Simulating Space Surveillance Networks

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SIMULATING SPACE SURVEILLANCE NETWORKS

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Generating observations for satellites is a difficult process because actual observations are usually withheld and sensor locations and performance are often unknown. While many tools exist, a comprehensive listing of sensor locations and characteristics is difficult to find. When sensor locations are known, the specific tracking frequency is very difficult to model as the observations generally result from ad hoc tasking directives, implemented by each sensor with individual constraints. Sensor operational open and close dates are not well known either for historical purposes. This paper summarizes open source data to establish a baseline of sensor locations, primarily using Google Earth. We also discuss techniques to accurately simulate the observations and arrive at realistic scheduling densities.

I. INTRODUCTION

Satellite mission design is often accompanied with detailed simulations of the sensor networks to determine the expected accuracy of the orbit determination. Obtaining observations for a particular satellite and time interval is a difficult process. Actual observations from one or more sensor networks that could support useful orbit determination error analysis but may be withheld from analysis efforts. Simulating the raw observation data (range, azimuth, and elevation) from scratch is difficult because the sensor locations and performance characteristics may not be known. Sensor locations are often inferred from various sources, but may not have sufficient fidelity for mission design applications.

Generating simulated observational data that accurately reflects the capabilities, policies, and tendencies of current operational use is key. The observational data should mimic what would be expected from the actual sensor networks, and sensor locations should be close enough to provide realism to subsequent analyses. This paper summarizes open source data to establish a baseline of sensor locations, primarily using Google Earth for verification of the sensor coordinates. These data provide a common baseline from which to simulate satellite observations, as well as a vehicle to input precise locations for actual operations. We also include information concerning the operational open and close dates where possible, and various notes on the sensors. We also describe a process to simulate realistic observations, accounting for tasking schedules, and real-world constraints on each sensor system. We note that Secure World Foundation (http://swfound.org) is planning to host information of this type on the web in the fall of 2011.

II. OBJECTIVE

This paper develops a baseline set of sensors to reflect the generic characteristics of several large space surveillance tracking systems. Using these pre-defined sensors, we simulate observations for analysis with the appropriate scheduling constraints. We group the sensor systems in broad categories. Major existing governmental networks include the Air Force Space Command Space Surveillance System (AFSPC SSN), Russian Space Surveillance System (RSSS), and the European Space Surveillance System (ESSS). Other governmental systems that are more focused include the AF Space Control Network (AFSCN), and smaller networks in Canada, India, Japan, Kazakhstan, Korea, and Ukraine. We note the International Scientific Optical Network (ISON) as a comprehensive system that maintains a complete geosynchronous (GEO) catalog. There is a network of amateur observers that interact to track objects. Their sites are much less defined than the other systems we discuss, but are very well organized. Finally, we include the Satellite Laser Ranging System (SLR) system as an excellent resource for developing reference orbits. We hope that these data will provide a common baseline from which to simulate

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satellite observations, as well as a vehicle to collect precise locations for actual operations. Vallado (2005) showed that orbital propagations could be aligned between various flight dynamics programs by careful treatment of the input data and parameters. Likewise, better aligned sensor databases will enable better simulated observations for use with different orbit determination programs.

We note an important caveat that. ***The intent is to have the sites be close enough to the actual site locations to provide a sense of realism for analytical studies, but if the locations are used for operational processing, bias values will need adjustment for uncertainties from the actual locations***. Further, we provide files compatible with Analytical Graphics Inc. ODTK program for ease of implementation and commonality. To underscore the importance of the approximate nature of these locations, we use “APPROX” in the title with each .tso file for ODTK, and each .kml file for Google Earth.

III. PROCESS

A variety of sources were used to develop the baseline parameters. The Internet provides access to a wealth of information, from determining overall sensor systems to research, to gathering specific site and sensor information. Generic site names and approximate locations are given in many places. We used Google Earth to refine these parameters and develop “closer” coordinates. We acknowledge that the geo-registration (tying a satellite image to specific latitude-longitude coordinates) of the images may not be precise, but for our purposes, it was assumed to be close enough for simulation purposes. Google Earth also gave us an approximate altitude. In some cases, searches took considerable time as little information was known. In other cases, it showed intentional imagery degradation or denial. (PCMag 2011). The operational dates represent probably the toughest and least accurate information we assembled.

Figure 1: Geo-Registration Errors: Finding the positions in Google Earth is not without error. Notice the apparent jump in a straight road. This represents at least an uncertainty of about 10 m. This is probably from a difference in elevation angle between the two images.

We list primary relevant web sites throughout the paper. Jaramillo et al. (2010: 51-53) lists general information about worldwide space surveillance systems, and was a starting point for many of the analyses. Some sensor numbers were derived from the Minor Planet Observatory Codes (MinorPlanet 2011). In cases where the numbers were unknown, radars were given “555” prefixes, phased arrays a “666” prefix, and optical sensors were given a “999” prefix within each sensor network. Distinguishing between radars and phased array radars was done only for nomenclature, and not physical operation. So numbers like 9992, 5551, and 6663 are possible for unknown sensor numbers.

IV. Sensor Characteristics

We included several types of sensors (radar, optical, phased array, interferometer, and transponder), although we did not attempt to meticulously attribute a specific design to each sensor. Detailing the specific azimuth, elevation, and range limits, frequencies, etc. is left to future work, although we did accumulate some information on this. We did include information where it was readily available, but it's not comprehensive.

A complete sensor characterization would also include sensor parameters. We note some general characteristics used for simulations in this paper. For phased array radars, we assumed range limits of 0 – 6000 km. However, we know that some radars (i.e. Millstone Hill) and phased arrays (i.e. Eglin) can observe GEO orbits, so we permitted a deep space radar class that was capable of observing GEO objects, 0 – 40000 km. Optical sensors were all rated for 0 – 99999 km. Simulations should incorporate visual magnitude limitations for a specific sensor if that is a limiting factor.

Because some SSN phased array radar faces are mounted on slanted planes relative to their zenith direction, each phased array face can actually track objects at any azimuth from 0-360°. However, it can be easier to specify each face's directionality if we allow elevations to exceed 90°. With this, the phased arrays can scan ± 60° in both azimuth and elevation relative to their boresight direction. Thus, in elevation from 0-120°. Phased array face directions were noted in the notes where they were known, but not in all cases. For simulation, a specifically tailored sensor is probably best (as opposed to a generic line-of-sight visibility) as discussed previously. In STK, this can be modeled using sensor objects and combining the constraints and objects.

Finally, interferometers consist of receiver and transmitter locations. Both are needed for operation, but simulations should only use the receivers. Some systems employ transponder operations, but we did not provide any special definitions for these sensors as they are specific to manufacturers' design.

We do not exhaustively list frequencies for systems because if the observations are calibrated, there is no need for the frequency. If the observations are not calibrated, then the frequency could be of use. For our purposes, we didn't consider this information at this time.

All longitude values are positive East, negative West.

V. United States Air Force Space Command Space Surveillance System - AFSPC SSN

The United States Air Force Space Command Space Surveillance Network (AFSPC SSN) system developed initially as a missile warning network. Over time, the missile warning functionality was modified into the current space surveillance operation. As a result, some sensors are not ideally situated for space observation, but rather potential ICBM incoming routes to the United States. This can limit some coverage, but there are usually redundant sensors.

The AFSPC SSN sensor locations in the paper are the result of consolidating data from numerous sources. Vallado (2007, 257-260) provides a general introduction into the AFSPC SSN system. These values are modified here with additional data from numerous Internet and literature sources: Au Chap 19 2011, Au USSPC (2011), Fas (Chap 7, 2011), Fas Geodss (2011), Fas Overview (2011), Fischer (1998), Peterson Factsheet (2011), Peterson Lib (2011), Wikipedia AFSSS (2011), and Wikipedia SSN (2011). Determining the geoid was difficult. For the SSN, we assume WGS-84/EGM-96. For all others, we assume EGM-96.

The Phased array and GEODSS systems often have multiple sensors at a single location. For some simulation purposes, it may be useful to have a single point at the center of each sensor, rather than the individual sensors. The following table shows these central locations, along with the remaining SSN sensors. The numbers for these central locations have been multiplied by 10 to distinguish them from the individual sensors. We use the same practice with phased array radars where there are separate numbers for each face.

Table 1: US AF Space Surveillance Network Sensors: The phased arrays generally separate each face to a separate sensor. We list a single location here and include the faces in the notes. These sensors also have sensor numbers multiplied by 10 (for example Sensor 382 is 3820). Note that the open date for Fylingdales is when the phased array conversion was complete.

SSN Sensors									
ID #	**Location**	**Name**	**Type**	**Latitude**	**Longitude**	**Alt (m)**	**Open**	**Close**	**Notes**
3820	Clear, AK	ClearPA	PhArry	64.300233	-149.190964	175.0	1-Jun-61		AN/FPS-123
3860	Cape Cod, MA	CapeCod	PhArry	41.752408	-70.538342	67.0	4-Apr-80		FPS-115
3880	Beale, CA	Beale	PhArry	39.136050	-121.350628	117.0	15-Aug-80		FPS-115
393	Shemya, AK	CobraDane	PhArry	52.737175	174.091528	68.0	13-Jul-77		AN/FPS-108, #3
3940	Thule, Greenland	ThuleSE	PhArry	76.569456	-68.298956	424.0	24-Jun-87		FPS-120
396	Cavalier, ND	PARCS	PhArry	48.724594	-97.899894	344.0	31-Mar-75		FPQ-16
3450	Fylingdales, UK	Fylingdales	PhArry	54.361775	-0.670033	258.0	18-Aug-92		PA FPS-120
2100	Socorro, NM	Socorro	Opt	33.817192	-106.659867	1510.0	1-Mar-83		40" FSQ 114, az
2300	Maui, HI	Maui	Opt	20.708400	-156.257433	3058.0	1-Mar-83		generic, also 235
2400	Diego Garcia	DiegoGarcia	Opt	-7.411714	72.452208	-61.2	30-Nov-86		generic
260	Moron, Spain	MOSS	Opt	37.150111	-5.591386	93.0	1-Sep-98		AN/FSQ-224
951	Maui, HI	MOTIF	Opt	20.708625	-156.257661	3026.0	1-Jan-79		1.2 m
952	Maui, HI	AMOS	Opt	20.708467	-156.257206	3026.0	1-Jan-63		0.6 m
961	Maui, HI	BDT	Opt	20.708549	-156.257564	3058.8	1-Jun-88		0.8 m
965	Maui, HI	AEOS	Opt	20.708228	-156.256636	3029.0	1-Jun-00		3.6 m
970	Maui, HI	Raven_MSSS	Opt	20.708463	-156.257488	3058.5			
998	Maui, HI	RMERaven	Opt	20.746206	-156.431650	83.0			
996	Flagstaff, AZ	USNO	Opt	35.184114	-111.740714	2303.0			1.3 m
9991	Albuquerque, NM	SOR	Opt	34.964231	-106.463869	1891.0			
9992	Cerro Tololo, Chile	MODEST	Opt	-30.169031	-70.806308	2205.0			
9993	Kirtland (AlbuRaven)	KirtlandRAVEN	Opt	34.963050	-106.497256	1725.0			
9994	Socorro, NM	SST	Opt	33.739408	-106.364325	2432.0	1-Jul-11		
333	Kwajalein Atoll	ALCOR	Radar	9.398614	167.482883	47.0	1-Jan-70		5670 MHz (C)
334	Kwajalein Atoll	ALTAIR	Radar	9.395472	167.479328	66.0	1-Jan-72		160 MHz (VHF),
335	Kwajalein Atoll	TRADEX	Radar	9.398733	167.482217	5.0	1-Jan-82		1320 MHz (L), 2
354	Ascension	Ascension15	Radar	-7.906608	-14.402497	59.0	1-Jan-57		FPQ-15
355	Ascension	Ascension18	Radar	-7.974386	-14.391703	143.0	1-Jan-57		
359	Clear, AK	ClearR	Radar	64.291242	-149.194103	213.0	1-Jun-61		CW FPS-92
363	Antigua	Antigua	Radar	17.143614	-61.792475	6.0	1-Jan-57		FPQ-14
369	Millstone Hill, MA	MILLH	Radar	42.617442	-71.490967	127.0	5-Oct-57		old 331, 1a, 1295
371	Millstone Hill, MA	MILLFIRE	Radar	42.617567	-71.492383	124.0			laser
372	Millstone Hill, MA	MILLHAY	Radar	42.623272	-71.488206	120.0	17-May-65		10 GHz (X), 96 (
373	Millstone Hill, MA	MILLHAX	Radar	42.622792	-71.487222	120.0	1-Jan-94		16 GHz (Ku)
375	Vardo, Norway	GlobusII	Radar	70.367153	31.127711	63.0			
399	Eglin, FL	Eglin	Radar	30.572394	-86.214692	36.0	29-Jan-69		FPS-85, also #39
932	Kaena Point, HI	KaenaPt	Radar	21.572056	-158.266578	300.0	1-Jan-72		FPQ-14
741	San Diego, CA	SanDiegoR	Intf	32.577492	-116.974731	125.4			rec
742	Elephant Butte, NM	ElephantButteR	Intf	33.445544	-106.998122	1443.6			rec
743	Silver Lake, MS	SilverLakeR	Intf	33.147342	-91.020897	10.5			rec
744	Tattnel, GA	TattnallR	Intf	32.043725	-81.926017	28.3	27-Oct-87		rec
745	Lake Kickapoo, TX	LakeKickapooT	Intf	33.553978	-98.762908	309.9	1-Jan-61		trans
746	Red River, AR	RedRiverR	Intf	33.330772	-93.550056	91.8			rec
747	Hawkingsville, GA	HawkingsvilleR	Intf	32.288950	-83.536283	77.2			rec
748	Gila River, AZ	GilaRiverT	Intf	33.113389	-112.030725	321.0			trans
749	Jordan Lake, AL	JordanLakeT	Intf	32.659064	-86.263514	99.2			trans
9995	LEO Satelite 34903	STSS ATRR	SB	0.000000	0.000000	0.0	31-Jan-11		no elements avail
9996	LEO Satelite 37168	SBSS-1	SB	0.000000	0.000000	0.0	23-Feb-11		a=634 km, i = 98

Some sites have several types of sensors at a single location (radar, optical, etc). Physically this is usually antennae or telescopes at separate locations within a certain facility. It may also be the specific directions the sensor can observe – or the obscura map (an azimuth elevation depiction of directions that are impossible to observe). For applications requiring the individual sensors for the SSN, we can use the parameters from Table 2.

Table 2: US AF Space Surveillance Network Sensors: This listing shows the various faces for the phased arrays and different camera directions for some optical sensors.

SSN Sensors									
ID #	**Location**	**Name**	**Type**	**Latitude**	**Longitude**	**Alt (m)**	**Open**	**Close**	**Notes**
211	Socorro, NM	SocorroCAM1	Opt	33.817267	-106.660092	1510.0	1-Mar-83		40" FSQ 114
212	Socorro, NM	SocorroCAM2	Opt	33.817269	-106.659619	1510.0	1-Mar-83		40" FSQ 114
213	Socorro, NM	SocorroCAM3	Opt	33.817061	-106.659619	1510.0	1-Mar-83		40" FSQ 114
231	Maui, HI	MauiCAM1	Opt	20.708158	-156.257633	3067.0	1-Mar-83		40" FSQ 114
232	Maui, HI	MauiCAM2	Opt	20.708158	-156.257319	3067.0	1-Mar-83		40" FSQ 114
233	Maui, HI	MauiCAM3	Opt	20.708633	-156.257294	3067.0	1-Mar-83		15" FSQ 114
241	Diego Garcia	DiegoCAM1	Opt	-7.411622	72.452025	-61.2	30-Nov-86		40" FSQ 114
242	Diego Garcia	DiegoCAM2	Opt	-7.411625	72.452431	-61.2	30-Nov-86		40" FSQ 114
243	Diego Garcia	DiegoCAM3	Opt	-7.411861	72.452369	-61.2	30-Nov-86		40" FSQ 114
344	UK	FylingA	PhArry	54.361775	-0.670033	326.0	18-Aug-92		PA FPS-120
345	UK	FylingB	PhArry	54.361775	-0.670033	326.0	18-Aug-92		PA FPS-120
346	UK	FylingC	PhArry	54.361775	-0.670033	326.0	18-Aug-92		PA FPS-120
382	Clear, AK	ClearPA	PhArry	64.300233	-149.190964	213.0	mid 1990's		AN/FPS-123
383	Clear, AK	ClearPA	PhArry	64.300233	-149.190964	213.0	mid 1990's		AN/FPS-123
386	Cape Cod, MA (NE)	CapecodNE	PhArry	41.752408	-70.538342	67.0	4-Apr-80		FPS-115
387	Cape Cod, MA (SE)	CapecodSE	PhArry	41.752408	-70.538342	67.0	4-Apr-80		FPS-115
388	Beale, CA (S)	BealeS	PhArry	39.136050	-121.350628	117.0	15-Aug-80		FPS-115
389	Beale, CA (NW)	BealeNW	PhArry	39.136050	-121.350628	117.0	15-Aug-80		FPS-115
392	Shmeya, AK	CobraDaneWE	PhArry	52.737175	174.091528	68.0	13-Jul-77	1-Nov-94	
393	Shmeya, AK	CobraDane	PhArry	52.737175	174.091528	68.0	13-Jul-77		AN/FPS-108
394	Thule, Greenland	ThuleSE	PhArry	76.569456	-68.298956	424.0	24-Jun-87		FPS-120
395	Thule, Greenland	ThuleN	PhArry	76.569456	-68.298956	424.0	24-Jun-87		FPS-120
398	Eglin, FL	EglinDS	Radar	30.572394	-86.214692	36.0	1-Jan-88		FPS-85
399	Eglin, FL	Eglin	Radar	30.572394	-86.214692	36.0	29-Jan-69		FPS-85

An example of how we used Google Earth is shown for the Diego-Garcia GEODSS facility. Photographs were sometimes valuable to understand the local orientation and setup (Fig. 2).

Figure 2: AFSPC Space Surveillance Network Sensors: The optical systems at Diego Garcia are shown in a picture (left) and from Google Earth (right). Notice the centrally located position for simulation of the facility, and not the individual telescopes. For simulations, a central location (red circle) is probably sufficient for many applications. Photo from http://upload.wikimedia.org/wikipedia/commons/2/22/GEODSS_Diego_Garcia_2006-05-01.jpg

VI. Russian Space Surveillance System - RSSS

The Russian Space Surveillance System has evolved over the years similar to the AFSPC SSN network. Beginning as a large network of phased array radars and radars forming a missile warning system, some of the sensors were gradually transitioned to perform space surveillance roles. Coverage of geosynchronous region seems to have been limited in the past. ISON (discussed later) covers the geosynchronous regime, but it’s not part of the RSSS. Today, the Russian Space Agency (Roscosmos) is responsible for the safety of Russian space activities. The Ministry of Defense is responsible for Russian military operations in space and space surveillance in support of these operations. Other organizations (Russian Academy of Sciences, Foreign Ministry etc.) are taking part in the development of SSA policy, data collection and sharing, and establishing international cooperation.

Globalsecurity Russia (2011) indicates that the primary radars for space surveillance are the Dnepr (1960's) and Daryal (1980's) EW systems. These systems include radars at Irkutsk (Mishelevka), Murmansk (Olenegorsk), Pechora, Balkhash and Mingechaur (Gabala. More recent listings suggest many of the phased array radars have closed, or been demolished (RussianForces 2011). However, the sensor at Mishelevka discussed as being demolished was actually the Dar'yal-U station at Mishelevka which actually was never finished. Podvig (2002) provides additional information on the radar systems. The ABM system near Moscow can also perform some space surveillance functions. Geimint Soviet (May 2011) provides detailed information on many of the sites, as well as an initial Google Earth .kmz file. Jaramillo et al. (2010: 55-56) and Ausairpower (May 2011) provide site locations and descriptions. There are optical sites located in Russia and Tajikistan.

Table 3: Russian Space Surveillance Sensors: The RSSS includes a number of accurate sensors. Additional optical sensors are listed under the ISON network.

RSSS Sensors									
ID #	**Location**	**Name**	**Type**	**Latitude**	**Longitude**	**Alt (m)**	**Open**	**Close**	**Notes**
6661	Olenegorsk, Russia	Olenegorsk	PhArry	68.113500	33.910500	240.0	1-Jun-76		325, 295
6662	Olenegorsk, Russia	Olenegorsk	PhArry	68.116600	33.920500	241.0	1-Jun-78		310, Dnepr
6663	Balkhash, Kazakhstan	Balkhash	PhArry	46.602890	74.528500	348.0	1-Jan-72		Dnepr
6664	Balkhash, Kazakhstan	Balkhash	PhArry	46.604460	74.532600	348.0			Dnepr
6665	Mishelevka, Russia	Mishelevka	PhArry	52.877936	103.272944	513.0	1-Jan-68		70, 200
6666	Mishelevka, Russia	Mishelevka	PhArry	52.874986	103.260700	493.0	1-Jan-68		130, Dnepr
6667	Pechora, Russia	Pechora	PhArry	65.210600	57.295600	102.0	1-Jan-84		Dar'yal
6668	Gabala, Azerbaijan	Gabala	PhArry	40.871514	47.808928	628.0	1-Jan-85		160, Dar'yal
6669	Baranovichi, Belarus	Baranovichi	PhArry	52.862000	26.467700	169.0	1-Jan-02		263, Volga
66610	Moscow, Russia	Moscow	PhArry	55.231090	37.294300	226.0			
66611	Moscow, Russia	Moscow	PhArry	56.173314	37.769239	263.0			60, 150, Don-2N
66612	Pavlovsk, Russia	Krona	PhArry	42.935333	132.577056	210.0			
66613	Lekhtusi, Russia	Lekhtusi	PhArry	60.275456	30.545033	92.0	1-Jan-06		Voronezh-M
66614	Armavir, Russia	Armavir	PhArry	44.925425	40.983892	254.0	1-Jun-09		Voronezh-DM
66615	Storozhevaya, Russia	Krona20ZH6	PhArry	43.825361	41.342739	1107.0			
191	Nurek, Tajikistan	Nurek	Opt	38.281592	69.223300	2217.0			
9992	Storozhevaya, Russia	Krona30ZH6	Opt	43.718331	41.226253	2115.0			

VII. European Space Agency Space Surveillance System – European SSS

The European Space Agency (ESA) is moving towards development of a highly accurate and modern space surveillance tracking system. Recent conferences at ESAC (2010) and INTA Headquarters near Madrid Spain (2011) have brought space professionals from all over the world to share ideas, techniques, and tools. They have many sensors, located in several countries. Initial planning is underway for a comprehensive coalition. Klinkrad (2002) provides a good reference into the activities that are on-going. See also Assembly (Apr 2011), Eiscat (Mar 2011), ESA Bulletin33 (Apr 2011), and Minorplanets (Mar 2011).

Table 4: European Space Surveillance Sensors: ESA is developing a growing number of high quality sensors to perform space surveillance. Locations referenced in the literature, but not found in Google Earth are identified with a "??" in the Notes.

European Sensors									
ID #	Location	Name	Type	Latitude	Longitude	Alt (m)	Open	Close	Notes
5551	Apt, France, receiver	GRAVESr	Radar	44.071508	5.534578	932.0	Dec 15, 2005		
5552	Dijon, France transmitter	GRAVESf	Radar	47.347778	5.515000	202.0	Dec 15, 2005		143.050MHz
5553	Wachtberg, Germany	TIRAFHR	Radar	50.616631	7.129611	270.0			
5554	Winchester, UK	Chilbolton	Radar	51.145022	-1.438447	83.0			
5555	Tromso, Nroway	EISCATn	Radar	69.586439	19.226111	69.0			
5556	Kiruna, Sweden	EISCATs	Radar	67.860778	20.433806	473.0			
5557	Sodankyla, Finland	EISCATt	Radar	67.363903	26.630417	204.0			
5558	Longyearbyen, Svalbard	EISCATsv	Radar	78.152669	16.058706	432.0			
5559	Effelsberg, Germany	TIRAEF	RadioTele	50.524803	6.883597	368.0			radio telescope
J04	Tenerife	OGS	Opt	28.300939	-16.511903	2392.0			
26	Zimmerwald, Switzerland	ZimLAT	Opt	46.877225	7.465225	897.0			
27	Zimmerwald, Switzerland	ZimSMART	Opt	46.876947	7.465086	897.0			
262	La Silla, Chile	TarotS	Opt	-29.261053	-70.731775	2385.0			
20	Nice France	TarotN	Opt	43.727458	7.299061	314.0			
511	Haute-Provence Observatory	ROSACE	Opt	43.931508	5.712447	653.0	Feb 2001		
J75	LaSagra, Spain	LaSagra	Opt	37.982600	-2.565600	1530.0			NEO
620	Mallorca	Mallorca	Opt	39.642842	2.950828	161.0	1-May-91		NEO
9991	Plateau de Caussols, France	Tarot	Opt	43.752056	6.923386	1270.0			
9992	Odeillo, France	SPOC	Opt	42.494775	2.030278	1543.0			??
9993	Castelgrande, Italy	TT1	Opt	40.940000	15.190000	904.0			??
9994	Montsec, Spain	FabraROA	Opt	42.051650	0.729639	1570.0			

Europe also has mobile tracking radars. The French General Directorate for Armament (DGA) MONGE hosts Normandie and ARMOR tracking radars and is shown in Fig. 3.

Figure 3: DGA Monge Tracking Ship: This system provides the capability to make observations from many parts of the world. (Photo from Military-today Jul 2011)

VIII. Other Governmental Systems

We group these sensors in a special section because the resources are generally smaller or more focused than the previous networks. Nevertheless, there is tremendous opportunity here for collaboration. Jaramillo et al. (2010: 51-53) lists general information of many other sensor systems. We note them here, but do not provide details as they are very specialized at this time.

A. United States Air Force Satellite Control Network - AFSCN

The AFSCN was developed in the 1960's to track active satellites. Wikipedia (AFSCN, 2011) suggests the sensor network operations began in about 1959, with a command center in Palo Alto CA. The center moved to Sunnyvale (Onizuka) CA, and is now at Schriever AFB in Colorado. The AFSCN network has published approximate locations for their sensor sites, but Coster (2001) provides a concise listing. For simulation purposes, these are often useful for owner-operator like tracking.

Table 5: AF Satellite Control Network Sensors: These sensors work with satellite transponders. We do not list a sensor on Kodiak island indicated to have closed in 1975.

AFSCN Sensors									
ID #	Location	Name	Type	Latitude	Longitude	Alt (m)	Open	Close	Notes
657	New Boston, NH	BossA	Trp	42.945986	-71.629423	199.0			SGLS-60 3607
623	New Boston, NH	BossB	Trp	42.944755	-71.630325	193.3			SGLS-46 3603
649	VAFB, CA	CookA	Trp	34.822614	-120.501857	268.7			SGLS-60 3107
620	VAFB, CA	CookB	Trp	34.825639	-120.505408	267.4			SGLS-46 3103
660	Guam	GuamA	Trp	13.615192	144.856049	216.0			SGLS-60 3707
625	Guam	GuamB	Trp	13.615874	144.855430	209.4			SGLS-46 3703
654	Kaena Point, HI	HulaA	Trp	21.562281	-158.242121	429.7			SGLS-60 3507
622	Kaena Point, HI	HulaB	Trp	21.568980	-158.262308	319.0			SGLS-46 3503
626	Oakhanger, UK	LionA	Trp	51.115097	-0.906110	143.9			SGLS-60 3407
629	Oakhanger, UK	LionB	Trp	51.117873	-0.906446	142.9			ARTS-51 3405
633	Colorado Springs, CO	PikeA	Trp	38.805938	-104.528484	1909.7			ARTS-51 3305
624	Thule, Greenland	PogoA	Trp	76.515191	-68.595725	148.0			SGLS-14 3907
628	Thule, Greenland	PogoB	Trp	76.515362	-68.598864	147.4			SGLS-46 3903
634	Thule, Greenland	PogoC	Trp	76.515701	-68.605081	144.8			ARTS-51 3905
637	Diego Garcia	ReefA	Trp	-7.270031	72.369998	-58.5			transp-23 4105

B. China

The Chinese Space Surveillance System (CSSS) is very difficult to obtain information on as there is very little information on the Internet. However, some links provided insight from which we performed additional searches. We found some phased array radars sites, most likely used with missile tests, but also possibly for space surveillance. Jaramillo et al. (2010: 51-53) list general information about the Chinese system. It states that the CSSS includes 6 ground stations in China, 1 Pakistan ground station, 1 Namibia ground station, and optical facilities at Purple Mountain. It's possible that many of these systems are designed for missile testing, but there could be space surveillance applications as well. Papers have discussed work on radar technology within China, but again, information regarding specific locations is lacking. (CAO Zhi-bin et al. 2009, Zhang Guangyi 1996, Wen Xun Zhang 1996).

Table 6: Chinese Space Surveillance System (CSSS): Information is very limited on these sensors and locations. Locations referenced in the literature, but not found in Google Earth are identified with a "??" in the Notes.

CSSS Sensors									
ID #	Location	Name	Type	Latitude	Longitude	Alt (m)	Open	Close	Notes
330	Purple Mtn, Xinjian, China	XOS	Opt	32.737044	118.463981	174.0			
337	Shanghai, Sheshan Obs	SHAO1	Opt	31.096378	121.188542	85.0			
9991	Guanxing Mtn, Qingdao	QOS	Opt	36.070181	120.321114	66.0			
9992	Huairou	HSOS	Opt	40.315494	116.594225	56.0			
9993	Shanghai, Xujiahui Obs	SHAO	Opt	31.190164	121.429419	17.0			
9994	Xinglong	LAMOST3	Opt	40.395744	117.575861	875.0			
9995	Xinglong	LAMOST	Opt	40.389094	117.489433	656.0			
9996	Heilongnjiang	HOS	Opt	47.500000	133.420000	153.0			??
9997	Yaoan, Yunan	YOS	Opt	25.600000	101.100000	153.0			??
5551	Xuanhua	Xuanhua	PhArry	26.621667	107.698056	875.0			??
5552	Xuanhua	Xuanhua1	PhArry	40.447829	115.117107	1286.0		closed	
5553	Xinjiang	LPAR	PhArry	41.641458	86.236956	933.0			

Like the European system, the Chinese system includes mobile sensors, including information suggesting there are at least 6 such systems. Wikipedia (Yuanwang 2010) suggests the ships have C- and S-band capabilities.

Figure 4: Chinese Space Surveillance Tracking Ship: Note the several large tracking dishes, similar to the Millstone Hill SSN tracking system. There are several other likely optical trackers, and since the ship designation is number 5, it is likely there are other ships with similar capabilities. Photo from Wikipedia (Yuanwang 2011)

C. Other Governmental

Canada, India, Japan, Kazakhstan, Korea, and Ukraine all have sensors capable of performing space surveillance activities. Each country has emerging space programs that require better SSA. Cooperation in the form of sharing observations does not yet exist, but the number of sensors indicates that such an activity would be highly valuable for sensor bias estimation, more complete close approach analyses, and general space operations.

Canada will operate the Sapphire satellite that hosts an optical sensor for space surveillance. The sensor acts as a contributing sensor o the US SSN. (Cfd-cdf 2011). They also have several optical sensors.

Japan resources consist of radars and optical sensors. Lab26 (2011) and Spaceguard (2011) provide some details. India has an ever expanding space program and has optical sensors capable of performing space surveillance. Korea has a few optical sensors.

Table 7: Other Governmental Space Surveillance System: Information is limited on these sensors and locations. However, each country is pursuing development of sensors to support space operations activities. Locations referenced in the literature, but not found in Google Earth are identified with a "??" in the Notes.

Other Sensors									
ID #	**Location**	**Name**	**Type**	**Latitude**	**Longitude**	**Alt (m)**	**Open**	**Close**	**Notes**
9991	Suffield, Alberta	CANSUF	Opt	50.293059	-111.104803	750.7			
9992	Valcartier, Quebec	CANVAL	Opt	46.875551	-71.470690	147.9			
9993	Ottawa, Ontario	CANOTT	Opt	45.354550	-75.891016	90.0			
9994	RMC, Kingston	CASTOR	Opt	44.231101	-76.467252	65.3			
9991	Udaipur, India	U1	Opt	24.604622	73.674200	587.0			
6661	Kamisaibara, Japan	KSGC	PhArry	35.331253	133.930308	750.0			3.265 MHz
9991	Ibaraki, Japan	NICTKashima	Opt	35.956269	140.657592	21.0			
9992	Bisei, Japan	BSGC	Opt	34.672000	133.545347	417.0			
9993	Nyukasa, Nagano	JAXANyukasa	Opt	35.901389	138.171667	1870.0			
9994	Chofu, Japan	JAXALEO	Opt	35.678719	139.556917	65.0			
5551	Shigaraki, Japan	MURadar	Radar	34.853908	136.105633	378.0	2-Sep-84		atmos, VHF
5552	Kagoshima, Japan	JAXAUchinoura	Radar	31.254464	131.078478	312.0			
5553	Nagano, Japan	JAXAUsuda	Radar	36.132997	138.362139	1462.0			
9991	Daejeon, Korea	KASI	Opt	36.397597	127.375036	107.0			
9991	Cirmea, Ukraine	Yevpatoria	Opt	45.189103	33.187047	16.0			
10018	Yevpatoria, Ukraine	YevpAZT8	Opt	45.219465	33.162594	9.4			
6661	Sevastopol, Ukraine	x14	PhArry	44.578756	33.386436	7.0	1-Jun-79		228, 173
6662	Mukachevo, Ukraine	x15	PhArry	48.377753	22.707628	138.0	1-Jun-79		194, 258
9991	Majdanak, Uzbekistan	Majd2	Opt	38.684789	66.943058	2727.0			Min of Def

IX. International Scientific Optical Network - ISON

Beginning in about 2001, a loose cooperation of optical observatories began, and by 2005 the International Scientific Optical Network (ISON) was created. Additional observatories have been added since then and they primarily study scientific and applied problems in space, specializing on geosynchronous satellites. Equipment modernization and updated software has taken place to provide increased capabilities. The Keldysh Institute of Applied Mathematics in the Russian Academy of Sciences (KIAM RAS) has been the principal scientific and organizational coordinator of ISON. By 2010, 33 telescopes at 23 observatories in 11 countries were operating around the world with over 90 researchers. The current tasks include regular GEO monitoring, new object discovery and tracking, and maintenance of as complete a catalog as possible. ISON is currently tracking 1557 objects in GEO compared to the TLE catalog of 1016 objects. The observers track between 150 up to 800 individual objects each night. The primary difference in the catalogs is faint objects (high area to mass ratios), debris not seen by the SSN, and classified objects. The data are stored at the KIAM Ballistic Center upon collection. The processing and analysis of information on space debris is also executed at the Center.

Table 8. International Scientific Optical Network Sensors: This collection of optical sensors enables a very complete GEO catalog to be maintained. Locations referenced in the literature, but not found in Google Earth are identified with a "??" in the Notes.

ISON Sensors									
ID #	Location	Name	Type	Latitude	Longitude	Alt (m)	Open	Close	Notes
10003	Mondy, Russia	MondyAZT14	Opt	51.621953	100.918758	2008.0			
10010	Arkhyz, Russia	ArkhyzZeiss600	Opt	43.650132	41.431058	2029.7			
10012	Terskol, Russia	Zeiss2000	Opt	43.276347	42.499483	3084.0			
10016	Mayaki, Ukraine	Mayaki600	Opt	46.397439	30.271719	22.0			
10019	Simeiz, Ukriane	SimeizZ1000	Opt	44.412381	33.991497	334.0			
10024	Pulkovo, Russia	Pulkovo200	Opt	59.771811	30.326025	92.0			
10031	Nauchnyi, Ukraine	CrAOATA64	Opt	44.726864	34.015689	595.0			
10041	Majdanak, Uzbekistan	MajdAZT22	Opt	38.673375	66.895545	2575.9			
10042	Arkhyz, Russia	SAOZeiss	Opt	43.646821	41.440380	2058.0			
10044	Dushanbe, Tajikistan	AZT8	Opt	38.490922	68.682582	732.2			
10059	Kitab, Uzbekistan	KitabORI2	Opt	39.133531	66.884678	658.0			
10064	Tiraspol, Moldova	TiraspSR220	Opt	46.836333	29.631347	35.0			
10067	Ussuriysk, Russia	UssuriyskORI	Opt	43.698564	132.165618	273.0			
10072	Tarija, Bolivia	TarijaORI	Opt	-21.595689	-64.624061	1850.0			
10077	Blagoveshchensk, Russia	Blagov250	Opt	50.318646	127.482078	220.0			
10078	Artem, Russia	Artem20	Opt	43.340189	132.070668	16.0			
10083	Milkovo, Russia	Milkovo220	Opt	54.694557	158.625927	174.4			
10092	Uzhgorod, Ukraine	UzhgT25	Opt	48.563551	22.453751	231.0			
10103	Mondy, Russia	AZT33IK	Opt	51.620292	100.921468	1993.0			
10112	Kharkov, Ukraine	Chuguyev25	Opt	49.641410	36.935380	174.0			
10240	Collepardo, Italy	CollepORI22	Opt	41.765283	13.375028	562.0			
10517	Zvenigorod, Russia	Zvenig50	Opt	55.699453	36.757308	196.0			
10526	Lesosibirsk, Russia	Lesosibirsk	Opt	58.183399	92.531017	93.0			
10531	Nauchnyi, Ukraine	CrAOZTSh	Opt	44.727919	34.015914	601.0			
10532	Nauchnyi, Ukraine	GAIShZ600	Opt	44.729719	34.016708	590.0			
10533	Nauchnyi, Ukraine	CrAOPH1	Opt	44.726950	34.017239	592.0			
10541	Nauchnyi, Ukraine	CrAORST221	Opt	44.729583	34.016236	594.0			
10901	Andrushivka, Ukraine	AbdrZ600	Opt	50.000844	28.997289	228.0			

X. Non-governmental Systems

Satellite owner operators use a vast international network of sensors to communicate with their satellites. During communication transmissions, transponders provide very accurate range, and sometimes angular information for orbit determination. We do not list these sites because there are literally hundreds of sites around the world. In addition, like the AFSCN, they are specifically for communication with the satellite, and not for passive satellite detection.

XI. Amateur Observers

Not often discussed, but becoming widely popular, the amateur community is beginning to be capable of delivering routine high quality observations to support integrated SSA. Vallado and Alfano (1999) introduced the notion that many distributed sensors could solve numerous difficulties and deficiencies in SSA. With the advent of the internet and significantly cheaper telescopes, amateurs can now take numerous observations, have the data processed, and even distribute catalogs to users.

Amateurs maintain reasonably current orbital elements on about 300 classified objects, including nearly all in LEO, and a large fraction of those in Molniya and GEO. Equipment ranges from binoculars and stopwatches, to telescopic video cameras with GPS time inserters. Automated and semi-automated data reduction is commonly used. The primary orbital model is SGP4; however, numerical methods are employed for long-term propagation of HEO and GEO orbits.

In the year ending in June 2011, twenty-six observers contributed 22,700 positional observations. Thirteen observers accounted for 95 percent of the data. Observers are located in the United States, United Kingdom, Canada, France, Italy, Netherlands, and South Africa.

XII. SLR Ranging Network - SLR

There are numerous sensors in the SLR Network and they are used in conjunction with satellites having laser retro-reflectors. See ftp://cddis.gsfc.nasa.gov/pub/slr/data/fr/ for a complete listing including some older satellites. These satellites are particularly useful for establishing truth and reference orbits*.

While not all satellites have these retro-reflectors, sufficient numbers of satellites do to warrant including these sites in the discussion. We have attempted to provide just the active sites as many have closed, moved, or are inactive. It is prudent to check the Internet sites to find out the current status of these sites (GSFC May 2011). Current data may show that older sites have closed.

Figure 5 shows some sensor system locations.

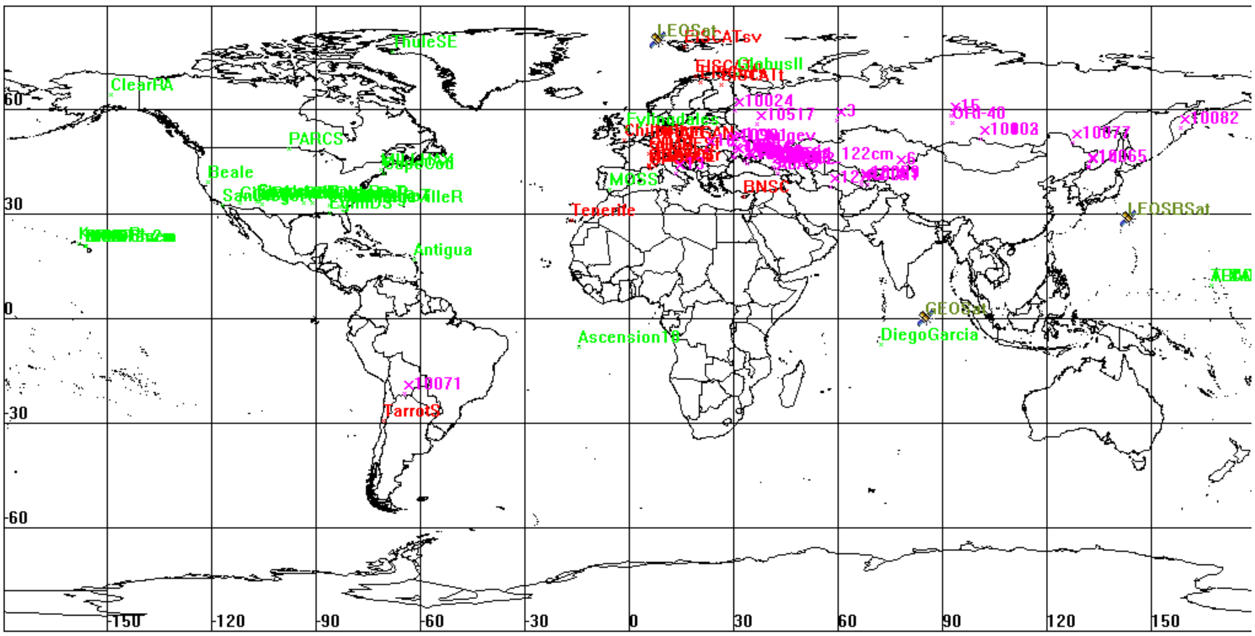

Figure 5: Sample Space Surveillance Site Locations: Representative sensor sites from the SSN (green), European (red), and ISON (magenta) networks are shown. Note the geographic distributions. Image courtesy of STK.

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* We note that many satellites now carry GPS receivers and they transmit data to the ground consisting of processed NAVSOL states, or raw signal observations. A comprehensive listing of satellites having GPS receivers is difficult to find. Some observations can be found at ftp://cddis.gsfc.nasa.gov/gps/data/satellite/.

Table 9: Satellite Laser Ranging Sites: This table shows the currently active stations that provide SLR measurements. The data is current for May 2011.

SLR Sensors									
ID #	Location	Name	Type	Latitude	Longitude	Alt (m)	Open	Close	Notes
1824	Golosiiv, Ukraine	GLSL	SLR	50.363300	30.496100	212.9	1-Apr-97		
1831	Lviv, Ukraine	LVIL	SLR	49.917600	23.957200	359.4	1-Oct-98		
1863	Maidanak 2, Uzbekistan	MAID	SLR	38.685737	66.943149	2711.3	1-Oct-90		
1864	Maidanak 1, Uzbekistan	MAIL	SLR	38.684894	66.943085	2713.6	1-Oct-90		
1868	Komsomolsk-na-Amure, Russ	KOML	SLR	50.694612	136.743828	269.5	1-May-92		
1870	Mendeleevo 1, Russia	MDVL	SLR	56.026700	37.223400	256.7	17-Apr-94		
1873	Simeiz, Ukraine	SIML	SLR	44.413186	33.990950	364.6	1-May-88		
1874	Mendeleevo 2, Russia	MDVS	SLR	56.027700	37.224900	228.3			
1879	Altay, Russia	ALTL	SLR	51.200000	82.300000	270.0	15-Sep-04		
1884	Riga, Latvia	RIGL	SLR	56.948550	24.059073	31.3	1-Sep-87		
1893	Katzively, Ukraine	KTZL	SLR	44.393173	33.970122	68.1	20-Sep-82		
7040	Wrightwood, CA	OCTL	SLR	34.382000	-117.683000	2200.0			
7045	Apache Point, NM	APOL	SLR	32.780361	-105.820417	2788.0			
7080	McDonald Observatory, TX	MDOL	SLR	30.680276	255.984818	2004.4	1-Jan-88		
7090	Yarragadee, Australia	YARL	SLR	-29.046518	115.346719	241.1	1-Jul-79		
7105	Greenbelt, MD	GODL	SLR	39.020615	283.172334	20.9	1-Mar-81		
7110	Monument Peak, CA	MONL	SLR	32.891757	243.577356	1839.0	15-Aug-83		
7119	Haleakala, HI	HA4T	SLR	20.706486	203.743084	3056.3	15-Sep-06		
7124	Tahiti, French Polynesia	THTL	SLR	-17.576800	210.393700	82.2	1-Aug-97		
7125	Greenbelt, MD	GF8Q	SLR	39.020269	283.172553	18.6			
7130	Greenbelt, MD	GO4T	SLR	39.020917	283.172571	19.9			
7231	Wuhan, China	WUHL	SLR	30.515700	114.489700	86.6	28-Dec-99		
7237	Changchun, China	CHAL	SLR	43.790513	125.443457	274.3	1-Jan-83		
7249	Beijing, China	BEIL	SLR	39.606935	115.892052	81.7	12-Dec-88		
7308	Koganei, Japan(CRL)	KOGC	SLR	35.710085	139.489124	122.5	1-Mar-88		
7343	Beijing (TROS), China**	BEIT	SLR	39.607600	115.892100	75.2			
7355	Urumqi, China*	URUL	SLR	43.810000	87.710000	845.5	15-Apr-03		closed
7356	Lhasa, China	LHAL	SLR	29.634900	91.037700	3604.1			
7357	Beijing-A, China	BEIA	SLR	39.607700	115.892700	72.0			
7358	Tanegashima, Japan	GMSL	SLR	30.556512	131.015413	141.1	25-Mar-04		
7370	Burnie, Tasmainia	BURF	SLR	-41.062214	145.881391	129.6			
7403	Arequipa, Peru	AREL	SLR	-16.465721	288.507067	2489.9	10-Jul-92		
7405	Concepcion, Chile	CONL	SLR	-36.843000	-73.025300	169.3	17-Apr-02		
7406	San Jaun, Argentina	SJUL	SLR	-31.508625	-68.623160	727.2	28-Nov-05		
7501	Hartebeesthoek, South Africa	HARL	SLR	-25.889735	27.686173	1408.1	12-Sep-93		
7604	Brest, France*	BREF	SLR	48.407861	-4.503833	104.8	10-Sep-04	31-Oct-04	
7806	Metsahovi (new)	METL	SLR	60.217200	24.394600	74.0	15-Oct-96		
7810	Zimmerwald, Switzerland	ZIML	SLR	46.877228	7.465219	951.1	3-Jul-95		
7811	Borowiec, Poland	BORL	SLR	52.276980	17.074585	122.6	13-May-88		
7820	Kunming, China	KUNL	SLR	25.029900	102.797200	1991.8	20-May-89		
7821	Shanghai, China	SHA2	SLR	31.096100	121.186600	100.0	10-Jul-05		
7823	San Fernando, Spain	SFEF	SLR	36.462730	-6.206190	64.0			
7824	San Fernando, Spain (new)	SFEL	SLR	36.465000	-6.205500	98.2	4-Apr-99		
7825	Mt Stromlo, Australia	STL3	SLR	-35.316100	149.009900	805.0	1-Aug-04		
7826	Mt Stromlo, Australia	STRK	SLR	-35.316300	149.009800	806.6			
7828	Paris, France (FTLRS)	PARF	SLR	0.000000	0.000000	0.0			
7829	Grasse, France (FTLRS)	GRAF	SLR	43.754680	6.921120	1321.3	20-Mar-07		
7830	Chania, Crete, Greece	CHAF	SLR	35.533100	24.070500	157.0			
7831	Helwan, Egypt**	HLWL	SLR	29.859009	31.342703	131.9	1-May-83		
7832	Riyadh, Saudi Arabia	RIYL	SLR	24.910200	46.400400	773.0	1-Aug-95		
7835	Grasse, France (SLR)	GRSL	SLR	43.754691	6.921122	1322.9			
7836	Potsdam, Germany	POTL	SLR	52.380018	13.064892	133.5	8-May-92		
7837	Shanghai, China	SHAL	SLR	31.097540	121.191739	27.8			
7838	Simosato, Japan	SISL	SLR	33.577694	135.937039	101.6	31-Jan-82		
7839	Graz, Austria	GRZL	SLR	47.067135	15.493360	539.4	1-Nov-81		
7840	Herstmonceux, United Kingd	HERL	SLR	50.867380	0.336123	75.4	1-Jan-82		
7841	Potsdam, Germany	POT3	SLR	52.383000	13.061400	123.5	20-Jul-01		
7845	Grasse, France (LLR)	GRSM	SLR	43.754600	6.921600	1323.1	1-Sep-80		
7848	Ajaccio, France (FTLRS)	AJAF	SLR	41.927400	8.762700	96.8	1-Sep-96		
7865	Stafford, Virginia	STAL	SLR	38.499215	-77.371107	23.9			
7941	Matera, Italy (MLRO)	MATM	SLR	40.648600	16.704600	536.9	1-Jan-00		
8834	Wettzell, Germany (WLRS)	WETL	SLR	49.144417	12.878007	665.4	1-Mar-89		

XIII. Simulating Realistic Tracking Schedules

To complete the analysis process, a method of accurately producing the simulated measurements is crucial for realism, and hence, accurate mission requirements verification. Too many observations give too conservative an answer. Too few obs can result in no solution at all. Recognizing that there are many flight dynamics programs in existence, we chose to use the STK ASCII report format of the accesses between a sensor and a satellite so that other programs could use the same simulation routines we developed. The only requirement would be to output sensor-satellite access times in the STK format. The Matlab and script routines will be placed on the web at http://centerforspace.com/.

We define the following terms. A ***revolution*** is completed each time the satellite makes one complete orbit about the Earth. This requires a reference point, often from the ascending node or perigee. A ***pass*** is made each time a satellite crosses above the horizon from a sensor. A ***track*** is the time period that a sensor actually observes a satellite as it passes overhead. For a Molnyia, a pass may last 7-8 hours. A track may only be 5-6 minutes in that time period. Within each track, we can further distinguish how often the sensor makes an ***observation***. This includes the time to gather radar impulses, or to acquire a CCD image, and it is often 20-30 seconds. The observation itself consists of the actual measurements, range, azimuth, elevation, right-ascension and declination, etc.

The usual approach to simulating observations is a simple line-of-site access between the sensor and the satellite. While easy to program, this approach will certainly yield too many observations. Consider a sensor tracking a GEO satellite. By definition, it will simulate observations continuously! As the number of constraints increases, the access times are more limited, and the resulting simulated observations better model the actual system. Constraints include items such as:

- Line of Sight
- Range, azimuth and elevation limits (angles and rates, az-el masks)
- Lighting (Direct, umbra, penumbra)
- Exclusions (Sun, Moon)
- Special Angular (grazing, beta, squint, etc angles)
- Local terrain and topography
- Custom (dynamic exclusions, target exclusions, boresight, vector, other advanced constraints)
- Communication limitations (signal, frequencies, SNR, etc)
- Sensor constraints (boresight, etc)
- Special user written constraints

We used STK as it already has these constraints (and more) embedded. Matlab scripts were generated to accomplish the actual observation thinning and the input was an ASCII output from a report in STK. Because the format depends on an STK chain access report, we provide an example report should another program be used in the initial access generation. The ASCII report contains start/stop times, and we felt this was the easiest point to provide an interface to accommodate different flight dynamics programs.

Each sensor has physical limitations and operational constraints that dictate to some extent how the system operates. Table 10 lists the control parameters we used. Although the sensor type seems to indicate a particular type of sensor has these characteristics, we felt it was better to allow individual sensors to have individual performance parameters. For instance, an optical observatory in NM will have a much lower missed track probability than a similar site at Diego Garcia, primarily due to weather considerations. The revisit time is intended primarily for sensors that might have continuous, or extended periods of time where the objects are observable. It limits the number of distinct tracks that can occur. We label these sensor type constraints. Note the inclusion of a missed track probability, which incorporates the random nature of events such as weather or over-scheduling into the simulated observations. We also include a way of integrating various sensors together so that the integrated simulation has a reasonable number of observations from the ensemble of sensors, and not just a single sensor operating in isolation with the inter-revisit time. This is the time interval after which no sensor will re-acquire the satellite.

Table 10. Sensor Tracking Parameters. This table shows the physical parameters that affect the number and frequency of observations from a given sensor. The Type is used to further refine the sensor characteristics in a later process. The revisit times specify an interval in which a given sensor, or sensor network will not re-look at a satellite for the specified time. All values are strictly notional.

	Pass length (min)	Obs Step (sec)	Revisit time (hr)	Inter-revisit time (hr)	Missed-Track Probability	Type
BNSC	6.0	20.0	8	3	25%	**Optical**
Diego Garcia	5.0	20.0	6	6	25%	**Optical**
KRAO	7.0	20.0	8	3	35%	**Optical**
ORI	8.0	10	8	3	20%	**Optical**
Tenerife	6.0	20.0	8	3	15%	**Optical**
LEO SBSat	8.0	30.0	6	N/A	5%	**Space Based Optical**

ODTK OBSERVATION GENERATION

For our test simulation, we considered a LEO and GEO satellite being observed from the SSN (Diego Garcia), a Space Based satellite, and European (Cyprus and Tenerife) and ISON (KRAO, ORI) sensors. Having these sensor all collaborate may seem far fetched, but data fusion represents a viable option to enhance SSA. The LEO satellite is in a typical Sun-synchronous orbit. The GEO satellite is at about 85 deg E longitude where the SSN coverage is very poor. Here, the European and ISON sensors can readily achieve information. However, each sensor system working independently is constrained by angles-only observations, or lack of measurements due to physical limitations. We compare the results for both individual and fused data.

The process is as follows. In STK, setup a Chain of the sensors to the satellites, including the SB satellite observing the other satellites. Then compute accesses and output the Individual Strand Access report for the chain. The ASCII output lists times where the sensor satellite pair is visible. An example is shown below.

```
Chain-SSN2Sats:  Individual Strand Access

BNSC to LEOSat
--------------
                    Start Time (UTCG)         Stop Time (UTCG)       Duration (sec)
                  ----------------------    ----------------------    --------------
                  15 Jul 2011 05:45:25.40    15 Jul 2011 05:52:19.59         414.187
                  15 Jul 2011 07:15:58.33    15 Jul 2011 07:27:13.07         674.743
...
                  21 Jul 2011 20:53:18.35    21 Jul 2011 21:02:43.39         565.044

Min Duration      19 Jul 2011 21:47:18.02    19 Jul 2011 21:49:19.18         121.159
Max Duration      15 Jul 2011 07:15:58.33    15 Jul 2011 07:27:13.07         674.743
Mean Duration                                                                525.674
Total Duration                                                             17347.246

BNSC to GEOSat
----------------

                    Start Time (UTCG)         Stop Time (UTCG)       Duration (sec)
                  ----------------------    ----------------------    --------------
                  15 Jul 2011 00:00:00.00    22 Jul 2011 00:00:00.00      604800.000
```

Figure 6: Sample Access Report: A sample access report is shown. The ASCII format enables other programs to create a similarly formatted report and then use the simulation routines to produce realistic simulated observations.

Next, process this access textfile and make individual files that specify the target and sensor names in each filename (LEOSat#BNSC.int specifies BNSC observing the LEOSat).

```
Fixhpintervals c:\stkodfiles\worldsensors\ testchain.txt  testchain.out
```

Now find the realistic scheduling using Matlab. (**writeaccessint2.m**) This process specifies each observation, so the files can become large. It's best to place all the interval files in a new directory (here called Int)

```
writeaccessint('c:\stkodfiles\worldsensors\testchain.out',
'TaskScheduleInt.txt', 'c:\stkodfiles\worldsensors\int\')
```

The results need to be loaded back into ODTK via anther script (**`AR_PopODTKIntervals.html`**). In this script, you can specify the filename, Sensor names, and observation time steps. Note that the time step is generally not needed because the Matlab script writes out each observation time. As the intervals are loaded into the ODTK simulator, you can clear the list, or keep the previous interval listing.

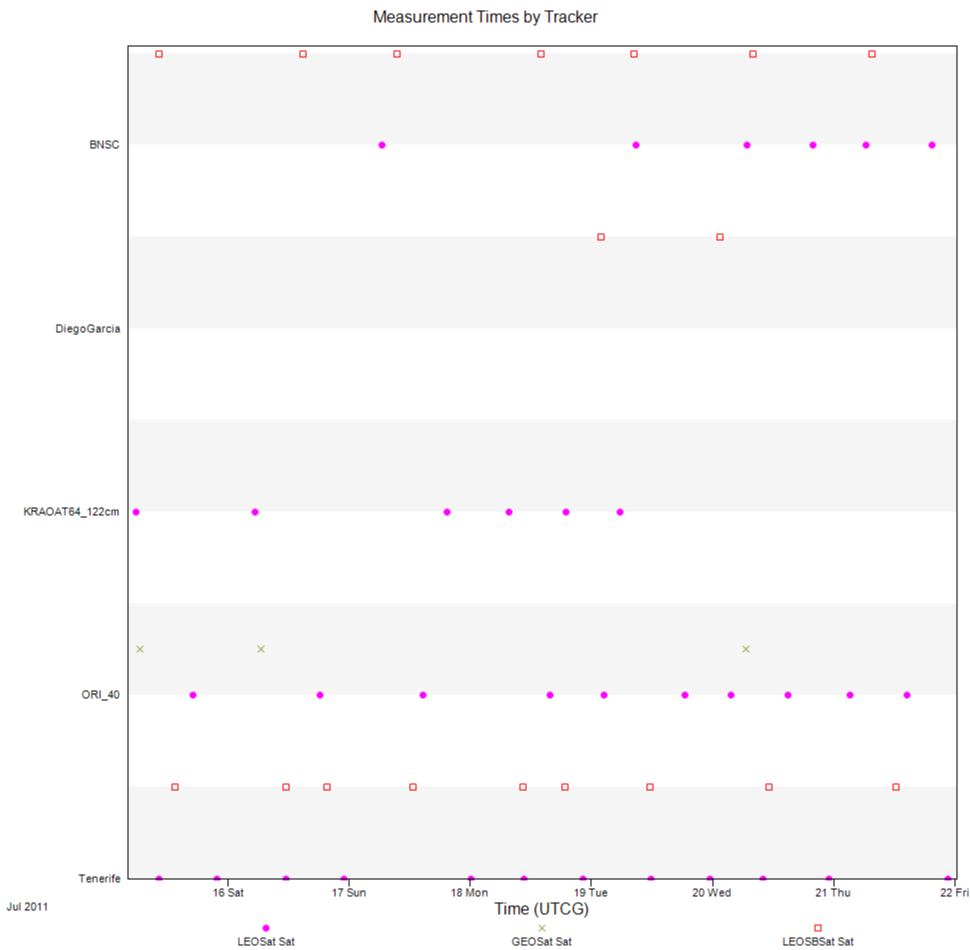

Figure 7: Simulated Observation Times. Observation times are shown for the LEO and GEO satellite.

Notice that the sensors observe relatively infrequently – our original intent. For comparison, if we had not thinned the observations, we would have found observations shown in Fig. 8. The increased observations will surely give more optimistic results in any resulting analysis.

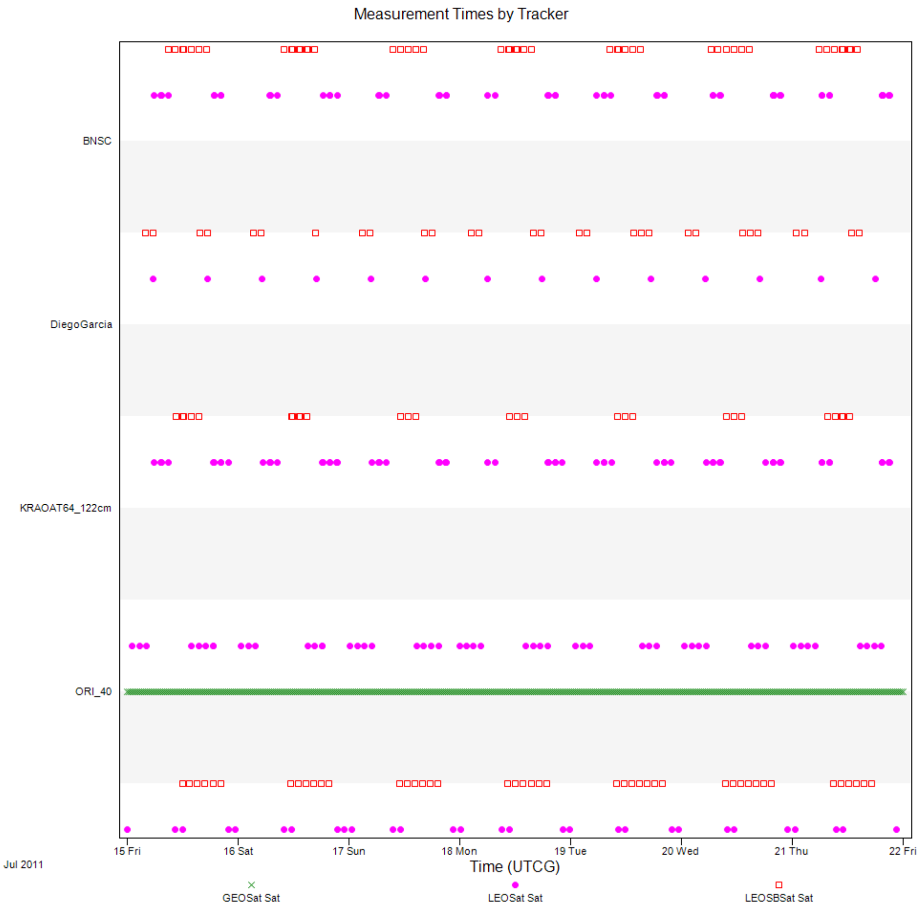

Figure 8: Simulated Observation Times. Observation times are shown for the LEO and GEO satellite without thinning. Note the continuous access for the GEO satellite.

XIV. SUMMARY and CONCLUSIONS

A comprehensive list of the larger space surveillance tracking systems has been developed. Sample limit characteristics are given to establish a baseline for use in developing simulated observational data for joint cooperative research and analysis. The overall goal is to establish the means to conduct reasonably accurate studies and to determine the benefits of doing joint tracking and processing of data. A framework is established for users to request simulated observations from the given sets of sensors. This will enhance the accuracy of studies and permit observational data to be formed for analysis purposes. Secure World Foundation is planning to host information of this type on the web in the fall of 2011.

We hope an outcome of this paper will be several fold. First, awareness of what sensors exist for space surveillance. Second, commonality in simulation studies. Finally and not least, opportunities to collaborate and share data and observations to develop and maintain more accurate satellite catalogs to support better Close Approach and RFI analyses and ensure safer operation in space. (e.g., see Lam, Junker, Anhalt, & Vallado 2010 when mixing angle data with range data to achieve better OD estimation). Global SSA is certainly possible if all these systems shared data.

If you have questions, comments, or corrections, please let us know!

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ISON sensor locations, as well as many other corrections throughout. Ted Molczan provided insight into the amateur operations as well as reviewing the entire document. Brian Weeden also provided excellent insight, and he will head the effort of Secure World Foundation to maintain a website listing of these sensors and additional information. Papers are in progress to describe this activity in additional detail. Jaganath Sankaran has also assembled an impressive list of sensor sites which we used to cross-check many of the sensor sites.

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APPENDIX – CLOSED SITES

Table A1: Closed Sensor Sites: This table shows some common sites that are closed. The information is provided for historical purposes only.

Closed Sensors									
ID #	**Location**	**Name**	**Type**	**Latitude**	**Longitude**	**Alt (m)**	**Open**	**Close**	**Notes**
3820	Eldorado	Eldorado	PhArry	30.978328	-100.552953	741.0	8-May-87	1-Sep-95	
3840	Robins, GA	Robins	PhArry	32.581250	-83.569167	83.0	29-Sep-86	1-Sep-95	AN/FPS-115
2200	Taegu, Korea	Korea	Opt	35.744072	128.608572	744.0			
315	Diyarbakir, Turkey	Pirincilik	Radar	37.905239	39.993372	844.0		1-Jan-95	fan FPS 17
329	Clear, AK	Clear	BMEWS	64.289475	-149.195081	181.0	1-Jun-61		FAN FPS-50
362	Grand Turk	Grandturk	Radar	21.462594	-71.132097	23.0			FPQ-13
365	Grand Bahama	GrandBahama	Radar	26.615778	-78.347769	7.0			FPQ-13
5	Malabar, FL	Malabar	BN	28.024522	-80.685028	7.0		1-Sep-95	
9993	Yuzhno-Sakhalinsk, Russia	x211	Opt	46.950000	142.730000	25.0		Closed	
6663	Balkhash, Kazakhstan	x10	PhArry	46.602906	74.528508	344.0		1-Sep-04	120, 184
6664	Balkhash, Kazakhstan	x11	PhArry	46.604683	74.532778	361.0		1-Sep-04	62
66619	Skundra, Latvia	x35	PhArry	56.715225	21.962917	0.0		1-May-95	
66620	Skundra, Latvia	x36	PhArry	56.708236	21.940967	0.0		1-May-95	
55510	x	x39	Radar	51.637772	30.702892	0.0		Closed	OTHR DUGA ??
55511	x	x40	Radar	50.892961	136.836772	0.0		Closed	OTHR DUGA ??
55512	x	x41	Radar	50.385550	137.328297	0.0		Closed	OTHR DUGA ??
55510	Old Nike radar	Billig	Radar	50.622825	6.744797	856.0			Closed Nike Rad
B34	Cyprus	BNSC	Opt	34.912181	32.883725	1760.0			
501	Herstmonceux, UK	PIMS	Opt	50.870164	0.345878	41.0		Closed	
993	Gibraltar	PIMS	Opt	36.118589	-5.346164	121.0		Closed	