The Next Generation Very Large Array - planning towards a Japanese contribution

Alvaro Gonzalez
On behalf of the ngVLA study group

Modified from original – Some information has been removed

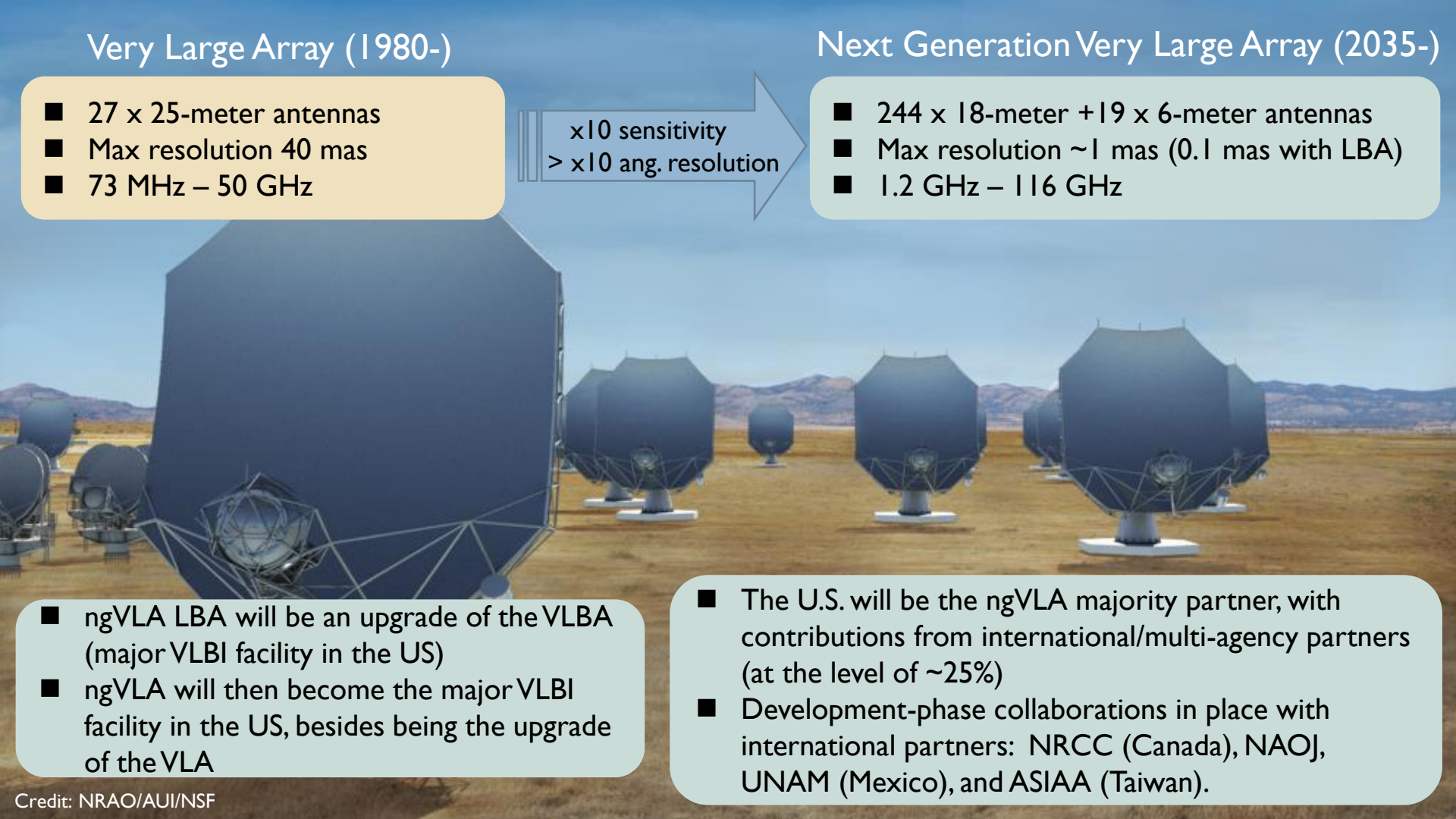
Very Large Array (1980-)

- 27 x 25-meter antennas
- Max resolution 40 mas
- 73 MHz – 50 GHz

x10 sensitivity
> x10 ang. resolution

Next Generation Very Large Array (2035-)

- 244 x 18-meter +19 x 6-meter antennas
- Max resolution ~1 mas (0.1 mas with LBA)
- 1.2 GHz – 116 GHz



- ngVLA LBA will be an upgrade of the VLBA (major VLBI facility in the US)
- ngVLA will then become the major VLBI facility in the US, besides being the upgrade of the VLA

- The U.S. will be the ngVLA majority partner, with contributions from international/multi-agency partners (at the level of ~25%)
- Development-phase collaborations in place with international partners: NRCC (Canada), NAOJ, UNAM (Mexico), and ASIAA (Taiwan).

Credit: NRAO/AUI/NSF

I. The ngVLA Instrument

Credit all figures: NRAO

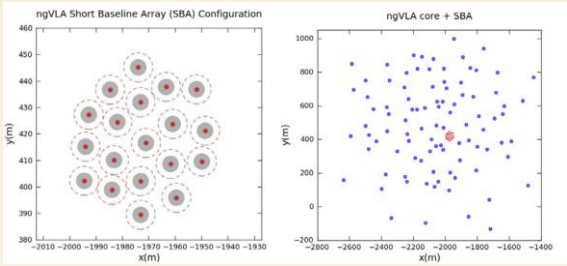
Array and Receiver Components

Main Array (MA)

- 214 x 18m offset Gregorian antennas
- Up to 1000 km baselines
- Fixed antenna locations near VLA site

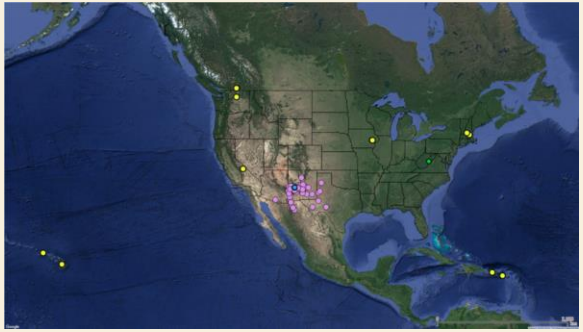
Short Baseline Array (SBA)

- 19 x 6m antennas
- 4 x 18m in TP mode to fill in (u, v) hole for imaging extended structure



Long Baseline Array (LBA)

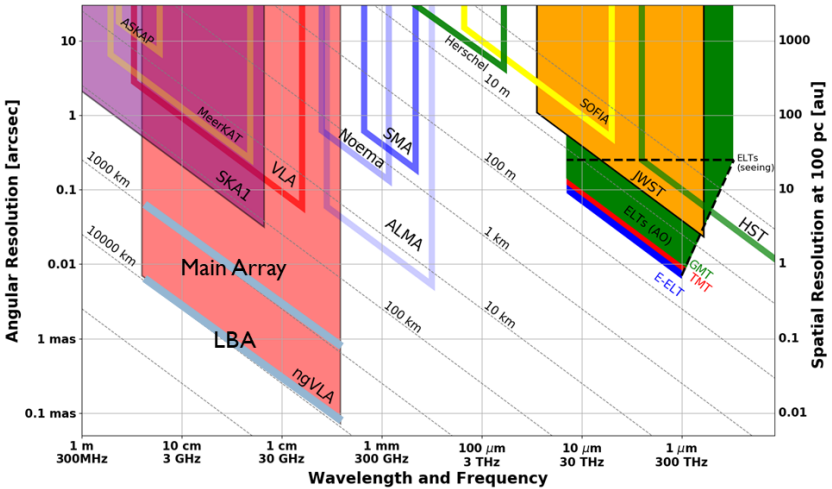
- 30 x 18m antennas located across continent for baselines up to ~9000km
- Operated in **VLBI** mode
- Max angular resolution = 0.1 mas

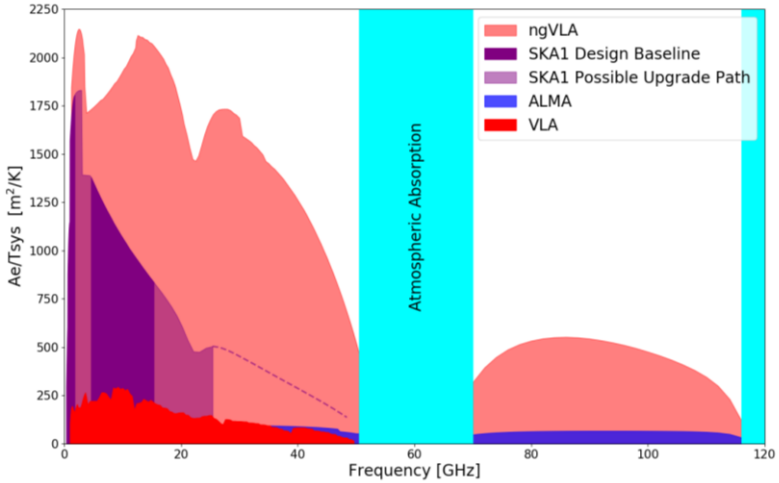


Band #	f_L GHz	f_H GHz	RF BW GHz	Major Emission Line
1	1.2	3.5	2.3	HI, H_2CO, H_2CS, OH
2	3.5	12.3	8.8	CH, H_2CO, SO_2
3	12.3	20.5	8.2	CH_3CN, CH_3OH, NH_3, SO
4	20.5	34.0	13.5	H_2O, NHD_2, NH_3
5	30.5	50.5	20.0	SO, SiO, CH_3OH, CS
6	70.0	116	46.0	CO, HCN, HCO^+, DCN

Angular Resolution / Sensitivity

Credit all figures: NRAO





Just Main Array:

- 10 x higher angular resolution than ALMA if we compare the highest angular resolution.
- 100 x times higher if we compare at the overlap frequency (100GHz)

LBA adds 10x resolution

Sensitivity improvement as large as a factor of 10x compared to existing instruments such as VLA or ALMA

Key Operation Concepts: a PI-science facility

Focus on PI science

Observing time will be allocated through open call for proposals following shares of contribution. It will include Open Skies

Proposal Evaluation

Peer review system will be adopted. Proposals will be evaluated based on scientific merit and technical feasibility

Time Allocation

PI is awarded time and not sensitivity. This is different from ALMA.

Data Product

Pipeline will automatically generate Science Ready Data Products for most standard projects (~80%). Expert modes will exist too.

Dynamic Scheduling

Time allocated dynamically according to the priority built into the queue.

Array Availability

No reconfiguration, meaning that the array will be used continuously with minimum downtime. Subarrays will be used for maintenance and commissioning activities

II. Background of the Study Group & Organization

The ngVLA Study Group

- In Japan, the origins of the ngVLA Study Group were two-fold:

1. Japanese Radio Astronomers started getting engaged in the science activities leading to the definition of ngVLA science case
2. The NAOJ ALMA Project initiated discussions with NRAO through the well-established ALMA collaboration based on the Community discussion.
   - ngVLA was identified as the future project plan which could help increase the scientific impact of ALMA even further

- The interest of the Community and the positive discussion between NAOJ ALMA Project and NRAO led to the creation of the ngVLA Study Group in FY2019 to explore an in-kind contribution unique from Japan based on the technical development heritage of NRO, ASTE and ALMA.
- Strong support from Udenkon as one of the top future priorities of the radio community

- Scientific activities are led by Community members in Japanese Institutes and Universities in collaboration with NAOJ staff
- Technical development is led by NAOJ exploiting synergies with ALMA Dev., and considering the involvement of the Community
- The management interface to NRAO is provided by NAOJ through the well-established collaboration in ALMA
  - A collaboration agreement was signed in April 2020 to extend collaboration beyond ALMA, to initial studies in ngVLA collaboration in technology development, among others
- Most SG members contribute through modest effort but high motivation!

Scientific involvement with NRAO and in Japan

- NRAO involved Japanese Community members early on through participation via SAC, TAC, Community Studies
- On the other hand, NRAO is seeking for a few selected international partners to contribute about 25% of the project costs.
- Inaugural international development meeting: Socorro (May 2019)
  - NAOJ invited; NRAO provided project overview; Initial discussion on possible interest in terms of construction deliverables
- NAOJ-ngVLA workshop, Mitaka (Sept 2019)
  - First ngVLA workshop outside of the United States
- Kikaku-session in ASJ Annual Meeting 2021 Spring with >170 participants
- ngVLA Development Days, online (July 2021)
- ngVLA-J memo series linked in NRAO website (2021)
- The ngVLA-J Project Book was published in October 2021
- NAOJ involved in key Working Groups (2020-2022): Total Power WG, VLA-ngVLA Transition WG, etc

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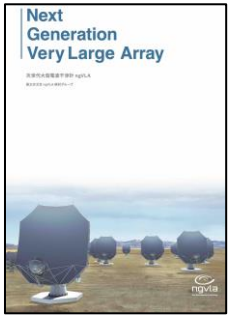

ngVLA Science/Technical Advisory Council

Science Advisory Council (2022-)

Modified from original – Names removed
Source information available publicly at:
https://ngvla.nrao.edu/page/sciencecouncil

4 members from Japan (3 from universities, 1 from NAOJ)

Technical Advisory Council

Modified from original – Names removed
Source information available publicly at:
https://ngvla.nrao.edu/page/technicalcouncil

2 members from Japan

Organization Synergies within ALMA / NAOJ

Construction/operation synergies with ALMA

- Human resources
- International relationship
- Knowledge
  - Project management
  - User support
  - Document control
  - Public outreach
- Engineering
  - Component level studies
  - Development, verification and integration and verification of receivers
  - Antenna manufacturing (with industry)
  - CSV/AIV
- Computing
- Science promotion

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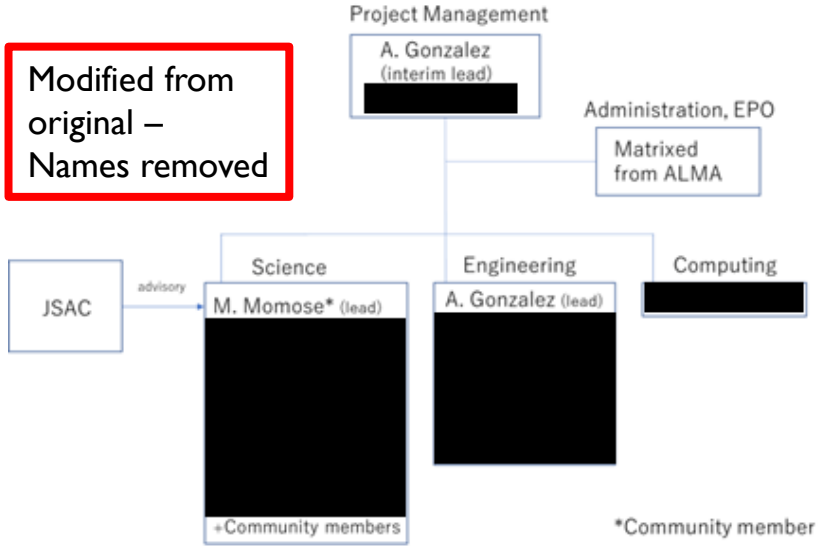

In the near term

Small effort contributions from many staff in the ALMA Project and other NAOJ Divisions (ATC, DoS, TMT) with support from the community

A few staff will focus on particular deliverables for certain periods of time.

III. Science Goals to be achieved by Japan

Key Science Goals

KSG1: Unveiling the Formation of Solar System Analogues on Terrestrial Scales

KSG2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

KSG3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present

KSG3: Using Galactic Center Pulsars for a Fundamental Test of Gravity

KSG4: Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

Modified from original – Images and scientific results removed

ASTRO2020: ngVLA-One of top priorities for US community

Excerpts from: Pathways to Discovery in Astronomy and Astrophysics for the 2020s, National Academies (USA). Available at: https://nap.nationalacademies.org/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s

ASTRO2020 recommendation

- Tied for 2nd top priority in the large ground-based telescopes, just after the US ELT (TMT + GMT), together with CMB-S4

A project of great scientific impact and influence in many fields of astronomy:

- "The ngVLA project is a powerful observatory that will replace both the JVLA and VLBA"
- "The project would have broad, flexible capabilities and provide science-ready data products accessible to a diverse community of users."
- "Such a facility would advance multiple high priority science questions from each of the six Science Panels, and open discovery space."
- "The ngVLA facility would be absolutely unique worldwide in both sensitivity and frequency coverage"

Critical importance for US astronomy in terms of science:

- CONCLUSION of ASTRO2020: "It is of **essential importance to astronomy that the JVLA and VLBA be replaced by an observatory** that can achieve roughly an order of magnitude improvement in sensitivity compared to these facilities, with the ability to image radio sources on scales of arcminutes to fractions of a milliarcsecond."

Scientific Synergies with other NAOJ instruments

Synergies with ALMA

	ALMA	ngVLA
Continuum SED	Dust (+ free-free)	Synchrotron (+free-free, dust)
Protoplanetary disks	Outer gaseous planets, smaller dust particles	Inner rocky planets, larger dust particles ("pebbles")
ISM in nearby universe	CO, CI, Small molecules, Simple organic mol.	HI, NH_3, Large molecules, including N-bearing organic mol.
High-z	High-J CO	Low-J CO

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Synergies with Subaru/TMT

- Same sky coverage (both ngVLA and Subaru/TMT are located in the northern hemisphere)
- Follow-up of high-z galaxies discovered by wide FOV surveys by the Subaru/HSC
- Formation and evolution of exoplanets, including the origins of planetary atmosphere with disk chemistry

➢ Investigating multi-wavelength synergy (incl. optical, X-ray) is one of the main objectives for the study group in FY2022-2023

Without ngVLA, we will miss the important detailed information regarding the formation of inner rocky planets like the earth, formation of stars in early galaxies, and understanding the chemical complexity (and ultimately to life) in the universe.

Science Working Groups in Japan

Modified from original – Name of SWG leads changed to their corresponding current main affiliations

FY2020-2021

- **5 Science WGs** in close collaboration with community: **14 online meetings in FY 2020 + lead discussion of MP2023 in FY2021**
  - SWG1: Formation of Planetary Systems (Lead from Ibaraki University)
  - SWG2: Star Formation and Astrochemistry in nearby Universe (Lead from Nagoya University)
  - SWG3: Evolution of Galaxies Over Cosmic Time (Lead from NAOJ)
  - SWG4: Using Pulsars in the Galactic Center as Tests of Gravity (Lead from Yamaguchi University)
  - SWG5: Evolution of Stellar and Supermassive BH's in the Era of Multi-Messenger Astronomy (Lead from NAOJ)
- Outcome
  - **Kikaku-Session** in ASJ annual meeting 2021 spring with > 170 participants
  - **29 ngVLA-J memo**
  - Science Sections of **ngVLA-J project book**

FY2022-2023

- **Science WGs "Ver. 2" with New Leads**
  - SWG1 : (**NAOJ**, **Kyoto Univ**, Ibaraki Univ)
  - SWG2 : (**Kyoto Univ , Gifu Univ**, Nagoya Univ)
  - SWG3 (Univ Tokyo, **Gifu Univ**, NAOJ)
  - SWG4 : (**Kanagawa Univ, Tokyo Metropolitan Univ**, Yamaguchi Univ)
  - SWG5 : (**Kanagawa Univ, Tokyo Metropolitan Univ**, NAOJ)

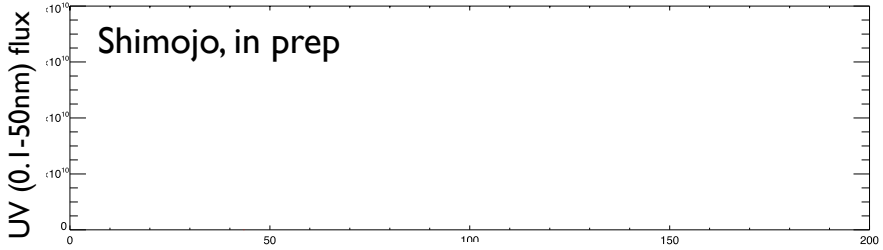
  → **Exploring further the topics that span multiple SWGs**

  → **Synergies with future instruments at other wavelengths in Astronomy and adjacent fields (Planetary sciences, High-energy physics, Astrobiology etc.)**
- **Resume community meetings from Jan. 2023 & their Goals**
  - Addition of **ngVLA-J memos + Summary document** by the end of FY2023
  - **Promotion to more research groups** in the community

Key Science Goal 6. Characterizing the Planetary Conditions in the Habitable Zone by Quantifying the UV Radiation from Stellar Atmospheres

Probe the strength of the stellar UV field by observing the cm emission from a stellar atmosphere, which has a profound effect on the planetary environment, affecting the atmospheric conditions such as the amount of carbon dioxide, determining the surface temperature, and impacting the possibility of planetary water, which leads to the representation of the "habitable zone".

The cm and UV are emitted from the same layer of the stellar atmosphere (Avrett & Loeser 2008).



ngVLA will probe:

- The activity level and strength of the UV field of stellar atmosphere
- The behavior of non-thermal electrons accelerated in stellar flares

Requirement:

10x sensitivity of JVLA, Polarization accuracy of < 1%

Japan has a 70-year history of monitoring the Sun with cm-waves using Toyokawa and Nobeyama Radio Polarimeters, which corresponds to ngVLA Band 1-6. Detailed comparison is possible!

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Science Requirements

	Science Goal	Detailed observation	Requirement
5 top level science goals (consistent with US/NRAO science goals)	Imaging the Sites of Planetary formation and Proto-planetary Disks	High resolution imaging of inner rocky planets	5mas, 0.02microJy (@30GHz)
	Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry and Astrobiology	Detect and image key molecules related to life	<50mas, ~0.1km/s
	Tracing Galaxy Evolution Through Cold Molecular Gas	Detect and image redshifted CO(1-0)/CO(2-1)	10mas, covering 10-116GHz (z=0-15)
	Using Pulsars to Pinpoint the Location of Gravitational Waves in the Milky Way Galaxy	Measure distance to milli-second pulsars and characterize gravitational waves in the galaxy	Astrometric accuracy of 0.1%
	Understanding the Formation and Evolution of Supermassive Black Holes in the Era of Time domain/Multi-Messenger Astronomy	Image the gas surrounding blackholes. Follow time evolution of BH and Neutron Star mergers.	0.1mas, time resolution of minutes
New goal from Japan	Characterizing the Planetary Conditions in the Habitable Zone by Quantifying the UV Radiation from Stellar Atmospheres	Image the cm emission from the star, and detect circular pol from sunspots of the star	10x sensitivity of JVLA, Polarization accuracy of < 1%

IV. Status of Technical Work in Japan

Possible hardware contributions from Japan

A good mix of Japanese in-kind contributions to the project tentatively agreed between NAOJ and NRAO in line with NAOJ / industry / community heritage and expertise, and the well-established collaboration through ALMA

Possible Japanese Hardware Deliverables to the ngVLA project

- Antennas (up to 53 units in SBA, LBA, TP)
- Photonic technologies: time-frequency ref. distribution
- Receivers: design of components, prototyping and production at ATC (using 3D printing)
- Cryogenics: cold-heads, compressors, dewars

NAOJ has initiated antenna design studies from FY2019 through small contracts with industry

Possible contribution of 20% of total number of antennas: 30 18-m antennas for LBA, 4 18-m antennas for TP observations, 19 6-m antennas for SBA
These antennas can be contributed at a later stage of construction, allowing Japanese contribution after TMT

Large construction budget needed post-TMT construction:

Year	Scale	Budget Use
FY2023-2025	Small	• Detailed studies and preparation towards prototyping
FY2026-end of TMT construction	Medium-Large	• Prototyping (incl. antennas) and testing • Start of construction
end of TMT const- FY2040	Large	• Full construction

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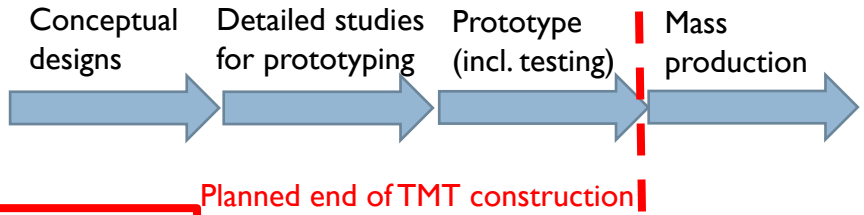
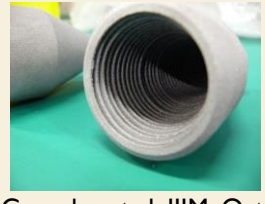
Plan for antennas:



Unique contribution from NAOJ ATC

3-D printing

Development of 3D printing of receiver components for effective mass-production



35-50 GHz AlSi10Mg corrugated horn successfully fabricated and tested at cryogenic temperature

Gonzalez et al, IJIM, Oct 2021

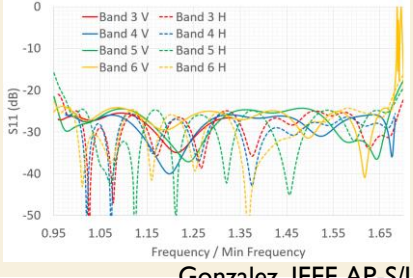
67-116 GHz AlSi10Mg corrugated horn + transition + OMT, fabricated in a single piece for improved performance

Gonzalez et al, SPIE 2020

Receiver development

Design of custom waveguide components for ngVLA receivers based on heritage from ALMA

Simulated performance of OMTs designed for ngVLA bands 3 through 6, all of them better than -24 dB at all frequencies

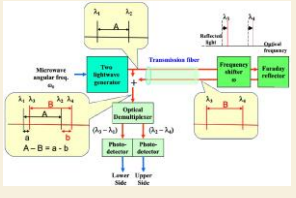


Gonzalez, IEEE AP-S/URSI 2020

Photonic technologies

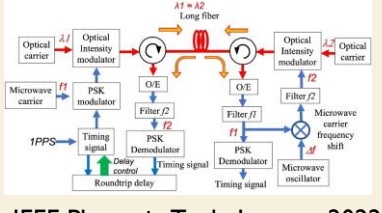
NAOJ proposals included in the conceptual design of ngVLA: time and frequency distribution systems

Measured transmission phase stability of 100GHz signal through a 250 km fiber spool using a novel technique



Kiuchi, Shillue, SPIE 2020

Novel high-accuracy time distribution successfully demonstrated over 250km



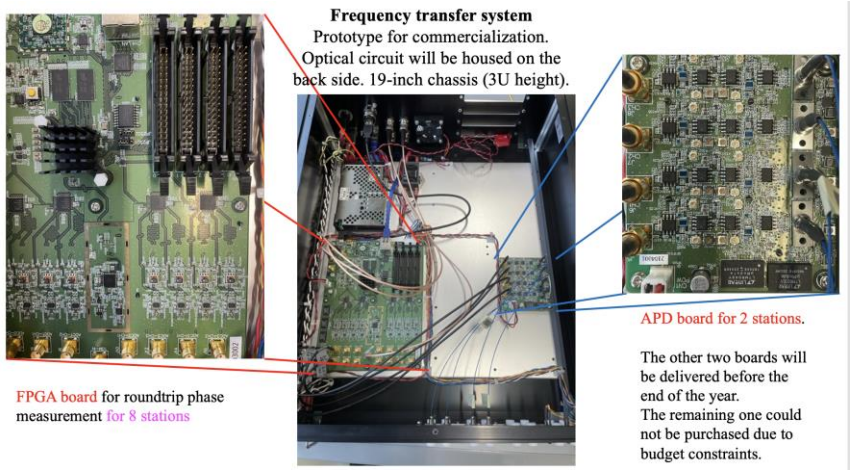
Kiuchi, IEEE Photonic Tech. Letters, 2022

NAOJ Advanced Technology Center is leading the field in several advanced technologies which can be readily applied to ngVLA: time and frequency distribution systems, waveguide components in receivers fabricated by 3D printing…

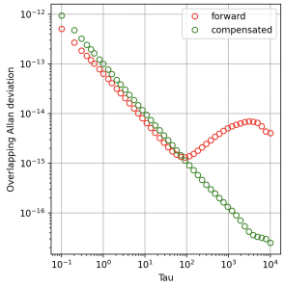
Photonic technologies

Leverage of ALMA development knowhow
Key researchers: H. Kiuchi, M. Fujieda

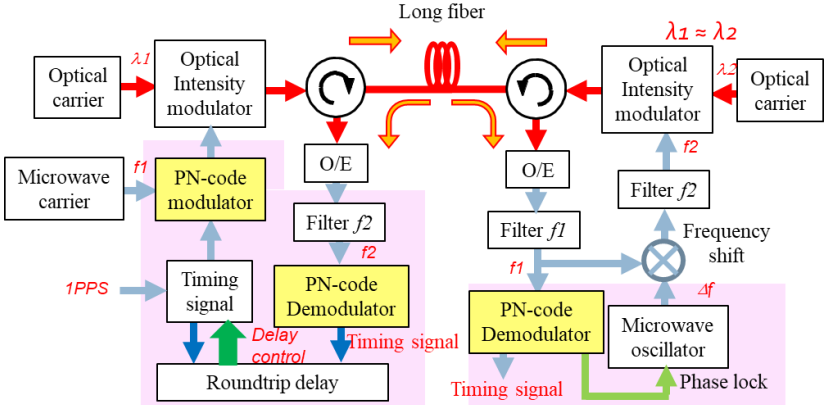
Frequency transfer system: prototype tests ongoing



Measured phase stability (co-variance) between two 100km transmission systems



Time transfer system: prototype under fabrication based on novel idea



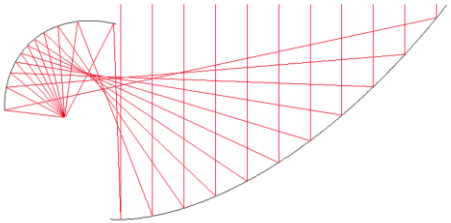
Adapted by the author from: Kiuchi, IEEE Photonic Tech. Letters, 2022

Plan for prototyping (in pink):
1 board (simultaneous delay measurement for 8 stations) for reference station
2 boards for remote stations

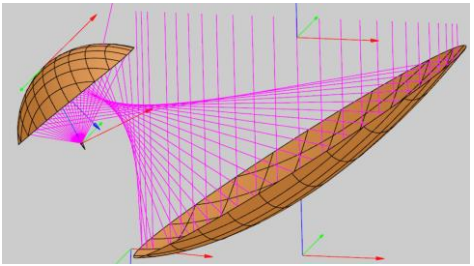
In-house antenna design

- At the request of NRAO, NAOJ is working on 6-m antenna optical designs
- Optimization with ray tracing
  - to modify the amplitude distribution (uniform -> Gaussian), the ray spacings were adjusted.
- Verification with full-wave simulation
  - the standard PO simulation was carried out to see how high aperture efficiency the obtained design achieves.
- Initial design done with Gaussian feed.
- Next steps: (1) use of actual feed horn design provided by NRAO, (2) refining the mirror periphery and outer shapes
  - Performance improvement expected

Leverage of ALMA development knowhow
Key researcher: H. Imada



ray-tracing result



PO sim. model

frequency	aperture efficiency	cross-polarization level	spillover efficiency
12.3 GHz	0.910	-41.9 dB	0.978
15.9 GHz	0.912	-42.1 dB	0.979
20.5 GHz	0.914	-42.3 dB	0.979

V. Significance of NAOJ lead

One of the great upcoming Large-Scale facilities

- ngVLA will be one of the great worldwide Large-Scale facilities in the 2030s-, playing a key role in scientific discovery together with ALMA and TMT, with interest and support by the Japanese Community

- The involvement of NAOJ in ngVLA is clearly in line with NAOJ Vision and Mission:
  - "To be innovators striving to solve the mysteries of the Universe."
  - "To develop and construct large-scale cutting-edge astronomical research facilities and promote their open access aiming to expand our intellectual horizons."

- ngVLA satisfies all key points for NAOJ participation:
  - One of the most advanced observing facilities in the world
  - Open use
  - Flexible international cooperation
  - Strong synergies with ALMA, TMT and Subaru

- A share of contributions by Japan in the order of 20% would allow the Japanese Community to access ~20% of observing time, which would allow to make the most of synergies with other NAOJ facilities:
  - This is comparable with our share of contributions in ALMA (25% - Oversubscription ~6!)
  - Such a budget scale (~hundreds M USD) is unfeasible for universities

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Role of Japan in International Project

- NAOJ and NRAO have a strong history of collaboration in the last 20 years through ALMA

- NRAO is interested in seeking about 25% international contribution to ngVLA from a few trusted and well-established partners.
  - Other prospective partners so far are Canada, Mexico and Taiwan

- NRAO established the International Development Consortium in 2019 to discuss possible contributions by Japan, Canada, Taiwan and Mexico
  - Japan has participated in the IDC from the first day
  - Initial interest in in-kind contributions to the project have been expressed by these prospective partners
  - Japanese contributions have been tentatively agreed with NRAO and would account for ~20% of constructions costs (NOTE: Antennas are a key deliverable for large participation)
  - Agreed contributions exploit NAOJ and Japanese industrial expertise and experience, and can find important spin-offs to community-led domestic projects and education

- An Agreement for Scientific and Technical Collaboration was signed between NAOJ and NRAO in April 2020 to extend our collaboration beyond ALMA, incl. initial studies in ngVLA

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Scope and Responsibilities

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20% Japanese contribution to the ngVLA project

This will in turn guarantee ~20% of the ngVLA observing time (~1600 hours/yr) for the Japanese community, leading to high science production with a publication rate comparable to that of ALMA (~70 papers/yr in Japan).

- A good mix of Japanese in-kind contributions to the project tentatively agreed between NAOJ and NRAO in line with NAOJ / industry / community heritage and expertise, and the well-established collaboration through ALMA

Phase of the project	Japanese Deliverables to the ngVLA project
Construction and commissioning	• Antennas (up to 53 units in SBA, LBA, TP) • Photonic technologies: time-frequency reference distribution • Receivers (design of components, prototyping and production at ATC) • Cryogenics: cold-heads, compressors, dewars • Commissioning of observing modes and software development • New analysis tools (e.g. sparse modeling), archive, phase correction
Operation	• Maintenance of antenna, cryogenics, receivers, reference signal distribution • Development and maintenance of software / archive (integrated computing team) • User support and science promotion

VI. Budget planning

Budgetary considerations

- The total construction budget is estimated by NRAO to be ~2,3B USD
- ~75% (1,7B USD) would be covered by the U.S.
- Remaining ~25% (0.6B USD) is expected to be contributed by international partners
- The ngVLA Study Group aims that Japan joins the ngVLA collaboration at a 20% level through the international contribution channel, which will amount to about 460 MUSD for the construction phase and about 18-19 MUSD during operations.

Reference: https://ngvla.nrao.edu/page/faq
What is it going to cost?

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Budgetary considerations in Japan

Goal: Post-TMT project in NAOJ

Year	Scale	Budget Use
FY2023-2025	Small	• Detailed studies and preparation towards prototyping
FY2026-end of TMT construction	Medium - Large	• Prototyping (incl. antennas) and testing • Start of construction
End of TMT construction -FY2040	Large	• Full construction

Modified from original – Example budget profile removed, others

- Japan needs to be ready to contribute heavily to construction after completion of TMT construction.
- However, we need appropriate budget from FY2023 and substantial budget from FY2026
- Highest priority would be TMT until the end of its construction both for the US (ASTRO2020) and Japan
- Large construction budget necessary until the end of the 2030s

Budget Sources in Japan

FY2019-FY2025: Development studies and preparation towards large-scale prototyping

-May be possible through NAOJ Leadership funds and external budget requests / collaboration and synergies
-Some ATC development can be contributed to ALMA, ngVLA (and other projects, e.g. from the community)
-Different activities based on availability of funds

FY2026-End of TMT construction: Antenna and HW prototyping and validation tests

- Frontier budget necessary

Commitment by Japan during this phase will be essential to realize ngVLA and support US / NRAO plans

If appropriate budget is not secured, the contribution by Japan could only be at the level of ~a few %, with a huge impact on the scope of the project, scientific return and involvement of the Japanese community.

Earlier availability of this budget would allow to reduce the annual budget needs and for longer testing and commissioning time

End of TMT construction-FY2040: Construction

- Frontier budget necessary

Modified from original

The need to contribute antennas

Why does Japan need to build antennas?

- NAOJ has extensive experience with compact arrays (ALMA Morita Array / ACA) and VLBI, both from hardware and software perspective. NRAO is relying on the advanced technical skills NAOJ/Japanese industry can offer.
- Strengthen the relationship with the private sector (SDG perspective)
- Operation frequency of ngVLA is consistent with the domestic telescopes at NRO and VLBI. This has several advantages, such as
  (1) prototype testing at domestic sites,
  (2) apply the same state-of-the-art technology at university led facilities for education,
  (3) science synergies with existing domestic telescopes (e.g. high resolution follow-up of sources observed at NRO).

What happens if Japan does not contribute antennas?

- The contribution would be limited to a few % of construction costs
- The merit of getting involved in the project is less in terms of scientific outcome and differential value of our contribution with respect to Open Skies

Modified from original

VII. Heritage

Top level summary – Japan's strengths & impact in joining ngVLA

High community demand for a next generation PI-driven cm/mm instrument

- Strong community interest (high # of participants in workshops, strong recommendation by Udenkon)
- Increasing number of Japanese ngVLA publications (memo series, project book)

Japanese contribution based on experience in ALMA construction and operation

- Various items with sufficient technical readiness (antennas, receivers, photonics, cryogenics)
- Rich experience in commissioning and software development together with NRAO
- Well-established connections with industry

Synergies and integration within NAOJ

- Open-use operation with full user support (like ALMA) → maximizing know-how and experience
- First case of combined operation with VLBI → efficient

Impact on industry and universities

- Possibility of large involvement of Japanese industry.
- Positive impact on engineering and technology for manufacturing (e.g., 3-D printing at ATC)
- Wavelengths observable from Japan: possibility to test prototypes on-sky and to do observations
- Possibility to collaborate with universities/institutes: Education, domestic projects, and other community-led ideas and collaborations

Building on NAOJ / Japan Radio Heritage

Technology dev. / Training of human resources / Education / Spin-off to Community initiatives / Industry Collaboration

mm-wave SD / interferometry

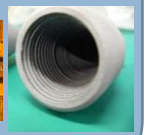
NRO

submm-wave SD

ASTE

(Sub)mm-wave SD / interferometry

ALMA



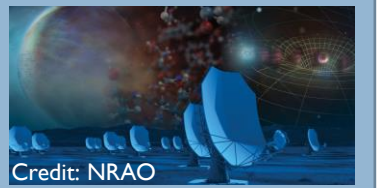
VLBI

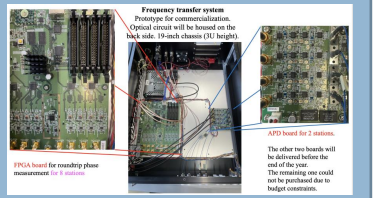
JVN / VERA / Others

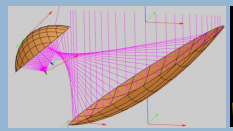
Science, Tech. & Ops Synergies

cm-mm-wave SD / interferometry / VLBI

ngVLA







Future Large-Scale International Project