Chinese Research in Space-Based Space Surveillance

Dr. Randy Liefer

Space Surveillance is a subset and contributor to space situational awareness (SSA), which in turn, is a subset and contributor to space domain awareness (SDA). To clarify the purpose and scope of this paper, these three terms are defined and their relationships illustrated.

SDA is the overall understanding of the space operational environment required to enable planning and execution of space operations involving satellites, supporting ground assets, plus the ground-to-space, space-to-ground and space-to-space communications links that connect satellites, users and operators.[1] The space operational environment encompasses active satellites (their locations, capabilities and intentions), orbital debris, space weather, terrestrial weather, policies, politics, and intelligence. SDA activities include collecting raw observables, identifying physical states and parameters (such as orbit, attitude, size, shape), determining functional characteristics (such as active vs. passive, thrust capacity, payloads), inferring mission objectives (such as communications, weather), identifying behaviors, and predicting credible threats and hazards.[2]

SSA is a subset of space domain awareness that focuses on the orbital segment. SSA is the requisite foundational, current, and predictive knowledge and characterization of space orbital objects including live satellites, dead satellites, and debris. It provides planners, users and operators with knowledge and characterization of objects in orbit to ensure safe, stable, and sustainable space activities.[3]

Developing and maintaining SSA requires three basic activities: data collection (i.e., space surveillance), data analysis (fusing and interpreting collected and historical data; then turning all that into useful information), and data dissemination (getting useful information to the users and operators).[4]

The definitions of SDA, SSA, and space-based surveillance have evolved differently according to culture and country. SDA language was introduced by the United States military in 2019 to emphasize that the space domain involves more than just objects in space. Authoritative literature and media from the Chinese military continues to use SSA terminology even as their growing infrastructure and organization clearly indicate that they, too, appreciate the bigger scope of SDA.[5] At the same time, Chinese researchers almost always describe their work on tracking and identifying space objects as SSA, though the U.S. community would call that "space surveillance" and not "space situational awareness."

This paper focuses on the collections piece of SSA. Using the "collect, analyze, disseminate" framework described earlier, space surveillance is the "collect" piece, which entails observing (or more generally, collecting upon) orbiting man-made objects often enough and with sufficient accuracy to enable the "analyze" piece to identify, characterize, and predict future locations of all those objects. That surveillance, or collecting, is currently done with three basic types of sensors: passive optical, active radar, and passive RF (listening to radio frequency signals that are either emitted or reflected by man-made objects). The vast majority of those sensors today are located on the ground. They can, however, be deployed on satellites themselves, enabling what is commonly called "space-based space surveillance" or, in Chinese literature, "space-based SSA".

What needs to be surveilled – numbers, sizes, orbits

Most papers on space surveillance and space situational awareness begin by describing the congested environment of live satellites, dead satellites and rocket bodies and other orbital debris. Estimates of tracked and untracked objects vary widely and are currently changing as new sensors, especially the Space Force's new "Space Fence," become operational.[6] Rough numbers of "about 25,000 objects, 10 centimeters or larger" are quoted in many papers and updated estimates are published regularly in NASA's *Space Debris Quarterly*.[7] The U.S. Space Force's Space-Track.org website (accessed in November 2023) lists about 28,000 tracked objects (spacecraft and debris) and another 16,000 "analyst objects" that are "variably tracked and in constant flux, so their catalog and element set data are not published."[8]

These numbers are only rough estimates of a reality that is changing rapidly due to two current developments. First, the number of commercial communication satellites in low Earth orbit (LEO) has grown to more than 5,000 in the last several years and is on its way to more than 50,000 by the end of the decade.[9] Second, the new Space Fence mentioned above now enables tracking of objects as small as one centimeter. As the new Space Fence's capability becomes fully exercised, the number of cataloged items may soon exceed 200,000.[10]

All of these objects, live satellites and debris, are not randomly distributed in space. The vast majority exist in one of five orbit types: geosynchronous Earth orbit (GEO), medium Earth orbit (MEO or semi-synch), LEO low inclination, LEO polar (or Sun-synchronous), and highly elliptical orbit (HEO or Molniya) (See Table 1).[11] Orbit types matter because sensor types and locations are optimized to observe objects in each of these orbital regimes. Further, once a space system has been developed and deployed to one of these orbital regimes, it has little or no capability to move to a different type of orbit. Practical limits on propulsion capability and propellant mass mean, for example, that a satellite in a low inclination LEO orbit cannot move to a highly inclined Sun-synchronous orbit or a satellite launched to the geosynchronous belt can't "fly" back to LEO.

Mission	**Orbital Type**	**Semimajor Axis (Altitude)**	**Period**	**Inclination**
Communication Early Warning Weather	Geostationary	41,158 km (35, 786 km)	~24 hours	~0^0
Remote Sensing	Sun-synchronous	~6,500-7,300 km (~300-1,000 km)	~90 minutes	~95^0
Navigation (GPS)	Semi-synchronous	26,610 km (20,232 Km)	12 hours	55^0
International Space Station	Low Earth Orbit	~6,800 km (~420 km)	93 minutes	52^0
Communication/Intelligence	Molniya/HEO	26, 571 km	12 hours	63.4^0

Table 1: Selected orbital elements for various missions[12]

<u>Sensor Types -Optical, Radar, Passive RF</u>

Three basic types of sensors are used to observe orbiting space objects: optical (or electro-optical), radar, and passive RF. A brief description of each is given here. All three types are currently in use. However, only optical sensors have been hosted on unclassified satellite systems dedicated to space-based space surveillance. Of note, laser ranging of uncooperative targets could produce information useful for space surveillance. Lasers for this application cannot "find" debris but, when cued by optical or radar sensors, could enhance the accuracy of the debris' orbit determination.[13] A laser's short wavelengths enable very accurate range measurements which in turn contribute to improved orbit determination. Though some research in this area has been reported, little or no space-based application for space surveillance seems near term practical.[14] Laser range finders are used on satellites over short distances to support rendezvous and docking but, due to power requirements, that application has not scaled to the distances required for space surveillance.

Optical

Telescopes collect light or other electromagnetic radiation emitted or reflected by an object and focus it into an image using lenses and mirrors. The main advantages of using optical telescopes for space surveillance is their ability to cover large areas quickly and to observe objects as far away as the GEO belt. Depending on their spatial resolution, telescopes for space surveillance can produce both angle data (azimuth and elevation, for example) for orbit determination and resolved images of the orbiting object that reveal details of the satellite's size, shape, and configuration. Spectral analysis of an optical observation can also reveal information about an object's materials or surface coatings. The main disadvantage of optical telescopes is that they require specific lighting conditions. The target has to be illuminated by the Sun and the telescope-target-sun angles must be favorable. For example, the images in Figure 1 below show examples of "good" Sun angles that would enable the red spacecraft to collect imagery of the blue target. Earth based telescopes also require clear skies to see an object. Space-based optical telescopes, of course, eliminate this weather constraint.

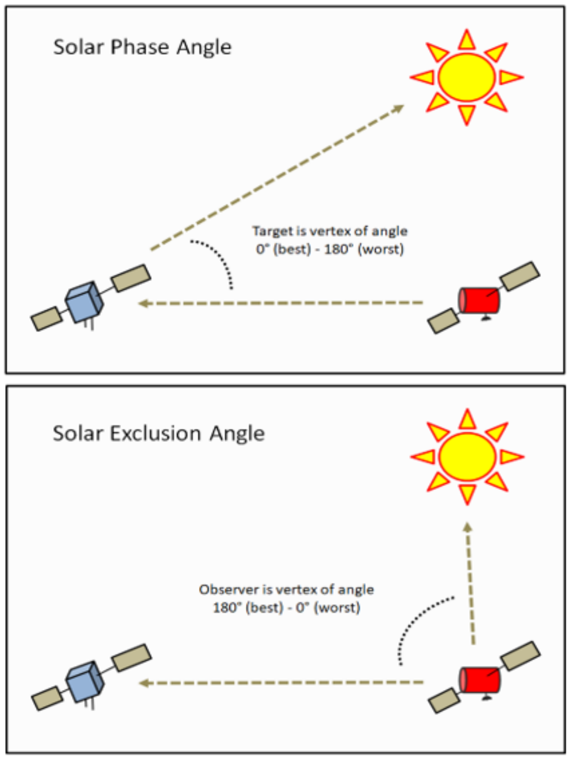

Figure 1: Sun angle geometry[15]

Radar

Because of the ability of phased array radar and the Space Force's Space Fence to make thousands of observations a day, ground-based radars provide the bulk of the space surveillance measurements out to LEO today.[16] Ground based space surveillance radar consists of a network of transmitters and receivers. Transmitters emit RF energy at specific wave lengths. Some of that energy is reflected back to receivers and can be used to calculate range, range rate, and angle-to-target information. Both mechanical, gimballed antenna and fixed antenna phase-array radars are used for ground-based space surveillance.

Space-based radar is used by many satellites for Earth observation and altitude measurement. The long wavelengths associated with radar frequencies require the use of synthetic aperture (SAR) technology to produce imagery with useful spatial resolution. By taking advantage of the motion of the imaging satellite relative to a target, signal processing techniques create a synthetic aperture that is hundreds of times larger than the actual physical dimensions of the satellite's antenna. Without this method, a conventional radar would need a physical aperture of more than 400 kilometers to match the resolution of a one-meter optical telescope.[17] Little or no information on space-based radar for space surveillance is available in unclassified literature today.

Passive RF

Radio transmissions from a satellite can be used to generate information useful for the space surveillance mission. Passive ranging and orbit determination can be accomplished by collecting and correlating RF signals at multiple ground antenna locations. The process is similar to the method GPS receivers utilize but in reverse. With each collection system calculating delay times from the transmitter, and using surveyed collection sites, the range and angles to the satellite can be determined thus providing the ability to generate state vectors and accurate ephemeris for the target satellite. The location of each collection system (either terrestrial or space-based) must be accurately known before the range and angle information can be useful. In addition, collecting, archiving and comparing satellites' payload and telemetry signals can aid in detecting maneuvers, revealing anomalies, and otherwise contributing to overall space situational awareness.[18] Little or no information on existing systems using space-based, passive RF collection for space surveillance of man-made objects is available in unclassified literature from any country today.

Ground-based vs space-based…. where to put the space-based sensors

A globally distributed network of ground-based sensors could, in theory, provide visibility from all parts of the Earth. However, political and geographical constraints, weather conditions and lighting requirements all conspire to preclude the ability to produce "anywhere, all the time" observations. Space-based space surveillance systems overcome all of these limitations (except for the lighting conditions needed for optical observation). In addition, depending on the orbits chosen for the surveillance satellites, distances between sensor and target can be greatly reduced, enhancing resolution for a given size sensing payload. Since diffraction-limited resolution is directly proportional to aperture (or lens) size, a surveillance satellite 1,000 km below the GEO belt could "see" a separation between two GEO objects about 30 times smaller than if the same surveillance satellite was trying to view those objects from LEO, which is approximately 30,000 km below GEO.

Since most satellites and debris exist in the orbit regimes described earlier (LEO, LEO-Sunsynch, MEO, HEO and GEO), it would seem to follow that space surveillance satellites would also reside in these orbits. In fact, space surveillance satellites have been deployed to all of these orbits except MEO and HEO. Though specific performance capabilities of these systems remain classified, their general orbits and missions are known. Systems include the Canadian

Sapphire, the U.S. Space Based Space Surveillance (SBSS), and the Geosynchronous Space Situational Awareness Program (GSSAP), for example. Some of these are described below.

Surveillance from LEO – advantages

Satellites in LEO orbits have line-of-sight to large portions of the GEO belt at any given time. Also, due to their short orbital period (one orbit in 90 – 120 minutes vs 24 hours for GEO), they will have line-of-sight to all portions of GEO 12 to 15 times a day. An observing satellite in a dawn-dusk Sun-synchronous orbit has the additional advantage of being illuminated by the Sun all the time. The U.S. Space Force's SBSS satellite operates in a LEO Sun-synchronous orbit. It is equipped with a gimballed optical telescope that can observe objects in both LEO and GEO orbits.[19] Sapphire is a Canadian satellite, also in LEO Sun-synchronous orbit, that uses an optical sensor to observe objects as far as the GEO belt. A smaller spacecraft than SBSS, its camera is fixed to the satellite structure and the entire satellite rotates to track/observe specific targets.[20]

Surveillance from LEO – disadvantages

The large distance between LEO and GEO (30,000 km or more) precludes high resolution imaging between these two orbital regimes with reasonable sized optics. Using the resolution calculations described earlier, a lens roughly 30 meters in diameter would be needed to achieve one-meter resolution from LEO to GEO (recall that the Hubble Space Telescope has an aperture diameter of only 2.4 meters). Observing LEO satellites from LEO is also possible. However, the high relative linear and angular velocities result in short viewing opportunities and impose difficult requirement on attitude control and agility. Surveillance satellites in LEO-Sun-synchronous orbits would benefit from moving in the same general direction and at smaller distances relative to other satellites and debris also in Sun-synchronous orbits.

Surveillance from GEO – advantages

Surveillance satellites in near-GEO drift slowly past the geostationary belt, enabling repeated slow passes at much closer distances. With small expenditures of propellant, they can also pause their drift and loiter near portions of the GEO belt that may be of interest. The U.S. Space Force's Geosynchronous Space Situational Awareness Program (GSSAP) is a constellation of satellites in "near GEO orbits" that perform this mission.[21]

Surveillance from GEO – disadvantages

Because surveillance satellites in near-GEO drift slowly past the geostationary belt, it takes a single satellite days or weeks to observe the entire belt. GSSAP overcomes this limitation by operating a constellation of several satellites. Though it would be possible, in theory, to surveille LEO objects from a satellite in GEO, the distances involved preclude any practical application. Finally, satellites at or near geosynchronous orbits are 50 to 100 times further from Earth that those in LEO orbits. Consequently, they require larger launch vehicles and are more expensive to buy and operate.

Selected papers on space-based SSA from Chinese academia available in English

Most of the available Chinese academic literature deals with optical sensors. For example, a detailed review article from Nanjing University includes "laser radars" in a single table with no further discussion and lists several references to laser measurement methods that appear not related to space applications.[22] A better review by researchers from the PLA's National University of Defense Technology (NUDT) and the National Innovation Institute of Defense Technology correctly notes that "space-based radars and laser systems have high energy consumption which limits their applications" then makes no further mention of either technology.[23] A few notable exceptions are discussed in the radar section below.

Orbits and geometry for space-based SSA using optical sensors

The review article from NUDT divides the geometry of space-based SSA into two categories of target orbits: LEO and beyond-LEO (which would primarily be GEO but also include MEO and HEO orbits).[24]

LEO to beyond LEO optical surveillance

LEO Sun-synchronous satellites observing objects beyond-LEO can use several basic strategies. One is to fix the sensor to the observing satellite that maintains a constant orientation throughout its orbit. Using this method, regions of space can be scanned as the observing satellite completes each orbit. Objects are thus observed as they pass through these regions. Space surveillance satellites using this strategy are usually placed in LEO Sun-synchronous orbits. Another strategy is to have the sensor on the surveillance satellite fix its view on a specific region in space. In an image obtained with this strategy, the stars are fixed points of light and the object is seen as an arc of light past the stars. Finally, the surveillance satellite can rotate or slew its sensor to track specific objects. NUDT authors have studied various viewing patterns to maximize the number of objects in the GEO belt that might be missed during a given period of time.[25]

Of course, "beyond LEO" includes not just the GEO belt but also satellites in MEO orbits, mostly navigation satellites including GPS, GLONASS, BeiDou, and Galileo, HEO orbits, and GEO Transfer Orbits (GTO. These large elliptical orbits typically have perigee at

LEO and apogee at GEO. They are used to move satellites from their LEO parking orbits to final mission orbits in GEO.

If the goal is to observe objects in all of these higher orbital regimes with optical telescopes on LEO satellites, additional research from NUDT and the Beijing Institute of Tracking and Telecommunications Technology makes a convincing argument for placing those observing satellites in equatorial LEO rather than Sun-synchronous LEO orbits. They propose equipping a single observing satellite with three sensors pointing in different directions (see Figure 2). They then calculate observations statistics for all "beyond GEO" orbits as a function of sensor field-of-view.[26]

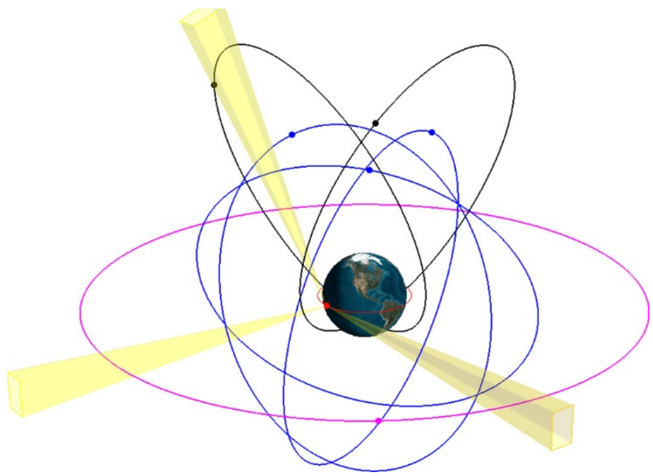

Figure 2: LEO to beyond LEO observation[27]

Near GEO to beyond LEO optical surveillance

Chinese and Western literature primarily talk about observing objects in the GEO belt or in HEO orbits with observing satellites themselves located in nearly geosynchronous orbits. An observation satellite orbiting 1,164 kilometers below GEO will drift by the entire GEO ring in about eight days.[28] A key advantage here is the much shorter distances between target and observer which enable not only tracking but resolved imaging of the target objects with relatively small optical instruments.

Space-based surveillance of LEO objects

Researchers from NUDT correctly note that using satellites to surveille objects in LEO is very difficult due to the high orbital velocities in LEO. Also, the widely varying orbital planes put these velocities in many different directions.[29] Researchers from the Nanjing University of Aeronautics and Astronautics claim that infrared sensors are used for to surveille objects in LEO but the example they cite is the U.S. Space Based Infrared Satellite (SBIRS) constellation.[30] SBIRS satellites actually use infrared sensors to detect rocket launches during boost phase and are not dedicated space-based space surveillance satellites. In the LEO orbital environment, observations of LEO satellites from other satellites carrying optical sensors produce short angles—only "observation arcs" with high relative angular velocities. Algorithms to calculate orbital parameters from these observation arcs could be improved if observations were made simultaneously from multiple observing satellites.

Researchers from NUDT modeled this complex geometry problem from first principles and then propose an optimal estimation algorithm to improve orbit determination by combining angles-only measurements simultaneously obtained from two observing satellites. Of course, observation opportunities and durations increase as the number of observing satellites is increased even further. These authors have also simulated the orbital mechanics of observing objects in LEO from a constellation of satellites. They propose several candidate constellations consisting of two or three satellites all in the same Sun-synchronous orbit but trailing each other by only a few degrees. They assess the relative performance of these constellations against multiple sets of target objects in highly inclined and Sun-synchronous orbits.[31]

Another team from the School of Geodesy and Geomatics at Wuhan University have evaluated, via simulation, several proposed constellations of scanning satellites in multiple Sun-synchronous planes. They assess the theoretical ability of optical satellites in those planes to catalog very small debris in LEO orbits based on assumptions of size, distribution, lighting conditions, reflectivity, and line-of-sight visibility. They conclude that more satellites lead to better performance but that "it is extremely difficult to catalog small debris" on the order of one cm or less.[32]

<u>Star trackers for surveilling LEO objects</u>

Most satellites today employ star trackers for attitude determination. Star trackers "look" at known stars or constellations and measure their angles relative to the satellite body enabling software to calculate the rotational attitude (i.e. pitch/roll/yaw), but not location in orbit, of the spacecraft. Under favorable lighting conditions, other satellites and debris are often seen transiting the star tracker's field of view. This has inspired a novel idea for surveilling LEO objects by using angles-only data from these devices when they "accidently" see satellites or debris. In 2022, researchers from the Chinese Academy of Sciences modeled these "free" observations and showed how they could be used to determine the orbital characteristics of the objects they see. They promise future work that will validate this concept with actual star tracker data (see Figure 3).[33] This concept has also been suggested by a number of Western star tracker manufacturers,[34] and by researchers from NASA[35] and Western academia.[36]

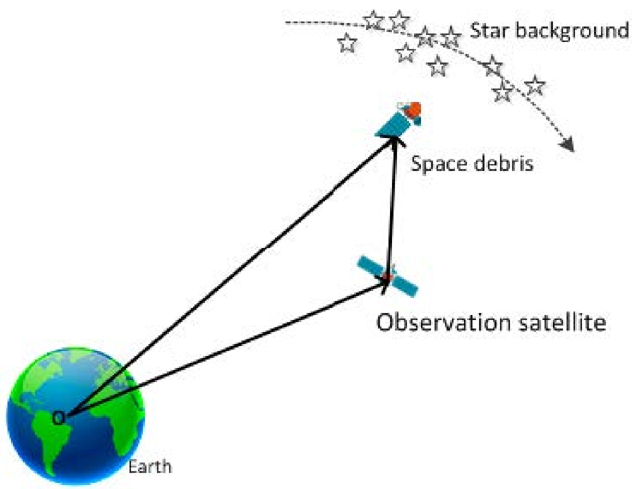

Figure 3: Star Tracker for Space Surveillance[37]

Radar for space-based space surveillance

The majority of space surveillance and tracking observations today are made by ground-based radar. These large, high-power systems operate either with large gimbaled antennas like the Haystack Ultra-Wideband Satellite Imaging Radar or even larger phased array antennas like the one at Eglin AFB in Florida.[38] The huge hardware and large power required to accomplish space surveillance with radars like these together make space-based radar for this application very difficult.[39] Two ways to potentially counter the high power and antenna size requirements are to use synthetic aperture techniques or to operate the radar transmitter only in short bursts. Both are discussed in the Chinese literature.

The question of how SAR technology could be applied to space-based observation of orbiting satellites or debris is investigated by research faculty from the University of Electronic Science and Technology of China.[40] They show that a synthetic radar system could not only detect small space debris but could use the rotational velocity of detected objects to obtain three-dimensional images of the object. Though their image processing algorithms are demonstrated only in the lab at distances of less than one meter, they promise future work at the much higher power levels needed for the long-range detection necessary for space surveillance. Other authors from the Harbin Institute of Technology propose a mission architecture that would deploy a SAR equipped, nadir (i.e. straight down) pointing satellite to detect and image objects below it in LEO orbits from 250 to 400 km of altitude.[41] They show that if the SAR satellite is placed in a 500 km orbit, it will have line of sight visibility to the entire 250 – 400 km "ring" every four days.

Another way to reduce the power demands of a space-based surveillance radar would be to transmit only in a series of short bursts, each on the order of 500 nanoseconds long. Such a system could detect, but not image, small objects at long distances. Researchers from Jilin University and Chang'an University postulate that such a "transient electromagnetic radiation" system could be useful for long range detection of small debris. Their work is, by their own admission, very preliminary but indicates feasibility that warrants further research.[42]

Passive RF for space-based space surveillance

Passive RF here refers to a class of bi-static radar systems that detect and track objects by receiving and processing RF energy that is emitted by a non-cooperative satellite. At least one group of Western researchers have proposed that passive RF receivers deployed to LEO on cubesats could use this passive RF concept as a low-cost way to gather space surveillance data.[43] However, no Chinese work in this area was found during the course of authoring this paper.

Lasers for space surveillance

High power, ground-based lasers can be used to conduct space surveillance. Lasers have been deployed on satellites for use as communication links; however, high power lasers for space-based space surveillance have not been reported in the open literature. China has recently orbited a space-borne laser altimeter for Earth observation (not space surveillance).[44] In addition, at least one team from the Chinese Academy of Sciences has proposed the design of a space-based laser for orbital debris removal.[45] The focus of those authors, though, is control of stray light in the laser's optical path. No attempt is made to apply the work to a practical satellite design or space mission.

Analysis and Recommendations

What's Known

Orbital mechanics, relative motion, viewing geometry and Sun angles for Earth-orbiting objects are all well understood problems. Based on the review of a limited number of Chinese research papers written in English and summarized in this paper, Chinese academics seem to be concerned with the same issues that must have also been addressed in the design and deployment of Western systems that are now on orbit performing the space-based space surveillance mission. Chinese researchers are considering the same kinds of target objects (orbital debris and live satellites) in the same orbital regimes as all space surveillance systems must address. As an indicator, consider that robust space surveillance is a prerequisite for any rendezvous, proximity operations or docking mission. Both China and the United States have successfully demonstrated all of these capabilities in both LEO and GEO orbits. Both countries need, and are pursuing, a reliable, robust SSA capability to track the same objects: their own satellites, other countries' satellites and debris.

The implementation of space-based surveillance of ground or orbiting targets relies, of course, on far more than academic research and computer simulations. Key required system capabilities include large optics, precise navigation, attitude determination, attitude control, and high data rate communication networks. These systems and subsystems have all been developed and implemented in "traditional" remote sensing satellites by a number of countries, including China, for many years and they are routinely used onboard the space surveillance satellite systems now operated by Western countries (GSSAP, Sapphire, and others mentioned in other parts of this paper). In addition, one commercial operator of optical imaging satellites (Maxar) has announced a plan to use its spacecraft to collect and market images of "non-Earth" objects. A high-resolution image of the International Space Station, taken by a Maxar satellite with a payload aperture of 1.1 meters and posted on their website, is clear evidence that the necessary technology is in hand and on orbit today (see Figure 4).[46] This new application of previously deployed Earth observation technology by commercial entities has been only recently allowed by U.S. regulators but, of course, those previous restrictions would not have applied to Chinese or other foreign satellite operators.[47]

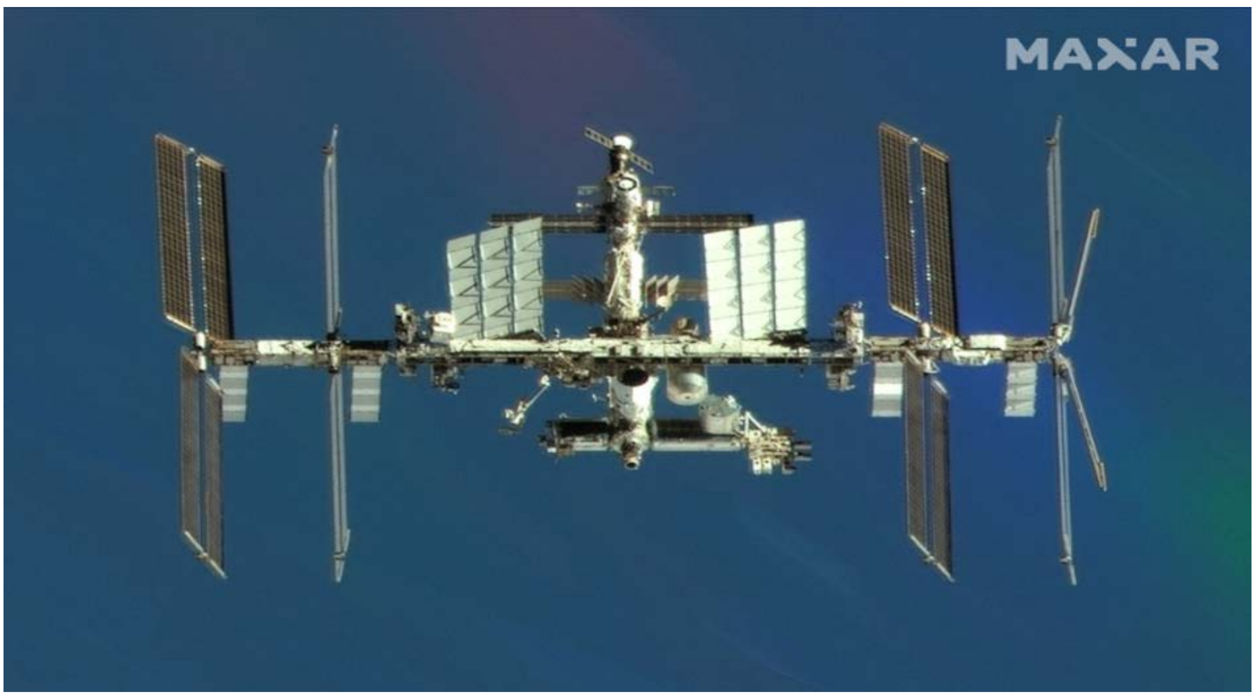

Figure 4: Image taken of the International Space Station by WorldView-3[48]

<u>What's Unknown</u>

It is interesting that none of the Chinese research papers reviewed for this project make any reference to any existing, operational or experimental Chinese space-based SSA systems. The research only analyzes proposed architectures and sensors in various orbital regimes via mathematical modelling and simulation. Most of them set the context of their research by referencing known Western systems (GSSAP, Sapphire and others mentioned earlier). A fairly extensive internet search of publicly available, English-language, Chinese research papers produced no descriptions of, or even references to, existing Chinese satellites used for space surveillance of orbiting targets.

There are a number of other recent, authoritative, unclassified, Western sources that describe Chinese space and counter-space capabilities in some detail to include satellite names, missions, payload types and launch dates. Four of these, reviewed for this paper, also make no mention of existing Chinese systems used for space-based space surveillance.[49] One does note briefly that the findings of this paper are consistent with Stokes et al, who conclude that "China's R&D community also has been exploring options for space-based SSA platforms."[50] In addition, Chinese language research conducted by the China Aerospace Studies Institute revealed a series of Chinese research and development satellites named Shi Jian and Shi Yan (translated "practice" and "experiment," respectively). The chief designer of three Shi Yan satellites is quoted as saying his satellites have leveraged their Earth observation capability to "pilot an on-orbit space situational awareness capability from Sun-synchronous orbit looking at GEO."[51] On the whole, it seems very probable that China has the capability for and is now accomplishing space-based surveillance of orbiting objects much like its Western competitors. Further speculation about specific systems or detailed capabilities is well beyond the scope of this paper.

What to Look for Next

With the deployment of mega-constellations of thousands of new satellites and the continued proliferation of orbital debris, the world's interest in and reliance upon space surveillance becomes increasingly urgent. As a result, the field of space-based space surveillance is in constant flux. Two major indicators of this rapid development are 1) the U.S. government's recent deployment of new capabilities and systems like GSSAP and others and 2) the recent changes, mentioned above, in the U.S. regulatory environment governing the on-orbit imaging of other orbiting objects.

In response to these trends, future researchers interested in China's space-based SSA programs and capabilities should look for evidence that similar changes are occurring in that country or some evidence that China is already allowing commercial entities based there to produce and share images of non-Earth objects. It is clear that Chinese academic researchers are studying all relevant science issues. Now, Western observers should look for confirmation that space-based space surveillance assets are actually deployed and operational. In addition, as U.S. commercial companies like Maxar find a market for selling space-based space surveillance imagery and other related products, researchers should look for indications that comparable, commercial Chinese space imagery constellations like Jilin and Superview plan to do the same.

A note on research methods

One of the goals of this effort is to show that it is possible to glean information from Chinese authors by collecting unclassified, English language, open-source research papers. The primary resource for this collection was the on-line tool Google Scholar. Hundreds of citations can be found there by using search words “space situational awareness”, “space surveillance”, or “space-based space surveillance” in various combinations. Most of the citations lead to abstracts for which the entire paper is available only for a fee through a service like ScienceDirect.com. Another source of potentially related citations is the endnote list for review articles by Chinese authors. Two of these review articles by Wang, Li et al and by Hu, Li et al are cited multiple times in this paper. For example, Wang and Li list 286 references in their endnotes of which about a third appear to written by other Chinese authors. Most of these are not available through the web-based search tools described above but could be accessed by research libraries at most universities where subscriptions to refereed journals produced by IEEE and AIAA, for example, are routinely maintained.

In short, a non-Chinese reading but diligent researcher can still gather important information from unclassified materials on space-based SSA. As noted in CASI’s paper on “Chinese Military Thinking on Orbits Beyond GEO,” often times an English language article is available for the Chinese articles.[52] This is often the case because China increasingly incentivizes its researchers to get global recognition for their basic and applied research, which can most easily be done if they translate what they have written into English.

This paper was presented at the CASI Conference 2024

Endnotes

[1] US Dept of Defense, Joint Publication 3-14, Joint Space Operations, 23 Aug 2023.
[2] Magee, P., Jah, M., & Larson, W. (2022). Space Domain Awareness. CEI Publications.
[3] US Dept of Defense, Joint Publication 3-14, Joint Space Operations, 23 Aug 2023.
[4] Bhavya, L., Balakrishnan, A., Buenconsejo, R., & Carioscia, S. “Global Trends in Space Situational Awareness and Space Traffic Management.” (2018) Institute for Defense Analysis Document D-9074.
[5] Burke, K. “The PLA’s New Base for Space Situational Awareness – Opportunities and Challenges for the US.” China Aerospace Studies Institute (CASI), Sept 2023.

[6] Fonder, G., Hack, P., & Hughes, M. "AN/FSY-3 Space Fence System – Sensor Site One/ Operations Center Integrations Status and Sensor Site Two Planned Capability." Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS), 2017.
[7] NASA Orbital Debris Quarterly News, Vol 27, Issue 4, October 2023.
[8] Space-Track.org, (Nov 2023) Developed by SAIC under contract to DFSCC CJ3/6. *https://space-track.org/.*
[9] Butash, T. "Low-Earth Orbit Mega Constellations Reach Record Capacity", Aerospace America, Dec 2021.
[10] Gruss, M. "Haney: US Partners to Have Indirect Access to Space Fence Data". SpaceNews, 21 Nov 2014.
[11] Sellers, J. (2015) Understanding Space: An Introduction to Astronautics, 4th Edition, Chapter 5. CEI Publications.
[12] Jerry Jon Sellers, William J. Astore, Robert B. Giffen, and Wiley J. Larson, Understanding Space: An Introduction to Astronautics, (New York: McGraw Hill, 2014).
[13] Greene, B. "Laser Tracking of Space Debris" 13th International Workshop on Laser Ranging Instrumentation, Oct 2002.
[14] Steindorfer, M., Kirchner, G., Koidl, F., Wang, P., Jilete, B., & Flohrer, T. "Daylight Space Debris Laser Ranging," Nature Communications, (2020); www.nature.com/naturecommunications.
[15] National Security Space Institute, Fundamentals of Orbits Course, Nov 2022
[16] Weeden, B. "Space Situational Awareness Fact Sheet" May 2017. Secure World Foundation. www.swfound.org.
[17] Sellers, J. (2015) Understanding Space: An Introduction to Astronautics, 4th Edition, Chapter 5. CEI Publications. Chapter 12.
[18] Prechtel, M. "Passive RF Sensing in Support of SSA." Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS), 2016.
[19] Air Force Space Command Fact Sheet. "Space Based Space Surveillance" March, 2017, updated July, 2019. https://www.afspc.af.mil/About-Us/Fact-Sheets/Article/249017/space-based-space-surveillance/.
[20] Kramer, H. "Sapphire (Space Surveillance)". June 2012. European Space Agency eoPortal. https://www.eoportal.org/satellite-missions/sapphire-space-surveillance#ois-optical-imaging-subsystem.
[21] Air Force Space Command Fact Sheet. "Geosynchronous Space Situational Awareness Program" March, 2017, updated September, 2019. https://www.afspc.af.mil/About-Us/Fact-Sheets/Article/730802/geosynchronous-space-situational-awareness-program/.
[22] Wang, B., Li, S., Mu, J., Hao, X., Zhu, W., & Hu, J. "Research Advancements in Key Technologies for Space-Based Situational Awareness". Space: Science and Technology, Volume 2022, Article ID 9812793, June 2022. https://doi.org/1034133/2022/9802793.
[23] Hu, Y., Li, K., Liang, Y., & Chen, L. "Review on Strategies of Space-Based Optical Space Situational Awareness." Journal of Systems Engineering and Electronics, Vol. 32, No. 5, October 2021.
[24] Hu, Li, Liang, and Chen. "Review on Strategies of Space-Based Optical Space Situational Awareness."
[25] Hu, Li, Liang, and Chen. "Review on Strategies of Space-Based Optical Space Situational Awareness."
[26] Hu, Li, Liang, and Chen. "Review on Strategies of Space-Based Optical Space Situational Awareness."
[27] Hu, Y., Li, K., Liang, Y., & Chen, L. "Review on Strategies of Space-Based Optical Space Situational Awareness." Journal of Systems Engineering and Electronics, Vol. 32, No. 5, October 2021.
[28] Hu, Li, Liang, and Chen. "Review on Strategies of Space-Based Optical Space Situational Awareness."
[29] Hu, Li, Liang, and Chen. "Review on Strategies of Space-Based Optical Space Situational Awareness."
[30] Wang, B., Li, S., Mu, J., Hao, X., Zhu, W., & Hu, J. "Research Advancements in Key Technologies for Space-Based Situational Awareness". Space: Science and Technology, Volume 2022, Article ID 9812793, June 2022. https://doi.org/1034133/2022/9802793.
[31] Li, Z., Wang, Y., & Zheng, W. "Space-Based Optical Observations on Space Debris Via Multiport View." International Journal of Aerospace Engineering, Volume 2020, Article IE 8328405, February 2020.
[32] Du, J., Chen, J., Li, B. & Sang, J. "Tentative Design of SBSS Constellations for LEO Debris Catalog Maintenance." Acta Astronautica, June 2018. https://doi.org/10.1016/j.actaastro.2018.06.054.
[33] Liu, M., Wang, H., Yi, H., Xue, Y., Wen, D., Wang, F., Shen, Y., & Pan, Y. "Space Debris Detection and Positioning Technology Based on Multiple Star Trackers." Applied Sciences 2022, 12 3593. https://doi.org/10.3390/app12073593.
[34] Rainbow, J. "Upgraded Star Trackers Could Give More Satellites a Debris-Monitoring Role." SpaceNews, 20 October 2023.
[35] Denver, T., Benn, M., Jørgensen, J. L., Jørgensen, P. S., Herceg, M., & Connerney, J. E. "Space Debris Detection and Tracking Using Star Trackers". *Geophysical Research Abstracts*, *21*., (2019).
[36] Clemens, S., Lee, R., Harrison, P., & Suh, W. "Feasibility of Using Commercial Star Trackers for On-Orbit Resident Space Object Detection." Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS), 2018.

[37] Liu, M., Wang, H., Yi, H., Xue, Y., Wen, D., Wang, F., Shen, Y., & Pan, Y. "Space Debris Detection and Positioning Technology Based on Multiple Star Trackers." Applied Sciences. 2022, 12 3593. https://doi.org/10.3390/app12073593.
[38] Jacobs, J., & Kennedy, T. "Haystack Ultra-Wideband Satellite Imaging Radar Measurements of the Orbital Debris Environment: 2018" NASA/TP-2020-5006606. NASA/JSC Orbital Debris Program Office, August 2020.
[39] Hu, Y., Li, K., Liang, Y., & Chen, L. "Review on Strategies of Space-Based Optical Space Situational Awareness." Journal of Systems Engineering and Electronics, Vol. 32, No. 5, October 2021.
[40] Yang, X., Pi, Y., Liu, T., & Wang, H. "Three-Dimensional Imaging of Space Debris with Space-Based Terahertz Radar." IEEE Sensors Journal, Vol. 18, No. 3, 1 Feb 2018.
[41] Cao, X., Su, F., Sun, H., & Zu G. "Space Debris Observation via Space-Based ISAR Imaging" 2007 International Conference on Microwave and Millimeter Wave Technology, April 2007.
[42] LI WenHan, LI He, LU KaiLiang, CUI HongLiang. 2018. "A new method for space-based detecting small-scale space debris with high-resolution using transient electromagnetism." Chinese Journal of Geophysics (in Chinese), 61(12): 5066-5076, doi: 10.6038/cjg2018M0022.
[43] Persico, A., Kirkland, P., Clemente, C., & Soraghan, J. "CubeSat-Based Bistatic Radar for Space Situational Awareness: A Feasibility Study" IEEE Transactions on Aerospace and Electronic Systems, Vol. 55, No.1, February 2019. DOI: 10.1109/TAES.2018.2848340.
[44] Xie, J., Huang, G., Liu, R., Zhao, C., Dai, J., Jin, T., Mo, F., Zhen, Y., Xi, S., Tang, H., Dou, X., & Yang, C. "Desing and Data Processing of China's First Spaceborne Laser Altimeter System for Earth Observation: GaoFen-7." IEEE Journal of Selected Topics in Applied Earth Observation and Remote Sensing, Vol. 13, 2020. DOI: 10.1109/JSTARS.2020.2977935.
[45] Han, P., Guo, J., Bao, Q., Qin, T., Ren, G., & Liu, Y. "Optical Design and Stray Light Control for a Space-Based Laser Space Debris Removal Mission." Applied Optics, Vol. 60, No.25, September 2021 DOI: 10.1364/AO.432386.
[46] "MAXAR Offers Non-Earth Imaging Solution". https://maxar.com/non-earth-imaging. Accessed 23 Jan 2024.
[47] Foust, John. "NOAA Lifts Many Commercial Remote Sensing License Conditions. SpaceNews, 8 Aug 2023.
[48] "MAXAR Offers Non-Earth Imaging Solution." https://maxar.com/non-earth-imaging.
[49] Gunter's Space Page, https://space/skyrocket.de/doc_sdat. Accessed 22 Jan 2024; Weeden, B., & Samson, V. "Global Counterspace Capabilities, An Open-Source Assessment." Secure World Foundation, April, 2023; Smid, H. "An Analysis of Chinese Remote Sensing Satellites." The Space Review, in association with SpaceNews, Sept, 2022; Stokes, M., Alvarado, G., and Weinstein, E., & Easton, I. "China's Space and Counterspace Capabilities and Activities." Prepared for the US-China Economic and Security Review Commission by the Project 2049 Institute, March 2020.
[50] I Stokes, M., Alvarado, G., Weinstein, E., & Easton, I. "China's Space and Counterspace Capabilities and Activities." Prepared for the US-China Economic and Security Review Commission by the 2049 Institute, March 2020. page 27.
[51] Burke, K. "Initial Analysis of Two Chinese Satellite Series: Shi Jian and Shi Yan." China Aerospace Studies Institute, March, 2022.
[52] Burke, K. "Chinese Military Thinking on Orbits Beyond GEO". China Aerospace Studies Institute, Sept, 2022. https://www.thespacereview.com/article/4387/1.