ESBO DS
Stratospheric Observatory

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LIST OF ABBREVIATIONS AND DEFINITIONS

Abbreviation	Definition
ADCS	Attitude Determination and Control System
BBA	Balloon-Based Astronomy
CFRP	Carbon Fibre Reinforced Plastic
COS	Cosmic Origins Spectrograph
ESBO *DS*	European Stratospheric Balloon Observatory *Design Study*
FIR	Far Infrared
HERO	Heterodyne Receiver for OST
HST	Hubble Space Telescope
MCP	Microchannel Plate
NIR	Near Infrared
OSS	Origins Survey Spectrograph
OST	Origins Space Telescope
PI	Principal Investigator
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPB	Super Pressure Balloon
SPICA	Space Infrared Telescope for Cosmology and Astrophysics
STIS	Space Telescope Imaging Spectrograph
STUDIO	Stratospheric UV Demonstrator of an Imaging Observatory
UV	Ultraviolet
UVIT	Ultraviolet Imaging Telescope
WFC3	Wide Field Camera 3

REFERENCE DOCUMENTS

[RD1]	OST Study Team (2019). Origins Space Telescope Mission Concept Study Report. Report to the U.S. 2020 Astrophysics Decadal Survey, August 2019.

1 INTRODUCTION

This document provides an overview of the potential development timeline for the ESBO astronomical balloon infrastructure.

ESBO, the European Stratospheric Balloon Observatory, is an initiative proposed by several European astronomical research institutes to establish an astronomical observatory infrastructure based on telescopes flown on stratospheric balloons. Balloon-based astronomy (BBA) provides very affordable and flexible access to wavelength ranges otherwise obscured by Earth's atmosphere and therefore not accessible to ground-based telescopes. ESBO thereby focuses on providing observational capabilities in the UV and far infrared (FIR) spectral ranges with different flight platforms.

This document's main purpose is to describe a development timeline and path to establishing the ESBO infrastructure, including required technical developments, administrative and political preparations, and eventually the sequence of possible flights.

The document thereby begins with recapitulating why balloon-based observation platforms are needed for the two wavelength ranges in question in section 2. It continues with a short description of the envisioned ESBO infrastructure in section 3. Section 4 then presents the coordinated development timelines for the different ESBO platforms, with section 5 providing rough estimates of the funding needs for establishing the infrastructure.

2 SCIENTIFIC RATIONALE

2.1 UV

In the UV, wavelengths shorter than 320 nm are practically inaccessible from the ground. The only way to observe at these wavelengths is thus to take measurements from above most atmospheric mass, i.e. either from space or from the high stratosphere. Two space observatories exist at the moment that serve the UV: NASA's Hubble Space Telescope (HST) with the Wide Field Camera 3 (WFC3) imaging instrument and the Indian ASTROSAT observatory with the Ultraviolet Imaging Telescope (UVIT).[1] The capabilities of both in regard to wide surveys are limited, with the WFC3 only providing a comparably small field of view and the UVIT having only a limited light-collecting area due to its relatively small telescope diameter of 0.3 m. Spectroscopic capabilities in the near UV are even more sparse, with only HST offering the Cosmic Origins Spectrograph (COS) and the Space Telescope Imaging Spectrograph (STIS), both with their own limitation, e.g. with regard to inner solar system pointing. Several concepts for space-based UV survey telescopes are currently being proposed[2], with the likelihood of their implementation being unclear, however. For several years to come, the two existing space-telescopes will thus remain the only non-solar UV telescopes.

ESBO will be able to offer:

- Photometric imaging / survey capabilities with the MCP detector developed during the ESBO *DS* project on the STUDIO platform, limited to night time operation;

[1] The Japanese HISAKI/Sprint-A spacecraft does not cover wavelengths longer than 148 nm and the NASA Interface Region Imaging Spectrograph spacecraft that also covers UV is specialized on solar observations.

[2] Including the World Space Observatory, that was first proposed more than 20 years ago and currently has a very uncertain fate, the Israeli ULTRASAT concept, and the Gravitational-wave Ultraviolet Counterpart Imager Mission proposed as a NASA Small Explorer mission

- Filter imaging of inner solar system planets e.g. for atmospheric studies with a minor upgrade of the STUDIO Attitude Determination and Control System (ADCS) to daylight capabilities;
- Potentially spectroscopic capabilities for both solar system and galactic observations with a new instrument on the STUDIO platform.

2.2 NIR (UNDER CONSIDERATION)

The original concept at the beginning of the ESBO *Design Study* (ESBO *DS*) project foresaw a Near-Infrared platform with spectroscopic capabilities. A need for such observational capabilities was identified particularly by three scientific areas:

- Study of exoplanet atmospheres;
- Study of the evolution of young stellar bodies (particularly of accretion);
- Study of small solar system bodies.

With the selection of Ariel as ESA's forth medium-class mission, planned for launch in 2029, the need for an additional, stratosphere-based capability for exoplanet transit-spectroscopy became questionable. The NIR platform – while it was still further developed during ESBO *DS* – was thus put on hold in favor of an intermediately-sized FIR platform.

2.3 FIR

The far infrared spectral region is equally inaccessible from the ground as the UV region. Due to this fundamental inaccessibility from the ground, the FIR astronomy cannot benefit from the technological trends of large atmosphere-correcting ground-based telescopes (using adaptive optics) and quality improvement through cooperation of ground-based telescopes. FIR observations are thus solely reliant upon air-, balloon-, or space-borne capabilities. With the last large FIR space observatory, Herschel, having reached the end of its mission after running out of cryogenic coolant fluids in 2013, the FIR observatories currently available are the Stratospheric Observatory for Infrared Astronomy (SOFIA) and balloon observatories. With the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) being discontinued as a candidate for ESA's M5 mission, new space-based observatories will furthermore not be available before the late 2030s at the earliest. The only large FIR space telescope currently under consideration remains the Origins Space Telescope (OST), submitted for review under the 2020 U.S. Astrophysics Decadal Survey, and not planned to launch before 2035[3]. OST furthermore does not include heterodyne instruments capable of providing very high spectral resolution of the order of 10^7 as required to advance our understanding of star and planetary systems formation and evolution (the highest spectral resolution instrument foreseen for OST is the Origins Survey Spectrometer (OSS), which does reach up to R~300,000, but only with a single pixel, making it unsuitable for any kind of mapping, and only at wavelengths longer than 100 µm[4] [RD1]).

With a large mirror capable of overcoming the confusion limit and heterodyne instrumentation, balloon-based telescopes can fill the gap of FIR observational capabilities after SOFIA and before

[3] The upcoming James Webb Space Telescope only covers the near and mid-infrared spectral regions up to approx. 28 µm, but does not offer any observational capabilities in the far infrared

[4] The originally foreseen Heterodyne Receiver for OST (HERO), which would have been able to provide spectral resolution up to 10^7, was removed from the baseline design before the submission to the decadal review to meet the cost cap.

OST. A large-array heterodyne instrument on a smaller telescope can furthermore complement SOFIA with much-needed survey capacities.

3 INFRASTRUCTURE CONCEPT

ESBO aims at establishing a full infrastructure for developing and operating balloon-borne telescopes, with the overarching goal of making observation time and instrument flight opportunities on these telescopes easily and freely available to the scientific community.
Most prominently, this includes three foreseen flight systems with different telescopes to be developed and deployed in a step-by-step approach.

Step 1 is the "STUDIO" gondola with a 0.5 m aperture UV telescope and instrument already almost fully developed and built during the ESBO *DS* project. It is primarily foreseen for short- to medium-duration balloon flights, i.e. either flying during the semi-annual turnaround conditions over Kiruna, Sweden (2 days), or during Northern summer on transatlantic flights from Sweden to Canada (7 days per flight). Depending on the successful maturation of Super Pressure Balloons (SPBs) required to fly ultra-long-duration flights in the Southern hemisphere, starting from New Zealand, these flights would be a medium-term up-scoping option for STUDIO.

Step 2 is a gondola with a 1/1.5 m class FIR telescope and a very high spectral resolution heterodyne instrument as a baseline first light instrument. It is primarily foreseen for long-duration flights on the polar flight routes, with a focus on flights in the Arctic during Northern Summer.

Step 3 is a gondola with a 5 m class FIR telescope and a large array, very high spectral resolution instrument baselined as first light instrument. This platform is equally foreseen for long-duration flights on polar flight routes.

The clear operational goal is to conduct a long science flight at least once a year. Among other things, this will require fast turnaround times of the flown gondolas and minimizing the risk of damage to the equipment upon landing using controlled landing techniques.
In order to maximize flexibility, ESBO will furthermore procure the flights themselves (including piloting of the balloon itself) from flight providers, while maintaining operation and responsibility of the gondolas.

Given that ESBO aims at reaching as many users in the relevant scientific communities as possible, the instrumentation approach is twofold. The first instruments for each platform are foreseen to be competitively selected instruments provided by external scientific groups ("PI instruments"). Observation time on these instruments would be openly available via calls for observations, with a certain share reserved for the instrument providing group. In addition to the PI instruments, instruments provided and maintained by the observatory itself based on consultations of the scientific community ("facility instruments") are planned to be deployed at a later stage.

Beyond the flight systems with telescopes themselves, the required infrastructure elements for ESBO also include ground systems (light blue), a governance and administration infrastructure (orange), and proposal/observer tools as well as data pipelines and processing tools (red) as illustrated in the general schematics in Figure 1.

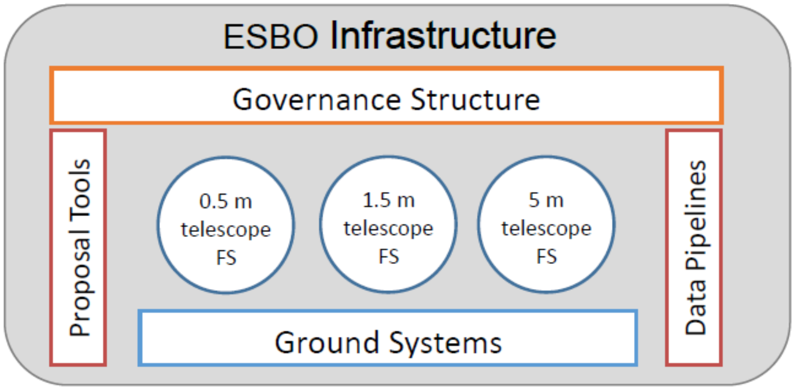
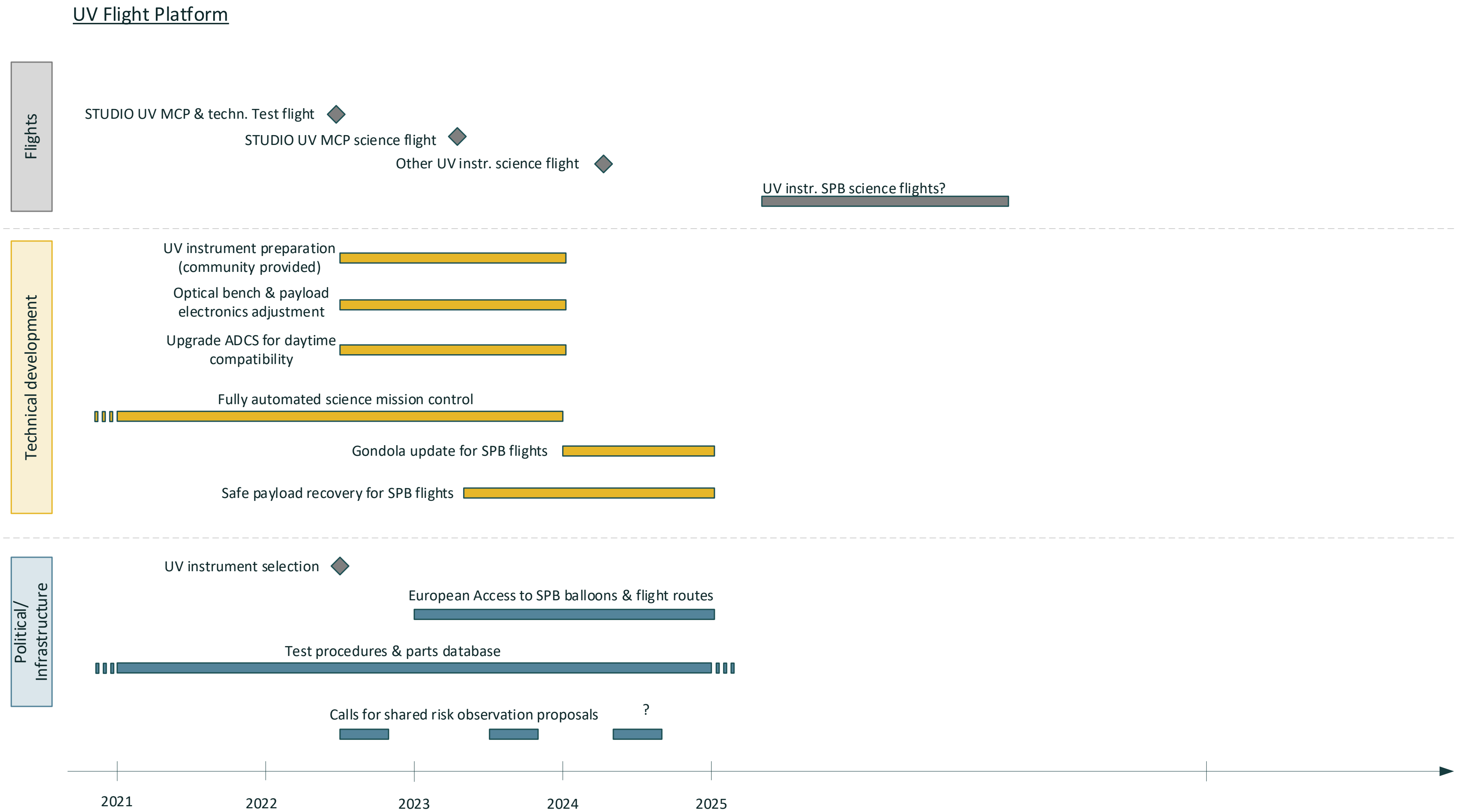


Fig. 1. General schematics of ESBO infrastructure (FS = Flight System).

4 REQUIRED DEVELOPMENT / ROADMAP

The following pages present the development roadmaps separately for the UV and the FIR flight platforms. The roadmaps thereby include both technical development and political/administrative efforts required to eventually achieve the flights and provide the observational services.

4.1 UV FLIGHT PLATFORM



4.1.1 Flights

The STUDIO prototype developed and built under ESBO *DS* will be the UV flight platform after its completion. A short (two days) test flight of the gondola and the MCP UV detector is planned for 2022. If successful, the flight will already deliver some first science results. A longer science flight with the MCP detector of around 7 days duration, including daytime science observations, is planned for 2023. A first 7 day flight with another instrument, e.g. a UV spectrograph, employing the same gondola, telescope, and image stabilization system, could then be performed in 2024. If European access to Super Pressure Balloon flights could be established, ultra long duration flights of the UV platform with equal shares of day and night observation conditions could be conducted.

4.1.2 Technical Development

<u>UV Instrument Preparation & Adjustment of Optical Bench & Payload Electronics</u>

The second UV instrument should be a community-provided, i.e. "PI", instrument. Several instruments for small satellites are currently under development which could be repurposed for the balloon platform. Along with a new instrument, smaller adaptations to the current optical bench, the payload electronics, and the modular payload software may be necessary, while maintaining the gondola, telescope, and image stabilization system.

<u>ADCS upgrade for daytime compatibility</u>

The current ADCS is a modular system, equipped with a star tracker as its most accurate sensor. While the current star tracker should still function under daytime conditions, it would require longer integration times and only be viable for use in limited regions of the sky. For full daytime capabilities, the ADCS would need to be upgraded either with a daytime-compatible star tracker (larger aperture) or with a highly accurate sun tracker, as e.g. used on the PoGO+ mission.

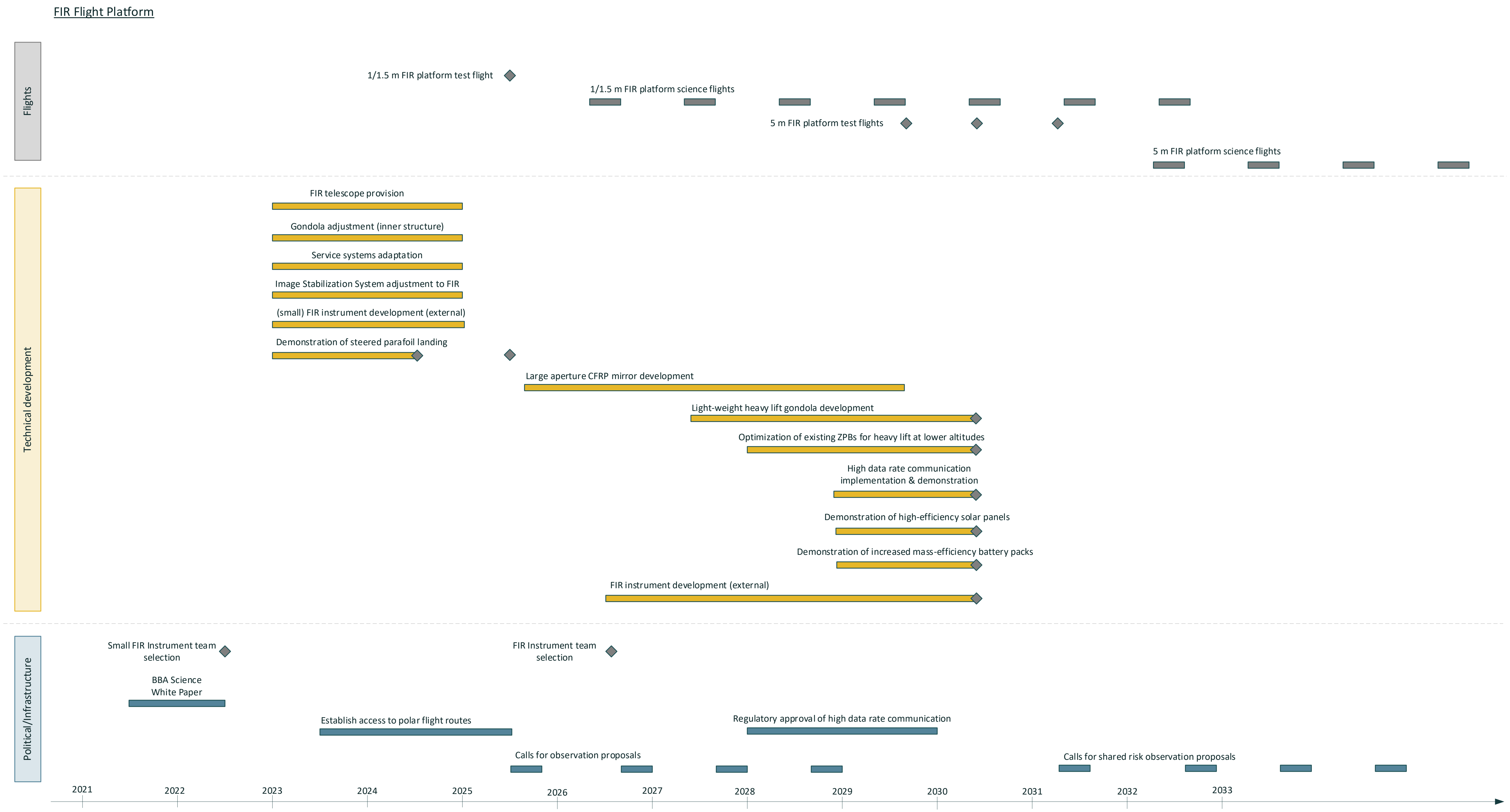
<u>Preparation for SPB Flights</u>

Some smaller adaptations will be necessary for SPB flights, particularly concerning an adjustment of the thermal covering / surface finishing to adjust for the different thermal environment as well as an adaptation of the power system to the longer mission and different day/night durations.

A larger item, however, will be the development of a strategy for safe payload recovery after SPB flights, which very likely would be on circumglobal trajectories from New Zealand and therefore predominantly over water.

As SPBs are currently only operated by NASA, as is the flight route from New Zealand, early efforts to make these flight options accessible to European payloads as well would be necessary.

4.2 FIR FLIGHT PLATFORM



4.2.1 Flights

Two flight platforms are foreseen to be developed and deployed step-wise for the FIR: a smaller, 1 m-class telescope, which can be installed in a gondola largely based on the STUDIO UV gondola, and a larger, 5 m aperture telescope to be flown in a largely newly developed gondola.

Given that for the 1 m-class platform, largely subsystems already developed for STUDIO can be used, a first (short-duration) test flight could be possible in 2025. Given that access to polar flight routes has been successfully established by that time, yearly long-duration (~30 to 40 days) science flights with the 1 m-class FIR platform could be offered starting in 2026.

Following the development of the required systems, (short-duration) test flights of hardware of the 5 m platform could be commenced in 2030 – with regular, yearly long-duration flights following in 2033.

Observation time on all science flights will be awarded openly via previous calls for observation proposals.

4.2.2 Technical Development – Small FIR Platform

<u>Adaptation of Gondola and Subsystems</u>

The STUDIO UV platform was developed with a scalable design, so that most of the subsystem designs can also be used for the small FIR platform only with minor additional development efforts necessary on the gondola/service systems side. A larger gondola (particularly the inner structure holding the telescope) will need to be manufactured, however, based on the scaled existing design, which will take some time and effort. In addition, particularly the power and thermal control systems will need to be adapted to the planned long duration polar flights and the FIR payload. The ADCS will benefit from the daytime compatibility already developed for the UV platform.

<u>FIR Telescope and Image Stabilization System</u>

More effort will be necessary on the payload side, where an FIR telescope will need to be designed/provisioned. Changes will also need to be made to the Image Stabilization System, changing the dichroic mirror for one suitable for the FIR and the tip/tilt mechanism to a cryogenic-temperatures-compatible one.

<u>Steered Parafoil Landings - Demonstration</u>

One of the most important technical developments within this step will be the demonstration of safely landing a balloon gondola on a steered parafoil – a key capability for sustainable regular flights of all ESBO platforms. Suitable suppliers capable of providing the required hardware have been identified, the next step needs to be a dedicated demonstration flight, including the still required technical preparations.

<u>FIR Instrument Development</u>

The first instrument for the small FIR platform is foreseen to be a community-provided “PI”-instrument. Based on the current needs assessment, it should likely be a larger-format heterodyne instrument based on detector and spectrometer technology already under development. The selection of the team providing the instrument should be taken in mid-2022 in order to allow for two years of instrument development and manufacture and one year of instrument installation and testing.

4.2.3 Technical Development – Large FIR Platform

Large Aperture CFRP Mirror

Carbon Fiber Reinforced Plastic (CFRP) mirrors have successfully been used for far-infrared telescopes for a while, offering an extremely good stiffness to mass ratio. Early issues of fiber print-through have been solved, at least for applications at the comparatively long wavelengths in question. CFRP mirrors have only been manufactured up to sizes of about 3.5 m diameter. An increase to 5 m diameter as required for the ESBO large FIR platform will therefore still require a significant development effort, particularly with regard to the optimization of the inner sandwich structure to meet the stringent mass requirement (mirror with an areal density of < 20 kg/m²) for installation on a balloon gondola.

Light weight heavy lift gondola

In order to meet the mass requirements of the large platform, a dedicated light-weight (reaching a structure mass fraction of ~10 %) CFRP-based gondola will need to be developed. While modular gondolas made from CFRP struts exist, the size of the required gondola combined with the mass of the telescope will pose a challenge so that sufficient development time needs to be allocated.

Optimization of ZPBs for heavy lift

While current Zero Pressure Balloons (ZPBs) are – what size and lift force are concerned – suitable to lift payloads heavier than 3.6 t to altitudes between 25 and 30 km, the payload weight attachment and distribution to the balloon (via load tapes on the balloon film) is not optimized for such high loads. An optimization in this regard needs to be carried out by balloon manufacturers.

High data rate communication

Large-format, high-resolution spectrographs suitable for spectroscopic surveys inevitably generate a large amount of science data. With conventional means, particularly during long flights, it would be very difficult to downlink the science data without accepting a large amount of on-board processing. As high-bandwidth satellite constellations are not available from the polar routes, other means need to be used, such as optical or X-band downlink, that can provide downlink rates of 100 Mbit/s or more. While both technologies are under development for stratospheric balloons and generally have been demonstrated, an operational solution needs to be implemented, also including suitable (potentially mobile) ground stations for the polar flight routes.

Demonstration of highly efficient power supply components

As the baselined large-array spectrograph has an average power consumption considerably higher than that of current balloon payloads, in order to meet the mass requirements, more efficient power supply components need to be used. On the one hand, this applies to the solar panels / solar cells. Here, a solar panel efficiency of at least 25 % (or a solar cell efficiency of > 30 %) along with a low area-specific mass of less than 3 kg/m² has to be reached. The efficiency can be reached with e.g. triple-junction cells, which still need to be demonstrated on stratospheric balloons, however.

On the other hand, this also applies to batteries, more specifically to the battery packaging. Currently available battery packs provide an energy density of approx. 80 Wh/kg. This is, to a large degree, owed to the packaging, however, and that boxes are made with lower capacities in order to provide more modular solutions (the lithium ion cells typically used themselves have an energy density of around 165 Wh/kg). For the FIR platform, thus more efficient battery packaging will need to be designed, reaching an energy density of > 120 Wh/kg for complete battery packs, optimized for a total storage capacity of > 12 kWh.

<u>FIR Instrument Development</u>

The first instrument for the large FIR platform is foreseen to be a community-provided "PI"-instrument. Based on the current needs assessment, it should likely be a large-format, high-spectral-resolution spectrometer (either heterodyne or incoherent detection). Prior to the selection of an instrument to be developed, further consultation with the scientific community will be undertaken, however, and a call for instrument proposals will be opened.

4.2.4 Political/Infrastructural Aspects

<u>Regulatory / political support of technological developments</u>

Some of the technology developments or demonstrations will need to go along with regulatory or political support. The later particularly applies to European access to polar flight routes – either by the means of gaining overflight rights for full circumpolar Northern polar flights or by negotiating infrastructure access for Southern polar flights. The former particularly applies to the regulatory approval of regular operation of high data rate communication links – be it optical or higher frequency radio bands – for the use of scientific balloon downlink.

<u>Instrument and observation calls</u>

The initial instruments both of the smaller and the larger FIR flight platforms are baselined to be PI instruments, i.e. to be provided by external research groups. In order to allow for sufficient time for the development, integration, and test of the instruments, a call for instruments along with an instrument selection should be made at least 3 years before a test flight for the small platform and at least 5 years before a test flight with instrument for the large platform. Starting with the first science flight of each platform, calls for observation proposals are planned for every year.

<u>Political Support</u>

A reliably regularly flying balloon observatory with shared observation is a novelty that will only be realizable with strong political support. To this end, it will be vital to show the need of the community for such an infrastructure. A science white paper and work through various national astronomical organizations will be effective tools to establish and build national and European support.

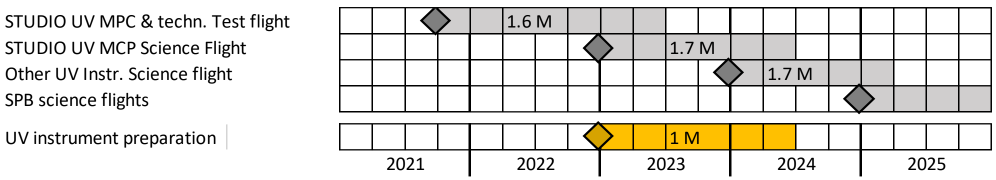
5 FUNDING NEEDS

In the following, we present the estimated funding needs over time to establish the infrastructure. All numbers are rough order of magnitude (ROM) estimates. The estimate is furthermore based on the assumption that the individual development steps (UV flight system → small FIR flight system → large FIR flight system) are carried out in this order. If one of the steps is skipped, certain increases will apply to the funding needs of the subsequent steps. The estimates furthermore assume that the ESBO infrastructure will be established if not as part of then at least connected to an existing observatory or relevant international organization so that partly existing infrastructure such as administrative infrastructure, space, and workshops can be used.

Instrument development is also listed in the following timelines for the purpose of completeness. Given that for all future infrastructure options, the first instruments are baselined to be PI instruments, it would be worthwhile to consider whether the funding for this instrument development should rather be provided via an agreement through national funding organizations or other schemes.

All numbers are ROM estimates in 2021 EUR.

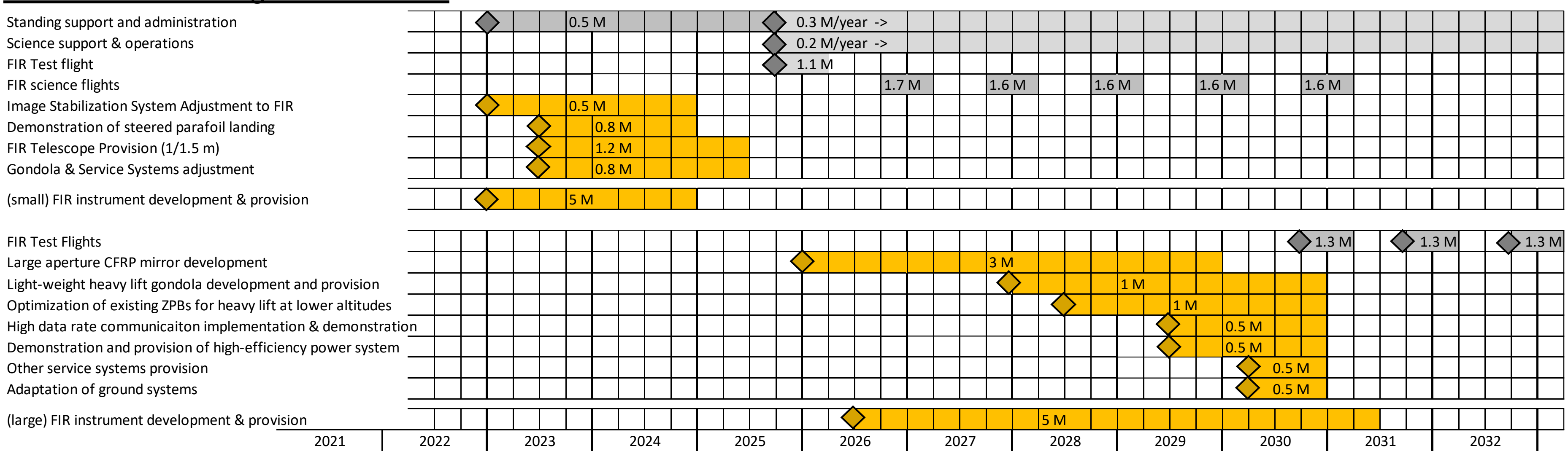
UV Platform Funding Needs Timeline



Infrastructure funding	
2 Full Science Flights, 1 Technology Test Flight with science until 2024	5 MEUR
Instrument funding	
Preparation of 2nd UV Instrument (could be ESBO-external funding)	1 MEUR

The quoted funding needs include all required funding estimated for the UV platform flights, including tests, flight preparation, and post-flight data analysis. Opposed to the following estimates for the FIR systems, it also includes funding to support scientific analysis.

FIR Platform Funding Needs Timeline



Provided funding estimates for FIR flights include estimated campaign costs from a European base for test flights and estimated campaign costs for polar flights for science flights. Flight cost estimates further include recovery costs, but no support funding for analysis of science data.

Small FIR Platform Summary

Infrastructure funding (preparatory phase)	
Administration	0.5 MEUR
Gondola & service systems development	3.3 MEUR
Test flight	1.1 MEUR
Infrastructure funding (operational)	
Administration & Techn. Team	0.5 MEUR/yr
Flights	1.6 MEUR/yr
Instrument funding	
Development & provision of FIR instrument	5 MEUR

Large FIR Platform Summary

Infrastructure funding (preparatory phase)	
Technology development (service systems, telescope)	7 MEUR
Test flights	3 MEUR
Infrastructure funding (operational)	
Administration & Techn. Team	1.5 MEUR/yr
Science Operations	3 MEUR/yr
Flights	2 MEUR/yr
Instrument funding	
Development & provision of FIR instrument	5 MEUR