PAYLOAD HAZARD REPORT		NO: ACES-15-WETTZELL
PAYLOAD: Atomic Clock Ensemble in Space (ACES)		PHASE: Delta-II
SUBSYSTEM: Laser / Radiation	HAZARD GROUP: Injury/Illness	DATE: Sep-05-2017
HAZARD TITLE: ISS Exposure To Ground Based LASER Radiation above Maximum Permissible Exposure limit		HAZARD CATEGORY ☒ CATASTROPHIC ☐ CRITICAL

APPLICABLE SAFETY REQUIREMENTS:

SSP51700 paragraph 3.2.3, 3.13.3, ANSI Z136.1-2014, ANSI Z136.6-2015

DESCRIPTION OF HAZARD:

Crew exposure of laser light above Maximum Permissible Exposure level from Ground Based LASER can lead to crew eye injury. Interference of Ground Based LASER with Visiting Vehicle Laser Navigation can lead to aborted docking attempts.
NOTE: Other participating Laser Ranging Stations targeting the ISS within the ACES ELT program will remain within the laser energy limits and wavelength documented in Annex 3 table 1

HAZARD CAUSES:

1. Improper ELT ground laser design exceed MPE (Maximum Permissible Exposure) for crew using optical instruments with magnification aids up to 400mm lens diameter)
2. Interference of Ground based laser signals with visiting vehicle laser navigation

HAZARD CONTROLS:

1.1 Innolas Laser Amplifier Power supply H/W switch off (by µController command in ELT mode) ensuring MPE compliance (Laser Energy for ISS ranging limited to 1mJ per shot and always eye-safe at ISS, independent of optics divergence)

SAFETY VERIFICATION METHODS:

1.1.1 Review of design (see Annex 1)
1.1.2 Analysis showing compliance to MPE limit at ISS when operating without Laser Amplifier (see Annex 2)
1.1.3 Functional Test confirming Laser Amplifier Power OFF in case of ELT Mode selection
1.1.4 Wettzell Laser Safety Officer (LSO) certification of as built laser system at Wettzell station compliance to Annex 1 and Annex 3

STATUS OF VERIFICATION:

1.1.1	Open
1.1.2	CLOSED -
1.1.3	Open
1.1.4	Open

APPROVAL	PAYLOAD ORGANIZATION	ESA SSP/ISS	NASA SSP/ISS
PHASE I			
PHASE II			
PHASE III			

PAYLOAD HAZARD REPORT		NO: ACES-15-WETTZELL
PAYLOAD: Atomic Clock Ensemble in Space (ACES)		PHASE: Delta-II
SUBSYSTEM: Laser / Radiation	HAZARD GROUP: Injury/Illness	DATE: Sep-05-2017

HAZARD CAUSES:

1. Improper ELT ground laser design exceed MPE (Maximum Permissible Exposure) for crew using optical instruments with magnification aids up to 400mm lens diameter)
2. Interference of Ground based laser signals with visiting vehicle laser navigation

HAZARD CONTROLS:

1.2 Laser Path blocked by beam blocking device (release acutator powered only if safe configuration is ensured via chain of microswitches monitoring that laser amplifier power status is OFF and monitoring that laser beam is bypassing Innolas amplifier). One of the two conditions ensures already MPE compliance.
1.3 ISS target data availability enabled only in ELT mode (forwarding to internal data base (RS232 cable) interrupted by HW switch)
1.4 Ground Operating Procedure specifying laser ranging to ISS without Innolas Laser Amplifier (Innolas Laser Amplifier Main Power Switch OFF, optical laser path configured to by-pass laser amplifier

2.1 Analysis showing that laser power reaching ISS level is compatible with VV laser navigation

SAFETY VERIFICATION METHODS:

1.2.1 Review of design (see Annex 1)
1.2.2 Analysis showing compliance to MPE limit at ISS when operating without Laser Amplifier (see Annex 2)
1.2.3 Functional Test confirming Beam Blocking Device always engaged in ELT Mode except when optical configuration bypassing the Laser Amplifier and Divergence setting to 200µrad is established
1.2.4 Wettzell Laser Safety Officer (LSO) certification of as built laser system at Wettzell station compliance to Annex 1 and Annex 3
1.3.1 Review of design (see Annex 1)
1.3.2 Functional Test confirming ISS target data forwarding to target database disabled except for ELT Mode
1.3.3 Wettzell Laser Safety Officer (LSO) certification of ISS target data unavailability except for ELT Mode
1.4.1 Wettzell Laser Safety Officer (LSO) certification of Ground Operating Procedure

2.1.1 Review of Analysis (see Annex 4)

STATUS OF VERIFICATION:

1.2.1	Open
1.2.2	Open
1.2.3	Open
1.2.4	Open
1.3.1	Open
1.3.2	Open
1.3.3	Open
1.4.1	Open
2.1.1	Open

Annex 1-1 of Unique Hazard Report ACES-15:

Fault Tolerance for Wettzell Laser Ranging System

Hazard:
Crew exposure of laser light **above Maximum Permissible Exposure level** from Ground Based LASER can lead to crew eye injury.

Conditions that need to be met to generate the hazard:

a. Ground laser pointing to ISS (needs high accuracy ISS tracking data)
b. Laser energy above Maximum Permissible Exposure Limit for Astronaut using up to 400mm diameter optical lens system

Controls to prevent hazard
for a.:

- tracking data can be copied to the telescope tracking system only in ELT mode (H/W switch interrupting the data transmission wire)

for b:

- laser beam path blocked by metal plate (beam blocking device) unless laser amplifier power status is OFF and laser beam is bypassing Innolas amplifier - this ensures compliance to Maximum Permissible Exposure level
  monitoring by h/w switches within the power supply line for the beam block "release actuator"
- Innolas Laser Amplifier power OFF - this ensures compliance to Maximum Permissible Exposure level

Failure Scenario for operations in ELT mode	Tracking data accessible YES / NO	**Beam path blocked** when Innolas power ON	**Beam path blocked** when laser path through Innolas	Innolas Amplifier Power OFF / ON via µ-controller	Eye safe @ ISS with magnifying lens YES / NO
H/W switch in ELT mode fails (remains in standard operations mode	NO (inhibit 1)	No	No	OFF (inhibit 2)	YES
Laser path by-pass detection µ-switch fails	YES		2 µ-switches in row (inhibit 1)	OFF (inhibit 2)	YES
Laser power status detection µ-switch fails	YES	1 µ-switch in (inhibit 1)		OFF (inhibit 2)	YES
Innolas Power Switch fails CLOSED	YES	1 µ-switch in (inhibit 1)	2 µ-switches in row (inhibit 2)	ON	YES

Annex 1-2 of Unique Hazard Report ACES-15:
Laser Intensity limitations by Wettzell Ground Based Laser station design

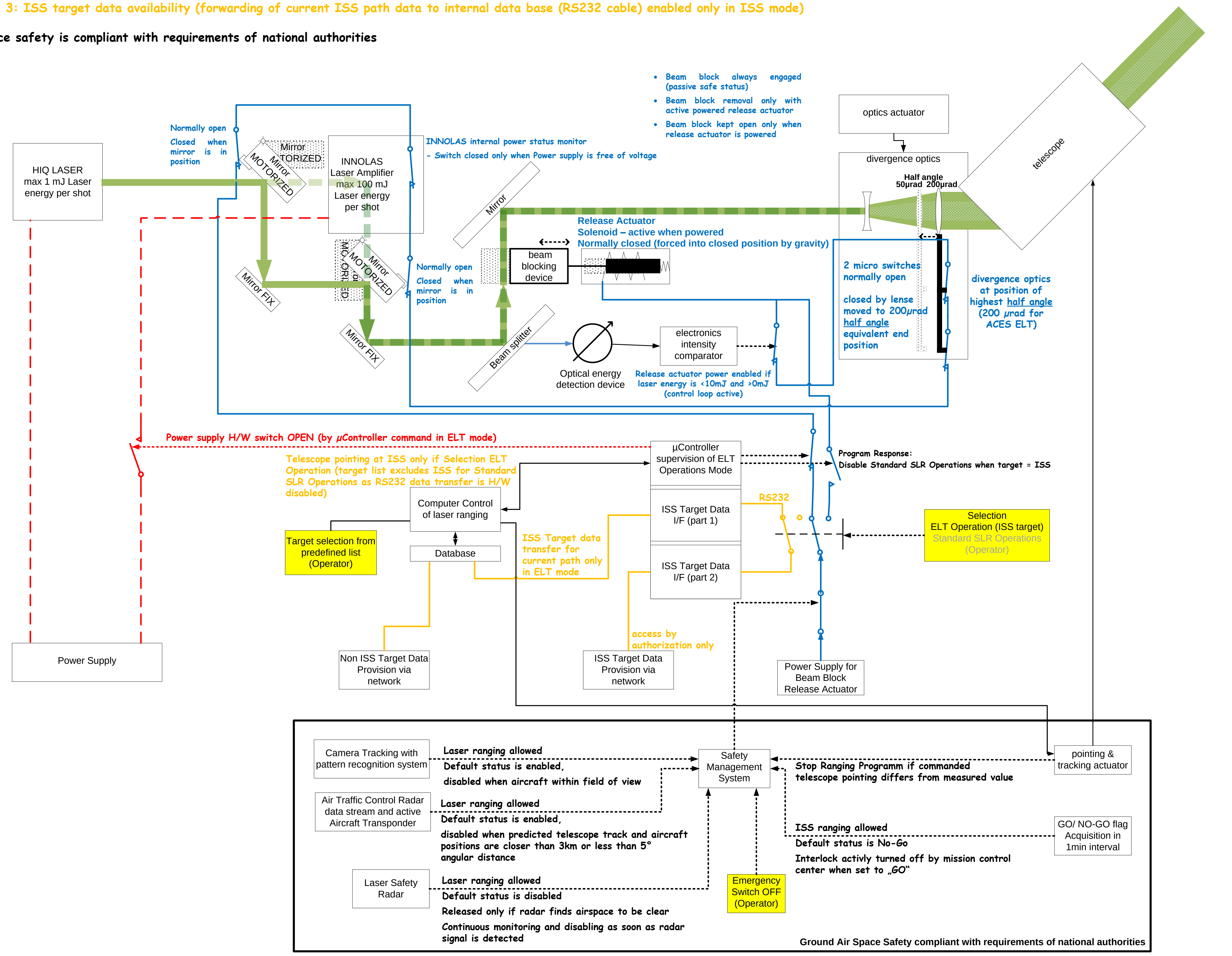
WETTZELL Laser Ranging System
ISS laser ranging (HIQ laser only, 200μrad half angle divergence)

Hazard Control 1: Innolas Laser Amplifier Power supply H/W switch off (by μController command in ELT mode)

Hazard Control 2: Laser Path blocked by beam blocking device (release acutator powered only if safe configuration is ensured via chain of microswitches (Innolas amlifier power status OFF, laser beam bypassing Innolas amlifier)

Hazard Control 3: ISS target data availability (forwarding of current ISS path data to internal data base (RS232 cable) enabled only in ISS mode)

Ground air space safety is compliant with requirements of national authorities



Annex 2 of Unique Hazard Report ACES-15:

Analysis showing compliance to MPE limit at ISS when operating without Laser Amplifier

Name	ACES Ground Laser Station	WLRS (8834)
Z136 Standard	Z136.1-2014	
Analysis Type	Single Wavelenth	
Laser	YAG	
Wavelength	532 nm	
Waveform	MP: 1.2e-011 s at 20s^-1	
Pulse Mode	MultiPulse	
Pulse Width	12 ps	
Pulse Repetion Frequency	Hz	500
Repetition Rate Power Limit Equation:	ANSI Z136.1 table 6c. (α≤5mrad)	1
Repetition Rate Power Limit to be used:		1
Transmit Telescope Efficiency	normalized to 1	0.5
Laser System Operating Mode		ELT Mode
Energy per pulse	mJ	0.4
Beam Distribution	Gaussian	
Beam Profile	Circular	
Beam Geometry		
Divergence	**half-angle in μrad**	200
Divergence	half-angle in rad	0.0002
Source	point source	
VisibilityConditions		
Distance Laser - Observer	km	400
MPE per ANSI for 1.2e-11 pulse	J/cm²	2.00E-07
MPE Rep.-Frequency Reduced		8.00E-08
MPE limit to be used	J/cm²	8.00E-08
atmospheric attenuation (Transmission 60 to 80%)	per ANSI-Z136.6 C4.1.3. Upward directed Beam	0.8
Radiant exposure at ISS distance **(crew unaided eye)**	energy (in J) * transmission / ((tan half-angle * distance (in cm))^2 * pi) [J/cm²]	7.96E-13
Impact of crew using Telescope		
Objective Diameter	mm	400
Objective Entry Surface	cm²	1256.64
Exit diameter	mm	7
Exit diameter surface	cm²	0.50
Optics power		50
optical efficiency	90%	0.9
Energy entering Objective	[J] Radiant exposure at ISS distance * surface Objective	1E-09
exiting at 8mm diameter	energy * 0.9	9E-10
radiant exposure exiting Objective	[J/cm²] energy exiting objective/ surface Exit	2.34E-09

Annex 3 of Unique Hazard Report ACES-15:

ELT Laser Safety Assessment

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0. Remark on the update of this document.

This Report was evaluated according to laser safety standard ANSI Z136.1-2014. In preparation of the ELT experiment the Wettzell Laser Ranging System received an upgrade of the ranging pulse laser with laser pulses as short as 12 ps. This step was necessary, because the old active-active mode locked laser could not be modified to comply with the ELT experimental requirements. The new laser system consists of two independent hardware components. These is a HiQ mode locked pulse laser (up to 667 Hz repetition rate, 0.4 mJ energy at 0.532 µm wavelength) and an Innolas amplifier stage with a maximum gain of a factor of 80. The laser and the amplifier are each entirely independent units. There is a free air space linking the two systems together. The setup therefore allows two independent states of operation, a low power (A) and a high power (B) setting. In the low power setting, which we consider the nominal state of operation for the ELT experiment, the Innolas amplifier is bypassed on a different optical route specific to the ELT application. In the scope of this document, we discuss this case as the operational ELT measurement environment. In addition to that, we discuss the full ranging system, including the Innolas amplifier stage as an example for the worst case scenario for a general laser ranging station participating in the ELT effort.

1. Short technical description of the Wettzell Laser Ranging System (WLRS) as one example of the systems used for the ACES optical time transfer experiment.

In Satellite Laser Ranging (SLR) a global network of stations measure the instantaneous round trip time of flight of ultra-short pulses of light to satellites equipped with special reflectors. This provides instantaneous range measurements of millimeter level precision, which can be accumulated to provide accurate orbits and a host of important science products. The International Laser Ranging Service (ILRS) [1] comprises an association of approximately 35 individual observatories run independently by national funding bodies or agencies. One of these SLR stations is the Wettzell Laser Ranging System (WLRS) operated by the Bundesamt fuer Kartographie und Geodaesie and the Technische Universitaet Muenchen (TUM) in Germany.

The WLRS now consists of a frequency doubled Nd:YAG pulse laser (pulse width nominal 12 ± 2 ps), a Coudé path telescope of 75 cm aperture and a precise timing and laser pulse detection system. Coordinated by the ILRS the WLRS performs routinely SLR measurements to about 30 different satellite targets from the low Earth orbit up to the moon*. Table 1 summarizes the important technical parameters of the WLRS for configuration (A) and (B). The laser system is located in a separate room and attached to the telescope via the Coudé port of the telescope. Please note the two different hardware configurations. The laser can be separated from the telescope by inserting a mechanical beam stop at any time. The transmission efficiency of the telescope does not exceed 65%. The intrinsic divergence of the telescope is larger than the atmospheric turbulence, hence this value is only given for the sake of completeness.

** The only observed lunar target is the Lunar Reconnaissance Orbiter (LRO). Because this requires one-way ranging only, the demands on laser power are moderate. In fact the observation permission for the LRO mission also required a serious limitation for the laser output beam power.*

Annex 3 of Unique Hazard Report ACES-15 (cont'd)

Table 1: The relevant system parameters of the WLRS ranging to the ISS

Parameter	Quantity
Wavelength	532 nm
A) Laser Energy per shot (at laser output) HIQ laser only	0.4 mJ
B) Laser Energy per shot (at laser output) HIQ + Innolas	32 mJ
Pulse Width	12 ± 2 ps
Repetition Rate (shots per second) (N)	nominal 500 Hz, max 667 Hz
Transmission through telescope	0.63
Transmission through atmosphere (max)	0.75
Minimum Range to ISS	380 km
Laser Beam Divergence (half angle)	Conf. A: 200 µrad; Conf. B 10-200 µrad
Atmospheric turbulence induced beam Divergence (half angle) typical	15 µrad
Diameter of Laser Spot at ISS	39 m
Total area illuminated at ISS	1180 m^2
Energy density for configuration (A)	2.34e-09 J/cm^2
Interlock (as defined by ILRS)	Go / no Go Flag
MPE_s (2nd Harmon. Nd:YAG < 100 ps) single shot per ANSI Z136.1 - 2014	2.00E-07 J/cm^2

1.1 Actual Laser Ranging Performance Requirements

The time transfer functions of the ELT experiment are depending on a carefully balanced link budget for the optical ranging. Both the detector on the satellite/ACES-ISS and the detector at the ground system have to be operated at the single photon detection level. The attenuation factor of the laser signal onboard the ACES payload is about 10^5. This requires an operational system setting according to table 2 for the WLRS in order to obtain the mission objectives.

Table 2: The relevant system parameters of the WLRS ranging to the ISS for nominal operation during the ELT experiment

Parameter	Quantity
Laser Energy per shot	0.1 mJ
Laser Beam Divergence (half angle)	200 µrad
Energy density at Columbus Module (TCA)	0.59e-9 J/cm^2
MPE (532nm. Nd:YAG < 100 ps)	2e-07 J/cm^2

2. Analysis showing that the laser power at ISS altitude is well below the threshold specified in the relevant standards (e.g. ANSI Z136.1) for naked eye observer.

The given laser system is characterized by the transmitted beam power, the transmission efficiency of the laser station and the atmosphere and the divergence angle of the beam. The first and the latter are automatically chosen and preset specifically for each target by the local controls of the WLRS ranging system. For the maximum permissible energy (MPE) of a frequency doubled Nd:YAG laser system with a pulse width of less than 100 ps a value of 2.00e-07 J/cm^2 is specified, when the laser pulse repletion rate is below 5 kHz (ANSI Z136.1 table 1). The laser energy density of the ranging system at the location of the target per unit area is given by

$$E = \frac{h_t T_{atm} E_t}{(J R)^2 p},$$

with η_t the transmit path efficiency, T_{atm} the transmission of the atmosphere E_t the transmitted energy per pulse. ϑ is the divergence half angle and R the distance between the ranging system and satellite. Figure 1 shows the energy density of the laser pulse at the location of the ISS for the 1 mJ and the 100 mJ case as a function of the divergence angle. The diagram includes the high power setting (worst case scenario). The desired operating

Annex 3 of Unique Hazard Report ACES-15 (cont'd)

level in order to comply with the mission requirements (single photon detection level at ELT Detector) is of the order of 10^{-13} J/cm^2, which is several orders of magnitude below the maximum permissible power setting and corresponds to the single photon signal levels both at the ISS and the WLRS.

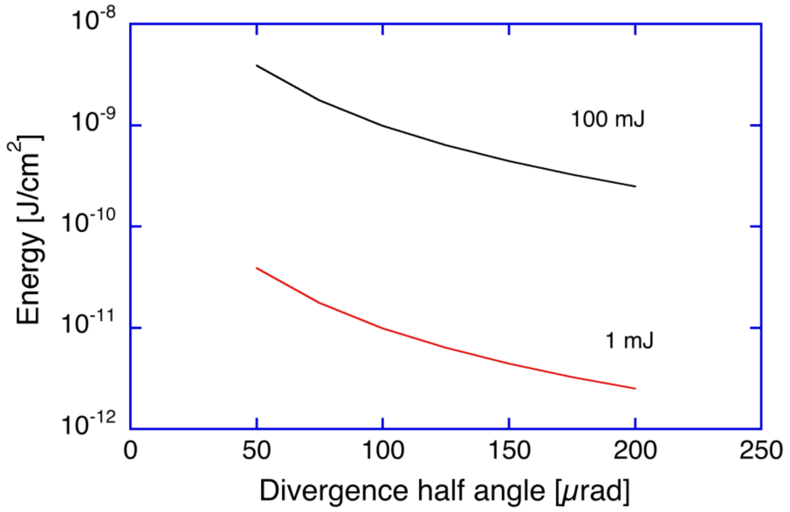

Fig. 1: The laser energy density at the minimum distance of the ISS (≈ 380 km) computed for the WLRS as a function of the divergence half angle.

From the energy density calculations it turns out that the WLRS system is eyesafe to the naked eye for both, configuration (A) and (B). For the use of binoculars or imaging device with a factor of 100 of magnification, configuration (A) remains eyesafe under all circumstances and configuraton (B) will only be eyesafe for the setting with the maximum divergence half angle of 200 µrad.

The aspect of ground air space safety is discussed hereafter only to provide the related background information, while the general operation of ILRS ground stations is outside of the scope of the ACES Project and a matter of national authorities. The International Laser Ranging Service (ILRS) routinely performs satellite laser ranging (SLR) to about 65 satellite targets used in space geodesy. These satellites are equipped with retro-reflectors in order to support SLR operations.

2.1 Camera Tracking

Several provisions or procedures ensure laser safety for SLR operations, independent of the momentarily used power setting. First of all the WLRS employs one narrow angle optical camera system (in the near infrared), which is rigidly mounted to the telescope such that it displays a spatial area of no less than 5 degrees around the laser beam. A pattern recognition system identifies aircrafts within this field of view and interlocks the laser. The system was certified according to German standards.

Annex 3 of Unique Hazard Report ACES-15 (cont'd)

2.3 Go/No-Go Flag

The ILRS has adopted several general procedures for safe tracking of vulnerable satellites. One of these features is the Go/No-Go flag. The mission control center[1] can set a status flag, which either allows or denies tracking for the SLR stations. Before and during ranging, ILRS approved SLR stations are interrogating this flag in 1 minute intervals. If tracking is allowed, the laser interlock is turned off. The entire procedure is set up such, that the default setting is “No-Go”. If the server for the Go/No-Go flag becomes unavailable (loss of contact) the laser interlock is no longer actively released and ranging stops. The same occurs if the mission control center sets the flag to “No-Go”. This could be for example when sortie activities take place at the ISS. It is recommended that the ELT experiment invokes the Go/No-Go flag.

2.4 Elevation mask.

Another proven ILRS safety procedure is the definition of an elevation mask, below or above which ranging is disabled. It is up to the mission control center to make use of this feature. During tracking a compliant SLR station is constantly comparing the elevation of the pointing angle of the telescope against this predefined value and activates or releases the interlock when the appropriate condition is met. This feature and also the Go/No-Go flag go through a rigorous ILRS validation procedure before a station is cleared for the tracking of delicate targets. As a result there were no incidents with SLR stations on satellite functions so far.

2.5 Laser Interlock

At the WLRS as well as on many other ILRS stations the laser is per default inhibited by interlock, which ensures that the laser does not fire during the slewing of the telescope when moving from one target to the next or when the telescope is not pointing to the target. This happens for example when a satellite target is too close to the sun for a telescope to follow. In such a case the telescope avoids sun illumination by offset pointing, while laser fire is suspended. When the satellite is more than 20 degrees away from the sun, tracking resumes.

2.6 Air Traffic Control Radar data stream and active Aircraft Transponder

The Geodetic Observatory Wettzell receives a realtime radar data stream from the air traffic control authority, providing aircraft positions, covering the general region around the SLR system. The SLR control program compares the predicted telescope track against the aircraft positions and disables the laser when the laser beam is 3 km and closer or has 5° angular distance (whichever comes first) with respect to the nearest aircraft. Another data stream transmitted from aircrafts, namely the automatic dependent surveillance broadcast (ADSB), is independently received by a local receiver and evaluated in the same way. This redundant information is used to enhance consistency for this method.

2.7 Off normal operations

During off normal operation states an independent interlock is disabling the laser through a shutter inside the laser oscillator. When the shutter is not powered it is in the closed state and prevents lasing. The shutter is activated only if all necessary conditions of laser fire are met at the same time. These conditions are additionally listed in table 3.

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[1] please note: The laser stations have no influence on the setting of the status flag

Annex 3 of Unique Hazard Report ACES-15 (cont'd)

Table 3: Conditions causing interlock

	Condition	
1	Safety Radar	always
2	Go/No-Go flag	when requested by mission
3	Elevation mask	when requested by mission
4	Telescope on target	always
5	Divergence setting is correct and valid	when requested by mission
6	Laser power below given limit	when requested by mission
7	Air traffic control data stream	always
8	ADSB beacon	always
9	Camera (vis + IR)	always

Condition 1: The safety radar is permanently operated during laser ranging activities. It releases the shutter only if the operation state is nominal.

Condition 2: Go/No-Go flag: This feature is available to all missions requesting control of the interlock via the control center. By default the flag is on No-Go. A tracking station must successfully acquire a "Go" status from the respective communication channel in order to release the shutter.

Condition 3: If an elevation mask is specified the laser is enabled under computer control only if the requirements of the elevation mask are met.

Condition 4: If the computer control finds a discrepancy between the commanded and the actual telescope pointing position, it interlocks the laser. The tolerance can be specified.

Condition 5: A mechanical hardware switch must be released by mechanically shifting a lense to a position of higher divergence in order to activate the safety shutter and to enable laser fire.

Condition 6: If the laser power is set below a pre-defined value, this function enables tracking.

Condition 7: The Air traffic control data stream is permanently used during ranging operations.

Condition 8: The ADSB beacon is permanently used during ranging operations.

Condition 9: A camera image of the area around the laser beam is constantly evaluated for close aircrafts by exploiting pattern recognition both in the visible and the IR domain.

3. Analysis showing that the laser power at ISS altitude is well below the threshold specified in the relevant standards (e.g. ANSI Z136.1) for observer using binocular. This analysis shall include also off nominal operations of the laser system.

The current design of ELT requires that participating SLR stations reduce their laser power to the point that single photon detection is achieved. The detector hardware layout requires an energy density at Columbus Module (TCA) at around 2.3e-13 J/cm^2, which is 5 orders of magnitude below the ANSI Z136.1 allowed margin for eye safety. The laser energy will get focused in case of binocular usage in the relation of front-lens cross section area to pupil cross section area. Using a front-lens diameter of 400 mm and considering a pupil diameter of 7 mm, the surface ratio is 3265. The resulting maximum power density for full laser energy operations of the laser source in configuration (A) and minimum divergence (0.4 mJ, 200 µrad) is 2.34e-9 J/cm^2, not considering any transmission losses of the binocular. This is the worst case off-nominal laser condition for configuration (A).

Annex 3 of Unique Hazard Report ACES-15 (cont'd)

The resulting energy density for the case of maximum laser source energy corresponding to configuration (B) and nominal divergence (32 mJ, 200 µrad) and the same surface ratio of 3265 for the binoculars or other magnifying devices as outlined in the previous paragraph is 1.87e-07 J/cm^2, not considering any transmission losses of the binocular. This is still compatible with the MPE (532 nm; <100 ps) 2.00e-7 J/cm^2.

However for a failure case of full laser power of 32 mJ corresponding to configuration (B) and a beam divergence of 10 µrad the corresponding energy density is 7.48e-5 J/cm^2, which exceeds the permissible power density of 2.00e-07 J/cm^2.

3.1 Precautions applied to prevent off-nominal operations pertinent to laser configuration (B)

The ranging system will be programmed to set the necessary (low) power level of E < 1 mJ needed for the ACES tracking automatically. **This is done under computer control prior to slewing the telescope into the position to point to the ISS**. The instantaneous laser beam power is measured by a power meter, while a mechanical shutter entirely blocks the entry path of the laser beam to the telescope. Only if a laser power of less than 10 mJ is obtained (this value corresponds to the limit when the worst case energy density is dropping below the permissible MPE level), the beam block can be mechanically removed from the laser path under computer control to allow laser tracking[2]. Since the power meter is implemented via a beam splitter into the optical path between laser source and divergence optics it permanently monitors the laser beam power. If the laser beam power increases during operations (failure case), the laser beam block is automatically re-inserted, not requiring any computer intervention. The default setting (no laser power) is when the sensor head blocks the laser beam.

A second redundant safety inhibit is that the telescope can only point and track the ACES Columbus module, when the beam divergence controlling mirror has reached the end position (corresponding to 200 µrad half angle beam divergence) and activates two micro switches wired up in series (added redundancy).

The Go / No-Go flag as described in chapter 2.3 can be used as well for ACES related operations to prevent laser ranging in case of sensitive visiting vehicle operations are planned that could interfere with the laser signal.

4. Evidence of the certifications from governmental authority regarding the safe operation at ground level (e.g. interference with air traffic, exclusion zones etc.)

4.1 No Flight Zone ED-R139

The SLR operations at the Geodetic Observatory Wettzell are protected by a no flight zone, labeled ED-R139. Although aircrafts at cruising altitudes of higher than 10000 feet can pass over the SLR facility, aircrafts at lower altitudes have to avoid the conical safety zone.

5. In addition to the above, there will be an assessment of potential interference with ISS visiting vehicles (e.g. ESA Automated Transfer Vehicle) by using a value of 5.6e-9 J/cm^2 (pulsed laser operation at λ = 0.532 µm) for the energy density.

The current design of ELT requires that participating SLR stations reduce their laser power to the point that single photon detection is achieved. The detector hardware layout requires a MPE 2.3e-13 J/cm^2, which is more than three orders of magnitude below the ANSI Z136.1 the allowed margin for eye safety.

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[2] The power meter and the corresponding electronic circuit generate a shutter enable signal. This shutter enable signal is only „true" if the measured beam power meets the condition, that the beam power is larger than zero and less than 10 mJ ($0.1 < E \leq 10$ mJ), covering the condition that „no power" at this safety device is also an unsafe state. Only if shutter enable is „true", the beam block can be removed from the laser path under computer control.

Annex 3 of Unique Hazard Report ACES-15 (cont'd)

Literature

[1] Pearlman, M.R., Degnan, J.J., and Bosworth, J.M., "The International Laser Ranging Service", Advances in Space Research, Vol. 30, No. 2, pp. 135-143, July 2002, DOI:10.1016/S0273-1177(02)00277-6.

First Draft: 7. June 2011
Revision: 4. March 2015

Annex 3 of Unique Hazard Report ACES-15 (cont'd)

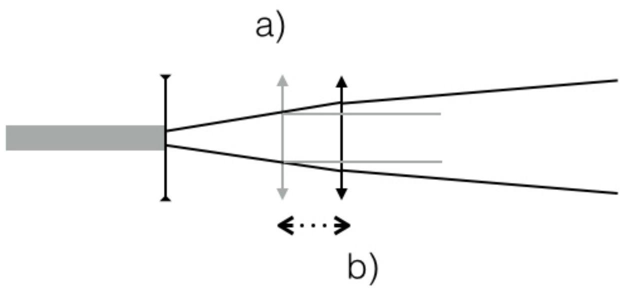
Appendix A: Laser intensity limitations - Summary

Laser intensity limitation (general scheme)

All the three groups of safety functions are linked in series and must be valid at all times throughout the ranging. If any of the criteria is not met during ranging, the laser is mechanically disconnected from the telescope and no light is emitted. The functions are:

a) The actual telescope pointing is within ±30 seconds of arc of the instantaneous target position as predicted by orbit calculations.
b) The Go/NoGo flag is true = set to Go
c) The divergence setting of the laser beam is set to high divergence values of 200 µrad or above. (see divergence setting description below)
d) The effectively generated laser energy is below 10 mJ for as long as tracking of the ISS lasts. (see laser intensity limitation below)

Laser Intensity Limitation through increased divergence

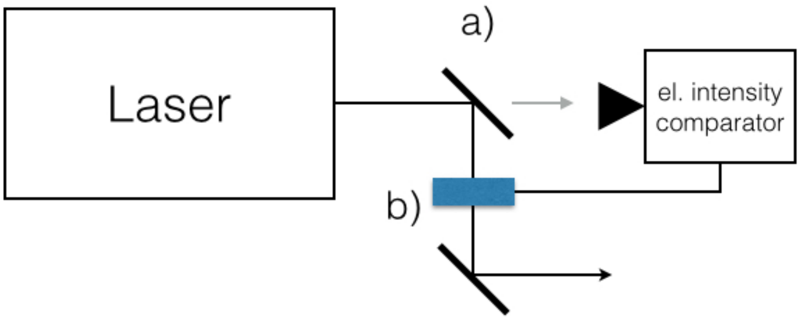


The laser beam divergence is set by a Galileo type of telescope consisting of a negative (divergent) and a positive (convergent) lens. The negative lens comes first and expands the laser beam as shown in the sketch above. When the two foci coincide the beam is collimated, corresponding to the nearest spacing of the two lenses (a). By mechanically shifting the lens to maximum distance (end of travel) on a one dimensional translation stage, the required beam divergence of 200 µrad is achieved. The arrival of the lens at this end position is detected by two micro-switches, which are activated by the lens mechanically pushing against the switches, closing the contacts. Only with the contacts closed a mechanical beam dump can be moved out of the beam path, allowing the laser beam to enter the telescope. However this requires a second condition to be met.

Annex 3 of Unique Hazard Report ACES-15 (cont'd)

Appendix A: Laser intensity limitations - Summary

Laser Intensity Limitation through in situ beam power monitoring



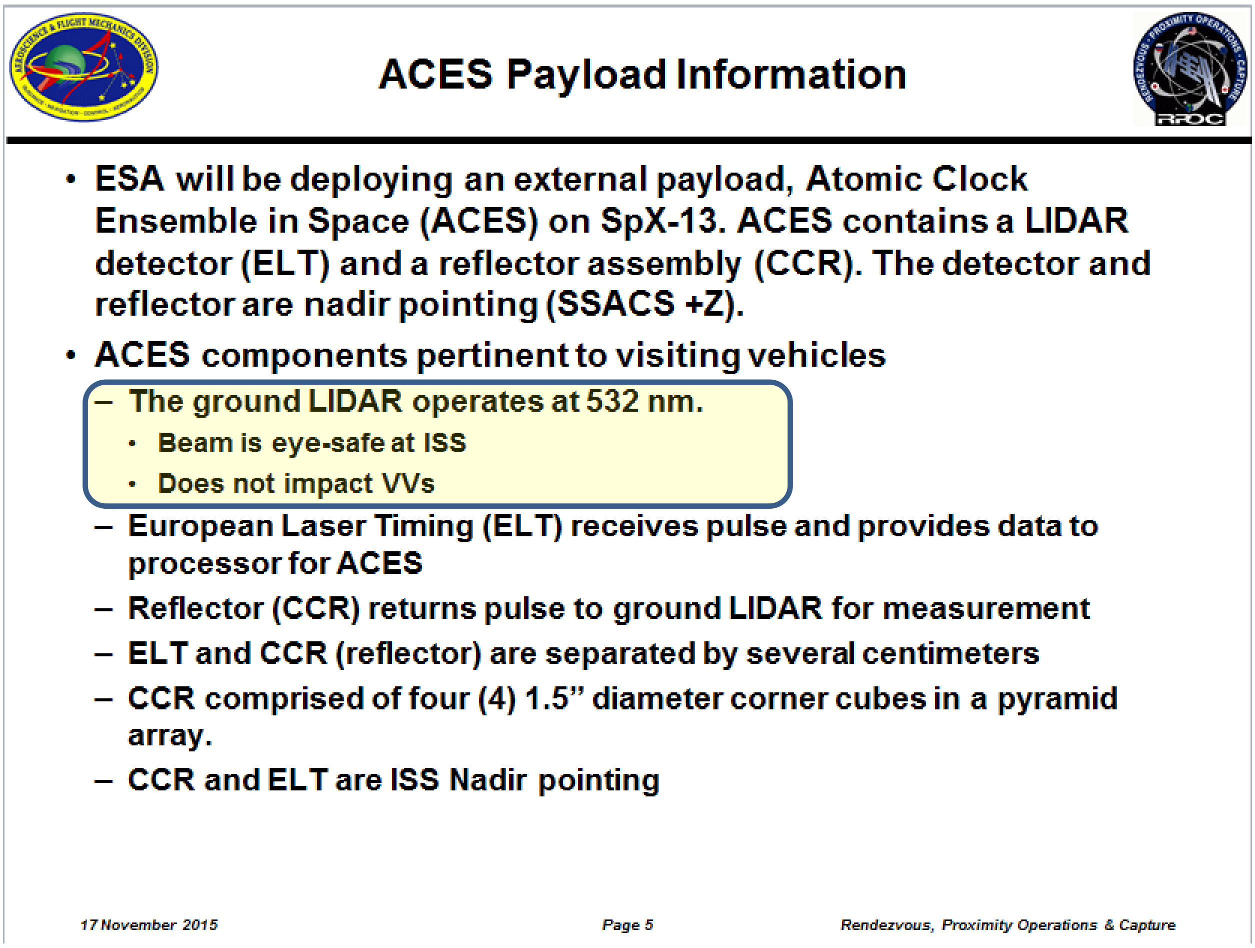
The laser beam coming out of the laser is reflected off from a beam splitter (a). An optical energy detection device behind the beam splitter constantly measures the transmitted laser energy. The measured energy value is inverted such that high laser energy corresponds to a low control voltage and low energy corresponds to a high voltage. In this way it is possible to reliably detect power loss at this control circuit. If the obtained voltage is above a given value, corresponding to a laser energy of 10 mJ or less and the beam divergence condition, explained in the previous paragraph, is met, the beam block (b) is released and can be lifted up under motor control by this autonomous safety device.

Power failure on this safety circuit or a beam divergence off from maximum will cut the actively held beam block from the power supply, dropping the beam dump back into the low position, which separates the telescope from the laser, while the other functions, such as the Go/NoGo flag and the Off-target pointing will lock the shutter in the laser cavity and inhibit the generation of laser pulses in this additional way.

These functionalities are shown in the Annex 1 of the Unique Hazard Report ACES-15

Annex 4 of Unique Hazard Report ACES-15

An analysis showing that laser power reaching ISS level is compatible with VV laser navigation has been performed by NASA-JSC (EG2) RPOC, see ACES CRR impacts to ISS Visiting Vehicles Presentation NASA-JSC (EG2) RPOC, 17-Nov-2015, slide 5.



The only additional assessment from ACES side that can be performed without knowledge of VV sensors sensitivity for 532nm laser is the fact that the ground laser intensity when targeting ISS remains always eye-safe and is orders of magnitude below sunlight intensity in the 532nm wavelength regime.