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Research on laser in-sky safety early warning method for high power debris laser ranging system

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ABSTRACT

A method for judging the in-sky safety of the laser beam pointing for high-power debris laser ranging (DLR) system is proposed. It realized the real-time safety area judgment and early warning of the laser beam intersection with the transiting aircraft. We build the laser beam pointing safety warning system at Changchun Station to validate the method. Results are showed the intersection time between the transiting aircraft and the laser beam accounts for 0.86% of the observation time, which does not affect the regular operation of the laser ranging system. the energy density of the aircraft outside the intersection area is between 10^{-14} ~ 10^{-25} J/cm^2, which is much smaller than the laser safety threshold corresponding to the ANSI Z136 standard. Result shows the effectiveness of the laser in-sky safety warning method on the high-power debris laser ranging system.

Laser Safety Distance

According to the Maximum Permissible Exposure (MPE) for human eyes given in ANSI Z136.1 standard with equations (1) and (2), the laser safety distances (R_{SD}) corresponding to lasers in DLR systems of different tracking stations are calculated as shown in Table 2. It can be seen that the laser safety distance of the station R_{SD} is usually more than 100 kilometers and covers all flight altitude range of the aircraft, so it is necessary to consider the laser safety of transit aircraft.

$$R_{SD}=\frac{1}{\varphi}\sqrt{\frac{-D_f^2}{ln\left(1-\frac{Q_{MPE}}{Q_0}\right)}-a^2} \quad (1) \qquad \mathrm{Q_{MPE}}=\mathrm{MPE}\times\frac{\pi\times\mathrm{D_f}^2}{4} \quad (2)$$

In equations (1) and (2), φ is the laser emission divergence angle (rad); Q_0 is the laser single pulse energy (J); a is the diameter of the laser beam (cm); D_f is the pupil diameter of the human eye, which is 7 mm; MPE=min(MPE1,MPE2,MPE3). The calculation methods of MPE_1, MPE_2, and MPE_3 are shown in Table 1, Equations 3 and 4.

Tab.1 MPE_1 for Point Source Ocular Exposure to a Laser Beam

Exposure duration /s	MPE_1/J·cm^{-2}
10^{-11} to 10^{-9}	$2.7\ t^{0.75}$
10^{-9} to 18×10^{-6}	5.0×10^{-7}

$$\mathrm{MPE_2} = 1.8\times t^{0.75}\times10^{-3}\,\mathrm{J\cdot cm^{-2}} \quad (3)$$

$$\mathrm{MPE_3} = n^{0.25}\times\mathrm{MPE_1} \quad (4)$$

Where n=F×t, F is the laser frequency, t is the maximum exposure time, 0.25s.

Tab.2 The safety distance of the laser at the station

Name	MPE/J·cm^{-2}	φ/acrsec	Q_0/mJ	a/cm	R_{HD}/m
Graz	5.0×10^{-7}	5	60	6	161231.28
Shanghai	5.0×10^{-7}	12	250	1	137146.12
Kunming	5.0×10^{-7}	8	300	82	410895.18
Changchun	5.0×10^{-7}	5	500	1.5	465489.36

Measures Taken

Through the analysis of the station laser, it can be seen that certain measures are needed to ensure the safety of the transit aircraft during the laser ranging operation. Here, the laser pointing Safe angle calculation method as shown in Equations (5) – (7) is proposed to define the safety zone for transit aircraft, as shown in Fig 1 (The laser outlet is the center, 2Ω is the safety angle, the laser safety distance R_{SD} is the generatrix, the circumvention zone is comprised by the laser danger range corresponding to the internal laser safety threshold(red zone in the figure) and the external warning range divided by the angular velocity of the aircraft and telescope(orange zone in the figure)). And a laser beam pointing safety warning system is set up at Changchun station to test the method, as shown in Fig 2.

$$\Omega = (\omega_1 \pm \omega_2)\Delta t + \arctan\left(\frac{L}{R}\right) \quad (5)$$

$$L = w_R + \sqrt{\frac{Q_0}{10\pi MPE}} \quad (6)$$

$$w_R = \frac{a}{2}\sqrt{1+\left(\frac{\lambda R}{\pi(\frac{a}{2})^2}\right)^2} \quad (7)$$

Where ω_1 is the apparent angular rate of the aircraft; ω_2 is the angular rate of the tracking telescope; Δt is the extrapolation time (the warning setting time), with a margin; R is the slant range between the aircraft and the telescope; L is the laser safety radius corresponding to the laser beam at a distance from R, and defines the energy Q_L = MPE of the radiation received by the aircraft at L; w_R is the effective cross-sectional radius of the base mold at a distance of R; λ is laser wavelength.

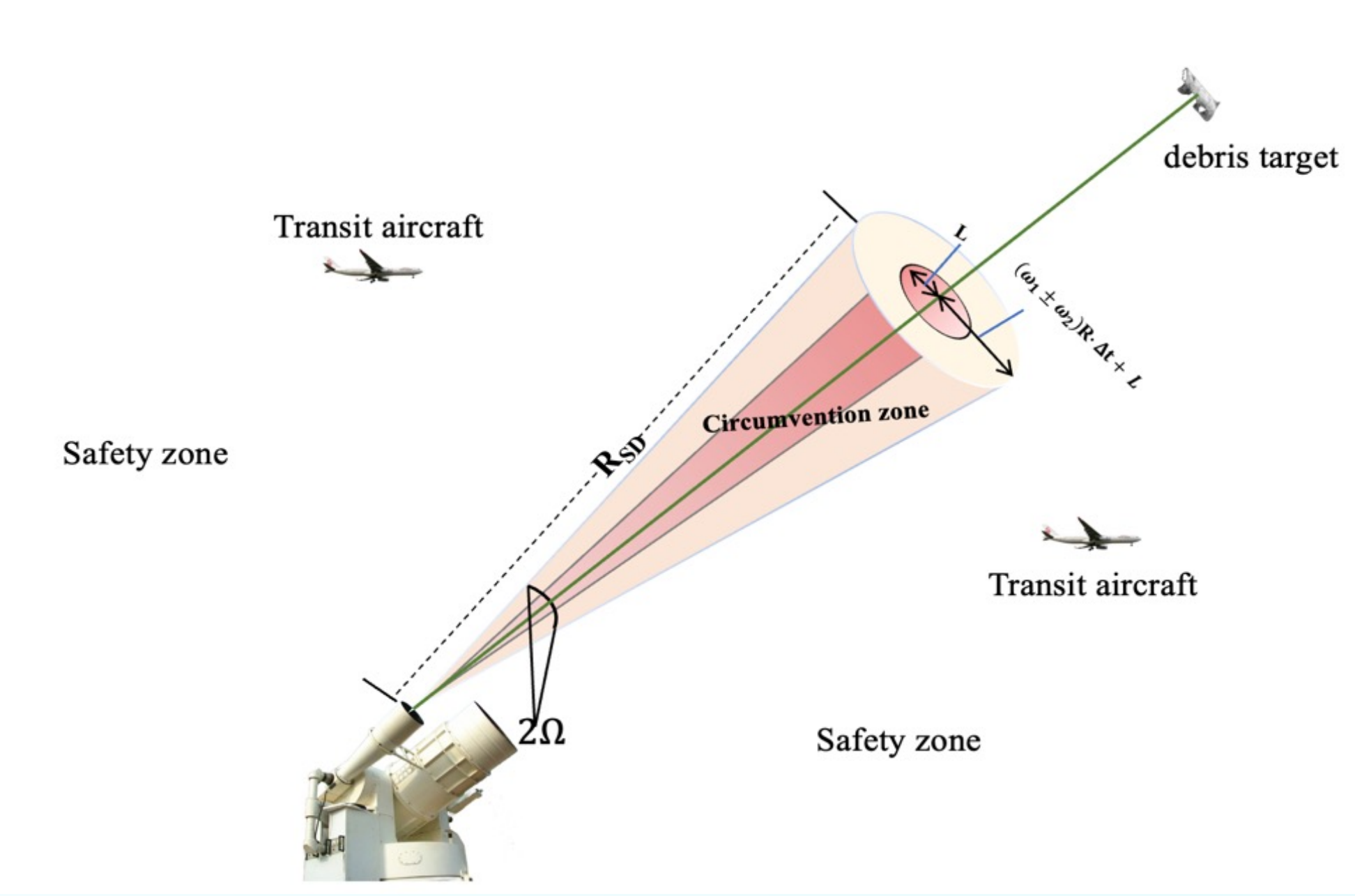
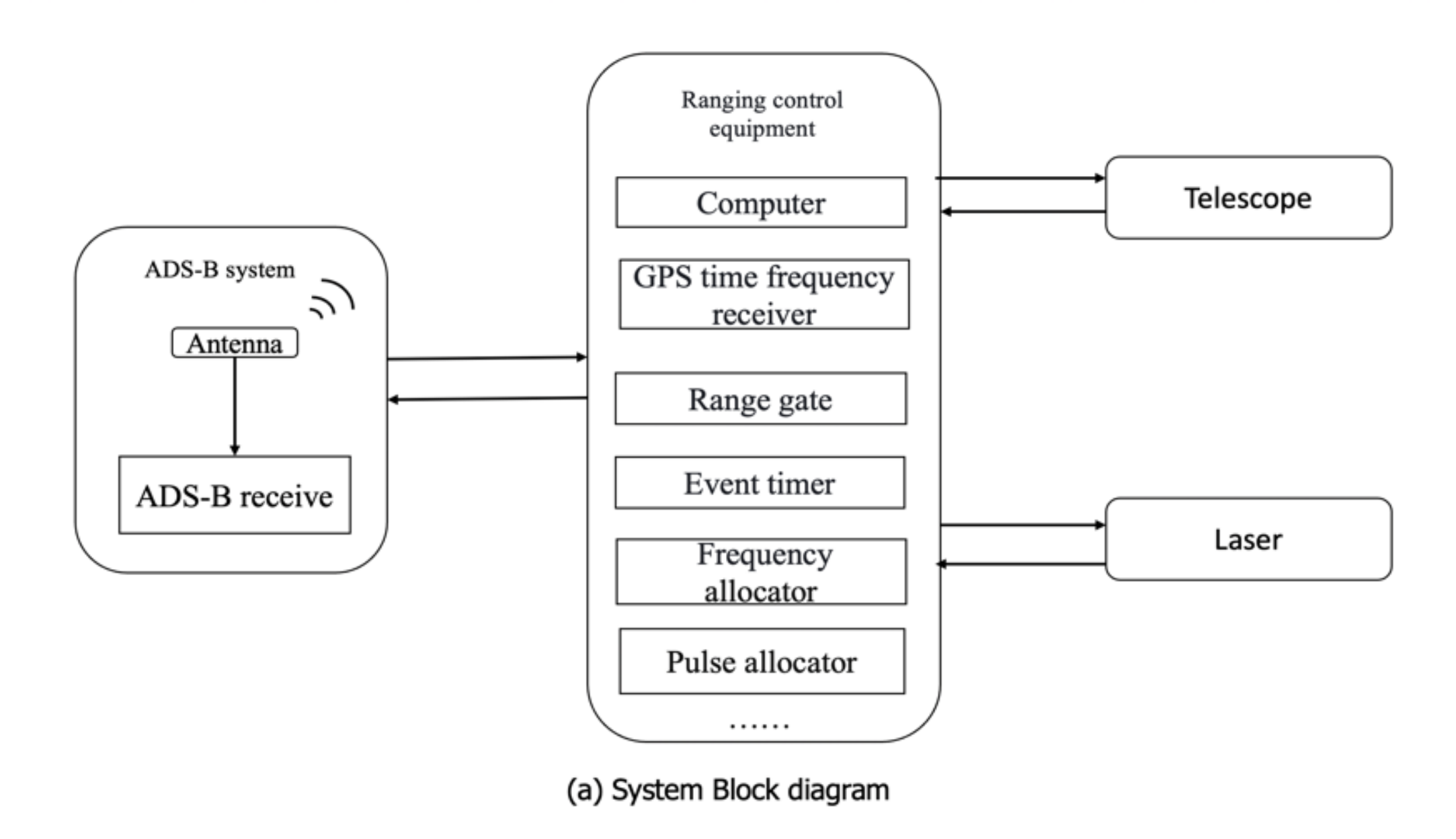


Fig.1 The laser is directed at the safety zone



(a) System Block diagram

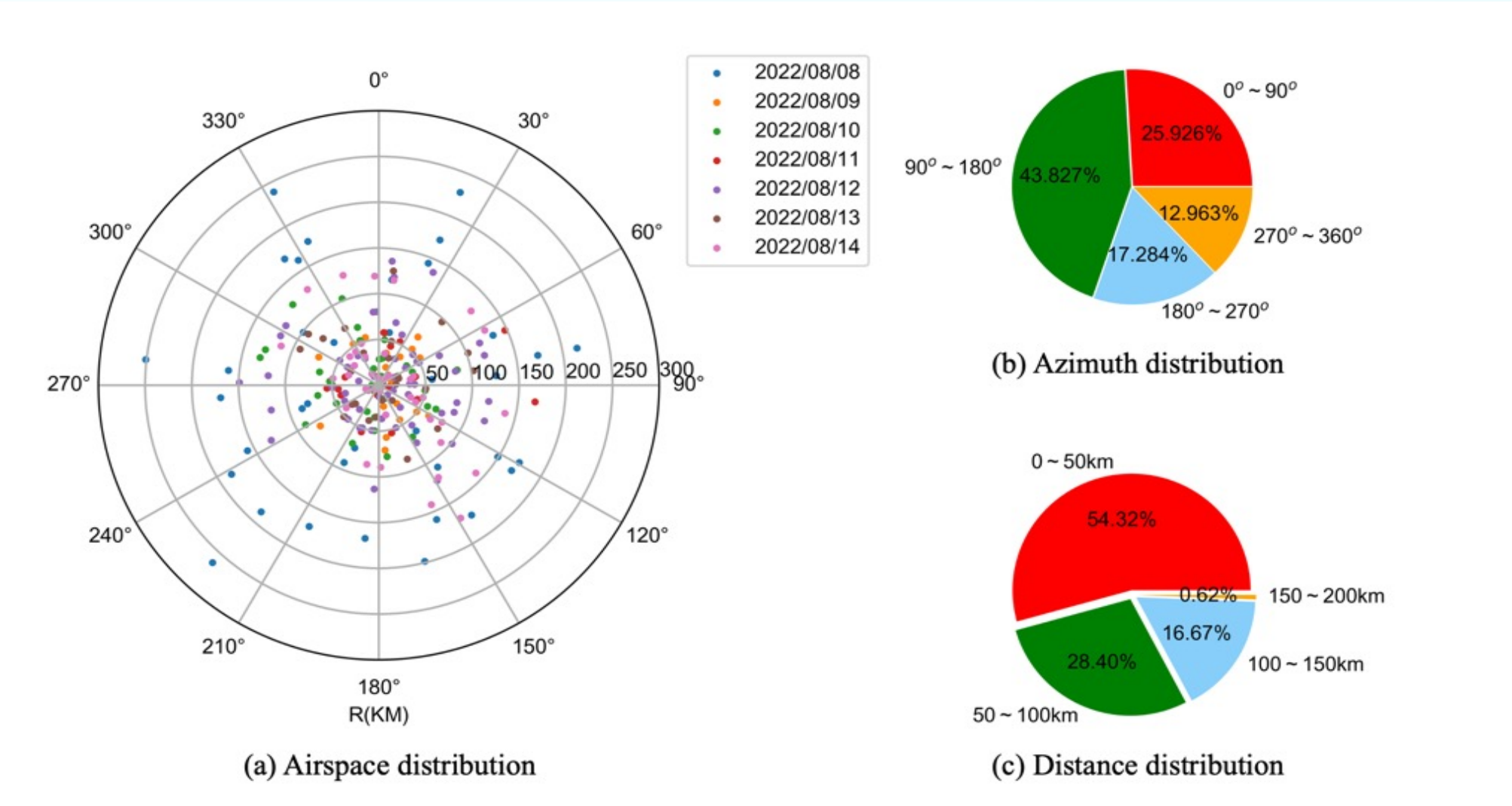
Fig.2 The laser beam is pointed at the security warning system

Data Analysis

A one-week-long experiment was conducted (from August 8 to August 14, 2022). In this experiment, real ADS-B trajectories were collected to intersect with real space-debris passes. The total observation time, the number of transiting aircraft, the number of observed passes, and the laser block time are shown in Table 3. Figure 3 shows the starting point azimuth, azimuth distribution and distance distribution when aircraft position coincides with laser beam and . Figure 4 shows the laser radiation energy received by the transiting aircraft in the safety zone are analyzed separately.

Tab.3 Observation records

Date（Y.M.D）	Observation Time (s)	Number of aircraft crossings (n)	Number of observed debris passes(n)	Laser block time (s)	Block time ratio (%)
2022/08/08	33098	45	46	105.70	0.32
2022/08/09	38412	151	44	265.70	0.69
2022/08/10	17089	153	23	260.78	1.53
2022/08/11	5640	102	12	100.68	1.79
2022/08/12	14001	128	22	257.70	1.84
2022/08/13	16502	153	19	78.69	0.48
2022/08/14	14702	178	21	124.12	0.84
Total	139444	910	187	1193.37	0.86



(a) Airspace distribution
(b) Azimuth distribution
(c) Distance distribution

Fig.3 All-sky avoidance distribution of laser beams

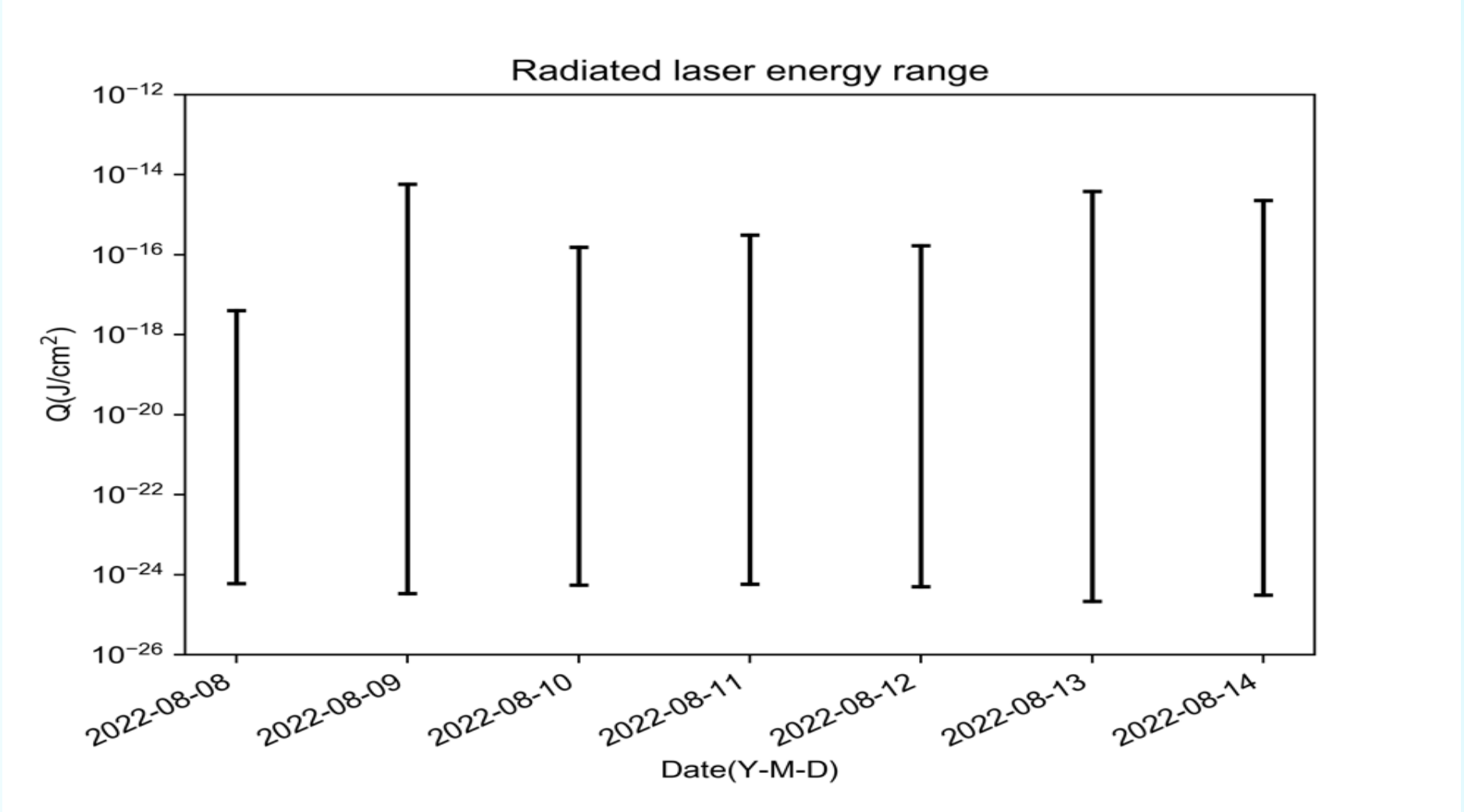


Fig.4 The range of energy that aircraft receives

CONCLUSION

The safety of lasers in different DLR system is analyzed and the laser pointing Safe angle calculation method is proposed. The Changchun station laser beam pointing safety warning system was set up. According to the experiment, intersection time between aircraft and laser beam takes 0.32% ~ 1.84% of observation time, which does not affect normal observation activities. With laser beam pointing safety warning system enabled, the laser energy on transit aircraft ranges between 10^{-14}~10^{-25}J/cm^2, which is much less than the MPE value of Changchun Station's laser. So It provides a theoretical basis and effective avoidance strategy for laser safety early warning of high-power DLR system.