BavariAE:
The Earth's atmosphere and exosphere explored by a minisat in the UV-VIS spectral region

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ABSTRACT

The "Bavarian Atmosphere Explorer" (BavariAE) is a minisat mission of ≈ 200 kg dry spacecraft mass orbiting the Earth on a high polar orbit at least half the way out to the geostationary orbit (GEO). It observes the Earth's exosphere and atmosphere with the Sun as a light source while it sets and rises beyond Earth. While orbiting the day side of Earth, a second observational mode will be utilized. In this mode, BavariAE will look down on the Earth's surface, observing an approximately 150 km wide circle of integrated light.

While the first observational mode will serve as a proxy for exoplanet transit spectroscopy, the second will serve as a proxy for reflection spectroscopy of exoplanets. By achieving precise, laboratory-like knowledge of Earth's atmospheric structure and composition, we will generate unique datasets that can be used to test, validate, and refine models of exoplanet spectroscopy.

Besides astronomy, geoastronomy, and astrobiology, BavariAE data will also have significant importance for climate research, upper atmosphere physics, and meteorology. During the first 1.5 years of the mission, we will scan the Earth's atmospheric and exospheric layers with a radial resolution of about 5 km above the Earth's surface. After the core mission is finished, a second operational phase is planned, using an improved radial resolution of around 2 km for one additional year.

An observational mode looking at the other Solar Systems' planets in reflection is under investigation. This would allow us to use the Solar System in all its variety as a proxy for future exoplanet observations.

The payload consists of an $R = 200,000$ Échelle spectrograph fed by two ≈ 10 cm aperture off-axis telescopes. The instrument will span a wavelength range from 2500 to 8000 Å (with a goal of 2000 to 9000 Å).

As BavariAE is not a mission that has to observe the strict rules of the European Cooperation for Space Standardization (ECSS), we will follow a *Space 2.0* approach to get into orbit reliably yet quickly. BavariAE is planned to serve as a crucial first step to validate the concept for the Theon[1] mission, our response to ESA's M8-call for mission opportunity. Synchronization with the first project phases of Theon is therefore an important part of our concept.

Keywords: minisat, exoplanets, Theon, exosphere, upper atmosphere, transit spectroscopy, reflection spectroscopy, Habitable Worlds Observatory, starshade

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1. INTRODUCTION

The temperature and pressure structure of the Earth's atmospheric layers, all the way out to the exosphere, is well measured by various missions (for example, by UARS,[2] CHAMP,[3] TIMED,[4] AQUA,[5] AURA,[6] Metop series,[7] GRACE-FO[8] or GOLD,[9] to name just a few). Mass spectrometers have been orbiting the layers of Earth's atmosphere for decades (Atmosphere Explorer series,[10] Dynamics Explorer,[11]... list not exhaustive). Even for our neighboring planet Mars, missions like NASA's MAVEN[12] satellite or India's Mars Orbiter Mission (MOM)[13] have explored this type of data. Yet this broad knowledge has never been confronted with the actual observables we will have of exoplanetary atmospheres – **spectra**.

While ground-based large and extremely large telescopes will focus on the near- to mid-infrared spectral windows to observe exoplanets during transit, space observatories like the James Webb Space Telescope (JWST)[14] cover the spectral range from 0.6 to 28.5 µm with different instruments,[15–18] providing resolutions up to a maximum of R ≈ 4000. As shown by Oklopčić[19] and Snellen,[20] several important atoms and molecules can be detected in the UV–VIS spectral range. These include species that are key to tracing the interaction between an atmosphere and the underlying planetary surface, thereby providing insights into the transition from a primary to a secondary atmosphere. Moreover, potential biosignatures can also be probed within this wavelength regime. Using the Earth's atmospheric and exospheric spectra in a quasi-laboratory-like setup (with most parameters a priori known from other measurements), therefore, allows us to validate and, if necessary, improve our models and make our methods fit for later exoplanet observations.

For BavariAE, we will establish two observational modes, whose datasets have scientific communities extending beyond astronomy, geoastronomy, and astrobiology.

1.1 Observational modes and science applications

In addition to the potential use of BavariAE for studying planets within our own Solar System, the mission will offer two distinct observation modes:

Transit mode: In this mode, BavariAE will observe the Sun as it sets and rises behind Earth, effectively scanning through the layers of the Earth's atmosphere. By using a slit that masks parts of the solar disk, a vertical spatial resolution of approximately 5 km in Earth's atmosphere can be achieved. This concept is illustrated in Figure 1 on the left.

Reflection mode: During the spacecraft's day-side transit over the Earth's surface, BavariAE will observe an integrated light circle with a diameter of about 150 km in reflected sunlight (sketched in Figure 1 right-hand side). This simulates the case of an exoplanet observed in reflection.

In the following sections, we describe these two complementary modes in more detail and outline their scientific potential.

1.1.1 Transit mode: Chords through the Earth's atmosphere

While BavariAE observes the sunrise or sunset through the Earth's atmosphere, it records data that emulates Earth as a transiting exoplanet. Figure 2 shows a comparison of simulated line of sight spectra in the Earth's atmosphere crossing 110 km above the Earth's surface for two different atmospheric models* (left), and a simulated spectrum of a R = 2.5 Earth radii sub-Neptune observed during transit (right). Both spectra show similar features, and we expect that the inverse problem – deriving the atmospheric conditions of an unknown exoplanet – can be trained using Earth as a test case, starting from well-known boundary conditions and gradually improving the models toward a full spectral retrieval. As an example for spectra of deeper exospheric layers, we show in Figure 3 chords crossing at 40 km (left) and 70 km height (right). The well-known ozone feature centered at

*The *Reference Forward Model* (RFM)[21] is a line-by-line radiative transfer code that focuses on molecular absorption, while *libRadtran*[22] is a versatile radiative transfer package that additionally accounts for scattering processes and uses different atmospheric databases. As a result, modeled spectra differ: RFM often shows higher transmittance because it neglects scattering and may miss absorption features (e.g., ozone), whereas libRadtran produces more realistic spectra due to its inclusion of scattering and pressure broadening effects missing in the chosen configuration of RFM.

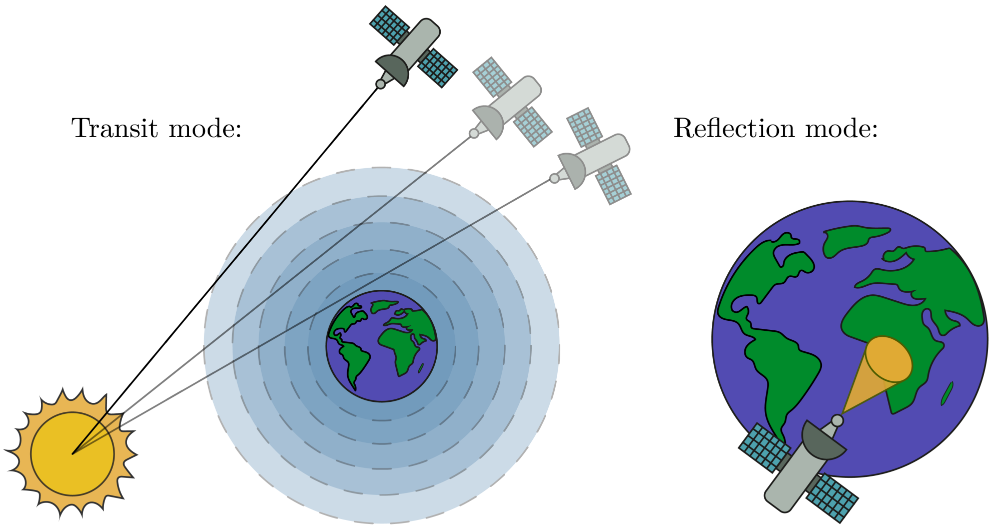

Figure 1. The two observational modes of BavariAE. Left: Transit mode – using the Sun during sunset and sunrise as a source, scanning chords through the Earth's atmospheric layers. Right: Reflection mode – looking on Earth during day-side passage, an unresolved area of ≈ 150 km in diameter will be observed in reflection. Sketch not to scale.

2700 Å and the effect of Rayleigh scattering increasing towards the blue in a λ^4 law is clearly visible in those denser layers of the Earth's atmosphere. An increase in pressure, and therefore in absorber column density, leads to stronger spectral lines. Here, retrievals can be easier, especially as denser layers of the Earth's atmosphere will not be or at least less affected by deviations from the assumption of local thermal equilibrium.

Including methods of geometrical ray tracing, taking into account the effect of light being deflected by density changes along the line of sight (the atmosphere acting as a ball lens), it becomes possible to compose a full model of the Earth as a transiting exoplanet. This allows the step from a single line of sight laboratory setup, to an integrated, mixed, light spectrum that simulates how the Earth would look like if observed by an astronomer lightyears away.

Besides the field of astronomy, meteorology, upper atmosphere physics, and climate research benefit from this unique data set. Especially as a resolution of R = 200,000 allows to do Doppler analysis and resolve the speed of the medium along the line of sight.

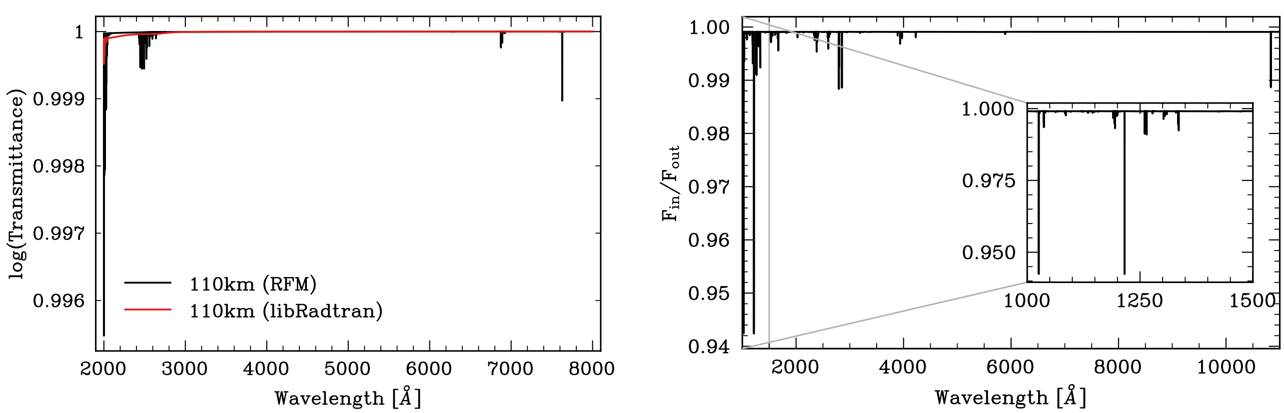

Figure 2. Comparing a chord 110 km above Earth (left)[23] to the simulated transit of a R = 2.5 Earth radii sub-Neptune (right).

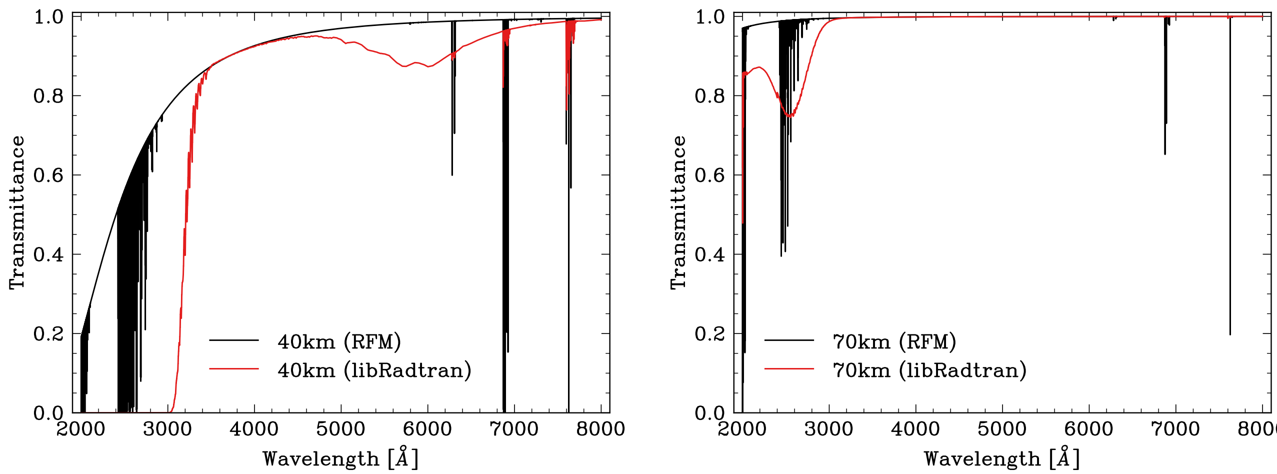

Figure 3. Chords through the Earth's exospheres simulated at 40 km (left) and 70 km height (right).[23] Note the structure of the ozone bands. In high spectral resolution and high signal-to-noise, they can easily be distinguished from other molecular or broadband features.

1.1.2 Reflection mode: The Earth in reflection

While the spacecraft does its day-side transit over the surface of the Earth, an integrated light circle with a diameter of ≈ 150 km will be observed in reflected sunlight. This mimics the case of an exoplanet in reflection. While for exoplanets, only a very low resolution of $R = 5-200$ will be possible at a low signal-to-noise ratio (SNR), BavariAE will be able to observe this signal with a moderate SNR even at $R = 200,000$ (see Chapter 3).
Figure 1 right side sketches the observation mode and the size of the observed zone on the Earth's surface. While the spacecraft crosses the poles, one will look down at an ice-world, over the ocean we will see a water-world, over the Amazonas a vegetation-world and when we pass the great deserts of Asia or Africa, we will mimic a desert-planet (Dune).

This dataset offers a unique opportunity to explore, test, validate, and improve our models for exoplanet reflection spectroscopy. Moreover, it can be combined with actual weather information, providing insights into cloud coverage, surface conditions, temperature, and seasonal variations. At a $R = 200,000$ Doppler broadening of spectral lines along the integrated line of sight will be measurable, important information for dynamical processes in the Earth's atmosphere will be gained.

1.1.3 General science considerations

Both observational modes deliver unique datasets with high SNR and high spectral resolution. As the mission lifetime spans more than 1 year in both geometrical slit resolutions of the transmission case, and more than 2 years in the downward-looking mode, evolution of the data along the seasonal cycle and the change of weather along this long temporal baseline can be obtained. This will make it possible to estimate the averaging times required for exoplanet observations, since "weather reports" for exoplanets will be hard to obtain. It will also help determine how weather and seasonal effects influence high-resolution spectra, and thus provide guidance on what can be expected across all spectral resolutions.

2. MISSION DESIGN

The BavariAE mission design is based on the excellent capabilities of the Bavarian space industry and its new micro- and minisat launcher companies. In order to accomplish the scientific goals of the BavariAE mission, the mission profile, launch, and scientific requirements have to fit in one set of basic boundaries.

One important and productivity-increasing boundary condition is that we are not obliged to follow the strict rules of the ECSS with respect to the qualification of components. In one sentence, this means: "If we think it can fly, we make it fly." Such concepts are often referred to as *Space 2.0* or *New Space* approaches. For us, this means a pragmatic way to get a scientifically important mission to fly within a relatively short time. Additionally, it allows the mission to not only generate its own excellent science, but also support the ESA M8 mission proposal *Theon*[1] with respect to technological and scientific aspects.

We will rely on proven technology and invest in development only where absolutely necessary and where we can benefit from BavariAE raising the technical readiness level (TRL) for the Theon mission.

2.1 Boundary conditions

We present the boundary conditions in this chapter, followed by the sizing and configuration argument for our optical telescope assembly (OTA) and payload module (PLM).

2.1.1 Minisat mission boundaries for BavariAE

The most stringent boundary conditions for our mission are set by the launch capacity of the Bavarian micro- and minisat launcher foreseen for the 2029-2030 launch window we are aiming for.

Mass: The spacecraft wet mass is limited to ≈ 250 kg. With this mass, it is possible to launch into a high orbit below GEO but well outside the main part of the Earth's exosphere. We are currently aiming at an orbital height of approximately 18 000 km. This will lead to an orbital period of approximately 10.5 h.

Size: A PLM volume corresponding to a footprint of $0.5\,\mathrm{m} \times 0.5\,\mathrm{m}$ and a height of 0.4 m is the current baseline.

Lifetime: We are aiming for a 1.5 years primary mission with a slit corresponding to a height resolution in the atmosphere of 5 km. The latter mission shall last for another 12 months with a resolution of 2 km in the atmosphere. A one-time mechanism – fail-safe in the 5 km mode – shall be the baseline, while switching between modes remains a mission goal.

Schedule boundaries: Schedule is a strong boundary. Since BavariAE serves to bring the Theon mission to technical and scientific maturity, we plan to be ready for launch at the end of 2029. First data would then be available and analyzed until ESA takes the final decision on the M8 mission in March 2030.

This is especially important for us because of the synergies we anticipate with two other space missions, which will be addressed in detail in Chapter 2.1.3.

2.1.2 Scientific boundary conditions

The boundaries on spectral resolution, spatial resolution (height in the atmosphere), and mission duration are science-driven.

While the Theon mission aims for a resolution in the main high-resolution band of $\mathrm{R} = 100,000$, and of $5-250$ in the low-resolution band, BavariAE goes for a factor of two higher resolution. This is easily possible as we look at the Sun as a source and our experiment is not photon-starved. With $\mathrm{R} = 200,000$ we can determine whether the $\mathrm{R} = 100,000$ for Theon is well justified and sufficient. Enhanced resolution provides increased capability for atmospheric science.
Even in the downward-looking (reflection mode) case, we have enough photons to reach an SNR of approximately 100 within a few seconds. Allowing to study "our *endoplanets*"[†] in very high resolution to learn about the effects to be expected in low-resolution for *exoplanets*.

For the mission duration, it is a requirement to cover the seasonal cycle at least once in both modes. We add commissioning time and one month of margin to both modes. An extended mission shall be possible.

[†]Planets of our Solar System

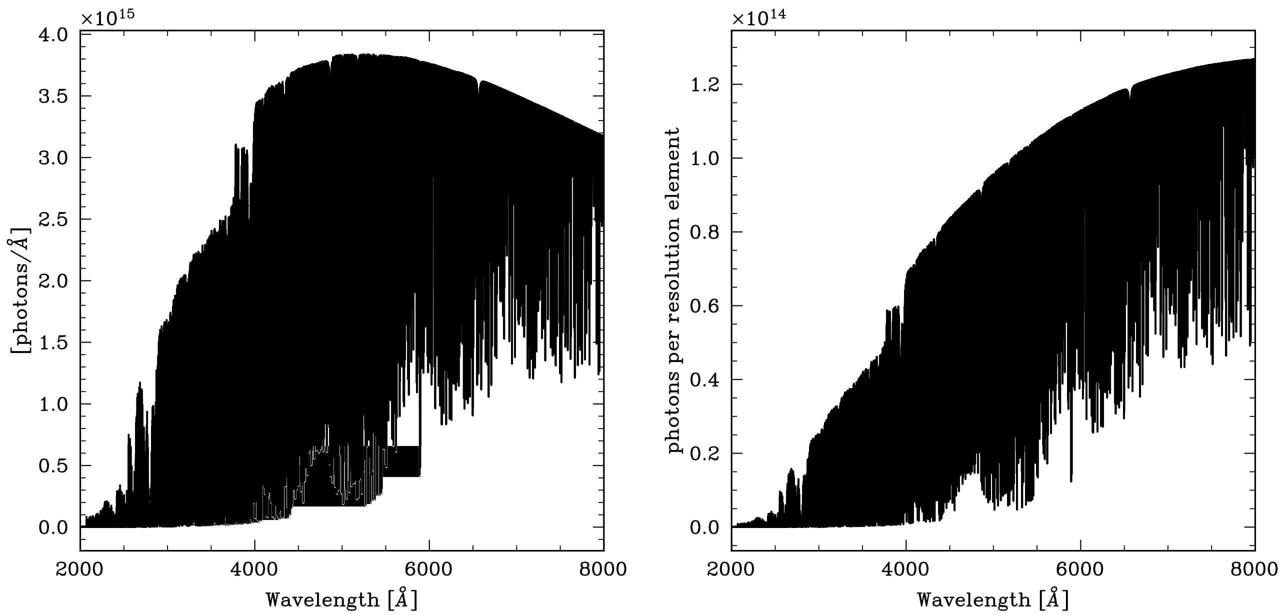

Figure 4. Flux in photons per second and per 10 cm aperture: Left – per Å, right – per resolution element.

2.1.3 Programmatic boundaries

Looking beyond the BavariAE mission horizon: BavariAE can serve as a first step on a path leading from BavariAE over Theon and Theon* (the starshade extension of Theon) all the way to the Habitable Worlds Observatory (HWO).[24,25] It is therefore desired to qualify the detectors and – as a possible side load – a standalone wavefront sensor together with the BavariAE mission. The qualification of very broad band, highly efficient Échelle gratings is desirable but not absolutely necessary, as we are in a photon-flooded situation.

In this sense, BavariAE is a mission that can allow future highest impact mission development and science exploration for Bavaria, Germany, and Europe.

3. TELESCOPE AND INSTRUMENTS

The telescope size is driven by spatial resolution, spectral resolution, and incident photon flux from the Sun as our light source. The solar flux for a 10 cm aperture telescope is shown in Figure 4. The model is based on the PHOENIX NewEra code.[26,27] The left side of Figure 4 presents the solar flux in photons, scaled with an exposure time of 1 s and a telescope aperture of 10 cm. The right-hand side plot shows the flux scaled to a $R = 200,000$ resolution element. With a peak flux well above 10^{14} photons per second and resolution element, we are definitely not photon-starved. We can therefore allow for an optical element sequence that is lossy, but guarantees high stability and reliability, both with respect to optics and operations.

The optical train, following the path of light, is as follows:

Telescope: The baseline design is a 10 cm diameter aperture telescope. It will be a relatively simple off-axis parabola, possibly with one fold mirror to achieve a compact assembly. The telescope and all spectrograph reflective elements are assumed to carry a Hubble Space Telescope primary mirror type of coating.[28]

Image slit: A slit with a slit height of 1 arcmin (1/30 of the solar diameter) corresponding to 5 km spatial resolution in the atmosphere of the Earth is chosen. For the second phase of the mission, an additional slit providing 2 km spatial resolution is foreseen.

Integrating sphere: To ensure stable illumination of the spectrograph, a 25 mm diameter integrating sphere coated with a broadband highly reflective white coating is intended.

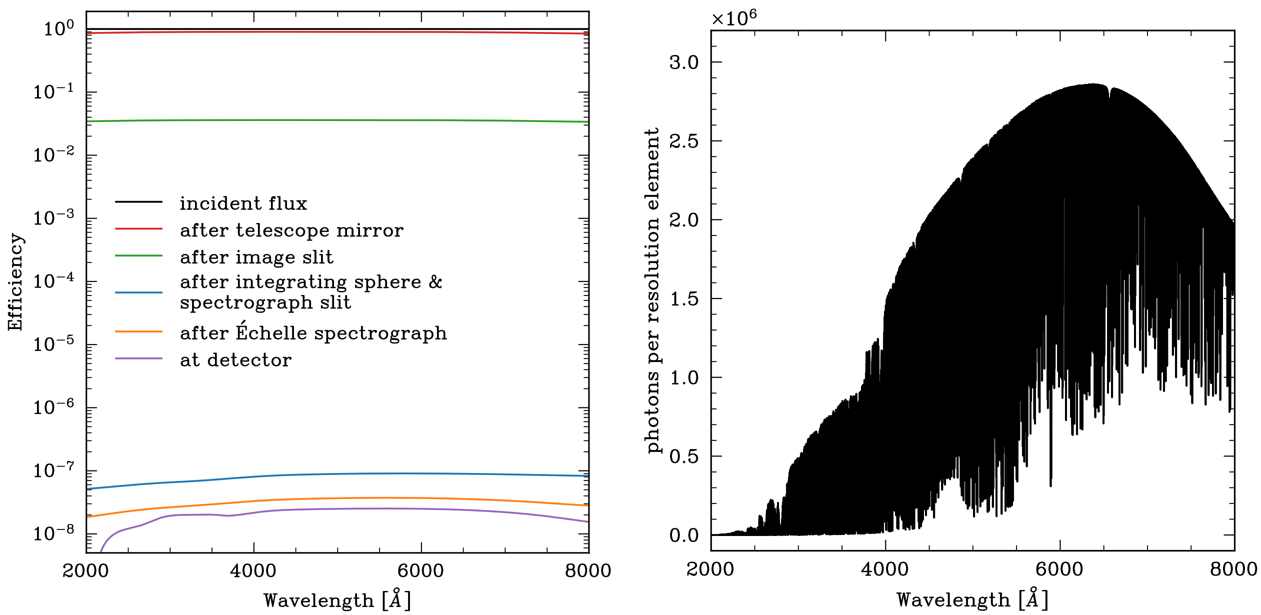

Figure 5. Left: Total system efficiency assumption. Right: Flux at the detector assuming conservative component efficiencies.

Spectrograph slit: The main instrument is fed by a spectrograph slit measuring 100 µm in length and 400 µm in width.

Échelle spectrograph: A spectrograph similar to the one intended for Theon is proposed. Whether this will follow a white-pupil design or adopt a more compact configuration without intermediate imaging remains an open trade study.

Detector: A commercially available CMOS detector[29] is selected as the baseline. More advanced options, such as wavelength-optimized delta-doping and gradient anti-reflection coatings tailored to the Échelle layout, are currently under discussion.

This configuration is optimized for *stability* rather than throughput. For estimating the efficiency of the Échelle spectrograph, we consider a baseline design with three mirrors with the same coating as applied to the Hubble Space Telescope primary mirror. We adopt a grating efficiency of 70 % and a cross-disperser throughput of 80 %. The grating efficiency values are conservative, underestimating the peak performance while slightly overestimating the efficiency at the order edges.

Taking all optical components into account, we obtain the total efficiency displayed in Figure 5 on the left-hand side. In total, we expect – observing in transmission – $\sim 0.5 \cdot 10^6$ photons per second and resolution element at 3000 Å, as shown in Figure 5 on the right. A peak flux up to $\sim 2.8 \cdot 10^6$ photons per second and resolution element is reached at around 6500 Å.

Even for the downward-looking mode, where we expect – albedo dependent – a factor of 10^3 to 10^4 fewer photons, we will reach a reasonable signal-to-noise of 20 . . . 100 within a few seconds. Enough not to have traveled too far over the surface in view. (We travel with a speed of $\approx 4\,\mathrm{km/s}$ across the Earth's surface.)

4. ELECTRONICS AND SPACECRAFT/INSTRUMENT CONTROL

As we have only one mechanism – the one time slit change assembly – instrument control will be limited to detector readout. We plan to use the Sun as a calibrator well above the exosphere to determine the spectrograph's wavelength solution and relative efficiency parameters.

The actual detector readout can be a proxy for the one that will be later used in Theon. Optimization for different readout times according to the high dynamic range of the spectrum shown in Figure 5 are desirable and can also help to optimize for Theon, both hardware-wise and in science return, long before Theon is implemented.

Two further cameras are under investigation: One of them looks down at Earth to simultaneously monitor the cloud coverage and surface condition with the downward-looking mode of BavariAE. A second one would be observing the image slit of the solar observation mode to make sure we are stabilizing on sunspots or actively scanning into sunspots. Those cameras would be commercial off-the-shelf systems, for example, used for CubeSats.
The stability of the Sun's image on the slit will also set the requirements for the line of sight (LOS) stability of the spacecraft. We expect a 1/10 of the slit stability leading to a LOS stability of the order of 6 arcsec.

A potential auxiliary wavefront sensor might be hosted on our platform for TRL maturation, which would require ASIC (Application Specific Integrated Circuit) control. The goal would be to develop a standalone wavefront sensor that does the necessary data processing "itself" and delivers a wavefront in a closed mathematical scheme (e.g., Zernike coefficients).

5. SUMMARY AND CONCLUSION

In summary, BavariAE will be a standalone scientific mission that offers great benefit to future space missions, such as Theon, Theon*, and the Habitable Worlds Observatory.
It will serve a wide range of scientific interests, starting with astronomy, geoastronomy, and astrobiology, and extending to climate research, upper atmosphere physics, meteorology, and even solar physics.

Besides its scientific goals and benefits, BavariAE will advance technology in the field of high spectral resolution observations for endo- and exoplanetary observations. Paving the ground for future scientific and industrial contributions of Bavaria to these important missions.

A further observing mode, looking at the Solar System planets, that reach an angular diameter of tenths of arcseconds as seen from the Earth's orbit, is under investigation. This could allow us to use these endoplanets as further proxies for exoplanetary science, making use of a high-resolution instrument *outside* of the Earth's atmosphere.

BavariAE: What UV is what you see.

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