The North America Array:
Technology Development and the Realization of SKA-High:

Activity White Paper submitted to Astro2010 Program Prioritization Panel

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Abstract

The North America Array (NAA) is a new initiative aimed at the realization of the high-frequency component of the Square Kilometre Array (SKA) program within North America. The primary activities of the NAA in the next decade are a technical development program and a prototype antenna station, leading up to SKA-high construction sometime after 2020. The total cost is estimated to be $32M over the decade. The key science drivers identified for the NAA cover a broad range of modern astrophysics, from studying the formation and evolution of planets, stars, and galaxies, to probing the overall structure of the Universe near and far. The ultimate goal of NAA is to exceed the sensitivity of the EVLA by a factor of 10 or greater, and thus survey speed by 100 or more, covering at least the core frequency range 5–45 GHz (with a goal of 1–50 GHz). The SKA-high is envisioned as the final component of the low/medium/high frequency triad of the International SKA Program, and the establishment of the NAA with project and science offices will enable our national astronomy community to take a strong leadership role in this flagship next-generation astronomical facility, and to make a compelling case for a site within the United States.

1. Summary

The NRAO has established a clear strategic plan (Lo et al., 2009, Astro2010 Position Paper, "The Impact of the National Radio Astronomy Observatory") for scientific discovery and technical development in the next decade which leads naturally to a long range vision for radio astronomy. This is one of five papers outlining these activities for the Program Prioritization Panel.

NRAO is first and foremost committed to the mission of enabling the astronomical community to carry out forefront research into the Universe at radio wavelengths. As a key part of that mission, NRAO will augment its participation in the Square Kilometre Array (SKA) program through strategic collaborations that leverage the expertise and infrastructure we have developed in building and operating the world-leading suite of facilities: ALMA, EVLA, GBT, and VLBA. In addition to playing key roles in the SKA-low and mid-frequency projects, NRAO will lead in the design, development, prototyping, and eventually the construction and operation of a high-frequency SKA facility.

The scientific potential of the SKA is presented in the SKA Science Book (Carilli & Rawlings, eds. 2004, New Astronomy Reviews, 48, 979–1563). In the "high-frequency" range up to 50 GHz the key science drivers require a radio interferometer with high sensitivity and survey speed with baselines to 3000 kilometers or longer. Therefore, we propose the establishment of the North America Array (NAA) initiative, building upon the nucleus of the EVLA, VLBA and GBT network of radiotelescopes, and harnessing the energy of North American astronomical community. There are compelling advantages to building on the infrastructure and experience that the U.S. has established at centimeter wavelengths, and to leverage our resources in building and hosting the NAA as the SKA-high.

In the 2010–2020 decade, we propose the following staged activities: (1) collaborations with SKA-mid precursors and pathfinding activities such as MeerKAT, (2) a SKA-high Technology Development Program (TDP-II) focusing on high-frequency low-cost antennas and systems, computing, and software readiness, and (3) the construction of a NAA Prototype Antenna Station (NAA-PAS) covering at least the core frequencies 5–45 GHz. The total cost is estimated to be $32M over the decade. Goals of these activities include derivation of a costing model for SKA-high, the preparation of a proposal to the next decadal review in 2019, and the building of a strong case for the U.S. to host the SKA-high to be submitted to the SKA-high site decision process in 2018–2020. We envision that beyond 2020 the SKA-high will be "grown" as the NAA from the EVLA and VLBA, ultimately attaining the full capabilities of at least 10 times the sensitivity of the EVLA. We feel that the NAA is one of the keystones in a forward-looking strategy cementing the foundation of U.S. astronomy as a leader in cutting edge facilities that enable truly transformational research.

2. Science Case

The NRAO strategic plan and vision is presented in the NRAO Astro2010 State of the Profession Position paper by Lo et al.: "The Impact of the National Radio Astronomy Observatory" (`http://www.nrao.edu/A2010/whitepapers/NRAO_AS2010_SoP_paper.pdf`), hereafter referred to as the *ImpactNRAO* Position Paper. In this we presented five principal strategic goals:

1. Complete ALMA and the EVLA successfully on schedule by the end of 2012.
2. Provide effective user support for a broad, multi-wavelength community.
3. Realize the vision of the SKA program, in partnership with the US and international community.
4. Achieve a quantum leap in GBT science capability with next-generation camera systems.
5. Maximize the scientific impact of the VLBA by key science programs and innovative partnerships.

This is one of five activity team responses that NRAO has submitted to the Program Prioritization Panels. We designate these as: (1) the NAA, this paper, (2) ALMA development (*ALMA2010*), (3) EVLA enhancements (*EVLA2010*), (4) a VLBA astrometric initiative (*VLBA2010*), and (5) GBT camera systems (*GBT2010*). For convenience, these are arranged around specific facilities, but we stress that these should be considered as a unified suite of activities fulfilling the observatory vision. These activity papers describe the implementation of one or more of our strategic goals through examples of well quantified, modest, and realizable projects in the coming decade. Each project has been crafted to produce ground-breaking results in topical areas of modern astrophysics, while also addressing key outstanding technical development issues on the path toward the Square Kilometre Array program.

The North America Array is the realization of the high-frequency component of the SKA (SKA-high, §3.3). In this document, we use the terms "SKA-high" and NAA interchangeably. We refer the reader to the complete SKA science case in the *SKA Science Book* (Carilli & Rawlings 2004, `http://www.skatelescope.org/pages/sciencegen.htm`), and to a number of Astro2010 science white papers with related research goals (collected at `http://www.nrao.edu/A2010/whitepapers/`). Here, we focus on the ultimate science return beyond 2020; the NAA activity in the upcoming decade concentrates on technology development rather than science delivery.

The SKA-high will have scientific impact in all five Science Frontier Panel themes. We do not have space here to do the broad science range justice, and only present a few key highlights from the Science White Papers submited to Astro2010:

2.1 Cosmology and Fundamental Physics

Megamasers, Dark Energy, and Black Hole Masses: Observations and modeling of H_2O megamasers in active galaxies with edge-on central disks can provide two major outputs: (1) geometric distance estimates to the galaxies; and (2) direct "weighing" of central black hole masses. The geometric distance measurements to galaxies at distances of 50–200 Mpc can provide precise constraints on the Hubble Constant, thus resolving degeneracies in measurements of dark energy. Measurement of H_0 in the Hubble flow to better than 1% is ultimately possible through this technique (Braatz et al. 2009, Astro2010 white paper, "Cosmology with Water-vapor Megamasers"; Greenhill et al. 2009, Astro2010 white paper, "Estimation of the Hubble Constant and Constraint on Descriptions of Dark Energy"). The near-term goal for the next decade is the direct-distance measurement to 10 galaxies in the Hubble flow, using their central H_20 megamasers. However, these measurements are sensitivity-limited and band-limited. Ultimately, SKA-high will have 2.5 times the EVLA sensitivity on long baselines (§3.3), or approximately 7 times the sensitivity of the VLBA (assuming *VLBA2010* improvements), thus probing a volume more than 18 times greater.

Weighing Dark Matter: Gravitational lensing provides a unique probe of deep potential wells in systems such as compact objects, galaxies, and clusters of galaxies (Koopmans et al. 2009, Astro2010 white paper "Strong Gravitational Lensing as a Probe of Gravity, Dark Matter, and Supermassive Black Holes"). Radio lensing observations have significant advantages over optical/infrared studies, such as lack of obscuration and the ability to see through the lensing galaxy, insensitivity to microlensing, and the possibility of extremely high resolution observation through long baseline interferometry. The VLA has been used to survey for gravitational lens systems (e.g., CLASS), and the VLBA has been used to search for central images that probe the inner profile of the lensing galaxy potential. These measurements provide constraints on the dark matter properties as well as on the possible presence of supermassive black holes in these systems. The EVLA and *VLBA2010* enhancements will provide new opportunities for lensing discoveries. However it is the SKA, through truly huge lensing surveys using the SKA-mid and deep high-resolution follow-up observations with the NAA/SKA-high, that will take the next important step in radio lensing studies, and will complement the next generation optical and infrared lensing searches.

2.2 Galaxies across Cosmic Time

Imaging Galaxies in the Early Universe With the impending completion of the ALMA and EVLA, a remarkable window into the formation and evolution of galaxies in the early Universe is about to be opened. The combined observations of molecular gas, using spectroscopy of higher order transitions with ALMA and lower transitions with the EVLA to reveal the fuel for star formation, plus continuum imaging of thermal dust emission with ALMA (tracing the star formation rate) and radio emission with the EVLA (tracing star formation and

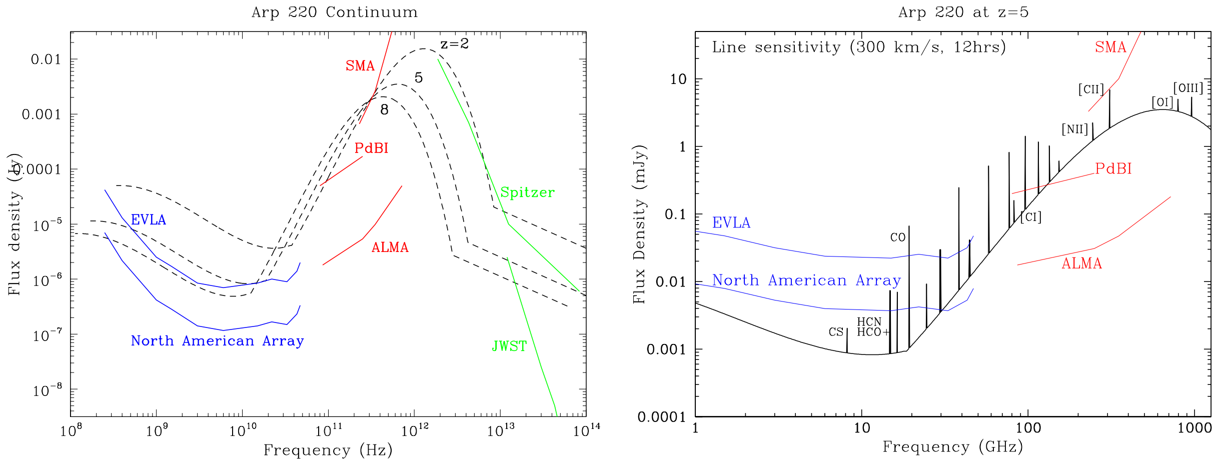

Fig. 1.— **Left:** The solid curves show the (1σ) sensitivity to continuum emission for select current and future cm and mm interferometers, as well as for space IR telescopes, in 12 hours. The dashed curves are the continuum spectra for Arp 220, the "canonical" extreme star-forming galaxy, at $z = 2$, 5, and 8. **Right:** The colored curves show the (1σ) sensitivity to spectral line emission in 12 hours for a 300 km s^{-1} line width. The solid curve is the spectrum including molecular and atomic fine structure lines, for Arp 220 at $z = 5$.

AGN activity), will provide unprecedented detail on the conditions which prevailed in the first galaxies. Such observations are the critical complement to studies of the stars and ionized gas in early galaxies by next generation optical and near-IR telescopes. For galaxies at $z \approx 5$, the CO 1-0 and 2-1 lines will be redshifted to 19 and 38 GHz, respectively. These transitions are crucial as total molecular gas mass estimators, and for study of galaxy dynamics and ISM physical conditions. The low order emission lines from high dipole moment molecules, such as HCN and HCO+, also redshift to this frequency range. The EVLA will be limited to detecting relatively massive galaxies, and thus the NAA is needed to take the next major, fundamental step, by increasing the sensitivity by a further order of magnitude, allowing for the study of the gas content of normal galaxies in the early Universe.

Figure 1, reproduced from Carilli et al. (2009, Astro2010 white paper, "Imaging the Cool Gas, Dust, Star Formation, and AGN in the First Galaxies"), shows the continuum and spectral-line sensitivity of various telescopes for a galaxy like Arp 220 at high redshift, assuming a collecting area of only three times the EVLA for the North America Array. We emphasize the complementarity of these different facilities: the EVLA will study the synchrotron emission associated with star formation and AGN, and the low order molecular transitions from CO and dense gas tracers. ALMA will detect the dust and higher order molecular transitions, as well as the Fine Structure lines, key diagnostics on thermal balance in the ISM. The optical/near-IR telescopes reveal the stars, star formation, and ionized gas. Galaxy formation is a complex process, and clearly such a pan-chromatic approach is necessary to reach a full understanding of galaxy formation back to first light.

2.3 Planetary Systems and Star Formation

Protoplanetary Disks: The last decade has seen a revolution in the study of star and planet formation, with the discovery of hundreds of extrasolar planets and first images of protoplanetary disks at optical, near-IR, and radio wavelengths. Missions such as Kepler will greatly increase the number of known extrasolar planets, and the upcoming completion of ALMA, EVLA, and JWST will provide dramatic advances in the detection and imaging of protoplanetary disks (see Bally et al. 2009, Astro2010 white paper, “Searching for the Secrets of Massive Star Birth”; Mundy et al. 2009, Astro2010 white paper, “Dust Enshrouded Star and Planet Formation”). For the Orion Molecular Cloud complex, at ~ 400 pc distance, imaging structures on 5 AU scales requires 10–15 milliarcsecond resolution. Most sites of massive star formation are more than 1 kpc away, and 100 AU at the Galactic center requires similar high resolution. This resolution is achievable at the shortest ALMA wavelengths, but a factor of at least 5 better over EVLA is needed at 1 cm wavelength. Furthermore, a limiting factor of millimeter and infrared observations is the tremendous opacity of the inner disk material, and penetrating to the heart of massive protostars will require the exquisite angular resolution at longer wavelengths provided. This is a key science driver for NAA, which with 2–3 times the EVLA sensitivity on baselines from 5 to 180 km, at frequencies above 25 GHz, provides the required capabilities.

2.4 Stars and Stellar Evolution

Super Star Clusters and Supernovae: Massive stars form in large quantities in merger and disturbed galaxies, typically in “super star clusters” (SSCs) just a few parsecs in radius (see Johnson et al. 2009, Astro2010 white paper “Intense Star Formation in Nearby Merger Galaxies” for more details.) These SSCs are most likely the preferred mode of star formation in merging galaxies at high redshift, so understanding the nearby mergers is essential to understanding how massive stars form in the early universe. The gas and dust components of SSCs will be studied with very high sensitivity by JWST, ALMA, and EVLA in the coming decade, but the SSCs in nearby mergers will remain completely unresolved. In order to resolve and image a significant sample of SSCs in the nearest ~ 10 major galaxy mergers, a resolution of 2–3 pc is needed at 80–100 Mpc distance; this corresponds to better than 10 milliarcseconds, far beyond the capabilities of JWST and EVLA. The NAA, with 2.5 times the EVLA sensitivity on baselines from 5 to 180 km (§3.3), fits this requirement perfectly.

Understanding the radio evolution of young supernova remnants (SNRs) in SSCs is a key to the characterization of their star-formation rates, which in turn will have a profound impact on our understanding of galaxy evolution in the early universe. Extending the sensitivity of observations below the “Cas A” radio luminosity threshold in galaxies such as Arp 220 and Arp 299 will enable measurements of SNR luminosity functions for the entire merger galaxies, and perhaps within individual SSCs. The *VLBA2010* bandwidth reaches SNRs with luminosities a factor of several above the Cas A goal, and the NAA is required to provide the next key improvement.

Supernovae and Gamma-ray Bursts: Supernovae, gamma-ray bursts and the evolutionary link between them are key research topics for many ground and space-based facilities in the next decade (see Soderberg et al. 2009, Astro2010 white paper, "Radio Clues to the Progenitors of 'Naked' Cosmic Explosions"). Radio observations remain the most sensitive probe of the mass loss history of the progenitor star and the total explosion energy. Radio VLBI is the only technique that can directly image the expanding shocked ejecta (e.g., SN 1993J), and for one nearby gamma-ray burst (GRB 030329), it has directly imaged the superluminal expansion. With the improved sensitivity of the NAA such measurements will be straightforward. Of crucial interest, however, are the Type Ia supernovae that are fundamental to our understanding of the acceleration of the universe. The SKA-high sensitivity of 10 times the EVLA (§3.3) is needed to discriminate between doubly-degenerate or single white dwarfs models by detecting multiple Type Ia supernovae in the radio regime.

Galactic Center Pulsars Radio pulsars orbiting Sgr A* represent accurate clocks moving in the spacetime environment of the Galaxy's central supermassive black hole. However, detection and timing of these pulsars is difficult because they are seen through a region of extremely strong scattering, which acts to broaden their pulses. Pulsars tend to have steep spectra, so significant collecting area is required to obtain sufficient sensitivity to detect and time Galactic center pulsars at the high frequencies required to reduce the effects of radio-wave scattering. Pulsar timing observations together with proper motions would yield 3D motions around SgrA*, both complementing existing NIR observations of massive stars, but also providing us with an unprecedented laboratory for studying gravity in the strong field regime (e.g., Kramer et al. 2004, in the *SKA Science Book*).

2.5 The Galactic Neighborhood

Local Group Motions: The use of a more finely-spaced network of calibrator sources on the sky due to higher sensitivity would enable astrometric accuracies of a few microarcseconds or better, allowing the accurate measurement of motions in the Local Group, thus characterizing its distribution of mass (including dark matter). At M31, for example, a motion of 100 km s^{-1} corresponds to over 30 μas per year, which would be measurable. However, the sources in these distant galaxies are quite weak, so the additional long-baseline collecting area of SKA-high will be critical. As pointed out by Reid et al. (2009, Astro2010 white paper, "Motions of Galaxies in the Local Group and Beyond"), measurement of the proper motion of the M31 nucleus vs. the Milky Way would then be feasible, improving our understanding of the disks, bulges, and dark matter halos of the dominant Local Group galaxies. Through precision astrometry enabled by the NAA, we can learn the ultimate fate of the Local Group.

3. Technical Overview

The long-term vision for the Square Kilometre Array program is presented in the PPP activity submission by Cordes et al. That document focuses on the SKA-mid component, but also describes the program as a whole. The role of NRAO in the SKA program was outlined our *ImpactNRAO* Position Paper. In this activity proposal, we are focusing on the technology development activities for the 2010–2020 decade for the SKA-high component as part of the North America Array initiative, as well as our plans to augment participation in other aspects of the SKA. To provide context, we begin by repeating the long-term plan given in *ImpactNRAO*; this is entirely consistent with the plans of the USSKA Consortium.

3.1 Layout of the SKA Program

An organizing framework of future centimeter/meter-wave telescopes is the SKA Program, which incorporates components at “low” (below 500 MHz), “mid” (0.3–10 GHz), and “high” (up to 50 GHz) frequencies (from Cordes et al., and Schilizzi et al. SKA Memo 100). We endorse a science-based approach to this program, with component projects led by the US and international communities.

At the lowest frequencies, probing the universe at the Epoch of Reionization (EoR) is a clear science driver, while radio transients will provide a window into the unknown. NRAO scientists and engineers will continue to collaborate on developmental telescopes (LWA, MWA and PAPER). We support the next steps toward SKA-low, which are the subjects of two PPP submissions (Backer et al. 2009, Taylor et al. 2009). Also, construction funding is being sought for a SKA-mid array in Australia or South Africa, as discussed in the USSKA Consortium PPP activity paper (Cordes et al. 2009). Primary SKA-mid science goals include tracing HI throughout the Universe for cosmology and to understand the evolution of the HI content of galaxies, and to carry out gravitational studies using pulsars. Cost-effective paths to SKA-mid are under development, aimed at construction readiness mid-decade.

The upper frequency range below the 50 GHz atmospheric cutoff is covered by the SKA-high component. This array will have at least 10 times the total collecting area of the EVLA (and therefore at least 100 times the survey speed), and resolution similar to the VLBA. In the international SKA program plan, the SKA-high construction commences after completion of the other two components, sometime after 2020. Observations at these higher frequencies are strongly affected by the troposphere, and thus a the SKA-high array should be sited at a high, dry location such as the EVLA site, rather than the lower-elevation sites under consideration for SKA-mid and SKA-low. Tests of cost-effective technology as described below will prepare NRAO and the community for the construction of the full North America Array (`http://www.nrao.edu/nio/naa`), as the implementation of SKA-high.

3.2 Development Plan in 2010–2020

The starting point for NRAO NAA and SKA development is the conclusion of the EVLA construction and the first US-SKA Technical Development Program (TDP-I) in 2012. At this point we will be fully operating the EVLA with initial science underway, and the *EVLA2010* and *VLBA2010* companion activities will augment our facilities with low-cost high-impact improvements. In addition, we will have the results in hand from TDP-I and PrepSKA, as well as at least one prototype mid-frequency (10–15m) antenna.

The NRAO SKA development plan for 2010–2020 has the following components:

1. Participate in the development of SKA-mid precursors and pathfinders, notably MeerKAT in South Africa and (perhaps) the Allen Telescope Array (ATA) in California, both to enable SKA-mid and to address common technical and operational issues.
2. Continue and expand the work of the USSKA Consortium Technical Development Project (TDP) in order to enable the required antenna and receiver performance for SKA-high, and to carry out the software and computing research and development necessary to prepare for NAA.
3. Construct and evaluate an SKA-high "station" of small (diameter of 10–15 meters) antennas. Use the test station to develop and evaluate the software needed for station beam-forming and cost-effective imaging on the long baselines of SKA-high. Develop SKA-high costing model.

3.2.1 SKA-mid Development and the Road to SKA-High

Many facets of SKA-high technology are based on capabilities under development for the SKA-mid. These include antenna and receiver performance, overall system design, correlation, and computing. The EVLA will act as a scientific and technical path-finder, but is highly leveraged on existing infrastructure, and is not intended to be an instrument whose cost/performance ratio can be scaled up to SKA-high. Thus, participation in development of at least one SKA-mid precursor telescope is necessary in order to test out the developments needed for SKA-high. For example, the ATA, through its RSSP activity (Bower et al. PPP submission), will provide experience in large-N array operation, computing, and algorithms, that will feed into NAA design, complementing TDP-II development. NRAO and ATA are actively exploring opportunities for cooperation.

An excellent opportunity early in the decade for NRAO collaboration is on the MeerKAT telescope in South Africa. MeerKAT, with 80 12m telescopes and single-pixel feeds, most closely resembles the reference design for SKA-high, when compared to the small 6m dishes of the ATA and the focal-plane-array systems of the Australian ASKAP. It is possible that the composite antenna technology being developed for MeerKAT will be the most cost-effective technology for an SKA-high antenna, and the receiver goal is for a performance of better than 3:1 bandwidth. Beyond the telescope hardware, the next-generation correlator system (low cost, high performance/power ratio) must be developed for MeerKAT.

NRAO presently has a Memorandum of Understanding in place for cooperation with the South Africa SKA Project Office (SASPO), which includes provisions for engineer exchange and cooperative development, and a number of engineering and scientist visits have taken place in the last year. NRAO and SASPO are cooperating on the development of the digital technology and resulting digital backends that are being implemented on the VLBA in the next year. MeerKAT is planning on using this same hardware for their first correlator. Thus the foundation has been laid for a stronger collaboration on MeerKAT in the next several years, which will have the dual benefits of moving SKA-mid closer to reality and developing the capabilities that ultimately are needed for SKA-high.

Again, we stress that there are many aspects of SKA-mid and SKA-high that are of common concern. Later in the decade, SKA-mid Phase 1 will be underway. Involvement of NRAO in all SKA activities and the availability of EVLA and eventually NAA for prototyping and testing will be invaluable for these projects to make progress on these challenging issues and to address items of risk.

3.2.2 TDP-II, 2012–2015

The USSKA Consortium, with Jim Cordes of Cornell as PI, is now engaged in the NSF-funded TDP-I. This effort is focused on producing the lowest-cost antennas and receiving systems that can meet the requirements of SKA-mid and laying the groundwork for the computing and software systems needed for SKA. The “SKA system” that is developed out of the USSKA TDP-I and the global PrepSKA program must be improved in order to meet the requirements of SKA-high, and to determine whether SKA-high is capable of performance up to the atmospheric O_2 cutoff at 50 GHz.

The TDP-II is a 3-yr concept study to take the output of the TDP-I and the PrepSKA Dish Verification Program and develop the final SKA-high antenna system and station options. This includes the final evaluation of the TDP-I antenna/receiver concept at the VLA site, and a study of the changes that must be made to this antenna to make it capable of operation at or above 25 GHz. At present, this element of the study cannot be characterized completely, since it depends on the not-yet-known output of TDP-I and PrepSKA.

For the NAA concept, we take as a goal the development of an antenna system that would ideally access the entire EVLA range 1–50 GHz. The TDP-II is aimed at the more restricted core range from 5–45 GHz with two low-noise wide-band receivers, one covering 5 to 15 GHz and the second covering 15 to 45 GHz. The important element here is trying to reach a 3:1 ratio between highest and lowest frequency in a receiver with the lowest possible system noise performance. Wider-band feed and receiver systems such as those at the ATA are possible, but they currently entail compromised system noise performance. NRAO staff at present have achieved outstanding system noise performance on 2:1 bandwidth receivers for the EVLA, but achieving the same performance at 3:1 bandwidth may require significant changes, such as use of linear-polarization rather than circular-polarization receivers.

A key element in TDP-II is an integrated system design that minimizes the overall SKA-high cost. In the NAA concept, it is envisioned that 50% of the ultimate SKA-high collecting area will be placed within 5 km of the center of the EVLA; to preserve wide field of view, each of these antennas will be correlated separately. However, the longer baseline (ultra-high resolution) science does not generally require the same large field of view. Therefore, the favored design involves forming one or more "station beams" from a patch of small dishes, and correlating the output data streams with other antennas and stations.

At present, we do not understand all of the required trade-offs. Some of these relevant issues, such as station beam-forming and imaging performance, are also part of the TDP-I computing investigation. Our work in TDP-II will build upon this, although there are unique aspects such as dealing with tropospheric aberrations in calibration and imaging. A strength of the computing and software aspects of TDP-II will be in the ability to extend the investigations started in TDP-I and feed back into the SKA-mid project.

The result of TDP-II would be a full design for an SKA-high station, to be built and tested in the second half of the 2010–2020 decade.

3.2.3 Implementation of a NAA Prototype Antenna Station, 2015–2019

At the end of TDP-II, a decision would be made about the readiness to construct a SKA-high NAA Prototype Antenna Station (NAA-PAS), selecting the option with the best performance/cost ratio. This station would be constructed at a current radio astronomy site to minimize infrastructure development; candidates include the EVLA site (the default plan), LWA sites, the ATA site in Northern California, the Owens Valley Radio Observatory in central California, the NRAO Green Bank site in West Virginia, or one of several VLBA station sites. The site determination will be made based on considerations of logistical support, weather characteristics for high-frequency performance, and data-transport requirements. The reference design for this station is 20 antennas of 12m diameter (hence effective collecting area slightly larger than a single 50m antenna), but the final station cost and composition, including the final dish diameters and numbers, will be determined based on the TDP results.

Presuming a "go" decision, the NAA station will be built in 2016–2018, after a year of detailed design. It then will be operated for a year correlated with the EVLA, in order to test out performance of the entire system required for beam-forming and imaging. Note that experience in running the NAA station with EVLA will allow independent testing and feedback into the SKA-mid project on issues such as station performance and implications for imaging software, without diverting SKA-mid personnel from construction efforts.

In parallel with the prototype station implementation, based on TDP-II, and our experience in the NAA station and SKA-mid construction, we will develop a NAA/SKA-high costing model that will allow us to prepare the next decadal proposal.

3.3 Conceptual Plan for the 2020–2030 Decade

The primary NAA activity goal for 2020–2030 is the construction of the full SKA-high in North America. The activity schedule (§6) includes a milestone for completion of the NAA-PAS in 2018. Science results from EVLA, VLBA, ALMA, JWST, SKA-mid and SKA-low, and future optical/infrared ground-based telescopes will illuminate the best path forward, and 2018 will be the natural time to make the final science/cost trade-offs. The SKA-high site decision is scheduled to occur in the period 2018-2020, and we will be poised to make a strong proposal for the NAA location. The 2018 decision milestone also allows sufficient time to develop a fully costed plan in advance of the 2020 decade survey. The cost model developed in 3.2.3 will likely need refinement closer to the data of submission of the actual funding proposal.

The long-term science goals discussed in §2 require total sensitivity of 10 times that of EVLA or greater. For the NAA concept, we follow the current SKA-high specification, with 50% of the collecting area within 5 km of the EVLA center, another 25% out to 180 km, and the final 25% out to 3000–5000 km. Thus, the sensitivity for imaging sources of low brightness temperatures would be 5 times better than EVLA, while the detection threshold for point sources would be 10 times better. Since the present VLBA has collecting area only 35% that of the EVLA, adding 2.5 times the EVLA collecting area on long baselines would improve the sensitivity on these long baselines by a factor of 7, at any given bandwidth. Finally, the collecting area of 2.5 times the EVLA in the 5–180 km range would provide more than 10 times the sensitivity and superior frequency coverage to eMERLIN.

The vision for the SKA-high is that it enhances, or if necessary eventually replaces, the EVLA and VLBA in a staged fashion. The current EVLA would still amount to 20% of the SKA-high core collecting area, while the ten VLBA antennas are equivalent to only 7.4% of the outer array. We anticipate that the SKA-high in North America will be built “from the inside out”, first augmenting the EVLA and inner VLBA on $\sim$ 100 km baselines, as this will give the most immediate science return. VLBA stations would be re-used as outer array sites where appropriate. The actual schedule beyond 2020 will be determined by the science drivers and the available funding profile.

Another aspect of facility management critical for the SKA is the planning for an implementation of a Science Operations model. The NRAO is in the process of putting into place an integrated set of community Science Centers for its observatories, in particular for ALMA and EVLA. A NAA Science Center will be grown from the EVLA center, and lessons learned here will be put into the plans for the SKA program as a whole.

4. Technology Drivers

4.1 Receptor performance/cost ratio

One key technology is the availability of low-cost collecting area at 25 GHz or higher. For EVLA and VLBA, antenna systems consumed 35–40% of the array capital costs. To minimize the cost for SKA-high, the receptors should cost no more than $400M. Depending on commodity prices, 270 VLBA 25m dishes would cost $1.1B to $1.6B, so our target is for SKA-high collecting area to cost 3–4 times less than this. Note that the SKA-mid requirements for high dynamic range at 1–2 GHz ($\lambda/100$ surface) correspond to $\lambda/16$ at 10 GHz, adequate for good performance, and within a factor of a few of the SKA-high goal at 25 GHz. Table 4.1 gives the number of dishes needed for 10 times EVLA collecting area:

Table 4.1. Required Number of Dishes for SKA-high

Antenna Diameter	25m	15m	12m	10m	6m
Number of Antennas	270	750	1200	1700	4700

The hydroformed 6m ATA antennas have achieved a low unit cost, but nearly 5,000 such dishes would be needed. Since SKA-high is not primarily a survey instrument, the wider field of view of small dishes is less important. The data-processing and operations costs (including power costs for processing) scale as N^2 or faster, increasing total cost for smaller dishes. We focus on 10–15m dishes; recent SKA studies have shown this to be the optimal range for total array cost vs. aperture size. The following efforts are under way internationally:

- ASKAP, ATNF, Australia: 36 12m dishes purchased for $10M Aus ($6.5M US), implying a cost of $220M US for 1200 dishes (see Table 4.1). Surface rms < 1 mm.
- Composite Applications for Radio Telescopes, DRAO, Canada: Single-piece composite 10m dishes; second prototype in 2008 (2008 prototype had rms of 0.5 mm).
- KAT/MeerKAT, SKA-South Africa: Prototype 15m composite dish produced. MeerKAT to have up to 80 12m composite dishes with 1 mm rms in 2012.
- Technology Development Program, USSKA Consortium: Low-cost SKA "system", including antenna with performance up to 25 GHz, to be tested by 2012.

Using the usual specification of $\lambda/16$ rms surface accuracy for operation at wavelength λ, a 25-GHz dish requires a surface accuracy of 0.75 mm or better, enabling observation of the H_2O line at 22 GHz; this is very close to the specification to be achieved (or already achieved) by the programs listed above. The highest desirable upper frequency is the atmospheric O_2 cutoff around 50 GHz (requiring 0.4 mm rms).

Although increasing field-of-view is not a SKA-high driver, options using focal-plane array feeds (multi-beam or beam-forming) are being investigated by a number of groups (e.g., SKA-mid). In the context of the SKA-high, the *GBT2010* activities are most relevant for us, and we will fold this work into our studies. Note that the antennas would have to be designed with a suitable focal plane.

4.2 Data transmission, Correlation, Computing Infrastructure

It will be a challenge to distribute and correlate the antenna data streams produced by the antenna station patches, particularly on continental baselines. With many more apertures and similar baselines, the SKA-mid will face similar issues. However, the extremely wide RF bandwidths ($>$ 10 GHz) needed for SKA-high mean that the transmission loads are potentially much higher. Correlation requirements are similar to or less than that of SKA-mid, due to fewer elements, but are still substantial and must be factored into operations costs in any event.

With next-generation radio arrays such as those of the SKA program, the lines between hardware and software, and between telescope electronics and computing, are blurred. The expansions envisaged for the *VLBA2010* activity will push the limits of wide-band antenna data-stream transmission and handling next decade. The SKA-high requirements are more extreme. VLBI-like antenna-based recording is unlikely to be possible (certainly not within the core array), and thus a real-time correlation system like a wider-band version of that needed for the SKA-mid will be required. This in turn requires "e-VLBI" mode single-pass correlation operation, which in turn implies stability in station beams (see 4.3).

Many of these issues were highlighted in the 2009 SKA Forum in Cape Town, South Africa (`http://www.skatelescope.org/pages/presentations_SKA_Forum2009.htm`). In particular, a presentation of SKA computing needs was given by B. Elmegreen of IBM (`http://www.skatelescope.org/pages/SKA_Forum_2009/ska2009_elmegreen.pdf`). In this, he expressed the challenges of Exascale computing that the SKA faces, including power consumption concerns (e.g., 1 Exaflop will might be expected to require 70 MW, or $70M in annual power costs at 10 cents/kw-hr). These will have to be addressed in the current TDP-I, in TDP-II, and in the ramp-up of construction to the full arrays.

There is clearly substantial overlap in the data handling technical drivers for NAA with those for other SKA components, in particular the SKA mid. The TDP-II program proposed here is designed to leverage TDP-I/PrepSKA and ongoing work on SKA-mid, to focus on unique issues facing the SKA-high, and to feed back information to the SKA program.

Extensive research and development critical to the successful implementation of the SKA-high and SKA-mid systems is required in this general area of Digital Systems (see also §7.2 work items 2–5). These are issues that are also important to other astronomical development programs at NRAO and in the community (ATA, MeerKAT, LWA), and to industry. We are exploring the concept of establishing a *Center of Excellence for Digital Technology* that would be built around the proposed NAA development but include partnerships with other stakeholders in this technology. We feel that the time is ripe for such an investment, and it would benefit the entire community. See also the "Digital Instrumentation for the Radio Astronomy Community" technology development white paper (Parsons et al.).

4.3 Beam Forming, Data Processing Algorithms, and Software

The hallmarks of the SKA-high project are obtaining high sensitivity at high resolution, exceeding the EVLA by an order of magnitude or more with the resolution of the VLBA. This is not primarily a survey instrument, although these sensitivity improvements combined with a designed field-of-view increase over EVLA will result an advance of more than two orders of magnitude in survey speed also. Making use of these gains though high-dynamic range calibration and imaging will be a challenge.

Particular challenges include the following:

- How good a "station beam" can be formed, and what are the computing requirements to form this beam? How stable will this beam be, particularly in the presence of tropospheric aberrations and refraction, and how will that impact calibration and imaging cost and performance?
- What are the trade-offs between linear and circular polarization in formation of the station beam and in combination of individual antennas and stations? Specifically, how much computing is required to enable accurate polarization calibration in the output data?
- What are the computing/data-processing implications of using different-size antennas in different parts of SKA-high? For example, one might imagine using small 6m antennas similar to those of the ATA on the short baselines, to retain maximum field of view, and low-cost antennas up to ~ 25 m in diameter on the long baselines, to reduce the computing cost of station beam-forming.
- The extreme data rates and volumes approach Exascale levels. As in the data distribution, correlating, recording, and pre-processing, this will be a challenge to realize even after 2025. Issues such as power consumption impact operations, while the ability to archive at anywhere near the raw data rates pushes storage media capabilities. What trade-offs are necessary, and what is a prudent staged ramp-up science operations model that makes use of projected advances in computing (e.g., "Moore's Law" and its ilk)?

Note that the SKA-mid project also has similar goals and even higher dynamic range requirements, due to its focus on surveys and presence of brighter sources within the large fields of view. Thus, many of these challenges are shared and thus common cause can be made in addressing these drivers and risks. In fact, since we will still be in the prototyping and testing phase while SKA-mid is in construction, we can make efficient use of the NAA for a variety of critical investigations into hardware and software issues that advance both projects. In particular, extending algorithm and computing development through TDP-II and into NAA construction will be of mutual benefit.

5. Organization, Partnerships, and Current Status

The North America Array is a proposed implementation of the high-frequency component of the Square Kilometre Array (SKA). The SKA (`http://www.skatelescope.org`) is managed by the SKA Science and Engineering Committee (SSEC, with 8/24 US members), with the SKA Program Development Office located in the United Kingdom. The USSKA Consortium (`http://usskac.astro.cornell.edu`) consists of 11 different universities and research institutes. The PrepSKA Board oversees the technology development program (`http://www.jb.man.ac.uk/prepska/`) funded by the European Commission, while the USSKA Consortium oversees the related Technology Development Project funded by the NSF (PI, Cornell University; `http://skatdp.astro.cornell.edu`) with representation in PrepSKA. See the SKA-mid PPP activity paper of Cordes et al. for more detail on the SKA Program structure. For example, the TDP-II proposed here will follow-on to TDP-I as an activity of the USSKA Consortium, with key work areas led by NRAO.

The PrepSKA program includes work packages to develop the overall long-term funding and management scheme for the SKA Program. This will consist of at least three projects (see §3.1) that are separated in time and quite possibly in location; each project will require strong central management with international oversight from the partners. Conceptually, the US is expected to contribute between 35% and 40% of the total SKA Program cost. The official long-term international plan approved by the SSEC has SKA-high construction beginning as early as 2022–2023 following completion of SKA-mid in 2023.

In the near term, there are many partnerships for technology development related to SKA. NRAO intends to form an SKA Project Office within the next year. This office will have primary responsibility for all SKA activities in NRAO. It will coordinate the external partnerships and bring increased focus to the SKA activities within NRAO. This Project Office will have oversight over the related areas of technology development in the NRAO Central Development Lab as well as the different NRAO telescope sites, and will have primary responsibility for moving toward realization of SKA-high.

We stress that in all aspects the NAA is an integral part of the community-based international SKA program. As we point out in §7, the SKA-high development proposed for these NAA activities is very closely aligned with that for SKA-mid, and the NAA developers and engineers will work closely with others within the SKA program on all aspects. We rely upon a substantial level of collaboration and contributed effort from the SKA community to reach our goals. In return, NRAO has considerable expertise in the design, construction, operation, and scientific use of cutting-edge radio facilities for the community, and establishment of the NAA project will leverage this experience for the benefit of the SKA. For example, there are complementary development efforts for *ALMA2010* and *GBT2010*) that will provide input on important aspects of our NAA/SKA development.

6. Activity schedule

The overall activity schedule was laid out in the technical description of §3. Here, we list the primary milestones of the North America Array activity and other related SKA activities for the next decade. Although one could generate a notional schedule for the 2020–2030 decade, this is highly dependent on the pace of technology development and the approval/construction pace for SKA-mid. Hence we restrict ourselves here to the milestones in the upcoming decade. Those milestones that are the direct responsibility of the present activity are **boldface**, other SKA activities are *italicized*, while a few other astronomy milestones of interest also are noted for context. Note that the SKA-mid activity milestones are taken from the Cordes et al. submission.

- 2009: **Form NRAO SKA Project Office**
- 2010: **Begin MeerKAT collaboration**
- 2012: *SKA TDP-I and PrepSKA technology programs complete*
- 2012: EVLA completion
- 2012: **Begin TDP-II**
- 2012–2013: *ASKAP and MeerKAT complete*
- 2012: ALMA 50-element inauguration
- 2013: ALMA completion
- 2013: JWST launch
- 2013: *SKA-mid infrastructure emplacement begins*
- 2015: **Completion of TDP-II**
- 2015: **Decision for NAA-PAS construction**
- 2016: **Production readiness for NAA-PAS**
- 2018: **Completion of NAA-PAS**
- 2018: *SKA-mid Phase 1 construction complete, begin final phase construction*
- 2018–2020: **SKA-high site selection**
- 2019: **Complete testing of NAA-PAS**
- 2019: **SKA-high submissions to decade survey**
- 2022–2023: **Goal date for start of SKA-high construction**
- 2023: *SKA-mid construction complete*

In the international SKA program plan, the SKA-high construction commences after that of the other two components, sometime after 2020. We use the official SKA program date 2022–2023 for possible start of construction, but the exact date of this milestone will clearly depend upon a number of factors including SKA-mid and low schedules, funding availability, science priorities for the 2020–2030 decade, and technological readiness. The last of these are the risks we aim at addressing through the NAA activity proposed here.

Site Selection: The SKA is an international collaborative partnership. As with the SKA-mid and SKA-low components, there will need to be an official site selection process, which the U.S. will participate in. The SKA-mid selection is scheduled to occur in early 2012, with candidate locations in Australia and South Africa. In the timeline, SKA-high site selection should occur in the 2018–2020 window. The U.S. did not submit a proposal for SKA-mid hosting, but has concentrated on the higher frequencies for which our sites are better suited. One of the main goals for the work proposed under the NAA is to develop a strong case for the U.S. site for the SKA-high. We feel that by building on the current national radio astronomy infrastructure, the NAA concept is the leading contender for the SKA-high.

Funding Profile and Schedule: The schedule assumes an ideal federal funding profile beginning in FY 2011. There are at least 6 years of development and prototyping in the timeline, plus milestones and pauses for decisions and preparation. This is a tight schedule in order to meet the end-of-decade milestones for SKA-high site selection and the next decadal survey.

Science Operations: This facility would potentially have a long operational lifetime, similar to that of the VLA/EVLA which will have reached its 40th year of operation in 2020. Part of the proposed development during the decade will be to draft a Science Operations Plan addressing issues of use of the array for key science, general observer science, user support, and data products and access (e.g., for Virtual Observatory like interfaces), as would be needed for the next decadal review. A conservative 20-year operational lifetime would be a reasonable starting point for lifecycle costs.

7. Cost Estimates

As indicated in §3, we currently have no reliable costing model for SKA-high. What we do have is experience from building, operating, and enhancing the VLA and VLBA, and from developing and constructing ALMA. We also have the costing projected for the SKA-mid (Cordes et al.). As part of the NAA development program in 2010–2020 presented in §3.2 we will develop a cost model based on the TDP-II results, the SKA-high prototype station, the *EVLA2010* and *VLBA2010* activities, the ATA RSSP project, and most importantly on the lessons learned from the SKA-mid and SKA-low development and construction. Given the SKA-high science case (§2), NSF Astronomy would be the primary funding source. There may also be overlap in interests between NAA and some NASA programs (e.g., with JPL and the DSN) that should be investigated and exploited where shown to be of mutual benefit.

We plan to involve the U.S. and international radio/mm/submm communities in these design and development activities as much as possible. There are many opportunities for community collaboration that will be enabled by ongoing science operations of EVLA and VLBA, and from the partnerships formed as part of the other NRAO Astro2010 activities. For example, the LWA activity (Taylor et al.) will be developing sites in New Mexico, which in turn will be of help in planning for the NAA-PAS and ultimately in siting the NAA.

Table 7.1. FY2009 Costs for NAA Activities (2010–2020)

Item	Name	Personnel (FTE yrs)	Personnel ($K)	Hardware ($K)	Subcntr. ($K)	Total ($K)
7.1	MeerKAT	6	660	40		700
7.2.1	Antenna Evaluation	12	1320	500	500	2320
7.2.2	Data Transmission	9	990	800		1790
7.2.3	Digital Signal Processing	9	990	500		1490
7.2.4	Digitization	9	990	700	500	2190
7.2.5	Monitor & Control	6	660	700		1360
7.2.6	Wideband Feed/Receiver	12	1320	500	500	2320
7.2.7	Alg., Comp. & Software	15	1650			1650
7.2.8	Concept Design	3	330			330
7.2	TDP-II Total					13450
7.3	Prototype Ant. Station	20	2200	10800	4800	17800
Total						31950

7.1 MeerKAT Collaboration ($700K over 3 years)

An early activity under the NRAO SKA Project Office will be the collaboration with the South African MeerKAT project (§3.2.1). This is for 3 years in 2010–2013, with 6 FTE years of NRAO engineer and scientist participation and $40K for travel/meeting expenses.

7.2 SKA TDP-II ($13450 over 3 years)

This is similar in scope to the original SKA TDP-I, which was recommended by the previous decadal panel with a cost of $22M (FY2000) over 5 years, and was funded by the NSF for $12M (FY2007) over 2007–2011. The TDP-II includes hardware costs to handle the TDP-I/PrepSKA antennas, plus personnel for design, dish verification, and software, computing, and algorithm studies. The TDP-II scope (§3.2.2) is aimed at mitigating the risks and challenges presented in §4. Note that 7.2.2–7.2.5 fall under the purview of a *Center of Excellence for Digital Technology* as proposed in §4.2. SKA-high development is closely aligned with that for SKA-mid, and the NAA developers and engineers will work closely with others within the SKA program on all aspects. Explanations of work items:

7.2.1 Antenna Evaluation: TDP-I/PrepSKA antennas will be delivered to the EVLA, and evaluated for use in the SKA-high. The antennas will be operated using EVLA/ALMA style electronics, SKA prototype hardware, and EVLA correlator and infrastructure. We will explore all antenna designs (e.g., ATA 6m and 10m–15m SKA-mid) and collate the results. These studies will determine the final NAA-PAS design and SKA-high array configuration.

7.2.2 Data Transmission Technology: The development of 40 Gbps (preferably 100 Gbps) data links will be necessary for moving data through SKA-mid/SKA-high systems, as the 10Gbps ALMA/EVLA links are insufficient. This work leverages technology being developed in the telecommunications industry (as EVLA and ALMA did), and is a candidate for collaborative development with activities such as MeerKAT, ATA, and SKA-mid.

7.2.3 Digital Signal Processing: Considerable R&D is required in digital signal processing. Use of high-speed low-cost DSP technology is required for beam forming and signal processing in SKA systems. We will expand NRAO participation in ongoing community DSP development efforts. This includes development of low cost, multipurpose FPGA technologies, beam forming techniques, parallel processing, and software correlator technologies.

7.2.4 Digitization: Digitizing the RF signal early in the signal path is absolutely necessary for the SKA. This will require the use of very high-speed low-cost digitizers packaged in RFI sealed housings. Funds are needed for test equipment and chip runs. NRAO must work closely with the semiconductor industry, corporate research labs, academia and other project groups such as MeerKAT and the members of the CASPER working group to be sure such devices are developed and that they meet the requirements for Radio Astronomy. This item includes providing modest R&D funding and engineering guidance to private industry.

7.2.5 Monitor & Control System: A monitor and control system for the thousands of SKA hardware subsystems will need to be much smaller and cheaper than those of EVLA and ALMA. Bi-directional optical communication over the same fiber as data transmission system is a logical first step. Additionally, small, low cost, RFI quiet monitor and control hardware needs to be developed. Considerable R&D is needed in this area.

7.2.6 Wide-band Feed and Receiver Design: Design and development of wideband (3:1 fractional bandwidth) feeds and polarizers are needed for meeting NAA frequency range goals at minimal cost without compromise in performance (§3.2.2). New broadband receiver systems would utilize custom Monolithic Millimeter-wave Integrated Circuits (MMIC). To carry out the development phase, expertise in the areas of electromagnetic feed, MMIC, and receiver system design, integration and testing will be employed.

7.2.7 Algorithms, Computing & Software: Exploration of data post-processing challenges, development of algorithms, and software planning (§4.3).

7.2.8 NAA Concept Design: Drafting of high-level specifications and requirements for the NAA prototype system, and as a preliminary for the NAA/SKA-high project as a whole.

7.3 NAA Prototype Antenna Station ($17800K over 4 years)

The primary deliverable is the construction of the NAA-PAS. As described in §3.2.3, the current concept is for 15–20 12m antennas, giving a total collecting area equivalent to a single 54m aperture. Because the design and cost for the NAA station depends upon the results of TDP-II and the 2015 NAA-PAS site decision, the cost is highly uncertain, which has been factored in to the estimates.

We adopt a unit cost of $600K per 12m antenna and RF/IF system, approximately twice that for the SKA-mid elements in SKA-mid (Cordes et al.). The reference design is for 16 of these antennas, for a total cost of $9.6M, half of which we expect to subcontract out for the antennas. If costs can be made as low as $480K per antenna system, then a station of 20 could be accommodated. In addition, we estimate $6M for data transmission and signal processing hardware, and $2.2M in personnel costs (20 FTE years). We expect to need more personnel than this, and will rely upon collaborations with SKA and partners for contributions for this work.

7.4 Long term (2020+)

We envision this to be a 10-year construction project, staged along with EVLA and VLBA operations and opening new sites and infrastructure along the way. This is intended to be a proposal-driven general user facility and not a streamlined survey instrument. We have no reliable estimates at this time of capital and total lifecycle costs for a full SKA-high. If we use the antenna cost goals (§4.1), a minimum capital cost would be $1000M. This should *not* be considered as a build-to-cost project, and a primary goal of NAA-PAS is to build a cost model to be used in conjunction with the high-level specifications and requirements and the science case to properly scope and cost the full SKA-high.