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Effects of Chinese Laser Ranging on Imaging Satellites

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Satellite Laser Ranging (SLR) is a widely used technique for determining the orbits of objects in space with high accuracy. There are at least 40 satellite laser ranging stations located in 23 countries. These stations are part of an international scientific collaboration, the International Laser Ranging Service, based at the Goddard Space Flight Center in Maryland, USA, which collects, merges, analyzes, and distributes data.

There are seven known laser ranging stations in China. The average laser power employed at most of the of the Chinese stations is below 1 watt, although experimental systems of approximately 40 watts have been used to characterize objects such as space debris.

This paper describes the potential effects of satellite laser ranging on earth-imaging satellites. It posits that although there are some circumstances that will result in permanent damage, in most cases laser ranging would have a low probability of permanent damage to the satellite's sensitive imaging sensor (detector). Due to the low probability of damage, laser ranging is an ineffective anti-satellite weapon. Nonetheless, the potential for even some damage warrants development of international rules governing satellite laser ranging.

INTRODUCTION

Satellite Laser Ranging (SLR) is a precise method for determining a satellite's orbit and is of scientific value in a number of fields, primarily earth and lunar geodesy.[1] For example, SLR is a useful tool for determining the earth's gravitational field and detecting movements of tectonic plates. The principle behind SLR is to precisely determine a satellite's location by measuring the distance from a ground station to a satellite by the time an ultra-short laser pulse fired

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from the ground takes to reach and be reflected back from the satellite. This process is called "ranging" to the satellite. By combining multiple measurements from worldwide time-synchronized stations, a satellite's orbit can be determined with sub-centimeter precision.

Beginning in September 2006 reports surfaced that, on multiple occasions, China aimed ground-based lasers at U.S. satellites. Few details emerged, leading to speculation and confusion about what actually occurred. Some claimed that these incidents were evidence that China was testing laser anti-satellite (ASAT) weapons. In particular, a story appearing in the *Defense News* claimed that China had recently "fired high-power lasers at U.S. spy satellites flying over its territory in what experts see as a test of China's ability to blind the spacecraft."[2]

Shortly after the release of the *Defense News* report, Command Sergeant Major David Lady of the Joint Functional Component Combat Command for Integrated Missile Defense, stated at the Strategic Space and Defense conference (October 2006) that these incidents were also detected, most likely by data obtained by the National Reconnaissance Office, after U.S. satellite operators observed that the satellites occasionally failed to perform over China.[3] "There had been times when we wondered at the sudden decline in effectiveness as the satellites passed over China." Major Lady stated that these anomalies were also detected by satellite tracking sensors at the Reagan Test Site on Kwajalein atoll. "We sensed the projection of beams against the spacecraft and could identify the streams of photons." According to *Jane's*, he stated that this was evidence of a Chinese laser countermeasure system. However, Donald Kerr, Director of the Pentagon's National Reconnaissance Office, while acknowledging that something had occurred, said that "it did not materially damage the U.S. satellite's ability to collect information."[4] In addition, Gen. James Cartwright, who was in charge of U.S. military operations in space at the time, said that the United States had not seen clear indications that China had intentionally disrupted American satellite capabilities.[5]

The details released to the public were insufficient to determine what actually happened. One theory is that China was testing laser weapons intended to disrupt the satellites. However, there are other reasons to illuminate satellites with lasers, and here we present analysis of a different possibility—laser ranging to determine satellite orbits—which appears to be compatible with the statements of Kerr and Cartwright, but is not evidence of laser ASAT weapons. Moreover, based on our analysis, we suggest a way to distinguish whether the lasers used were appropriate for ranging or for a laser ASAT weapon.

LASER RANGING CAPABILITIES IN CHINA

The worldwide network of laser ranging stations is part of the International Laser Ranging Service[6] (ILRS), based at the Goddard Space Flight

Center in Greenbelt, Maryland, USA. The ILRS collects, merges, analyzes, and distributes SLR data from 40 stations in 23 countries (see Figure 1). These SLR stations track approximately 31 satellites that support passive geodetic, remote sensing, navigation, and engineering missions.

This paper discusses two classes of satellites, cooperative and uncooperative. Cooperative satellites are fitted with passive retro-reflecting mirrors providing strong reflected signals. Uncooperative satellites do not have retro-reflecting mirrors resulting in much weaker return laser pulses.

The ILRS primarily tracks cooperative satellites. There are seven SLR stations in China that are members of the ILRS. These seven stations are engaged in geodetic research using pulsed lasers of roughly 1 W average power. Five stationary stations are located in Shanghai, Changchun, Beijing, Wuhan, and Kunming (see Figure 2). There are at least two functional mobile stations. During 2000–2001 these mobile units were deployed in Western China, in Lhasa, Tibet and Urumchi, Xinjiang.[7] One mobile station may be located northeast of Changchun, close to the North Korean border and the town of Tonghua.[8]

Although the SLR stations normally range to cooperative satellites, the Shanghai station has the capability to range to orbital debris on an experimental basis. In late 2005, as part of a cooperative effort between the two countries; China installed an SLR station in San Juan, Argentina, similar in design to the other fixed stations in China.[9] The authors are not aware of any additional SLR stations that might, for example, be operated by the Chinese military.

DAYTIME vs. NIGHTIME SLR

Conducting SLR during the day is more complicated than at night since the much brighter sky background during the day increases the difficulty of detecting a weak laser return signal reflected by a satellite. However, collecting SLR data during the day as well as night permits a better determination of the satellite's orbit. Wavelength filters and electronic "range-gates" on the satellite can suppress sky noise dramatically, and post-processing permits the extraction of the true reflected laser signal photons from random background photons. Daylight SLR does not requires a more powerful laser due to these filtering technologies and post processing techniques. Many of the ILRS stations regularly track cooperative satellites during the day (Figure 3).

The Shanghai Astrophysical Observatory pioneered daylight SLR capability for China in 1996 but daylight tracking has reportedly been suspended

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[1]International Laser Ranging Service, ILRS Governing Board Meeting, Vienna, Austria, April 2006, <http://ilrs.gsfc.nasa.gov/docs/gbinfo060407.pdf> (March 2009).

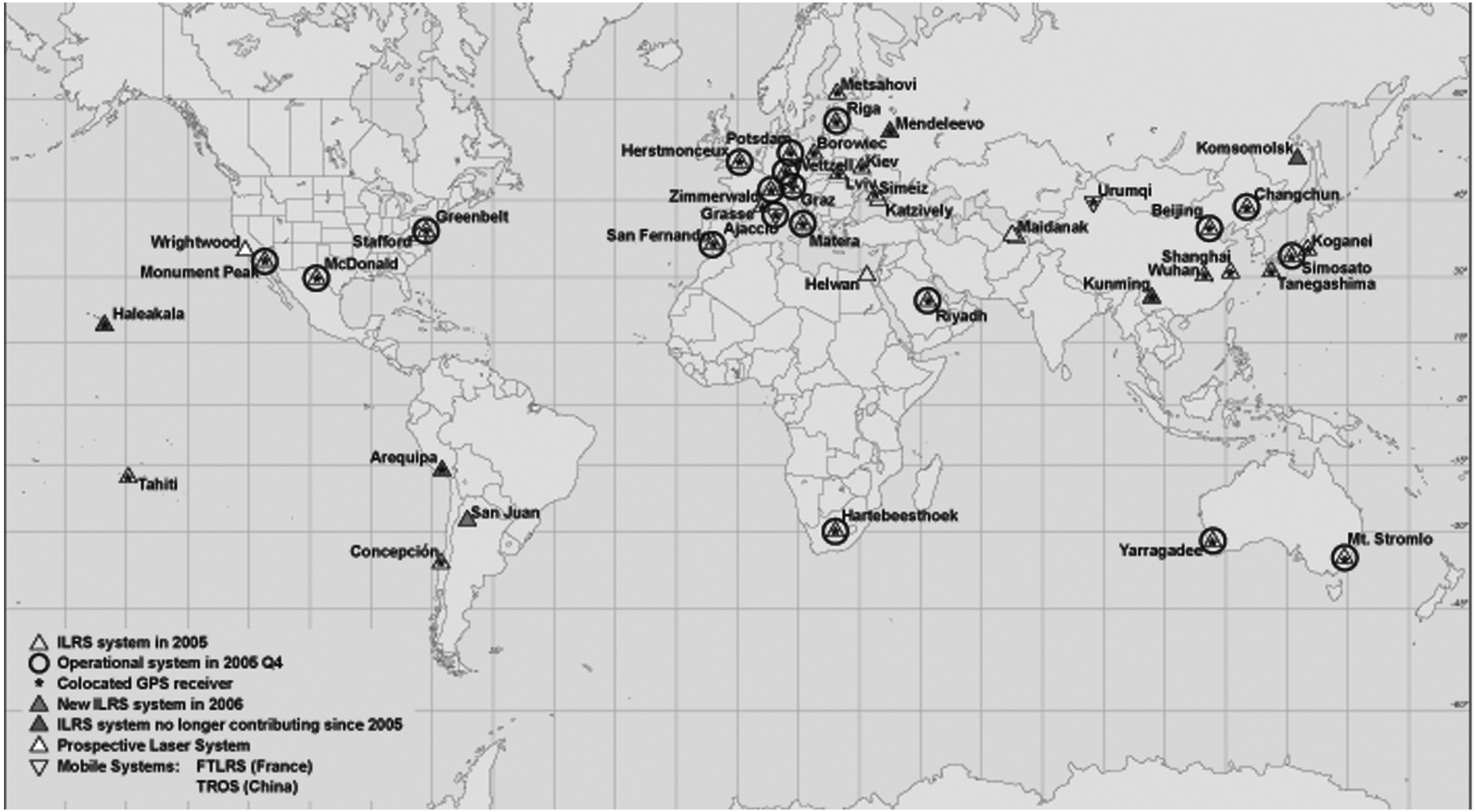

Figure 1: International Laser Ranging Service network in 2005, Q4.[1]

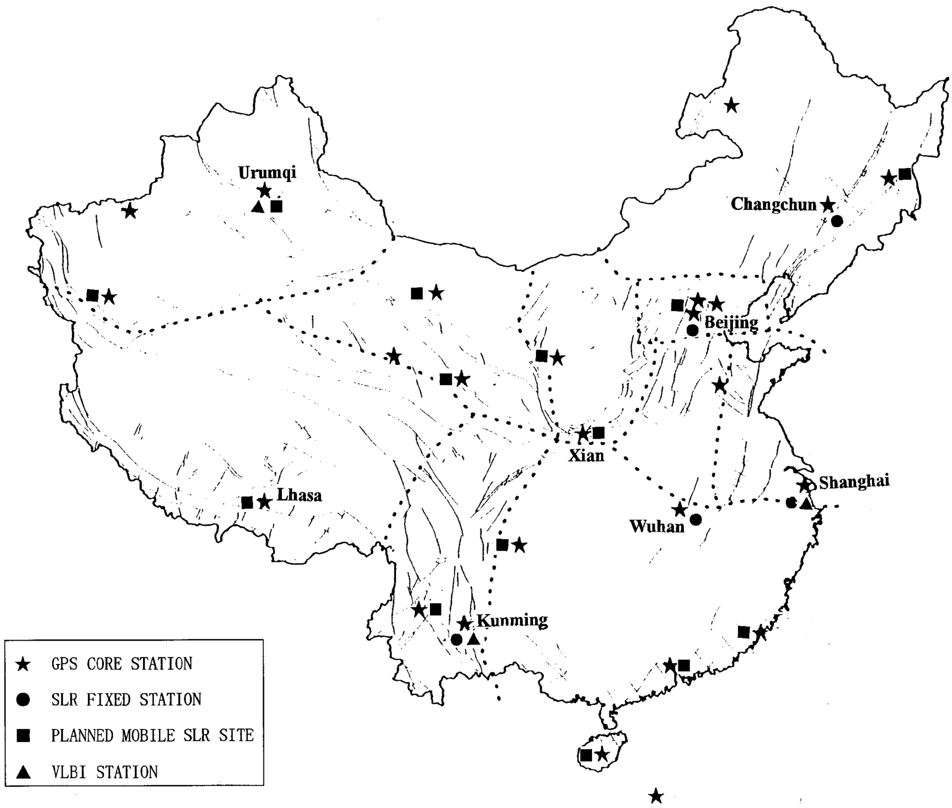

Figure 2: Distribution of Chinese fixed satellite laser ranging stations and the planned mobile sites.[2]

since 2001. Recently the Changchun Observatory[11] in northeast China near North Korea (Figure 4) acquired daylight SLR capability.[12–14] The Kunming SLR station has been reported to be preparing for daytime SLR.

Ranging to uncooperative satellites may be useful for tracking and maintaining a catalog of space objects such as the orbits of reconnaissance satellites passing overhead.

It is not known whether any of the Chinese SLR stations regularly range to uncooperative satellites. Shanghai has the capability to collect orbital information on space debris on an experimental basis using a 40 watt (W) average power pulsed laser. It is possible that similar lasers are now operational at other Chinese SLR sites and may be an effective method of obtaining orbital information on large satellites in low earth orbit (LEO).[15]

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[2]International Laser Ranging Service, ILRS 1999 Annual Report, Section 4. Network Reports, 116, http://ilrs.gsfc.nasa.gov/reports/ilrs_reports/ilrsar/1999/ilrsar99_section4.pdf> (March 2009).

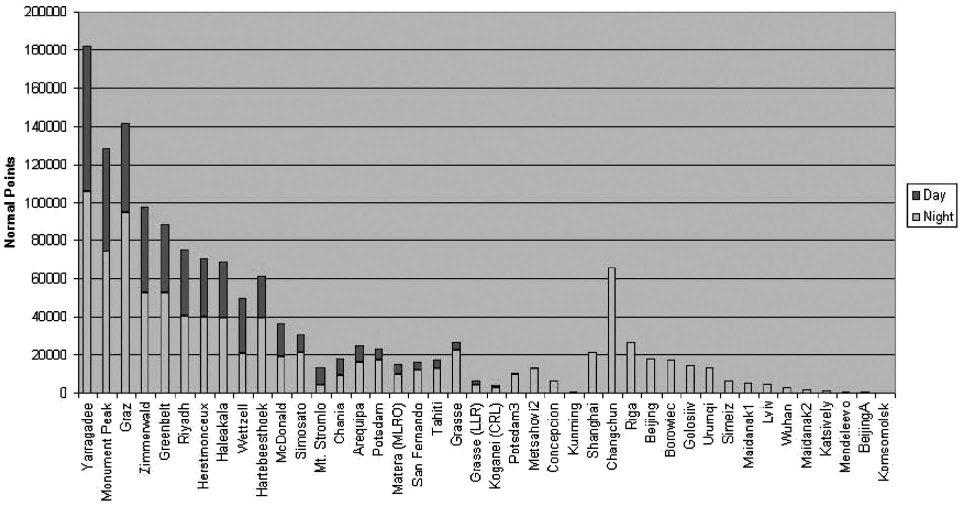

Figure 3: Daytime *vs.* nighttime SLR capability for International Laser Ranging Service stations worldwide. Normal points (y-axis) are averages (approximately 2 minutes long) of multiple single shot ranges to a given satellite.[3]

IMPACTS OF LASERS ON GROUND-IMAGING SATELLITES IN LOW EARTH ORBIT

If lasers similar to those used in the Chinese SLR stations were used for ranging to a ground-imaging satellite in LEO, and the SLR operators were careful to avoid ranging when the satellite was overhead (i.e. near the zenith, when its detectors could view the laser), it would be essentially harmless – although potentially noticeable. If the SLR operators were not careful, and they ranged to an imaging satellite close to the zenith, then there is an approximately 1 in 1,000 chance that they could cause some damage to the filters covering the sensors, or possibly to a small section of the sensor itself, if the ground region viewed by the satellite as it passed overhead included the location of the laser (see the following sections for details on how this was derived). (This also assumes that the satellite does not have shutters or other systems that would protect the detector from high-intensity light.) The power of the 1 and 40 W SLR systems is too low to interfere with the satellites through heating effects or to cause physical damage to components other than the sensitive imaging sensor.

Researchers and SLR operators in China are aware of these dangers and are likely to follow established operational guidelines to prevent occurrences of potentially harmful illuminations.[16]

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[3]International Laser Ranging Service site list, <http://ilrs.gsfc.nasa.gov/stations/sitelist/> (March 2009).

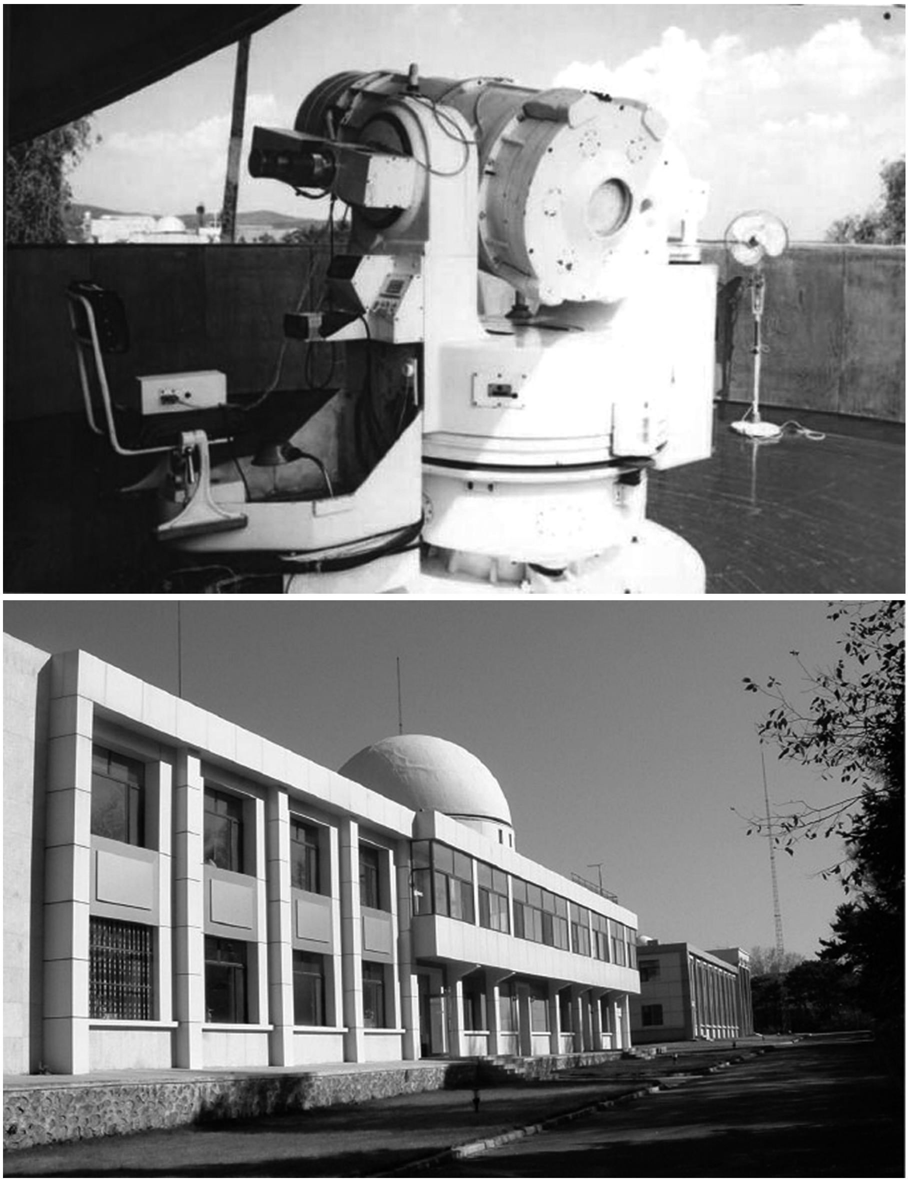

Figure 4: Changchun station.[4]

China's currently known SLR ranging stations should not be considered ASAT weapons due to the low probability of assured damage to a ground-imaging satellite's imaging sensor. However, even the slightest probability of sensor damage in an inadvertent or improper laser ranging argues for

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[4]International Laser Ranging Service, ILRS 1999 Annual Report, Section 4. Network Reports, 118, http://ilrs.gsfc.nasa.gov/reports/ilrs_reports/ilrsar/1999/ilrsar99_section4.

development of international rules governing the use of SLR, such as prohibiting unauthorized SLR or allowing SLR only when the satellites are away (i.e., 30 degrees or more) from the local zenith, as viewed from the SLR stations.

CHINESE SLR STATION LOCATIONS AND SPECIFICATIONS

The Chinese SLR stations typically use a solid-state Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) pulsed laser to generate 0.532 micrometer (0.532×10^{-6} m) wavelength green light with a 200 picosecond (200×10^{-12} sec) pulse width. This laser has an energy of 0.1 J per pulse and possible repetition rates of 1, 2, 4, 5, 8 and 10 Hz (pulses per second), corresponding to a maximum average power of 1 W (for the maximum 10 Hz rate). In practice, a repetition rate of 4 to 8 Hz is used.[17] The aperture of the transmitting and receiving telescope is 15 cm and 60 cm respectively. The lasers at the Changchun station operate with these parameters. Lasers at other Chinese fixed SLR sites are similar in design. The Chinese SLR systems currently operate with one pulse at a time during transit between the ground and the satellite. Systems with higher repetition rates are more complex because multiple pulses are in transit between the ground and the satellite and sophisticated techniques are necessary to correlate transmitted and received pulses in order to determine the time of flight.

The Shanghai Astronomical Observatory is experimenting with a higher powered laser at the same wavelength, producing 2 J pulses of 10 nanosecond (10×10^{-9} sec) duration at a 20 Hz repetition rate corresponding to an average power of 40 W. This experimental laser is focused through a 21 cm aperture telescope and is reportedly used for ranging to orbital debris.[18] A similar system at Mt. Stromlo in Australia is reported to track 15 cm debris fragments at about 1250 km altitude.[19] A 40 W laser with these parameters is capable of ranging on an uncooperative satellite, depending on its size and altitude.

Lasers at the mobile stations are reported to have an average maximum power of about 0.4 W[20] with 15–40 mJ per pulse and a 10 Hz repetition rate.

EFFECTS OF 1 to 40 W LASERS ON IMAGING SATELLITES

High-resolution earth-imaging satellites orbit at altitudes of 1,000 kilometers or less and travel at approximately 7 km/sec, relative to the surface of the earth. An SLR station can view the satellite for approximately 15 minutes during each orbit. Most earth-imaging satellites use imaging sensors (linear detectors) to produce their images using the "pushbroom" method (Figure 5).[21] The sensors contain an array of light-sensitive elements, or pixels, that measure

pdf> (March 2009). More detailed information can be found at <http://www.cho.ac.cn/> (March 2009).

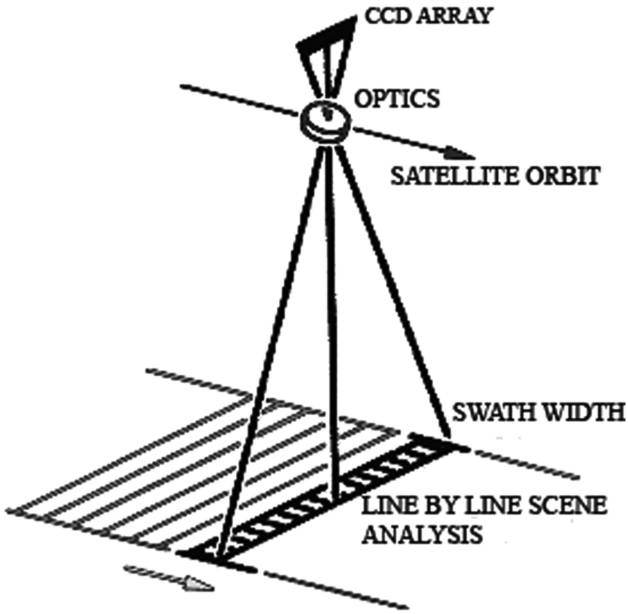

Figure 5: An illustration of the "pushbroom" method of satellite imaging.[5]

light at different wavelengths. As the satellite orbits over the earth, the sensors collect a series of linear images that are combined to form a two-dimensional color image, in a method similar to a desktop scanner.

Most sensors are covered by filters that permit only a specific range of visible light frequencies to reach the sensors. Narrow-band filters allow a limited range of frequencies to be collected, for example, only the red part of the light spectrum.

The satellite's telescope collects light from the ground and focuses it on the sensor. It has a total field of view of about 1 degree, corresponding to 10 km on the ground (Figure 6). It moves along the ground at approximately 7 km/sec, imaging a thin strip of the ground as it moves, utilizing approximately 10,000 pixels of the linear detector array. Each pixel corresponds to approximately a 1-meter $\times$ 1-meter region on the ground. A spot on the ground will remain in the telescope's field of view for about 1.5 sec if it passes through the center of the field of view, even though it is only imaged by the sensor strip for 10^{-4} seconds. A ground based laser from an SLR station can illuminate an LEO satellite during the 15 minute interval that it is in view of the station.

As an example, Geoeye/Space-Imaging's IKONOS satellite has a resolution of approximately 1-meter. Its imaging sensor contains a strip of 13,500 pixels

[5]Figure from SPOT website:<http://spot4.cnes.fr/spot4_gb/hrvir.htm> (March 2009).

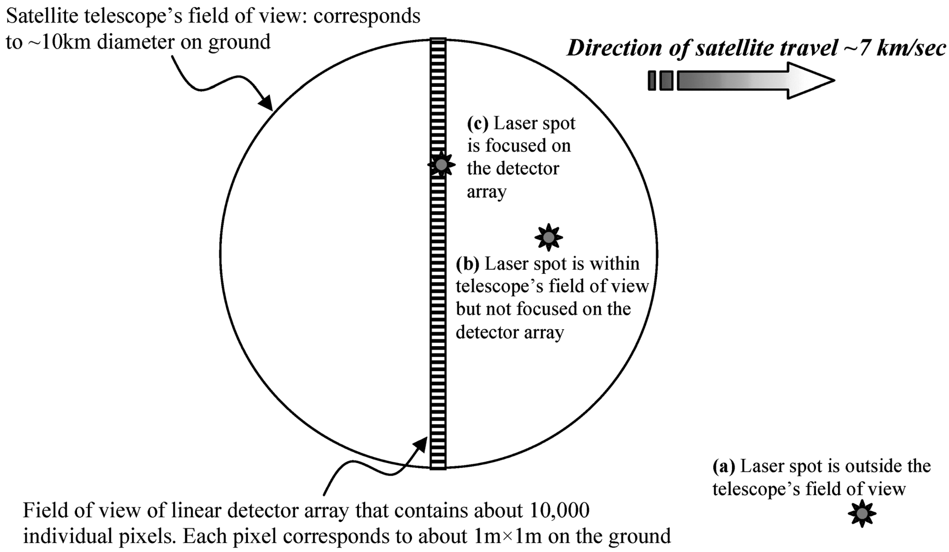

Figure 6: A schematic of the field of view of an imaging satellite's telescope and the linear detector array that collects the signal from the ground. Three locations of the laser aimed at the satellite are shown corresponding to the three cases examined in the text.

and views a swath on the ground 10km wide and approximately 1-meter in the direction of motion.[22] At a speed of 7 km/s, the swath passes over a 1-meter area in approximately 10^{-4} sec.

When a ground-based laser is trained upon an earth observing satellite, it can have one of several effects, in order of severity:

a) If the laser is outside the field of view of the satellite's telescope, then a small amount of laser pulse may reach the satellite's imaging sensor and has the potential to scatter into the telescope optics. This small amount of light may produce slight changes in the background noise level of the sensor pixels, which are potentially detectable by the satellite operators.[23] If a filter effectively excludes the laser's frequency then these effects may be reduced or eliminated altogether.

b) If the satellite's telescope views the region on the ground that contains the laser illuminating the satellite, but the image of the laser does not fall upon the linear detector (see Figure 6), then it is still possible that a small fraction of laser light will be diffracted onto the detector.[24] For low laser power, if this light is transmitted through the filter, it would result only in a region of enhanced brightness in the reconstructed image. However, if the laser source is powerful enough, then the laser light that is diffracted onto the detector can be strong enough to overwhelm the light collected from the ground in the area immediately around the laser and obscure the image in that small area, while not damaging the detector. This is referred to as "dazzling," and is temporary and reversible.[25] Dazzling only occurs in a small area near the source of the laser during the single second that the laser is in the visible field of the telescope—it does not obscure images at greater distances. A more detailed description of dazzling can be found in the Appendix.

c) If the satellite's linear detector views the spot on the ground where the laser is located, then a bright image of the laser will be focused onto the detector, assuming the laser is pulsing at the time. This will occur only during that short period ($\sim 10^{-4}$ sec) when the satellite's detector directly views the region on the ground containing the laser (see Figure 6). In this case, the effect on the satellite will depend on the power of the laser. Assuming the filter is transparent to the laser light, at sufficiently low laser power, this would result only in a bright spot on the image of the ground. At somewhat higher power, the laser light can be strong enough to overwhelm the light reflected from the ground scene and obscure the image in a small region around the location of the laser, while not damaging the pixels. As in (b) above, this latter case is called dazzling and it is a temporary and reversible effect.

   If the filter covering the detector does not transmit the laser light's wavelength, then it will keep this light from getting to the detector pixels and dazzling will not occur. If the power of the laser is sufficiently high, and if the thin filter covering the detectors is not transparent to the laser light, the laser may permanently damage the filter. If instead, the filter does transmit the laser light, a small number of pixels around the location of the laser image may sustain permanent damage.[26,27] In this case, the affected pixels would be "blinded" permanently. For the laser powers considered here, only a few pixels could be damaged. As noted, for a pulsed laser operating at the low repetition rate considered here, the chance that a pulse is present at exactly the right time to damage the detector is very low.

Although there are no reports that Chinese SLR stations are illuminating uncooperative space objects besides debris, it is worth examining the potential for dazzling or blinding by pulsed lasers.

If a pulsed laser with a repetition rate of 10 Hz and short 0.1 J ranges an imaging satellite while the laser is in the field of view of the telescope, and the sensor is unfiltered, the sensor will be dazzled at each pulse. The image will be impacted approximately 10 km from the laser (Appendix 1). If a satellite with a 1 degree field of view passes over the laser, the laser will remain in the satellite's field of view for up to two seconds. For a 10 Hz pulsed laser, if the laser were in the field of view for 1.5 seconds, the telescope would see 15 pulses. Consequently, this would lead to 15 instances of dazzled pixels interleaved within the 15,000 linear images the detector would collect during that time that would be used to construct the ground image, which would therefore have a very minor effect on the reconstructed ground image. This assumes that the filters are transparent to laser light's frequency; if not, the dazzling will be less severe or possibly undetectable.

If the laser's pulse coincides at exactly the moment (10^{-4} sec) that the satellite's telescope is viewing the laser, it is likely that the filter and/or the pixels viewing the laser and a few surrounding pixels may sustain permanent damage. The energy delivered by a 0.1 J pulse is approximately 100 times greater than the energy that is required to cause permanent damage. However, because the laser emits pulses every 0.1 seconds, the probability of the laser damaging the sensor or the filter in a single pass is only 10^{-4} sec/0.1 sec = 0.1%, or 1 in 1,000.

20 Hz, 40 W lasers have a greater probability of damaging the filters or the sensor because each pulse contains 2 J. If a 40 W laser passes through the filter, an area in the several tens of kilometers around the laser[28] will be intermittently dazzled.[29] In the unlikely event that the laser emits a pulse during the 10^{-4} seconds that the sensor is in view of the laser, the filter and/or the pixels viewing the lasers and adjacent pixels are likely to sustain permanent damage. Assuming that the laser fires every 0.05 sec, the probability that the laser will cause permanent damage to the filter and/or the sensor is 10^{4} sec/0.05 sec = 0.2%. This example assumes the satellite is equipped with a robust Silicon based sensor; other sensor materials typically have lower damage thresholds.[30]

Even if the laser is outside the view of satellite's telescope, stray light from the illumination may scatter within the satellite optics and, if unfiltered, may alter the background levels of the sensor. Any anomalous background levels are likely to be detected by the satellite operators during the regular (typically daily) health and status monitoring.[31]

CONCLUSION—POSSIBLE "RULES OF THE ROAD"

If an SLR station illuminated an imaging satellite when the satellite was not viewing the ground region containing the laser, any stray laser light reaching the detector or filter would not be intense enough to cause damage. Thus, assuming that the satellites image sections of the earth directly below them, SLR could be conducted safely when the satellite was low in the sky relative to the SLR station. For example, the French SPOT4 satellite has an oblique viewing capability of a maximum of 27 degrees on each side of its local vertical.[32] Therefore, creating a "no-SLR" exclusion zone of 30 degrees about the local vertical for an SLR station ranging to uncooperative satellites (i.e. those without retro-reflectors and not designed to be ranged-to) may be reasonable enough to ensure that the detectors of imaging satellites will not incur damage. However, if a given country is interested in ranging to its own uncooperative satellites, exceptions could be approved and catalogued via some agreed-upon forum such as the ILRS.

Finally, we note that the laser powers used for SLR are low enough that they would not interfere with satellites through heating effects or by causing physical damage to parts of satellites other than the sensors.

Future SLR systems may reduce concerns of damaging space based detectors by significantly reducing the power per pulse and increasing the pulse repetition rate. NASA has developed the SLR2000 system that operates with two hundred times the repetition rate (2,000 Hz) of the systems discussed previously with approximately one-thousandth of the energy per pulse (135 mJ).[33]

NOTES AND REFERENCES

1. Goddard Space Flight Center's Laboratory for Terrestrial Physics 2001 Annual Report <http://ltpwww.gsfc.nasa.gov/ltp/2001_annual_report/4_laserinst.pdf> (December 2006).

2. Vago, Muradian, "China Attempted to Blind U.S. Satellites with Laser," *Defense News*, 28 September 2006 <http://www.defensenews.com/story.php?F=2125489) (January 2007).

3. "US Claims that China has Used Lasers to Attack Satellites," *Janes Defense Weekly*, 16 October 2006 < http://www.janes.com/aerospace/military/news/jdw/jdw061016_1_n.shtml> (January 2007).

4. Andrea Shalal-Esa, "China Jamming Test Sparks U.S. Satellite Concerns," Reuters, 5 October 2006.

5. Elaine M. Grossman. 2006. Top Commander: Chinese Interference with U.S. Satellites Uncertain. *Inside the Pentagon* 22(41) (12 October) <http://www.worldpoliticswatch.com/article.aspx?id=267> (January 2007).

6. The International Laser Ranging Service maintains a website at <http://ilrs.gsfc.nasa.gov/> (December 2006).

7. International Laser Ranging Service, ILRS 2001 Annual Report, 1–3 <http://ilrs.gsfc.nasa.gov/reports/ilrs_reports/ilrsar/2001/Section_4_web.pdf> (December 2006).

8. Although not related to the SLR stations, researchers from the 55th Research Institute of the Ministry of Industrial Electronics, located in the nearby town of Jinzhou in Liaoning province, have reported that China possesses reflective mirrors and adaptive optics capabilities comparable to those of the United States' STARFIRE optical range. See: Wang Min. 1999. "Anti-Satellite Optical Sensor Laser Countermeasure Technology," *Electro-Optics and Passive Countermeasures* 2:19-22 (in Chinese).

9. Details of the San Juan station can found at the ILRS website <http://ilrs.gsfc.nasa.gov/stations/sitelist/> (December 2006).

10. W. A. Baum, The Detection and Measurement of Faint Astronomical Sources, *Astronomical Techniques, Stars and Stellar Systems II* (Chicago: University of Chicago Press, 1962), 1–33.

11. The Changchun Observatory is located at latitude 43.7905°N and longitude 125.4433°E <http://www.cho.ac.cn/> (December 2006).

12. F. Yang, "Current Status and Future Plans for the Chinese Satellite Laser Ranging Network," *Surveys in Geophysics* 22(5) (2001): 465–471.

13. You Zhao et al. "Progress for Daylight Tracking in Changchun SLR System." (paper presented at the 14th International Workshop on Laser Ranging, 7–11 June 2004,

San Fernando, Spain) <http://cddis.nasa.gov/lw14/docs/papers/upg2_yzm.pdf> (December 2006).

14. You Zhao et al. "Fulfillment of SLR daylight tracking of Changchun Station. (paper presented at the 15th International Laser Ranging Workshop, 15–20 October 2004, Canberra, Australia) <http://ilrscanberraworkshop2006.com.au/workshop/abstracts/Fulfillment%20of%20SLR%20daylight%20tracking%20of%20Changchun%20station.pdf> (December 2006).

15. An LEO satellite orbits the earth at altitudes of approximately 200 km to 2,000 km, travels at high speeds to resist the pull of gravity (approximately 27,000 km per hour) and orbits the planet in 90 minutes.

16. Niu Yanxiong et al. "Investigation of Laser Disturbance and Damage to Satellite-borne Photoelectric Detecting System" *Acta Photonica Sinica* 33(7) (2004).

17. Chengzhi Liu et al. "The Performance of Changchun SLR Station" (paper presented at the 14th International Workshop on Laser Ranging, San Fernando, Spain, 7–11 June, 2004) <http://cddis.nasa.gov/lw14/docs/papers/upg1_lcm.pdf> (December 2006).

18. Yang Fumin et al. "The Experimental Laser Ranging System for Space Debris at Shanghai" (paper presented at the 15th International Laser Ranging Workshop, in Canberra, Australia, 15–20 October, 2006) <http://ilrscanberraworkshop2006.com.au/workshop/abstracts/Experimental%20Laser%20Rangin%20System%20for%20Space%20Debris%20at%20Shang.pdf > (December 2006).

19. B. Greene, "Laser Tracking of Space Debris" (paper presented at the 13th International Workshop on Laser Ranging Instrumentation, October 2002) <http://cddis.nasa.gov/lw13/docs/presentations/adv_green_1p.pdf> (December 2006).

20. International Laser Ranging Service, ILRS 2001 Annual Report, <http://ilrs.gsfc.nasa.gov/reports/ilrs_reports/ilrsar/2001/Section_4_web.pdf> (December 2006).

21. An alternative is the "step-stare" method. A two-dimensional array of detector pixels, similar to a digital camera's sensor, a patch of ground is tracked and imaged by the camera, followed by the next patch of ground.

22. G. Petrie, "Optical Imagery from Airborne and Spaceborne Platforms." *GeoInformatics*, 5(1) (2002):28–35.

23. For example, the pixels on CCD sensors on board the orbiting "CHANDRA" X-ray Observatory are continuously monitored for health and safety, and operators are notified if anything anomalous is found. <http://cxc.harvard.edu/mta_days/mta_bad_pixel/mta_bad_pixel_list.html> (December 2006).

24. D. Wright, L. Grego, and L. Gronlund, *The Physics of Space Security, A Reference Manual* (Cambridge: American Academy of Arts and Sciences, 2005) 117–147. <http://www.ucsusa.org/assets/documents/nwgs/space_security.pdf> (March 2009).

25. Wright et al., *Physics of Space Security.*

26. Wright et al., *Physics of Space Security.*

27. This assumes that the satellite does not have shutters or other systems to protect the detector from high-intensity light.

28. If the field of view of the detector is smaller than several 10's of km, then dazzling can only occur in the full field of view.

29. Wright et al., *Physics of Space Security.*

30. F. Bartoli et al. "Irreversible Laser Damage in IR Detector Materials," *Applied Optics* 16 (1977):2934–2937.

31. See note 23.

32. Website of *The SPOT Earth Observation System*, General Architecture <http://spot4.cnes.fr/spot4_gb/satellit.htm> (December 2006).

33. J. McGarry, T. Zagwodzki and J. Degnan. "SLR2000 Closed Loop Tracking with a Photon-Counting Quadrant Detector" (paper paper presented at the 13th International Workshop on Laser Ranging, 7-11 October, in Washington, D.C., 7–11 October 2002). <http://cddis.nasa.gov/lw13/docs/papers/auto_mcgarry_1m.pdf> (December 2006).

34. Wright et al., *Physics of Space Security.*

35. Wright et al., *Physics of Space Security*.

36. Bartoli et al., "Irreversible Laser Damage."

37. The atmospheric transmission (T) for visible laser light for elevation angles above about 10 degrees ranges from ~0.5 to ~0.8. Since very low elevation angles and not considered, and as a conservative measure, $T = 1$. For more accuracy, the parameter $T =$ e$-\tau$ sec(Z), where $\tau = 0.009\ \lambda{-}4{+}0.223$ and Z is the angle from the zenith, and λ is the wavelength of the light in microns. See e.g., Kaula, W. M. 1962. *Advances in Geophysics, Volume 9,* Edited by H. E. Landsberg and J. van Mieghem (New York, Academic Press, Inc., 1962) 191–293.

38. Bartoli et al., "Irreversible Laser Damage."

APPENDIX: LASER DAZZLING AND DAMAGE ESTIMATES

Dazzling

Dazzling is a temporary and reversible phenomenon and occurs when the intensity of the—direct or scattered—laser light incident on a given pixel is strong enough to overwhelm the light that would have been collected from the region on the ground corresponding to that pixel. In effect, the laser light "swamps" the signal from the ground.

Scattering of the laser light in the satellite optics occurs due to two main mechanisms. Firstly, the finite diameter of the telescope mirror leads to diffraction, which spreads roughly 16% of the incoming laser intensity into a pattern of concentric rings around the main image of the laser spot. Secondly, imperfections in telescope optics lead to "leakage" of intensity from a perfectly point-like image of the laser spot into a slightly extended region. Such imperfections can also result in "glints" or bright reflections from edges of the optical elements and/or their support structure.[34] We estimate the size of the region of the sensor that would be dazzled by a pulsed laser in the following manner. A satellite in LEO will pass over a 1-meter area on the ground in roughly 10^{-4} sec. For a satellite with 1-meter ground resolution, we would therefore expect that the pixels that make up the sensor would collect photons for approximately that same length of time before reading out the value and resetting to collect photons from the adjacent 1-meter area.

A pixel detecting a 200 picosecond pulse with energy of 0.1 J collects the same number of photons as a 1 kilowatt continuous laser for 10^{-4} sec. The dazzling effect is the same in both cases and the image will be impacted for approximately for 10 km from the laser.[35] The maximum region that can be dazzled cannot exceed the field of view of the sensor.

The duration of the dazzling is determined by the cycle time of the pixels rather than the length of the pulses, so dazzling will last approximately 10^{-4} sec rather than 20 picoseconds.

Damage

If a laser is illuminated for 10^{-4} sec or less, the damage threshold for silicone-based sensor materials is[36] 100 J/cm^2, or 10^6 J/m^2. This applies both to the pulsed and continuous lasers because the duration of the illumination is determined by the time it takes the satellite to cross one resolution unit on the ground, 10^{-4} sec.

Assuming a λ = 0.5 micrometer wavelength laser and a D_L = 15 cm diameter focusing mirror, similar to the lasers at the Chinese SLR stations,, the laser will be focused at range R = 800 km into a spot of diameter $1.22\lambda R/D_L$, or:

$$1.22(0.5 \times 10^{-6}\ \mathrm{m}) \times (8 \times 10^5\ \mathrm{m}/0.15\ \mathrm{m}) = 3.25\ \mathrm{m}.$$

To be conservative in the damage estimates we have not considered the effects of atmospheric defocusing of the laser, which broadens the spot size at the satellite.

Assuming a 0.1 J pulse (and atmospheric transmission of 1)[37], and a 1-meter diameter mirror on the satellite's telescope, then the amount of that energy going through the telescope is:

$$0.1\ \mathrm{J} \times (1/3.25)^2 \sim 0.01\ \mathrm{J}$$

This energy will be focused by the satellite optics onto one pixel, which for imaging satellites is approximately 10 micrometers (10^{-5}m) on a side. Focusing 0.01 J on an area of 10^{-10} m^2 gives a power density of:

$$0.01\ \mathrm{J}/(10^{-10}\mathrm{m}^2) = 10^8\ \mathrm{J/m}^2.$$

This density is 100 times the damage threshold of 10^6 J/m^2, and will damage the pixel unless the laser light is filtered. In this case both the pixels and the filter may be damaged. As noted above, the probability of such a laser pulse being fired just as the satellite is viewing the spot on the ground containing the laser is only 0.1%.

Note that silicon based sensors are at least an order of magnitude more robust against laser damage than other typical sensor materials.[38]