft launched before the year 2010), then a valuable contribution to a sustainable solution would be achieved.

IADC, however, has no regulatory power. The subjects of public international law are States. Thus, a legal obligation – a code of conduct to begin with – should be endorsed by the United Nations (UN), *e.g.* in a General Assembly Declaration.

In a recent preparatory UNCOPUOS meeting in Berlin in December 2000, the US-delegation made an eight-step proposal to achieve "widespread international adoption and implementation of voluntary debris mitigation practices as expeditiously as possible". The Scientific and Technical Subcommittee of UNCOPUOS is invited to review the IADC-developed standards and finally to endorse them. However, the ultimate step in any form of a UN declaration is missing in the US proposal. Such a declaration is required in the opinion of the authors and will be a necessary development.

States would then implement their international obligations on a national level also in accordance with Art. VI Outer Space Treaty. Operators who are manoeuvring spacecraft should be under a national obligation (*e.g.* license condition) to frequently check the trajectory of their satellites to avoid collisions with other objects. Failure to use this information or to act thereon could be considered as fault on part of the respective launching State under Art. III Liability Convention.

In other words, if all other operators know trajectories of de-orbiting satellites and a collision occurs because an operator of an active object either did not check its future trajectory or did not act upon such information, there should be no fault on the part of the de-orbiting company, thus no fault of the respective launching State. In the mid-term future rules of the road and traffic systems may even become necessary.

As mentioned above, the necessary information for collision avoidance is commercially available as long as the orbital data for catalogued objects is provided by United States Space Command (USSPACECOM) and its component services (Air Force Space Command, Naval Space Command, Army Space Command). As discussed below, this is a reasonable assumption.

It is believed that exoneration from liability is the only acceptable incentive for operators to opt for the

possibly more expensive de-orbiting. Why else would a commercially operating company assume a higher risk for no immediately demonstrated benefits as long as there is no legal obligation?

4.2. Some challenges for the future

One challenge is that all of the above remains wishful thinking as long as USSPACECOM data is not widely obtainable. However, this paper assumes that the information will be publicly accessible eventually because in the US,

> [t]he Partnership council, which consists of the NASA administrator, the Commander in Chief of the US Space Command, and the director of NRO [National Reconnaissance Office] have established a study group to determine how space surveillance network products can be made available to commercial and foreign entities. [17]

The council has existed for a number of years and is still studying issues relating to security and liability.

When such information is provided even without assumption of liability it will become a tremendous step forward. The example of the Global Positioning System (GPS) has shown that it is widely used for general aviation, maritime and recreational users without such assurances. Applications based on GPS signals are manifold. As an analogy, free USSPACECOM data could be used by commercial entities to provide collision avoidance support thereby engaging those companies in a (limited) liability.

By using such information the probability of collisions would drop considerably and so would the potential for liability. Should the current space surveillance network be modernised and expanded, as recommended by the Space Commission [18], the accuracy of its data would even increase.

With regard to GPS, in a 1994 and 1996 exchange of letters, both the US and Russia (GLONASS System) have committed to provide their signal, subject to available funding, for 10 and 15 years respectively. In the absence of a firm commitment by the USSPACECOM, a similarly "soft" commitment could be a significant contribution. Liability nevertheless remains an issue should objects collide because operators relied, directly or indirectly, on faulty USSPACECOM data. In that case, neither operator would be responsible. A plaintiff may sue USSPACECOM and test their waiver of liability.

Another future challenge needs to be addressed: The collision avoidance analysis performed by the operator of a de-orbiting satellite is based on the latest orbital data which may be in some cases one day old or even older. Meanwhile an active satellite may have manoeuvred into the path of the de-orbiting satellite and a collision may occur although the analysis had indicated a zero risk. Neither party would be at fault and the question as to the apportionment of damages needs to be answered.

However, since these collisions are so unlikely (already without collision avoidance the average time interval between collisions of two catalogued objects is calculated to be 14 years) they constitute an insurable risk. One form of existing space insurance, the "in-orbit policy", provides cover on an agreed value basis for these risks. A future alternative to spread this residual risk is in the form of funds. They could equally provide compensation but it remains questionable whether there is a sufficient number of interested underwriters.

5. CONCLUSIONS

An accumulation of defunct satellites at disposal orbits above 2000 km should be prevented to preserve these regions useful for future generations. Therefore, LEO satellites should be de-orbited after end-of-mission. It is technically feasible to de-orbit a spacecraft with solar electric propulsion without collision risk if the orbital data of all known satellites is available and used. If a policy decision to provide such data by USSPACECOM was made, and if a legal obligation for all satellite operators was established to use the data for collision avoidance, space would be a safer place.

The authors are aware that with the ongoing commercialisation on the verge of a new *millennium* many practical and legal issues will arise and be solved over time. Nevertheless, this should not be an excuse for ignoring the information that is available now. States and private operators should act and agree on a code of conduct, some basic elements of which were outlined in this paper.

With the growing importance of constellations as well as international efforts towards active space debris prevention, a favourable legal framework for de-orbiting spacecraft is desirable. It may be a small step for governments to agree upon but a giant leap towards a sustainable solution to the space debris issue.

6. ACKNOWLEDGEMENTS

The authors thank Peter Wegener for providing space debris flux data based on the MASTER model.

7. REFERENCES

1. Alby, F., Danvel, M., Hourtolle, C., Frayssinhes, E., Debris Assessment for Skybridge Constellation, IAA-99-IAA.6.6.01, 50th Int. Astronautical Congress, Amsterdam, The Netherlands, 1999.
2. Guidelines and Assessment Procedures for Limiting Orbital Debris, NASA Safety Standard 1740.14.
3. European Space Debris Safety and Mitigation Standard, Issue 1, Rev. 0, draft of an ASI, BNSC, CNES, DLR and ESA working group, September 2000
4. Kato, A., The safe disposal of mission terminated LEO spacecraft, ISTS 2000-n-14, 22nd Int. Sym. On Space Technology and Science, Morioka, Japan, May 28 – June 4, 2000.
5. Wiedemann, C., et al., Results of the Upgrade MASTER Model, IAA-99-IAA.6.4.05, 50th Int. Astronautical Congress, Amsterdam, The Netherlands, 1999
6. Brownlie I. Principles of Public International Law (Oxford: Clarendon Press, 1998) at 301
7. Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 27 January 1967, 610 U.N.T.S. 205
8. Skybridge online (date accessed: 20 August 2000) www.skybridgesatellite.com/inside/cont_62.htm
9. Statute of the International Court of Justice, see Charter of the United Nations, 26 June 1945, Can. T.S. 1945 No.7 at 48.
10. Malanczuk, P. "Review of the Regulatory Regime Governing the Space Environment" (1996) ZLW 37-62 at 53
11. Convention on the International Liability for Damage caused by Space Objects, 29 March 1972, 961 U.N.T.S. 187
12. Convention on Registration of Objects Launched into Outer Space, 14 January 1975, 1023 U.N.T.S. 15
13. 47 U.S.C. et seq. (1996) and FCC Satellite Communication Rules, 47 C.F.R Part 25 (1997) implementing the Communications Act
14. Commercial Space Launch Act of 1984, as amended 49 U.S.C. §§ 70101 et seq. (1994) implemented by Commercial Space Transportation Rules 14 C.F.R. Ch. III (1998) *i.e.* no FAA payload review under 49 U.S.C. (§ 70117 [b]), 14 C.F.R. (§ 415.53 [a])
15. UNISPACE III Report, UN Doc. A/CONF 184/6, G.8.b.ii, para. 370
16. Technical Report on Space Debris, UN Doc. A/AC.105/720, p. 33 at 102
17. Minutes of meeting, Working Group 4, 18th IADC meeting, Colorado Springs, July 2000
18. Report of the Commission to Assess United States National Security Space Management and Organization, Pursuant to Public Law 106-65, 11 January 2001, Executive Summary at 31