EISENHOWER CENTER
FOR SPACE AND DEFENSE STUDIES

Space and Verification

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Volume II: Technical Assesssment

Space Treaty Verification Mechanisms

Objective: The objective of this study is to assess the ability of current technologies to verify adherence to space treaties and conventions, and conceive requirements for verification techniques and processes. The intent, where ever possible, is to have treaties that can be verified technically and for the relevant data to be internationally available.

Background: A companion political and legal study will develop candidate treaty and convention vehicles the critical elements of which can be credibly verified using current technologies.

That study will investigate the historical background, technological feasibility, and implications for national security policy of any international agreement requiring states to exercise restraint in their space activities, either through declaratory policy, informally agreed or binding “rules of the road,” or formal international agreements limiting weapons or activities in space. It will assess a range of potential verification options to support an expanded set of international norms to protect interests in space and achieve a commonly understood level of spaceflight safety. The appendix presents relevant alternative perceptions from the technical community.

Approach:

Verification assesses adherence to the provisions of an agreement. Therefore, we must conjecture what such provisions might be, such as the equivalent of "trespass," denying a legal owner the benefits of his property. Next, we must identify what is observable in order to perceive an untoward act. One such event might be unplanned or clearly anomalous changes in the orbit of a satellite. Then, what technical capabilities are able to gather those observations, how well, and how often?

This is accomplished parametrically, since as technologists we cannot presume to judge what might be sufficient for diverse national interests.

We also focus on civil and commercial means rather than National Technical Means. One reason is that verification itself should be transparent to stakeholders. The observations and inferences of the verification system should not be arguable. They will all be uncertain to some degree, but the uncertainty can and should be quantified. These capabilities are ubiquitous, operated and controlled by diverse authorities and responsible parties. No single authority or stakeholder could prevent the collective perception. Since these capabilities demonstrate a stake in the collective success, there should be sincere collaboration. Since owning or operating these systems is a much less intense investment than actually developing, launching, or operating satellites, nations with limited resources could also contribute. We call these "Persistent Technical Means."

Space treaties must consider the three major mission elements: launch, on-orbit operations, and disposal or re-entry. We examine each independently.

Launch

Launch activities can intrude on the common benefits of space, and the freedom to exploit those benefits by launching satellites can be compromised by untoward actions on the Earth or in space. Table 1 lists broad treaty elements that might apply, acts that might violate them, the observables of those acts, the mechanisms for perceiving those observables, and the mitigations that those observations might enable.

Treaty Provision	Possible Violation	Observables	Perception Mechanisms	Mitigation Measures
Freedom of Access	Interference with launch communication and control	EMI/RFI	Local Terrestrial Sensors	Emission control
			Satellite receivers	Geolocation and identification
			Aircraft receivers	
	Positioning satellites improperly during launch windows	Radar, EO	Radar and Optical Sensors	NOTAMS and closures
Registration Convention	Unannounced or anomalously timed launch	Preparations	I&W	Sanctions
		Launch emissions	Launch detection satellites	Interference to inhibit launch
		Presence of an unidentified satellite	Space surveillance	Persistent tracking
Debris Mitigation	Unnecessary release of launch related objects	Multiple, unanticipated objects	Radar and EO/Space and Terrestrial	Best practices
	Conjunction with resident spacecraft	Trajectory	Radar and EO/Space and Terrestrial	SSA
	Anomalous staging or orbit insertion	Objects in unintended orbits	Radar and EO/Space and Terrestrial	SSA
	Spent boosters jeopardizing resident spacecraft	Objects persisting in close conjunction	Radar and EO/Space and Terrestrial	SSA, Evasive Capability
Freedom of Action in Space	Launch into occupied regions	Selection of launch windows and trajectories	Launch detection satellites	Launch Collision Avoidance
			I&W	

Table I: Elements of Treaty Verification Related to Launch Activities

We will not examine each entry exhaustively, since our objective is to introduce this subject and demonstrate the approach to conceiving verification measures. We will trace the process through one element of treaty provisions in each phase of spade missions.

Freedom of access to space can be compromised by impairing a party's ability to launch spacecraft and establish them in desired orbits. Announcing launches, assuring safety on the ground and in the air, and being forthcoming about intended uses and orbits of a spacecraft should not enable others to prevent or inhibit the launch. However, the ill-intentioned could interfere with command and control communications and guidance systems electromagnetically. They could position spacecraft so that the planned launch trajectory would conjunct with the resident object or make favourable launch windows infeasible. Even informal rules of the road should grant the right of way to a resident spacecraft.

One could perceive electromagnetic violations with sensors distributed within a broad area around the launch location and along the trajectory. Such sensors could be on the surface of the Earth, in aircraft, or exploit the inherent capabilities of geostationary communication satellites, which are very sensitive to weak emissions.

Attempts to intentionally block a launch window or corridor with satellites could be perceived through space surveillance and tracking. One can perceive even subtle maneuvers that would place a resident spacecraft in an otherwise unusual location at an inopportune time. This might not require an extensive and exquisite space situational awareness scheme, since the inhibiting satellite would have to pass within the fields of regard of sensor systems that would prudently observe the flight and insertion independent of on-board systems.

Since this kind of violation would have to be executed before the vulnerable spacecraft could be launched, there would be time for deliberate mitigation through demarche or action in kind by the potentially offended party.

This is the logical thread through one warp of the fabric of treaty provisions, potential abrogation, and decisive mitigation. Such verification is feasible now and in the future because of the proliferation of sensitive electromagnetic systems – even cell phones – whose functions would be affected by such ill-intentioned emissions. Although this is perhaps a disingenuous example, it illustrates how a ubiquitous, distributed, common civil technology could contribute to treaty verification. There are also numerous satellite communication antennas, sometimes densely distributed in major cities that might be affected. The warning mechanism would include angry viewers whose television reception was affected. Existing geolocation systems would locate and isolate the intrusion.

On Orbit

Treaty Provision	Possible Violation	Observables	Perception Mechanisms	Mitigation Measures
Freedom of Movement	**Interference with telemetry, commanding, or communications**	**EMI/RFI**	**Distributed receivers**	**Emission control**
	Inhibiting authorizing, peaceful, and productive maneuver or repositioning	**Unwise or dangerous maneuver**	**Space surveillance**	**Collision Avoidance**
Freedom of Action	**Interfering with executing a peaceful and productive mission**	**Radar, EO**	**Radar and Optical Sensors**	**NOTAMS and closures**
		Presence of an unidentified satellite	**Space surveillance**	**Persistent tracking**
Debris Mitigation	**Release of non-mission related objects in protected regions**	**Multiple, unanticipated objects**	**Radar and EO/Space and Terrestrial**	**Best practices**
	Conjunction with resident spacecraft	**Trajectory**	**Radar and EO/Space and Terrestrial**	**SSA**
	Anomalous staging or orbit insertion	**Objects in unintended orbits**	**Radar and EO/Space and Terrestrial**	**SSA**
	Spent boosters jeopardizing resident spacecraft	**Objects persisting in close conjunction**	**Radar and EO/Space and Terrestrial**	**SSA, Evasive Capability**

Table II: Elements of treaty verification related to on-orbit operations

Table II is a candidate verification space for on-orbit operations. Standards and collaborative operations will make the path through this verification matrix more feasible. Consider debris mitigation and freedom of action, which are not totally independent. Collisions will create debris. Close conjunction between satellites might result in collision. Such conjunctions might be inadvertent, or they could be intentional. Standards can narrow the action space for both kinds of events. For example, monitoring and reporting the amount of propellant and/or energy stored in a satellite and reporting such to trusted authorities allows prediction of physically possible maneuvers. However imprecise such measurements might be, they are a guide to what is possible when two satellites are in close proximity and estimating the consequences of an inadvertent or intentional collision. Those who are forthcoming and collaborative will know when a safe end-of-life disposal can be initiated. Those who might be jeopardized would better know the maneuver capability of their fellow travellers. Rules of the road should dictate that the more maneuverable and energetic spacecraft gives its less capable companions wider berth, as is the case when upbound vessels on inland waterways give way to downbound vessels. This can only be effective if relevant measurements are made and the information is shared. There are international standards for such measurements. Now the spectrum of violations is narrowed to those who do not provide such information, who can be monitored by other means to perceive dangerous acts.

Would satellite operators share such information? Perhaps there are competitive or proprietary pressures. Perhaps there are national security interests. Still there are few reasons why spacecraft with scientific missions would not do so, and this would still narrow the need for uncooperative monitoring and action.

But dangerous situations will still occur, making warning and mitigation important for treaty enforcement. After voluntary use of diverse operational standards, the volume of spacecraft that need be monitored aggressively will be reduced. Ubiquitous space surveillance will not be necessary. Collaborative space surveillance can fill part of the remaining mission spectrum.

Satellites are not everywhere in near-Earth space. Objects associated with launch are clustered in the latitudes of the launch sites. Every satellite also has a mission which dictates its orbit. For example, there is a unique relationship between orbit altitude and inclination for sun-synchronous satellites. These spacecraft will generally be in retrograde, high inclination orbits. Sensors do not have to see everything, everywhere to detect them. Sun-synchronous satellites generally pass over a given area on the Earth at predictable times and can therefore be observed and tracked easily. If they do not visit on schedule, something unusual must have happened. We illustrate in the following analysis the degrees of observability possible with different sets of collaborative sensors in locations that today host relevant sensors, generally civil, commercial, and scientific systems.

There are two excellent examples of the potential of civil and commercial capabilities contributions to verifying treaties and preserving both freedom of action and the space environment: conjunction assessment and radio frequency mitigation.

Assessing Conjunctions and Confirming Maneuvers

Earth orbiting satellites exist in a relatively dense operational environment. There are hundreds of close approaches each day. How close an approach matters is subjective. Operators of geostationary satellites are concerned when satellites are within 50 km of each other. Low Earth orbit satellite operators often have a threshold of five km. It is important that the threshold close approach be consistent with the precision of the orbit information. Very often, LEO orbits are imprecise by more than five km, so a five km keepout range is not sufficient.

A close approach is rarely a collision. It is difficult to discriminate imminent threat from inconsequential flyby. Satellite orbits are not Keplerian ellipses. The deviation of a satellite's instantaneous orbit from that ideal is often larger than the close approach distance of concern. Even the United States Air Force Space Surveillance Network (SSN) cannot gather data sufficient for complete collision avoidance. Civil and commercial persistent technical means (PTM) can overcome these deficiencies or even independently contribute to verifying treaties and rules of the road.

Figure 1 depicts an abstraction of the USAF SSN and a set of world-wide civil, commercial, or academic observation capabilities. The graphic includes the ground track of a hypothetical sun-synchronous satellite that executes a maneuver over the Indian Ocean.

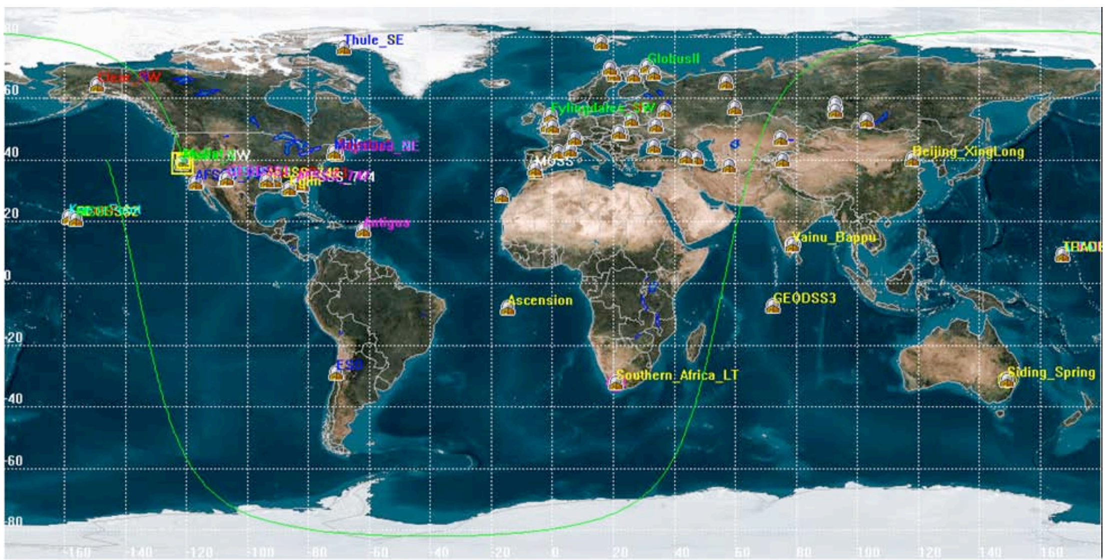

Figure 1: Abstraction of the United States Space Surveillance Network and Civil, Commercial, and Academic Observation Sites

Figure 2 focuses on the Indian Ocean. This is a stressing but very likely situation.

SSN sensors are sparse in the Southern Hemisphere for several very logical reasons. There are few suitable land masses in the Southern Hemisphere. The low-Earth orbit elements of the SSN are predominantly contributing sensors whose primary mission is missile warning. When the system was developed, there was no ballistic missile threat from the Southern Hemisphere. There are observatories at the tip of Africa, in India, in Australia, and no doubt elsewhere that have many more observation opportunities than the SSN.

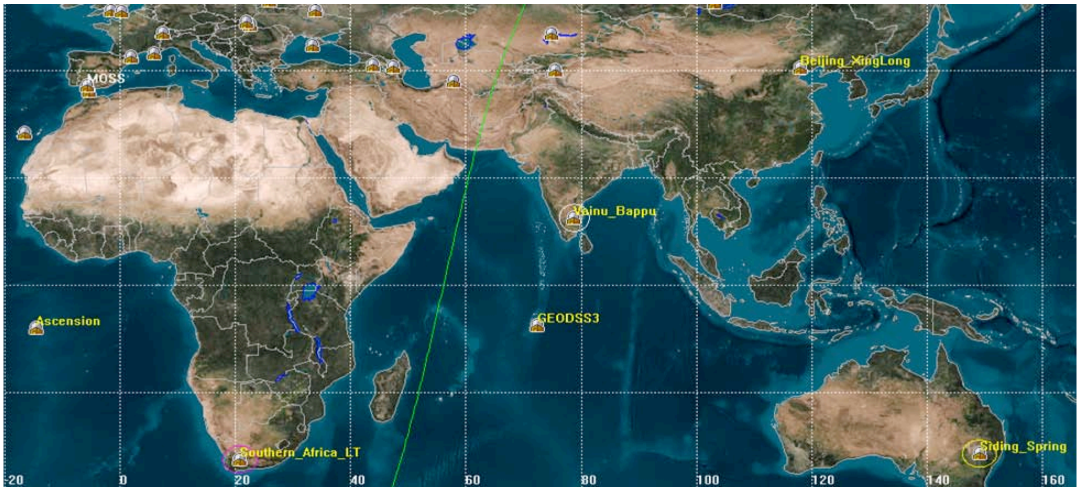

Figure 2: Satellite maneuver in the Southern Hemisphere

The situation is also technically complex since historical orbit information for this satellite would not be applicable once the maneuver was initiated. Many observations would be required, and it would take many days to accrue sufficient observations for a confident orbit. Furthermore, even if the maneuver was pre-planned and announced in advance, operational and physical mechanisms for tracking through the maneuver do not exist at present.

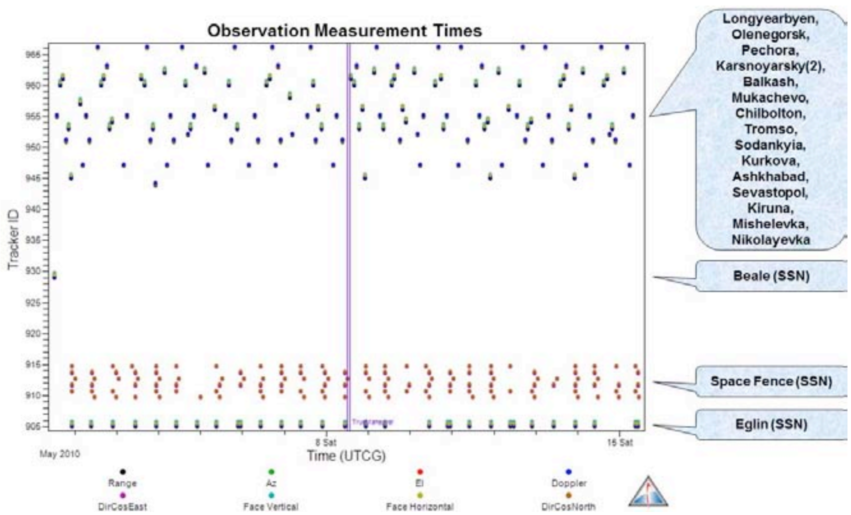

Figure 3: SSN and PTM observation opportunities over two weeks

Figure 3 compiles observation opportunities for the SSN and PTM.

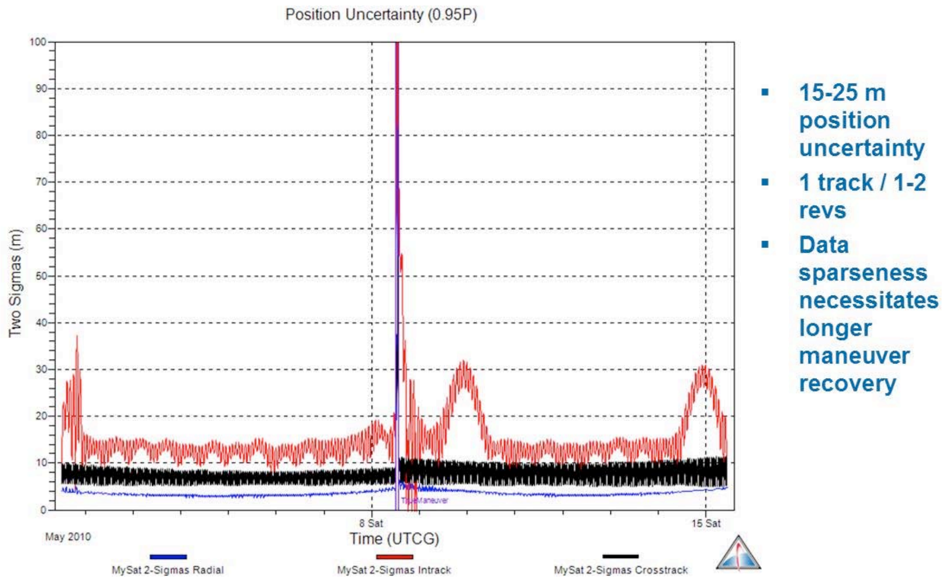

Figure 4: Satellite position uncertainty derived from SSN observations.

Figure 4 employs state of the art orbit determination techniques, showing the residual uncertainty in the orbit derived from observations available on each date. The large excursion is due to the maneuver. It takes several days to recover the new orbit.

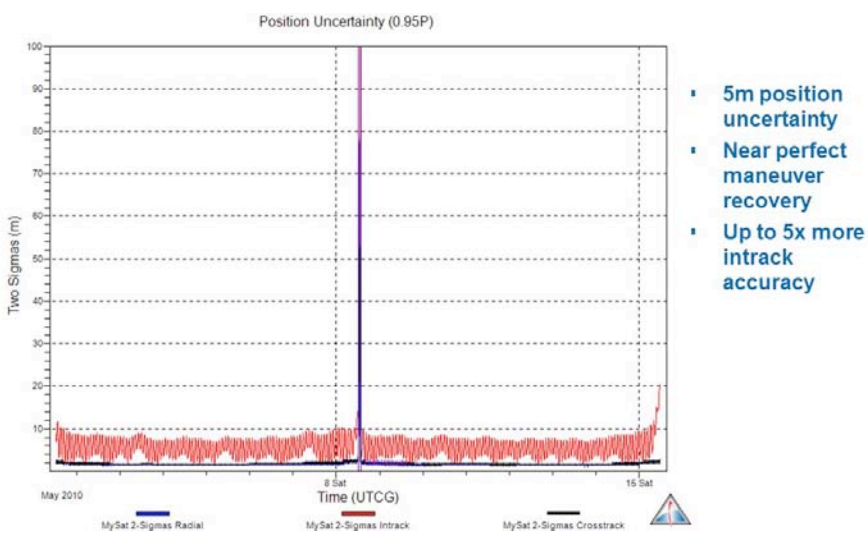

Figure 5: Satellite position uncertainty derived from persistent technical means.

Figure 5 describes the precision of orbits derived from the civil, commercial, and academic persistent technical means. Our analysis includes the fact that the observations are of diverse measure--some are based upon radar while some angles are only optically based. We also ascribe optical system characteristics comparable to the Global Electro-Optical Deep-Space Surveillance System (GEODSS). The new orbit is recovered very quickly after the maneuver. There is a three- to five-fold improvement in orbit precision. Combining both SSN and PTM observations improves precision by another 20%.

It is important to note that state of the art adaptive statistical filters were employed. Less robust techniques, such as least squares and its differential corrections, would be much less precise. We also assume that sensors are well calibrated and measurement uncertainties are well characterized. Academic and scientific sensor systems are more likely well calibrated than operational Air Force sensors.

The precision with which orbits of satellites hundreds or thousands of kilometres distant can be determined is astounding. Astrodynamics has advanced tremendously as computational capabilities expand. However, tens of meters matter greatly for conjunction assessment. Consider that this degree of imprecision is on the order of or greater than the largest dimension of most satellites. That can be the difference between direct contact and close passage.

To further illustrate the benefits of PTM, consider a geostationary satellite that executes a maneuver over the Indian Ocean. Figure 6 shows the SSN and PTM observation opportunities.

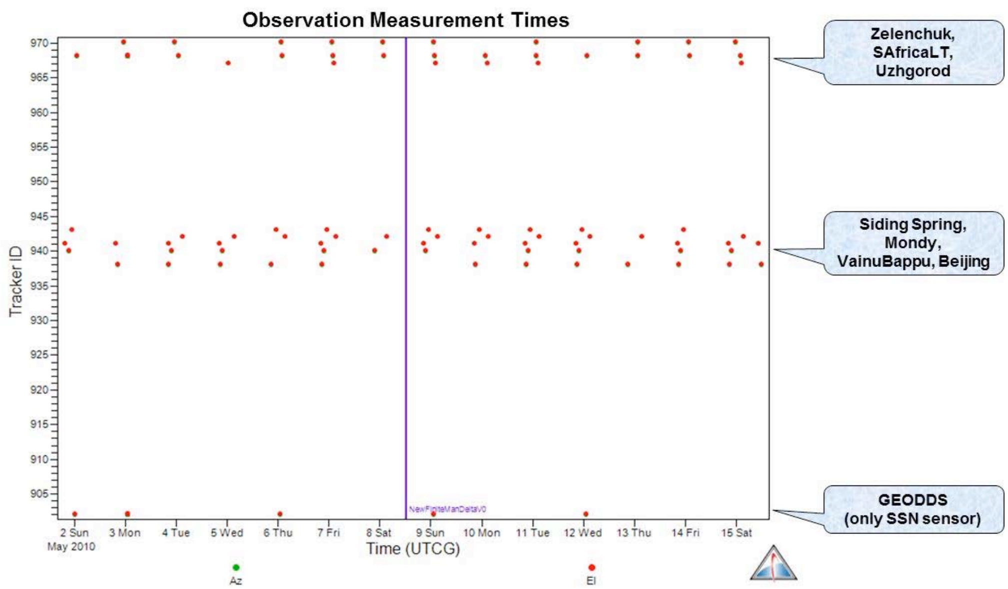

Figure 6: Observations of a geostationary satellite over the Indian Ocean.

Space surveillance is essential even for geostationary satellites. Geostationary satellites are not really fixed in space relative to a spot on the equator. Because the Earth is not a perfect sphere (its mass is not distributed uniformly within or on the Earth) and due to perturbations such as solar radiation pressure, station keeping is necessary.

SSN radars are generally not able to track geostationary satellites either physically or procedurally. GEODSS is dedicated to deep space surveillance. Note in Figure 6 that many more observation opportunities are available using PTM. The International Scientific Observation Network (ISON) of the Keldysh Institute for Applied Mathematics (KIAM) takes advantage of many of these opportunities.

Figure 7 describes orbit precision associated with using only SSN observations.

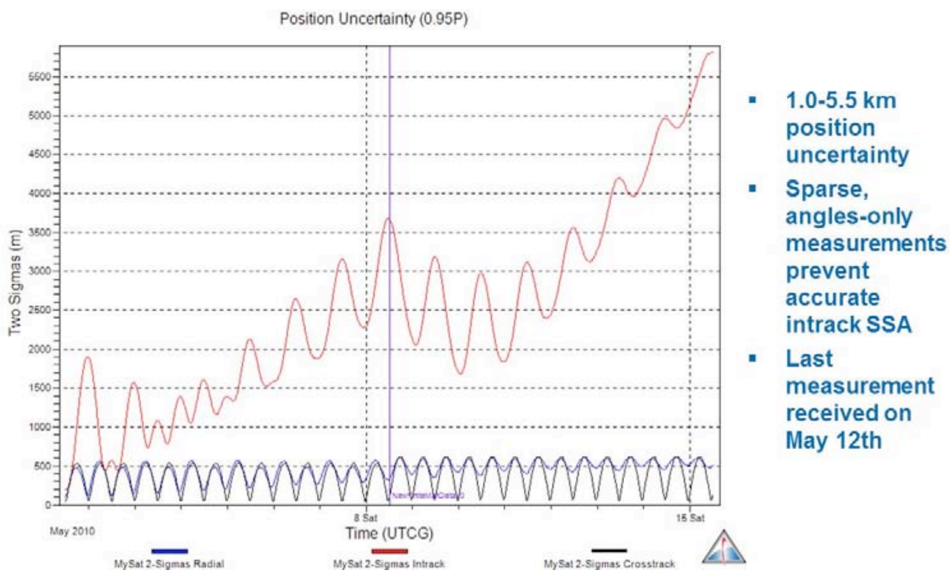

Figure 7: Precision of orbit determination for a maneuvering geostationary satellite using only SSN observations.

Astrodynamicists well know that position along track is always worse than either radial or cross track uncertainties. Over the two week period, orbital uncertainty grows by many kilometres.

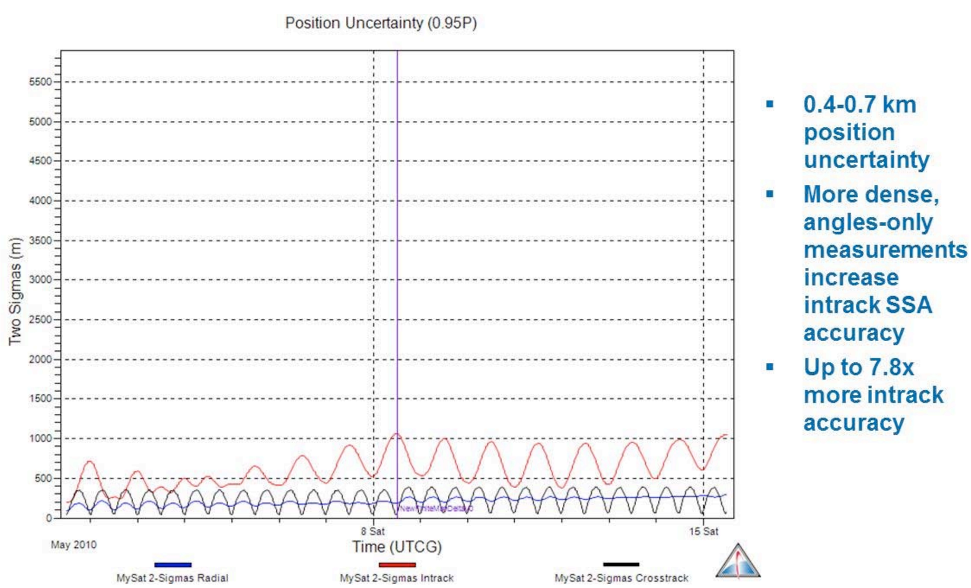

Figure 8: Precision of orbit determination for a maneuvering geostationary satellite using persistent technical means.

The threshold separation for concern among geostationary satellite operators is about five kilometres. The SSN alone is often not precise to within five kilometres. From a probabilistic perspective, the chance that a conjunction will result in direct contact is small when the uncertainties are large. Even without the mathematics, if we do not know where a satellite is within a very large volume, the probability that it might be in any satellite sized volume within that space is small. The likely outcome is that threatening events might not be perceived as such.

This demonstrates that PTM can add considerable value to synoptic space surveillance and even more to conjunction assessment. But it is still insufficient.

The process will fail if observers cannot exchange observations that can be combined responsively to achieve maneuver confirmation and conjunction assessment. Mechanisms and technologies to achieve this exist and are in use.

The first mechanism is the ability to exchange data and orbit information clearly and completely. The Consultative Committee for Space Data Standards (CCSDS) and the Space Operations Subcommittee of the International Organization for Standardization (ISO) have developed and promulgated standards for those exchanges. Any common communication system such as the internet is sufficient for this exchange.

The Space Data Center (SDC) of the Space Data Association (SDA) demonstrates that technology supports exploiting civil, commercial, and academic PTM. The SDA is a consortium of geostationary communication satellite operators. The SDC accepts orbit data or observations from PTM, determines orbits with state of the art precision, transmits orbit data, and conducts conjunction assessment with full involvement of the potentially threatened parties. This is well described in the literature and on the internet.

The International Scientific Observation Network (ISON) proves that well characterized, independent observations from civil and commercial telescopes can be combined rigorously and that high quality orbits can be derived from such observations. Figure 11 shows the current ISON consortium.

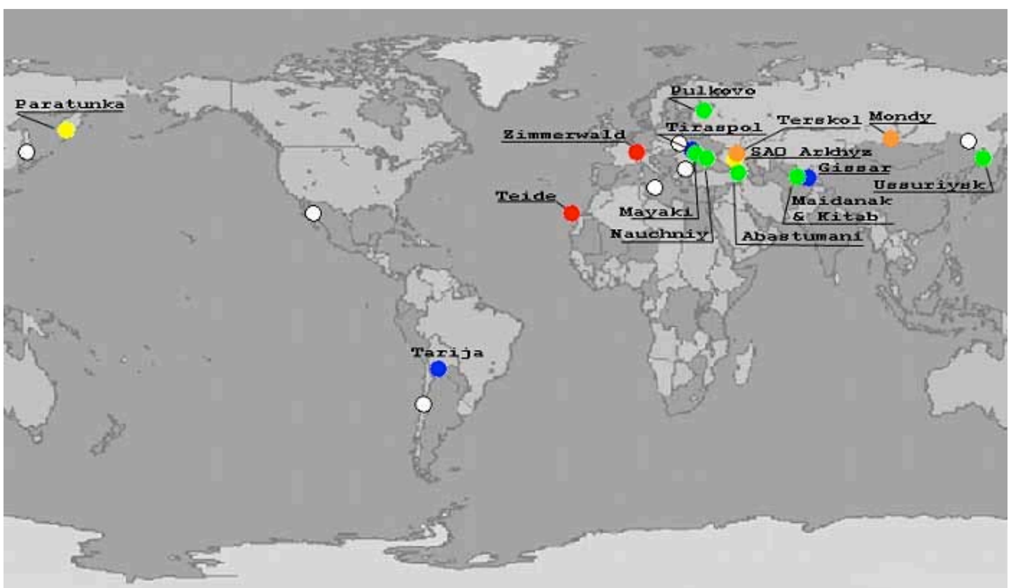

Figure 9: International Scientific Observation Network (ISON) of the Russian Academy of Science Keldysh Institute of Applied Mathematics (KIAM)

National space agencies and authorities and the civil, commercial, and academic sectors are collaborating through ISO and CCSDS to develop conjunction assessment and warning processes that enable world-wide military and civilian capability.

This study can only demonstrate that there are almost no physical or technical impediments to verifying treaties and monitoring rules of the road. There are two avenues to practical employment: international diplomatic means and civil or commercial collaboration of necessity, with the latter progressing much more rapidly.

Mitigating Radio Frequency Interference (RFI)

The electromagnetic spectrum is a high demand resource. Diffraction spreads beams even in free space. The great distances from Earth surface to satellites lead to extremely large beam extents still with sufficient intensity to be perceived by current and future communication systems. Small antennas have greater diffractive spread. Antennas several meters are still considered small. So-called Very Small Aperture Terminals (VSAT) range from 75 cm to 1.2 meters in diameter. VSAT's have become ubiquitous. Installation and maintenance can be reasonably imprecise while still delivering or capturing sufficient energy from intended partners. The imprecision can also illuminate other satellites, who become victims of the interference that is not always unintentional. Therefore, we should treat electromagnetic interference in the same manner as physical interference with satellites.

As with physical interference among satellites, electromagnetic interference is best mitigated through communication and collaboration among stakeholders. There is no normative, institutional scheme for both governmental and non-governmental operators. The Satellite Users' Interference Reduction Group (SUIRG), a consortium under the same principles as the SDA, fosters developing such a scheme. This requires the discipline to exchange sufficient information completely and in a normative format. The ability to accomplish this has been demonstrated. The physical ability to locate and characterize interference sources will require international cooperation.

Figure 10 depicts geolocation physical principles.

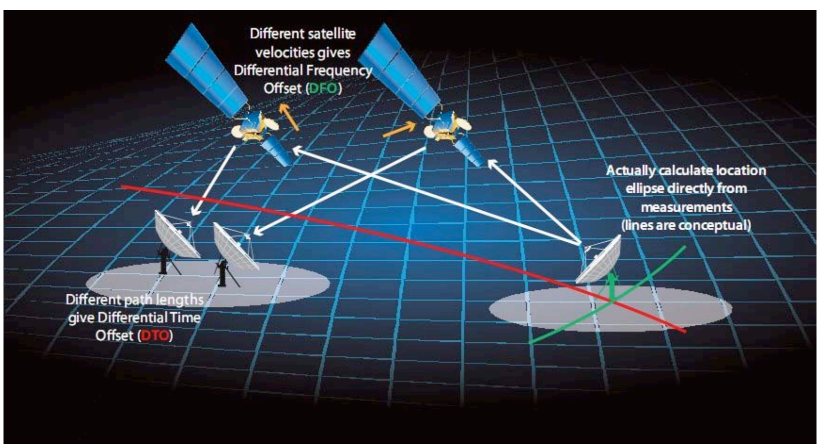

Figure 10: Physical principles of interference location.

Time and frequency difference of arrival are the fundamental elements of emitter location. At least two satellites must perceive the same interference source. Two geostationary satellites perforce have different locations and velocities. The position difference leads to different flight times for the same modulation characteristic of the interference emission. Just as an ellipse is the locus of points the sum of whose distances from each of two foci is constant, the time difference of arrival measurements put the emitter on a line on the surface of the Earth. The velocity difference between the two satellites leads to different Doppler shifts at each location. The apparent frequency difference places the emitter on another line locally normal to the time difference of arrival line. The intersection of these lines is the emitter location—a process called cross-correlation.

There are, however, uncertainties in the positions and velocities of the satellite, imprecision in ground antenna pointing, and many other sources of measurement noise. The locations of the reporting satellites relative to ground stations and the geometry of the triad affect the geolocation process,

These biases and uncertainties can be diminished considerably if there are meticulously registered and calibrated ground based “reference emitters.” These serve two needs. First, they can be used to calibrate transmission and reception characteristics of the satellite. Second, since the location of the reference emitter is known exquisitely, two satellite geolocation of the known emitter helps remove biases and uncertainties. The benefits diminish with distance from the reference emitter. Reference emitters are widely available but not widely employed. It is estimated that as few as 50 reference emitters distributed around the globe might enable precise world-wide RFI geolocation. Figure 11 illustrates an adequate distribution. Communication satellites are shown in yellow.

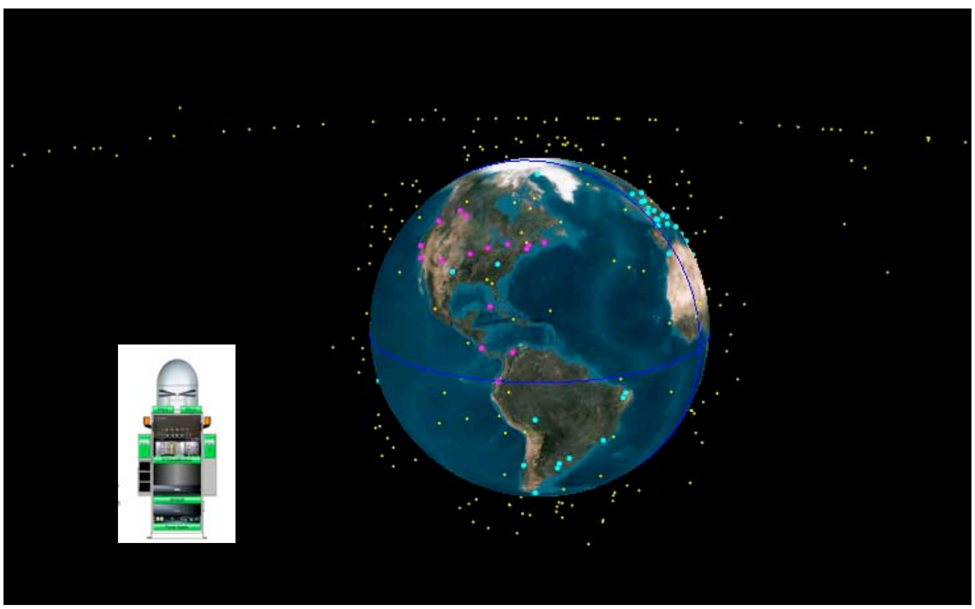

Figure 11: Candidate reference emitter distribution

Organizing and operating the distributed, collaborative capability is easily achievable as demonstrated by operations such as the satellite laser ranging network.

Situational Awareness with Hosted Payloads

Payloads augmented to satellites for purposes other than the primary mission can accomplish much at modest cost. Hosted payload concepts are being implemented widely. The Commercially Hosted Infrared Payload (CHIRP) Flight Demonstration Program, which will launch a wide field-of-view, passive infrared sensor on a commercial GEO (AMC 1R) in 2010.

Civil or United Nations payloads on commercial satellites could add significantly to perceiving violations of rules of the road. Figure 12 shows the ability of two satellites at geostationary altitude (in this case two TDRS satellites) to observe and determine orbits of another high altitude satellite and a low altitude satellite (TDRS 1 and TDRS 5 with Sinosat 1 and Orbcom FM-11).

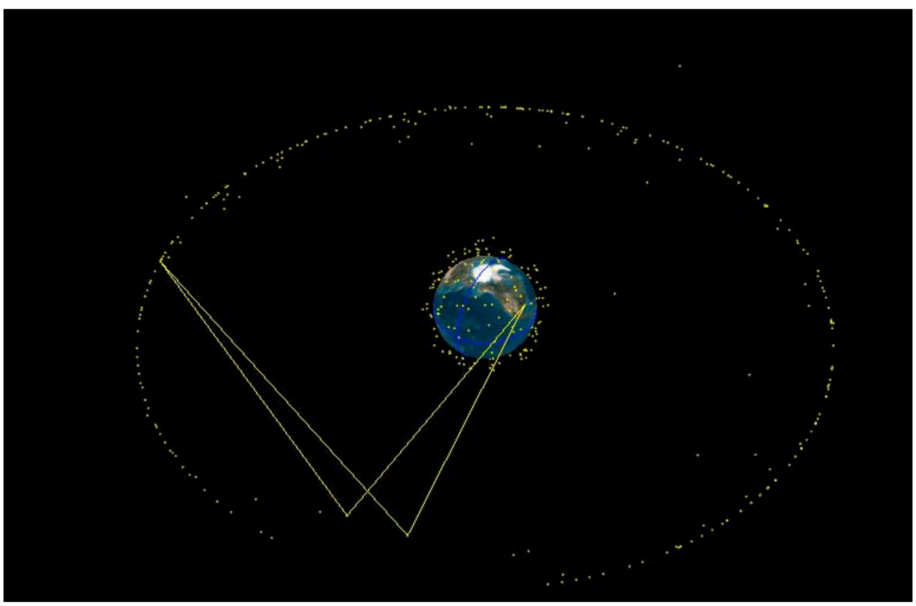

Figure 12: Hosted payloads on TDRS 1 and TDRS 5 ability to access SinoSat 1 and Orbcomm FM-11

Telescopes with 20 cm apertures or smaller and modern focal plane array and computational capability can comfortably observe and discriminate among satellites at great distances. Hosts and their orbits must be chosen judiciously since just being able to perceive a distant object is not sufficient. If the hosts and the satellite of interest are coplanar (e.g., all geostationary) techniques for determining the position of the object fail. In technical terms, some state variables are not observable. Good multilateration geometries must be maintained. Lines of sight should not be collinear or diametrically opposed, for example. Figure 12 illustrates good multilateration geometries for both geostationary and lower orbits.

The electromagnetic domain of the observations is different than for RFI mitigation, but the process is similar. If the hosts are communication satellites, observations could be inserted within or superimposed on transmissions. Otherwise, the observations could be inserted into TT&C data streams. Delay tolerant protocol standards and CCSDS space link extensions facilitate distributing these observations for collaborative fusion and assessment.

Disposal

Treaty Provision	Possible Violation	Observables	Perception Mechanisms	Mitigation Measures
Passivation	Failure to deplete energy	Lack of observable propellant expulsion or momentum dump	Space surveillance	Sanction
		Continued transmission	RFI monitoring	Avoidance
		Lack of passivation plan		Disallowed operation
Safe Re-orbit	Collision Threat During Orbit Transfer	Unsafe maneuver or trajectory	Space surveillance	Conjunction Assessment
	Inappropriate final orbit	Orbit lifetime estimate exceeds limits	Orbit analysis	Disallowed operation
		Lack of disposal Plan		Disallowed launch or operation
Treaty Provision	**Possible Violation**	**Observables**	**Perception Mechanisms**	**Mitigation Measures**
De-orbit	Collision Threat During De-orbit	Estimated conjunctions	Space surveillance	Conjunction Assessment
	Unsafe Reentry Trajectory	Inappropriate impact area	Reentry estimates	Sanction
		Lack of disposal plan		Launch Denied

Table III: Disposal phase verification measures

Satellites must not be a hazard to other satellites or to people or property on the Earth. Disposing of satellites safely is a difficult task. Passivation is the least acceptable mitigation measure. This reduces the likelihood of a debris event. Removing the satellite to an orbit unlikely to precipitate conjunctions with active satellites is the next level of disposal. Eventually, neither of these will be acceptable because even readily accessible disposal orbits will be crowded. This means that less accessible and more energy intensive disposal trajectories might be necessary. When the cost of disposal rises to become a significant portion of the overall cost of the productive mission, it might no longer be desirable to exploit space for those capabilities.

Ironically, the energy required for safe disposal diminishes the higher the orbit. The dilemma for high orbits is that the payload fraction of the launch mass is very small and even a small amount of additional stored energy might be a large payload decrement. Reentry is the only disposal alternative that assures that space will be preserved indefinitely for productive uses. Orbits with apogees up to about 800 km altitude will decay naturally, although generally under the whims of nature rather than positive control. Below about 500 km, the decay should occur within the 25 year Interagency Debris Coordinating Committee (IADC) guideline.

Allocating orbits under the aegis of a central authority would compromise freedom of access. Safe disposal by mutual agreement, even at considerable cost, seems a good alternative.

Many of the disposal phase measures are best enforced before launch. Standards now exist for spacecraft passivation, reentry management, and disposal from geostationary orbit. Launches should not be permitted without addressing such provisions. This does not assure that these plans will be executed properly or at all. If they are not, mitigation may be limited to sanctions on future operations and giving errant satellites wide berth until uncooperative disposal mechanisms are feasible.

Recommendations

We recommend more complete exploration and analysis of the launch, on orbit, and disposal matrices created in this paper. Provisions of treaties and agreements currently being considered should be the highest priority. Technical means that exist but might require wider exploitation or extension should lead applications. Persistent Technical Means for ground-based space situational awareness and ubiquitous reference emitters for mitigating RFI are most mature and suitable. These require coordination and integration more than investment. They could be pursued unilaterally to build confidence. Hosted payloads would be next. Such missions would be at the expense of revenue producing main mission capabilities. Mechanisms for reimbursing owner/operators for this inconvenience would be required. Collaboration among payloads, data dissemination, data processing, and coordinated responses are critical and should be pursued in parallel with payload development and deployment.

Conclusion

We have demonstrated an approach to applying current technology to the verification of provisions of potential space treaties, agreements, conventions and other vehicles that would preserve the space environment and freedom of access for productive purposes. This study is representative, not exhaustive. We have expanded two threads, maneuver detection and radio frequency interference mitigation with examples of current technology and procedures to serve desired ends. We have emphasized civil, commercial, and academic capabilities. Exploiting these Persistent Technical Means requires international cooperation and collaboration. Required collaboration can be initiated unilaterally, serving also as confidence-building measures. An example exists in the Space Data Association, which is international, industrial, and ultimately trustworthy. We hope that the principles, analytical approach, and specific suggestions of this study will be scrutinized, validated, and applied widely.

APPENDIX

This appendix presents perspectives on verification from the technical community.

At least five factors have arisen to threaten the various formal and informal agreements that have so far reinforced an element of stability in the space domain:

1. Increasing dependence on satellite systems.

2. Reemergence of Earth and space-based weapons programs directed against space assets, either through kinetic kill or other forms of physical or virtual disruption of space assets and their products.

3. The growing number of actors in space, contributing to congestion and proliferation in debris, especially in Low Earth Orbit (LEO) and Geosynchronous Equatorial Orbit (GEO).

4. The expected availability of lower cost launches that will greatly increase the number of spacecraft launched and strain already overtaxed mechanisms for monitoring orbital position, spectrum allocation, and conjunction avoidance.

5. The use of very small systems in space that go below the current threshold of space surveillance systems.

These five factors converge in the increasing importance of improved Space Situational Awareness (SSA) for the international community. Improved SSA should also enhance technical monitoring capabilities for verifying compliance with agreements. Some steps have already been taken to improve information sharing among friendly space faring nations and commercial satellite operators. However, there is as yet no consensus on how these data might be used to support the kind of stability and predictability that has characterized the space environment for several decades.

Verification

No agreement can ever be verified unequivocally. Some treaties cannot be verified at all.

The first statement is a mathematical fact. If there are any valid perceptions, there must also be invalid perceptions and missed valid perceptions. These three categories are not independent, but they do depend on the quality of the perceptions and the variations among valid and invalid perceptions. One can improve the probability of valid detection with a greater breadth of discriminants and more precise observations. No one can deny that verification is always uncertain.

We must determine what is sufficient for the purpose. As stated, sometimes no verification is sufficient. The best examples are two important arms control treaties; i.e. the 1963 Partial Test Ban Treaty (Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water) to which there currently are over 120 states parties, and the 1967 Outer Space Treaty which has been ratified by 100 States and signed by 26 additional states. One of the main reasons for their success is the perceived self-interest of states party to them. A treaty may have only limited ability for verification, but, in due course a more complete system of verification of one or many of the clauses may either become possible or improve.

Past practice shows that multilateral treaties generally do not contain any effective or detailed verification mechanisms while bilateral arms control agreements (like the ABM Treaty) often have some sort of verification provisions. This may be because bilateral treaties are generally concluded between parties of equal capability. Multilateral treaties include parties with diverse capabilities. Many might not be able to perceive violations which nonetheless could harm them.

Internationally, the manner and nature of an agreement affect the scope and verifiability of provisions: whether agreements, concords, resolutions, or treaties. The best time to agree to a treaty can be before the full implications of the area of concern are understood. Some resolutions cover new ground, such as the Space Debris Guidelines, while other earlier resolutions were aimed at clarifying aspects of the original treaties, e.g. "launching state" and "registration." In this area there has been a strong reluctance to re-negotiate the original treaties so clarifications and additions have been produced as Principles and Resolutions. In some situations, international standards were always seen as the long term solution to implementable and verifiable texts.

The Space Protocol of the International Institute for the Unification of Private Law (UNIDROIT) is an important contribution, but it was drafted without sufficient consideration of the nature of financial interests in space systems or the special characteristics of systems in space. One contribution of the present study is to illuminate those characteristics and foster a living database of capabilities to support such work.

Space systems contribute greatly to monitoring and verifying many regional and multilateral treaties. Appendix A reviews these treaties and the contributions of space systems. The Outer Space Treaty is most relevant, but it deals with hostile acts and weaponization. This study encompasses many potentially harmful acts that are not necessarily hostile, which may be unique. The current agenda item and Working Group on "the long-term sustainability of outer space activities" within the UN COPUOUS Science and Technical Subcommittee is an excellent review of such acts. It provides significant substance for our analysis emphasizing: "proliferation of space debris; safety of space operations particularly the problems involved in operations in the geostationary orbit, in mid-Earth orbits (around 20,000 km altitude) and in low-Earth orbits (up to 1,000 to 1,500 km altitude); management of the electromagnetic frequency spectrum; and natural causes of disturbances affecting space systems: space weather, solar flares, micrometeorites, etc."

The general thread for negotiating treaties is to obtain the best level of agreement as soon as possible and refine and clarify specific issues as time and necessity require. Exquisite and unarguable verification is not necessary or even achievable.