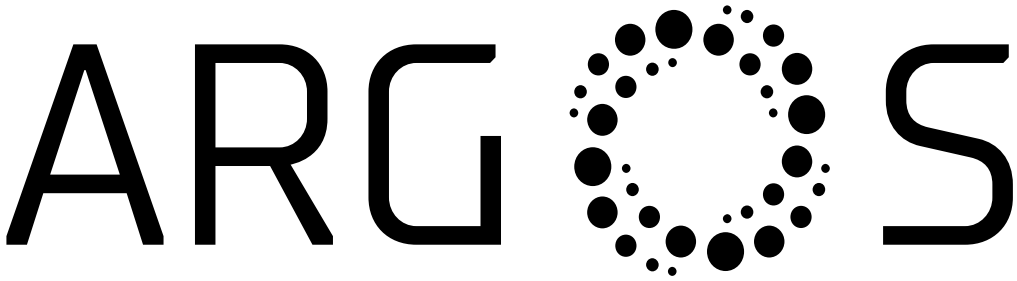

Conceptual Design Study

Designing a Next-Generation Interferometer for Multi-Messenger Astronomy

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1.1.1 Document history

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1.1.2 Peer review history

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1.1.4 Disclaimer

ARGOS-CDS is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. The European Union cannot be held responsible for them.

1.1.5 Applicable documents

In the event of conflict between the contents of the following documents and this document, the following documents shall take precedence.

1. ARGOS-CDS Grant Agreement (no 101094354): ARGOS_Grant_Agreement_101094354_v1.pdf
2. ARGOS level 0 science requirements: ARGOS_D2.2_Lev0_v1.pdf

1.1.6 Reference Documents

In the event of conflict between the contents of the following document and this document, this document shall take precedence.

1.1.7 Abbreviations and Acronyms

Acronym	Description
ARGOS-CDS	Argos Conceptual Design Study
ASP	Argos Scientific Priorities
CA	Consortium Agreement
DM	Dispersion Measure
DoA	Description of Action (Annex I of the Grant Agreement)
DoW	Description of Work (Annex I of the Grant Agreement)
EC	European Commission
EVN	European VLBI Network
EWG	Engineering Working Group
GA	General Assembly
PC	Project Coordinator
PMC	Project Management Committee
RFI	Radio Frequency Interference
SEFD	System Equivalent Flux Density
SNR	Signal-to-noise ratio
SWG	Science Working Group
TRL	Technology Readiness Level
VLBI	Very-long baseline interferometry
WP	Work Package

1 Background and Scope of this Document

1.1 Background

ARGOS is a concept for a leading-edge, low-cost, sustainable European facility that will enable, for the first time, continuous wide-field monitoring of the sky at centimetre wavelengths, while publicly distributing science-ready data and alerts in real time. ARGOS will address multiple fundamental scientific questions, from the nature of dark matter and dark energy to the origin of fast radio bursts and the properties of extreme gravity, satisfying urgent needs of the community.

The facility is currently undergoing its conceptual design phase. The project operates within the Horizon Europe framework and is bound by the Grant Agreement 101094354 with the EC (ARGOS Conceptual Design Study; ARGOS-CDS). The DoW (Annex I of the Grant Agreement) determines the work to be carried out as part of the project. The overarching goal for ARGOS-CDS is to produce a detailed design study that will make the strategic and scientific necessity for such a facility clear and accessible to funding and policy bodies.

***Figure 1.1**: Overview of the system engineering phases and major milestones in ARGOS-CDS.*

Timewise, ARGOS-CDS is divided in three main phases, as shown in Figure 1.1. The ***concept phase*** covered the first 6 months of the project. The main objective during this phase was to conduct detailed background investigations of available technologies, market trends and previous work.

During the ongoing ***definition and preliminary design phase***, technical activities are focusing on performing requirements analyses and trade-off studies between candidate design solutions. These studies currently consider a range of criteria including science objectives, construction, operations and maintenance costs, site and architectural constraints, logistics and operations complexity, complementarity to other facilities, environmental impact, technology. Science activities support the engineering effort with modelling, simulations, and iterative refinements of the science requirements.

Following the PDR on month 18, *ARGOS-CDS* will enter a 1.5-year *Detailed Design Phase.* Preliminary designs will be refined, verified, and finally documented in detail. For subsystems relying solely on COTS components and/or existing TRL9 designs, the equipment will be purchased and/or assembled, and thoroughly tested to guarantee compliance with the design specifications.

1.2 Scope

This document has been compiled as part of the definition & preliminary design activities. It outlines the verification and early commissioning activities that will be performed ahead of the critical design review. The purpose of these activities will be to test the functionality for critical components of the instrument, and to verify that the adopted design can satisfy the high-level science requirements. It is important to note however, that this plan is not meant to describe the verification and validation (V&V) plan for the full ARGOS array. The latter shall be developed at later stages of the project, when a detailed roll-out timeline has been established.

1.3 ARGOS pathfinder

As described in the Grant Agreement, most science verification activities will be executed by the ARGOS Science working group using the ARGOS pathfinder array. The latter will be deployed at the

FORTH campus in Crete. The site offers adequate, well-characterized RFI environment, significant supporting infrastructure, including a building to host the prototype HPC correlator, and solar panel arrays that will be incorporated in *ARGOS-pathfinder*, strong level of engineering support, facilities for educational activities and public engagement and e) close proximity to Skinakas, which hosts leading-edge multi-messenger facilities for time-domain astronomy such as the TURBO and the wide-angle/high-precision WALOP optical polarimeter of the PASIPHAE project. These facilities will be used extensively for validation of *ARGOS-CDS* products (triggers, transient detection), and scientific synergies. The prototype array shall consist of 5 to 6 fully-steerable dishes deployed over a maximum baseline of approximately 300m, as well as a fully-functional scaled-down version of the ARGOS backend and science pipelines. Section 2 describes the verification and validation activities to be performed with the array, while section 3 provides the level-0 science requirements that will allow to carry out the early verification plan.

2 Verification plan

The following validation matrix provides an overview of the tests, commissioning observations and simulations that we plan to perform ahead of the CDR, to verify that the adopted design provides the desired functionality.

Complementarity to other facilities

Requirement ID	Description	Verification plan	Acceptance method / deliverable
L0_01	ARGOS shall be deployed at a location in Europe that allows access to at least 40% of the SKA and Rubin Observatory fields.	N/A	N/A
L0_02	ARGOS shall have a total collecting area to within 20% of the SKA-MID 1 collecting area.	N/A	N/A
L0_03	The Galactic centre shall be visible from the ARGOS deployment site for a minimum of three hours per day.	N/A	N/A
L0_04	ARGOS shall provide access to elevation angles between 15 and 90 degrees, and to azimuthal angles between 0 and 360 degrees	Verify that the motors can drive the dishes to the required azimuthal and elevation angles	ARGOS Pathfinder commissioning report
L0_05	Argos shall provide a half-power beam width of at least 2.3 deg at the lower edge of its band.	Simulations and near-field lab measurements of the feed; beam-characterization of the feed+reflector system with transit observations of celestial flux standards.	ARGOS pathfinder commissioning report

L0_06	ARGOS shall cover the frequency range between 1 and 3 GHz to allow follow up of time-varying SKA discoveries such as pulsars and FRBs, and to provide a high-frequency counterpart to LOFAR2.0.	Simulations and lab measurements.	ARGOS pathfinder commissioning report
L0_07	All final data products shall have a noise level degraded due to RFI by no more than 10% in respect to the thermal noise of the array. The latter refers to the noise of an observatory compatible with the requirements listed above, scaled by the number of elements used when the data are being captured.	Use ARGOS pathfinder to perform observations of celestial flux standards to determine the system temperature. Verify that the system temperature is mainly limited by degradation due to RFI	ARGOS pathfinder commissioning report
L0_08	Argos shall provide an angular resolution of at least O(5") at the upper end of its band	N/A	N/A
L0_09	Argos shall provide an effective bandwidth of no less than 95% of the frequency coverage enabled by its receivers (~2GHz) centred around 2GHz), for both perpendicular polarization states.	Baseband recording with ARGOS pathfinder	ARGOS pathfinder commissioning report
L0_10	Argos shall capture and process (correlate and beamform) data over its entire effective bandwidth, in both polarizations and in real time		
L0_11	To enable the potential better coverage of SKA bands in the future, ARGOS reflectors should be sensitive to frequencies up to 8 GHz.	Simulations and lab measurements	ARGOS pathfinder commissioning report
L0_12	ARGOS shall provide continuous sidereal tracking of single targets and/or celestial positions (from few seconds to continuous 24/7 monitoring for circum-polar targets)	Verify that ARGOS pathfinder can accurately track point-like celestial flux standards (i.e. keep targets at the centre of its synthesized primary beam for indefinite periods of time). Verify that the telescope control system and backend can switch from motor-based tracking to	ARGOS pathfinder commissioning report

			digital tracking for near-zenith targets above 85 deg elevation	
	L0_13	ARGOS shall be capable of tracking celestial objects moving with speeds from 0 to 20 times the sidereal rate up to 85 degrees elevation, to enable fast drift-scan surveys and monitoring of near-earth objects.	Perform laboratory tests to verify that the ARGOS pathfinder mounts can drive the reflectors at the desired speeds, along pre-determined paths	ARGOS pathfinder commissioning report
L0_14		ARGOS shall be compatible with the EVN	Verify that the ARGOS pathfinder backend can produce, store, and transmit VDIF files with EVN-compatible channelization and frame rate. Verify that the ARGOS telescope control system can interface with EVN Field System Version 10	ARGOS pathfinder commissioning report / Open Data
	L0_15	To position itself as a SKA follow-up instrument and a Vera Rubin counterpart, ARGOS shall provide at least four observing modes: pulsar timing, imaging (fast cadence/accumulation), single burst transient search, and VLBI. To enable commensal FRB searches, the transient search mode should be provided simultaneously with at least one of the other two.	Use ARGOS-pathfinder to verify that the backend can provide the desired functionality. Perform pulsar timing observations and commensal FRB searches with ARGOS pathfinder.	ARGOS pathfinder commissioning report / Peer review

Pulsar Timing

L0_16	In timing mode, ARGOS shall synthesize in real time at least sixteen independent full-stokes coherent tied-array beams using all available elements of the array.	N/A	N/A
L0_17	All time-domain products shall have a fractional error in absolute flux (ΔF/F) measured against an established celestial flux standard, better than 2%		

L0_18	All time-domain products shall have a fractional error in polarization degree and polarization angle, measured against an established celestial polarization standard, better than 1%	Use ARGOS-pathfinder to perform regular (ideally daily) observations of 15-20 pulsars. The target list should include targets with diverse flux, dispersion-measure and polarization properties, as well as bright PTA pulsars with well-known pulse characteristics (e.g. PSR J1713+0747). A subset of PTA pulsar observations should be performed concurrently with other EPTA telescopes. The resulting dataset shall be used to verify that the measured fluxes, polarization properties and dynamic spectra are consistent with the literature values and/or the observations performed with other telescopes. Verify that the desired backend functionality (i.e. automated TOA generation and ephemerides updating; alerts) is provided consistently. Use synthetic data injections to further verify that the timing pipeline provides the desired functionality (e.g. alerting for profile changes and /or glitches).	ARGOS pathfinder commissioning report / Peer review / Public data
L0_19	ARGOS shall provide real-time coherent de-dispersion and folding for at least one tied-array beam per sub-array group, and for dispersion measures up to 1000 pc cm^3.		
L0_20	ARGOS shall produce full-stokes coherently de-dispersed pulse profiles with a frequency resolution of 20 kHz and a time resolution of at least 1 μs.		
L0_21	To enable precision pulsar timing, the timing accuracy of the observatory clock should be better than 10 ns over 10 years in respect to UT1.		
L0_22	ARGOS shall record coherently de-dispersed pulse profiles (integrated over frequency and time) with a SNR>1000 in Stokes I, for MSPs with flux-densities >1 mJy, within one hour of total integration time		
L0_23	ARGOS shall observe the 25 brightest EPTA pulsars with a median cadence of no more than 3 days and an integrated SNR>500, in under 33% of the total observing time.		
L0_24	ARGOS shall provide full-stokes, 50 MHz sub-banded times of arrival as part of its regular processing pipeline.		
L0_25	As part of its regular processing pipeline, ARGOS shall flag statistically significant pulse profile changes in respect to a reference profile.		

L0_26	ARGOS shall provide updated timing ephemerides for all its pulsar targets. The timing ephemerides shall be updated with a cadence of less than 24 hours.		
L0_27	ARGOS shall provide alerts for glitches, strong scattering events, and other timing irregularities for all its pulsar targets		
L0_28	ARGOS shall provide a minimum of 4 sub-array (multi-pointing) timing modes		

Imaging

L0_29	ARGOS shall point at any direction on the sky in less than 3 minutes.	Use ARGOS pathfinder to verify that the driving system provides the desired functionality	
L0_30	ARGOS shall offer a survey speed figure-of-merit of at least 10^7 deg^2 m^4 MHz K^{-2}	N/A	
L0_31	All image-domain products shall have an absolute photometric accuracy of at least 5%	While this requirement is challenging to verify with ARGOS pathfinder, image quality will be assessed by comparing observations with simulated images of matched resolution	ARGOS pathfinder commissioning report
L0_32	All image-domain products shall have an absolute astrometric accuracy (fractional error in the position of a point source relative to the adopted celestial reference frame) of at most 10% of the synthesized beam.	N/A	N/A
L0_33	ARGOS shall provide a frequency accuracy of at least 10^{-11} over 10 years	Verify that the frequency accuracy is limited by the accuracy of the observatory clock.	ARGOS pathfinder commissioning report / peer review

L0_34	All image-domain products shall have an accuracy in absolute polarization degree and angle, measured against an adopted celestial polarization standard, better than 2% across the entire field of view of the synthesized beam	Use ARGOS pathfinder to perform observations of celestial flux and polarization standards. Verify that the polarization accuracy, dynamic range and polarization dynamic range scale as expected with the number of antennas participating in the observation. Use synthetic images to compare imaging performance.	ARGOS pathfinder commissioning report / peer review / open data
L0_35	For unresolved sources, ARGOS shall provide a peak intensity to background intensity rms ratio (brightness dynamic range) of 40 dB at 25 arcsecond spatial and 1 MHz frequency resolution.		
L0_36	For unresolved sources, ARGOS shall provide a polarization dynamic range (peak intensity to instrumental polarized response) of 30 dB at 25 arcsecond spatial and 1 MHz frequency resolution.		
L0_37	ARGOS shall provide real time imaging over its FoV with a time resolution of at least 1 second.		
L0_38	ARGOS shall provide real-time detections and astrometric positions for all point sources detected with a significance greater than 10 sigma.	Use ARGOS pathfinder to verify that the backend provides the desired functionality	ARGOS pathfinder commissioning report / peer review / open data
L0_39	ARGOS shall switch between imaging and time-domain modes within less than 30 seconds		
L0_40	ARGOS shall provide a minimum of 4 multi-pointing imaging modes	N/A	N/A

Fast transients and commensal modes

L0_41	ARGOS shall provide a real-time tied-array beam mode for single burst transient searches over its entire half maximum power beam width.	N/A	N/A
L0_42	ARGOS shall provide a real-time de-dispersion and transient		

	search mode, for dispersion measures up to 3000 pc cm^{-3}		
L0_43	ARGOS shall provide low-latency (<1 min) alerts for time-domain transients with flux, DM, polarization and positional information.	Use ARGOS pathfinder to perform observations of repeating FRBs and verify that the desired functionality is provided.	Peer review / public alerts
L0_44	ARGOS shall store raw beam-formed data for up to 10 time-domain bursts for offline processing.		
L0_45	ARGOS shall have no more than 10% SNR loss compared to ideal matched filtering when searching for transients of minimum widths of 0.1 ms between DMs 0 and 3000 pc/cm^{-3}		
L0_46	ARGOS shall record frequency-resolved, Stokes-I timeseries with a minimum frequency resolution no greater than 250 kHz and minimum time resolution no greater than 30 μsec, for a minimum of 16 beams		

3 ARGOS pathfinder level – 0 requirements

Requirement_ID	Description
PA_L0_1	All final data products shall have a noise level degraded due to RFI by no more than 20% in respect to the thermal noise of the array. The latter refers to the noise of an observatory compatible with the requirements listed above, scaled by the number of elements used when the data are being captured.
PA_L0_2	Argos pathfinder shall provide an effective bandwidth of no less than 95% of the frequency coverage enabled by its feeds (~2GHz) centred around 2GHz), for both perpendicular polarisation states.
PA_L0_3	Argos pathfinder should provide an incoherent half-power beam width of at least 2.3 deg at 1.0 GHz
PA_L0_4	Argos pathfinder shall provide continuous sidereal tracking of single targets and/or celestial positions (from few seconds to continuous 24/7 monitoring for circum-polar targets)
PA_L0_5	Argos pathfinder shall be compatible with the EVN

PA_L0_6	In timing mode, Argos pathfinder shall synthesize in real time at least one independent full-stokes coherent tied-array beams using all available elements of the array.
PA_L0_7	Argos pathfinder shall be able to provide real-time coherent de-dispersion and folding for at least one tied-array beam per sub-array group, and for dispersion measures up to 1000 pc cm^3.
PA_L0_8	Argos pathfinder shall automatically produce full-stokes coherently de-dispersed pulse profiles with a frequency resolution of **20 kHz** and a time resolution of at least 1 μs.
PA_L0_9	Argos pathfinder shall be able to record coherently dedispersed pulse profiles (integrated over frequency and time) with a SNR > 10 in Stokes I, for MSPs with flux densities > 1 mJy, within one hour of total integration time
PA_L0_10	Argos pathfinder shall be able to provide full-stokes, 50 MHz sub-banded times of arrival as part of its regular processing pipeline.
PA_L0_11	As part of its regular processing pipeline, Argos pathfinder shall be able to flag statistically significant pulse profile changes in respect to a reference profile.
PA_L0_12	Argos pathfinder shall be able to provide updated timing ephemerides for all its pulsar targets. The timing ephemerides shall be updated with a cadence of less than 24 hours.
PA_L0_13	Argos pathfinder shall provide alerts for glitches, strong scattering events, and other timing irregularities for all its pulsar targets
PA_L0_14	Argos pathfinder shall be able to point at any direction on the sky in less than 5 minutes.
PA_L0_15	Argos pathfinder shall provide real time imaging over its FoV with a time resolution of at least 1 second.
PA_L0_16	Argos pathfinder shall provide real-time detections and astrometric positions for all point sources detected with a significance greater than 10 sigma
PA_L0_17	Argos pathfinder shall provide a real-time mode for single burst transient searches over its entire half maximum power beam width.
PA_L0_18	Argos pathfinder shall provide a real-time de-dispersion and transient search mode, for a restricted dispersion-measure range of ΔDM=200 pc cm^{-3} at DM=1000 pc cm^{-3}

PA_L0_19	Argos pathfinder shall provide low-latency (<1 min) alerts for time-domain transients with flux, DM, polarization and positional information.
PA_L0_20	Argos pathfinder shall be able to store raw voltage data for up to 2 time-domain bursts for offline processing.