The Total Power Array Concept of Operations & System Level Requirements

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2	2022-03-01	Mason	Final draft for TPWG.
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4	2022-04-14	Mason	Incorporate minor changes suggested by E.Murphy, submit for release.
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1 Introduction

1.1 Purpose

This document presents a description of the physical concept for the Next Generation VLA (ngVLA) Total Power Array (TPA) and how it will be operated, and a set of system-level technical requirements related to it.

1.2 Scope

The scope of this document is the TPA and, where explicitly indicated, the closely related but distinct short baseline array (SBA).

2 Related Documents and Drawings

2.1 Applicable Documents

Ref. No.	Document Title	Rev/Doc. No.
AD01	ngVLA Science Requirements	020.10.15.05.00-0001-REQ
AD02	System Requirements	020.10.15.10.00-0003-REQ
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	Array Configuration Reference Design	020.23.00.00.00-0002-DSN
AD05	Antenna Preliminary Technical Requirements	020.25.00.00.00-0001-SPE
AD06	Observing Modes Framework	020.10.05.05.00-0005-PLA
AD07	Observing Modes Status Levels	020.10.05.05.00-0004-PLA
AD08	System Reference Design	020.10.20.00.00-0001-REP

2.2 Reference Documents

Ref. No.	Document Title	Rev/Doc. No.
RD01	ngVLA Science Use Case Parameterization Spread Sheet	2017-06-20 V24
RD02	ngVLA Reference Design Development & Performance Estimates	ngVLA Memo #17
RD03	Summary of the Science Use Case Analysis	ngVLA Memo #18
RD04	Reference Observing Program	020.10.15.05.10-0001-REP
RD05	Envelope Observing Program	020.10.15.05.10-0002-REP
RD06	A New Technique For Heterodyne Spectroscopy: Least-Squares Frequency Switching	Heiles et al. 2007, PASP 119:643
RD07	The Robustness of Least-Squares Frequency Switching	Winkel & Kerp 2007, ApJS 173:166
RD08	Investigation of Spectral Baseline Properties of the Green Bank Telescope	Fisher, Norrod & Balser 2003, Green Bank Electronics Division Internal Report 312

Ref. No.	Document Title	Rev/Doc. No.
RD09	NGVLA Antenna On-the-Fly Mapping Use Cases	Mason & Mangum 2022, NGVLA antenna memo #13
RD10	Investigate properties of data obtained by fast-scanning and generate initial maps	
	ALMA JIRA issue, CSV-2982	
RD11	The continuum sensitivity of GBT Receivers	B. Mason 2013, GBT Memo 282
RD12	Gain stabilization for radio intensity mapping using a continuous-wave reference signal	Pollak et al. 2019, MNRAS 489, 548

3 Background and Methodology

The ngVLA reference design includes several 18m antennas operated in a total power mode in order to provide information on larger spatial scales than the shortest baselines of the interferometric array are capable of accurately measuring. In order to minimize construction and operation costs, an important constraint is that these total power antennas use maximally interchangeable (ideally identical) componentry with other antennas in the array. The Total Power Working Group (TPWG) was convened in May 2021 in order to further develop this concept; to consider in detail the completeness and adequacy of the existing ngVLA System Requirements with respect to total power; and to define extensions and modifications to ngVLA System and Subsystem requirements as needed.

The TPWG carried out a detailed review and gap analysis of the System Requirements [AD02] in the context of the ngVLA Science Requirements [AD01], Reference Observing Program [RD04], Envelope Observing Program [RD05], and other identified science use cases [RD01, RD03]. This review and analysis identified several extensions and modifications to existing system requirements. The TPWG also considered the ngVLA Operations Concept [AD03] and developed a supporting concept of TPA operations.

The structure of this document is as follows. The basic concept of the Total Power Array (TPA) is described in Section 4, and Section 5 describes the TPA operations concept, specifically focusing on Scientific Operations. Section 6 presents the changes to the ngVLA system requirements which the TPWG recommends.

4 The Total Power Array

The TPA will consist of approximately four[1] designated antennas out of the ngVLA Main Array which are optimized for single dish performance. Their constituent components will, to the extent feasible, be interchangeable with other main-array 18m antennas, with some minor differences to optimize single dish science performance. In order to simplify maintenance and operations (e.g. scheduling), the TPA should be located on the plains of San Augustin. The antennas should not be closer to each other than ~1km in

[1] The exact number of TPA antennas which is needed to support the expected ngVLA science program is yet to be specified. It will be determined by the time of the Preliminary Design Review by an update to the Envelope Observing Program (EOP: RD05) which takes into account the array configuration the project adopts as a baseline going into the PDR.

order to minimize correlated atmospheric signals in the data. It is desirable for TPA antennas to be usable as elements of interferometric sub-arrays for both science and calibration observations. TPA antennas will be outfitted with standard ngVLA Water Vapor Radiometers (WVR), the data from which will be usable for opacity and atmospheric emission corrections in the single dish components of the calibration and imaging pipeline.

5 Concept of Operations

The ngVLA Concept of Operations will apply to the TPA, with total-power-specific elaborations, extensions or exceptions as follows. The translation of this concept into system requirements is presented in Section 6; note that the capture is necessarily incomplete at this high level.

The TPA will be capable of providing suitable large spatial-scale information for (at a minimum) all standard-mode, interferometric imaging observations made by the ngVLA's constituent sub-arrays which have baselines up to at least 40km (with a goal of 100km). Supporting TP+interferometric combination with even longer baselines (> 100 km) is desirable, though there are no currently identified science cases requiring this and the size of the image products is a consideration. It is primarily a spectroscopic capability, although it will also provide continuum and polarimetric capabilities, with the continuum sensitivity likely limited to providing effective bandwidths < 1 GHz. The Short Baseline Array (SBA) will provide uv-coverage in the gap between the TPA dish size and the minimum spacing accessible with good coverage by the main ngVLA interferometric array.

Inclusion of TPA (and SBA) observations in a science program will be triggered by a PI-provided largest angular scale (LAS) exceeding that which can be usefully imaged by the SBA (or ngVLA core sub-array, for the SBA). In order to support existing or proposed ngVLA observations which were defined without adequate *a priori* information about LAS, both SBA and TPA will be requestable in a quasi-stand-alone mode. For standard-mode observations defined with reference to a corresponding and suitable interferometric sub-array observation, the TPA total integration time on source will be calculated by observatory provided heuristics; these heuristics will account for the uv-coverage of the interferometric antennas used, the number of total power antennas used, and differences in the sizes of the areas mapped due, e.g., to the necessity of a "guard band" or dictated by differences in the antenna primary beams or scan strategies. It is desirable for these heuristics to be overridable by the PI, although doing so may affect the status level of the TPA observation [AD07]. For example, it could result in the observation being categorized as non-standard or shared risk and exempted from observatory-provided combined imaging with interferometric data products.

It is desirable for both TPA and SBA to be requestable in a fully stand-alone mode without reference to a defined interferometric array science observation. This would enable them to provide pilot / pathfinder observations, among other applications.

The observatory will determine OFF position(s) for total power observations which require them; principally these will be TPA spectral line observations. OFF positions will be determined using existing catalogs where applicable (e.g. CO, 21cm, continuum surveys, etc.), supported by observational searches if needed. It is desirable for the PI to be able to specify or request OFF positions which would supersede observatory-provided ones.

TPA data will be calibrated, imaged, and quality-assured by observatory-provided pipelines and processes with appropriate single-dish calibration, imaging, and QA heuristics. For TPA observations which are defined with respect to an ngVLA interferometric observation, successful completion of both sets of observations will trigger combined (TPA+interferometric) imaging provided the observations are standard imaging modes and meet applicable QA standards. The pipeline will support multiple, standard methods of single dish+interferometric data combination, e.g. feathering and SDINT, and will allow re-imaging of interferometric data with the benefit of TP data in cases where TP data were not available at the time the interferometer image was created.

6 Total Power Requirements

The following subsections describe extensions or modifications to the ngVLA system requirements that are needed to support total power observations. New requirements are assigned sequential 4-digit identifiers preceded by "TP"; it is expected that these identifiers may be superseded by proper system requirement identifiers in a future version of the ngVLA system requirements which incorporates the changes described here. Existing requirements are referenced by their current requirement identifiers based on Rev.C of [AD02]; section numbers and suggested categories given in square brackets also correspond to Rev.C of [AD02], with references like "6.1.x" indicating suggested sections that are not present in the current document. The text of new or modified requirements is in an *italic* font in the "parameter: value" form used in [AD02] and elsewhere; changed portions of existing requirements are <u>underlined</u>. Comments, when provided, follow the requirement(s) in regular text. For new or materially modified requirements the driving science or stakeholder requirements are also provided. Unless otherwise stated requirements apply to the TPA system as a whole.

6.1 Functional & Performance Requirements

SYS0002 [6.1, L1 Functional Operating Mode Requirements; modification]: "Interferometric Mode" will be renamed "Correlation Mode" and the text modified as follows:

***<u>Correlation</u> Mode**: The system shall provide a <u>Correlation</u> Operating Mode with concurrent computation of <u>cross-antenna</u> correlations (parallel and cross polarization) and <u>same antenna</u> auto-correlations (parallel and cross polarization) for all antennas or any subset of the antennas, with tunable spectral and time resolution.*

Other references in the requirements will need to be changed accordingly. The purpose here is to more clearly disambiguate conventional interferometric modes and total power modes from each other and from the correlation operating mode which encompasses both of them.

SYS0007 [6.1, L1 Functional Operating Mode Requirement; modification]

***Total Power Mode**: The system shall provide a <u>correlation</u> operating mode which <u>supports the specific requirements associated with accurately measuring the total power spectral density of the astronomical sky</u>.*

SYS0008 [6.1, L1 Functional Operating Mode Requirement; clarification]

***On the fly mapping mode**: The system shall provide a correlation operating mode whereby larger areas than the antenna primary beam are mapped by a continuous scan of the field. This operating mode will support both conventional interferometric and total power observations.*

TP0001 [6.1.1, L1 Subarray Functional Requirement; new goal]

***Number of total power subarrays**: It is desirable to support at least two fully independent total power subarrays, each with at least one TP antenna.*

Traceability: SCI0009, SCI0010, SCI0016, SCI0018

Science cases: SS4, SS7, SUN1, SUN3, SUN4

This functionality is desirable in order to support simultaneous, multi-frequency total power observations (solar or cometary, for instance).

TP0002 [6.1.2, L1 Correlation Operating Mode functional requirement; new requirement]

***Limited correlation products**: The system shall provide the option to produce auto- and cross-correlations for all antennas, or only same-antenna correlations for all antennas.*

Traceability: SCI0104

Total power observations will not in general benefit from the presence of cross-antenna correlations, although it is desirable to have the capability to provide them without changing functional modes, e.g., for antenna pointing measurements. Same-antenna correlations comprise auto-correlations as well as cross-polarization correlations from the same antenna.

TP0003 [6.1.x, L1 Total Power Performance Requirement; new requirement]

***Total Power Performance**: Except as described in TP0004 the TPA will be capable of providing suitable large spatial-scale information for, at a minimum, all standard-mode, interferometric imaging observations made by compatible ngVLA subarray combinations; including Stokes I and full-Stokes spectral line cubes and continuum images. Compatible subarray combinations are those with approximately uniform uv-coverage from spacings of 12m or less, up to the subarray maximum baseline; with the maximum supported by TPA not to be less than 40km (goal: 100km, or longer if image product sizes are not prohibitive).*

Traceability: SCI0104

Science Cases: NGA2 (KSG3.3.5), NGA8 (KSG3.3.3)

TP0004 [6.1.x, L1 Total Power Performance Requirement; new requirement]

***Total power continuum performance**: It will be possible to collect continuum observations with the TPA, but the continuum image sensitivity may only be scientifically suitable for a subset of science cases as it is expected to be set by receiver gain fluctuations rather than radiometric photon noise statistics.*

Traceability: SCI0104

Science Cases: NGA3, SS4, SS6, SS7

Single dish radio receivers generally achieve a sensitivity which is limited by receiver gain and atmospheric emission fluctuations unless special-purpose architectures are adopted to mitigate these systematics. The changes to the ngVLA reference design that would be required to achieve this would have a complex and significant impact on the ngVLA electronics. Since there is no key science driver to justify the cost that would be entailed, we do not consider it further, and expect that the continuum sensitivity of the TPA will be limited to effective RF bandwidths of ~100 MHz to (if SYS1601 is fully achieved) 1 GHz. Detailed discussion of these issues as encountered at the GBT is given by [RD10], and for ALMA by [RD11]. There are science cases that will nevertheless require total power continuum data, such as solar and some solar system and Galactic use cases.

SYS4401 [6.1.8, L1 TP Operating Mode Functional Requirement; clarification]

***Power Spectral Density Scale**: The system shall generate same-antenna correlation products at a period synchronized to twice the switched power reference trigger signal, with separate accumulated cal ON and cal OFF data and metadata to distinguish them.*

TP0005 [6.1.8, L1 TP Operating Mode Functional Requirement; new requirement]

***TP Reference Positions:** The TP operating mode will allow zero, one or two periodically observed off-source reference positions to be specified per pointing or contiguous region mapped. Reference positions will be specifiable either in celestial coordinates, or as Elevation/Cross-elevation offsets from the field center. This requirement applies to all TP observations, regardless of mapping mode (single pointing; mosaicked pointings; or OTFM).*

Traceability: SCI0104

SYS4402 [6.1.8, L1 TP Operating Mode Functional Requirements; modification]

***Autocorrelation Integration Intervals**: The system shall have the capability of bracketing and integrating autocorrelation power around a pointing position, at time intervals spanning from 0.01 to 1 sec (for OTFM observations), and 0.1 to 10 sec (for single-point tracking observations) based on ~~on source status and~~ the switched power trigger signal.*

It is not necessary to synchronize TP data acquisition with on-source status dynamically and at the integration level; any needed flagging can be addressed in post-processing given TP0007. This requirement together with SYS4401 noise diode cycle times as short as 5ms for TP observations. (see also SYS2001)

SYS4403 [6.1.8, L1 TP Operating Mode Functional Requirement; deletion]

~~***PSD Differencing**: The system shall be capable of automatically differencing the power spectral density of two pointing positions, or system states, to yield a field power spectral density.*~~

The PSD Differencing requirement is to be removed and its system requirement ID retired. The TPA concept we have developed favors use of metadata and offline post-processing for TP calibration operations; given the data volumes involved for TP, the increase in storage and computation burden is not expected to be significant in comparison to those associated with interferometry.

TP0006 [6.1.x, L1 TP Operating Mode Performance Requirement; new requirement]

TP OTFM Performance*: It shall be possible to fully sample a 60 Nyquist pixel by 60 Nyquist pixel region of sky in 9 minutes or less at λ=2.7mm, and in 60 minutes or less at λ=21cm, while maintaining: a referenced pointing accuracy of 0.1 beam FWHM or better; uniform integration time per sky pixel to within 10% within the region of interest; and with at least 50% of the total time spent acquiring data within the 60x60 region of interest. This requirement will apply while scanning relative to a tracked location on the sky in celestial coordinates for all elevations between 70 degrees and the functional minimum elevation of 12 degrees [SYS1102].*

Traceability: SCI0004, SCI0104

Science Cases: NGA2 (KSG3.3.5), NGA8 (KSG3.3.3)

Context and discussion of this requirement is provided in [RD09]. Note that that at the lowest frequencies it implies antenna motions ~30 arcmin/sec, which is faster than current tracking requirements but within required slew rates and with a relaxed pointing specification.

6.2 Requirements affecting Data Products, Data Processing, & Supporting Data Stores

TP0007 [6.3.1, L1 Low Level TP Data Products requirement; new requirement]

Antenna position information*: During total power observations the system shall record information that will allow reconstruction of both the commanded and actual beam-center trajectories on the sky in celestial coordinate systems. This information will be recorded at a time resolution equal to (or smaller than) the greater of 0.1sec and the autocorrelation integration period.*

Traceability: SCI0004, SCI0104

TP0008 [6.3.1, L1 Low Level TP Data Products requirement; new requirement]

WVR information for total power*: During total power observations at Band 3 and higher, the system shall record WVR information in order to facilitate removal of atmospheric emissivity fluctuations from the data.*

Traceability: SCI0004, SCI0104

TP0009 [6.3.6, L1 Data Processing Requirement; new requirement]

Data combination: *For Standard Observing Modes that make images from multiple sub-arrays—including combining data from TP and interferometric arrays—the automated pipeline will make combined image products.*

Traceability: SCI0104, STK0805

TP0010 [6.4, L1 Supporting Data Stores]

TP Reference Position database: *A database shall be provided to store information related to TP reference positions, including measured TP spectra and associated QA metrics.*

Traceability: SCI0104, STK0805

6.3 Gain, Stability & Temporal Requirements

SYS1601 [Sec. 6.14 L1 Gain Stability Requirement; modification]

TP Antennas Gain Stability: *TP Antenna dG/G including any applied online calibrations shall not exceed 1E-3 over a 60 sec period. Goal not to exceed $3.2x10^{-5}$ over 1 second.*

Achieving this goal will permit radiometer-equation noise limited continuum observations with 1 GHz bandwidth under stable atmospheric conditions. The 1 second timescale is derived from the approximate crossing time for a Nyquist pixel in the 21cm OTFM use case of TP0006; Nyquist pixel crossing times at higher frequencies are smaller, e.g., by one order of magnitude for the 2.7mm OTMF use case of TP0006.

This requirement has been clarified to apply to the overall system gain including any shorter timescale online calibrations applied. A short mathematical overview of gain stabilization techniques is given by [RD12]. We note that application of cal diode normalization of the data on an integration by integration basis online is not likely to be desirable for gain stability/noise reasons.

TP0011 [Sec 6.14 (see also 7.6), L1 Gain Stability Requirement; New Requirement]

Bandpass Shape Stability*: The autocorrelation bandpass shape of TP antennas— including any shorter timescale online calibrations— will be stable such that the average of any 100 MHz interval within the band will not vary by more than $4x10^{-4}$ relative to either adjacent 100 MHz interval over 40 seconds. This requirement will apply over slews up to 4 degrees and with antenna temperature changes of up to 5 Kelvin, including any system deviation from linearity over this range in antenna temperature.*

Traceability: SCI0102, SCI0104, SCI0108

Science Cases: NGA2 (KSG3.3.5), NGA8 (KSG3.3.3)

This requirement is critical for the core science of the TPA: broad spectral line total power mapping. The timescale is the switching time for position switched/OTF mapping observations which is approximately 40 seconds for a minimum 50% observing efficiency (10 seconds slew each way; 10 seconds ON; 10 seconds OFF). This requirement could be relaxed by considerably reducing the position switching cycle time (e.g., by including a nutator on the TPA antennas). The timescale and the antenna motion components of this requirement derive from considering maps several square degrees on aside (e.g. NGA 2 / KSG 3.3.5), with OFF positions measured at a cadence consistent with the fast phase switching requirement (CAL0207: 3 degree slew and settle within 7 seconds), assuming 50% observing efficiency. The antenna temperature variation figure derives from several comparable criteria: the change in static atmospheric Tsys at Band 6 for a 5 degree elevation slew going up from 30 degrees elevation under good conditions; the dynamic change in atmospheric emission that is expected to be seen under median Band 6 observing conditions; and the level of variation in Galactic Synchrotron that would be seen near the Galactic plane at the bottom of Band 1.

This requirement, like TP0010, applies to the net system gain including any shorter timescale calibrations that were applied to the data.

SYS2001 [Sec. 6.17 L1 temporal requirement; modification]

Temporal resolution: *Correlator visibility integration time shall be tunable, with a range of 5 sec to 100 msec (possibly at limited bandwidth) or better. Goal to support integration times as short as 1 msec at limited bandwidth. <u>TP integration times will be tunable down to an integration time of 10 msec at full bandwidth.</u>*

Traceability: SCI0004, SCI0104.
See also SYS4402.

SYS0106 [Sec. 6.17 L1 temporal requirement; clarification]

On-the-fly Mapping—Data & Control Rates*: The system shall support <u>interferometric</u> on-the-fly (OTF) mapping rates of 2x sidereal at 28 GHz, with data dump rates and delay update rates <400 msec at the full system bandwidth. Goal to support rates <50 msec at reduced bandwidth or spectral resolution (i.e., fixed data output rate).*

This requirement has been clarified to apply specifically to conventional interferometric observations. The corresponding TP requirement is TP0006.

6.4 Observation Preparation & Scheduling Requirements

TP0012 [Sec. 6.20.3, Observation Preparation, Execution & Scheduling Requirement; new requirement]

Inclusion of TP & SBA: *Inclusion of total power and/or SBA in a proposed observation will be triggered by a PI-specified science parameter (Largest Angular Scale or LAS).*

Traceability: SCI0104, STK0805

TP0013 [Sec. 6.20.3, Observation Preparation, Execution & Scheduling Requirement; new requirement]

Stand-alone TPA & SBA: *It shall be possible to request SBA &/or TPA observations with reference to any suitable, already proposed or executed ngVLA observation ("quasi-stand-alone"), with a goal of allowing fully stand-alone SBA and TPA observations to be requested.*

Traceability: SCI0104, STK0805

The intent of this requirement is to support the science goals of proposals which were initially defined without adequate *a priori* information regarding large-scale emission in the target region(s).

TP0014 [6.20.3, Observation Preparation, Execution & Scheduling Requirement; new goal]

Concurrent TP and interferometric observations*: it is desirable to be able to perform TP observations concurrently with other ngVLA subarray observations of the same science target, up to differences in observing sequences dictated by the differing integration times and calibration needs of the different subarrays.*

Traceability: SCI0010, SCI0016

Science Cases: SS4, SS7, SUN1, SUN3, SUN4

The intent of this goal is to support observations of variable phenomena which require both TP and interferometric data; primarily these are solar and solar system use cases.

6.5 *Other Recommendations*

This section presents several recommendations which, while not demonstrably demanded by ngVLA key science cases, were considered to be important based on experience with a variety of other single dish facilities.

TP0015: Sidelobes & stray radiation mitigation

In order to maximize the main beam efficiency and minimize the antenna side lobes, *it is highly desirable for the TPA receivers to illuminate the aperture with a tapered illumination profile, such that the peak of the first sidelobe is at least 23 dB below the maximum antenna gain; while maintaining a FWHM of 1.2 λ/D or less for the main beam width.* Similarly it is highly desirable to minimize spillover beyond the secondary, particularly at 21cm (near the bottom of Band 1). These optimizations are particularly important for Galactic 21cm observations, such as those in KSG 3.3.5 (NGA 2), and should not come at the expense of a penalty of more than 1% to the point source sensitivity of the main interferometric array as a whole.

We note that while this optimization is highly desirable from the total power perspective, it will necessitate use of fully heterogeneous-array imaging algorithms for interferometric sub-arrays which use both antennas which implement it, and standard main-array antennas.

Science Cases: NGA2 (KSG 3.3.5), SS4, SS7, NGA14

TP0016: Reflection mitigation

To reduce the potential for standing waves, *it is desirable that the TP antenna design minimize unintended multiple-reflection paths for radiation to enter the receiver*, for example by suitably arranged reflective and/or absorptive baffles. This is particularly critical for total power observations of bright sources [RD08].

Science Cases: SS4, SS6, SS7

TP0017: Daytime High Frequency Operation

Because of the anticipated high demand for Band 6 total power observations as well as the disproportionate impact of primary aperture thermal deformations on total power data, *it is desirable for TPA antennas to maintain precision operations during the daytime in order to meet demand for targets at a wide range of hour angles*. This need might be partially addressed by identifying and using periods when the radiative environment is thermally favorable (e.g., overcast but stable conditions), rather than solely using the sun elevation as a proxy metric of the radiative environment.

Science Cases: SS4, SUN3, SUN4

TP0018: Frequency Switching

Frequency switching is a desirable capability for a range of Galactic TP science cases, especially 21cm observations of neutral hydrogen, particularly in light of relatively recently developed forms of the technique [RD06, RD07]. A preliminary evaluation of the capability against the reference design was carried out, with the conclusion that frequency switching would likely not imply a major perturbation to the system design [AD08] *except* for Band 1, which uses a direct digitization architecture. The needed changes to the Band 1 receiver were deemed too substantial to recommend at present, particularly given the complex trade-offs that might be incurred; therefore, since Band 1 is the primary science driver for the capability, the TPWG elected not to include Frequency Switching in the system concept. *Should the Band 1 receiver design change in such a way as to simplify the implementation of frequency switching it would be desirable to consider including frequency switching for the TPA.*

With the current TPA system concept it will be necessary to develop an accurate total power bandpass calibration scheme using the noise diode.

Science Cases: NGA2 (KSG3.3.5), NGA14

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