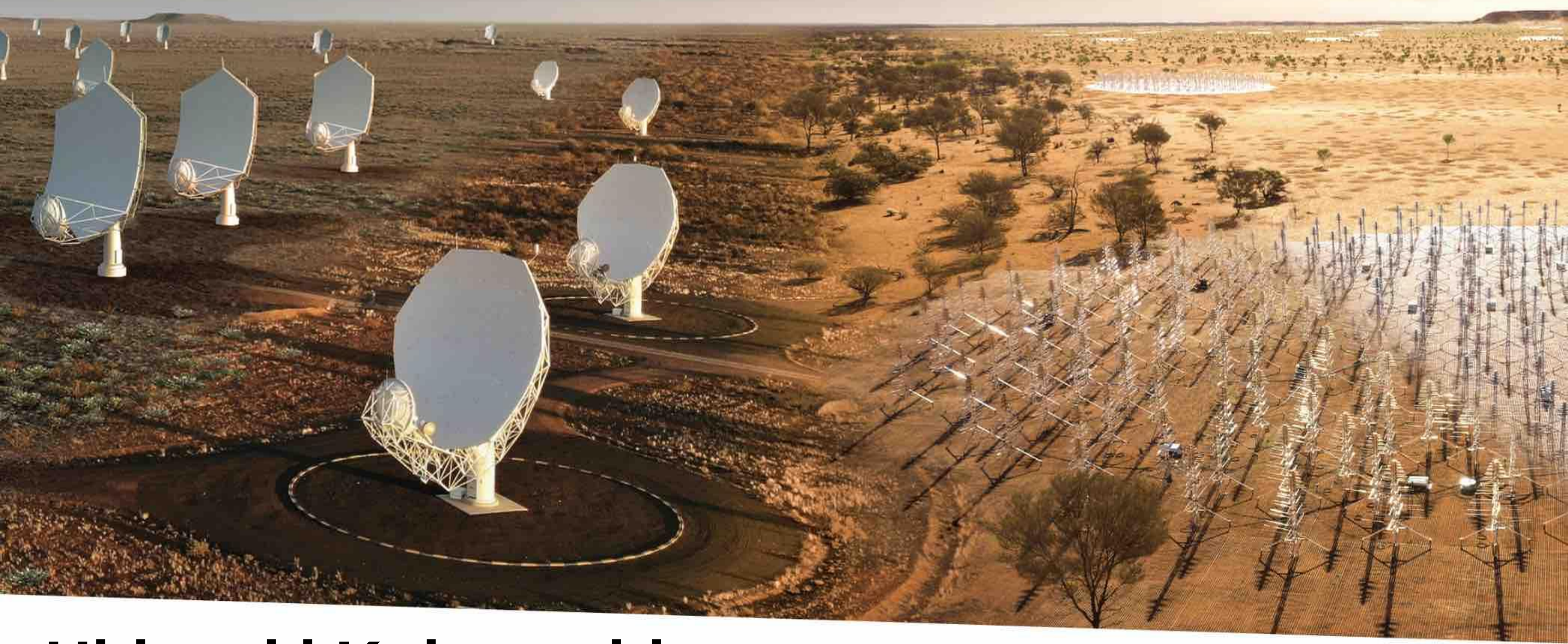
SKA1 commitment plan of Japan



Hideyuki Kobayashi

Group Leader

NAOJ SKA1 STUDY GROUP
国立天文台SKA1検討グループ

Overview

Square Kilometre Array (SKA)

The world 16 countries commit ~2B Euro in total and construct/operate the world-largest radio interferometer in 2020's

SKA Convention (2021.1.15~)

Inter-governmental organization
SKA Observatory

Decision Making
SKAO Council

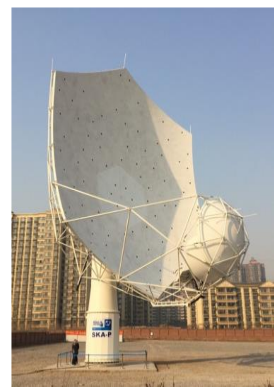
- **Science and Engineering Advisory Committee**
- **Finance Committee**
- **Time Allocation Committee**
- **Other Committees**

Australia LOW Observatory (50-350 MHz)

131k units (512 stations)
Max 65km baseline (SKA1)
↓
1.25M units (4880 stations)
Max 300km (SKA2)

South Africa MID Observatory (0.35-15.4 GHz)

197 (15m & 13.5m) dishes
Max 150km baseline (SKA1)
↓
2000 (15m) dishes
Max 3000km (SKA2)



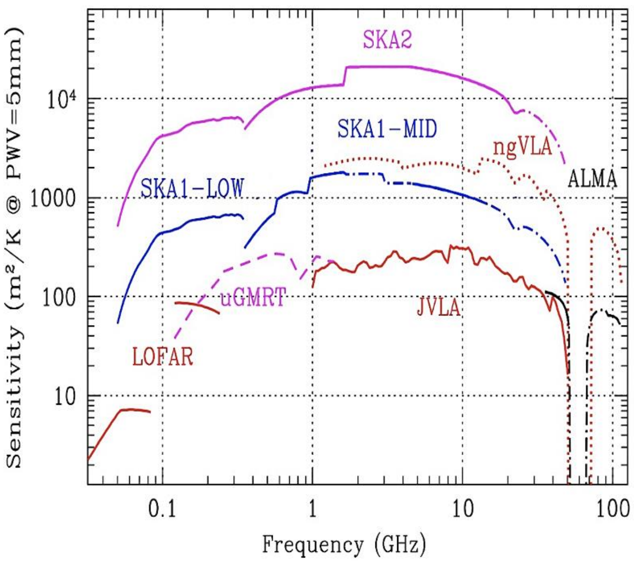
UK Headquarter

At Jodrell Bank Observatory

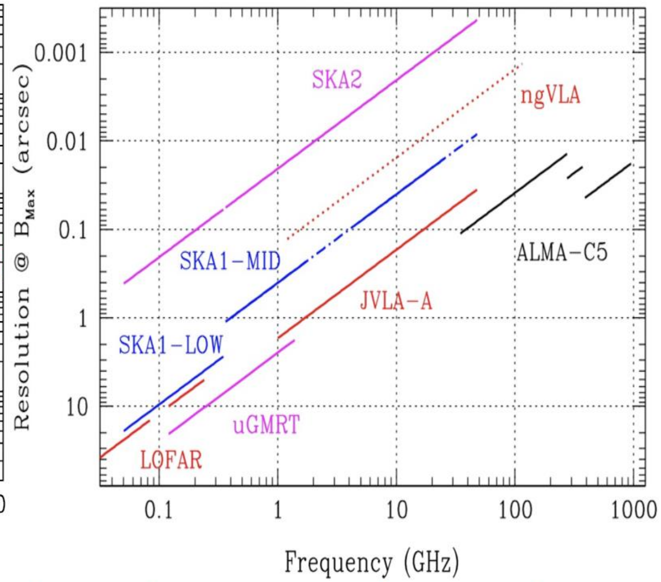
- SKA1: **10x better sensitivity, 10x better resolution,** wider field-of-view & multi-mode → **100x better survey capability** than before
- **Diverse Science** (Epoch of Reionization, Gravity Theory with Pulsars, Magnetism, Cosmology, Galaxy Evolution, Astrobiology, Transients, …)
- The community (SKAJP, #264 members) wants NAOJ to offer 2% share of the SKA1 time
- SCJ Masterplan: "priority large" in 2010; 2011; 2014. "priority large candidate" in 2020

Ultimate Survey Performance

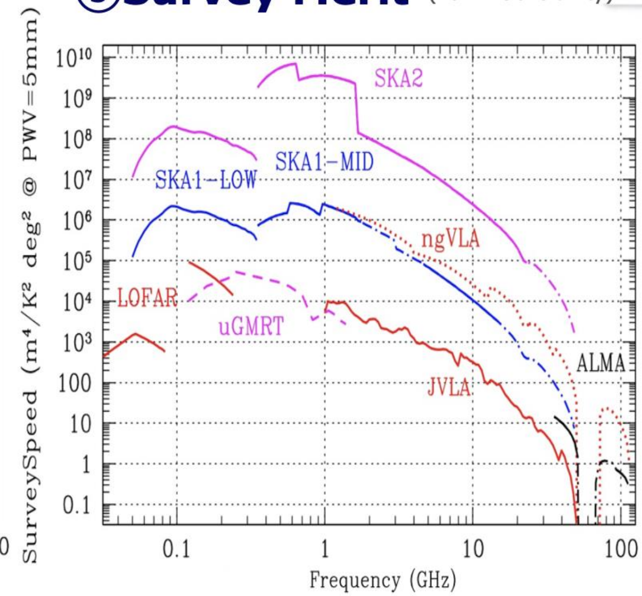
①Sensitivity



②Resolution



③Survey Merit (FoV x Sensitivity)



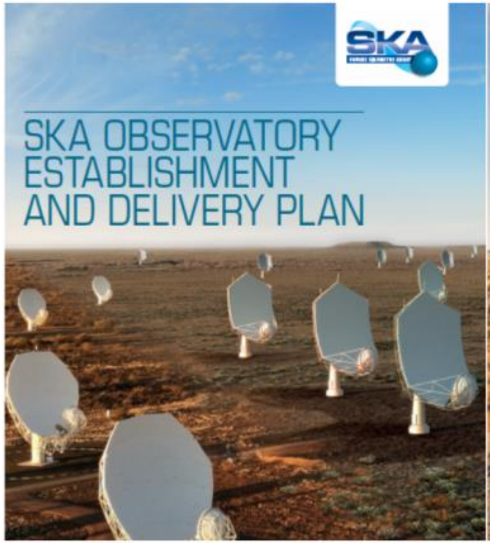
④Multi-mode

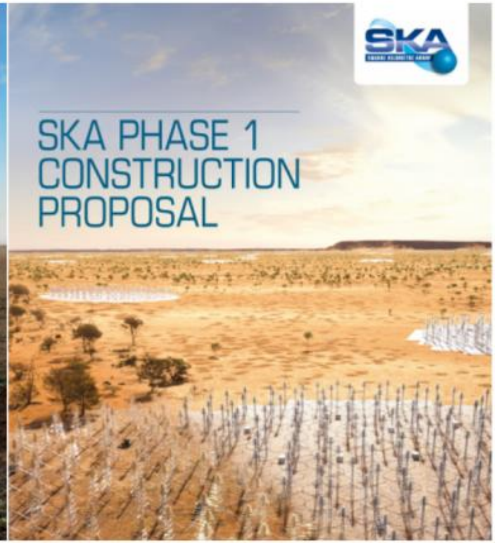
We can perform multiple observing modes simultaneously

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	2	810.0	3	1500	810.0	16	810.0	2

- The sensitivity and resolution are **10 times better** than the current largest facilities
- The survey merit is **100 times better** than the current largest facilities
- **An effective annual operation time is much larger than 8760 hours** because
  - There are two telescopes: LOW and MID
  - There are multi-beam and multi-mode capability of the backend system
- Those specifications provide **ultimate survey performance**

SKA1 Construction & Operation





■SKA Phase 1 (SKA1)

- The construction and operation of SKA1 were endorsed at the first Council in February 2021
- SKA1 construction was started in July 2021

■Cost for SKA1 to 2030

- Construction：1297 M€
- Operation: 725 M€

Although the SKA Council has ambition to the SKA phase 2, the Council has concentrated on the implementation of the SKA phase 1. There is less discussion about the phase 2, so that the budget and schedule for the phase 2 are totally unclear. Therefore, this A-project proposal scopes only the phase 1 and does not include the phase 2 of the SKA.

SKA Observatory Development Program (SODP) is out of the scope of the SKA1 design and construction. However, the SODP is within the budget of the SKA phase 1. Therefore, this A-project proposal includes the participation to the SODP.

SKA1&2 Headline Science 1

	SKA1	SKA2 = 10*SKA1
Cosmic Dawn and the Epoch of Reionization	Direct imaging of EoR structures ($z = 6 – 12$)	Direct imaging of Cosmic Dawn structures ($z = 12 – 30$)
	Power spectra of Cosmic Dawn down to arcmin scales, possible imaging at 10 arcmin.	First glimpse of the Dark Ages ($z > 30$).
Cosmology & Dark Energy	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: competitive to Euclid.	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: redefines state-of-art.
	Primordial non-Gaussianity and the matter dipole: 2x Euclid.	Primordial non-Gaussianity and the matter dipole: 10x Euclid.
Galaxy Evolution probed by Neutral Hydrogen	Gas properties of 10^7 galaxies, $\langle z \rangle \approx 0.3$, evolution to $z \approx 1$, BAO complement to Euclid.	Gas properties of 10^9 galaxies, $\langle z \rangle \approx 1$, evolution to $z \approx 5$, world-class precision cosmology.
	Detailed ISM of galaxies (50pc@3Mpc), diffuse IGM down to $N_H < 10^{17}$ at 1 kpc.	Detailed ISM of galaxies (50pc@10Mpc), diffuse IGM down to $N_H < 10^{17}$ at 1 kpc.
Galaxy Evolution probed in the Radio Continuum	Star formation rates (10 M_o/yr to $z \sim 4$).	Star formation rates (10 M_o/yr to $z \sim 10$).
	Resolved star formation astrophysics (sub-kpc active regions at $z \sim 1$).	Resolved star formation astrophysics (sub-kpc active regions at $z \sim 6$).

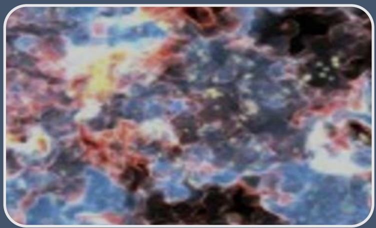
SKA1&2 Headline Science 2

	SKA1	SKA2 = 10*SKA1
Strong-field Tests of Gravity with Pulsars and BHs	1st detection of nHz-stochastic gravitational wave background.	GW astronomy of discrete sources: constraining galaxy evolution, cosmological GWs and cosmic strings.
	Discover and use NS-NS and PSR-BH binaries to provide the best tests of gravity theories and General Relativity.	Find all ~40,000 visible pulsars in MW, use the most relativistic systems to test cosmic censorship and the no-hair theorem.
The Origin and Evolution of Cosmic Magnetism	The role of magnetism from sub-galactic to Cosmic Web scales, the RM-grid @ 300/deg^2.	The origin and amplification of cosmic magnetism, the RM-grid @ 5000/deg^2.
	Faraday tomography of extended sources (100pc@14Mpc, 1kpc@z≈0.04)	Faraday tomography of extended sources (100pc@50Mpc, 1kpc@z≈0.13)
The Transient Radio Sky	Use fast radio bursts to uncover the missing "normal" matter in the universe.	Fast radio bursts as unique probes of fundamental cosmological parameters and intergalactic magnetic fields.
	Study feedback from the most energetic cosmic explosions and the disruption of stars by super-massive black holes.	Exploring the unknown: new exotic astrophysical phenomena in discovery phase space.
The Cradle of Life & Astrobiology	Proto-planetary disks; imaging inside the snow/ice line (@ < 100pc), Searches for amino acids.	Proto-planetary disks; sub-AU imaging (@ < 150 pc), Studies of amino acids.
	Targeted SETI: find airport radars for 10^4 nearby stars.	Ultra-sensitive SETI: find airport radars for 10^5 nearby stars, TV ~10 stars.

Japanese Key Science

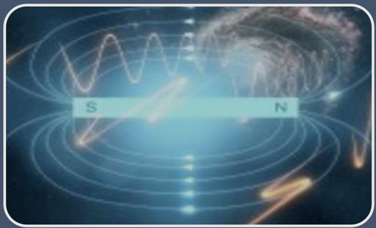
Developed at SKA-JP Science Strategy Workshop in July 2021

Japanese community determined three key science areas



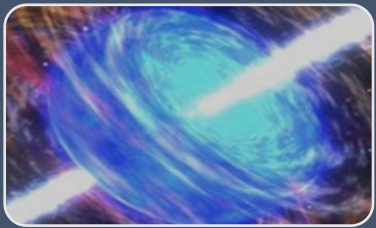
Deciphering the cosmic reionization with cosmology and astrophysics

- Our strengths: theory and distant galaxy surveys, Our technique: foreground removal, calibration, Link: **Cosmology, galaxy evolution**



In-depth/Tomographic study of the magnetic field governing the cosmic hierarchy and activities

- Our strengths: high-energy astrophysics, Our technique: Faraday Tomography, Link: **ISM, star and planet**



Pioneering long-wavelength gravitational-wave astronomy with pulsar observations.

- Our strengths: multi-messenger astronomy, VLBI, Our technique: time-domain analysis and pulsar timing array, Link: **Transients, VLBI**

- **Also promote individual science goals including "unknown"**
- **Encourage software developments for the key science areas**

Target Share of Science

■**We target to obtain the share of science outputs larger than 2%, which is Japanese share of the telescope time.**

- Although there are huge uncertainties, the 2% corresponds to

Common-use category	# of proposals	# of approvals	# of papers
Key Science Projects (KSPs, large & long-term proposals)	15-30	3	6
PI Proposals (PIPs, small & short-term proposals)	33-66	6	6
Total	48-96	9	12*†‡

* This number per cost is comparable to those of Subaru, Suzaku, and ALMA.
† This number is comparable to the current SKAJP's output using SKA pathfinders.
‡ This number is also the target for SKA precursors before SKA1 is in operation.

Common-use category	CPU Power	Storage	FTE
SKA Regional Centre (SRCs, data center and user support)	0.1-0.7 PFlops	50 PB	4#

\# This number is for the international SRC network only. Further 8 FTEs are requested for domestic tasks.

Engineering Contribution

- **The development plan has been made with long discussion with the community and SKAO. The plan links to Japan's key science objectives and engineering know-how.**

EoR, Cosmology, Galaxy Evolution

Magnetism, Pulsars, Transients, ISM

Milky Way, Cradle of Life, AGN

LOW	Band 1	Band 2	Band 3	Band 4	Band 5a	Band 5b	Band 6/7
0.05–0.3	0.3–1.0	1.0–1.7	1.7–3	3–5	5–8	8–15	15–25~50

Band B: 5–25~50

Frequency (GHz)

1. Assembly, Integration, and Verification (AIV) and Commissioning and Science Verification (CSV)
- One of the most important tasks to realize the designed performance of SKA
- SKAO (and world) has high expectations for Japanese technological capabilities

2. VLBI system (both LOW and MID)
- VERA's experiences of MID VLBI, a new frontier of LOW VLBI, toward global VLBI

3. Software ・EoR calibration and imaging pipeline ・Magnetism Faraday Tomography pipeline

4. Band6/7/B receiver
- Scientific needs
- VLBI experiences
- Continue research, test, and design

Japan’s Responsibility for AIV

SKA SQUARE KILOMETRE ARRAY
NAOJ SKA1 STUDY GROUP

- **There is <u>the fair work return policy</u> in the SKA project**
  - Return 70% of financial contribution by procuring something (goods, human resources, etc) from that country
  - In other words, each country must undertake work of 70% or more of the contribution
- **Regarding Japan's contribution, SKAJ will consult with SKAO according to the earned budget in future (Cooperation Agreement)**

Contract	Tier 1 Lead	Status	Other Participating Countries	Contract type
Low Infrastructure	Australia	Conditional	-	ECCs
Low Infrastructure PSC	Australia	Conditional	-	PSC
Low Field Node	Italy	Conditional	Australia, United Kingdom	PSC, ECC (SC)
Low Digitisation	Italy	Conditional	Australia, India, United Kingdom, Netherlands	PSC, ECC (SC)
Low AIV PSC	Australia	Conditional	Japan, Netherlands	PSC
Low CSP	Netherlands	Conditional	Australia	ECC
Low Clocks	United Kingdom	Conditional	Switzerland	ECC
Low Timing	United Kingdom	Conditional	China, Spain	ECC
Mid Infrastructure	South Africa	Conditional	-	ECCs
Mid Infrastructure PSC	South Africa	Conditional	-	PSC
Mid Dish Structure	China	Conditional[1]	Italy, South Africa, Spain, Germany	ECC (SC)
Mid Dish PSC	South Africa	Conditional	-	PSC
Mid Digitisation	Sweden	Provisional[1]	Canada, France, South Africa	ECC
Mid AIV PSC	South Africa	Conditional	Japan and Portugal	PSC
Mid CSP	Canada	Conditional	TBD	ECC
Mid Clocks	United Kingdom	Conditional	Switzerland	ECC
Mid Timing	United Kingdom	Conditional	Australia, Spain	ECC
Mid Cryo	United Kingdom	Conditional[1]	(France, Germany)	ECC
MID SPF Services	South Africa	Conditional	-	ECC (SC)
Mid Band 1 SPF	Sweden	Conditional	India, Spain	ECC
Mid Band 2 SPF	South Africa	Conditional	-	ECC
Mid Band 5 SPF	United Kingdom	Conditional[1]	Sweden, (France, Portugal, Spain)	ECC
Low SPC	France	Conditional[2]	-	ECC (PSC)
Mid SPC	France	Conditional[2]	-	ECC (PSC)
Low Networks	Unallocated	-	-	ECC
Mid Networks	Portugal	Conditional[2]	-	ECC (PSC)
OMC	India	Conditional	Italy, Portugal, South Africa, United Kingdom	PSC
SDHP	United Kingdom	Conditional	Australia, China, Germany, India, Italy, Netherlands, Portugal, South Africa	PSC
Low CPF	United Kingdom	Conditional[2]	-	ECC (PSC)
Mid CPF	United Kingdom	Conditional[2]	-	ECC (PSC)
MeerKAT Integration	South Africa	Conditional	-	PSC

Engineering Target of AIV

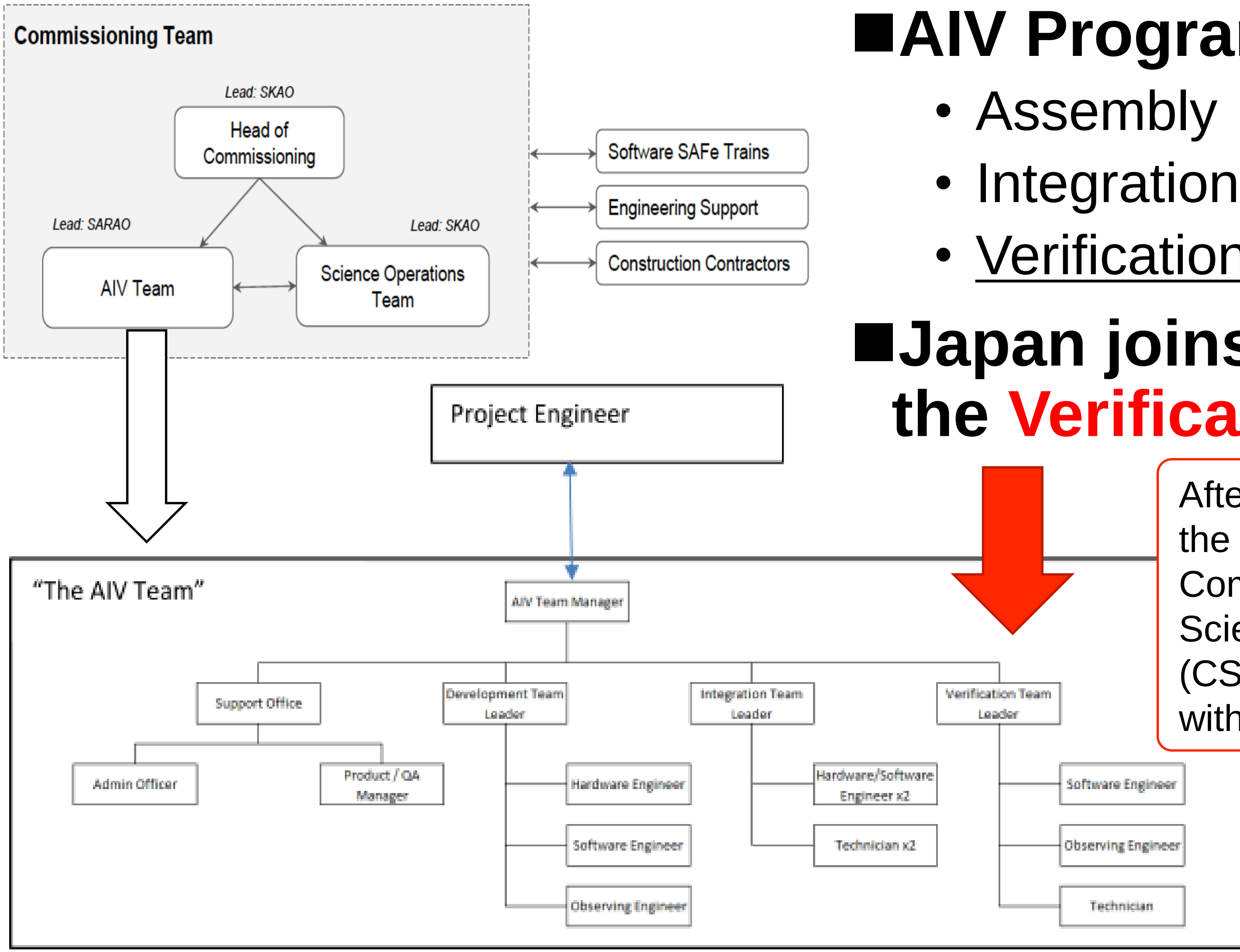


Figure 4: The AIV Team has Clear Reporting Lines.

- **AIV Program contains**
  - Assembly
  - Integration
  - <u>Verification</u>
- **Japan joins (leads) the Verification Team**

After the construction, the team will contribute Commissioning and Science Verification (CSV) in collaboration with science team

SQUARE KILOMETRE ARRAY
NAOJ SKA1 STUDY GROUP

Progress of SKAJ AIV Activity

■ MoU of AIV contribution from 2010

- 1.5 FTE contribution to AIV MID and LOW from Mizusawa VLBI Observatory
  - ✓ MID: Attending DISH AIV activity with SARAO(SA) (Sunada)
  - ✓ LOW：Joining the AIV team with CSIRO(Oz) to make test procedures of the integration and verification (Kono)

■ New technology for ‘AIV’

- System engineering experiences for ‘mass production telescope’
- Virtualization technology, collaborative software development environment, unit test module, device control toolkit (TANGO)、Behavior Driven Development
- Improve the skills of participating staff and give back to Japan

■ Key for future telescope system development in Japan

- Japan should play a key role of future telescope developments with science and engineering feasibility considerations.

No down, Automated

kubernetes

Co-work

GitLab

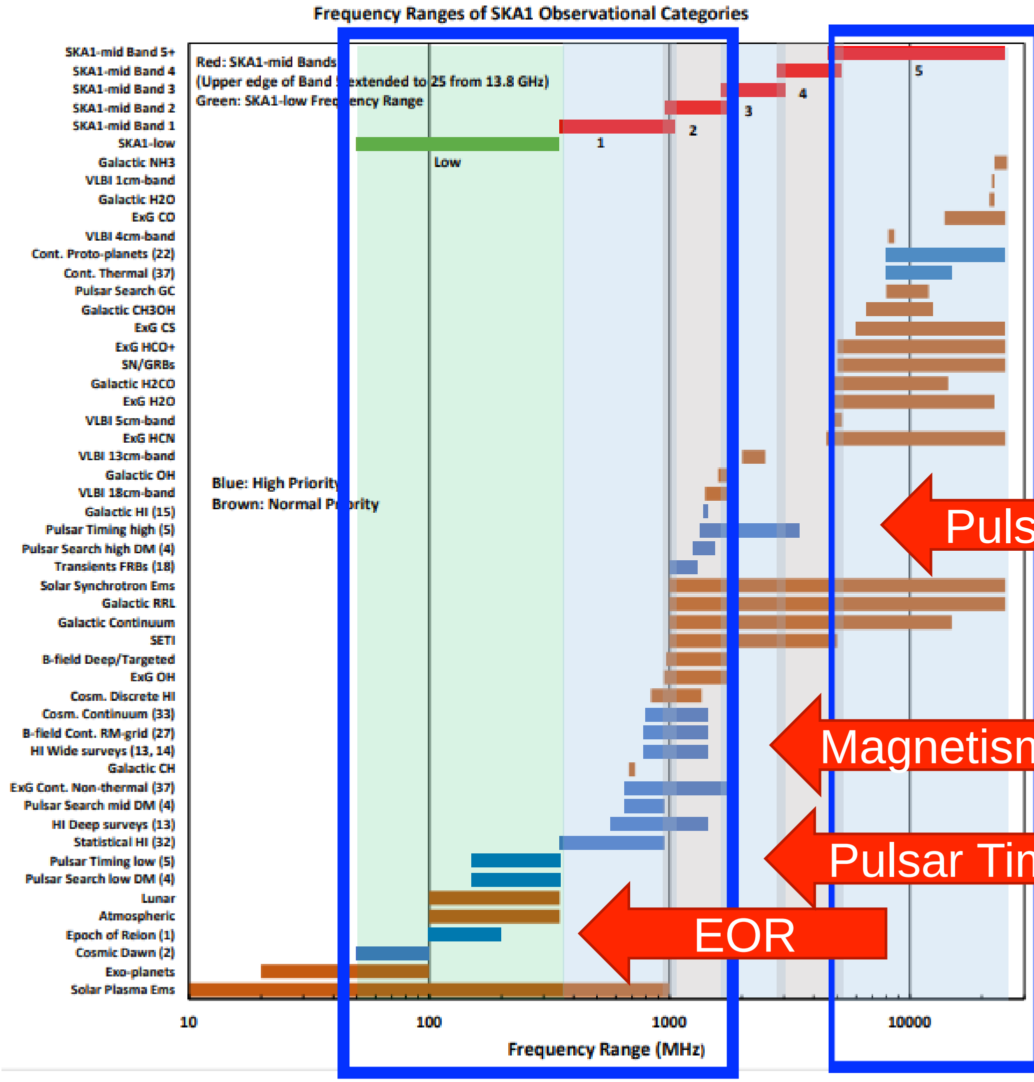
Share test information

pytest

HW control common

TANGO

SODP: Frequency range of SKA1



SKA LOW 50-350MHz

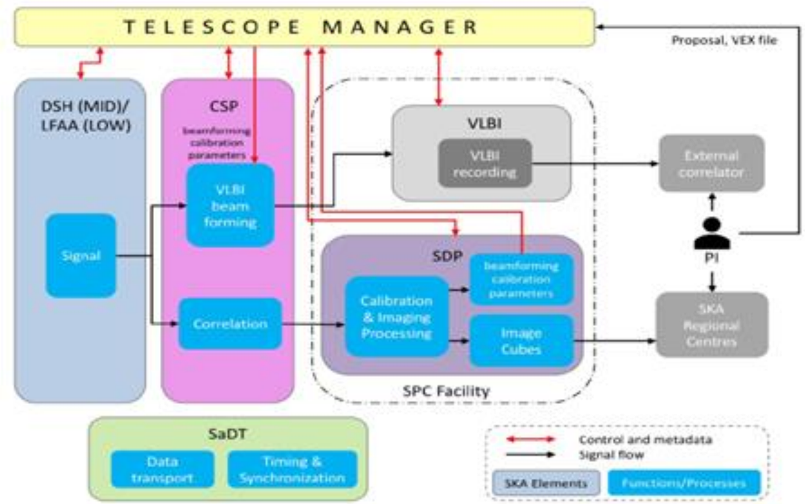
SKA MID
Band1 350-1050MHz
Band2 950-1760MHz
Band5 4.6-15.3 GHz

SKA Construction proposal 2020

SKA SQUARE KILOMETRE ARRAY NAOJ SKA1 STUDY GROUP

SODP: VLBI

- **Goal: Develop the multi-beam VLBI system and its calibration method**
- **SKA-VLBI is recognized as a major SODP candidate. Some functionality tests are planned at AA* (AA3+AA4)**
  - Test of integration between CSP# and the VLBI system (both HW and SW)
    - ✓ Use voltage output mode (common with pulsar data) from CSP
  - Development and implementation of high-speed VLBI recording system
    - ✓ recording more than 4 beams
  - Upgrade of partner VLBI stations + development of a new correlator
    - ✓ Wideband, multi-beam
    - ✓ data reduction and calibration (e.g., direction-dependent self-calibration)
- **SKAJP VLBI WG is discussing development plans toward future VLBI test using SKA (from 2027)**



SKA1-MID						
#sub-array	#VLBI beam	Bandwidth (per pol, MHz)	Digiti-zation	Sampling	Data rate (Gbps)	Buffer size (1h, TB)
1	4	256	2	Nyquist	8	3.5
1	4	512	2	Nyquist	16	7
2	4	512	2	Nyquist	32	14
1	4	2500	2	Nyquist	78.12	34
1	16	512	2	Nyquist	64	28
1	52	200	2	Nyquist	81.25	35.7
10	52	200	2	Nyquist	812.5	357
SKA1-LOW						
#sub-array	#VLBI beam	Bandwidth (per pol, MHz)	Digiti-zation	Sampling	Data rate (Gbps)	Buffer size (1h, TB)
1	4	256	2	Nyquist	8	3.5
1	16	256	2	Nyquist	32	14
1	16	256	8	Nyquist	128	56.3

CSP = central signal processor

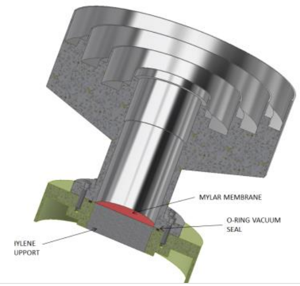
SODP: Receiver

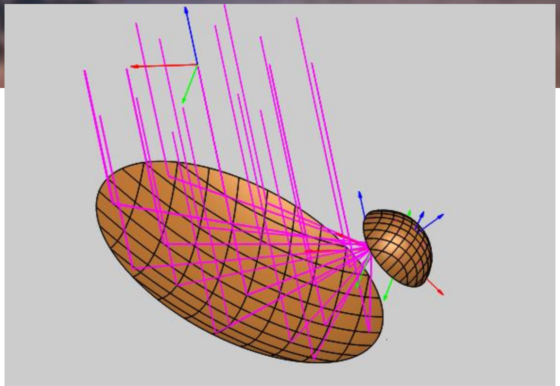
■ SKA1 Study Group Activities

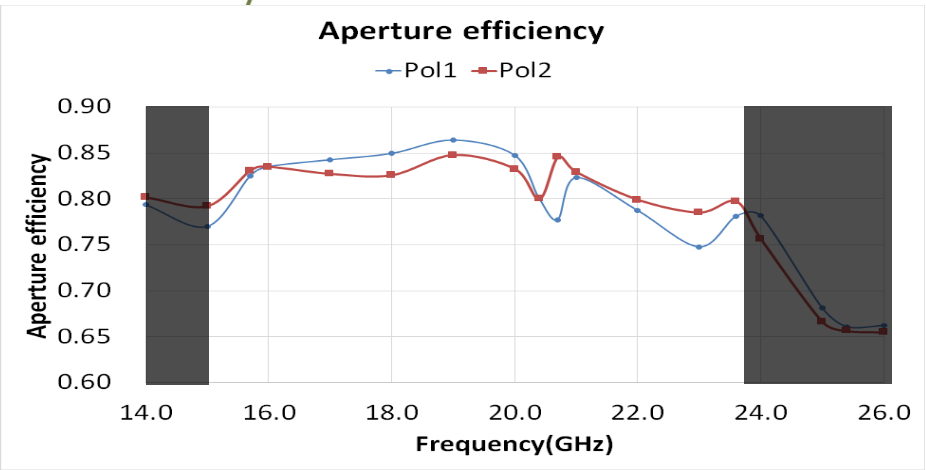
- **Kimura（JAXA）+2019**
  - ✓ Axially corrugated horn
  - ✓ Design using Champ
  - ✓ SKAO's GRASP model was already integrated
- **Yamasaki（Osaka Metropolitan Univ.)**
  - ✓ Optics design of **Band 6 (15-29GHz)**
- **Sumitomo Heavy Industry (SHI)**
  - ✓ Visited South Africa with SHI
  - ✓ Sumitomo FA40 cooling test

■ In the SKA A-project, we

- Continue scientific and engineering researches about the possibility to expand the observing frequency up to 26 GHz
- Watch the on-going study of antenna specification (antenna pointing accuracy)







https://www.shi.co.jp/

SRC: Commitment and Plan

■ Contribution to SRC Steering Committee Working Groups*

- NAOJ(Hirota, Akahori), Tsukuba U.(Yoshikawa), Yunnan U.(Shimabukuro), Kumamoto U. (Takahashi)
- Study of requirements and functions
- Consideration of an international cooperative development system

■ Collaboration with SHAO

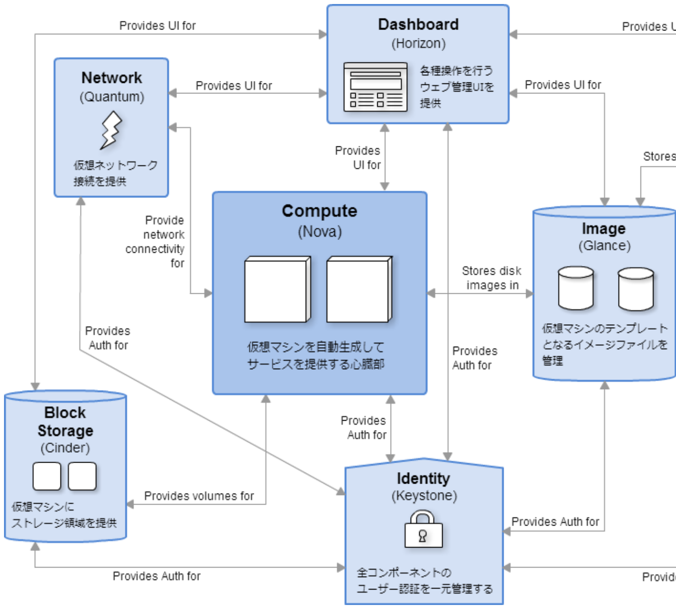
- MoU between SHAO and NAOJ
- East Asia Science WS in May 2019 (JSPS：Bilateral Seminar）
- Collaboration of MWA data analysis

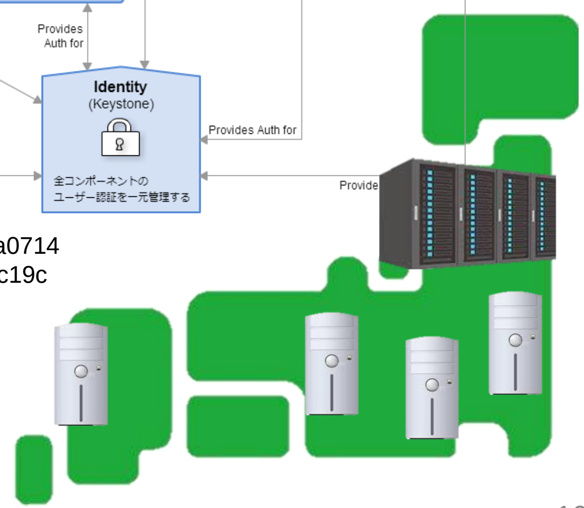
■ In the SKA A-project, we

- Prototype JP-SRC
  - ✓ OpenStack-base on-premise Cloud
- Test performance of astro-data analysis on Cloud
- A part of KAKENHI (submitted)
  - ✓ NAOJ Mizusawa, ADC & Tsukuba

*SRCSC WGs

WG0: SRC Network Architecture, WG1: Data Logistics, WG2: Operations, WG3: Pipeline, WG4: Archive, WG5: Computing, WG6 Science User Engagement





https://qiita.com/t_nakayama0714/items/183942514e7253b2c19c

Construction Schedule

■ ***Are the milestones and project schedule highly feasible?***

■ **Phased integration of arrays is planned.**

Early (AA2) operation 2025~
Full (AA4) operation 2028~

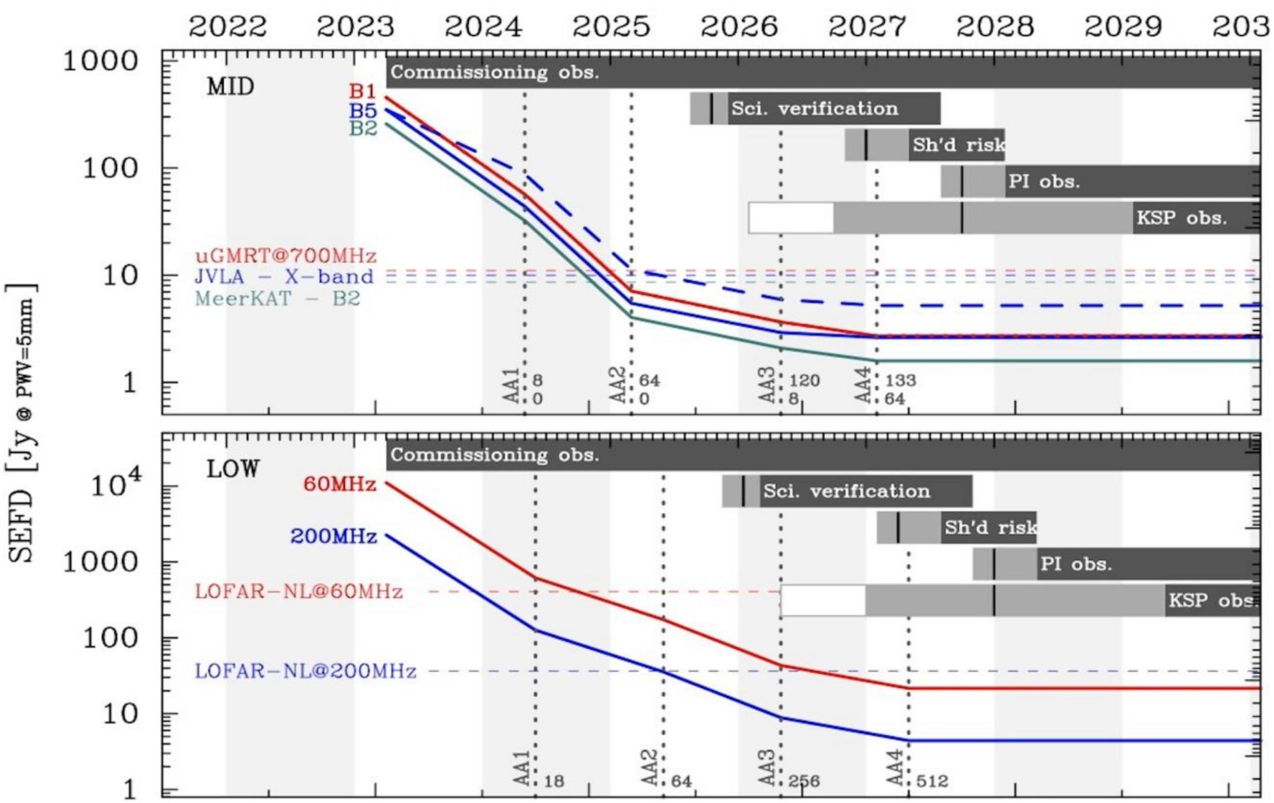
SKA1 Early

Early science
Data release

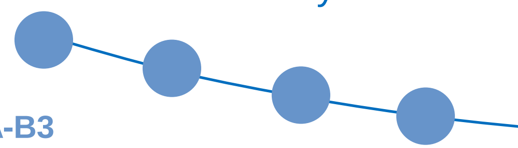
SKA1 extension or toward SKA2

SKA1 stable operation

ngVLA Early



If the construction starts from 2030
based on Decadal Survey 2020



ngVLA-B3
(12-21GHz) SEFD

SODP (SKA Observatory Development Program)
Some candidates

- Extend B_{max} to 300 km
- Band 3/4 (2-5 GHz)
- Band 6/7 (15-50 GHz)
- Band 1 phased array feed
- # of beamform to 1500
- Data processor to 100 PFlops

Schedule

Phased integration of Arrays

2024Q4 2025Q4 2026Q4 2027Q3

Review 2028
End of Construction 2029 July

Table 34: Characteristics of each Array Assembly (AA) milestone and the functionality delivered.

Telescope		AA0.5	AA1	AA2	AA3	AA4
LOW	Stations	8	18	64	256	512
	Observing Modes*	Basic imaging		Pulsar Timing, Dynamic Spectrum	Pulsar Search, Transient Capture	VLBI
MID	Dishes	4	8	64	121	197
	Integrated MeerKAT dishes	0	0	1	8	84
	Receiver bands	1, 2	1, 2	1, 2 5 (on 32 dishes)	1, 2 5 (on 64 dishes	1, 2, 5
	Observing Modes*	Basic imaging	Basic Pulsar Timing	Pulsar Search	Scaled up capability of existing functions	Dynamic Spectrum, Transient Capture, VLBI

* The observing modes shown are in addition to those delivered in previous Array Assemblies.

AA*

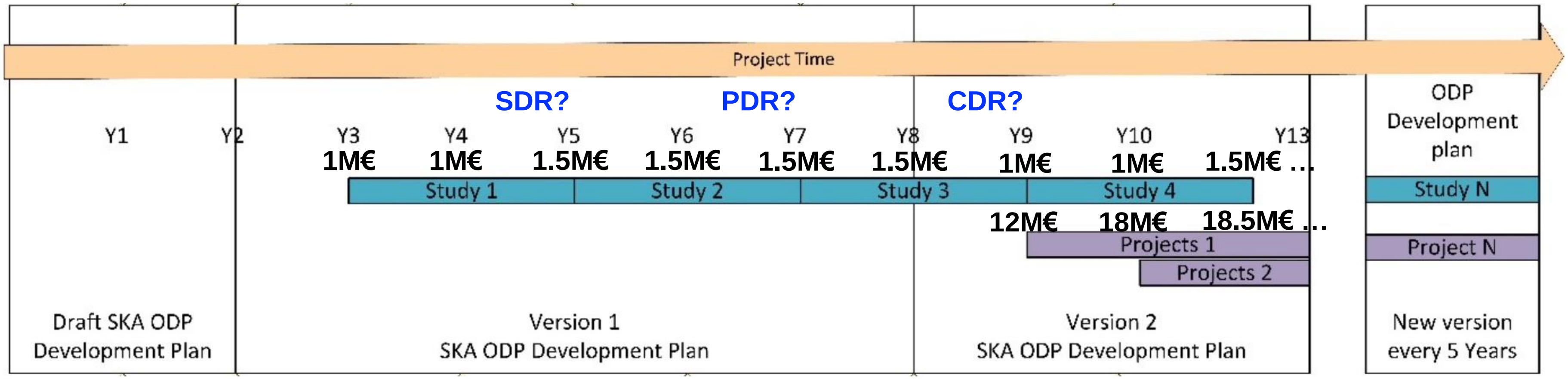
Decision of delivery system

AA3 and AA4 was combined as AA* to reduce the risk in the case of budget shortage in future

[S参4,18]

Schedule

SODP Plans



■A SODP “study” has a term of two-three years

- A study will be awarded up to 300 k€/yr, typically 50-100 k€/yr (like NAOJ共同研究開発経費)
- Will go to the next step through reviews (system design review, preliminary design review, critical design review)

■SODP refers the SODP development plan

- The SODP development plan is based on the regularly-updated Science and Technical roadmaps to keep the significance and freshness of the development

Budget Plan

- ~20% contingency and 2% inflation are considered.
- Total 2022M€ for the construction and operation
- Total 1659M€ expected from 16 countries
  - 81.6% of total cost
- Shortage of 373M€ (18.4%)
- See also risk mitigation
  - The construction flexibly optimizes the array configuration at each array assembly phase according to the earned budget

Budget Share

- **Telescope time allocation is based on the contribution**
  - Contribution to the infrastructure is discounted by half
- **9 out of 16 countries are minor partner (<3%). This means that it is essential to form the international collaboration teams for construction**
- **With the 2% share of time, we aim to obtain the science output as much as possible → Science strategy (set the key sciences)**

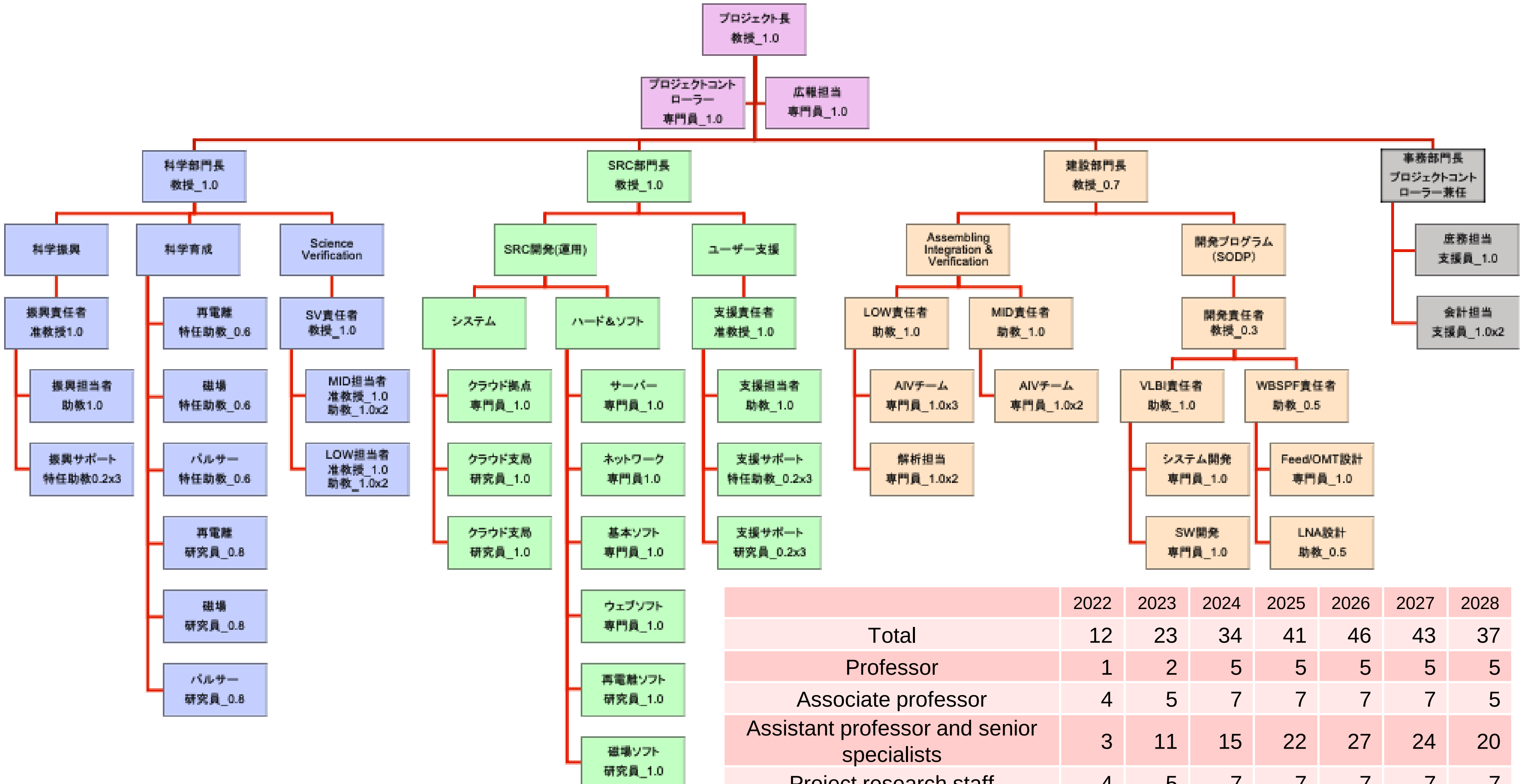
Japanese Budget Plan

■Budget for the construction period

- Total 5,507 M¥ consists of the contributions to:
- SKA1: Construction 1,122 M¥, Operation 1,998 M¥, SODP 564 M¥, total 3,685 M¥
- SRC: 960 M¥ (corresponding to 2% of SRC-Network costs)
- Domestic science promotion, user support, etc: 862 M¥

Staffing

■Mizusawa staff + newly hired

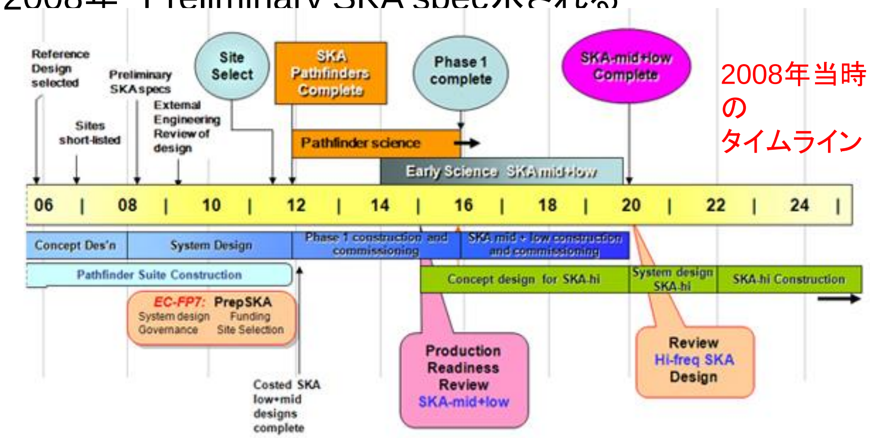


	2022	2023	2024	2025	2026	2027	2028
Total	12	23	34	41	46	43	37
Professor	1	2	5	5	5	5	5
Associate professor	4	5	7	7	7	7	5
Assistant professor and senior specialists	3	11	15	22	27	24	20
Project research staff	4	5	7	7	7	7	7

SKA-JP発足前後の動き

日本国内
2004年頃　**NAOJ電波専門委員会のもとSKA検討Working Group発足**
2004年11月　SKAワークショップ＠三鷹開催
2004年12月　合同シンポジウム「次世代天文学-大型観測装置とサイエンス」
他分野からSKAに対する高い関心。SKAに焦点を当てた宇電懇シンポ開催へ(2006年)。
2006年　2月　SKAワークショップ＠野辺山開催
高い関心が示されつつも、その後、議論は継続されず。
2008年　5月　日本SKA consortium結成
NAOJ SKA検討WGとは独立に結成（ボトムアップでの議論を開始）
発起人は、徂徠和夫（北海道大学）、萩原喜明（国立天文台）、中西裕之（鹿児島大学）
2008年　5月　学術シンポジウム＠本郷
日本SKAコンソーシアムとして、プロジェクトを紹介

国際的な動き
2004年　SKAサイエンスブック初版出版
(Carilli & Rawlings)
キーサイエンスが(1) Cradle of Life, (2) Testing GR with pulsars, (3) Cosmic magnetism, (4) Galaxy Evolution, Cosmology and Dark Energy, (5) Epoch of reionization の5つに選定
2006年　Reference Design選定
2007年　SKA建設地がオーストラリア・南アフリカに絞られる
2008年　Preliminary SKA spec示される



2008年当時の
タイムライン

SKA-JPと国立天文台の協力による国際交流強化

2008年11月　国内研究会SKA Workshop 2008 の開催（NROワークショップ）
日本のキーサイエンス、技術開発と科学研究のコンビネーションを議論
2009年　2月　SKA国際委員会へオブザーバー出席開始（中西）
国際プロジェクトとして日本からの貢献の可能性について議論
2010年　1月　国内サイエンス ワーキング グループ形成
宇宙磁場、宇宙論、位置天文学、活動銀河核、星間化学、パルサーの議論開始
2010年　3月　学術の大型施設計画・大規模研究計画のマスタープランで重点大型計画
LCGT, TMT, SPICA, Astro-HとともにSKAが掲載
2010年11月　国際研究会(SKA-JP Workshop 2010) 開催
「広帯域」をキーワードとすることで同意
2011年度　頭脳循環助成金により、国際共同研究が活性化

SKA-JPサイエンス検討推進、東アジア地域の連携強化

2011年4月　**SKA Funding Boardへの国立天文台執行部のObserver 参加　（その後、Board, Councilと継続）**
2011年11月 Workshop on East-Asian Collaboration for SKA 2011開催 @ KASI
　　SSEC8のサテライト会議として開催。東アジア地域の協力関係を議論
2012年 9月 East Asia SKA Consortium Workshop on HI 2012開催 @ NAOC
　　HIサイエンスと東アジア地域の協力関係を継続議論
2012年 6月 SKAサイエンス会議「宇宙磁場」（第1回）
　　この後、SKA-JP subSWG主導の研究会が年１回以上開催されるようになる
2013年 9月 SKA Science Workshop In East Asia 2013 @ 名古屋大学
　　東アジア地域におけるSKA時代に向けたサイエンスを議論
2013年12月 宇電懇シンポジウム@国立天文台
　　日本の電波天文学の大型将来計画としてのSKAの位置づけ、具体的参入に向けた方策を議論
2014年より **国立天文台の大学支援事業により、熊本大から豪機関、鹿児島大からSKA機構本部へ派遣**
2014年　**学術会議マスタープラン　重点大型計画に掲載**
2015年 3月 SKA-Japanワークショップ2015 @ 国立天文台
　　SKA-Japanが目指すサイエンスを議論

2011@KASI


2012@NAOC


2013@名古屋大学

SKA Project　提案

■ **2017年10月　水沢VLBI観測所計画部門（将来計画としてのSKA検討G）**

■ **2017年度末　サブプロジェクト申請（水沢VLBI観測所）**

- 2018年度から、プロジェクト目標に「水沢VLBI観測所プロジェクトの将来計画として、SKAに参加する可能性を、日本の得るべき科学目標、貢献内容、予算、人員等に関する観点から検討し、具体案を幹事会議に提示する。」
- 他の将来計画との比較検討が必要/予算の実現性の検討が必要/水沢VLBIとの整合性を理由に検討グループになった。

■ **2018年度 - 2021年度　SKA1検討グループ**

- 日本の科学目標の明確化・具体化
- 参加案をSKA本部と整合を持って提案
- SKA計画への参加の開始

■ **2020年度　学術会議マスタープランで重点大型候補**

■ **2022年度からのAプロジェクト提案→サブプロジェクト化**

- 審査委員会からサブプロジェクトが適当と報告
- 予算計画の検討（運営費交付金への影響の低減と実現性）

■ **2023年度　学術会議「未来の学術振興構想」**

- 天文学･宇宙物理学分科会から「最優先の計画」の１つとして推薦

SKA Project 提案

SQUARE KILOMETRE ARRAY
NAOJ SKA1 STUDY GROUP

■2017年度末 サブプロジェクト申請（水沢...

- 2018年度から、プロジェクト目標に「水沢... KAに参加する可能性を、日本の得るべき科学... 検討し、具体案を幹事会議に提示する。」
- 他の将来計画との... VLBIとの整合性を理由に検討グループにた...

■20... グループ

- ...
- ... 提案
- ...

■2020...

■2022... プロジェクト化

- 審査... が適当と報告
- 予算... 交付金への影響の低減と実現性）

■2023年度 ...学術会議「未来の学術振興構想」

- 天文学・宇宙物理学分科会から「最優先の計画」として推薦

新たな研究分野創出のプロセス

プロジェクト定義の変化（Aプロ⇒小規模プロジェクト）

サブプロジェクトの未定義

プロジェクト提案要件の不確定性

Summary

■SKA1 commitment plan

- Bottom-up plan with >2% contribution/observation time
- 3 Japanese Key Science(EoR, Magnetism, Pulsar)
- Engineering contribution
  - ✓AIV/SV
  - ✓SRC
  - ✓Development (VLBI, Band 6)
- Budget size for construction(～2028) ; 3,685M¥ contribution to project, 960M¥ for SRC, 862M¥ for domestic promotion
  - ✓9,529M€ for construction and early science period(～2033）
- Need to start from 2025 at the latest case

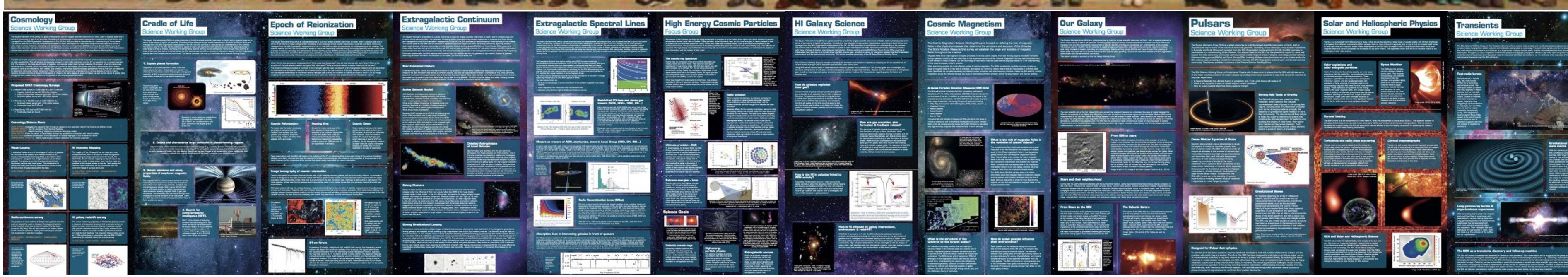
Appendix

1.1 Impacts and Influences

SKA Science

■ **Scientific importance of SKA1 is evident from world's attention**

- There are 1115 researchers (from 43 countries) in the international SKA science working group as of March 2021.
- SKA Science Book was published in 2015 with 2000 pages.
- A lot of *Nature/Science* papers from SKA precursors/pathfinders



国立天文台(水沢VLBI観測所)の活動

国立天文台のあゆみ~注視から事業化の本格検討へ

2000年代~	2015-2017	2017.10~	2019.4~
SKA科学技術委員会、SKA理事会に**オブザーバ参加**	大学研究者を**SKA本部等へ長期派遣(大学支援経費)**、情報収集を加速	**水沢VLBI観測所が新部門を立ち上げ**、推進室設置に向けて準備を開始	プロジェクト化の可否検討のために**SKA1検討グループを発足し調査費を措置**

水沢VLBI観測所のあゆみ~将来プロジェクトとしての位置づけ

VERA運用の効率化に取り組み、**プロジェクト経費を一時期より半減**、VERA運用とも両立しながら観測所から検討グループに**フルタイム換算で4名以上(のべ9名)の職務移行**

プロジェクト化に向けた取り組みの例

科学振興

SKA本部からVERAを**SKA先行機に認定**
→SKAJPからのVERA新規ユーザーを獲得し、新分野*を開拓

地域センター(SRC)

上海天文台との**SRC協力に関する覚書の締結**
→職員1名がSKA本部とクロアポしSRCを担当、SRCの開発を加速

技術貢献

SKA天文台とのプレ建設期における**AIVの覚書の締結**
→1.5FTE(のべ5名)の職員を割当て、AIVの新技術*を会得しスタッフのスキルも向上

*突発天体、パルサー、宇宙磁場、宇宙生命など

*仮想化技術、共同ソフトウェア開発環境、ユニットテストモジュール、デバイス制御ツールキットなど

Science Traceability Matrix

- ***Scope of the project: Are the scope and responsibility defined clearly and appropriately?***
- **The followings are the STM for Japanese key science objectives**

Science Objectives	Science Question	Science Target	Science Goals	Science Requirement	Facility	Impact
1.Deciphering the cosmic reionization with cosmology and astrophysics	How were the first stars, black holes, and galaxies born in the Universe? What role did they play in the EoR?	HI line of the intergalactic medium located far beyond the redshift of 7	Detection of HI line with respect to the CMB background	Several sq. deg. FOV, resolution less than a few arcmin, Tsys < a few mK, accurate foreground removal, 50-350 MHz	MWA → **LOW**	Understand the physics of galaxy formation and evolution and the EoR, constrain the IMF of first stars, test the cosmologies beyond the standard theory
2. In-depth/Tomographic study of the magnetic field governing the cosmic hierarchy and activities	How was the magnetic field born and evolved? How has it affected the structure of the Universe?	Astronomical objects from the Sun to the cosmic large-scale structure from the redshift of 0 to 30	Compile x5 larger polarization source catalog (~100/deg2) with information of Faraday depth (RM)	All-sky FOV, 1-10" resolution, high sensitivity (2-4 uJy/beam) and high polarization purity (<30dB), RM resolution less than 1 rad/m2 (=wideband)	ASKAP MeerKAT → LOW Band 1 **Band 2** Band 5	Unveil non thermal part of the Universe, precisely understand the formation and evolution of celestial objects
3. Pioneering long-wavelength gravitational-wave astronomy with pulsar observations	When were SMBHs formed? How did they evolve? Was the cosmic string formed in the early Universe?	Pulsars in the Milky Way (millisecond pulsars)	Compile x5 larger pulsar catalog, measure ToA of stable pulsars with an accuracy of 100 nano second	500 beams pulsar search, 2 weeks cadence and 10 years monitor, optimum frequency for individual FOV	PTAs → **LOW** **Band 1** **Band 2** Band 5	Prove the nHz GW and the method, understand SMBH formation and evolution, limit the amount of cosmic string.

Japan: the required computational resource = 0.1-0.7 PFlops, storage size = 50 PB

2.1 Scope of the project

Key Science Project Parameters

Science Objective	SWG	High Priority Science Objective Number	SKA1 Component	Band	Mode	Frequency			Sensitivity			Observing Area					Integration						
						Range Low - High	Resolution Initial:Cal:Final	Spectral Dynamic Range (I_max/ I_min)	RMS Noise Min:Max @ Beam @ Bandwidth	Brightness Dynamic Range (I_max/ I_min)	Polarisation Dynamic Range (I_max/ P_min)	Total Area	Area of Single Pointing/ Beam	Angular Resolution Min:Max	Targets/ Beams	Tracking	Total	Per Pointing	Dump Rate / Temporal Resolution	Epochs	Cadence Min:Max	# Sessions per Interval	Time per Session
EoR - Imaging AASKA14:001	CD/EoR	1	SKA1-LOW	N/A	Imaging	50 - 200 MHz	4:4:1000 kHz	50 dB	1.4:100 mK @ 300 arcsec @ 1 MHz	50 dB	45 dB	100 deg2	20 deg2	10:1000 arcsec	5 Fields/ 2 StationBeams	Sidereal	5000 hr	2000 hr	0.4 s			1000	5 hr
EoR - Power Spectra AASKA14:001	CD/EoR	2	SKA1-LOW	N/A	imaging/Power Spectrum	50 - 200 MHz	4:4:1000 kHz	50 dB	4.6:330 mK @ 300 arcsec @ 1 MHz	50 dB	40 dB	1000 deg2	20 deg2	10:1000 arcsec	50 Fields/ 2 StationBeams	Sidereal	5000 hr	200 hr	0.4 s			1000	5 hr
			SKA1-LOW	N/A	imaging/Power Spectrum	50 - 200 MHz	4:4:1000 kHz	50 dB	14:1000 mK @ 300 arcsec @ 1 MHz	50 dB	35 dB	10000 deg2	20 deg2	10:1000 arcsec	500 Fields/ 2 StationBeams	Drift	5000 hr	20 hr	0.4 s			1000	5 hr
Pulsar Searching AASKA14:040	Pulsars	4	SKA1-LOW	N/A	Non-Imaging	150 - 350 MHz	20:20:75 kHz	30 dB	20 μJy/Beam @ 145 arcsec Cont	30 dB	25 dB	30000 deg2	11.3 arcmin2	320 arcsec	1 Target/ 500 Tied-Array Beams	Sidereal	12750 hr	40 mn	50 μs			3200	4 hr
			SKA1-MID	SPF1	Non-Imaging	650 - 950 MHz	20:20:75 kHz	30 dB	13 μJy/Beam @ 65 arcsec Cont	30 dB	25 dB	2400 deg2	1.2 arcmin2	105 arcsec	1 Target/ 1500 Tied-Array Beams	Sidereal	800 hr	10 mn	50 μs			100	8 hr
			SKA1-MID	SPF2	Non-Imaging	1250 - 1550 MHz	20:20:75 kHz	30 dB	7 μJy/Beam @ 45 arcsec Cont	30 dB	25 dB	2400 deg2	0.39 arcmin2	60 arcsec	1 Target/ 1500 Tied-Array Beams	Sidereal	2400 hr	10 mn	50 μs			300	8 hr
Pulsar Timing AASKA14:037	Pulsars	5	SKA1-LOW	N/A	Non-Imaging	150 - 350 MHz	20:20:75 kHz	30 dB	10 μJy/Beam @ 8 arcsec Cont	30 dB	40 dB	0.9 arcmin2	65 arcsec2	8 arcsec	50 Targets/ 1 Tied-Array Beam	Sidereal	4300 hr	40 mn	100 ns	130	2 wks	1075	4 hr
			SKA1-MID	SPF2	Non-Imaging	950 - 1760 MHz	20:20:75 kHz	30 dB	3 μJy/Beam @ 7 arcsec Cont	30 dB	40 dB	0.7 arcmin2	50 arcsec2	7 arcsec	50 Targets/ 1 Tied-Array Beam	Sidereal	1600 hr	15 mn	100 ns	130	2 wks	200	8 hr
HI - High z AASKA14:128	HI	13	SKA1-MID	SPF1	Imaging	790 - 950 MHz	4:50 kHz	30 dB	16 μJy/Beam @2-10 arcsec Line	50 dB	35 dB	5.4 deg2	1.1 deg2	3:5 arcsec	5 Fields	Sidereal	5000 hr	1000 hr	0.15 s			625	8 hr
HI - Low z AASKA14:129	HI	14	SKA1-MID	SPF2	Imaging	1300 - 1400 MHz	4:15:20 kHz	30 dB	14 μJy/Beam @2-10 arcsec Line	50 dB	30 dB	3.8 deg2	0.38 deg2	3:5 arcsec	10 Targets	Sidereal	2000 hr	200 hr	0.15 s			250	8 hr
HI - Galaxy AASKA14:130	HI	15	SKA1-MID	SPF2	Imaging	1415 - 1425 MHz	0.5:4 kHz	30 dB	75 μJy/Beam @2-10 arcsec Line	45 dB	30 dB	1080 deg2	0.38 deg2	5:60 arcsec	2840 Pointings	Sidereal	12600 hr	4.4 hr	0.15 s			1575	8 hr
Transients - FRB AASKA14:055	Transients	18	SKA1-MID	SPF1	Non-imaging/ Commensal	650 - 950 MHz	20:20:75 kHz	30 dB	7 mJy/Beam @ 65 arcsec Cont	30 dB	25 dB	30000 deg2	1.2 arcmin2	105 arcsec	1 Target/ 1500 Tied-Array Beams	Sidereal	10000 hr	2 msec	50 μs	1.20E+06	2 msec	1250	8 hr
CoL - Planet formation AASKA14:117	Cradle of Life	22	SKA1-MID	SPF5	Imaging	8 - 12 GHz	80:80:4000 kHz	30 dB	80 nJy/Beam @ 0.04 arcsec Cont	40 dB	25 dB	0.05 deg2	0.005 deg2	0.04:1 arcsec	10 Targets	Sidereal	6000 hr	600 hr	0.15 s			750	8 hr
Magnetism - RM-grid AASKA14:092	Magnetism	27	SKA1-MID	SPF2	Imaging	1000 - 1700 MHz	10:1000 kHz	30 dB	7 μJy/Beam @ 2 arcsec Cont	45 dB	30 dB	31000 deg2	0.38 deg2	2 arcsec	81600 Pointings	Sidereal	10000 hr	7.4 mn	0.15 s			1250	8 hr
Cosmology - High z IM AASKA14:019	Cosmology	32	SKA1-MID	SPF1	Auto-correlations	350 - 1050 MHz	10:300 kHz	45 dB	3.3 mJy/Beam @ 1.7 deg Line	40 dB	40 dB	30000 deg2	1.4 deg2	1.7 deg	21500 Pointings	Drift	10000 hr	2.2 hr @ 190 Dishes	0.15 s			1250	8 hr
Cosmology - ISW, Dipole AASKA14:018, 032	Cosmology	33	SKA1-MID	SPF2	Imaging	1000 - 1700 MHz	10:1000 kHz	30 dB	7 μJy/Beam @ 2 arcsec Cont	45 dB	30 dB	31000 deg2	0.38 deg2	2 arcsec	81600 Pointings	Sidereal	10000 hr	7.4 mn	0.15 s			1250	8 hr
Continuum - SFR(z) AASKA14:067	Continuum	37 + 38	SKA1-MID	SPF2	Imaging	1000 - 1700 MHz	10:1000 kHz	30 dB	1.3 μJy/Beam @ 0.5 arcsec Cont	60 dB	30 dB	1000 deg2	0.38 deg2	0.5:1 arcsec	2600 Pointings	Sidereal	10000 hr	3.8 hr	0.15 s			1250	8 hr
			SKA1-MID	SPF2	Imaging	1000 - 1700 MHz	10:10:1000 kHz	30 dB	0.25 μJy/Beam @ 0.5 arcsec Cont	60 dB	30 dB	7.8 deg2	0.38 deg2	0.5:1 arcsec	21 Pointings	Sidereal	2000 hr	95 hr	0.15 s			250	8 hr
			SKA1-MID	SPF2	Imaging	1000 - 1700 MHz	10:10:1000 kHz	30 dB	65 nJy/Beam @ 0.5 arcsec Cont	60 dB	30 dB	0.38 deg2	0.38 deg2	0.5:1 arcsec	1 Pointings	Sidereal	2000 hr	2000 hr	0.15 s			250	8 hr
			SKA1-MID	SPF5	Imaging	7 - 11 GHz	80:80:4000 kHz	25 dB	400 nJy/Beam @ 0.05 arcsec Cont	45 dB	30 dB	0.5 deg2	30 arcmin2	0.05:1 arcsec	61 Pointings	Sidereal	1000 hr	16.4 hr	0.15 s			125	8 hr
			SKA1-MID	SPF5	Imaging	7 - 11 GHz	80:80:4000 kHz	25 dB	50 nJy/Beam @ 0.05 arcsec Cont	45 dB	30 dB	30 arcmin2	30 arcmin2	0.05:1 arcsec	1 Pointing	Sidereal	1000 hr	1000 hr	0.15 s			125	8 hr

Japanese members have contributed the development of the above KSPs

SKA JPなどの活動経緯

SQUARE KILOMETRE ARRAY
NAOJ SKA1 STUDY GROUP

コミュニティのあゆみ~14年目を迎え成熟

国際活動

2011
東アジア
SKA科学
会議

2012-2014
「頭脳循環」
SKA関係国に
長期滞在

2013 東アジアSKA科学会議

2015年-2017年
「大学支援経費」
SKA本部に長期滞在

2016~
MWAに
正式参加

2018 ASKAP・MWAの
国際会議を国内に招致

2019 東アジア
SKA科学会議

2021 東アジア
SKA科学会議

2010/2011
マスタープラン
重点大型計画

2014 マスタープラン
重点大型計画

2017 マスタープラン
提案見送り

2020 マスタープラン
重点大型候補

2020 日本版白書の更新

国内活動

2008
日本SKA協会発足

2013 宇宙電波懇談会
シンポジウムSKA特集

2015 日本版SKA科学白書の出版

2015 日本天文学会セッション

2015 SKA-Japan
ワークショップ

2016 SKA-Japan
シンポジウム

2017 日本物理学会セッション

2017 水沢SKA科学報告書の出版

2019 SKA-Japan
シンポジウム

2021 SKA-JP
科学戦略会議

過去13年実績：論文405編、獲得資金3.72億円(間接経費込)、修士151名博士31名

Chibueze+21(Nature)やEnoto+21(Science)など先行機や国内鏡での観測で存在感示す

SKAへの参加費を含めた**大型科研費を申請中**

SQUARE KILOMETRE ARRAY
NAOJ SKA1 STUDY GROUP

1. 科学検討

SKA-LOW-VLBI検討

- **300MHz帯VLBIの重要性が国際的に認識される(2019 SKA-VLBI国際会議)**
  - 日本から飯館・豊川の参加の可能性
- **SKAJPでの検討状況(9件) →**

SKA−VLBI 性能諸元

2020 年 9 月 15 日
今井 裕(鹿児島大学)、青木貴弘(山口大学)
赤堀卓也(国立天文台)、小林秀行(国立天文台)

概要 この文書では SKA 計画の外観をまとめた上で、SKA−VLBI の感度、角度分解能、視野などの性能諸元を示す。末尾には、本検討に用いた情報をまとめる。

付録 B2. SKA1−LOW 局とパートナー局の基線感度(300sec, 16 MHz)

	周波数 [GHz]	.150	.235	.325
アンテナ名	国名	感度 [μJy]		
MWA	Australia	383	107	75.7
GMRT 45m	India	985	587	415
GMRT (all)	India	180	107	75.7
Iidate	Japan	953	678	526
FAST	China	96.8	69.2	54.0
LOFAR Station	Europe	1021	1548	2282

付録 C2. SKA1−LOW 局とパートナー局の基線長と角度分解能

	周波数 [GHz]	.150	.235	.325
アンテナ名	基線長 [km]	分解能 [mas]		
MWA	0	0	0	0
GMRT 45m	6867	60	39	28
GMRT (all)	6867	60	39	28
Iidate	7597	54	35	25
FAST	5923	70	45	32
LOFAR Station	13666†	30	20	14

†コモンスカイがほとんどないため 1 日の間に観測できる時間がわずかに限られる

- **z~4の衝突銀河**のOHメーザー探査
- **ガンマ線連星**HESS J0632+057の300 MHz帯VLBI観測を軸とした多波長同時観測で探るガンマ線の起源
- **系外超新星(残骸)における若い中性子星**の探査およびCSMとの相互作用をプローブとした親星の質量推定
- **太陽系外惑星**の電波放射(アストロメトリを用いた主星電波との切り分け)
- 300MHz帯VLBI観測による**かに星雲**wisps構造の時間変化 (Magnetism)
- **X線連星ジェット**の多周波数偏波観測
- 300MHz 帯VLBI観測による**系外銀河核周円盤の磁場**探査
- マゼラン雲内部の**パルサー探索**
- アンドロメダ銀河等での**パルサー探索**

1. 科学検討

https://www.skatelescope.org/wp-content/uploads/2020/02/ScienceCase_band6_Feb2020.pdf

15GHz以上の科学事例検討

Freq. (GHz)	0.05	0.3	1.0	1.7	3	5	8	15	25~50
	LOW	Band 1	Band 2	Band 3	Band 4	Band 5a	Band 5b	Band 6/7	

Band B (8–50 GHz)

■高周波観測の実現性

＊280ミクロン

- 主鏡鏡面RMS誤差要求＊はVLAと同等
- 15-50 GHzのシーイングもVLAと同等
- MIDもMeerKATも空きスロット一つあり
- 15-25GHzは技術的な達成見込み高い

■高周波観測の科学事例と要求

1. Introduction
2. Solar System
3. Astrochemistry and the formation of stars and planets
4. Galactic Structure
5. Nearby Galaxies
6. Cosmology and the History of the Universe
7. Transient Phenomena

日本人も著者で多数参加
筆頭5名・共著12名

Tomoya Hirota (3.9PI, 3.10Co, 7.3Co)
Kazuhiro Hada (5.4PI)
Takuya Akahori (7.3PI, 5.4Co)
Kohji Yoshikawa (6.6PI)
Haruka Sakemi* (7.5PI)
Yoshi Hirata* (3.7Co)
Takeru Murase* (3.7Co)
Toshihiro Handa (3.7Co)
Hiroshi Imai (3.8Co)
Koichiro Sugiyama (3.8Co)
Sujin Eie* (7.3Co)
Takeru Enoto (7.3Co)
Takahiro Aoki (7.3Co)
Tomoaki Oyama (7.3Co)
Mami Machida (7.5Co)
*当時大学院生