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Technical Report on INNA project proposal to SEIA – Executive Summary

1. Background

The INNA project (INNA - Proyecto Integrado de Infraestructura Energética para la Generación de Hidrógeno y Amoníaco Verde) has been admitted by the Servicio de Evaluación Ambiental, II Región de Antofagasta (SEA Antofagasta), to the environmental evaluation process (EIA) on 27 December 2024 by resolution number 202402001195 under file 2163335618.

Sites for professional astronomical observatories are chosen based on several characteristics that make them the most-suitable sites to host the biggest, best, and most expensive telescopes. Among these parameters are atmospheric characteristics like **optical turbulence**, wind velocity, outer scale length, **seeing**, isoplanatic angle, coherence time, extinction, **dust**, cloud cover, humidity, precipitable water vapor, sky emission, **sky darkness**, **light pollution**, but also ground characteristics like soil properties and **seismicity**.

Cerro Armazones was chosen as the site for ESO's ELT in 2010, on the basis of a rigorous evaluation of a variety of sites in Chile and elsewhere. It is located only some 25 km from ESO's Paranal Observatory, the home of the Very Large Telescope (VLT) since the 1990s. The outstanding Paranal site is one of the best characterised sites in the world and therefore serves as the world-wide reference to compare the best astronomical sites.

The extended valley between Paranal and Armazones was chosen as site for the southern site of the Cherenkov Telescope Array Observatory (CTAO-South) in 2018 for similar characteristics.

Both new observatories, ELT and CTAO-South are currently under construction while Paranal has passed its 25th year of operation. The two new observatories are projected for a minimum lifetime of 25 years, Paranal is expected to last another 25 years.

Any change of the characteristics of an astronomical observatory site will change its performance and by this its scientific discovery potential and scientific productivity. ESO's observatories are widely recognised as the scientifically most productive ground-based telescopes in the world.

Consequently, this report focuses on those site characteristics that are most critical for the performance of the ESO observatories and that could be impacted the by the INNA project, i.e.

- the **artificial light contamination ("light pollution")** of the night sky due to the installation of artificial light sources as part of the INNA project,

- the increase of ground motions (**vibrations** or micro-seismic noise) due to the installation of wind turbines as part of the INNA project, and
- the increase of ground layer **atmospheric turbulence** also due to the installations of wind turbines.
- the **dust contamination** of optical surfaces (like telescope mirrors and instrument lenses) due to the dust generated by the construction and operation of the INNA project.

Detailed analyses of these impacts at the three observatory sites (Paranal, Armazones and CTAO-South) have been performed. They show that the INNA project executed at the currently baselined site will significantly and negatively impact the performance of all ESO's telescopes at the site, in a way that due to the proximity, could not be mitigated.

2. Executive Summary

2.1. Light Contamination

ESO's Paranal Observatory site in the Atacama Desert in the North of Chile is today among the very darkest astronomical observation sites in the world as has been recently confirmed by an independent study. Only 6 out of 28 professional observatories in the world are found at a sky contamination level of less than 1% at zenith in the visual wavelengths (V-band). The second in the ranking is the Armazones site.

The darkness of the sky is a fundamental characteristic of an astronomical observatory sites as it determines the contrast between the astronomical object of interest and the brightness of the sky. The darker the sky, the fainter the astronomical object that can be examined. The sky brightness has two components. First, the **natural sky brightness** determined by natural phenomena like light scattered from the moon, the ecliptic (the so-called "zodiacal light"), the Milkyway, the brightest stars, and the natural air glow of the atmosphere. Second, the human-made, **artificial sky brightness**, contributed by artificial light sources like streetlights, car headlights, position lights, and many others.

The actual darkness of the sky is determined by the sum of the natural and artificial sky brightness – and the telescope cannot distinguish the two. Any contribution from artificial sky brightness has a negative impact on the capabilities of a telescope. A 1% artificial light contamination means that above every 100 photons from the natural sky brightness, there is 1 on average which comes from light pollution, which cannot be distinguished by another photon coming from a faint object at the edge of the Universe as detected by the most powerful telescope ever built – like the ELT. **Every photon counts in astronomical research.**

By the application of state-of-the-art models for the natural sky brightness (SkyCalc) and the artificial sky brightness (Illumina) we have

- Established the low level of artificial sky brightness at the Paranal, Armazones, and CTAO-South sites, making them still the darkest observatory sites in the world,
- However, noted that the artificial sky brightness has considerably increased by a factor of 3.0 to 3.7 between 2012 (shortly after the site for the ESO ELT site was chosen to be Armazones, and 2024 due to an increasing number of new artificial light sources at distances between 50 and 100 km from the observatory sites:

Illumina Model	Paranal 2012	Paranal 2024	Armazones 2012	Armazones 2024	CTAO-S 2012	CTAO-S 2024
V-band artificial sky brightness at 45 deg elevation [mag/arcsec^2]	**27.80**	**26.60**	**27.21**	**25.78**	**27.75**	**26.35**
V-band artificial sky brightness at 45 deg elevation increase [mag/arcsec^2]		-1.20		-1.43		-1.40
V-band artificial sky brightness at 45 deg elevation increase		x2.97		x3.71		x3.66
V-band artificial sky brightness relative to natural sky brightness at 45 deg elevation	**0.37%**	**1.10%**	**0.63%**	**2.34%**	**0.38%**	**1.39%**
V-band artificial sky brightness increase relative to natural sky brightness at 45 deg elevation		+0.73%		+1.71%		+1.01%

- Estimated that the INNA project assuming the installation of idealised "perfect" luminaries will increase the artificial sky brightness by another +5% to +55%:

Illumina Model	Paranal 2024	Paranal INNA	Armazones 2024	Armazones INNA	CTAO-S 2024	CTAO-S INNA
V-band artificial sky brightness at 45 deg elevation [mag/arcsec^2]	**26.60**	**26.27**	**25.78**	**25.73**	**26.35**	**25.88**
V-band artificial sky brightness at 45 deg elevation increase [mag/arcsec^2]		-0.33		-0.05		-0.47
V-band artificial sky brightness at 45 deg elevation increase		+35%		+5%		+55%
V-band artificial sky brightness relative to natural sky brightness at 45 deg elevation	**1.10%**	**1.49%**	**2.34%**	**2.45%**	**1.39%**	**2.14%**
V-band artificial sky brightness increase relative to natural sky brightness at 45 deg elevation		+0.39%		+0.11%		+0.75%

- Found that the current design of the INNA luminaries leads to an illumination of the INNA facilities by an average factor of 5 lower than required by the Chilean norm for the illumination of industrial workplaces. When factoring in the 5-times increase of the luminous flux of the INNA luminaries as required to satisfy the norm, we estimate that the INNA project would increase the artificial sky brightness by another 23% to 269% with respect to the current sky conditions:

Illumina Model	Paranal 2024	Paranal INNAx5	Armazones 2024	Armazones INNAx5	CTAO-S 2024	CTAO-S INNAx5
V-band artificial sky brightness at 45 deg elevation [mag/arcsec^2]	**26.60**	**25.49**	**25.78**	**25.56**	**26.35**	**24.93**
V-band artificial sky brightness at 45 deg elevation increase [mag/arcsec^2]		-1.11		-0.22		-1.42
V-band artificial sky brightness at 45 deg elevation increase		x2.79		x1.23		x3.69
V-band artificial sky brightness relative to natural sky brightness at 45 deg elevation	**1.10%**	**3.07%**	**2.34%**	**2.88%**	**1.39%**	**5.12%**
V-band artificial sky brightness increase relative to natural sky brightness at 45 deg elevation		+1.97%		+0.55%		+3.74%

- Estimated that in the presence thin cirrus clouds corresponding to 13% of the observatories' valuable observing time, the nearby INNA luminaries will increase the artificial sky brightness by a factor of 1.5 to 2.8:

Modelo Illumina	Paranal 2024	Paranal INNA +nubes	Armazones 2024	Armazones INNA +nubes	CTAO-S 2024	CTAO-S INNA +nubes
Brillo artificial del cielo en banda V a 45 grados de elevación [mag/arcsec^2]	**26.60**	**25.68**	**25.78**	**25.33**	**26.35**	**25.21**
Aumento del brillo artificial del cielo en banda V a 45 grados de elevación [mag/arcsec^2]		-0.92		-0.45		-1.14
Aumento del brillo artificial del cielo en banda V a 45 grados de elevación		x2.33		x1.52		x2.84
Brillo artificial del cielo en banda V en relación con el brillo natural del cielo a 45 grados de elevación	**1.10%**	**2.56%**	**2.34%**	**3.54%**	**1.39%**	**3.95%**
Aumento del brillo artificial del cielo en banda V en relación con el brillo natural del cielo a 45 grados de elevación		+1.46%		+1.21%		+2.56%

In the presence of thick clouds this factor can raise to 6.3 (or 9% of increase relative to the natural sky brightness at 45 degree elevation) for CTAO-South.

In the case of a 5-times increase of the luminous flux and the presence of thin cirrus clouds the factor would raise to 10.0 (or 12.4% of increase relative to the natural sky brightness at 45 degree elevation) for CTAO-South.

Considering these findings, we conclude that the impact of the INNA project on the performance of the Paranal, Armazones, and CTAO-South observatories would be substantial.

In particular, that the Paranal Observatory which today is probably the last observatory in the world close to an 1% sky contamination level in the V-band at 45 degree elevation relative to the natural sky brightness would be degraded by the INNA project to a sky contamination level of 1.5% to 3.1% is considered as not acceptable.

Further, that the largest optical ground-based telescope in the world, the ESO ELT at Cerro Armazones in Chile, would have to operate at a sky contamination level of 2.5% in the V-band at 45 degree elevation relative to the natural sky brightness because of the INNA project and other recently installed nearby projects is also considered as not acceptable.

Our models actually show that in the case of the ELT at Armazones some simple adjustments in the luminaries of nearby light sources could restore a contamination level of close to 1% (and further lower the contamination level at Paranal).

2.2. Vibrations

ESO operates at Cerro Paranal since more than 20 years the VLT Interferometer (VLTI) which combines coherently the light collected by the four 8-m VLT Unit Telescopes (UT's) as well as by four additional, movable 1.8m Auxiliary Telescopes (AT's).

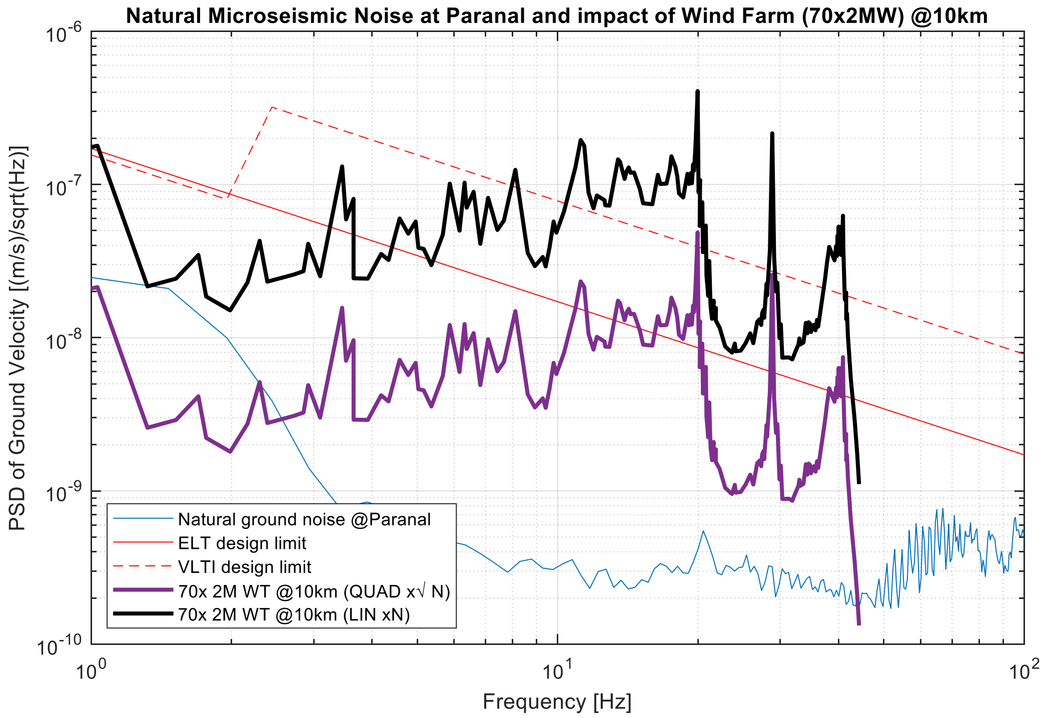
This interferometric array is similar to a radio interferometer such as ALMA but it operates in the optical wavelengths (0.6 to 13µm). This imposes to combine the optical beams physically as opposed to electronically and digitally (using super computers to correlate the signals) limiting the possibility to correct disturbances by post-processing. This calls for a very stable environment.

The VLTI is the only facility in the world where astronomers can study the Universe in the optical domain at angular resolution below 1 milliarcseconds (1 arcsec = 5.10^{-6} radians) with the sensitivity provided by very large telescopes.

Furthermore, the future 39-m ELT under construction at Armazones features a segmented primary mirror (M1) made of 798 hexagonal segments that needs to be permanently kept perfectly aligned (phased) like an interferometer to obtain its unique spatial resolution from the largest optical telescope mirror in the world.

ESO has first established the baseline for the **true level of natural ground vibration on the Paranal observatory platform,** which is significantly lower than what INNA reports. The study addresses only the vibrations generated by the wind turbines (in particular the vertical accelerations) and that are transmitted through the ground. In this study a simplified model has been used, assuming a hard ground (appropriate for the Paranal territory), either coherent or incoherent seismic signal introduced by the 70 wind turbines and two different models for the propagation of the power spectral density through the ground.

Our impact analysis of the INNA wind farm on the ground vibration at Paranal shows that **the limits imposed by the VLT Interferometer (VLTI) and the Extremely Large Telescope (ELT) are likely to be exceeded**.



Considering these findings, we conclude that the impact of the INNA project on the performance of the VLTI at Paranal and the ELT at Armazones observatories would be substantial.

2.3. Atmospheric turbulence

Turbulence blurs the images produced by the telescopes. The size of a long-exposure image of a star on the detector is proportional to this turbulence and is characterized by the full-width-half-maximum of such image which is called the "*seeing*" measured usually in arcseconds (1/3600 degrees or 5.10^{-6} radians). The more turbulence is present in the atmosphere, the larger is the *seeing* and the more blurred is the image.

The Chilean Atacama Desert is one of the best places on Earth with respect to the seeing. The main reason is the cold Humboldt current in the pacific that creates an inversion layer above the ocean that blocks most of the turbulence in the few hundreds of metres above the sea. The Paranal and Armazones observatory sites are among the best in the World in terms of *seeing*, with "good seeing" values between 0.3 and 0.5 being characteristic. Any degradation of the seeing would be a dramatic loss of astronomic scientific capability world-wide. This also holds when adaptive optics correction is used since the lower the atmospheric disturbance is, the better is the image sharpness after the (imperfect) adaptive optics correction.

Wind turbines and, even more, large wind farms, generate turbulence in their wake. Research has progressively found evidence of wakes at increasingly large distances reaching values of 55 to 100 km. All 3 observatory sites will receive turbulent kinetic energy injected by the wakes of the wind farms. Under good seeing conditions, the estimates show **an increase of 17% for**

0.5 arcsec very good seeing and 43% for 0.3 arcsec. This happens precisely for winds coming from South-South-East which is precisely when good seeing conditions happen. **The typical "good seeing" episodes will move from being in the range 0.3-0.5 arcsec to 0.4-0.6 arcsec.** This will result in a substantial deterioration of the capability to perform deep-sky or resolved observations of the sky, for which telescopes like VLT and the ELT were precisely designed.

An additional negative effect into the image quality by increasing turbulence at the observatory sites will be created by the INNA Photovoltaic (PV) plant. Temperatures around 3 degrees higher above the PV panels are commonly measured, generating thermal kinetic energy. Our estimates show **similar values of such turbulent kinetic energy as those generated by the wind farms, further degrading the seeing at the observatory sites.**

2.4. Dust

Through direct measurements, Paranal Observatory has been established to be an extremely clean site with very low levels of dust particles:

	Paranal MP10 [µg/m3]	Paranal MP2.5 [µg/m3]
Air quality measured 2001-2006 (annual average)	**1.74**	**0.55**

No long-term variations or trends have been observed so that we conclude that the air quality measured here also corresponds to the current air quality.

The table below summarises the current baseline for the air quality at Paranal Observatory and the amount of additional contaminants modelled for the third year of construction of the INNA project. We find an increase of contaminants by +75% and +73% for MP10 and MP2.5 due to the INNA project, respectively.

	Paranal MP10 [µg/m3]	Paranal MP2.5 [µg/m3]
Air quality measured 2001-2006 (annual average)	**1.74**	**0.55**
Air quality modelled INNA construction year 3 (annual average)	**1.30**	**0.40**
Increase of contaminants during INNA construction year 3	**+75%**	**+73%**
Air quality modelled INNA construction year 3 (P98 24 hrs)	**9.50**	**3.10**

As expected from its proximity, **CTAO-South is the telescope that will be affected most by the INNA project construction**. In particular because the mirrors of the CTAO-South telescopes cannot be protected from dust as they have not telescope enclosures

The impact of a +75% increase of dust content in the air due to the construction of the INNA project, results in a direct faster degradation of the telescope mirror reflectivity, and therefore in a loss of light collecting capacity of all the telescopes. Besides a loss in effective collecting area or transmission of around 2.5%, dust accumulation would increase maintenance costs and an additional 2% loss of observing time due to cleaning procedures that would have to be done more frequently.

Paranal Observatory	Effective Transmission [%]
With current MP10 over a period of 4 years (week 1 - 208)	**78.2%**
With MP10+75% over a period of 4 years (week 1 - 208)	**74.9%**
Transmission reduction over 4 years of INNA construction	**-4.1%**
With current MP10 over 1 year (week 1 - 52)	**82.3%**
With MP10+75% during year 3 of INNA construction (week 1 - 52)	**80.2%**
Transmission reduction during year 3 of INNA construction	**-2.5%**

The massive increase of emission of solid particles (“dust”) during the construction and operation phase of the INNA project will increase the deposition of dust particles on the mirrors and other optical surfaces of the ESO telescopes at the Paranal, Armazones, and CTAO-South sites. Simulations shown that the dust will propagate from the INNA sites to all three observatory sites.

To maintain the performance of the three observatories, the mirror cleaning activities have to be increased accordingly or lower levels of telescope performance (i.e., lower transmission) would have to be accepted if no additional effort for the mirror cleaning can be found at the observatories.

Considering these findings, we conclude that the impact of the INNA project on the performance of the Paranal, Armazones, and CTAO-South observatories would be substantial.

3. Conclusion

As a conclusion, the INNA project would degrade the performance of all the telescopes at the Paranal/Armazones site (VLT and VLTI in Paranal, ELT in Armazones and CTAO-South) to unacceptable levels. The driver is the very short distance from the INNA facilities to the observatory sites. As all mitigating actions have already been taken, these negative and unacceptable impacts cannot be avoided or mitigated, unless the INNA project moves away.

Should the INNA project be approved, the value of the telescopes installed or planned by ESO would be substantially decreased. These losses are manyfold and not recoverable world-wide.