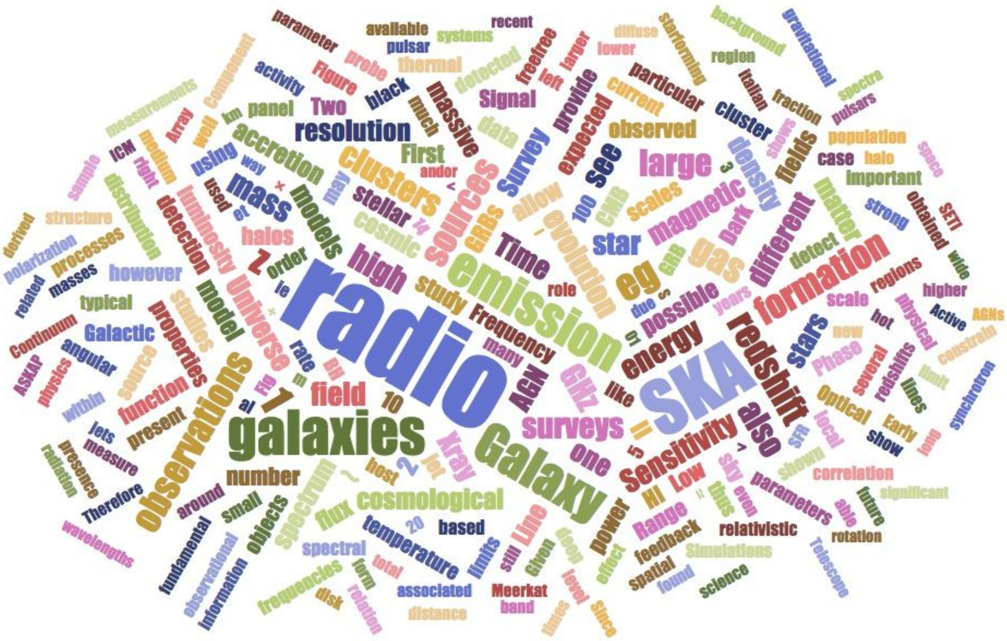
An Italian Roadmap towards the SKA



by

the Italian SKA Board

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Cover Figure:
Word-cloud obtained from the *Italian SKA White Book*

Executive Summary

Questo documento di *Roadmap* si propone di fornire linee guida generali a supporto della Direzione Scientifica e degli altri organi decisionali INAF, al fine di valutare come meglio investire risorse nel progetto SKA per massimizzarne il ritorno nei vari ambiti di interesse (industria, scienza, know how tecnologico, etc.).

La filosofia con cui è stato concepito è quella di un documento snello e schematico, corredato di Appendici più dettagliate. La *Roadmap* si deve intendere come un documento aperto, vista la lunga scala temporale del progetto SKA. Pertanto le informazioni maggiormente soggette alla necessità di aggiornamenti, sono, ove possibile, organizzate in tabelle, onde facilitarne la revisione. Il documento è pensato soprattutto per un uso interno a INAF, e quindi per lettori *esperti*. Tuttavia, se utile, si può renderlo fruibile da una platea più ampia.

Il documento (redatto in inglese) e' organizzato in tre parti:

I. <u>Progetto SKA:</u> breve descrizione del progetto SKA, delle sue principali finalità scientifiche, e dell'attuale modello operativo.
II. <u>SKA in Italia:</u> ricognizione dettagliata delle attività recenti e/o in corso in Italia in ambito SKA, organizzata intorno ai cosiddetti tre pilastri SKA: scienza, tecnologia, industria. In ambito scientifico viene dato risalto anche alle potenziali sinergie tra SKA e altre *facilities* astronomiche di interesse INAF; in ambito tecnologico vengono discusse anche le prospettive relative allo sviluppo di un centro di archiviazione ed elaborazione dati per SKA in Italia (*Italian SKA Data Center*).
III. <u>Linee guida e raccomandazioni:</u> presentazione di una serie di considerazioni e linee guida generali intese a valorizzare l'investimento italiano in SKA, e a massimizzarne il ritorno scientifico, tecnologico e industriale. Le raccomandazioni tengono conto e sono precedute da un sunto schematico dei punti di forza e debolezza, sfide e opportunità (*SWOT analysis*), definiti sulla base delle expertise e degli interessi esistenti in Italia, (nonché delle sinergie con altri progetti di interesse INAF), già presentati nella Parte II di questo documento.

Il documento è corredato da una serie di Appendici, che presentano materiale istruttorio più dettagliato. Attività ed iniziative concrete messe in atto, proposte o avallate da questo *Board* dal suo insediamento (Gennaio 2018) ad oggi, sono dettagliate in Appendice D.

Un ruolo importante nel definire la parte propositiva del documento (Parte III) è stato svolto dalla discussione plenaria organizzata nell'ambito del *II Workshop Nazionale SKA*, tenutosi a Bologna, nei giorni 3-5 Dicembre 2018. In quell'ambito sono state presentate e discusse con la comunità le diverse iniziative e idee maturate all'interno del *Board.* I risultati della discussione e i suggerimenti della comunità sono stati tenuti in debito conto nel finalizzare questo documento di *Roadmap*.

Le principali conclusioni e raccomandazioni sono qui brevemente sintetizzate (per maggiori dettagli si rimanda al capitolo 12):

- È importante prepararsi adeguatamente allo sfruttamento scientifico dello SKA, sia attraverso un ampio coinvolgimento nei programmi osservativi in corso presso i radio-interferometri di nuova generazione attualmente disponibili, sia attraverso simulazioni e lavoro teorico dedicato.
- Un adeguato livello di finanziamento delle attività connesse allo SKA è strategico in preparazione degli *SKA Science Key-Projects*. Varie forme di finanziamento sono auspicabili: da PRIN a bandi nazionali per una serie di posizioni di dottorato di ricerca e post-doc mirate allo SKA; a finanziamenti dedicati per visite di scambio a medio/lungo termine con i paesi ospitanti (Australia e Sudafrica) e la sede centrale dello SKA (Regno Unito); all'organizzazione di scuole ed altri eventi di formazione. E' di fondamentale importanza che i finanziamenti siano resi disponibili su base regolare e garantiti nel corso dei prossimi anni.
- I precursori SKA rappresentano un'occasione unica per rafforzare le competenze tecnico/scientifiche dei ricercatori italiani. Così come già fatto per LOFAR, forme di coinvolgimento formale nei precursori ASKAP e MeerKAT devono essere esplorate.
- Diverse sono le attività in corso utili per sviluppare competenze nella gestione e nell'elaborazione di grandi moli di dati radio interferometrici. Queste iniziative vanno incoraggiate, così come la partecipazione a progetti di *Innovation Technology* (IT) finanziati dall'Unione Europea, essenziali per costruire le competenze e le funzionalità necessarie a supportare la ricerca *data-driven* con strutture di archiviazione ed elaborazione dati di nuova generazione. Per lo sviluppo di un vero e proprio *SKA Data Center* nazionale (si veda iniziativa relativa al Tecnopolo di Bologna) sono tuttavia necessari interventi più complessi, quali il pieno sfruttamento delle sinergie esistenti nell'ambito di collaborazioni formali con i grandi centri di calcolo, come il CINECA, e la creazione di uno stretto coordinamento all'interno dell'INAF. Cio' al fine di non disperdere le competenze maturate nell'ambito dei vari progetti INAF *data-driven,* e di utilizzare al meglio i presenti e futuri investimenti in hardware, software e personale informatico.
- Può essere utile creare uno o più *Focus Groups* SKA nazionali, ma solo se è possibile identificare un chiaro mandato. A titolo di esempio, tali gruppi potrebbero essere responsabili (o assistere questo *Board*) nell'aggiornamento di casi scientifici SKA di interesse nazionale, nonché nell'approfondimento delle potenziali sinergie tra SKA e altre facilities astronomiche di interesse INAF.
- Questo è un momento critico per gli aspetti tecnologici del progetto SKA: la maggior parte dei consorzi di progettazione SKA hanno chiuso le loro attività ed è iniziata una nuova fase, chiamata *Bridging* e coordinata direttamente da *SKA Office,* che porterà alla definizione delle tecnologie finali di costruzione di SKA1 e ai bandi di gara industriali. In

questa nuova fase è strategico che le attività R&D italiane siano adeguatamente supportate e difese da INAF, in modo da massimizzare la visibilità dell'INAF nel progetto SKA e la sua capacità di competere con successo a livello internazionale.

- Diversi partner industriali hanno partecipato alle attività R&D di SKA nel quadro delle attività di design di SKA. In vista della costruzione di SKA, è importante pubblicizzare le opportunità di SKA presso le industrie il più ampiamente possibile, attraverso gli uffici INAF preposti. Per rendere queste iniziative efficaci, è essenziale agire con largo anticipo rispetto ai bandi di gara per la costruzione di SKA1.

Part I - General Introduction

Astronomy and astrophysics are experiencing a true golden age, which is rapidly transforming and expanding our knowledge of the Universe, as illustrated by two crystal-clear examples: the discovery of Earth-like planetary systems, potentially able to host life, and the recent detection of gravitational waves from outer Space. These breakthrough achievements are the result of a new strategy put in place to build major astronomical infrastructures, which is based on international collaboration and cooperation, rather than on mere competition. In this general context, the world astronomical community considered it essential to join forces and share its scientific, engineering and industrial expertise for the realization of the Square Kilometer Array - the largest telescope in the world - with the ambitious goal to revolutionize our understanding of the Universe and the fundamental laws of physics.

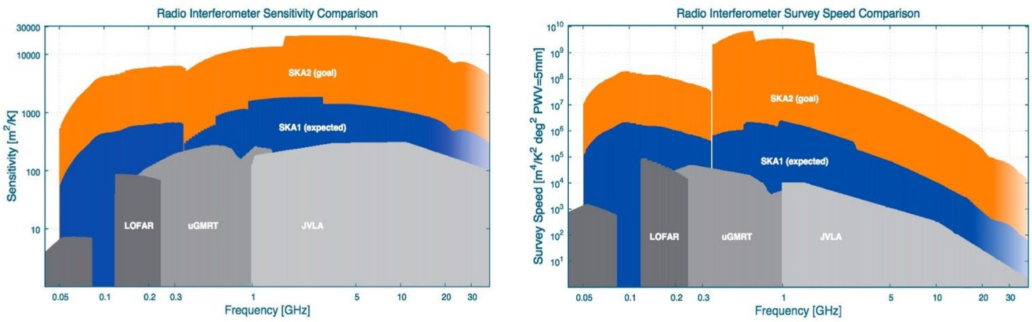
1. The Square Kilometre Array

The Square Kilometre Array (SKA[1]) will operate on a continental scale through two large antenna networks located in Australia and South Africa. The antennas will be connected to each other with high speed fiber optics links and will operate simultaneously, working together to produce the final output signal, through radio-interferometric techniques. Unique features of the SKA are: the large collection area (1 km^2, or 10^6 m^2); the wide operational frequency range (from 0.1 to 25 GHz); the large field of view (up to 50 square degrees at the lowest operational frequencies); the large number of antennas (thousands of dishes and millions of low frequency dipoles), and their large-scale distribution (over 1000 km distance from each other on the two sites); the exquisite purity of the polarized radio signal; the ability to observe simultaneously in different directions of the sky. All this together will make the SKA the most powerful radio astronomy facility ever built: it will have a sensitivity 50 times greater than any other existing radio telescope and will be able to carry out maps of the whole sky at unprecedented speed.

The SKA poses unprecedented technological challenges, and is being developed over a phased timeline: a pre-construction phase, started in 2012, involving the detailed design, implementation, R&D work, and contract preparation; and two main building phases (SKA1 and SKA2). SKA1 will consist of two elements: one operating at low frequency (SKA-LOW in Australia) and one operating at intermediate/high frequency (SKA-MID in South Africa); SKA2 is expected to yield a factor 10 increase in sensitivity over SKA1. A phased approach allows maximum exploitation of advances in technology, as well as incremental fine-tuning of science drivers and technical requirements. Paving the way to the SKA, developments in receiver technology, high-speed digital signal processing and broad-band optical fibre links between antennas have led to several upgrades of existing facilities, as well as to the construction of new-generation radio telescopes, collectively known as SKA *Pathfinders* (e.g. JVLA, e-MERLIN, ATCA-CABB, Apertif, uGMRT, LOFAR, etc.). Among them the so-called SKA *Precursors*, built at the SKA

[1] skatelescope.org

observing sites (MeerKAT and HERA in South Africa; MWA and ASKAP in Australia). All these are essential technological and scientific test-beds for the first phase of the SKA[2].



SKA Sensitivity and Survey Speed in comparison with SKA Pathfinders. Credits SKA Organization

2. Science Vision

Originally referred to as *Hydrogen Telescope*, the SKA concept arose around a clear but extremely ambitious goal: filling in the gaps in our understanding of the Universe, by observing its most abundant constituent - the Hydrogen - on all scales (from sub-galactic to the cosmic web) and at all cosmic epochs, from the so-called *Dark Ages* and *Cosmic Dawn* to the current epoch of accelerating expansion, driven by the as yet unexplained force of Dark Energy. This requires superb sensitivity (1 square km collecting area) over a very large range of frequency and spatial resolutions. It is clear, however, that a radio telescope with these capabilities will also enable a wealth of other unique discoveries to be made, in areas as diverse as the formation of Earth-like planets, the detection of gravitational waves, the origin of cosmic magnetic fields, the formation and growth of stars, galaxies and black holes, etc. In fact the SKA will revolutionize our knowledge in all fields of modern astrophysics and cosmology, and will have important scientific applications also in the field of general and astro-particle physics.

The SKA is designed to be a survey instrument, and it is envisaged that a large fraction of its observing time will be dedicated to the execution of large surveys, organized in international *Key Science Projects.* Nevertheless a fraction of its time will be available to PI-led proposals.

The main areas of research identified as key objectives for the SKA are briefly illustrated below. However, the SKA will make many more scientific discoveries, more than our current knowledge allows us to imagine today. For a full overview we refer to the International SKA Science Book (*Advancing Astrophysics with the Square Kilometre Array*, Eds. R. Braun et al., 2015).

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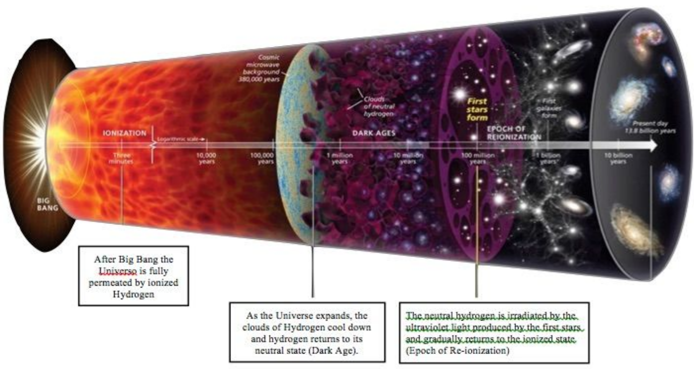
[2] An updated list of pathfinders and precursors is maintained at the SKA web site: https://www.skatelescope.org/precursors-pathfinders-design-studies/

2.1 Dark Ages: Cosmic Dawn and Epoch of Reionization

The SKA will be able to observe and understand the evolution of matter in the Universe up to primordial times, even before the formation of the very first stars

Hydrogen is the most abundant element in the Universe and provides the raw material from which the stars are formed. The 21 cm line radio emission provides the best viewing window to detect the presence of neutral Hydrogen (HI) in the Universe. Observations with increasing wavelength (from 1.4 GHz to 50 MHz) allow us to trace the HI back in time, up to the cosmological era in which the gas in galaxies was first transformed into stars (Epoch of Re-ionisation), and even further back in time, during the so-called *Dark Age.* SKA will be the only telescope capable of directly observing these distant epochs, and will allow us to observe the *Cosmic Dawn*, when the first stars and the first black holes formed a few hundred million years after the Big Bang.

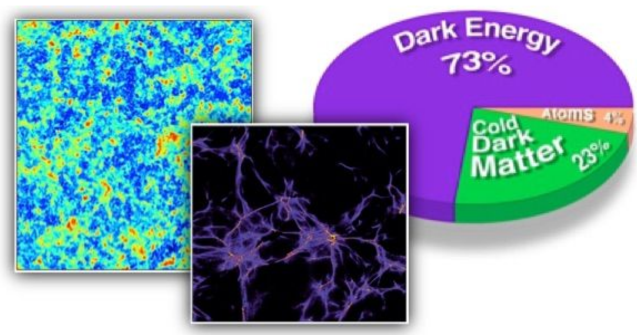


The cosmological timeline of the Universe, from the Big Bang (left) to the present day (right). The SKA will trace the neutral Hydrogen across its entire cosmic evolution, and will observe, for the first time, two critical phases of such evolution: the Epoch of Re-ionization and the the Dark Ages (for a total time frame ranging from a few tens of millions to about a billion years after the Big Bang)

2.2 Cosmology and Dark Energy

The SKA will be able to derive the equation of state of Dark Energy

The Universe expands faster and faster. This behavior is surprising and can be explained in two ways: postulating the existence of a new and unknown component called *Dark Energy*; or by modifying Einstein's theory of General Relativity. To disentangle between these two hypotheses it is necessary to reconstruct the three-dimensional distribution of matter in the Universe and its



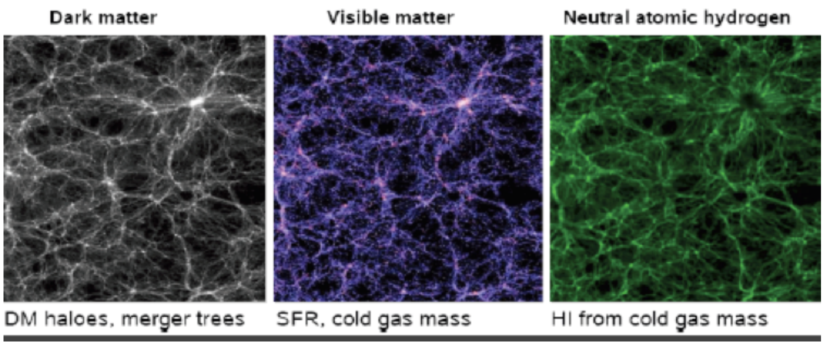
The simulated distribution of neutral hydrogen at the time of the formation of the first stars (left; Mesinger et al. 2011) and in more recent times (middle; Villaescusa-Navarro et al. 2015). Estimation of the contribution of the different components in today's Universe (right): Dark Energy (73%), Dark Matter (23%), known particles (4%)

evolution on cosmological scales. This can be done effectively by exploiting the sensitivity and the large field of view of SKA, thanks to which it will be possible, for the first time, to observe the HI associated with the large-scale cosmic structures in different epochs of the life of the Universe.

2.3 Galaxy Evolution

The SKA will allow to observe for the first time the galaxy evolution, as traced by the accumulation and utilisation of atomic Hydrogen throughout cosmit time.

Neutral hydrogen is the *missing link* in our current models of galaxy evolution. A wide range of models and simulations exist, but none of them fit all the data. The main current limitation is the lack of observational constraints on the HI content of galaxies in the redshift range at $0.2<z<2$, a critical time span for galaxy evolution. The unprecedented ability of the SKA to detect HI over cosmic time will allow us to fill this gap. Commensal observations in radio continuum and HI will trace HI and star formation in galaxy disks, AGN-driven HI outflows on (sub-)kpc scales, as well as AGN cores and inner jets on pc scales, hereby allowing us to probe the role of HI content in galaxy formation and evolution, as well as the interplay between nuclear and star formation activities up to the epoch of their peak.

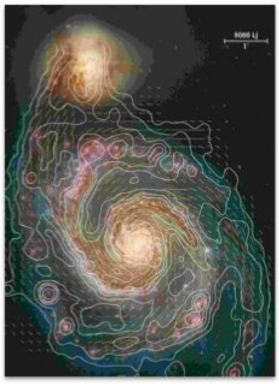


Galaxy formation and evolution simulations: dark matter (left; Springel et al. 2005); visible matter (center; De Lucia et al. 2006, 2007); neutral atomic hydrogen (right; Obreschkow et al. 2008)

2.4 Cosmic Magnetism

The SKA will be able to study the origin and the cosmological evolution of magnetic fields in the Universe

Magnetic fields are present throughout the hierarchy of the structures of the Universe, from planets to stars, from galaxies to galaxy clusters. Theoretical studies indicate that magnetic fields would extend even along the cosmological filaments that make up the largest-scale structure of the Universe. We know that magnetic fields play a fundamental role in controlling the formation and evolution of celestial bodies, and are key ingredients in controlling the transport and acceleration of high energy particles in astrophysical systems. However we do not yet understand their origin and how they are conserved on cosmic scale times. SKA will finally open a window on cosmic magnetism: it will be able to reveal the polarized radio emission produced by relativistic electrons traveling in magnetic fields, out to the furthest edge of the Universe. Key for these studies is the wide range of operational frequencies allowed by the SKA.



The spiral galaxy M51 (Fletcher et al. 2011). The optical image (HST) is superimposed on contours indicating the intensity of radio emission (Effelsberg and VLA) and by polarization vectors showing the orientation of the magnetic field of the galaxy along the spiral arm

2.5 General Relativity and Gravitational Waves

The SKA will be able to test the laws of physics in extreme conditions, such as those established in the vicinity of pulsars and black holes, and detect the passage of gravitational waves

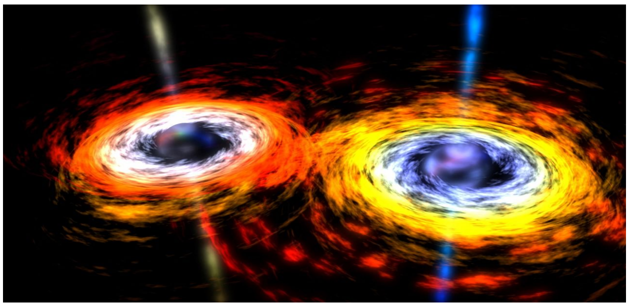


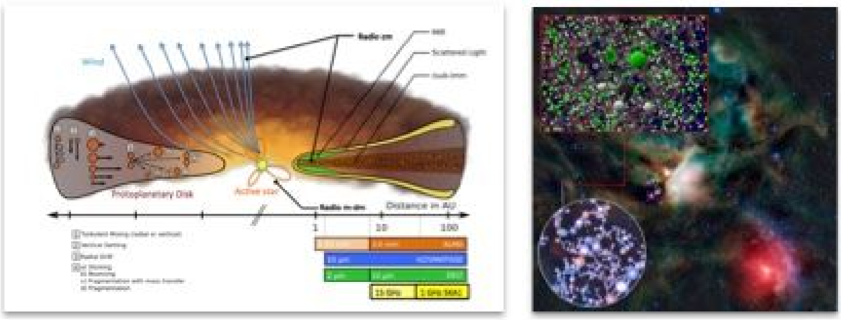
Illustration of two super-massive black holes catched in the act of merging

The study of the extreme physical conditions that are established around pulsars allows us to verify the general theory of relativity of Einstein and compare its predictions with those of other theories of gravitation. The SKA will discover tens of thousands of pulsars, some of which in orbit around black holes. Such binary systems can be used to verify the predictions of the general theory of relativity for black holes. Pulsars observations with the SKA do represent a very promising tool for the detection of gravitational waves produced by super-massive black holes in the formation and coalescence phase of galaxies. In their orbital path black holes emit gravitational waves of ultra-long period (over 1 year) that can be detected by the SKA using the observations of a series of millisecond pulsars. This would also contribute significantly to cosmology studies.

2.6 The Cradle of Life

The SKA will be able to search for extra-solar planets and life forms in the Universe

The first decade of the 21st century witnessed the discovery of an increasing number of planets outside our solar system. Most known planetary systems have a very different architecture from the Solar System. It is therefore natural to ask the question of how common, or unique, is the process that led to the formation of our system and, in particular, of a planet like the Earth where life could develop. Observations with the SKA will help us to understand how the planets form and evolve and how the chemical complexity that leads to the formation of the biospheres develops. The sensitivity of SKA and its ability to reveal the finest details, especially at its highest operational frequencies, will allow us to study the evolution of dust and the formation of the rock nuclei of the planets, as well as to study the chemical and physical processes that lead to the formation of rare and complex molecules, including amino acids, the building blocks of life.



Protoplanetary disk model (left; Testi et al. 2015) with highlighted the physical processes observable with SKA. Some of the complex pre-biotic organic molecules revealed in the radio band (right; Martín-Doménech et al. 2017; Fayolle et al. 2017)

3. SKA and other Facilities working together

Many scientific challenges are addressed most effectively when several independent observatories operating in different portions of the electro-magnetic spectrum are used together. Indeed important synergies do exist with several of the planned facilities, each unique and world-leading in their fields, which are already operational and/or expected to become available on a timescale similar to the SKA one.

3.1 The Bursting Sky

The SKA will discover and localize thousands of Fast Radio Bursts, paving the way towards the understanding of this puzzling transient phenomenon.

One of the science fields where multi-band synergies play a crucial role is the study of transient sources (Supernovae, Gamma-Ray Bursts, Tidal Disruption Events, etc.). Indeed to get a comprehensive view of transient phenomena, their light curves need to be traced as long as possible and at as many bands/frequencies as possible. This because different bands trace different physical components and/or epochs of the transient phenomenon.

One of the most interesting classes of transient sources is today represented by the so-called *Fast Radio Bursts* (FRB), first discovered in 2007. Many theories have been developed to explain this puzzling phenomenon, but none has been confirmed so far. The SKA will discover and follow-up thousands of them, enabling precise association with the objects that host them. The study of FRBs with the SKA will open a completely new window on the cosmos.

3.2 Multi-messenger Astronomy

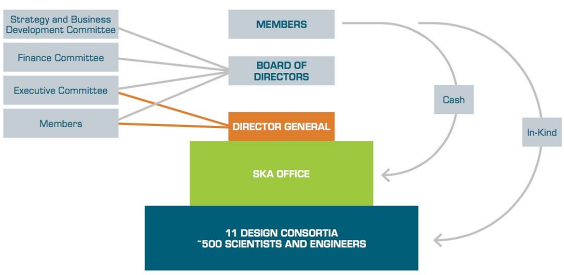
The SKA will enable precise localization of gravitational waves and neutrino sources, and follow-up studies of their radio counterparts.

The combination of electromagnetic light with gravitational waves or neutrinos has come of age. The detection of gravitational waves and a kilonova from a merging neutron star binary[3], and the identification of a flaring blazar[4], in coincidence with a high energy neutrino, mark the beginning of an era where the detections of sources beyond the electromagnetic spectrum will become increasingly common. The sensitivity and high resolution enabled by the SKA will play a central role in the global efforts to identify and follow-up the electro-magnetic counterparts of sources initially located by either gravitational wave or neutrino observatories. More specifically, SKA radio follow-up observations of GWs will provide important constraints on the energetics of the explosion, on the geometry of the ejecta, as well as on the environment of the merger.

Synergies and multi-messenger applications which are particularly relevant to the Italian community will be discussed in Part II of this document; some specific examples are presented in Appendix C.

4. The Project Organization

The SKA will operate through an Intergovernmental organisation (IGO; the SKA Observatory), whose underlying principles will be to ensure equitable distribution of both costs and benefits. Indeed the IGO funding model links Members' contributions to their eventual capability to exploit the SKA. The benefits, in terms of both fair industrial return and access to the telescope, will likewise be proportional to a Member's contribution. Special terms apply for the host countries, recognising that they will gain additional local benefits from the presence of the SKA facilities. Both contractual/industrial opportunities and access to observing time for non-members will be extremely limited.



SKA Organization structure. Credits SKA Organization

The IGO will supersede the *SKA Organization*, a UK not-for-profit private

[3] Abbott et al. 2017, PRL, 119, 161101

[4] Paiano et al. 2018, ApJL, 854L, 32P

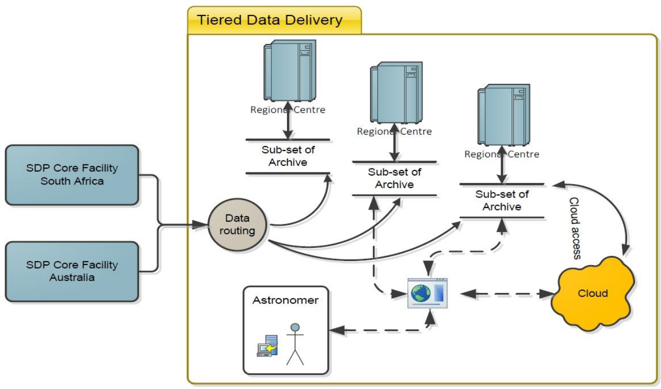
company formed in 2011, that is coordinating the design and pre-construction phase of the SKA project, until the IGO gets ready to take over. The governing body of the SKA Organization is the *Board of Directors*, a body required under company law in England, acting in the best interests of the project and appointed by the Members of the SKA Organisation.

The SKA Headquarters have been established at Jodrell Bank (Manchester, UK).

4.1 The SKA Operational Model and the concept of SKA Regional Centers

From an operational point of view the SKA Observatory will consist of a distributed science and operations network, including the two observing sites (in Australia and in South Africa) and the headquarters. While archiving capabilities for observatory data products and *standardized* data processing pipelines will be available at SKA-dedicated data centers in the two hosting countries, it is expected that further processing and analysis will be needed in many cases to get final, science-ready data products.

This has led to the development of the concept of so-called *SKA Regional Centers (SRC),* a distributed network of data centers housing high-end computing facilities, as well as long-term archiving capabilities for advanced data products. SRCs are also expected to provide proposal preparation and data handling support to final users.



Sketch of the SKA data flow from SDP core facilities to final users. Credits SKA Organization

While SRCs will necessarily work in close collaboration with the SKA Observatory and the SKA data centers on sites, they are not budgeted as part of the SKA project. Indeed countries interested in investing into SRCs may or may not be funding members of the SKA project itself.

Given the strategic role that SRCs will play for a full exploitation of the SKA, and the mutual interconnections between SRC and SKA *Science Data Processing* (SDP) core facilities in Australia and South Africa, the SKA Board is interested in closely following and coordinating SRC initiatives. This was done initially through the *SKA Regional Centre Coordination Group* (SRCCG), and now through a more formally structured *SKA Regional Center Steering Committee* (SRCSC).

The SRCSC, established in 2019, will guide the definition, creation and support of a long-term operational ensemble of computational/data-intensive infrastructure and supporting services, to enable the successful completion of all SKA science programs (large and small) and the long-term curation and functionality of the SKA Science Archive. The organizational and operational model for SRCs is currently under development, but it is very likely that its ensemble will be formally coordinated by an independent body.

Part II - SKA in Italy

Italy is one of the founding members of the *SKA Organization* and one of the seven countries[5] that has signed the IGO convention on March 12th, 2019. The Italian participation to the SKA project is coordinated by the National Institute for Astrophysics (INAF). As a member country, Italy is present in all the *SKA Organization* advisory committees and managing bodies.

The Italian community actively participates in the various scientific and technological activities ongoing as part of the SKA project, both at national and international levels. In several cases Italian scientists and engineers play leading roles. In addition, several Italian scientists and engineers are part of the staff of the *SKA Office* (Jodrell, Bank). Some of them are INAF employees seconded to the SKA Organization.

At the end of year 2017 an *Italian SKA Board* has been appointed by the INAF UTG-II Head. This body is expected to support INAF in harmonizing and coordinating SKA-related Italian activities, and to propose actions that maximize the scientific and technological return on investment, and ultimately the Italian visibility in the international SKA context. The Board brings together INAF personnel with a recognized expertise in the SKA project, that have responsibility roles in (or relevant to) the SKA project, at national and/or international levels.

More details on the involvement of Italy in the ongoing SKA-related activities are presented in the following sections. A complete census of the Italian representatives in SKA committees (both at national and international levels) and of the researchers playing leading roles in the SKA project is presented in Appendix A.

5. SKA Design and Pre-construction activities

In 2013 twelve *Design Consortia* (DC) were established to provide prototypes for all SKA1 elements (antennas, receiving and signal processing systems, telescope control software, etc.). In addition three *Advanced Instrumentation Programmes* (AIP) were established, aimed at exploring SKA2-related technology.

Financial support to enable design activities were meant to be provided locally through national grant awards or other mechanisms (members' *in kind* contribution). Over 500 engineers and scientists from 20 countries have been involved in the Design of SKA1. The *Design Consortia* were expected to conclude their prototypes by the end of 2018. Indeed most of them have already passed the Critical Design Review (CDR). AIP, on the other hand, are long-term programmes, envisaged to continue for several years in the future.

[5] Australia, China, India, Italy, Portugal, South Africa, United Kingdom.

Italy has been actively working for four *Design Consortia* and one AIP project (started in 2017), namely:

- ➢ Low Frequency Aperture Array (LFAA) - responsible for the design of SKA1-LOW antennas, on-board amplifiers, and the local station signal processing and hardware.
- ➢ Dish - responsible for the design and verification of the SKA1-MID antenna structures, opticas, feed suites, receivers, and all supporting systems and infrastructure.
- ➢ Telescope Manager (TM) - responsible for the development of all hardware and software necessary to control the telescope and associated infrastructure. It includes the SW necessary for scheduling telescope operations and central monitoring key performance metrics.
- ➢ Central Signal Processor (CSP) - responsible for the design of the central processing *brain* of SKA1, the first stage of signal processing, where correlation and beamforming takes place. It includes a pulsar search processor.
- ➢ AIP - Phased Array Feeds (PAF) - responsible for the development of cost effective wideband, multi-pixel, wide field-of-view (FOV) receivers for the SKA. These receivers replace conventional single pixel feed receivers located at the focus of the offset parabolic dish antennas to provide a multi-pixel "camera" on the sky.

INAF has been playing leading roles in software development, particularly for the *Local Monitor and Control* (LMC) in both *Telescope Manager* (OA Trieste and then OA Abruzzo) and *Dish* (OA Catania) consortia. In addition it is responsible for the development of a receiver and its acquisition chain for the LFAA (IRA). The group at OA Arcetri actively contributed to the *Control Signal Processor.*

The Italian role in the above activities is analytically described in the table below, where we highlight the R&D contribution, the investment, the expertise, industrial applications and potential return (a description of Italian industrial engagement in the SKA pre-construction phase is given in Section 6).

SKA1 Pre-construction phase: Design and AIP developments in Italy[6]

Design Consortium	R&D	FTE	Costs (k€)	expertise/ leadership	Industrial applications	Industrial return
LFAA	Design of antennas; LNA; analog receivers; RFoF optic systems; data acquisition systems and integrated cabinet;	63.5 (some shared with CSP)	3500 TD: 1130	All activities listed in R&D Receiver WP leader	*Production:* antennas; RFoF based receiving systems; data acquisition boards;	85-120 M€ for a SKA1-LOW compatible production (subject to procurement

[6] FTE and costs for Design Consortium activities are intended from 2013 to the CDR (with the exception of the Dish Consortium, whose CDR is still pending, and FTE and costs are updated to the end of 2019). FTE and costs for AIP-PAF refer to years 2017 (when the project started) to 2019. FTE are subdivided in permanent staff (TI), personnel contracts (TD); External collaborations (C). Costs include in kind contribution from permanent staff. The potential industrial return reported in the last column only refers to the activities described in the table and led by INAF. The reported values should be considered only as indicative, as they are based on the construction costs reported in the SKA cost-book, a document which is still subject of updates.

	beam forming firmware; array calibration using UAV **LFAA CDR: Dec. 2018**[7]	TI: 28.2 TD: 27.1 C: 6.3			high performance integrated cabinets	scenario)
Dish	Implementation and testing of the control and monitoring system prototype; harmonisation and standardization of SKA1-MID control systems; realization of graphical interfaces for DSH.LMC **DSH CDR: TBD**	20 TD: 12	1080 TD: 600	Control systems, framework TANGO, system modeling with SysML LMC sub-element Leader	*Development:* codes for control systems; framework for automatic SW testing & continuous integration; *Participation in the realization:* Dish's ACU; rugged computers	~3 M€ for SW of LMC system, computers for 133 dishes of SKA1-MID, (incl. SW engineering, management, HW deployment, FAT, transport, support and spares
CSP	*Pulsar Search:* GPU programming and LMC; *LMC:* functional model and base classes. Digital signal processing model **CSP CDR: Feb. 2019**	17 TI: 10 TD: 7	1120 TI: 700 TD: 263 Other: 157	Modelling, GPU coding, TANGO control system	Code development for CSP.LMC & PSS.LMC	2-3 M€ for CSP.LMC 0.3-0.4 for PSS.LMC
TM	Design & prototyping of TM.LMC, incl. Maintenance Plan; Design & prototyping of Observation Data Archive (ODA); Design & prototyping of Authorization, Authentication and Auditing (AAA); Definition of UI Design Principles, based on experience at major facilities (e.g. ALMA LOFAR, MeerKAT) **TM CDR: July 2018**	32 TD: 20.2 C: 1.5	2700 TI: 900 TD: 1000 C: 360	All activities listed in R&D	*SW development*: -AAA services -database management and maintenance -logging services -monitoring and control (lifecycle management), including fault management -development & testing of user interfaces	2.3 M€ LMC 0.4 M€ ODA 1.4 M€ AAA 0.4-1.4 M€ UI (subject to technology choice and followed approach)
PAF	Development of "Warm Section" multi-channel heterodyne receiver in C-Band (4-8 GHz) for PHAROS2. Development of digital beamforming firmware. EM simulations and optimization of coupling between PAF and antenna optics.	7	225	All activities listed in R&D	Production of heterodyne multi-channel receivers and acquisition boards	Difficult to quantify now, given that SKA2 design has yet to be defined

[7] The LFAA CDR meeting was held in December 2018, where supplemental work was deliberated to test the calibratability of the log-periodic antennas. This is being undertaken as part of the bridging. The CDR will be formally closed only at the conclusion of such activities.

These activities have been supported by *ad hoc* funding from MIUR (*Astronomia Industriale: 30 MEu*). All the above Consortia have now passed CDR, with the exception of the Dish element, where CDR is still pending.

5.1 Bridging

In January 2019 INAF and SKAO have signed a bilateral MoU for the so-called *Bridging Phase*. This phase covers the time span between the close out of element CDR and the acceptance of the construction proposal. The intention behind the Bridging Phase is to ensure completion of the SKA designs, obtain an accurate and reliable costing, and finalise plans for construction and operations. Bridging activities are organized in *Agile teams* under the coordination of the SKA Office. As for the Design phase, Bridging is still considered *in kind* contribution from SKA members. At the moment two main Bridging activities involving INAF are in place, as described below.

SKA1 Bridging phase (2019)

Task	**R&D**	**FTE**	**Costs (k€)**
Software development	Continuation of LMC activities for TM and CSP Software development under the SAFe approach	4.1	305
SKA1-LOW	Continuation of LFAA activities; Antennas, receivers, calibrations	7.7	650

5.1.1 SW development

This essentially consists in the continuation of the INAF-led LMC activities undertaken as part of the TM and CSP Consortia during the Pre-Construction Phase.

INAF members from TM Consortium are belonging to two separate Teams, namely the *System Team* and the *Buttons Team*. The former (*System Team*) is a cross-cutting team aimed at providing virtualization services for the software development activities of all other teams (according to an overall architecture and technological solutions which are under design and prototyping) as well as defining the whole software deployment and maintenance process, including in particular the testing activity. The latter (*Buttons Team*) is engaged with the design and prototyping of a platform for the generation of Graphical User Interfaces (Webjive) and some aspects of the Observation Manager, in particular the Observation Data Archive which must meet demanding requirements related to distribution and data handling.

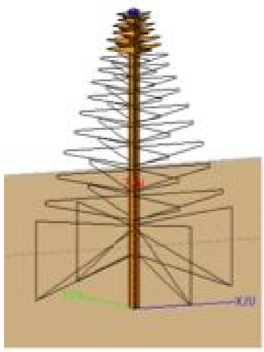
INAF members from CSP Consortium are associated to the *PSS Team* and their main activity is focussed on Folding algorithms for the identification of pulsars candidates, and their optimization. They also provide collaborative support to another team (*CIPA Team*) for the development of a working CSP LMC system prototype.

It is important to remark that almost all the software developments are carried on in the context of the TANGO Controls framework, which has been chosen during the Pre-Construction Phase as the control main skeleton of the whole SKA system. Over the last years INAF people has been gaining considerable competences with TANGO which is now acknowledged by the SKA Organisation. This acknowledgement has recently led to the official creation of a TANGO Community of Practice (CoP), led by INAF members.

5.1.2 SKA1-LOW development and testing

This mainly consists in the continuation of INAF-led LFAA activities. In the context of the overall SKA-Low bridging programme, INAF and the Curtin University node of the International Centre for Radio Astronomy Research (ICRAR) have signed a MoU, to establish a formal partnership aimed at combining complementary technology and skills to advance the design of SKA1-LOW. This bilateral collaboration builds on the successful LFAA INAF-led design activities (compliant receiving chain and SKALA4 log-periodic antenna design) on one side, and on the established ICRAR MWA technology on the other.

The outstanding objective of this project is to resolve the highest priority technical risk in the SKA-LOW station reference design identified at LFAA CDR, i.e. station calibratability. To reach this goal the following pathway has been identified:



SKALA4 Antenna Design

1. realize and verify a SKA-LOW (256 element) station architecture based on the SKALA4-Al reference design and compliant receiving and backend systems, as implemented by INAF, at the Murchison Radio Observatory (MRO);
2. realize and verify a SKA-LOW (256 element) station architecture based on the risk mitigation bowtie dipole antenna at the MRO;
3. provide a platform for the testing of alternative compliant technologies for SKA-LOW, pending project approval. This represents a long-term important but non-critical path for this project.

Establishing log-periodic antenna calibratability represents a critical path for SKA-LOW, and a very aggressive schedule has been established for this project: the intent is to execute the substance of the critical path activities by the end of calendar year 2019, i.e. within 1 year from the signing of the MoU. Non-critical path activities may extend over a longer period of time.

6. Industrial Engagement in SKA Pre-construction Phase

The technological R&D activities carried out as part of the design and bridging phases outlined in the previous sections have often been done in close collaboration with industrial partners. In the following we briefly summarize such partnerships for each of the involved design consortia, and we provide an outlook of the industrial perspectives for the industrialization and construction phases (see also last two columns of the table above). The potential industrial return of INAF-led design activities is based on estimates of construction costs evaluated by the design consortia themselves in close coordination with SKAO, and should be considered as indicative. Finalized construction costs will be delivered by the SKAO as part of the System CDR, planned for the end of year 2019.

6.1 LFAA

The LFAA engineering activities have been carried out, since the very beginning, with the support of industrial partners. This was motivated by the very challenging and conflicting design requirements. The Industrial competencies have been strategic to balance the extremely high performance requirements with very severe constraints such as high reliability, low cost, readiness for mass production, high reproducibility etc.

The phase 1 of SKA-LOW involves the realization of approximately 130,000 double-polarized wire antennas connected to 260,000 receiving and acquisition chains (300,000 when considering spares). These numbers need the implementation of the best engineering production practices, often obtained with dedicated assembly lines, and the application of "state of the art" qualification standards.

Industrial partners involved in LFAA design and bridging activities

A close interaction between companies and INAF research groups, as well as the mutual transfer of know-how has been very important and fruitful, also in view of the industrialization phase[8], when the role of companies operating on the market will be crucial.

To date, industrial partnerships have been established with companies belonging to the SME sector, thanks to their higher flexibility, which allowed them to quickly respond to the need of modifying specifications during construction, and thanks to the fact that they are more used to operate in a context of prototyping and small productions, ideal for the case of test arrays.

For the future it is very important to involve a "Prime", able to manage and coordinate the work and the production quantities involved in the construction of SKA1-LOW.

The potential industrial return for INAF-led LFAA activities is in the range 85-120 M€, depending on the procurement scenario.

[8] Industrialization is the phase when the various stages of production are defined: components' details, storage, equipment for the assembly phases, test procedures and preparation of test benches, packaging for a possible shipping.

6.2 Dish

The *Local Monitor and Control* (LMC) system of the dishes of SKA1-MID has been developed in Italy. The main LMC design activities and the management have been provided by INAF. In the last two years, two Italian companies, SAM and EIE, contributed to the project.

LMC is a software running in a dedicated computer installed in the pedestal of the dish. It is the interface between the *Telescope Manager,* which manages the observations and the overall operation of the array, and the instrumentation of the dish, including the dish structure itself, its movements, the receivers and the signal to be provided to the central correlator of the array. The prototype of the LMC software has been developed by INAF, the automated tests by SAM, the procurement of the hardware by EIE.

Among the most important activities for the construction phase, there are the industrialisation of the software and the development of *Open Source Methodologies*. The ongoing collaboration between the INAF research teams and the two companies has led to the development of an *Open Source* platform that has important industrial applications.

Current estimates of the construction costs for DSH.LMC (133 dishes) give a grand total of 3.043.000€, where 2.258.000€ are for the software and management, and 785.000€ for the hardware.

6.3 Telescope Manager

During the pre-construction phase, INAF has lead the design of the TM LMC system, devoted to the functions of monitoring (including Logging), control (largely consisting of Lifecycle Management) and fault management of TM.
Two *extra-WBS*[9] activities of TM – which however had a more general importance for the entire SKA project – were also carried under INAF guide, namely the definition of principles for the design of the *Graphical User Interfaces* (GUIs) and the architectural analysis of the *Authorization, Authentication and Auditing* (AAA) system.

Contracts with national industrial partners have been activated during both the design and the bridging phases. The definition of the architecture of the monitoring and control system was carried out in the pre-PDR phase in close collaboration with *Telespazio/Finmeccanica* in Rome/Naples. At a later stage (critical design phase) the analysis of the requirements for designing efficient and ergonomic GUIs was done in collaboration with *Interaction Design Solution* (IDS) in Trieste. The contract with IDS was then renewed for the bridging phase, in view of the definition of the requirements for the technological down-selection of a platform for the construction of user-driven, TANGO-compliant web interfaces. The strong industrial

[9] The Work Breakdown Structure (WBS) organizes and defines 100% of the scope of project work to be accomplished and displays it in a way that relates work elements to each other and to the project's goals

collaboration established with *Consorzio Elettra* (Basovizza, TS) is also worth mentioning. This has led INAF to start a discussion on the need for a framework to serve as the central nervous system of the SKA, which has finally led to the choice of the *TANGO Controls* framework.

All of these collaborations can potentially bring to Italy important contracts in the construction phase. Given the TANGO-based architecture of the whole SKA and the TANGO controls competences acquired by INAF teams, the role of INAF in the construction of the monitoring and control architecture of the SKA (e.g. through the definition of TANGO Base Classes for the realization of the SKA TANGO devices) could be crucial. Another important point is that INAF is currently the only institution to effectively work on GUIs: in addition to defining and customizing a platform for building GUIs, the entire set of tools (buttons, consoles, diagrams, etc. ...) will have to be developed.

The collective estimated value for these industrial activities is between 5 M€ (for GUIs only) and 15M€ (including the full development of TANGO commonalities).

6.4 AIP-PAF

PHAROS2 is a 4-8 GHz cryogenically cooled Phased Array Feed (PAF) under development in the framework of the PAF Advanced Instrumentation Program (AIP), resulting from the collaboration of INAF with international partners. The instrument is a demonstrator of possible technologies that could be adopted for SKA-MID on a longer term, and will be installed for testing purposes at the focal plane of the 25-m diameter Pickmere antenna, one of the antennas of the e-Merlin interferometer in the UK. INAF has a major role in the PHAROS2 development and provides to the project the following items:

A. a multi-channel room temperature heterodyne receiver (Warm Section) covering 2.3-8.2 GHz;
B. an FPGA-based digital backend based on italian Tile Processing Module (iTPM), adopted from the SKA LFAA project.

The Warm Section (WS) multi-channel receiver is the first of its kind to be developed for a PAF application and will enable first-ever radio astronomy observations in C-band with a PAF. The WS receiver is the signal chain section located between the cryogenically cooled PHAROS2 antenna array and the digital beamformer. INAF has written a new firmware for the FPGA-based iTPM digital backend in order to perform the beamforming for the PHAROS2 demonstrator.

The PHAROS2 WS and digital backend were developed by INAF in collaboration with italian industrial partners. In particular, the following companies were involved in the collaboration:

- the WS circuit boards were fabricated and assembled by the two following companies: *ELCO S.p.A.* (Carsoli, AQ, Italy) and *TEBO* (San Lazzaro di Savena, BO, Italy);

- the *Wavelength Division Multiplexing* fiber-optics links (pre-ADU and optical transmitter) employed for the Intermediate Frequency signal transportation were produced by *Optel* (Rome, Italy);
- the *Analog to Digital Unit* (ADU) was acquired from *Sanitas EG* (Milano, Italy).

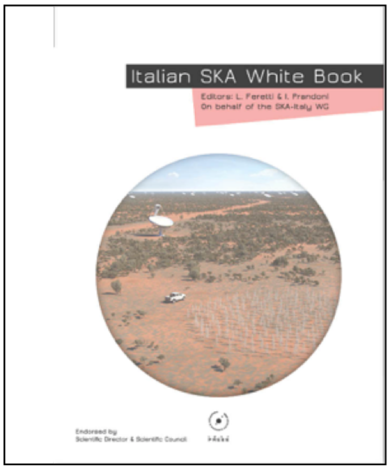
At present the SKA project focus is on SKA1 construction and meeting the SKA1 cost cap. Thus, it is likely that PAFs will not find application on SKA in the near future. Also, the technologies used for PAFs might change considerably in the upcoming years, specifically with regards to the signal digitization, that is likely to cover increasingly broader bandwidths. However, the analogue WS receiver that INAF developed is currently a necessary piece of hardware for PAFs designed to operate beyond few GHz, as a direct sampling of the RF signal by ADCs is only possible up to several GHz. The existing high-performance ADCs have limited bandwidth and maximum frequency, which makes them suitable solutions for PAFs radio astronomy application up to S-band (or lower frequency), but not yet for 4-8 GHz or beyond. A WS multichannel receiver, of the type that INAF developed for the first time, it is likely to be a necessary piece of hardware for any PAF operating at frequencies beyond 15 GHz for at least the next few years.

In summary, the INAF developments carried out in the framework of the PHAROS2 PAF AIP might have a strong industrial involvement in the construction of the SKA beyond phase 1, as a large number of WS multi-channel receivers and digital backend/beamformer might need to be produced for the project. The key parts of the PHAROS2 hardware developed by INAF were all produced by Italian companies.

7. SKA Science Case

7.1 The Italian SKA White Book and the Italian contribution to the SKA Science Book

Front page of the Italian SKA White Book



In 2012, in collaboration with the Ministry of Education and Research, INAF organized the *First National Conference of Science and Technology of SKA* (Rome, 19-20 June). The conference kicked off the process of collecting and selecting SKA-related scientific projects, on topics of interest to the Italian astronomical community. This process ended in 2014 with the publication of the *Italian SKA White Book* (2014, Eds. Feretti et al., INAF Press, ISBN 978-88-98985-00-5). More than ninety Italian researchers contributed to the writing of the book. The Italian astrophysical interests, as depicted in that book, cover the following broad research areas:

cosmology; galaxy formation and evolution; AGN physics; galaxy clusters and magnetic fields; stellar astronomy; inter-stellar medium, solar system, planetary systems, bioastronomy.

The SKA Organization published in 2015 the new *SKA Science Book* entitled *Advancing Astrophysics with the Square Kilometer Array*. This book (2 volumes, about 2000 pages) contains the proceedings of the international scientific conference held in Giardini Naxos (Italy) in June 2014, organized in collaboration with INAF. Thanks to the coordination work done for the drafting of the Italian White Paper, the Italian scientific community was able to respond massively to the request for scientific cases for the SKA Science Book. Italian scientists are co-authors of 53 of the 152 chapters of the SKA Science Book and appear as first authors in 26 of these.

SKA Science Book chapters: pie-chart showing leading authors by country

Updates of the SKA-related scientific activities ongoing in Italy were presented in the framework of the *II National Workshop of SKA Science and Technology*[10] (Bologna, 3-5 December 2018), where also technological and industrial activities were reviewed.

7.2 International Science Working Groups

The scientific themes of SKA are continuously updated and refined by dedicated international working groups (*Science Working Groups* and *Focus Groups*, hereafter collectively referred to as SWG), composed of scientists experts in the field coming from the countries already involved in SKA, or strongly interested in entering the project. Each SWG typically has **two co-chairs**, which are renewed on two-year time scales. Currently two groups have Italy-based co-chairs. Altogether more than **eighty Italian** scientists are **members** of the SWGs (**almost 9%** of the total members, see Table below, updated to the end of 2018). About 70% of them are INAF researchers. Only two groups have a high fraction (>~50%) of Italian members not belonging to INAF: Cosmology and Epoch of Reionization. In 2019 a new SWG has been set up on “Gravitational Waves”. This SWG is mainly focused on gravitational wave cosmology. Its team is still in the process of being formed and its science case is still under development.

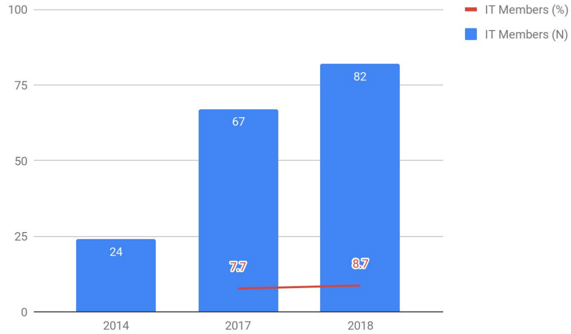


Chart showing the number (blue) and the fraction (red) of Italian members of the SWGs along the years.

It is interesting to note that the scientific interest to the SKA is rapidly growing in

[10] https://indico.ict.inaf.it/event/

the Italian community as a whole: the number of Italian members of SWG has more than tripled in the last four years (2014-2018), and the overall fraction of Italian members in SWGs has increased by 1% (from ~8% to ~9%) in the last year! This latter result is probably the effect of INAF recent investments in SKA science (SKA/CTA PRIN, see Appendix B; formal involvement in the International LOFAR Telescope), as well as European Research Grants on SKA-related science, obtained by young Italian researchers.

International SKA Working & Focus Groups - Italian participation updated to end 2018

#	**SKA Working/Focus Group**	**Members**	**IT Members**	**chairs/core**
1	Solar, Heliospheric & Ionospheric Physics	78	1 (1.3%)	
2	Our galaxy	60	8 (13.3%)	chair/ 1 tier-1 member
3	Cradle of Life	60	6 (10%)	
4	Pulsars & Gravity	80	4 (5%)	1 ex-chair/1 tier-1 member
5	Transients	69	5 (7.2%)	
6	HI in galaxies	69	3 (4.3%)	
7	Continuum extra-galactic science (AGN/galaxies, galaxy clusters)	113	13 (11.5%)	2 ex-chairs/2 core members
8	Extragalactic line (non-HI) science	40	1 (2.5%)	
9	Magnetism	76	11 (14.5%)	1 ex-chair/5 core members
10	Cosmology	130	16 (12.3%)	1 core member
11	Epoch of Reionization	72	8 (11.1%)	chair
12	VLBI	72	6 (8.3%)	4 core members
13	High-energy cosmic particles (Focus)	25	-	
All	**November 2018**	**944**	**82 (8.7%)**	
All	**November 2017**	**871**	**67 (7.7%)**	
All	**2014**		**24**	

8. Italian involvement in SKA Pathfinders and Precursors

8.1 The International LOFAR Telescope (ILT)[11]

On April 16 2018 the Consortium LOFAR-IT[12] led by INAF joined the LOFAR ILT, the largest SKA pathfinder. A LOFAR 2.0 station will be installed in Medicina in 2021-22. INAF has an important

[11] www.lofar.org
[12] www.lofar.inaf.it

role in the design of the LOFAR 2.0 receivers (RCU chain) and will be involved in several other activities, including the development of telescope software/pipelines.

LOFAR-IT is installing a national computing infrastructure to support LOFAR data analysis; the infrastructure is distributed over three INAF nodes (IRA, CT, TS) and includes the supercomputing center C3S in Torino. The participation of IT in LOFAR and its evolution in LOFAR 2.0 is important as it allows the IT community (technical and scientific) to tackle unique problems in view of the SKA, including the calibration and imaging of radio signals at low frequencies and the transport, analysis and archiving of massive data.

The International LOFAR science community is currently organized in six key projects (KP): *Epoch of Reionisation*[13], *Survey Key Project*[14]; *Transient Sources*[15]; *Ultra High-Energy Cosmic Rays; Solar Science & Space Weather*[16]; *Cosmic Magnetism*[17]. The access of Italian scientists to KP Consortia is coordinated by the *LOFAR-IT Board*. In addition to participation to KPs, the Italian community has 66 hours of LOFAR guaranteed time every year. Additional observing time can be obtained through the regular competitive proposal calls. Currently, Italian scientific interests towards LOFAR are mostly focused on galaxy clusters, AGN, galaxy evolution, cosmic magnetism, transient sources and solar system; the LOFAR KP Consortium with largest Italian participation is *Survey*, where the Italian is the third most represented community.

8.2 The electronic European VLBI Network (eEVN)[18]

The eEVN - the subset of EVN antennas connected to the EVN correlator at JIVE through optical fiber link, allowing real-time VLBI - is considered a technological pathfinder of the SKA. Indeed, the inclusion of a high-resolution component with baselines longer than 1000 km and Very Long Baseline Interferometry (VLBI) capabilities has long been considered an essential part of the SKA concept, to maximize the impact of the SKA in a number of key science areas. One of the most relevant is the need for milliarcsecond resolution to localize transient sources, such as for instance FRBs and GWs, to name a couple among the most interesting classes of transient sources that have recently come to prominence. But several more science areas (either galactic or extragalactic) will require VLBI capabilities: from cosmological studies based on gravitational lensing to star formation studies based on masers observations. Another remarkable example is represented by resolved studies of the distant Universe, where SKA-VLBI will allow to resolve the mutual interplay between star formation and AGN in high-redshift galaxies. In addition, SKA VLBI capabilities will allow to exploit the existing synergies between SKA and ELT, in any astrophysical area requiring angular resolutions of the order of the milli-arcsecond.

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[13] www.lofar.org/astronomy/eor-ksp/epoch-reionization
[14] www.lofar-surveys.org/index.html
[15] www.transientskp.org/
[16] www.lofar.org/astronomy/solar-ksp/solar-physics-and-space-weather
[17] www.lofar-mksp.org/index.html
[18] www.evlbi.org/home

Different approaches will be considered for SKA1 and SKA2 to achieve high resolution. In SKA1, the SKA core will be incorporated as an additional element in existing VLBI networks, hence boosting their sensitivity, with correlation accomplished using current VLBI correlators. Implementation of the high-resolution component in SKA2 will be accomplished by having the remote stations an integral part of the array, with a significant portion of the collecting area (e.g. 25%) extending thousands of kilometres from the core, and with processing carried out with the SKA processor. This second-stage approach will make SKA a true array of transcontinental dimensions providing milliarcsecond resolution at sub-μJy sensitivities.

Italy is a long-standing member of the EVN and participates in VLBI operations with the two 32-m radio telescopes located in Medicina and Noto, and with the 64-m Sardinia Radio Telescope, located in San Basilio, Cagliari. The Italian radio telescopes and the internationally recognized Italian expertise in VLBI techniques represent an asset in the ongoing developments towards SKA-VLBI. Feasibility studies of VLBI-compatible modes within MeerKAT and SKA1-MID are already under development, as well as the *African VLBI Network* (AVN), which will supply seven 32-m class radio telescopes to VLBI operations between Africa and Europe in the GHz regime. It is worth to highlight that EVN+AVN observations will allow to perform follow-up at mas scales of SKA1-MID radio sources. No other VLBI array has the required sensitivity and sky coverage to perform such follow-up studies. Due to their favourable location at the Southern tip of Europe, the Italian antennas located in Medicina, Noto, as well as the SRT, are bound to play a key role in the VLBI operations with MeerKAT, AVN, and SKA1-MID, as they optimize the common sky coverage and considerably reduce the gaps in the u-v coverage. Indeed Italy is very actively collaborating on VLBI developments with the South African partners, and this collaboration has been formally established in bilateral projects (Progetti di Grande Rilevanza Italia-Sudafrica) funded by the MAECI since year 2015[19].

8.3 Involvement in other Pathfinders/Precursors

Italy is not formally involved in other pathfinders and precursors. Nevertheless, thanks to their internationally recognized expertise, several Italian researchers have access to guaranteed time at these facilities, through their involvement in the approved legacy/key projects programme. In some cases with leading roles. In the table below we provide a brief overview of the main legacy/key projects ongoing and/or planned surveys with SKA Pathfinders and Precursors, where the role of Italian scientists has been highlighted.

The participation to these large survey projects includes involvement in commissioning and early science operations, and represents a good opportunity to get early access to new technologies and to contribute to data reduction pipelines, that will be relevant to the SKA. For instance Italian researchers have been contributing to the commissioning of MeerKAT and ASKAP, and to

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[19] For a more detailed discussion of the impact of VLBI networks on SKA-related science, and on the role played by the three Italian antennas we refer to the document: *Science, Perspectives and Impact of the use of the three Italian Antennas for VLBI*, by T. Venturi, produced as part of the activities of INAF UTG-II.

the development of *ad hoc* radio interferometry pipelines. Noteworthy are the contributions of INAF scientists to MeerKAT (OACa), and ASKAP (OACt) pipelines.

Also very important is the acquisition of observing time through competitive calls. Italian scientists are very successful in getting proprietary time based on scientific merit at those pathfinders and precursors where an open time programme is available. Two notable examples are the JVLA and the uGMRT. The Italian radio astronomical community getting (J)VLA and (u)GMRT time on the basis of individual projects has been allocated several thousands of observing hours over the past 15-20 years. The long-standing use of (u)GMRT, in particular, has built a considerable experience in dealing with the calibration and imaging problems at frequencies in the range 100 MHz - 1 GHz. The synergy between uGMRT and MeerKAT is a key added value to both instruments, which is already being explored and exploited in the area of AGN and galaxy cluster studies - two areas where the potential of MeerKAT in terms of sensitivity and simultaneous u-v coverage over a broad range of angular scales is particularly relevant for the complexity of the radio sources of interest (both areas are included in the more general 'galaxy formation and evolution' category in the table below). Indeed Italian researchers have also obtained MeerKAT observations as part of its open time programme.

Italian Involvement in Legacy surveys[20] at Pathfinders and Precursors[21]

SKA Science	Instrument	Key Project	Observing mode/band	Italian involvement
EoR	HERA	Epoch of Reionization[22]	Continuum/50-250 MHz	Survey Member
Galaxy Formation & Evolution	eMERLIN +JVLA	*e*-MERlin Galaxy Evolution Survey (*e*-MERGE)[23]	Continuum/ L and C bands	Leader of C-band survey element / Survey Member
Galaxy Formation & Evolution	JVLA	The JVLA COSMOS Large Project[24]	Continuum/ S band	Survey Member
Galaxy Formation & Evolution	ASKAP	The ASKAP HI all-sky survey - WALLABY[25]	HI line /L band	Survey Member
Galaxy Formation & Evolution Cosmic Magnetism	MeerKAT	MeerKAT International Giga-Hertz Tiered Extragalactic Exploration (MIGHTEE) Survey[26]	Continuum + polarization + HI line / L band (+S band)	Survey Member

[20] Legacy surveys are very large observational projects (>~1000 observing hours) established through dedicated calls, and/or surveys that are formally defined as "large" in standard calls. In case of dedicated instruments (like e.g. HERA) they are the only scheduled observational programme.

[21] We do not include here facilities where Italy has granted access through an institutional involvement (like LOFAR). This table refers to pathfinders and precursors where Italian participation to legacy surveys is only based on their scientific/technical recognized expertise (see Sect. 8.3).

[22] https://reionization.org/

[23] www.e-merlin.ac.uk/legacy/projects/emerge.html

[24] http://jvla-cosmos.phy.hr

[25] www.atnf.csiro.au/research/WALLABY/

[26] https://idia.ac.za/mightee/

Our Galaxy				
Galaxy Formation & Evolution Cosmic Magnetism	MeerKAT	The MeerKAT Fornax Survey[27]	Continuum + polarization + HI line / L band	Survey PI / Survey Member
Galaxy Formation & Evolution Our Galaxy	ASKAP	Evolutionary Map of the Universe (EMU)[28]	Continuum/ 1.4 GHz	Leader of RQ AGN WG / Leader of Our Galaxy survey / Member
Cosmic Magnetism	ASKAP	Polarisation Sky Survey of the Universe's Magnetism" (POSSUM)[29]	Polarization/ 1-1.7 GHz	co-chair of Science WG / Survey Member
Pulsars	MeerKAT	MeerTIME[30]	timing/ L band	Leader of Globular Clusters observations / Survey Member
Transients & Pulsars Our Galaxy	MeerKAT	Transients and Pulsars with MeerKAT (Trapum)[31]; The HUNt for Dynamic and Explosive Radio transients with MeerKAT (ThunderKAT[32])	Searching/ L band	Survey Member

INAF participates also to other experiments that, despite not being formally included among SKA pathfinders and precursors, play a relevant role in preparation to the SKA. Among all, we cite the Epoch of Reionization experiments (PAPER[33], LEDA[34], REACH[35]). In addition, INAF leads an ongoing effort to equip the *Northern Cross* at IRA-Medicina and transform it into a *Fast Radio Burst* (FRB) search machine.

9. Exploiting synergies

Many scientific areas will benefit from synergic observations with the SKA and other existing or upcoming facilities operating at other wavelengths. Several examples are mentioned in the new *INAF Strategic Vision*[36] document produced by the INAF *Scientific Council* in 2019, where the

[27] http://erg.oa-cagliari.inaf.it/meerkat-fornax-survey/
[28] www.atnf.csiro.au/people/Ray.Norris/emu/
[29] www.dunlap.utoronto.ca/~askap.org/possum/
[30] www.meertime.org/
[31] www.trapum.org/
[32] www.thunderkat.uct.ac.za
[33] http://eor.berkeley.edu/
[34] www.tauceti.caltech.edu/leda/
[35] www.astro.phy.cam.ac.uk/news/REACH
[36] www.inaf.it/it/sedi/sede-centrale-nuova/consiglio-scientifico/archivio_verbali/2019/documento-visione-strategica

focus is on topics, methodologies and facilities that are of particular interest for INAF and for the Italian community. A brief, non-exhaustive, list extracted from this document includes[37]:

- Formation and evolution of the Solar System (dust aggregation processes in primitive bodies and exo-planetary systems): SKA, ALMA, JWST
- Evolutionary processes giving origin to the emergence of life (detection of complex organic molecules and ices): ALMA, SKA
- Global star formation properties in the Milky Way (star formation rates, efficiencies, etc.): SKA, ALMA, JWST
- Developing new-generation stellar models (astrometry, accurate asteroseismology, resolved studies of AGB stars, updated magnetic fields): Gaia, TESS, PLATO, JWST, ALMA, VLT, LSST, ELT, SKA
- Physics of accretion and ejection onto/from compact objects (accretion modes; winds and jets): SKA, ALMA, Athena, CTA, LIGO/VIRGO
- Particle acceleration processes at all scales (jet structures on (sub-)parsec scales; hot spots and radio lobes in radio galaxies; radio relics in galaxy clusters; supernovae remnants; pulsars, gamma-ray bursts, etc.): SKA, ALMA, Athena, CTA, IXPE
- Understanding gravity in the strong field regime (event horizon; GR and alternate gravity theories tests), SKA, ALMA, VLT, ELT, Athena
- Constraining the Equation of State for the nuclear matter (mass and radius of neutron stars), SKA, VLT, ELT, Athena
- Multi-messenger astronomy (search for e.m. counterparts of GWs and neutrinos): LIGO/VIRGO, all existing and new-generation telescopes
- Properties of the first galaxies and BHs; sources of reionization (21cm tomography; IR/sub-mm/X-ray surveys): SKA, ALMA, JWST, SPICA, Euclid, ELT, WFIRST, Athena
- Feedback processes among the different components of galaxies (stars, gas, dust) and AGN (detailed observations of gas kinematics, outflows, inflows.): SKA, ALMA, JWST, SPICA, EUCLID, VLT, ELT
- External and internal mechanisms regulating the efficiency of star formation and the structural parameters of galaxies (high resolution and statistical studies from deep multi-wavelength and large area surveys): SKA, ALMA, JWST, SPICA, EUCLID, VLT, ELT
- Census and distribution of mass/energy in large-scale structures (X-ray and S-Z effect observations; radio halos and relics; WHIM emission): Athena, SKA
- The nature of Dark Matter and Dark Energy (growth of structure; galaxy surveys): Euclid, SKA, VLT, LSST
- Understanding gravity on large cosmological scales (large scale structure; Sandage test): Euclid, ELT, SKA

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[37] This list schematically indicates topics, methods (in parenthesis) and facilities. For brevity we only list the most representative facilities for each observing band. This means that SKA precursors and pathfinders, even if relevant, are not explicitly mentioned. For more details we refer to the *INAF Strategic Vision* document.

Synergies between the SKA and facilities working at other wavebands were also presented and discussed at the *II National Workshop of SKA Science and Technology* (Bologna, 3-5 December 2018), in a dedicated Session organized in close collaboration with UTG-I and UTG-III. For an overview we refer to the website of the workshop[38], where all presentations are available. In addition the exploitation of synergies is an important goal for a number of projects funded under the SKA/CTA PRIN scheme (see Appendix B).

The synoptic table presented here gives a broad overview of the synergies identified through the various processes outlined above, mapped against the research areas that will be addressed by the SKA. For brevity we limit our analysis to the following telescopes: ALMA and JWST (IR/mm); EUCLID, ELT, LSST (optical/NIR); Athena, CTA (high-energy); LIGO/VIRGO (GW detector).

Overview of synergies between SKA and other major facilities

SKA Science	Telescopes							
	ALMA	JWST	ELT	LSST	Euclid	Athena	CTA	LIGO/VIRGO
Sun & Solar System	●	●		●				
Our Galaxy	●	●	●	●		●	●	
Cradle of Life	●	●	●					
Pulsars & Gravity						●	●	●
Transients & Multi-Messenger	●	●	●	●	●	●	●	●
Galaxy formation and Evolution	●	●	●	●	●	●	●	●
Cosmic Magnetism						●		
Cosmology			●	●	●	●		●
Epoch of Reionization		●	●		●	●		
High Energy Cosmic Particles							●	

This table does not claim to be complete; its scope is rather to provide an instant picture of the Italian interests in scientific areas synergistic to SKA. For a more in depth description of these synergies we refer to Appendix C.

10. Towards a European SKA Regional Center

The SKA e-infrastructure poses unprecedented challenges. High volumes of data will be transported through its dedicated network, and data will be reduced in near real time. With data rates from the dishes of over 1 Petabits per second and 10 Petabits per second from the low-frequency phased-arrays, the total data rates when the SKA1 is complete and starting operations are expected to exceed the total global internet traffic at present day rates. This implies strong requirements in terms of large bandwidth network - to transfer the huge amounts of data expected - storage capacity and computing power, not to mention the needs of ad hoc SW development and engineering. Recently, a scaling study has been undertaken by SKA Office to assess the computational resource requirements over time from the initial roll-out of the arrays through commissioning and into routine operations. The outcome of this study is presented in the table below, which shows the ramp-up in the required storage and processing

[38] https://indico.ict.inaf.it/event/685/

at the SRCs (G. Davis, SKA Document SKA-BD-28-11a). These requirements are to be met by the SRCs in aggregate, not individually.

This estimate is based on a number of assumptions and there is, as expected at this stage of the project, significant uncertainty. Such requirements should then be considered as indicative, as well as the given timeline. In particular, it is worth to mention that this estimate of the requirements has been derived using a scaling argument from Science Data Processor (SDP), which is a well-understood system; it is not based on a bottom-up derivation of processing requirements according to currently-foreseen user needs. We then expect a possibly significant revision over the years, based on inputs from SKA Science Working Groups, initial experience with proto-typical SKA data reduction pipelines, and also according to the evolving construction and early-stage/full array observations schedule.

SKA aggregate computational requirements over time (updated Nov. 2018)

Year	Storage *PBytes*	Processing *PFlops*
2022	5	
2023	24	7
2024	150	35–80
2025	365	35–80
2026	900	35–80
2027	1400	35–80
2028	1700	35–80
2029 onwards	continued growth at 0.5–1 TB/yr	35–80

The current SKA Data Center model is based on the concept of a number of regionally-funded Regional Centers, outside the scope of the SKA project. The implementation of the SRC functionality is expected to differ widely from region to region: they may build on existing infrastructure, or they may be developed in collaboration with other compute-intensive areas of science. Allowing for and accommodating this diversity is one of the strengths of the regional model. Accordingly, it is the responsibility of the regions to develop their own cost estimates and business cases corresponding to their own circumstances and aspirations. Nevertheless, the SKA Office has attempted an estimate of the cost of the SRCs, using the SDP cost model as a tool, since it is sufficiently detailed and parametric, and has been thoroughly scrutinised as part of ongoing work to understand and control the capital cost of SKA1. Using this cost model, the estimated global cost of the SRCs is:

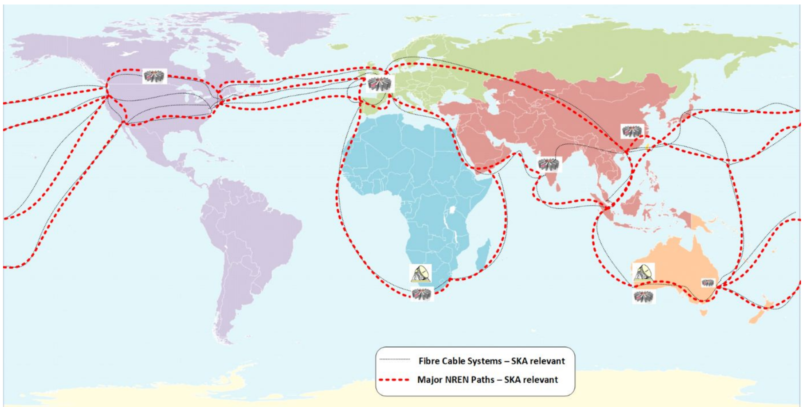
- Capital cost: €50–80M over 2024–28
- Non-staff operations: €2M/yr

The capital cost includes the processing and storage identified in the table above; it does not include buildings or infrastructure, since this will be heavily dependent on local circumstances. The cost of storage is assumed to be incurred incrementally over the period 2024–28, to take advantage of reducing hardware cost over time. Hardware costs beyond 2028 are very difficult to forecast at the present time and are not included here. The non-staff operational cost is comprised of power consumption and data transfer between SRCs.

This estimate does not include personnel. Staffing costs are extremely difficult to estimate, in part because of regional diversity, and in part because the software support requirements are not yet adequately defined.

It is also important to underline that the estimated costs are based on a large number of assumptions. There are as a consequence significant uncertainties. For more details on both the computational resource requirements and the cost estimates we refer to the SKA documents available at the SKA website at the SKA Regional Center page[39].

Efforts towards the establishment of a European SRC are ongoing. One important initiative in this direction is represented by the *Advanced European Network of E-infrastructures for Astronomy with the SKA* (AENEAS[40]) project. The AENEAS project is a 3 year initiative funded by the Horizon 2020 program of the European Commission to develop a science-driven, functional design for a *European Science Data Centre* (ESDC) to support the astronomical community once the SKA becomes operational. AENEAS brings together all of the European member states currently formally part of the SKA collaboration as well as potential future EU SKA national partners, the SKA Organisation itself, and a larger group of international partners including the SKA site host countries. AENEAS partners also include several key, EC e-infrastructures such as GÉANT[41], the European GRID Initiative (EGI[42]), the European Virtual Observatory (EURO-VO[43]), and the Research Data Alliance (RDA[44]), as well as world-class, European research infrastructures including the Joint Institute for VLBI ERIC (JIV-ERIC[45]) and the International LOFAR Telescope (ILT).



Fibre Cable systems and major NREN (National Research and Education Network) paths. Extra links and/or bandwidth specifically dedicated to SKA traffic will exploit the existing routes. Credits SKA Organization

[39] https://astronomers.skatelescope.org/the-ska-regional-centres/
[40] www.aeneas2020.eu/
[41] www.geant.org/
[42] www.egi.eu/
[43] www.euro-vo.org/
[44] www.rd-alliance.org/
[45] www.jive.nl/

Italy plays an important role in the AENEAS project. In addition to being responsible for WP5, thanks to the experience gathered in more than 10 years of activity by the Italian node of the *European ALMA Regional Center*[46], the INAF participates in all the main activities, with around 14 units of personnel from 3 Structures, and a total budget of 280 kEur over 3 years. These activities include all the elements needed to develop a distributed data center: from calculation of the computing and processing requirements (WP3), to data transfer (WP4), user interfaces and support (WP5), interaction in a Clouds environment and data access policies (WP6).

The challenges presented by the scale, rate, and complexity of data that the SKA will generate provide an exciting opportunity for modern e-infrastructure providers and require to re-assess current models of data management, computing, and networking. Similar challenges, however, are shared by other major research facilities. Recognizing the increasing demands of data-driven research, Europe is supporting a number of projects, aimed at facilitating the development of next-generation European e-infrastructures (see table below). Italy (and INAF) is involved in all of them, sometimes with leading roles.

EU-funded projects for research e-infrastructures

Project	**Aim**
ESCAPE[47] European Science Cluster of Astronomy & Particle physics ESFRI research infrastructures	ESCAPE intends to address the Open Science challenges shared by ESFRI facilities (CTA, ELT, EST, FAIR, HL-LHC, KM3NeT, SKA) as well as other pan-European research infrastructures (CERN, ESO, JIV-ERIC, EGO-Virgo) in astronomy and particle physics research domains
EOSCPilot[48] The EOSCpilot project will support the first phase in the development of the European Open Science Cloud (EOSC)	EOSC is a cloud for research data in Europe allowing for universal access to data through a single online platform. EOSC will federate existing resources across national data centres, e-infrastructures and research infrastructures
Exanest[49] European Exascale System Interconnect and Storage	Exanest develops and prototypes solutions for some of the crucial problems (interconnection networks, storage and cooling) on the way towards production of Exascale-level supercomputers
EUROEXA[50]	EuroEXA targets to provide the template for an upcoming exascale system by co-designing and implementing a petascale-level prototype with ground-breaking characteristics.

10.1 Prospects for an Italian SKA Regional Center

The structure of the SKA Regional Centres is still to be defined. This is the main task of the recently appointed SKA Regional Centre Steering Committee (SRCSC), in which Italy has a seat

[46] www.eso.org/sci/facilities/alma/arc.html
[47] escape2020.eu/wp_escape.html
[48] www.eoscpilot.eu/
[49] www.exanest.eu/
[50] euroexa.eu/index.html

for its own representative. In particular, the mission of the SRCSC is "*to define and create a long-term operational partnership between the SKA Observatory and an ensemble of independently-resourced SKA Regional Centres*". In the longer term, the SRCSC will be superseded by the operational partnership that will be formed as a result of its work.

In this context, the results of the aforementioned European (i.e. the AENEAS) design study, that will be finalized by the end of 2019, will represent a relevant starting point for a larger planetary planning. For instance, it will be important a detailed analysis of the pros and cons of having an European centralized SKA Regional Centre, with few poles located in various European Countries.

Under the working hypothesis that the global SRC network in its steady fully operational regime i) requires approximately 1 Exabyte of storage (per year) and some tens of PFlops of computing power, ii) is based on a handful of SRCs spread over the world, and iii) relies on an European SRC with poles distributed in 4-5 countries, we can infer the requirements that Italy - and INAF in particular - needs to fulfill to be able to play an active role in the SKA e-infrastructure. We estimate that the Italian pole should have the capacity to host, at regime, about few tens of PB of storage (per year), a computing power of some PFlop, and at least 100 Gbps networks. In addition, expert staff is needed, for the management and development of both IT infrastructures (i.e. archival and software), as well as of data reduction and analysis software. All of the above is predicted to be necessary over an approximate decade timescale.

An overview of the IT resources and services currently available to research and academic institutions in Italy is provided below (2019):

<u>HPC:</u>

- **CINECA**: Italian super-computing centre offering a HPC peta-scale computing facility: ~25 PFlops
- **SISSA:** "Ulysses" cluster with about 7000 Cores for scientific computing
- **ENEA:** CRESCO Cluster with about 5000 Cores dedicated to scientific computing
- **INFN**: more than 30.000 cores and 20 PB storage dedicated to INFN activities

<u>Network:</u>

- **GARR**: national infrastructure - backbone: 400 Gbps (up to 1 Tbps soon)
- **INAF** Structures on 10 Gbps at the moment:
    - VLBI Antennas (SRT, Mc, Nt)
    - OATrieste
    - OA Cagliari, IRA (Bologna), OA Catania (upgrading to 10 Gbps)

<u>HTC & Cloud:</u>

- **Italian Computing and Data Infrastructure**, including all major institutions involved in HTC, HPC and Cloud computing, i.e. **INAF, INFN, CNR, ENEA, CINECA, GARR**

- **GARR Cloud,** offering cloud services to the Italian academic and research community based on open standards
- **INFN** distributed computing infrastructure for HTC and Cloud built for high-energy physics experiments (LHC) with a main node (TIER-1) in Bologna

The overall computing and archiving resources currently available to INAF scientists are as follows (2019):

- INAF distributed HPC/HTC infrastructure involving different INAF structures, overall offering the following resources: ~25 TFlops (processing); ~500 TB (storage)
- INAF-CINECA MoU, offering HPC resources for Astronomers
- Cagliari HTC-HPC and storage system: 12+ nodes dualCPU-dualGPU, with about 3 PB of storage capabilities (under development) .
- LOFAR.IT distributed infrastructure based on 4 sites in Italy, offering HTC resources for LOFAR data reduction and analysis[51]
- INAF cloud service, offering a EOSC compatible cloud access to computing and storage resources based on OpenStack
- INAF archive/storage:
    - IA2 data center: 0.5 PB on disk + 8 PB on tape
    - SRT data center: 2.5 PB on disk + 8 PB on tape
    - >3 PB on disk shared across several structures and project

Particularly relevant INAF projects towards the development of a SKA e-infrastructure are the *Italian Center for Astronomical Archives* (IA2[52]) and SRT data centers, which provide archival resources for the facilities managed by INAF (IA2 also hosts the datasets of the first *SKA Data Challenge*[53]). In addition to IA2 archiving resources, INAF makes available *Tier2/Tier3* computing resources, through the CHIPP[54] project, and computing time at CINECA[55], through ad hoc INAF-CINECA agreements, for initial tests finalized to the development of SKA-related ICT expertise and capabilities. Worth mentioning are also the ongoing INAF *Virtual Observatory* activities in the context of the *International Virtual Observatory Alliance* (IVOA[56]).

The LOFAR-IT initiative goes a step beyond, and represents a first attempt to develop a stand-alone distributed infrastructure for low-frequency data reduction and analysis. Actions towards the mid-frequency SKA precursors are also ongoing. INAF is currently involved in a number of bilateral activities with Australia and South Africa, aimed at improving the existing data reduction pipelines for ASKAP and MeerKAT[57], as well as testing and developing federated

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[51] For more details we refer to: www.lofar.inaf.it/index.php/analisi-dati/calcolo
[52] www.ia2.inaf.it/
[53] astronomers.skatelescope.org/ska-science-data-challenge-1/
[54] www.ict.inaf.it/computing/chipp/
[55] www.cineca.it/
[56] www.ivoa.net
[57] INAF is involved in the parallelization of the codes for both ASKAP and MeerKAT (and LOFAR through the LOFAR-IT initiative), as well as in the development and optimization of source finding and visualization tools

cloud and data exchange systems, targeted to scientific use, using data acquired through the SKA precursors located in these countries. Transfer testing activities from Australia have already enabled more than 100 TB of *Murchison Wide-field Array* (MWA[58]) data to be moved to the IA2 center in Trieste. There are also ongoing discussions regarding the possibility to mirror the ASKAP data reduction pipeline in Italy, in collaboration with CINECA.

In the second quarter of 2019 a new opportunity developed rapidly: the possibility to establish an INAF *computing facility* at the *Tecnopolo*[59] in Bologna. The SRC will be hosted there[60] and will be an important part of this infrastructure. This initiative will be developed in close synergy with the participation to the SUPER and European HPC projects (that will also involve the main partners of *Tecnopolo*: CINECA and INFN in primis). For INAF, this could result in a possible HW investment plan for a total capital of around €12 million over the next 10 years.

This scenario offers a realistic opportunity to develop either a stand-alone Italian SRC or a very relevant pole of a European SRC.

More in general, the creation of an INAF computing facility provides an excellent opportunity to maintain the INAF expertise (and in several cases leadership) in a number of e-technologies related with an efficient operation of HPC, HTC and archive systems for large astronomical data, but requires a strong coordination inside and outside the SKA project: it is important to bring together and efficiently exploit the experience acquired and being acquired as part of the various ongoing projects requiring large IT resources, as quickly as possible.

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[58] www.mwatelescope.org/

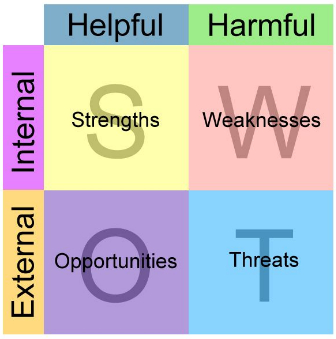
[59] The *Tecnopolo* in Bologna will host a new super-computing infrastructure, funded through the EC *EuroHpc Joint Undertaking* project. This facility will be partly supported by the MIUR and by *Regione Emilia Romagna* (through the SUPER project), and includes as main partners CINECA and INFN.

[60] The President of INAF and the INAF Council have deliberated, as the first of a number of general guidelines for investment based on SKA related funding, the creation - in the context of the Bologna *Tecnopolo* - of an INAF e-infrustructure able to serve the needs of the SKA, via setting up some kind of partnership with INFN and CINECA (the terms of which will be the subject of specific agreements).

PART III - Towards an Italian SKA Roadmap

The national SKA-related activities, extensively discussed in Part II of this document, can be distilled in a list of points highlighting the strengths and weaknesses of the Italian participation to the project, as well as the opportunities or threats that Italy can seize or face (SWOT analysis).

11. SWOT Analysis



Strengths

- Expertise in low frequency technology (LFAA antenna and receiving chain)
- Expertise in monitoring and control system softwares and TANGO framework
- Expertise in *Graphical User Interfaces* and *Authorization, Authentication and Auditing* systems
- Expertise in high-frequency (>5 GHz) PAF components technology
- Membership in the EVN (SKA-VLBI pathfinder)
- Membership in the International LOFAR Telescope (SKA-LOW pathfinder)
- Scientific leadership in precursor/pathfinders legacy surveys
- Involvement (and leadership) in various SKA-related research projects
- Expertise in interferometry and VLBI techniques
- Long-standing expertise in radio-continuum surveys and polarization/Faraday rotation techniques
- Wide community interest in exploiting multi-facility synergies in galactic, extra-galactic and multi-messenger (SKA-related) science
- Membership or scientific agreements for most of the major 21st century facilities, presenting synergies with the SKA (ALMA, Euclid, ELT, LSST, Athena, CTA, VIRGO, etc.)
- Expertise in science data handling, publication and preservation
- Expertise in computing coding management and optimization
- Long-standing experience in user support activities through Italian participation to the ALMA Regional Center European network

Weaknesses

- Few responsibility roles compared to the technological effort and competences put into the SKA project
- Inadequate administrative support for large industrial bids in view of in kind contribution
- No institutional involvement in the two mid-frequency precursors (ASKAP and MeerKAT)
- Little expertise in HI and EoR techniques

- No involvement in the *Science Data Processor* (SDP) SKA consortium, the SKA design consortium responsible for the definition of the SKA data processing requirements
- Existing e-infrastructures not adequate to SKA data center requirements

Opportunities

- Exploit the successful SKALA4-Al antenna design produced by the LFAA team to get the Italian design the reference baseline for SKA1-LOW
- Exploit the excellent work done by INAF consortia in Local Monitor and Control design activities to get an Italian leadership in the construction phase
- Exploit involvement in LOFAR to increase scientific involvement in SKA pathfinders, as well as skills in low-frequency data reduction and analysis techniques
- Exploit obvious synergies (e.g. with ALMA) to enlarge the number of interferometry data reduction experts (at higher frequency)
- Exploit involvement in EVN, VLBI expertise, and strategic location of Italian antennas to establish institutional collaborations with South Africa (towards both MeerKAT and AVN)
- Build on technological involvement in high frequency PAF technology and existing strong mm/sub-mm community to develop an ad hoc Italian PAF science case
- Build on strong INAF expertise in redshift surveys to increase the community interests and expertise in HI surveys
- Exploit multi-facility synergies to increase the community interests around SKA science cases, strengthening the Italian community in view of the definition of the SKA Key projects
- Build on existing and under development IT and user support expertise, activities and e-infrastructures to grow into a national SKA Regional data center

Threats

- Italian man power may not reach critical mass to get a leadership in LMC software development during construction
- Italian leadership may be at risk in some scientific areas (see HI and EoR weaknesses)
- Italian leadership may be at risk in SKA-MID science
- INAF may not get the data handling capabilities and expertise required to get leadership of SKA Key-Projects

12. Conclusions and Recommendations

Following a careful analysis of the current Italian participation in the SKA project, as described in Part II of this document and in the SWOT analysis, a number of initial considerations and recommendations can be made, that we believe can foster the growth and visibility of INAF and Italy in the SKA project.

It is important to stress that our recommendations take due account of the results of the open discussion held at the *II National Workshop of SKA Science and Technology* (December 3-5, 2018), whose scope was: a) to provide an opportunity for a general informal discussion of the

SKA project from an Italian perspective; and b) to gather input from the wider community on the measures that the *Board* was considering in preparation of this document.

The recommendations outlined below intend to provide general guidelines, and will be transformed into specific actions to be proposed to the INAF management. Some of them, that we considered more urgent, have indeed already gone through this process, producing an initial set of initiatives, that we report in Appendix D.

12.1 Recommendations

1. It is important to get prepared to the scientific exploitation of the SKA, either by getting involved in observational projects for existing and/or forthcoming radio facilities (pathfinders and precursors), or through simulation/theoretical forecasting work. Also important is the exploration of possible synergies with existing and forthcoming facilities working in different wavebands. All this is essential preparatory work in view of proposing Italy-led *SKA Key Science Projects,* and/or getting leadership roles in international *SKA Key Science Projects*. Dissemination talks informing on the scientific opportunities offered by the SKA and its precursors should be given at national workshops and conferences, to enlarge the pool of researchers potentially interested in the SKA.
2. An adequate level of funding of SKA-related activities is strategic in preparation to the SKA *Science Key-Projects*. Various forms of funding were discussed: from PRINs to national calls for a number of SKA-targeted PhD/post-doc positions; from dedicated funding for medium/long-term exchange visits with the SKA host countries (Australia and South Africa) and the SKA Headquarters (UK). Ideally a mix of all the aforementioned opportunities should be offered, in order to satisfy different needs. Some of the discussed forms of funding (visit exchanges, dedicated PhD/post-doc positions) would fit very well in the context of SKA-focused bilateral agreements. Considering that the next 5 years will be critical for both the scientific exploitation of the SKA precursors and the preparation of SKA Science key project, it is of paramount importance that funding to support SKA-related science projects are made available on a regular basis and guaranteed over the years. We judge that the investment in SKA-related postdoc positions should be of the order of three per year. Three-year positions would ensure the possibility of attracting the best talents from abroad.
3. SKA precursors represent a unique opportunity to strengthen the technical expertise of Italian researchers. The current efforts to facilitate LOFAR data processing in Italy, as well as the active involvement in the development and optimization of LOFAR pipelines, will likely play an important role in view of SKA-LOW surveys. Similar efforts should be made towards the two SKA-MID precursors (ASKAP and MeerKAT). As highlighted at the *II National Workshop of SKA Science and Technology*, several Italian groups are actively contributing to data processing and pipeline development efforts in the framework of ASKAP and MeerKAT legacy surveys. This high level of participation is encouraging, but a coordinated approach is essential to avoid duplication of effort and to optimize the use of (the limited) resources. In addition it would guarantee data processing capability

access and support to a wider community. The ASKAP and MeerKAT legacy surveys are starting now and this is the time when international teams are seeking resources (man power, storage and processing power). This is therefore a critical time for INAF to take action and better organize the Italian engagement in ASKAP and MeerKAT. In addition to adequate data reduction and analysis support, other forms of involvement should be explored, possibly by a dedicated working group, under the coordination of the SKA mid frequency precursors UTG-II advisor.

4. A number of other measures can be taken to support the involvement of the Italian community in SKA-related science. It is suggested that schools/data tutorial are organized, so as to allow a broader community to obtain real experience with radio interferometric data (specifically for LOFAR, ASKAP and MeerKAT). These initiatives should be coordinated at national level, and should exploit as much as possible the existing expertise and man power (e.g. LOFAR-IT, ALMA Regional Center, IA2, ICT). Other envisaged SKA-related initiatives include a) the exploitation of the SKA Data Challenges and b) a programme of seminars at the various INAF structures. In addition it would be useful to get INAF personnel actively involved in the post-SDP bridging activities.
5. While the afore-mentioned measures (see items 3 and 4) can be seen as initial steps towards an active development of SKA-specific data handling skills, more demanding steps are required to build a national SRC (see Tecnopolo initiative). These include developing synergies with large computing centers, such as the CINECA, and creating close coordination within INAF so that the Italian SRC becomes a sustainable structure either from a hardware or a software point of view. Given the implied investments in budget and manpower, the Italian SRC should serve as an accumulation point for the INAF e-infrastructure activities. This is another area where dedicated working groups are envisaged, to provide in-depth feasibility studies.
6. INAF is currently involved in a number of EU-funded IT projects, that are essential to build the capabilities to support data-driven research with next-generation facilities, as well as in the AENEAS project, aimed at developing a science-driven, functional design for a SKA distributed and federated European Science Regional Center. Other projects will be proposed in the Horizon 2020 framework for the next future, and INAF should be ready to catch these opportunities.
7. There is a need to update the *Italian SKA White Book*, published in 2014, considering the major discoveries/advances of the last years (e.g. gravitational waves, multi-messenger science, etc.), in which the Italian community is strongly involved. The feeling is that we should not produce a new version of the *White Book,* but rather a short document briefly summarizing the state of the art of SKA-related science, including those science cases that are missing in the White Book.
8. A brief discussion of synergies has been included in the present *Roadmap* document, but it would be useful to expand it in a brief document dedicated to science synergies, reflecting Italian scientific interests and focusing on facilities of major interest for INAF. Both the updated science and the synergy documents could be *addenda* of the *Roadmap* document.

9. There is a clear opportunity for developing an Italian science case for SKA Band 5 (approximately covering the frequency range 5-15 GHz, but possibly extending up to 25 or even 50 GHz). Band 5 is of major interest for science areas, where strong synergies with ALMA and/or CMB experiments exist. In addition, Band 5 surveys with SKA would largely benefit from the deployment of Phased Array Feeds (PAF), and INAF is involved in the development of PAF as part of the SKA Advanced Instrumentation Programme.
10. It may be useful to create one or more national *SKA Focus Groups*, but only if clear *Terms of Reference* can be identified. As an example such Group(s) could be responsible for (or assist the *Board* in) updating the science and synergy cases, as well as in developing the Band 5 science case (see items 7, 8 and 9). One single *Focus Group* may facilitate the exchange of information among different scientific communities and facilitate cross-fertilization.
11. This is a critical time for the technological side of the SKA project: most of the SKA design consortia have closed their activities, and a new phase, called *Bridging*, has started, which will lead to the definition of the final technologies for the construction of SKA1 and tender calls. In this new phase a different model has been adopted by SKA Office (SKAO), where international consortia are substituted by teams directly managed by SKAO. This means that INAF/Italian staff previously working on similar tasks (see e.g. Local Monitor and Control) in the framework of different design consortia, could now work together as part of the same team. It is strategic for the bridging phase that this process is encouraged as much as possible, so as to reach the critical mass to form national teams. More in general it is essential that the Italian R&D activities are adequately supported and defended by INAF, in order to maximize the visibility of INAF in the SKA project and its ability to compete successfully at the international level.
12. The main reason behind the recently started SKA-LOW bridging activities is the need to investigate the calibratability of the station reference design of log-periodic antennas. A mitigation solution would be the deployment of MWA-like dipoles (Australian design) instead of log-periodic antennas (It/UK designs). While INAF should be ready to exploit any final architecture adopted, this would admittedly have a strong impact on the breadth of science that SKA-LOW can deliver, since MWA-like dipoles can efficiently work only in the lower part of the frequency range allowed by log-periodic antennas. It is therefore strategic to have Italian experts in the calibration team, and enough man-power, to be able to fully evaluate the calibratability of log-periodic vs MWA-dipole antennas.
13. Several industrial partners have been involved in SKA-related R&D activities in the framework of the SKA pre-construction activities. In view of the SKA construction it is important to advertise SKA opportunities to industries as widely as possible. This can be done through the organization of industrial days and/or other initiatives, as judged best by INAF dedicated offices. An early involvement of industries in engineering and system industrialization activities will facilitate the development of ad hoc expertise, building on past activities carried out in the framework of other related projects. To be effective, this has to be done well in advance with respect to coming tender calls. Considering that

the SKA construction proposal is now planned to be ready for Q4 2020, such initiatives should be planned very timely.

Appendices

Appendix A: Italian Representatives and Leaderships in SKA

Below a list of the Italian representatives in SKA advisory committees and governing bodies, as well as Italian scientists and engineers playing leading/coordinating roles in SKA-related scientific and technical activities, either at national or international level.

Italian representatives in SKA Organization Committees[61]

Committee	Italian Representative	Affiliation
Board of Directors	Prof. N. D'Amico (voting) Dr. F. Zerbi	INAF INAF
Science & Engineering Advisory Committee (SEAC)	Prof. A. Ferrara (chair) Dr. G. Pareschi	SNS INAF
Strategy and Business Development Committee (StratCom)	Dr. L. Valenziano	INAF
Finance Committee	Mr. F. Iannaccone	MEF
SKA Regional Center Steering Committee (SRCSC)	Dr. A. Possenti	INAF
Council PreparationTask Force (CPTF)	Prof. N. D'Amico	INAF, Univ. Cagliari
Joint Working Group for Transition (JWGT)	Dr. F. Zerbi	INAF

Italian SKA Board

Member	Role	Responsibility	Member	Role	Responsibility
Dr. I. Prandoni	chair	UTG-II Advisor for the SKA; Chairship Science WG	Dr. J. Monari	member	LFAA Design & Bridging Coordinator
Dr. D. Fierro	Deputy chair	Pre-construction Coordination; Head of INAF DS Section-C	Dr. A. Navarrini	member	PAF AIP Design Coordinator
Dr. G. Bernardi	member	Chairship Science WG	Dr. A. Possenti	member	UTG-II Advisor for Big Data; Chairship Science WG
Dr. G. Brunetti	member	UTG-II Advisor for SKA low-frequency precursors; chair of LOFAR-IT	Dr. R. Smareglia	member	Head of INAF ICT and Science Data Management
Dr. R. Cassano	member	Chairship Science WG	Dr. C. Trigilio	member	Dish Design Coordinator
Dr. G. Comoretto	member	CSP Design Coordinator	Dr. G. Umana	member	UTG-II Advisor for SKA mid-frequency precursors; Chairship Science WG; Chairship Board Dish
Dr. M. Dolci	member	SW Bridging Coordinator	Dr. T. Venturi	member	UTG-II Advisor for VLBI

[61] Updated lists of SKA committees' membership are maintained at the SKA website (see *Contacts* link).

Leadership roles in SKA Design Consortia and AIP

Design Consortium/AIP	Italian Member	Leadership Role
LFAA	J Monari	Receiver WP Leader
Dish	C. Trigilio	LMC Task Leader
TM	R. Smareglia	LMC Task Leader
PAF AIP	A Navarrini	National Coordinator

Leadership roles in SKA Bridging

Bridging Activity	Italian Member	Leadership Role
All Activities	I Prandoni	INAF Reference person
LFAA	J Monari	National Coordinator
SW Development	M. Dolci	National Coordinator

International Science Working Groups and Focus Groups - Italian Leadership roles[62]

#	SKA Working/Focus Group	Chairships	Core/Tier 1 memberships
1	Solar, Heliospheric & Ionospheric Physics		
2	Our galaxy	G Umana (INAF-OACt)	C. Trigilio (INAF-OACt)
3	Cradle of Life		
4	Pulsars & Gravity	A Possenti (INAF-OACa) (2015-17)	A Possenti (INAF-OACa)
5	Transients		
6	HI in galaxies		
7	Continuum extra-galactic science (AGN/galaxies, galaxy clusters)	R Cassano (INAF-IRA) (2015-17) I Prandoni (INAF-IRA) (2013-15)	R Cassano (INAF-IRA) I Prandoni (INAF-IRA)
8	Extragalactic line (non-HI) science		
9	Magnetism	F. Govoni (INAF-OACa) (2013-15)	A Bonafede (UniBo) L Feretti (INAF-IRA) G Giovannini (UniBo) F Govoni (INAF-OACa) V Vacca (INAF-OACa)
10	Cosmology		S Camera (UniTo)

[62] An updated list of Science WG and Focus Groups members is maintained at the SKA telescope website: https://astronomers.skatelescope.org/science-working-groups/

11	Epoch of Reionization	G Bernardi (INAF-IRA)	
12	VLBI		G Giovannini (UniBo) M Giroletti (INAF-IRA) M Orienti (INAF-IRA) F Panessa (INAF-IAPS) T. Venturi (INAF-IRA)
13	High-energy cosmic particles (Focus)		

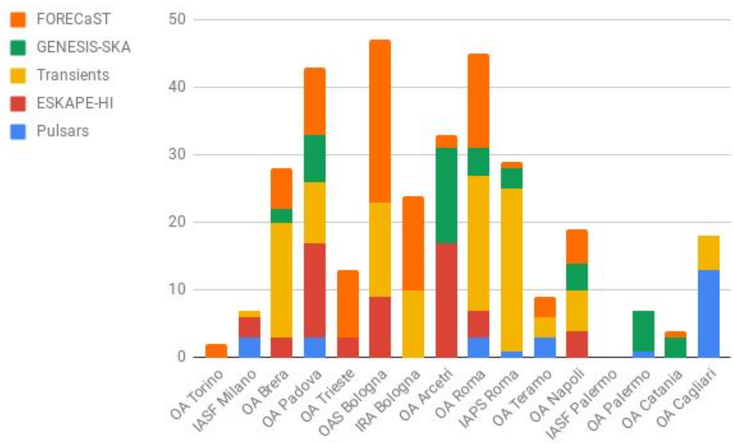
Appendix B: SKA/CTA PRIN

In 2016, through a competitive call for tenders (Bando PRIN SKA-CTA), INAF dedicated a budget of about 3 Million Euros to support scientific projects related to SKA and / or CTA. Seven projects were financed in 2017. Two of these projects were entirely related to CTA, while four projects were entirely related to SKA and one to both SKA and CTA (see the table below).

Summary of funded SKA/CTA Projects

Title of the project	**PI of the project**	**Instrument**	**Budget (Euro)**
ASTRI/CTA Data Challenge	P. Caraveo	CTA	**679.830**
Opening a new era in pulsars and compact objects with MeerKat	A. Possenti	SKA	**306.000**
Empowering SKA as a Probe of galaxy Evolution with HI (ESKAPE-HI)	L.K. Hunt	SKA	**410.823**
Towards the SKA and CTA era: discovery, localisation, and physics of transient sources	M. Giroletti	SKA and CTA	**480.000**
GEneral conNditions in Early planetary Systems for the rISe of life with SKA (GENESIS-SKA)	C. Codella	SKA	**480.000**
FORmation and Evolution of Cosmic STructures (FORECaST) with Future Radio Surveys	I. Prandoni	SKA	**320.000**
Probing particle acceleration and γ-ray propagation with CTA and its precursors	F. Tavecchio	CTA	**320.000**
Total			**2.996.653**

The following histogram illustrates, for the financed SKA projects, the distribution of researchers among the INAF Structures. Although the graph contains some repetitions (since some researchers are involved in two proposals) it is evident the involvement of several INAF Institutes.



In the following we briefly describe the financed projects related to the SKA:

Opening a new era in pulsars and compact objects science with MeerKat

The goal of this project is to exploit two MeerKat Key Science Projects (KSPs) focused on pulsar Timing (dubbed MeerTime) and on pulsar Searching (dubbed Trapum). These KSPs have been already approved to use a few thousands of hours of telescope time over the next few years. MeerTime and Trapum will open a new era not only in addressing key and long-lasting questions of fundamental physics and astrophysics (all of them also being drivers for the scientific cases of SKA), but also because they will explore and finally use completely new methodologies, which will be later transferred to the future SKA experiments.

Empowering SKA as a Probe of galaxy Evolution with HI (ESKAPE-HI)

Galaxies are assembled over cosmic time through the conversion of the available gas reservoir to stars. As atomic gas (HI) is the main constituent of this gas reservoir in galaxies, the origin of HI and its ultimate fate are intimately linked with galaxy evolution; understanding this link is one of the main science drivers of SKA. The goal of ESKAPE-HI is to build up all that is needed for an effective scientific exploitation of SKA for our understanding of the role of Hi in driving galaxy evolution up to redshift ~ 2, the "cosmic high-noon".

Towards the SKA and CTA era: discovery, localisation, and physics of transient sources

The goal of this project is to maximise the science return from the participation of INAF to SKA and CTA consortia in the following areas: understanding the physics of known transients, discovering and recognising new classes of transients, and exploiting transients as probes of the Universe both locally and at high redshift. This investigation covers a large range of approaches: theory, observations, data analysis and technology.

GEneral conNditions in Early planetary Systems for the rISe of life with SKA (GENESIS-SKA)

The recipe to make a habitable planet like our own Earth requires a relatively small rocky planet, at the right distance from the host star, with a not too thick atmosphere rich in volatiles and capable of developing complex organic chemistry. The goal of the GENESIS-SKA project, is to study dust evolution, planet formation, and pre-biotic chemical complexity in the context of preparation of SKA Key Programmes. The project is featuring synergies between astronomical observational and modeling efforts, laboratory experiments, and quantum-chemical computations. The SKA telescope will permit to study in detail the evolution of dust as it evolves into planetesimals and rocky planets and to detect heavy complex organic molecules that today are beyond the reach of our observing capabilities.

FORmation and Evolution of Cosmic STructures (FORECaST) with Future Radio Surveys

This project is organized around three broad, strongly interconnected research fields that are unanimously recognized as key drivers for next-generation extragalactic radio-continuum surveys. These are: the epoch of reionization, galaxy formation and evolution, cosmology. This project represents the first coordinated attempt to combine the existing theoretical, observational, and technical expertise, to build a strong cosmology/extra-galactic SKA community in Italy. It paves the road to a full exploitation of unprecedented scientific opportunities offered by the SKA and its precursors.

Appendix C: Examples of synergic use of the SKA and other major facilities

We provide here a description of existing scientific synergies between the SKA and other major facilities that will be operational in the next decades. For brevity we limit our analysis to the following telescopes: ALMA and JWST (IR/mm); EUCLID, ELT, LSST (optical/NIR); Athena, CTA (high-energy); LIGO/VIRGO (GW detector). Special focus is given to science themes that are of major interest for the Italian community, as illustrated in the INAF *Strategic Vision* Document (2019), and/or presented at the Synergy Session of the *II National Workshop of SKA Science and Technology* (3-5 Decembre, 2018).

ALMA

The *Atacama Large Millimeter/submillimeter Array* (ALMA[63]) is the largest (sub-)mm infrastructure ever constructed (66 antennas which can be configured to achieve baselines up to 16 km). ALMA is a very flexible observatory supporting a vast range of scientific areas.

ALMA and SKA have a complementary frequency coverage, and trace complementary physical processes and/or components. ALMA traces the cold atomic and molecular gas and dust while SKA will essentially probe both the free-free thermal and the non-thermal synchrotron emission. The high spatial resolution provided by both ALMA and SKA will allow a punctual, spatial comparison between these components, providing information about the contribution due to higher energy phenomena associated to magnetic fields, cosmic rays and accretion processes. As an example, for studies of star formation, ALMA observations trace how cold dust and gas is assembled on the small scales, within a molecular cloud, and how disks around young stars are formed. SKA will be essential for complementing these studies by tracing the higher energy phenomena associated with the accretion of this material on to the star, probing the stellar and disk magnetospheres, and the ionising feedback from outflows and stellar winds.

Other significant synergies between the two instruments are:

A. Complete coverage of the full range of molecular transitions and star-formation tracers to gather a complete picture of the physical environments in protoplanetary disks around young stars;
B. Synergical observations to study solids grown to pebble sizes in protoplanetary disks. SKA observations will be able to detect and resolve spatially the wind emission from the disk/star, which needs to be carefully accounted for and removed to study the dust properties;
C. Synergical observations to characterize different molecular species in statistically significant samples of galaxies and for a wide range of redshifts.
D. Complementary information on the molecular gas (ALMA) and photoionized gas flow (SKA) in protoplanetary disk around young stars;

[63] www.almaobservatory.org

E. Complementary information on AGN and star formation activity from the synchrotron and free-free components (SKA) and on dense molecular clouds and warm dust heated by star formation (ALMA).

ATHENA

The *Advanced Telescope for High ENergy Astrophysics* (Athena[64]) is the X-ray observatory large mission selected by the ESA, within its Cosmic Vision 2015-2025 programme, to address the Hot and Energetic Universe scientific theme, and it is provisionally due for launch in early 2030's. Athena will have three key elements to its scientific payload: an X-ray telescope with a focal length of 12 m and two instruments: a Wide Field Imager (Athena /WFI) for high count rate, moderate resolution spectroscopy over a large field of view (FoV) and an X-ray Integral Field Unit (Athena /X-IFU) for high-spectral resolution imaging.

The *Athena* Science Study Team (ASST) and the Square Kilometre Array (SKA) Organisation agreed to undertake an exercise to identify and develop potential synergies between both large observatories. The coordination of this exercise was assigned to the *SKA-Athena Synergy Team (SAST[65]),* who produced the *SKA-Athena Synergy White Paper[66],* in close collaboration with experts of the astrophysical community. The *White Paper* is intended to be an open access resource offered to the astronomical community to promote and foster a combined exploitation of *Athena* and SKA in early 2030. It describes in detail a number of scientific opportunities that will be opened up by the combination of *Athena* and SKA observations in a great variety of scientific areas, covering the following main topics:

A. Tracing the history of cosmic structures thanks to SKA and Athena surveys.
B. Understanding the feedback of active galactic nuclei in galaxy clusters.
C. Studying non-thermal phenomena in galaxy clusters.
D. Detecting both thermal and non-thermal emission of the cosmic web, to constrain its unknown physical conditions
E. Unravelling the physics behind extreme accretion conditions in neutron stars and black holes
F. Comprehending the nature of and mechanisms behind many Galactic objects (e.g. young stellar objects, ultracool dwarfs, star-planet magnetic interaction, massive stars, pulsars and supernova remnants).

CTA

The *Cherenkov Telescope Array* (CTA[67]) is a gamma-ray observatory, designed to investigate the very high-energy emission from a large variety of celestial sources, in the 20 GeV – 300 TeV energy range. Full-sky coverage is guaranteed by two distinct arrays, one located in La Palma (Canary Islands) and the other at Paranal (Chili). Wider field of view, improved sensitivity and higher sensitivities will enable the CTA to map the sky hundreds of times faster than previous

[64] www.the-athena-x-ray-observatory.eu/
[65] SAST: R. Cassano, R. Fender, C. Ferrari and A. Merloni
[66] The *SKA-Athena Synergy White Paper*, published on July 24th, 2018, is available on arXiv
[67] www.cta-observatory.org/

TeV telescopes, allowing detailed imaging of a large number of gamma-ray sources, probing much larger distances in the Universe, and to perform population studies and accurate variability and spatially-resolved studies. CTA will address a wide range of major questions in astrophysic, focusing on the mechanisms of cosmic acceleration and the physical processes in extreme environments (close to neutron stars and black holes). It will also explore the frontiers of physics, beyond the standard model (nature of dark matter).

The combination of CTA and SKA will bring significant insight into the physics of non-thermal sources of the Universe. The SKA will probe the non-thermal universe via synchrotron emission from relativistic electrons. Such emission provide fundamental clues of particle acceleration mechanisms, due to the inferred presence of magnetic fields and the presence of relativistic electrons, either directly accelerated or produced as secondaries. In addition, dark matter annihilation scenarios usually lead to the production of synchrotron-emitting secondaries along with gamma-ray emission. The SKA, with its unprecedented angular resolution, will allow precise localisation of acceleration zones, while the combination of radio measurements with those at very high energies can provide limits on the electron density independently of assumptions about magnetic field strengths, and can help to determine which of several competing non-thermal processes dominate at the highest energies.

Some examples of significant synergies between the two instruments are:

A. synergical SKA and CTA observations will allow to understanding the physics of known transients, discovering and recognising new classes of transients, and exploiting transients as probes of the Universe both locally and at high redshift.
B. observations in the two energy domains will deeply enhance our understanding of global energetic and processes of particle acceleration and cooling in radio-loud AGNs, providing news clues of the observed strong but not trivial correlation between powerful emission in the radio and the very high energy (VHE) gamma-rays. Combining SKA and CTA results should solve the long-standing issue of unification scenarios of extragalactic radio sources.
C. the superb sensitivity of SKA, in combination with the use of high-energy facilities, should allow us to better study and constrain different physical processes in a variety of interesting Galactic objects, from pulsars, PWN and supernova remnants. SKA will increase by a large number the detected pulsar population, while CTA is expected to provide a spectral gamma-ray characterisation of several pulsars and enhance their multi-wavelength emission models. SNRs are the most interesting Galactic sources that can be studied simultaneously with the SKA and the CTA. Although the hypothesis that SNRs are by far the main contributor of Galactic cosmic rays has gained an enormous consensus among the scientific community, a conclusive evidence still lacks. The two observatories will provide complementary information on the local conditions in and around the remnant, and provide us with insights on the fundamental phenomena resulting in particle acceleration.
D. the sensitivity of CTA would allow to reveal a large number of weak and/or transient sources, to be identified through careful studies conducted at other wavelengths such as

radio. When searching for faint gamma-ray sources counterpart, pure positional coincidences are not significant enough and additional physical criteria are needed, such as radio spectral index, variability, polarization, or compactness, requiring high angular resolution. Thus, detailed studies with SKA will tremendously improve our capability to identify the counterparts large populations of unidentified gamma-ray sources.

ELT

The *Extremely Large Telescope* (ELT[68]) is a revolutionary new ground-based telescope concept that will have a 39-metre main mirror and will be the largest optical/near-infrared telescope in the world. The ELT will tackle the biggest scientific challenges of our time, including tracking down Earth-like planets around other stars in the "habitable zones" where life could exist. It will also perform "stellar archaeology" in nearby galaxies, as well as make fundamental contributions to cosmology by measuring the properties of the first stars and galaxies and probing the nature of dark matter and dark energy.

One notable example where the combination of ELT and SKA is particularly relevant is the study of the epoch of reionization. The end of the so called dark ages will be explored by SKA which will produce high resolution maps of the sky at 21cm, thus giving us key information on the time and spatial evolution of the neutral hydrogen content at the earliest epochs. However only by studying both reionization and the galaxies responsible for the ionizing photons we will be able to fully understand this process. The ELT will give us key information on this early galaxy and black hole population.

EUCLID

Euclid[69] is an European Space Agency (ESA) medium-class space mission, planned to be launched in 2022. The Euclid mission aims at understanding why the expansion of the Universe is accelerating and what is the nature of the source responsible for this acceleration, referred to as dark energy. Euclid will explore how the Universe evolved over the past 10 billion years (the period over which dark energy played a significant role in accelerating the expansion), and will address questions related to fundamental physics and cosmology on the nature and properties of dark energy, dark matter and gravity. The imprints of dark energy and gravity will be tracked by using two complementary cosmological probes to capture signatures of the expansion rate of the Universe and the growth of cosmic structures: Weak gravitational Lensing and Galaxy Clustering (Baryonic Acoustic Oscillations and Redshift Space Distortion).

SKA HI galaxy and intensity mapping surveys will provide complementary constraints, especially at low redshifts and on the largest scales. Combining Euclid and SKA weak lensing experiments will allow to beat systematic effects. Together SKA and Euclid will allow to better constrain several cosmological parameters. Strong synergies exist also in the domain of Euclid legacy science, particularly for galaxy evolution studies: by combining HI and optical spectroscopy, as well as radio continuum and polarization information, SKA and Euclid will provide a

68 www.eso.org/public/teles-instr/elt/
69 www.euclid-ec.org/

comprehensive view of the many ingredients and parameters that influence galaxy and AGN co-evolution (galaxy stellar and HI masses, star formation rates, AGN-driven outflows, magnetic fields, etc.).

JWST

The *James Webb Space Telescope* (JWST[70]), is a large, space-based observatory, optimized for infrared wavelengths, which will complement and extend the discoveries of the Hubble Space Telescope. The longer wavelengths enable JWST to look further back in time to see the first galaxies that formed in the early universe, and to peer inside dust clouds where stars and planetary systems are forming today. JWST will study every phase in the history of our Universe, ranging from the first luminous glows after the Big Bang, to the formation of solar systems capable of supporting life on planets like Earth, to the evolution of our own Solar System.

JWST and SKA have unique and complementary capabilities in imaging and characterising the ionised, atomic and molecular gas and dust in and around galaxies, up to high redshifts. This will potentially revolutionise our view of the gas content in the ISM and circum-galactic medium of galaxies.

LIGO/VIRGO

A good example of independent telescopes that provide access to complementary source populations applies to the Gravitational Wave (GW) spectrum, where LIGO[71]/VIRGO[72] is probing the merger of compact objects: binary black holes (up to several times as massive as the Sun), binary neutron stars, as well as black holes-neutron star binaries.

In this context, SKA will exploit multiple synergies: on one side by directly probing the ultra-low frequency window of the GW spectrum, resulting from the coalescence of supermassive black holes binaries (typically one million times the mass of our Sun), via the timing of an array of millisecond pulsars; on another side by monitoring the radio light curve (including polarization information) of the electromagnetic emission following the GW events involving at least one neutron star.

LSST

The *Large Synoptic Survey Telescope* (LSST[73]) is a wide-field 8m class telescope designed to obtain multi-band images over a substantial fraction of the sky every few nights. Multiple goals are expected in many relevant astrophysical areas, such as : (i) taking an inventory of the Solar System; (ii) mapping the Milky Way; (iii) exploring the transient universe; and (iv) probing dark energy and dark matter.

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[70] www.jwst.nasa.gov/

[71] www.ligo.org/

[72] www.virgo-gw.eu/

[73] www.lsst.org/

The SKA and LSST offer significant synergies, in particular in time-domain astrophysics. Simultaneous observations of the transient sky carried out with SKA and LSST will allow us to study "known" and yet "unknown" classes of transient phenomena with unprecedented accuracy. The comparison between LSST and SKA transient catalogues will be crucial to:

A. exploit multi-messenger astronomy, by discovering transients and collecting light curves at different wavelengths,
B. discover transients that are missed by optical surveys, e.g. dust enshrouded explosions of massive stars,
C. improve the transient classification in the radio bands exploiting the optical features,
D. compare the detection algorithms in the optical and radio images and find systematics.

Appendix D: Ongoing Board-promoted initiatives

In the following we provide a list of the ongoing INAF initiatives, promoted and/or endorsed by the Italian SKA Coordination Board from its establishment (December 2017) onwards. Most of such initiatives are supported by INAF through the UTG II and/or the DS.

Updated to July 2019

- **II National Workshop of SKA Science and Technology (December 2018).** This workshop has been organized by the Board in collaboration with INAF-UTG-II, and it is the second of a series (the first was organized in 2012). Its main scope was to review SKA-related scientific, technological and industrial activities in progress in Italy, in a more mature phase of the SKA project, as well as to involve the astrophysical community at large in tracing an Italian roadmap towards the SKA. Particular attention was given to exploring possible synergies between SKA and other scientific and technological projects relevant to INAF, through a dedicated Session (organized in close collaboration with UTG-I and UTG-III). According to the original aims the Board envisages a 2-year appointment for such National workshops.
- **National LOFAR Data School (June 2019)**. This is the first of the LOFAR data analysis schools, organized as part of LOFAR-IT initiatives[74]. The Italian SKA Board fully endorses such initiatives.
- **Workshop on SKA Data Challenges (September 2019).** The workshop aims to be an event for astronomers and engineers interested to apprehend the SKA basics. Taking the opportunity offered by the "First SKA data challenge", most of the main issues associated with data transfer, analysis, archiving, and data access will be addressed. All these aspects are important to get prepared to handle SKA data. This workshop is organized by the ALMA Regional Center in the framework of the Italian SKA Board initiatives to promote the SKA project in Italy.
- **Visits to SKA host countries and SKA Headquarters.** To foster the Italian participation in observational projects using SKA precursors, medium/long-term exchange visits with the SKA host countries (Australia and South Africa) need to be supported. Such support can now be given through dedicated UTG-II funding upon motivated requested. Visits to the SKA Headquarters (UK) are also supported.
- **SKA postdoc position on low frequency antenna calibration.** It is strategic to have Italian experts in the low-frequency calibration team, and enough man-power, to be able to fully evaluate the calibratability of log-periodic vs dipole antennas. Experts in these matters in Italy are a few, all keen to be involved, but need help for data acquisition and analysis. Man power dedicated to this activity should be hired as soon as the deployment of the phase-1 stations will be completed (mid 2019). Considering the

[74] For more details on LOFAR-IT initiatives we refer to the LOFAR-IT website: www.lofar.inaf.it/

need to closely interact with the INAF staff involved in the calibration task, we proposed to advertise the position at Arcetri. The call has been published at the end of July 2019.

- **SKA national postdoc programme (SKA-PRO).** In the framework of the initiatives to promote the SKA project in Italy, the Italian SKA Board has proposed a national programme for postdoc positions (named SKA-PRO). The SKA-PRO programme is meant to support preparatory SKA-related research and strengthen the involvement of Italy in scientific activities in preparation for the SKA key-science projects (KSP). The SKA-PRO positions are open to any research area covered by the SKA, with particular attention to projects of legacy value. The projects can be carried out in any of the INAF structures, in collaboration with INAF groups active in SKA-related research. Both the research project and the host INAF structure are proposed by the candidates. To make this programme attractive and competitive at international level the Board envisages 3-year positions. An additional grant should be provided to support traveling and other research-related expenses (HW, publications, etc.). Call in preparation.
- **LOFAR national postdoc positions.** Similarly to the SKA national postdoc programme, LOFAR-IT[73] has established a national postdoc LOFAR programme. The Italian SKA Board fully endorses such initiative. Call in preparation.
- **SKA-related Seminars.** In the framework of the initiatives to promote the SKA in Italy, dissemination plays an important role. Members of the Italian SKA Board are actively involved in giving seminars on the SKA project at INAF structures, as well as at national workshops and conferences. Such talks can also be focused on SKA precursors and pathfinders and/or specific scientific themes.
- **Italian engagement in mid-frequency precursors.** A number of scientific and technical working groups have been established to organize and coordinate the involvement of the Italian community in ASKAP- and MeerKAT-related activities. This is part of initiatives of UTG-II SKA-Mid precursors Advisor. The Italian SKA Board fully endorses such initiatives.