# Satellite Laser Ranging in China

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## ABSTRACT

Satellite Laser Ranging (SLR) is a widely used technique for determining the orbits of objects in space with high accuracy. There are seven known SLR stations in China, two of which are mobile. These stations are part of a scientific collaboration called the International Laser Ranging Service (ILRS) based at the Goddard Space Flight Center in Greenbelt, Maryland. The typical average laser power used in the Chinese SLR stations is below about 1 Watt (W), although experimental systems of roughly 40W have also been used to characterize objects such as space debris. Most of the ranging takes place at night although some capability for more technically challenging daytime SLR reportedly exists at two of the fixed stations. In this paper, we consider laser ranging to an earth-observing imaging satellite and what effect that might have on the satellite. We show that under a broad set of conditions such ranging would not adversely affect the satellite's sensitive detector, but that cases exist in which the effects can be significant, although the probability of damaging the detector is extremely low. We find that SLR cannot be considered an anti-satellite (ASAT) weapon and, in fact, would be ineffective in this role. Nonetheless, the possibility of laser ranging to ground-imaging satellites without authorization, resulting in unexpected detector performance, is motivation for converging on a set of international rules governing it use.

## INTRODUCTION

Satellite Laser Ranging (SLR) is a method of determining a satellite's orbit very precisely, and is of scientific value in a number of fields, primarily earth and lunar geodesy.[2] For instance, SLR is a very useful tool in accurately determining the earth's gravitational field and detecting small tectonic plate motions. The basic idea 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 from the ground takes to reach and be reflected back from the satellite, and by determining the angle to the satellite from the ground-station. This process is called "ranging" to the satellite. By combining many such measurements from time-synchronized stations worldwide a satellite's orbit can be determined with sub-centimeter precision.

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[2] See, eg., Goddard Space Flight Center's Laboratory for Terrestrial Physics 2001 annual report: http://ltpwww.gsfc.nasa.gov/ltp/2001_annual_report/4_laserinst.pdf , accessed December 7, 2006.

**FIGURE 1: INTERNATIONAL LASER RANGING SERVICE (ILRS) NETWORK IN 2005 Q4**

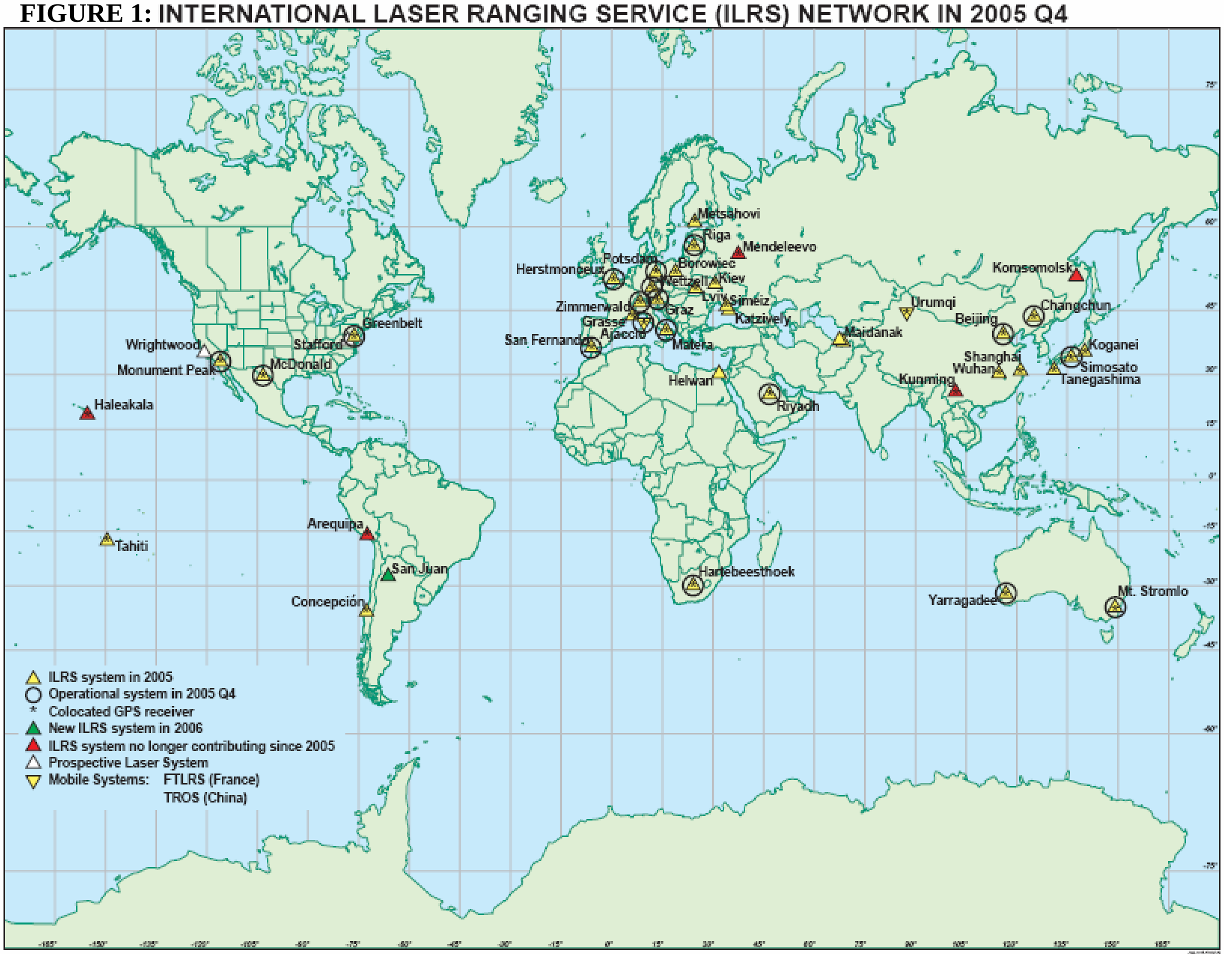


*Figure from ILRS Governing Board Meeting April 2006: http://ilrs.gsfc.nasa.gov/docs/gbinfo_060407.pdf*

China is part of a world-wide network of laser ranging stations known as the International Laser Ranging Service[3] (ILRS) based at the Goddard Space Flight Center in Greenbelt, Maryland. The ILRS collects, merges, analyzes and distributes SLR data from 40 stations in 23 countries (Fig. 1). These SLR stations track about 31 satellites that are fitted with passive retro-reflecting mirrors to give a strong reflected signal; these satellites include passive geodetic, remote sensing, navigation and engineering missions. These satellites are called "cooperative;" those without retro-reflecting mirrors are called "uncooperative" as their return laser pulses are much weaker.

The five fixed Chinese SLR stations are located in Shanghai, Changchun, Beijing, Wuhan and Kunming (see Figure 2). There are also at least two mobile SLR stations. The SLR stations normally only range to the cooperative satellites, even though the Shanghai station also ranges to orbital debris on an experimental basis. We are not aware of any additional SLR stations that might, for example, be operated by the Chinese military.

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[3] The International Laser Ranging Service (ILRS) maintains a website at: http://ilrs.gsfc.nasa.gov/ , accessed December 7, 2006.

In late 2005, China also installed a SLR station in San Juan, Argentina as part of a cooperative effort between the two countries. It is similar in specifications to the other fixed stations in China.[4]

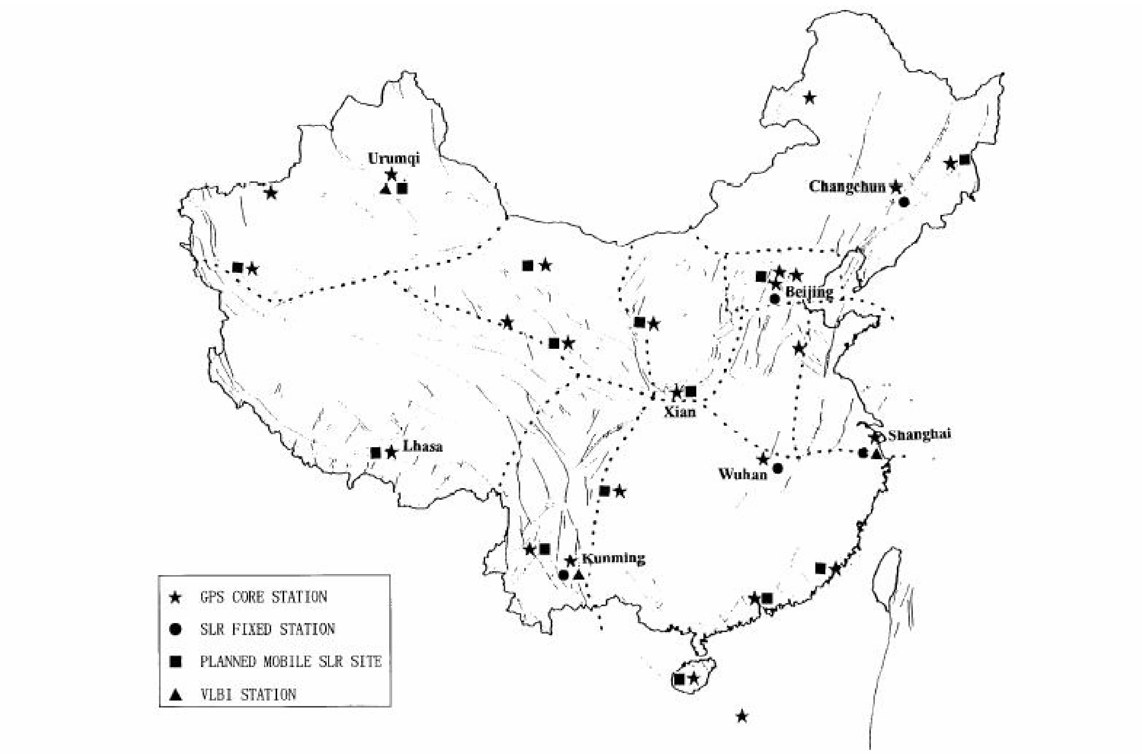



**FIGURE 2: Chinese fixed and mobile SLR sites, also from the 1999 ILRS report.**
**http://ilrs.gsfc.nasa.gov/reports/ilrs_reports/ilrsar/1999/ilrsar99_section4.pdf**

## 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 at night permits a better determination of the satellite's orbit. Many of the ILRS stations regularly track cooperative satellites during the day (Figure 3). Until about 1996 daylight SLR was not a mature technology in China; however, the Shanghai Astrophysical Observatory pioneered its development in China, and very recently the Changchun Observatory[5] in northeast China (Figure 4) has also acquired daylight SLR capability. [6, 7, 8] The Kunming SLR station has also been reported to be configuring

[4] Details of the new San Juan station can be linked via the ILRS website: http://ilrs.gsfc.nasa.gov/stations/sitelist/, accessed December 7, 2006.
[5] The Changchun Observatory is located at a latitude and longitude of (43.7905°N, 125.4433°E). See: http://www.cho.ac.cn/, accessed December 7, 2006
[6] Fumin Yang, "Current Status And Future Plans For The Chinese Satellite Laser Ranging Network," 2001, *Surveys in Geophysics* **22**, Issue 5, p.465-471
[7] You Zhao et al., "Progress for Daylight Tracking in Changchun SLR System," 2004, presented at the 14th International Workshop on Laser Ranging in San Fernando, Spain, June 7-11, 2004 http://cddis.nasa.gov/lw14/docs/papers/upg2_yzm.pdf , accessed December 7, 2006.

to do daytime SLR in the future. Daylight tracking has, however, reportedly been suspended at the Shanghai station since 2001 because the system was not stable. There is a plan to upgrade the capability of daylight tracking for the entire Chinese SLR network starting in 2007.[9] It is unknown whether any of the Chinese SLR stations range to satellites that do not have retro-reflectors, although the Shanghai SLR station is known to conduct SLR to space debris on an experimental basis using a 40W average power laser. This may be a plausible method of obtaining orbital information for large satellites in low earth orbit where the intensity of the reflected pulse could be strong enough.

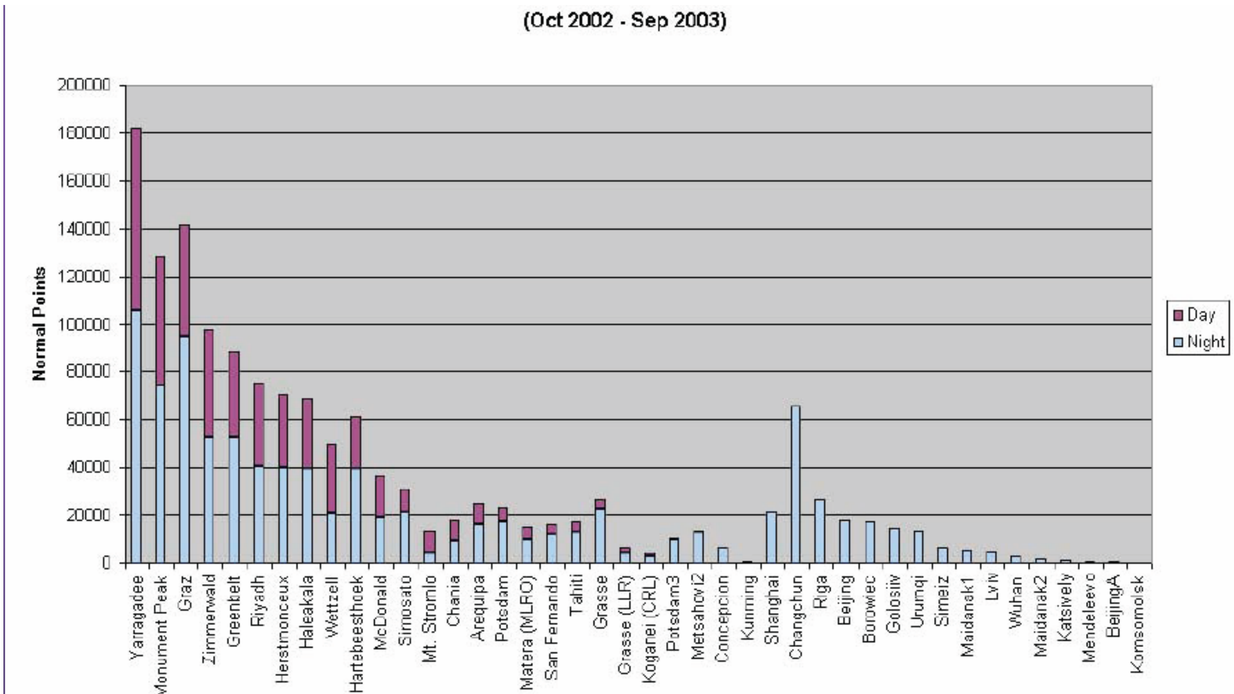



**FIGURE 3: Daytime *vs.* Nighttime SLR capability for ILRS stations worldwide. Note: the Shanghai Observatory had intermittent daytime SLR capability from about 1996 until roughly 2001. Figure from Ref. 8.**

As noted above, the main difficulty in daytime *vs.* nighttime SLR has to do with the much brighter sky background: the sky is a factor of about $10^7$ brighter during the day than at night at visible light wavelengths.[10] However, the use of wavelength filters and electronic "range-gates," which permit the ground-based sensor to detect signals with arrival times a few nanoseconds ($10^{-9}$ sec) before and after the reflected laser pulse is expected to arrive, can suppress the sky noise dramatically. Post-processing can then permit the extraction of the true reflected laser signal photons from the randomly timed sky background photons. A more powerful laser is not necessary for daylight SLR, and at Changchun the same laser used for night-time SLR is also used for daylight SLR.

[8] You Zhao et al., "Fulfilment of SLR daylight tracking of Changchun Station" , 2006, presented at the 15th International Laser Ranging Workshop, Canberra, Australia 15-20 October 2006 http://ilrscanberraworkshop2006.com.au/workshop/abstracts/Fulfillment%20of%20SLR%20daylight%20tracking%20of%20Changchun%20station.pdf , accessed December 7, 2006.
[9] Dr. Yang Fumin (Shanghai SLR station), personal communication, November 2006.
[10] Baum, W. A., "The Detection and Measurement of Faint Astronomical Sources", 1962, in *Astronomical Techniques, Stars and Stellar Systems* **II**, Univ. of Chicago Press, Chicago, pp. 1-33.

**FIGURE 4: Changchun SLR station , located at 43.7905 N latitude and 125.4433 E longitude; see http://www.cho.ac.cn/, accessed January 7, 2007. Images from the 1999 ILRS report, http://ilrs.gsfc.nasa.gov/reports/ilrs_reports/ilrsar/1999/ilrsar99_section4.pdf, accessed December 7, 2006.**

## SUMMARY OF TECHNICAL DISCUSSION

We are aware of seven SLR stations in China engaged in geodetic research using pulsed lasers of roughly 1 W average power. At least one of these stations (Shanghai) also has SLR capability to collect orbital information on space debris on an experimental basis using a 40 W average power pulsed laser. Two of the Chinese SLR stations are mobile. The Changchun station, in northeastern China near North Korea, reportedly also has daylight SLR capability as of this year.

It would be possible in some cases to use SLR to range to satellites that do not carry retro-reflectors, depending on details such as their size and altitude and the signal processing at the SLR site, in order to collect information on their orbits. Such information would be useful to a country interested in maintaining a catalog of space objects it is concerned about or particularly interested in. For example, a country may be interested in knowing the orbits of reconnaissance satellites that pass over its territory; these satellites change their orbits relatively frequently and since they are typically large and at low altitudes, they are likely to be attractive objects to track with SLR.

Below we analyze what effect the types of lasers used in SLR may have on a ground-imaging satellite in low earth orbit (LEO), i.e. those orbiting at altitudes ranging from a couple of hundred kilometers to about 2,000 km. 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), 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 a roughly 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. (This also assumes that the satellite does not have shutters or other systems that would protect the detector from high-intensity light.) However, researchers in China are aware of the dangers that lasers pose to ground imaging satellites' detectors, and it is likely that SLR operators have guidelines that avoid any such potentially harmful illumination.[11] In any case, the laser powers used for SLR are low enough that they will not interfere with satellites through heating effects or cause physical damage to parts of satellites other than possibly the sensitive detectors.

[11] Niu Yanxiong, et al., "Investigation of Laser Disturbance and Damage to Satellite-borne Photoelectric Detecting System" *Acta Photonica Sinica* **33**, No. 7, July 2004.

As a result, China's currently known SLR ranging stations cannot be considered ASAT weapons due to the low probability of assured damage to a ground-imaging satellite's detectors from their lasers. In fact, they would be ineffective in such a role.

However, even the small probability of detector damage in an inadvertent or improper SLR use argues for developing a set of international rules governing the use of such systems. For instance, all unauthorized SLR activities to satellites could be disallowed. Alternatively, restrictions could be instituted on allowing ranging to satellites only when they were below some angle from the vertical when viewed from the SLR station. In this case, it would be almost certain that an imaging satellite was not observing the laser at the same time that the laser was ranging to the satellite.

## TECHNICAL DISCUSSION

### I. LASER POWER LEVELS AND LOCATIONS

The Chinese SLR stations typically use a solid-state Nd:YAG (Neodymium-doped Yttrium Aluminum Garnet) pulsed laser to generate 0.532 micrometer ($0.532 \times 10^{-6}$ m) wavelength green light with a 200 picosecond ($200 \times 10^{-12}$ sec) pulsewidth. It 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.[12] The aperture of the transmitting telescope is 15 cm and that of the receiving telescope is 60 cm. These parameters apply to the laser used at the Changchun station, but the lasers used at other Chinese fixed SLR sites are very similar in design.

The Shanghai Astronomical Observatory is also experimenting with a higher average power laser at the same wavelength: it produces 2 J pulses of 10 nanosecond ($10 \times 10^{-9}$ sec) duration at a 20 Hz repetition rate. This corresponds to an average power of 40 W. This experimental laser is focused through a 21cm aperture and is reportedly used for ranging to orbital debris.[13] (A similar system at Mt. Stromlo in Australia has been reported to track 15 cm debris fragments at about 1250 km altitude.)[14] Such a laser would clearly also be capable of conducting ranging on a satellite without retro-reflecting mirrors, depending on its size and altitude. It is possible that similar lasers are now available at other Chinese SLR sites also.

A map of the locations of Chinese SLR sites is shown in Fig. 2: note the mobile SLR sites, at least two of which are currently functional. During 2000-2001 these mobile units were deployed in Western China, in Lhasa, Tibet and Urumchi, Xinjiang.[15] A possible location for one of the

[12] Chengzhi Liu, et al., "The Performance Of Changchun SLR Station," 2004, presented at the 14th International Workshop on Laser Ranging in San Fernando, Spain, June 7-11, 2004 http://cddis.nasa.gov/lw14/docs/papers/upg1_lcm.pdf , accessed December 7, 2006.
[13] Yang Fumin, et al., "The Experimental Laser Ranging System for Space Debris at Shanghai," 2006, presented at the 15th International Laser Ranging Workshop, Canberra, Australia 15-20 October 2006 http://ilrscanberraworkshop2006.com.au/workshop/abstracts/Experimental%20Laser%20Rangin%20System%20for%20Space%20Debris%20at%20Shang.pdf , accessed December 7, 2006.
[14] Dr. Ben Greene, EOS Technologies, "Laser Tracking of Space Debris," 2002, presentation at the 13th International Workshop on Laser Ranging Instrumentation, October 2002: http://cddis.nasa.gov/lw13/docs/presentations/adv_green_1p.pdf , accessed December 7, 2006.
[15] The International Laser Ranging Service (ILRS) 2001 annual report: http://ilrs.gsfc.nasa.gov/reports/ilrs_reports/ilrsar/2001/Section_4_web.pdf , accessed December 7, 2006.

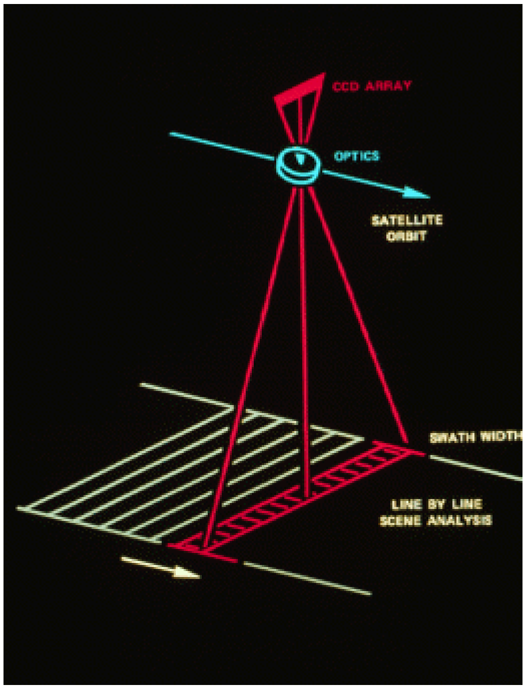
mobile stations is shown as northeast of Changchun, close to the North Korean border and the town of Tonghua.[16]

The two Chinese mobile sites which have been reported in the literature have lasers with 15-40 mJ per pulse and a 10 Hz repetition rate, for an average maximum power of about 0.4 W.[17]

## II. EFFECTS OF 1 to 40 W LASERS ON IMAGING SATELLITES

High-resolution earth-imaging satellites typically orbit at altitudes of 1,000 kilometers or less and travel at high speed (roughly 7 km/sec) relative to the surface of the earth. They are thus in view from a given location on earth for only about 15 minutes as they pass across the sky. Modern imaging satellites typically carry a set of linear detectors, each of which is an array of light-sensitive elements called pixels. Each linear detector collects light at a different wavelength. The detectors sweep over the earth during the orbit, and this series of linear images from the detectors are then combined to form a color, two-dimensional image, in a manner similar to the operation of a desktop scanner. This is referred to as the "pushbroom" method (Figure 5).[18]

**FIGURE 5: An illustration of the "pushbroom" method of satellite imaging. As the satellite orbits, it detects the light from successive thin strips of the ground. The images from these strips are merged electronically to form a two-dimensional image of the ground. A detector for a high-resolution ground imaging satellite typically has about 10,000 pixels arranged in a line.** ***Figure from SPOT website: http://spot4.cnes.fr/spot4_gb/hrvir.htm*****.**




[16] 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, "Anti-Satellite Optical Sensor Laser Countermeasure Technology," *Electro-Optics and Passive Countermeasures* (in Chinese) **2**, 1999, pp. 19-22.

[17] The International Laser Ranging Service (ILRS) 2001 annual report: http://ilrs.gsfc.nasa.gov/reports/ilrs_reports/ilrsar/2001/Section_4_web.pdf , accessed December 7, 2006.

[18] Alternatively, a two-dimensional array of detector pixels, similar to a digital camera's sensor, can also be used in what is called the "step-stare" method, where one patch of ground is tracked and imaged by the camera, followed by the next.

The detectors are usually covered by a filter that permits only a certain range of light frequencies to be transmitted to the detector. A narrow-band filter will only allow a very limited range of frequencies, for example, only the red part of the spectrum. Splitting the incoming light into the various filtered bands that are simultaneously detected by separate detectors allows the satellite operators to reconstruct a color image.

As a concrete example, consider Geoeye/Space-Imaging's IKONOS satellite which has approximately 1-meter resolution. Its linear (pushbroom) detector contains a strip of 13,500 pixels and views a swath on the ground about 10km wide, and roughly 1 meter along the direction of motion.[19] As it is traveling at about 7 km/s, this swath crosses over any 1-meter spot on the earth in about $10^{-4}$ sec.[20]

If a ground-based laser is trained upon such a satellite it can have one of several effects, ordered by increasing severity:

> a) If the satellite's telescope never views the particular region of ground containing the laser, then the only laser light reaching the satellite's linear detector would be a relatively small amount that may scatter into the satellite's telescope optics (see Figure 6). Because the amount of light would be small, this might be detectable only as a small change in the background noise level of the detector pixels. However, since these levels are carefully monitored, even such small changes would be noticeable to the operators of the satellite.[21] If the filter on the detector effectively excludes the laser light's frequency then it is possible that even this small effect would be further reduced or possibly non-existent. As a satellite in LEO is in view from a given location on the earth for about 15 minutes, this is the maximum time that it could be illuminated by a laser at that site.
>
> b) If the satellite's telescope (which has a field of view of roughly one degree) views the region on the ground that contains the laser that is illuminating the satellite, but the image of the laser does not fall on the linear detector (see Figure 6), then it is still possible that a small fraction of laser light will be diffracted onto the detector.[22] 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

[19] G. Petrine, "Optical Imagery from Airborne and Spaceborne Platforms", *GEOInformatics*, Jan/Feb 2002, 28-35

[20] The satellite's telescope that collects the light from the ground and focuses it on the detector has a total field of view of about 1degree (corresponding to 10 km 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 will only be imaged by the detector strip for just the $10^{-4}$ seconds mentioned (see Figure 6).

[21] For example, the pixels on CCD detectors on board the orbiting "CHANDRA" X-ray Observatory are carefully and continuously monitored for health and safety, and operators are notified if anything anomalous is found. See, http://cxc.harvard.edu/mta_days/mta_bad_pixel/mta_bad_pixel_list.html , accessed December 7, 2006.

[22] See Section 11 and appendices of D. Wright, L. Grego, and L. Gronlund, *The Physics of Space Security*, American Academy of Arts and Sciences (AAAS), 2005, available on-line at http://www.ucsusa.org/global_security/space_weapons/the-physics-of-space-security.html , accessed December 7, 2006.

the image in that small area, while not damaging the detector. This is referred to as "dazzling," and is a temporary and reversible effect.[23] It is important to note that such dazzling can only occur in a relatively small area around the location of the laser—it cannot obscure images of the ground far from the laser. Such an effect could occur during the roughly 1 second that the laser is in the field of view of the telescope.

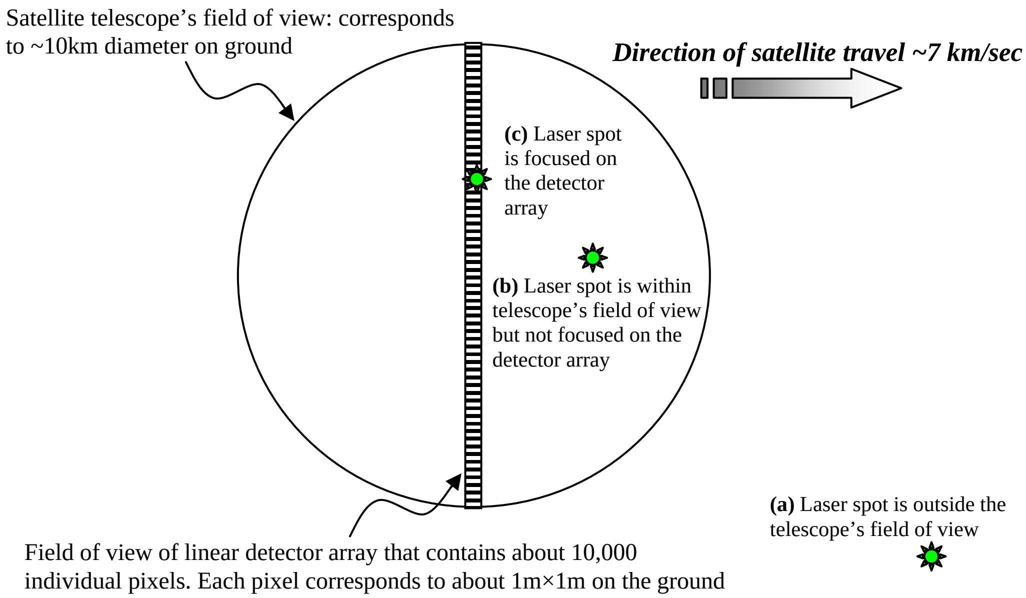



**FIGURE 6: A sketch of the overall field of view (FoV) of an imaging satellite's telescope showing the linear detector array that collects the signal from the ground. This roughly 10 km diameter FoV moves along the ground at ~7 km/sec (ie. at the same speed as the satellite), imaging a thin strip of the ground as it moves using the approximately 10,000 pixels of the linear detector array. Each pixel corresponds to roughly a 1m×1m region on the ground. Three locations of the laser aimed at the satellite are shown corresponding to the three cases examined in the text. In case (a) the laser is located outside the telescope's FoV and can only cause a small offset in the background noise levels of the detector pixels. In case (b) the laser is located within the FoV of the telescope but not on the detector array, and thus only some of the light diffracted from the telescope optics can land on the detector array, possibly resulting in some dazzling. In case (c) the laser is imaged onto the detector array. In this case dazzling or even damage of the detector and/or the filter may occur.**

c) If the satellite's linear detector happens to view 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—see next section). This can occur only during that short period (~$10^{-4}$ 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, then 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.

[23] Wright et al, *Physics of Space Security.*

> 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.[24,25] In this case, one would say that the affected pixels have been "blinded," as it is a permanent effect. For the laser powers considered here, only a few pixels could be damaged. As noted below, 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.

## III. PULSED LASERS

We are not aware of Chinese SLR stations illuminating any uncooperative space objects besides debris. We consider here, however, what the possible effects could be of illuminating an earth-imaging satellite with pulsed lasers of the kind used by the Chinese SLR stations.

As noted above, the main type of laser used by Chinese SLR stations is a 10 Hz repetition rate laser with 0.1 J per 200 picosecond pulse and a 1 W average power. A higher power experimental laser at the Shanghai station has a 20 Hz repetition rate with 2 J per 10 nanosecond pulse, and an average power of 40 W. Below we give some estimates for dazzling or permanent damage that may be expected from the types of lasers used at Chinese SLR facilities, if they were used to range to imaging satellites (further technical details may be found in the Appendix, and the results are summarized in Table 1).

Assume a pulsed laser with a repetition rate of 10 Hz and short 0.1 J pulses is trained upon an electro-optical imaging satellite in LEO, and the ground track of the satellite is such that the field of view of its telescope passes over the location on the ground where the laser is located. Then during the time the laser is in the telescope's field of view, the satellite's detector that collects light around the frequency of the laser would be dazzled briefly each time the laser pulses. This laser power is high enough that it would dazzle pixels corresponding to ground distances out to roughly 10 km around the laser (see Appendix). If the telescope's field of view is 1 degree, then as the satellite passes overhead, the laser would remain in the field of view for up to one to two seconds (depending on the altitude of the satellite and whether the location of the laser passes through the center of the field of view or off toward one side). 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 not even noticeable at all.

If a pulse from such a laser happens to coincide exactly with the short time ($10^{-4}$ sec) that the linear detector on the satellite is directly viewing the laser, then it is likely that the filter and/or the detector pixel directly viewing the laser and a few pixels around it will sustain permanent damage. This is because the energy deposited by a 0.1 J pulse is about 100 times that needed to induce permanent damage (see Appendix). However, because the laser only emits pulses every

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[24] Wright et al, *Physics of Space Security.*

[25] As noted above, this assumes that the satellite does not have shutters or other systems that would protect the detector from high-intensity light.

0.1 seconds, the probability of this happening in a single pass is just $10^{-4}$sec/0.1sec= 0.1%, or 1 in 1,000.

For the 20 Hz, 40 W average power laser the situation is more severe as each pulse contains 2 J. If such a laser's light passes through the filter it will result in a region several tens of kilometers across[26] being dazzled intermittently at the 20 Hz pulse frequency.[27] And, again, in the unlikely event that laser emits a pulse during the $10^{-4}$ seconds when the laser is being viewed by the linear detector, it is likely to lead to permanent damage of the filter and/or the detector pixel viewing the laser. Due to the higher power in this case, a few adjacent pixels may also suffer irreversible damage. Since the laser fires every 0.05 sec, the probability that such permanent damage of the filter and/or the detector will happen is $10^{-4}$sec/0.05sec= 0.2%. (In the above we have assumed a robust Silicon based detector; other detector materials typically have lower damage thresholds.[28])

Even when the satellite's telescope is not viewing the region containing the laser, the stray light from the laser illumination may scatter within the satellite optics and, if the laser light wavelength is transmitted by the filter, it may alter the background levels of the detector. Such anomalous background levels should be evident during the regular (typically daily) health and status monitoring checks carried by the satellite operators.[29]

As discussed above, if an SLR were to illuminate a satellite when the satellite was not looking at the ground region containing the laser, any stray laser light that reached the detector or filter would not be intense enough to cause damage. Thus, assuming these satellites image sections of the earth fairly directly below them, SLR could be done safely when the satellite was low in the sky relative to the SLR station. For instance, the French SPOT4 satellite has an oblique viewing capability of a maximum of 27 degrees on each side of its local vertical.[30] Thus a "no-SLR" exclusion zone of 30 degrees about the local vertical for an SLR station may be a reasonable rule to ensure no damage could possibly result to the detectors of imaging satellites.

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

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 above but about one-thousandth of the energy per pulse (135 microjoules).[31] Systems such as the Chinese SLR system are designed to have only one pulse in transit from the

[26] Of course, if the field of view of the detector is smaller than several 10's of km, then only the full field of view, and no more, can possibly be dazzled.
[27] Wright et al, *Physics of Space Security.*
[28] F. Bartoli et al., "Irreversible Laser Damage in IR Detector Materials," *Applied Optics* **16** (1977) 2934-2937.
[29] For example, the pixels on CCD detectors on board the orbiting "CHANDRA" X-ray Observatory are carefully and continuously monitored for health and safety, and operators are notified if anything anomalous is found. See, http://cxc.harvard.edu/mta_days/mta_bad_pixel/mta_bad_pixel_list.html , accessed December 7, 2006.
[30] "The SPOT Earth observation system," http://spot4.cnes.fr/spot4_gb/satellit.htm , accessed December 7, 2006.
[31] J. McGarry,T. Zagwodzki and J. Degnan, "SLR2000 Closed Loop Tracking with a Photon-Counting Quadrant Detector" 2002, 13th International Workshop on Laser Ranging, Washington, D.C., Oct 7-11 2002, http://cddis.nasa.gov/lw13/docs/papers/auto_mcgarry_1m.pdf, accessed December 7, 2006.

ground to the satellite at a time; systems with higher repetition rates are much more complicated because many pulses are in transit at the same time and sophisticated techniques must be used to correlate transmitted and received pulses to determine the time of flight.

## OTHER RELATED NOTES

*Changchun Laser Industry*

The city of Changchun where the new daylight SLR capability has come on-line in 2006 is also home to the Changchun New Industries Optoelectronics Tech. Co., Ltd. (CNI), founded in 1996.[32] It is claimed to be the largest manufacturer and supplier of diode pumped solid-state (DPSS) lasers in China. CNI produces continuous wave (CW) lasers, modulated and Q-switched laser modules at different wavelengths, including UV, visible and Infrared. In addition, CNI reportedly has the capability of laser device design, optical coating, device fabrication, component assembly and system integration. CNI manufactures an off-the-shelf 8 W 532 nm DPSS laser module, as well as a 10 W 1064 nm infrared DPSS laser.

A recent paper from the Shanghai Institute of Optics and Fine Mechanics reports on a new 714 W continuous wave (CW) laser at 976 nm wavelength.[33]

*Space Object and Debris Monitoring Research Center in Nanjing*

In March 2005, the Chinese Academy of Sciences opened a new "Space Object and Debris Monitoring Research Center" at the Purple Mountain Observatory in Nanjing, the capital of China's Jiangsu Province. The goal is to build a system to warn of possible collisions of China's piloted spacecraft with other objects in orbit. The research scope covers the building of a space debris database, real-time tracking and monitoring of space debris, searching for undiscovered space debris, conducting warning technology research for possible collisions with debris during spaceship launches, and the establishing of a risk assessment system.[34]

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## APPENDIX – Laser Dazzling and Damage Estimates

*Dazzling:*
We estimate the size of the region of the detector that would be dazzled by a pulsed laser in the following way. A satellite in LEO will pass over a 1-meter area on the ground in roughly $10^{-4}$ sec.

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[32] The Changchun New Industries Optoelectronics Tech . Co., Ltd. (CNI) website, http://www.cnilaser.com/index.htm , accessed December 7, 2006.

[33] Jun, Z., et al. "A Continuous Wave 714W Fiber Laser with China-made Large Mode Area Double-Clad Fiber", 2006, *Acta Optica Sinica* **26**, No. 7.

[34] "CAS sets up the first space debris monitoring center in China", press release March 21, 2005, Chinese embassy in Romania: http://www.chinaembassy.org.ro/rom/kjwh/t188324.htm , accessed December 7, 2006 see also: Purple Mountain Observatory website: http://www.pmo.ac.cn/index.asp, accessed December 7, 2006.

For a satellite with 1-meter ground resolution, we would therefore expect that the pixels that make up the detector would therefore collect photos for roughly that same length of time before reading out the value and resetting to collect photons from the adjacent 1-meter ground area.

If a pixel detected a 200 picosecond pulse with an energy of 0.1 J, it would collect the same number of photons[35] as if it detecting a 1 kilowatt continuous laser for $10^{-4}$ sec. Therefore, this pulse would be expected to have the same ability to dazzle as a 1 kW continuous laser, which is estimated to dazzle a section of the detector corresponding to roughly 10 km on the ground.[36] The maximum region that can be dazzled cannot, of course, exceed the full field of view of the detector.

The duration of the dazzling would be determined by the cycle time of the pixels rather than the length of the pulses, so it would be expected to last for roughly $10^{-4}$ sec rather than 20 picoseconds.

*Damage:*
For laser illumination timescales of $10^{-4}$ sec or less, the damage threshold for silicone-based detector materials is reported to be[37] 100 J/cm$^2$, or $10^6$ J/m$^2$. This applies both to the pulsed and continuous lasers as the timescale is set by the time it takes the satellite to cross one resolution unit on the ground, which in our case is roughly $10^{-4}$ sec.

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

$$1.22\ (0.5\times10^{-6}\ \text{m}) \times (8 \times 10^5\ \text{m}/0.15\ \text{m}) = 3.25\ \text{m}.$$

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

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

This energy will be focused by the satellite optics onto one pixel, which for imaging satellites is on the order of 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:

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

This density is 100 times the damage threshhold of $10^6$ J/m$^2$, and will therefore damage the pixel unless the laser light is stopped in the filter material. If the laser light is stopped by the filter material, however, then filter may suffer damage instead. In any case, it appears that irreversible damage will take place, either of the detector or the filter, or possibly both. As noted above, the

[35] The atmospheric transmission ($T$) for visible laser light for elevation angles above about 10 degrees ranges from ~0.5 to ~0.8. Since we are not concerned with very low elevation angles, and to be conservative in our estimates we have taken $T$=1. To be more accurate one may use the parameterization $T=e^{-\tau}\sec(Z)$, where $\tau=0.009\ \lambda^{-4}+0.223$ and Z is the angle from the zenith, and $\lambda$ is the wavelength of the light in microns. See eg. Kaula, W. M., "Celestial Geodesy", in 1962, *Advances in Geophysics* **9**, ed. by H. E. Landsberg and J. van Mieghem, Academic Press, New York, pp 191-293.
[36] Wright et al, *Physics of Space Security*.
[37] Bartoli et al, "Irreversible Laser Damage."

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 detectors are at least an order of magnitude more robust against laser damage than other typical detector materials.[38]

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