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HYDROGEN INTENSITY AND REAL-TIME ANALYSIS EXPERIMENT

TELESCOPE MECHANICAL ASSEMBLY REQUIREMENTS DOCUMENT

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BASELINED VERSION 1

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1. Introduction

1.1. Purpose

This document describes the requirements for the Hydrogen Intensity and Real-time Analysis eXperiment's (HIRAX)'s foundation, dish mount, dish, and receiver support components which make up the Telescope Mechanical Assembly (TMA). These requirements will be used to inform an open design and supply tender for the initial 256 dishes to be built at the South African Radio Astronomy Observatory (SARAO) site in the Karoo, South Africa.

1.2. Scope

The scope of this document is to record the science, system, and subsystem of the TMA. This document does not present or discuss engineering requirements corresponding to the design of the TMA. The design requirements will be provided by the design and supply contractor for this subsystem and will be evaluated in a corresponding design review.

1.3. Collaboration

The HIRAX project is a large international collaboration. The collaboration currently comprises 24 institutions in addition to the University of KwaZulu-Natal (UKZN): South African Radio Astronomy Observatory (SARAO), University of the Western Cape, University of Cape Town, Durban University of Technology, Stellenbosch University, Rhodes University, African Institute for Mathematical Sciences, Botswana International University of Science and Technology, Laboratoire Astroparticules et Cosmologie at Universite Paris 7, Inter-University Centre for Astronomy and Astrophysics, University of Toronto, Perimeter Institute, Canadian Institute for Theoretical Astrophysics, University of British Columbia, West Virginia University, NASA Jet Propulsion Lab, Yale University, Carnegie Mellon University, University of Wisconsin, University of Oxford, McGill University, École polytechnique fédérale de Lausanne, Universite de Geneve, and Eidgenössische Technische Hochschule Zürich. These collaborators contribute significantly to instrumentation development, telescope deployment and student training.

1.4. Requirement Levels

The requirements in this document have been categorised in six requirements levels (Table 1). For the purposes of this document, Level 6 requirements only pertain to the TMA.

Table 1: Requirement Level Definitions and Acronyms

Req Level	Definition
Level 1	Key Science Goals (KSG) - The highest-level science goals and stakeholder goals Project Constraints (CON) - Internal and external programmatic constraints to the project
Level 2	Sub-Key Science Goals (Sub-KSG) - The direct sub-goals required to achieve the high-level science goals
Level 3	Supporting Key Science Goals (Supporting-KSG) - The supporting goals required to achieve the sub-goals
Level 4	Science Requirements (SCI) - The telescope properties and performance requirements to achieve the KSGs
Level 5	System Requirements (SYS) - The requirements on the overall telescope system to achieve the SCI
Level 6	Subsystems Requirements (TMA): The requirements on the TMA to achieve the SCI, presuming an architecture SYS

1.5. Verification Techniques

HIRAX uses the verification techniques as outlined by the International Council on Systems Engineering (INCOSE), REF 9 (Table 2).

Table 2: Verification Techniques

Technique	Definition
Inspection (INSP)	Technique based on visual or dimensional examination of an element; the verification relies on the human senses or uses simple methods of measurement and handling. Inspection is generally non-destructive, and typically includes the use of sight, hearing, smell, touch, and taste, simple physical manipulation, mechanical and electrical gauging, and measurement. No stimuli (tests) are necessary. The technique is used to check properties or characteristics best determined by observation (e.g. paint color, weight, documentation, listing of code, etc.).
Analysis (ANLY)	Technique based on analytical evidence obtained without any intervention on the submitted element using mathematical or probabilistic calculation, logical reasoning (including the theory of predicates), modeling and/or simulation under defined conditions to show theoretical compliance. Mainly used where testing to realistic conditions cannot be achieved or is not cost-effective.
Analogy or Similarity (ALGY)	Technique based on evidence of similar elements to the submitted element or on experience feedback. It is absolutely necessary to show by prediction that the context is invariant that the outcomes are transposable (models, investigations, experience feedback, etc.). Similarity can only be used if the submitted element is similar in design, manufacture, and use; equivalent or more stringent verification actions were used for the similar element, and the intended operational environment is identical to or less rigorous than the similar element.
Demonstration (DEM)	Technique used to demonstrate correct operation of the submitted element against operational and observable characteristics without using physical measurements (no or minimal instrumentation or test equipment). Demonstration is sometimes called 'field testing'. It generally consists of a set of tests selected by the supplier to show that the element response to stimuli is suitable or to show that operators can perform their assigned tasks when using the element. Observations are made and compared with predetermined/expected responses. Demonstration may be appropriate when requirements or specifications are given in statistical terms (e.g. mean time to repair, average power consumption, etc.).
Test (TEST)	Technique performed onto the submitted element by which functional, measurable characteristics, operability, supportability, or performance capability is quantitatively verified when subjected to controlled conditions that are real or simulated. Testing often uses special test equipment or instrumentation to obtain accurate quantitative data to be analyzed.
Sampling (SAMP)	Technique based on verification of characteristics using samples. The number, tolerance, and other characteristics must be specified to be in agreement with the experience feedback.

1.6. Verification level

The verification level refers to when and at what level the verification are done. The possibilities are:

- Design: Verification is done during the design phase, sometimes by design review.
- Prototype: Verification is done during the prototype phase, usually on the prototype itself. It is usually done only once during development.
- Production: Verification is done during production, on every production model.

1.7. Verification location

The verification location refers to the location where the verification is done. The possibilities are:

- Factory: Verification is done at the supplier factory, by the Supplier. The Client may repeat these tests, or may witness these tests.
- Site: Verification is done at the site, by the Client (default) or the Supplier (specified if applicable).

1.8. Definitions

1.8.1. Accuracy: Maximum absolute difference between the ideal value and the mean achieved value, averaged across the array. See also par. 1.9.1.1.1.

1.8.2. Precision: RMS scatter about the mean achieved value. See also par. 1.9.1.1.2.

1.8.3. **Dish:** The parabolic reflector that focuses light onto the receiver. The ideal dish shape is given by the paraboloid of revolution, $\mathbf{z = (x^2 + y^2)/5.52}$ for $\mathbf{sqrt(x^2 + y^2)} \leq 3$, where linear dimensions are in meters. This paraboloid has a focal height of 1.38 m, diameter of 6 m, and a focal ratio of 0.23.

1.8.4. **Receiver:** The antenna and electronics that sit at the focus of the dish and that convert received radio waves into electrical signals. The receiver consists of a cloverleaf antenna and cylindrical reflective feed can.

1.8.5. **Receiver Support:** The mechanical structure that attaches the receiver to the dish, ensuring that the receiver is positioned precisely at the focus. The support structure also provides environmental protection for the receiver and the RFoF electronics.

1.8.6. **Radio-frequency over Fibre (RFoF)**: The electronics that convert radio-frequency signals from the receiver into optical signals that are passed along optical fibres from the telescopes to the correlator. The RFoF transmitter units are located on the sky side directly “behind” the feed can of the receiver.

1.8.7. **Dish Mount:** The mechanical structure that attaches the dish to the foundation and that allows the dish elevation angle to be changed.

1.8.8. **Foundation:** The structure that interfaces with the ground and that supports the dish mount.

1.8.9. **Telescope Mechanical Assembly:** The non-electrical components of each telescope, comprising the dish, receiver support, dish mount, and foundation.

1.8.10. **Telescope:** A single, complete observing element of the HIRAX array, including mechanical and electrical components.

1.8.11. **Visibilities (array and beam factors):** The fundamental output of an interferometer is the *visibility*, the time-averaged product of the electric field measured by two antennas. $V_{ij}=\langle E_i^* E_j \rangle$. By noting that the average of E^2 is the power from a given direction, we can integrate over space to get $\langle V_{ij} \rangle = \int I(\boldsymbol{\theta})A(\boldsymbol{\theta})\exp(2\pi i\mathbf{B}\cdot\boldsymbol{\theta}/\lambda)d^2\Omega$ where I is the intensity in direction θ, A is the sensitivity of the instrument in that direction (the *primary beam*), B is the vector separating the two antennas, and λ is the observing wavelength. In the small-angle/flat-sky limits, this reduces to measuring one component of the 2D Fourier transform of the sky (times primary beam) at a wavevector of **B**/λ, which by convention is called **u**.

1.8.12. **Gain:** The gain of an antenna is defined to be its response at the peak of the beam divided by the response of an ideal spherically symmetric antenna.

1.8.13. **Solid Angle:** If an antenna beam pattern A(θ) is normalized so the peak response is one, the antenna solid angle is the effective area of sky seen by the antenna. Mathematically, it is $\iint A(\theta)\, d\Omega$. For a perfectly efficient antenna, the gain and solid angle will be inversely proportional to each other.

1.8.14. **FoV:** The field of view (FoV) is the (approximate) diameter of the patch of sky seen by an antenna, where the gain is a significant fraction of the peak. Several definitions are possible - the 3 dB point where the beam has fallen by half, the distance to the first null, or the diameter of a disk that has the same solid angle as the beam are sensible definitions.

1.8.15. **Baseline:** The baseline is defined to be the vector separation between two antennas. Colloquially, the pair of antennas is also often referred to as a baseline.

1.8.16. **uv coordinates:** The **uv** coordinate is the baseline vector divided by the observing wavelength. This sets the output phase of an interferometer as a function of position on the sky (technically, under the assumption there is no differential phase introduced by the primary beams of the two antennas).

1.8.17. **System Temperature:** The radiometer equation gives the measurement noise for low frequency radio telescopes: $dT/T=1/(Bt)^{½}$ where T is the noise temperature, dT is the measurement uncertainty, B is the system bandwidth, and t is the observing time. Essentially, one gets an independent measurement of the signal level every 1/B seconds (as long as $h\nu \ll kT$), so the total number of independent measurements is Bt, and so the fractional uncertainty in measuring the power level in a system is $1/(Bt)^{1/2}$. The relevant power is the total signal seen by the system, which is referred to as the *system temperature*. In the Rayleigh-Jeans limit, noise temperatures are additive, and so the system temperature can be thought of as the sum of several contributions, such as the receiver noise itself, power from the sky, ground spillover, and absorptive losses: $T_{sys}=T_{rec}+T_{sky}+T_{spill}+T_{abs}+\ldots$ In the limit that absorption is small, its dominant effect is to replace a fraction of the signal with room temperature emission. Assuming 300K for ambient, then 0.1 dB of absorption before the LNA will contribute 300*(10^(0.1/10)-1)=7K to the system temperature.

1.8.18. **Noise Spectrum**: To determine the observing time required to measure a power spectrum, we must first determine dT in the radiometer equation. When observing a diffuse field, a single baseline sensitive to features of size θ_{bl} will see $(\theta_{pb}/\theta_{bl})^2$ independent features that sum incoherently, where θ_{pb} is the primary beam size. Since both θ_{bl} and θ_{pb} depend on the dish separation and dish size in wavelengths, the ratio is set by the baseline length in units of dish size. For a maximally short baseline, there are ~7 independent patches (the exact number depends on the dish illumination pattern), with the number increasing with the square of the baseline length over the dish size. Because these patches add incoherently, and interferometers average the temperature in their field of view, if the typical temperature of a patch due to the power spectrum is T_{ps}, then the temperature measured by the interferometer will be $T_{ps}/(n_{patch})^{1/2}$ ~0.4 T_{ps}/(B/D) where B is the baseline length and D the dish diameter. Keeping B/D low is the motivation for compact arrays. We can now use the radiometer equation to estimate the observing time to reach an SNR of 1: $0.4T_{ps}/(B/D)=T_{sys}/(Bt)^{1/2}$ or $t=7(T_{sys}/T_{ps})^2(B/D)^2/B$.For a power spectrum of 100 μK on a 60m baseline with a BAO signal coherent over 30 MHz and given a 50K system temperature, we can plug in to get 7 $(50/1e\text{-}4)^2$ $(10)^2/(30e6)$ or 1600 hours. With a ~5 degree primary beam there are ~15000/5^2 ~600 independent primary beams and so this survey would require a million hours. For a redundant array, there are ~ndish simultaneous baselines measuring the same UV point (assuming the baseline length is substantially smaller than the array size), and so a 256-dish array would take ~4000 hours/6 months of on-sky time (Ref 5).

1.8.19. **Relevant angular scales for HIRAX:** The normal modes on the surface of a sphere are spherical harmonics: $Y_{lm}(\theta,\varphi)=P_{lm}(\cos(\theta))\exp(2\pi i m\varphi)$ where *l* and m are integers, $l\geq0$, $-l\leq m\leq l$, and P_{lm} are the associated Legendre polynomials. The number of "wavelengths" across the sphere in a Y_{lm} is given by *l*, and so (half-wavelength) feature sizes correspond (roughly) to 180/*l* degrees. Much like an N-dimensional box can be described by a set of Fourier coefficients, the spherical sky can be described as the sum over the spherical harmonics: $T(\theta,\varphi,\nu)=\sum\sum a_{lm}(\nu)Y_{lm}(\theta,\varphi)$. On linear scales, we expect the sky to be a Gaussian random field, which means the real/imaginary parts of the a_{lm} are Gaussian random variables with random phase. The complete statistical information of a 2-dimensional Gaussian random field is contained in the *power spectrum*: $C_l\equiv\langle|a_{lm}|^2\rangle$. The response of a visibility will peak when $l=2\pi u$ (this can be derived by placing an EW-oriented baseline at the equator, setting $m=l$, and noting that the phases will match up when $l=2\pi u$). For HIRAX-256, the wavelength is ~0.5m and the dish spacings range from ~6 to ~100m, so the u range is 12-200 and the l range is then ~75 to 1200.

1.8.20. **Radial and transverse wavenumbers, $k_{\parallel}$ and $k_{\perp}$**: If we restrict ourselves to scales small compared to the distance to the observer, we can break down the wavevector of a 3D plane wave down into the components parallel and perpendicular to the line-of-sight, $k_{\parallel}$ and $k_{\perp}$. For the first peak of the BAO power spectrum (150 Mpc, or k~0.06 h/Mpc), $k_{\parallel}$ appears along the frequency axis, with characteristic length of ~20 MHz, and $k_{\perp}$ appears in the spatial direction, with characteristic wavelength of ~1.5-2.5 degrees for HIRAX, corresponding to l~200, or 10-20m baselines. Harmonics in the BAO power spectrum will show up with higher $k_{\parallel}/k_{\perp}$, corresponding to finer frequency structure and longer baselines.

1.9. General notes on accuracy and precision

1.9.1. Accuracy and Precision for mounting on the foundation, dish mount, dish vertex relative to mount, dish diameter and receiver support

Most specifications pertaining to dimensions are differentiated into two components, namely Accuracy and Precision. The differentiation of these specifications to the two components of Accuracy and Precision is intended to aid the Dish supplier to pass parts that have a **constant sidedness, and may reduce cost**.

It is important to understand both the definitions of Accuracy and Precision (as defined in par. 1.8.1 and 1.8.2). This is expanded below.

1.9.1.1. Definitions

1.9.1.1.1. Accuracy

Accuracy is defined as the absolute difference between the mean achieved value and the ideal value. The mean achieved value is calculated from measurements on each part, averaged across n dishes in the array, calculated and interpreted in the way as described below.

1.9.1.1.2. Precision

Another very important part of the specification is Precision. Precision will be calculated as the RMS value of parts around the abovementioned calculated mean.

1.9.1.2. Mathematical relations for Accuracy and Precision

Mathematical relations describing the manner in which both Accuracy and Precision are calculated, are provided below.

A discrimination is made between values as zero dimensional, one dimensional and two dimensional values referenced in specifications.

1.9.1.2.1. Zero Dimensional values

Zero dimensional values are specified when there is only single value measurement to be made to achieve a specification, in some sense similar to a scalar value. The vast majority of specifications relates to zero dimensional values.

1.9.1.2.1.1. Accuracy for zero dimensional values

In the case of zero dimensional values, where a single value measurement is made, the mean or average value will be calculated in accordance with the relation:

$$\bar{p}^0 = \frac{1}{n}\sum_{i=1}^{n} p_i^0 \quad \ldots (1),$$

where n is the number of dishes over which the average is taken at that time, which may be a subset of the total number of dishes, the summation is over n, and i is an index that denotes a single dish.

The value p_i^0 is the (single) value of the measurement of the dimension or feature that should be controlled. These values will be averaged over n dishes to determine the mean, $\bar{p}^0$, for those sample of dishes that are considered.

For each dish then, the value of $|q^0 - \overline{p}^0|$ (where |.| denotes absolute value, and q^0 represents the ideal measurement value for the feature to be controlled) is then compared with the accuracy specification. For the first dish, the first value of p_i^0 may be used as the first average. After the second dish, the average $\overline{p}^0$ can be calculated from (1) for n=2 but might not be representative. Stability of $\overline{p}^0$ will improve as n grows larger.

When the Dish number approaches 10 (2 prototype dishes, and 8 Pre-production dishes), the average $\overline{p}^0$ will start to settle to a defined value. The Pre-production dishes are deemed as part of the production run.

When a specification is defined in a plane, for example the x-y plane, the measured values p_i^0 should be split into x,y or r, ϴ, to make them zero-dimensional, for example p_{xi}^0 and p_{yi}^0 .

The value of $p_i^0 = \sqrt{\left(p_{xi}^0\right)^2 + \left(p_{yi}^0\right)^2}$ and $\bar{p}^0 = \frac{1}{n}\sum_{i=1}^{n} p_i^0$ shall be calculated, and the value of $|q^0 - \overline{p}^0|$ shall be within the accuracy specification.

When the accuracy is defined in a volume, the above shall be extended to three dimensions.

1.9.1.2.1.2. Precision for zero dimensional values

The Precision will be calculated as the RMS value of parts around the calculated mean.

The average Precision for a zero dimensional value for n dishes, $\tilde{P}^0$

$$\tilde{P}^0 = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(p_i^0 - \bar{p}^0\right)^2} \ldots (2),$$

shall be determined, and compared to the precision specification.

In equation (2), p_i^0 is the measured value for each dish. The subscript i denotes the i^{th} dish.

When precision is defined in a plane, for example the x-y plane, the value of p_i^0 and $\overline{p}^0$ shall be calculated as above, and the value of $\tilde{P}^0$ shall be within the precision specification.

1.9.1.2.2. One Dimensional values

One dimensional values are specified when there are multiple measurements specified on a requirement. The only example is the dish diameter, where 30+ points are specified to be measured to determine the dish diameter. The values are termed one dimensional as the dish diameter may be expressed as a single dimensional function of the azimuthal angle measured around the dish main axis.

1.9.1.2.2.1. Accuracy for one dimensional values

In the case of one dimensional values, where a number of measurements are made, the mean or average value will be calculated in accordance with the relation:

$$\bar{p}^1 = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{1}{n_p}\left(\sum_{j=1}^{n_p} p_{ij}\right)\right] \ldots (3),$$

where p_{ij} is the j^{th} measured value of the dimension or feature that should be controlled of the i^{th} dish, n_p is the number of measurement points, (n_p >30 measurement points specified as in the case of the dish diameter, TMA.201).

Thus, the summation over subscript j is over all measurement points, and the summation over subscript i is over n dishes. The subscript i denotes the i^{th} dish.

n is the number of dishes over which the average is taken at that time, and may be a subset of the total number of dishes.

For each dish then, the value of $|q^1 - \bar{p}^1|$ (where |.| denotes absolute value, and q^1 represents the ideal measurement value for the feature to be controlled) is then compared with the accuracy specification.

For the first dish, the average $\bar{p}^1$ will not be available, and the dish supplier may use the first value of $\frac{1}{n_p}\left(\sum_{j=1}^{n_p} p_{ij}\right)$ as the first average. After the second dish, the average $\bar{p}^1$ can be calculated from (4) for n=2 but might not be representative. Stability of $\bar{p}^1$ will improve as n grows larger.

When the Dish number approaches 10 (2 prototype dishes, and 8 Pre-production dishes), the average $\bar{p}^1$ will start to settle to a defined value.

1.9.1.2.2.2. Precision for one dimensional values

The Precision will be calculated as the RMS value of parts around the calculated mean $\bar{p}^1$.

The Precision value in one dimension for one dish will be calculated in accordance with the relation:

$$\tilde{P}_i^1 = \sqrt{\frac{1}{n_p}\sum_{j=1}^{n_p}\left(p_{ij} - \bar{p}^1\right)^2} \quad \text{... (4),}$$

Where $\tilde{P}_i^1$ is the precision value for a one dimensional value of the ith dish.

1.9.2. Accuracy and Precision for the Dish surface

The Accuracy and Precision of the dish surface is calculated in a similar, but slightly generalized and somewhat different way.

For the Dish Surface (TMA.202 and TMA.204) accuracy and precision, multiple (x,y,z) measurements of the (optically) reflective surface of the dish shall be done using laser scanning or photogrammetry.

For each dish (subscript i), the average dish shape shall be realized as a paraboloid of revolution, $p_i(x,y)$, using a best least squares fit from the collection of measured points. After measurement on each dish, the **average** of the best-fit paraboloid **for n dishes**,

$$\bar{p}(x,y) = \frac{1}{n}\sum_{i=1}^{n} p_i(x,y)) \ldots \text{(5),}$$

may be determined, where **n = number of dishes considered.**

The summation over n will be compared against the ideal paraboloid, $q(x,y) = (x^2 + y^2)/5.52$.

In the accuracy specification, the maximum deviation from the ideal paraboloid shall be calculated i.e.

$$P_{max} = \mathrm{MAX}(|\bar{p}(x,y) - q(x,y)|) \quad \text{... (6)}$$

The MAX function shall be evaluated at each point measured, and P_{max} shall be better than 3 mm.

For the first dish, the average paraboloid of revolution $\bar{p}(x,y)|_{n=1}$, is available and may be used for the accuracy and precision calculations. After the second dish, the average $\bar{p}(x,y)$ can be calculated for n=2 but might not be representative. Stability will improve as n grows larger.

When the Dish numbers approach 10 (2 prototype dishes, and 8 Pre-production dishes), the average paraboloid of revolution $\bar{p}(x,y)$, will begin to settle.

The precision of each dish (subscript i) will be calculated in accordance with the relation:

$$\tilde{P}_i(x,y) = \sqrt{\frac{1}{n_p}\sum_{j=1}^{n_p}\left(P_{ij}(x,y) - \bar{p}(x,y)\right)^2} \text{ ... (7)}$$

Where P_{ij} (x,y) is, individual measurements done on the surface of each dish and n_p the number of measurement points. The summation is over all points measured.

The value of $\tilde{P}_i(x,y)$ will be evaluated for each dish, and will be compared to the precision value specified for each dish. A small deviation from a constant sidedness is thus acceptable within the allowed precision value.

It is important to realise that, as dishes may conform to accuracy specifications, some may fail the precision specifications if they have a varying sidedness. Parts that have a **constant sidedness** may pass both.

1.9.3. Application of the accuracy and precision requirements for acceptance of Dishes

For zero dimensional, one dimensional and Dish surface (or two dimensional) values, the acceptance criteria for Dishes shall be as follows:

For the first n dishes (the value of n is nominated by the supplier, but shall be between 10% and 20% of the total dish population, see below), the average shall be calculated over a population of n dishes. Prior to all n dishes being manufactured, the average shall be calculated over all available dishes starting from the pre-production dishes.

Thereafter (after the first n dishes has been manufactured and accepted), the average value calculated over the first n dishes manufactured and accepted, shall be frozen up to the full number N=258 (256 plus two prototypes) have been produced. The Pre-production dishes shall be deemed as part of the production run (part of 256).

The acceptance of the dishes is somewhat different between the first n dishes manufactured and accepted, and the rest of the dishes. This is explained below:

1.9.3.1. First n dishes manufactured and accepted.

The *accuracy* of each dish shall be evaluated using the population average over the first n dishes manufactured and accepted, i.e. for the first n dishes, the values of $|q^0 - \overline{p}^0|$ for zero dimensional values, $|q^1 - \bar{p}^1|$ for 1 dimensional values and P_{max} for dish surfaces, shall be less than the specified accuracy value. Note that the average is evaluated over the first n dishes manufactured, and the accuracy shall be calculated over all available dishes starting from the pre-production dishes.

The *precision* for zero dimensional values of each dish shall be evaluated as a population average, i.e. the value of $\tilde{P}^0$ shall be less than the specified precision value.

The one dimensional and dish surface *precision* shall be evaluated on a per dish basis. Thus, for each dish, the value of $\tilde{P}_i^1$ and $\tilde{P}_i(x, y)$, shall be less than the specified precision value.

Dishes will be accepted as individual dishes, based on the above. For the first production dishes, when the number (subscript i) of the dish being accepted is less than the agreed value of n, the data available up to the ith dish (i.e. average calculated up to and including the value of i) shall apply.

1.9.3.2. Dishes manufactured and accepted after the initial n dishes (Dish number > n).

The *accuracy* of each dish shall not be evaluated anymore, and is not specified as a requirement for any zero, one and two-dimensional quantities, after the initial n dishes has been manufactured and accepted. The population average calculated over the first n dishes manufactured and accepted, i.e. the value of $\overline{p}^0$, for zero dimensional values, $\bar{p}^1$ for 1 dimensional values and $\bar{p}(x, y)$ for dish surfaces shall be fixed after n dishes has been manufactured and accepted, and the fixed values shall be used to determine the precision of dishes manufactured after the initial n dishes. Let these fixed values be denoted as

$$\bar{p}_n^0 = \frac{1}{n}\sum_{i=1}^{n} p_i^0 \ldots (8);$$

$$\bar{p}_n^1 = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{1}{n_p}\left(\sum_{j=1}^{n_p} p_{ij}\right)\right] \ldots (9);$$

and

$$\bar{p}_n(x, y) = \frac{1}{n}\sum_{i=1}^{n} p_i(x, y) \ldots (10).$$

These values (subscript n) shall be determined at n and fixed for all subsequent dishes. The subscript n is used to distinguish it from the averages for the initial n dishes manufactured.

1.9.3.2.1. Precision of zero dimensional values after the initial n dishes

For zero dimensional values, and after the n initial dishes has been manufactured and accepted, the values of a rolling precision of n dishes, i.e. the values of

$$\tilde{P}_i^0 = \sqrt{\frac{1}{n}\sum_{j=(i-n)+1}^{i}\left(p_j^0 - \bar{p}_n^0\right)^2} \text{ ... (11)},$$

shall be evaluated for each dish after the n[th] dish, where p_j^0 is the measured values for the n dishes manufactured and accepted subsequent to the i[th] dish. The subscript i in $\tilde{P}_i^0$ denotes the i[th] dish after the initial n dishes.

$\tilde{P}_i^0$ is the precision value for a zero dimensional value of the i[th] dish after the initial n dishes.

Thus, the values of $\tilde{P}_i^0$ shall be less than the specified precision value for the dishes manufactured and accepted after the first n dishes. Note that the average $\bar{p}_n^0$ is evaluated over the first n dishes.

1.9.3.2.2. Precision of one dimensional values after the initial n dishes

The values of

$$\tilde{P}_i^1 = \sqrt{\frac{1}{n_p}\sum_{j=1}^{n_p}\left(p_{ij} - \bar{p}_n^1\right)^2} \text{ ... (12)},$$

shall be evaluated for each dish, where p_{ij} is the measured value for each dish manufactured and accepted subsequent to the first n dishes. The same nomenclature as in equation (3)) is used, except the subscript i denotes the i[th] dish after the initial n dishes.

Thus, the values of $\tilde{P}_i^1$ shall be less than the specified accuracy value for the dishes manufactured and accepted after the first n dishes. Note that the average $\bar{p}_n^1$ is evaluated over the first n dishes.

The dish one dimensional *precision* shall be evaluated on a per dish basis. Thus, for each dish manufactured and accepted subsequent to the initial n dishes, the value of $\tilde{P}_i^1$ for dish one dimensional values shall be less than the specified precision value.

1.9.3.2.3. Precision of two dimensional (dish surface) values after the initial n dishes

The values of

$$\tilde{P}_i(x,y) = \sqrt{\frac{1}{n_p}\sum_{j=1}^{n_p}\left(P_{ij}(x,y) - \bar{p}_n(x,y)\right)^2} \text{ ... (13)},$$

shall be evaluated for each dish, where P_{ij} is the measured value for each dish manufactured and accepted subsequent to the first n dishes. The same nomenclature as in equation (7)) are used, except the subscript i denotes the i^th dish after the initial n dishes.

The dish surface *precision* shall be evaluated on a per dish basis. Thus, for each dish manufactured and accepted subsequent to the initial n dishes, the value of $\tilde{P}_i(x, y)$ for dish surface values shall be less than the specified precision value.

1.9.3.2.4. Nominated value of n dishes

The supplier may nominate n, but the minimum value must be more than or equal to 10% of the entire population of 256 dishes. The maximum value shall be less than or equal to 20% of the entire population.

1.9.3.2.5. Dishes accepted as individual dishes

Dishes will be accepted as individual dishes, based on the above.

1.9.4. Trending of Accuracy and Precision requirements

The result of measurements, and the compliance to each requirement for which an accuracy or precision requirement are specified, shall be trended as part of the Verification, to indicate process stability, and to ensure that specifications are met.

The precision and accuracy for each dish and for every requirement shall be calculated, based on the data of all dishes previously manufactured. The data shall be used to trend the conformance of all the dishes to the requirements as specified for 256 dishes, and shall also be used to indicate process stability. If trending shows a clear tendency towards nonconformance for increased dish numbers, the Dish supplier shall modify the manufacturing process, or take the necessary steps to rectify the problem or to mitigate problematic trends, before manufacturing subsequent dishes.

1.9.5. Accuracy vs. Precision requirements

In the event that a Dish manufacturer deems the overhead effort to adhere to both accuracy and precision requirements too onerous, or too costly, the values allocated to the precision requirements may be interpreted as a maximum absolute deviation from the ideal.

1.10. Coordinates and Mathematical Quantities

We introduce the following coordinates and mathematical quantities to define the placements and orientation angles of each telescope mechanical assembly and its constituent subsystems. Figures 1-3 illustrate these coordinates and angles.

- **Dish vertex and focus:** these quantities are determined by the best-fit paraboloid of revolution for each dish.
- **Boresight vector:** vector joining the vertex to the focus for each dish

- **Array coordinates (X, Y, Z):** X points to the east, Y points to the north, and Z points upward, with the origin at the array center.
- **Elevation axis center (X_i, Y_i, Z_i):** for telescope mechanical assembly number "i" within HIRAX, these coordinates give the nominal location of the elevation axis center in the array.
- **Elevation axis center errors (dX_i, dY_i, dZ_i):** array coordinate errors in the location of the elevation axis center for telescope mechanical assembly number "i" within HIRAX.
- **Dish vertex offset Z_{off}:** when pointed at zenith, the ideal (error-free) location of the dish vertex is **(X_i, Y_i, $Z_i + Z_{off}$)** in array coordinates.
- **Elevation angle E:** the nominal elevation angle, referenced from the horizon, determined by the rotation angle about the elevation axis.
- **Elevation axis alignment error α:** this angle describes the misalignment between the elevation axis and the X axis (east-west line).
- **Boresight error β:** this angle describes the misalignment between the boresight vector and the nominal pointing vector determined by the elevation angle E.
- **Dish vertex position (X_v, Y_v, Z_v):** the location of the dish vertex in array coordinates after a rotation to the nominal elevation angle E. The ideal position of the dish vertex is determined by rotating the error-free zenith position, (X_i, Y_i, $Z_i + Z_{off}$), to the nominal elevation angle about the elevation axis, which is tilted by α. The errors in the actual position of the dish vertex relative to the ideal position (after rotation) are described by (dX_v, dY_v, dZ_v).
- **Dish coordinates (x, y, z):** coordinates defined by the best-fit paraboloid so that the vertex sits at the origin, the boresight vector points in the z direction, and x is aligned with X.
- **Receiver position (dx, dy, f + dz):** position of the receiver in dish coordinates, where (dx, dy, dz) are translational errors, and f is the nominal focal height.
- **Receiver orientation angle errors (γ, δ):** angles describing the misalignment of the receiver with respect to the dish. Let **R** denote the vector joining the vertex to the center of the receiver plane. In the absence of error, the receiver plane should lie perpendicular to **R**; the angle describes the error in azimuthal clocking with respect to the cardinal directions.

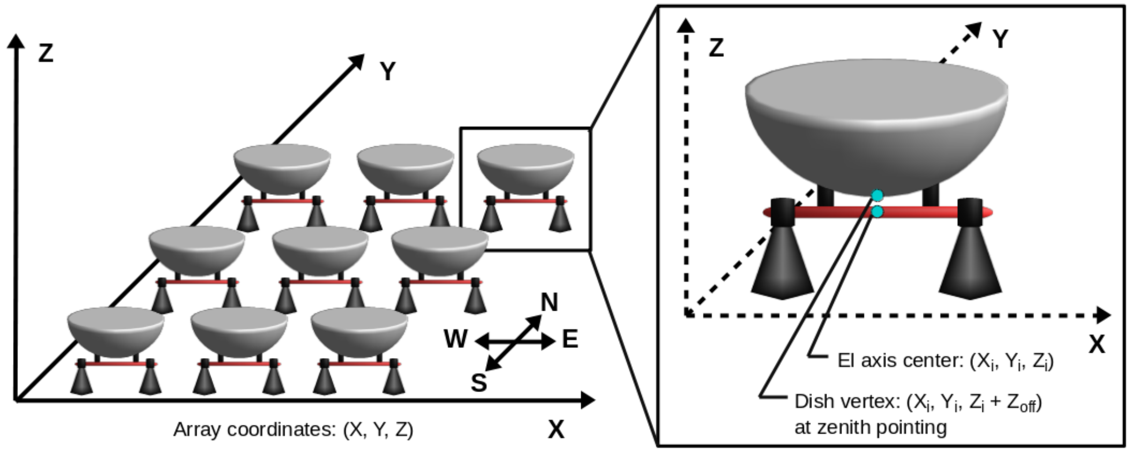

Figure 1: The array coordinates are defined such that X points east, Y points north, and Z points up. The inset shows an ideal, error-free dish pointing at zenith. The coordinates of the center point of the elevation axis are (X_i, Y_i, Z_i) for telescope number "i" in HIRAX, and the coordinates of the dish vertex are (X_i, Y_i, Z_i + Z_{off}).

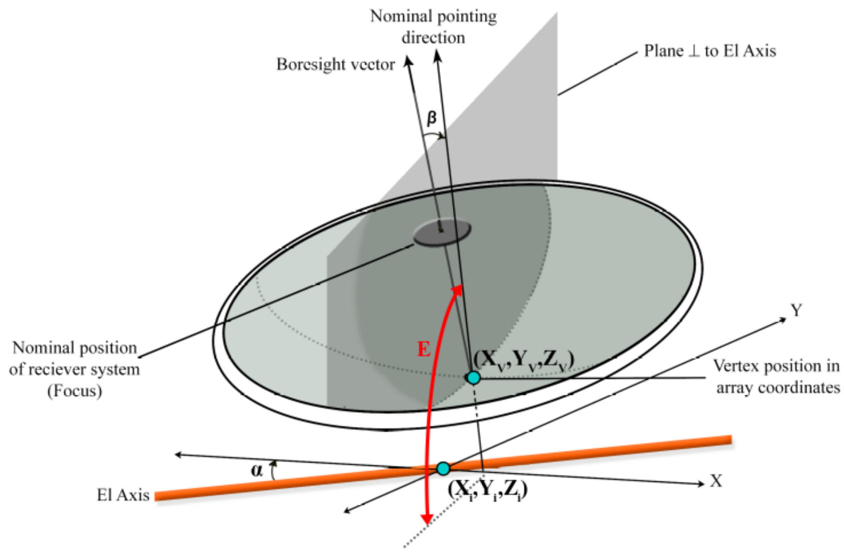

Figure 2: Errors in the elevation axis, boresight pointing, and dish vertex position at a given nominal elevation angle E. The misalignment of the elevation axis with respect to the X axis is described by the angle α. The angle between the boresight vector and the nominal pointing direction is described by the angle β. The dish vertex may have translational errors with respect to the ideal position, and the vertex coordinates at elevation angle E are given by (X_V, Y_V, Z_V); see text for details.

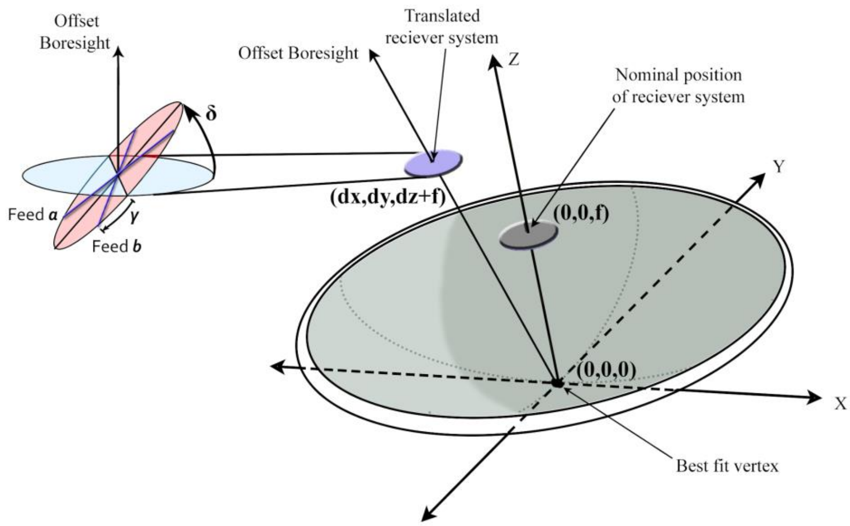

Figure 3: The dish coordinates (x, y, z) are defined with respect to the best-fit paraboloid of revolution. The vertex is located at the origin, the vector between the vertex and the focus defines the z direction, and x is aligned with the array coordinate axis X (east direction). The focus of the dish is located at (0, 0, f), where f is the focal height. The receiver is located at (dx, dy, dz + f), where (dx, dy, dz) describe translational errors with respect to the focus position. The error in polar orientation angle (δ) of the receiver is defined relative to the vector that joins the vertex to the center of the translated receiver system. The error in azimuthal orientation angle (γ) of the receiver is defined relative to the cardinal directions.

1.11. Referenced Documents

The following documents provide context and/or source material for this document and the documented requirements (Table 3).

Table 3: Reference Documents

REF #	Document Name	Author
REF1	*Environmental Conditions for the SKA1 Mid SIte in South Africa. 301-000000-009, rev 2.*	South African Radio Astronomy Observatory (SARAO)
REF2	*International Standard for Classification of Environmental Conditions, IEC 60721-3-4*	International Electrotechnical Commission (IEC)
REF3	*HIRAX: A Probe of Dark Energy and Radio Transients*	Newburgh et al 2016
REF4	*HIRAX Business Plan for the National Research Foundation (NRF) Strategic Research Equipment (SRE) Grant*	The HIRAX Project
REF5	*Late-time Cosmology with 21 cm Intensity Mapping Experiments*	Bull et al 2014
REF6	*HIRAX Requirements Simulations Report*	HIRAX Cosmology Simulations Working Group

REF7	*Coaxing cosmic 21 cm fluctuations from the polarized sky using m-mode analysis*	Shaw et al 2014
REF8	*Initial draft of HIRAX telescope requirements, November 2019*	Prof. Cynthia Chiang, HIRAX Dish Subsystem Working Group
REF9	*INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities 4th Edition*	International Council on Systems Engineering (INCOSE)
REF10	*System Design Document*	The HIRAX Project

2. Science

2.1. Constraining Dark Energy

HIRAX is expected to create competitive constraints on the history of the expansion of the universe by statistically measuring the Baryon Acoustic Oscillation (BAO) feature over four billion years of the universe’s history. This will shed light on the nature of dark energy, one of the most perplexing unsolved problems in modern cosmology. There is significant potential for instrumental and calibration systematic effects to obscure this measurement, necessitating strict tolerances on the dish and feed system. For this reason the science-derived requirements on the TMA are primarily driven by this use case.

2.2. Fast Radio Bursts

These bright, extragalactic, millisecond duration events with an unknown source of emission have garnered increased attention within the astronomical community and HIRAX's large collecting area and mapping speed will allow it to detect about one new Fast Radio Burst (FRB) each day, creating a path ro determine the source of these mysterious phenomena.

2.3. Cross-correlation Studies

These studies shed insight into the evolution of the clustering of neutral hydrogen gas relative to galaxies and probe the evolution of neutral hydrogen gas relative to the dark matter. HIRAX's location in the southern hemisphere is a competitive advantage in these studies as most future optical galaxy surveys, such as the Large Synoptic Survey Telescope (LSST), will be located in the southern hemisphere.

2.4. Pulsar Science

HIRAX will be a competitive instrument for pulsar science, owing to a combination of its large collecting area, wide field of view, and high time resolution. The telescope will monitor the sky daily for periods of months, enabling the measurement of the dispersion measure of pulsars to aid external constraints on timing measurements.

2.5. Star Formation and Galaxy Evolution with Hydrogen Absorbers

By probing Hydrogen absorbers along the line-of-sight to distant quasars, HIRAX will allow the study of star formation mechanisms and Active Galactic Nuclei (AGN), providing insight on the physical processes affecting the evolution of galaxies. HIRAX will enable the study of such systems out to redshifts of 2.5, covering the epoch where both cosmic star formation and AGN activity peak. HIRAX is expected to detect an order of magnitude more hydrogen (HI) 21cm absorbers than are known today.

3. Operational Concept

3.1. Technique

HIRAX is a proposed radio telescope managed out of UKZN. The telescope will be an interferometer array made up of 1024 closely-packed dishes (Figure 4). Currently, the project has funding to build at least 256 instrumented telescopes, which will be built in the following phases: 2-qualification dishes (not part of the operational telescope), an 8-element array, a 128-element array and a 256-element array. If funding is extended, the array will be built up to a 1024-element array. HIRAX is an interferometer that will use an array of closely-packed 6-m telescopes, operating at frequencies 400–800 MHz, to measure the BAO signal at a redshift range of 0.8-2.5 through 21-cm HI intensity mapping. Intensity mapping captures the aggregate emission of hundreds of galaxies simultaneously, yielding rapid, statistical measurements over large volumes without the need for detecting individual galaxies. Measurements of the BAO peak position over this large volume serve as a standard ruler that allows us to chart the expansion history of the Universe and search for the growth spurt introduced by dark energy.

Each telescope in this interferometer array will focus radio waves onto its receiver, which measures and amplifies the signals. These radio signals will be converted to optical using RF over optical fibre (RFoF) transmitters, then passed over optical fibre to the digital backend, where the data from all dishes will be brought together. Within the digital backend, the optical signal from each telescope will be converted back into radio, digitized and channelized. The electronics will then perform a “corner turn” operation to group data from all telescopes for each frequency channel. Finally, all pairs of telescopes will be cross-correlated to form visibilities, the fundamental data product of a radio telescope, which will be stored as the raw dataset. The raw data will also be processed into formed beams that will be used to search for FRBs and pulsars.

Figure 4: Conceptual image of the HIRAX Array in the Karoo. Not representative of actual dish design to be determined by the TMA tender.

3.2. System

A block diagram of the HIRAX System can be seen in Figure 5. The front-end hardware for this system includes the receiver, receiver support, dish, dish mount, and foundation. The receiver will interface with the top of the receiver support. The receiver support will interface with the dish, the dish will interface with the mount, and the mount will interface with the foundation. Power and fibre cables will need to run through the receiver support and to the back side of the HIRAX dish, where they will be routed down/through the mount and over the foundation. From the foundation, the cables will run through trenches until they reach shielded container 1 containing the F-engine and first part of the digital back-end.

The back-end hardware includes the F-engine (housed in RFI shielded container 1); the X-engine, pulsar search engine and FRB search engine (housed in RFI shielded container 2), and the support and archive PCs (housed in RFI shielded container 3). The cables will first interface with the digital backend via the F-engine in shielded container 1. The power and fibre cables will then move to shielded container 2, housing the X-engine, FRB search engine and pulsar search engine. The power and data cabling will then interface with shielded container 3 which houses the support and archive PCs. Finally the fibre cable will leave shielded container 3 and interface with the SARAO data system, where the data will be transported to the Centre for High Performance Computing (CHPC) in Cape Town. The power cables will run from shielded container 3 into shielded container 4, which will house the power station. The power cables will leave the power station and SARAO will facilitate the interface with Eskom's overhead power lines.

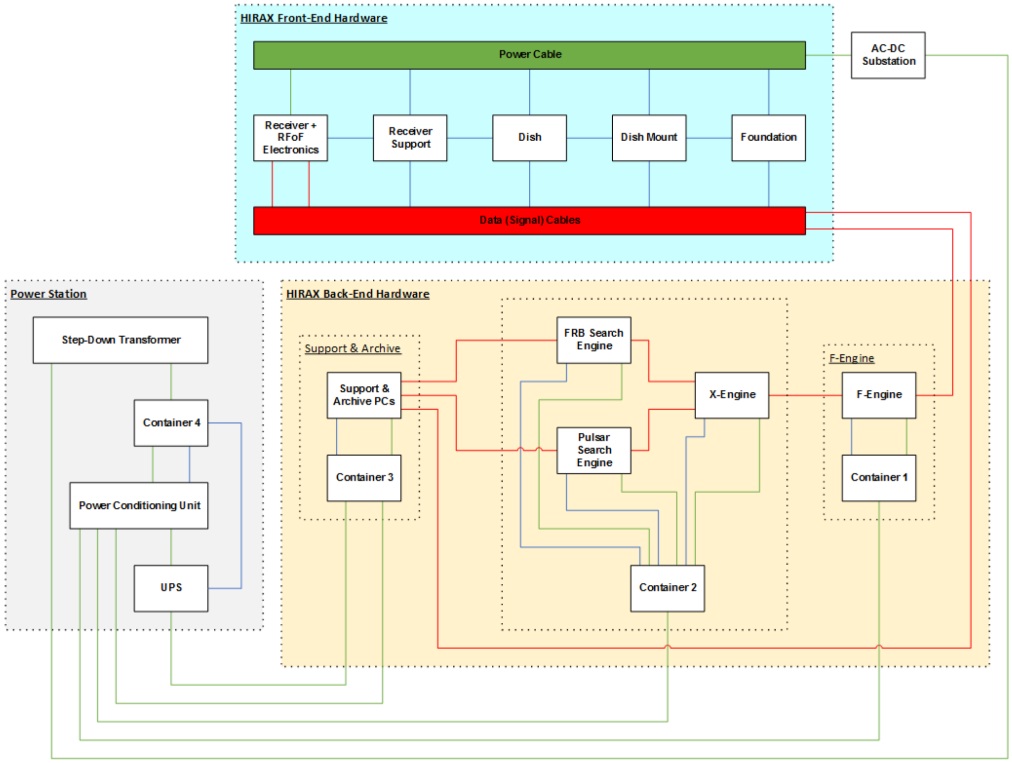

Figure 5: HIRAX System Diagram

3.3. Telescope mechanical assembly

Each telescope mechanical assembly (TMA) consists of the dish, receiver support, dish mount, and foundation. All of these parts remain stationary during HIRAX observations; therefore, only manual adjustment mechanisms are required. The main observing mode consists of all telescopes pointing at a fixed elevation and measuring (unattended) the strip of sky that passes through their field of view over a period of several months before being manually re-pointed. The HIRAX science goals dictate a strict level of repeatability between the telescope mechanical assemblies. The online data calibration and compression scheme assumes that telescope pairs with identical baselines observe identical signals from the sky, which are then averaged together. Therefore, even slight variations between telescopes can severely compromise the fidelity of the science data. Each telescope mechanical assembly must therefore be manufactured and installed with a high level of repeatability, with stringent tolerances on mechanical alignment, surface accuracy, etc. Furthermore, the manual repointing mechanism must be relatively simple and fast to operate safely. Figure 6 shows a conceptual mock-up of the TMA and figure 7 displays a mock-up with reference to the feed interface.

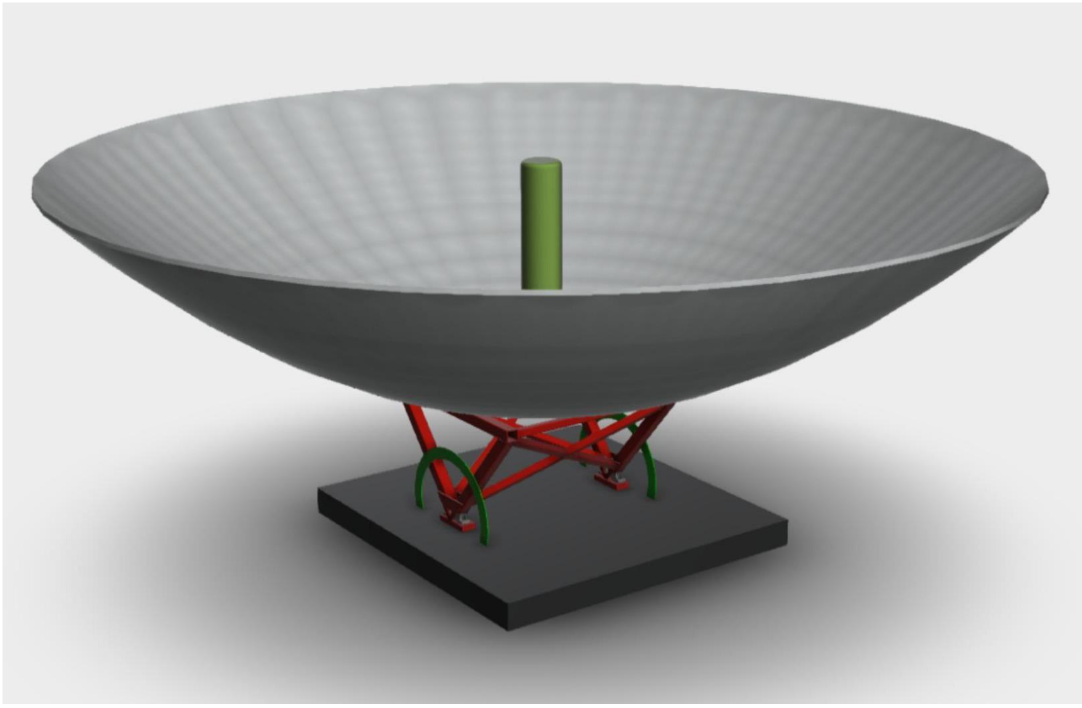

Figure 6: Conceptual mock-up of the TMA. Not representative of an actual design.

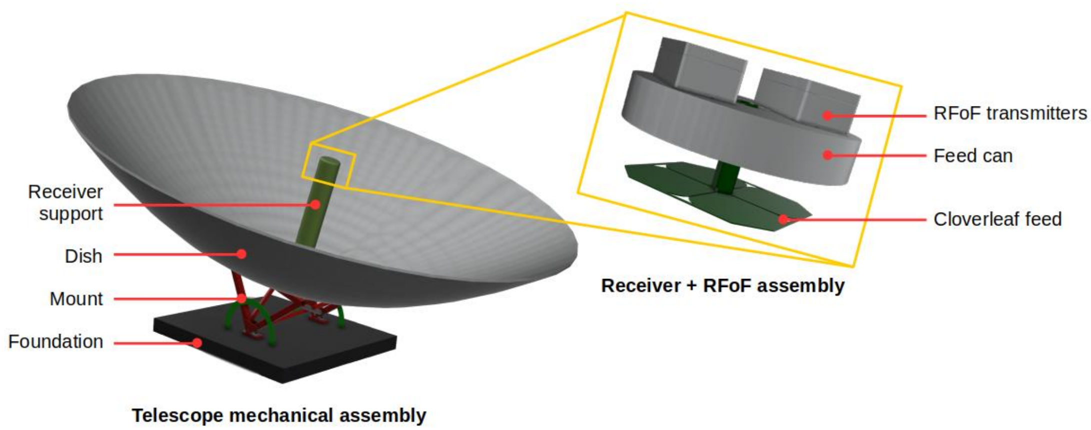

Figure 7: Conceptual mock-up of the TMA pointed off zenith, with the receiver and RFoF assembly that are housed inside the receiver support structure (central column). Not representative of an actual design.

4. Environment

4.1. Location

Figure 8 displays the HIRAX instrument sites in South Africa. The HIRAX project currently hosts its prototypes at the SARAO site in Hartbeespoort (-25.89025, 27.6858) - see figure 9. The HIRAX project will host its two qualification dishes and its main array at the South African Radio Astronomy Reserve outside of Carnarvon in the Karoo. The qualification dishes will be built at the Klerefontein (-30.96955, 21.98896) and the main array will be built at Swartfontein (-30.69629327, 21.5723648) - see figure 10.

Figure 8: HIRAX sited in South Africa

Figure 9: The HIRAX prototype location at SARAO's Hartebeesthoek Radio Observatory

Figure 10 : The HIRAX qualification dish location at Klerefontein and main array site at Swartfontein.

4.2. RFI

The array will be located on the SARAO site in the Karoo, a world-class radio quiet site that provides several significant strategic advantages to the experiment. These include an extremely low radio frequency interference (RFI) environment protected by local regulations as well as modern infrastructure for site access, power and internet connectivity. See Figures 11 below. Figure 12 and 13 show the RFI environments for Swartfontein and Klerefontein respectively.

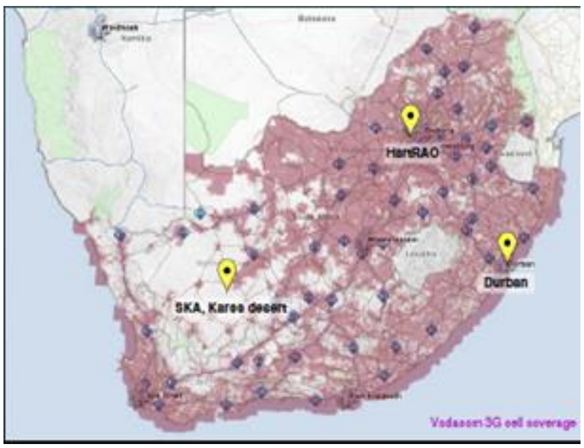

Figure 11: Image of RFI contamination in South Africa

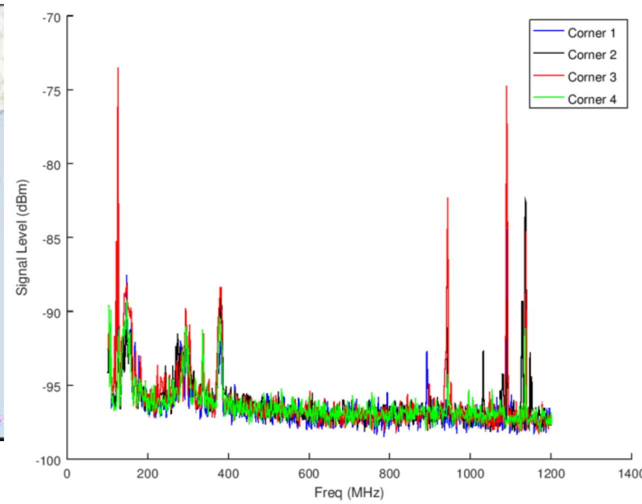

Figure 12: RFI measurements (vertical polarization) at the HIRAX Swartfontein site in the Karoo show no detectable contamination in the 400-800 MHz band. Measurements were carried out at each corner of the site to guard against local propagation effects. Data courtesy of Carel van der Merwe.

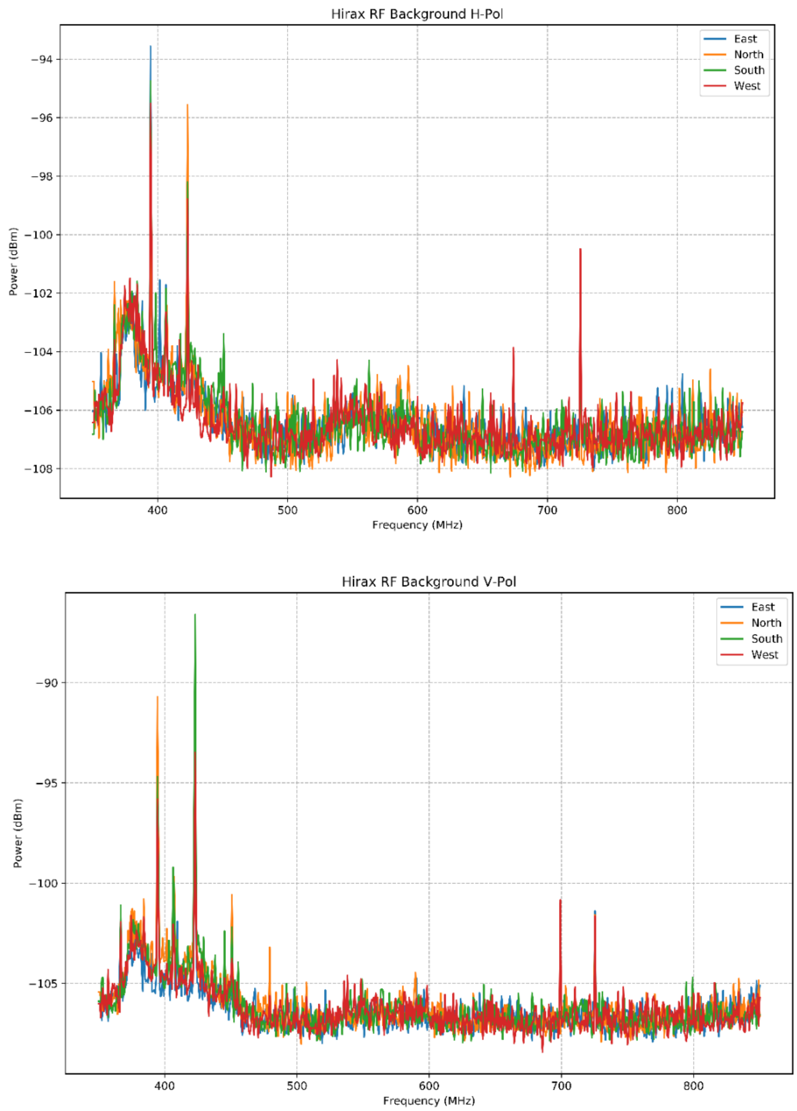

Figure 13: RFI measurements at the HIRAX Qualification Array Site at Klerefontein in the Karoo, with horizontal and vertical polarizations shown in the upper and lower panels, respectively. Plots courtesy of Carel van der Merwe.

HIRAX and all of its contractors must comply with SARAO-site RFI restrictions. No equipment is allowed on Site without having first obtained the necessary SARAO RFI Permit (temporary installation) or Certificate of Compliance (permanent or semi-permanent installation), in accordance with the SARAO Policy for the Control of RFI on the Karoo Site. This includes any electrical equipment that may produce intentional radio frequency transmissions, such as mobile phones, laptops, Bluetooth transmitters, satellite phones and electronic tablets, as well as equipment that may produce unintentional electromagnetic radiation such as digital cameras, petrol vehicles, welding machines, electrical power tools, generation equipment and inverters.

A risk analysis will be done by SARAO on the RFI characterised equipment for the different phases: Design, Installation, Operations including Maintenance. This risk assessment will determine an attenuation deficit which has to be achieved to not exceed the tolerable power level (frequency dependent) at the nearest SKA/MeerKAT dish. The attenuation deficit will take into account distance and topography. If equipment is needed which exceeds the attenuation deficit, and which cannot be shielded, an agreement will need to be reached on conditions of use (time of day or notification of operators, etc).

4.3. Site Development

Appropriate built environment professionals have been appointed to conduct the site evaluation, site development planning and design, and construction monitoring for the site development. The site development plan will set requirements for HIRAX site development; including; fencing, road access, power and data cabling, trenching and conduits, electrical substation and backup power supply, infrastructure containers, and lightning protection.

4.4. Geotechnical

A Geotechnical Engineer and Topographical Land Surveyor were appointed by the UKZN Infrastructure Projects and Planning section (who will be managing the HIRAX site development tender) in July 2019. Site investigations were completed confirming that the site was suitable for the equipment. The geotechnical information will be included in the information pack for all equipment tenders.

4.5. Environmental Conditions

The environmental conditions that can be expected for non weather protected equipment during the operational deployed lifetime are described in this section (Table 4-8). These conditions were evaluated by SARAO as part of their document 301-000000-009, rev 2, *Environmental Conditions for the SKA1 Mid Site in South Africa,* REF1. These conditions were classified using the International Standard for Classification of Environmental Conditions, IEC 60721-3-4, and tailored based on actual measured environmental conditions. Note that the wind speeds are stated for a height of 10m above the ground. The HIRAX telescopes are expected to be much closer to the ground.

Table 4: Climatic Conditions: REF1

Conditions	Expected Conditions		Comments
	IEC 60721-3-4		
Ambient Temperature	Class 4K4H	(1,2)Low: -5 ^{C} (1,2)High: 40 ^{C}	The extreme ambient temperatures are adjusted based on the expected site conditions. Refer to section 6 for the statistical distribution of the measured temperature conditions on the SKA1 Mid site.
Relative Humidity		Low: 4 % High: 100 %	
Absolute Humidity		Low: 0.9 g/m^3 High: 36 g/m3	

Rain Intensity		[1,2]15 mm/min	
Rate of Change of Temperature		5.0° C/10min	
Air Pressure		Low: 70 kPa High: 106 kPa	
Solar Radiation		1120 Watt/m^2 (peak)	The expected daily average solar radiation is 450 Watt/m2.
Heat Radiation	Class 4Z1	None	
Wind Speed	Class 4Z5	[1,2]44.4 m/s max gust	The extreme wind speed is adjusted based on the expected site conditions.
Condensation	Class 4K4H	Yes	
Precipitation		Rain: Yes	
		[1,2]Snow: Yes	Limited to light snowfall of 20mm with a density of 130kg/m3.
		[1,2]Hail: Yes	Limited to hailstones with impact energy of ±11J. This is typically tested by means of ice balls of size 38mm in diameter at ±27.4m/s.
Low Rain Temperature		5°C	
Water from Other Sources than Rain	Class 4Z7	[1,2]Yes	Limited to splashing, water run-off from structures and ground level water pooling to a depth of 200mm.
Ice and Frost Formation	Class 4K4H	[1,2]Yes	Limited to frost formation on exposed surfaces.
[1] Values of the IEC standard is adjusted [2] Values of the ETSI standard is adjusted			

Table 5: Biological Conditions: REF 1

Conditions	Expected Conditions Comments	Comments
	IEC 60721-3-4, Class 4B2	
Flora	Yes	Non weather-protected locations at the site(s) will be areas with limited presence of mould and fungus. The presence of animals such as rodents, termites, snakes, scorpions, bees, birds & nests are likely.
Fauna	Yes	
[1] Values of the IEC standard is adjusted [2] Values of the ETSI standard is adjusted		

Table 6: Chemically Active Substances: REF1

Conditions	Expected Conditions IEC 60721-3-4, Class 4C1	Comments
Salts	None	Non weather-protected locations at the site(s) will be located in remote rural areas, away from coastal regions.
Sulphur Dioxide	0.1 mg/m^3	
Hydrogen Sulphide	0.0 mg/m^3	
Chlorine	0.1 mg/m^3	
Hydrogen Chloride	0.1 mg/m^3	
Hydrogen Fluoride	0.003 mg/m^3	
Ammonia	0.3 mg/m^3	
Ozone	0.01 mg/m^3	
Nitrogen oxides	0.1 mg/m^3	
(1) Values of the IEC standard is adjusted (2) Values of the ETSI standard is adjusted		

Table 7: Mechanically Active Substances:SARAO document 301-000000-009, rev 2, *Environmental Conditions for the SKA1 Mid SIte in South Africa*

Conditions	Expected Conditions IEC 60721-3-4, Class 4S2(4S3)	Comments
Sand	*(1,2) 300 (1000) mg/m^3*	*Non weather-protected locations at the site(s) will be located in remote areas away from sources of dust and sand. During the lifetime limited exposure over short periods is expected due to occasional wind driven dust and sand as per Class 4S3 (typically <3% of lifetime wind higher than 10m/s) as well as due to road and ground works during the SKA1 building phase and road maintenance.*
Dust (suspension)	*(1,2) 5 (15) mg/m^3*	
Dust (sedimentation)	*(1,2) 20 (40) mg/m^2/h*	
(1) Values of the IEC standard is adjusted (2) Values of the ETSI standard is adjusted		

Table 8: Mechanical Conditions: SARAO document 301-000000-009, rev 2, *Environmental Conditions for the SKA1 Mid SIte in South Africa*

Conditions	Expected Conditions	Comments
	IEC 60721-3-3, Class 4M1	
Stationary vibration	(2)0.3 mm, 2-9Hz	Non weather-protected locations at the site(s) will be located in remote areas and not exposed to significant external vibration and shock sources. However equipment may be subjected to vibrations and shock due to neighbouring mounted equipment and normal maintenance activities.
	(2)1 m/s2, 9-200Hz	
Non-stationary vibration, including shock	(2)40 m/s2, 22ms	
(1) Values of the IEC standard is adjusted (2) Values of the ETSI standard is adjusted		

4.6. Natural Disasters

HIRAX and all of its contractors must adhere to all disaster management policies developed by the guest instrument host institution, SARAO, and the consortium lead institution, UKZN. The most likely serious natural disaster to occur on the HIRAX main site in the Karoo is a hailstorm. Because these events occur annually, the dishes must be built to withstand hail and, as mentioned above, the electronics will be housed in weatherproof containers.

4.7. Health and Safety

HIRAX and all of its contractors must adhere to all occupational health and safety management policies developed by the guest instrument host institution, SARAO, and the consortium lead institution, UKZN.

The mechanical design of HIRAX is relatively simple, with no parts that move during observations. The main observing mode will consist of all dishes pointing at a fixed elevation and measuring (unattended) that patch of sky repeatedly over a period of several months before being manually re-pointed. The manual adjustment mechanism and process will be designed to ensure that it can be operated safely. The risks to health and safety during regular HIRAX operations are therefore minimal. However, the lead institution is currently working with their OH&S department to formalize any possible health and safety risks in the project's risk management process.

During integration of the telescope mechanical assembly (at both the main site at Swartfontein and during testing at Klerefontein) and re-pointing of the array, on-site personnel will take sensible precautions such as the wearing of hard hats and enclosed shoes. Students will at all times be supervised by an experienced member of the HIRAX team (several team members have experience in deploying telescopes in harsh environments, such as the Atacama Desert and Antarctica). Full training will be given in the safe use of any necessary tools or equipment.

4.8. Security

The HIRAX equipment will be located on the secured SARAO site. The overall SARAO site fencing and a SARAO security checkpoint will be located along the Southern side of the HIRAX site. Additionally, the HIRAX dishes will be contained within its own 6-foot fence perimeter with locked access. All power, data, and back-end computer equipment will be housed in weatherproof and locked containers. All cabling will be trenched underground, and the dishes themselves will be bolted into foundations.

4.9. Site Access

Access to the HIRAX site will be strictly controlled. Visitors to the HIRAX site will first have to be authorised by SARAO together with their vehicles, equipment, etc. This will be done via the HIRAX Project Manager. Once the HIRAX Project Manager receives signed authorisation for visitors to access the HIRAX site, the visitors must first proceed to the SARAO offices at Klerefontein where they will receive a Health & Safety induction. Once SARAO has cleared the visitors to proceed to the main site, the visitors must then report to the responsible HIRAX team member on the HIRAX site so as to access the HIRAX site. Note, Carnarvon is the nearest town within proximity to the HIRAX site, and will take about 45 minutes commute on well paved roads.

4.10. Maintenance

HIRAX is required to function for at least a ten-year period; therefore, each telescope mechanical assembly must have a minimum ten-year lifespan. The project will replace electronic components at regular intervals. HIRAX is designed to be modular and redundant to eliminate single-point failure modes, and individual components will be designed to have high reliability. A site manager will be on-hand to oversee maintenance and repairs on-site, and report to the construction and operations team.

5. Detailed Telescope Mechanical Assembly Requirements

This section documents the detailed requirements pertaining to the TMA at the subsystem level and will support the associated tender for this subsystem (Table 9)

The requirements in the table below are organized in the following way:

- TMA 1XX – Receiver Support Requirements
- TMA 2XX – Dish Requirements
- TMA 3XX – Dish Mount Requirements
- TMA 4XX – Foundation Requirements
- TMA 5XX – System Quality Factors (Reliability, Maintainability & Availability)
- TMA 6XX – Environmental Requirements
- TMA 7XX – Flexibility and Expansion Requirements
- TMA 8XX – Design and Construction Requirements

Number	Element	Description	Category (C=Compulsory, Ma=Major, Mi=Minor, N/A=Not Applicable)	Comment
TMA.101	Mounting of Receiver Support to Dish	The TMA receiver shall be attached to the dish vertex by means of a hollow cylindrical tube, called the receiver support structure, made entirely from non-conductive material.	C	
TMA.102	Diameter of Receiver Support Structure	The diameter of the support structure shall not be more than 350 mm.	Ma	
TMA.103	Axial Circular symmetry of Receiver Support Structure	The cylindrical part of the Receiver Support structure shall be circularly symmetric in form to an absolute deviation less than 1 mm.	Mi	1 mm absolute deviation is relatively easy to achieve, therefore stated as such
TMA.104	Receiver Support Structure RF Attenuation	The receiver support structure shall have an RF attenuation of less than 0.05 dB.	Ma	
TMA.105	Mounting of RFoF Electronics on Receiver Support	The receiver support structure should include provision for mounting the RF over Fibre (RFoF) electronics behind the receiver (i.e. behind the mounting point for the feed Can).	Ma	
TMA.106	Protection of RFoF Electronics by Receiver Support	The receiver support structure shall enclose the receiver and provide protection to the RFoF electronics (i.e. RFoF housing) from the elements with an IP65 rating.	Ma	
TMA.107	Allow for Power & Signal to/from RFoF Electronics	The receiver support structure shall allow for fibre bundles and electrical conductors to be routed from the RFoF Electronics to the dish vertex.	C	

Number	Element	Description	Category (C=Compulsory, Ma=Major, Mi=Minor, N/A=Not Applicable)	Comment
TMA.107.1	Routing of Power & Signal to/from RFoF Electronics	The nominal routing path for fibre bundles and electrical conductors through the receiver support structure shall be along the central axis of the receiver support structure. The fibre bundles and electrical conductors shall be routed in such a way that the relative movement of the fibre bundles and conductors to the receiver support structure is less than 2 mm RMS in the lateral direction (i.e. perpendicular to the central axis.	Ma	
TMA.107.2	Rigidity of Receiver Support Structure	The mounting of the receiver to the dish vertex shall be sufficiently rigid so that the receiver shall not move by more than 1.0 mm in the xy-plane and 0.5 mm along z-axis in dish coordinates, when the dish elevation is changed from Zenith to the extreme angles of ±30º.	Ma	Rigidity of 1 mm under gravity is easy to achieve
TMA.107.3	Rigidity of Receiver Support Structure During Survival Conditions	Transient deformations during survival or operating conditions that exceed the maximum accuracy requirements on the receiver support structure, shall not be permanent. Upon return of the environmental conditions from survival to normal, each TMA receiver support structure shall return to a state that meets requirements under normal environmental conditions without any manual intervention.	C	
TMA.107.4	Mechanical Interface between Receiver Support Structure & Receiver Hardware	The Client shall specify the mechanical interface between the receiver support structure and the Receiver hardware.	C=Adherence to Interface drawing	
TMA.107.5	Receiver Hardware Adjustability	It shall be possible to service, adjust and replace the feed hardware in situ (i.e. without removing the receiver support structure from the dish).	C	
TMA.108	Accommodation of RFoF Inside the Receiver Support Structure	The receiver support structure shall accommodate the RFoF transmitters such that no part of the support structure protrudes by more than 200 mm beyond the dish aperture.	Mi	
TMA.109	Position of TMA Receiver relative to the Focus Position	The TMA receiver shall be positioned near the dish focus in accordance with the Interface drawing as defined in TMA.107.4, with an accuracy of better than 3 mm and a precision of better than 0.5 mm in the x-y plane and with an accuracy of better than 3 mm and a precision of better than 0.5 mm along z-axis in dish coordinates	Ma	Notes regarding accuracy and precision applies
TMA.110	Orientation of TMA Receiver Relative to Dish Boresight Vector	The TMA receiver shall be orientated perpendicular to the Dish boresight vector to within a polar angle (delta) of 5 arc minutes accuracy and 2.5 arcminutes precision. The corresponding specifications for the azimuthal angle (gamma) shall be an accuracy of 7.5 arcmin, and a precision of 2.5 arc minute.	Ma	Notes regarding accuracy and precision applies
TMA.201	Dish Diameter	Each dish of the TMA shall have a diameter of 6.0 m with an accuracy of 3.0 mm and a precision of 1.0 mm. The latter requirements shall be satisfied on at least 30 equi-spaced circumferential points along the dish aperture.	C	Notes regarding accuracy and precision applies
TMA.202	Dish Shape Accuracy	The optically reflective surface of each dish of the TMA shall have a least squares best-fit paraboloid of revolution that has an accuracy of 5.0 mm or better with respect to the ideal shape $z = (x^2 + y^2)/5.52$, for $\mathrm{sqrt}(x^2 + y^2) <=3$, where linear dimensions are in meters. This accuracy requirement applies to the dish at any Zenith angle between -30 and +30, Refer to TMA.616 for other environmental conditions	C	Notes regarding accuracy and precision applies

Number	Element	Description	Category (C=Compulsory, Ma=Major, Mi=Minor, N/A=Not Applicable)	Comment
TMA.203	Embedment of conductive layer (if applicable)	If the optically reflective surface and the RF reflective surface differ, then the precision of the difference for each TMA dish (calculated per dish) shall be better than 1mm.	C	Notes regarding accuracy and precision applies
TMA.204	Dish Static Surface RMS	The optically reflective surface of each dish of the TMA shall have a measured surface with a precision better than or equal to1.0 mm relative to the mean best-fit paraboloid of revolution (averaged over all dishes being assessed). The precision shall be calculated over for every dish produced, with measurement of each subsequent dish, together with calculation of the precision of each subsequent dish, as well as trending of all dish measurements to indicate process stability. See also requirement TMA.507. This precision requirement applies to the dish at any Zenith angle between -30 and +30.	C	Notes regarding accuracy and precision applies
TMA.205	Dish Reference Surface	The Dish should have a reference surface, perpendicular to the main (vertex to focal point) axis of the dish, that is suitable to place an inclinometer to measure dish Zenith angle, or dish elevation, whichever is the easier to realize. The reference surface shall be perpendicular to the main (vertex to focal point) axis of the dish within a positional accuracy of better than 3 arcmin and a precision of better than 30 arcsec. This requirement applies to the dish at any Zenith angle between -30 and +30. Note that some inclinometers have a magnetic base, which might affect the choice of material.	C	Notes regarding accuracy and precision applies
TMA.206	Dish Vertex Position Deviation	The dish vertex positional deviation (dX_V, dY_V, dZ_V) relative to the center of the elevation axis shall be within an accuracy of better than 3 mm and a precision of better than 1 mm, both measured in dish coordinates across the full range of operating elevation angles.	Ma	Notes regarding accuracy and precision applies
TMA.207	Inter-Dish Separation	The TMA array shall have a maximum separation of 2 m (soft limit) to 3 m between the edges of neighboring dishes.	N/A to Dish Supplier	
TMA.208	Dish Electrical Connectivity	Each TMA dish shall have a conductive surface. To ensure sufficient electrical connectivity, woven metal mesh shall not be used. All gaps must have a maximum linear dimension of 5.0 mm and total maximum filling fraction (open area) of 80%.	C	
TMA.209	Dish Surface Conductivity	The entire surface of the dish paraboloid shall be conductive with an electrical conductivity of no less than 1x10^6 S/m.	Mi	
TMA.210	Dish Protective Layer	The TMA, specifically the dish and receiver assembly, shall be covered with a protective layer. The protective layer shall not attenuate the reflection of radio waves from the dish by more than 0.02 dB.	Ma	
TMA.301	Orthogonality of the Dish Boresight Vector	The boresight vector of each TMA dish shall be orthogonal to the dish elevation axis, with departures from nonorthogonality (angle beta) of better than 3 arc minute accuracy and better than 1 arc minute precision. This requirement applies to the dish at any Zenith angle between -30 and +30.	Ma	Notes regarding accuracy and precision applies
TMA.302	Elevation Axis Center Position Accuracy	The TMA elevation axis center position in array coordinates shall have a maximum absolute deviation (after adjustments) of 1 mm in the XY plane and 2 mm in the Z direction, relative to the nominal (Xi, Yi, Zi) coordinates. The nominal (Xi, Yi, Zi) coordinates will be specified by the HIRAX team. These deviations are denoted as (dXi, dYi, dZi). This requirement applies to the dish at any Zenith angle between -30 and +30.	Ma	Absolute deviation after adjustments

Number	Element	Description	Category (C=Compulsory, Ma=Major, Mi=Minor, N/A=Not Applicable)	Comment
TMA.303	Elevation Axis Alignment	The absolute alignment error (angle alpha) of the TMA elevation axis with respect to the X axis (Global East-West line) in array coordinates shall be better than 5 arc minute accuracy and precision better than 1 arc minute. This requirement applies to the dish at any Zenith angle between -30 and +30.	Ma	Notes regarding accuracy and precision applies
TMA.304	Mount Elevation Range	The TMA shall have an elevation range ±30° from zenith.	C	
TMA.305	TMA Elevation Adjustment	The TMA shall have a manual elevation mechanism that is either continuously adjustable or has adjustment increments of <=2.5°, with an accuracy of better than or equal to 10 arc minute and a precision of better than or equal to 1 arcmin, at any given elevation angle setting. If increments of <=2.5°, are used, these increments shall be equispaced with an accuracy of better than or equal to 5 arcmin.	C	Notes regarding accuracy and precision applies
TMA.306	TMA Elevation Lock	After being adjusted to the preferred elevation position, the TMA shall be locked in position. This locking action shall not result in the TMA deviating from the adjusted elevation position by more than 40 arcsec.	Ma	Relaxed.
TMA.306.1	TMA Elevation Lock Rigidity	After locking to the correct elevation angle, the dish locking mechanism shall withstand maximum operational wind and other external effects as specified, and not move permanently from the adjusted position.	C	
TMA.307	Mount Setting Adjustment	The TMA mount shall incorporate an installation procedure and fine adjustment mechanism and procedure which will allow for the correction of misalignment of the dish elevation axis (angle alpha) as well as the dish X-Y and Z position, (dXi, dYi, dZi) during installation, as well as to counteract inaccuracies and out of flatness of the dish foundation, changes in positioning and pointing of the telescopes over time due to factors such as mechanical vibration, thermal cycling, foundation settling, and others. Once installed, and after compensating for the inaccuracies and out-of-flatness of the dish foundation, the maximum absolute value of the angular adjustment shall be no less than ±5 arc minutes, and the maximum absolute value of the translation adjustment shall be not less than ±5 mm. The total range of the adjustment shall be commensurate with the mount installation procedure and the accuracy requirements of the dish vertex and elevation axis center, as stated in TMA.302, TMA.303, TMA.304 and TMA.305, as well as the accuracy and flatness of the Dish foundation, which is specified as degree of Accuracy I i.a.w. SANS2001 construction works Part CC1 Concrete works, page 57. Note: This could imply that the total range of the translation and angular adjustments needed may be much more than the minimum specified above.	C	
TMA.308	Locking of Dish Mount	The Dish mount shall be locked into place once it is adjusted to the correct position and orientation. This locking action shall not result in the misalignment of the dish elevation axis or the dish elevation angle deviating from the adjusted orientations by more than 40 arcsec, and the positions deviation by more than 0.2 mm.	Ma	Relaxed

Number	Element	Description	Category (C=Compulsory, Ma=Major, Mi=Minor, N/A=Not Applicable)	Comment
TMA.309	Mount Fixation to Foundation Under Normal Operating Conditions	The dish mounting shall be fixed to the foundation in such a way that the fixation of the mounting to the foundation shall withstand the maximum operational wind and other operational effects as specified, and not permanently deform.	C	
TMA.310	Mount Fixation to Foundation Under Abnormal Operating Conditions	The dish mounting shall be fixed to the foundation in such a way that the fixation of the mounting to the foundation shall survive the maximum wind as specified, and not fail to fix the mount to the foundation (plastic deformation is allowed).	C	
TMA.401	Foundation Height	The top of the foundation of the dishes shall not be higher than 0.5 m above ground level. If the latter is exceeded a protective frame shall be built around the foundation. (Requirement for civil contractor)	Ma	
TMA.402	Dish Height	The maximum height of any part of the dish above the foundation shall not exceed 4.0 m in any configuration, including the ±30° elevation case.	Mi	
TMA.501	TMA Operational Life	The TMA system shall under normal operating conditions have a lifespan of at least 10 years.	Ma	
TMA.502	Mobile Maintenance Structure	A structure that allows technicians to perform onsite maintenance on the receiver without stepping on the dish, shall be provided as part of the special equipment supplied with the dishes.	Ma	
TMA.503	Dish Water Drain	Provision shall be made to drain excess water from the dish in the event of precipitation of 15 mm/min or 50 mm/h over a period of 4 hours. Drainage of excess water shall be completed within 5 min after precipitation has stopped. The size of the drainage holes shall be consistent with the maximum linear dimension of 5.0 mm. Multiple drainage holes are allowed.	Mi	
TMA.504	Cleaning of Dish Drainage Holes	It shall be possible to inspect and clean the drainage holes, as debris may be blown onto the dish and block the drainage hole(s). The latter must be done without damaging the protective layer of the dish. The dish supplier shall specify the method of cleaning.	Mi	
TMA.505	Cleaning of Dish & Receiver	It shall be possible to clean the protective layer covering the dish and receiver assembly, from built-up dust and sand, using pressurized water and/or conventional household cleaning agents containing less than 5% ammonia, without permanently damaging the protective layer of the dish. The Dish supplier shall specify the method as well as the maximum pressure and nozzle size of the cleaner.	Mi	
TMA.506	Drainage of Excess Water from Foundation	Provision shall be made in the dish foundation design and the site civil preparation that will ensure that excess rain water (that is drained for a dish) be routed away from the foundations and not enter or affect the cable and fibre trenching.	Mi	
TMA.507	Dish Surface Quality (precision)	The optically reflective and measured surface of the dish, as specified in TMA.204, relative to the mean best-fit paraboloid of revolution (averaged over all dishes being assessed up to date of manufacture) shall be measured for each dish. The precision of the dish shall be calculated, based on the data of all dishes previously manufactured. The data shall be used to trend the conformance of all the dishes to the requirements as specified in TMA.204 to indicate process stability.	C	Original TMA 507

Number	Element	Description	Category (C=Compulsory, Ma=Major, Mi=Minor, N/A=Not Applicable)	Comment
TMA.507.1	Dish Surface Quality (accuracy)	The accuracy of the optically reflective and measured surface of the dish, as specified in TMA.202, shall be calculated, based on the data of all dishes previously manufactured. The data shall be used to trend the conformance of all the dishes to the requirements as specified in TMA.202 to indicate process stability.	C	Added a variant of TMA.507, applied to accuracy
TMA.508	Dish Protrusions	The dishes shall not have sharp protrusions, burrs or corners that could injure personnel working on or in the vicinity of the dishes.	Ma	
TMA.509	Mount Elevation Locking	The locking mechanism that locks the dish in place shall be designed such that the dish does not dislodge from the locked elevation position (and resulting in injury of personnel working on or in the vicinity of the dish) in the event of: 1) Wind loading up to 1.1 times the maximum allowed wind speed. 2) Unbalance loads due to the accumulation of hail stones, water or debris. 3) Collapse of the measurement frame. 4) A person with a mass of <= 120 kg standing on or hanging of any edge of the dish.	C	
TMA.510	Access to RFoF Electronics via Receiver Support	The receiver support structure shall provide easy access to the RFoF Electronics for maintenance purposes to the extent of opening/dismantling and closing within 10 minutes.	Ma	
TMA.511	Mount Elevation Repointing Time	The TMA shall have an elevation repointing procedure which is easy to perform with a team of 2-3 people, taking no more than 10 minutes per telescope, and with minimal auxiliary equipment. This may include an inclinometer of suitable accuracy and repeatability.	Ma	
TMA.512	Mount Setting Repositioning Time	The full set of fine adjustments for telescope positioning and pointing of the TMA shall be manageable by a team of 4-5 people, taking no more than 1 hour per telescope. This fine adjustment procedure may use auxiliary equipment, but if necessary, the special Mobile Maintenance Structure, portable hoists or truck-mounted cranes may be used for this procedure.	Mi	
TMA.601	TMA Minimum Ambient Temperature Survival	The TMA system shall survive under a minimum ambient temperature of -7°C.	Ma	
TMA.602	TMA Minimum Ambient Temperature Operations	The TMA system shall operate normally (i.e. within the normal operating, repeatability and accuracy specifications) under the normal site environmental parameter of a minimum ambient temperature of -5°C.	Ma	
TMA.603	TMA Maximum Ambient Temperature Survival	The TMA system shall survive under a maximum ambient temperature of 45°C.	Ma	
TMA.604	TMA Maximum Ambient Temperature Operations	The TMA system shall operate normally under the normal site environmental parameter of a maximum ambient temperature of 40°C.	Ma	
TMA.605	TMA Solar Radiation Operations	The TMA system shall operate normally under the normal site environmental parameters of solar radiation of 1200 W/m² from twilight to dawn.	Ma	
TMA.606	TMA Humidity Operations	The TMA system shall operate normally under the normal site environmental parameter of 95% Relative Humidity.	Ma	
TMA.607	TMA Precipitation Rate Survival	The TMA system shall survive under a rate of precipitation of 50 mm/hr over 4 hours.	Ma	

Number	Element	Description	Category (C=Compulsory, Ma=Major, Mi=Minor, N/A=Not Applicable)	Comment
TMA.608	TMA Windblown Particle Survival	The TMA system shall meet all performance requirements after being exposed to the following sand and dust conditions: 1) Blowing Sand Conditions: Sand concentration of 1000 mg/m³ ±150 mg/m³ at an air velocity of 10 m/s ±1.5m/s. 2) Blowing Dust (Suspension) Conditions: Dust concentration of 15 mg/m³ ±2.5 mg/m³ at an air velocity of 10 m/s ±1.5m/s. 3) Blowing Dust (Sedimentation) Conditions: Dust concentration of 40 mg/m³/h ±10 mg/m³/h at an air velocity of 10 m/s ±1.5m/s.	C	
TMA.609	TMA Windblown Particle Operations	The TMA system shall meet all performance requirements while being exposed to the following sand and dust conditions: 1) Blowing Sand Conditions: Sand concentration of 300 mg/m³ ±150 mg/m³ at an air velocity of 10 m/s ±1.5m/s. 2) Blowing Dust (Suspension) Conditions: Dust concentration of 5 mg/m³ ±2.5 mg/m³ at an air velocity of 10 m/s ±1.5m/s. 3) Blowing Dust (Sedimentation) Conditions: Dust concentration of 20 mg/m³/h ±10 mg/m³/h at an air velocity of 10 m/s ±1.5m/s.	Ma	
TMA.610	TMA Hail Survival	The TMA system shall survive hail up to 20 mm, limited to hailstones with impact energy of ±11 J.	C	
TMA.611	TMA Ice Survival	The TMA shall survive an ice loading of 5.4 kg/m² on all exposed surfaces (which corresponds to a glaze ice thickness of 6.0 mm with a density of 900 kg/m³ - IAW MIL-STD-810F Method 521.2).	C	
TMA.612	TMA Wind Speed Survival	The TMA system shall be designed to survive the following wind conditions (at a height of 10 m above ground level and a nominal air density of 1.05 kg/m³ at 20°C): 1) Peak wind speed: 20 m/s (3 second gust). 2) Peak survival wind speed: 44.4 m/s (instantaneous gust).	C	
TMA.613	TMA Wind Speed Operations	The TMA system shall be designed to operate under the following wind conditions (at a height of 10 m above ground level and a nominal air density of 1.05 kg/m³ at 20°C): 1) Average wind speed: 4.2 m/s; 2) Maximum average wind speed (10 min averages): 13.5 m/s.	Ma	
TMA.614	TMA Earthquake Survival	The TMA system shall survive an earthquake with a maximum peak acceleration of 1 m/s², Seismic Zone 1 as defined in IEC 60721-2-6.	C	
TMA.615	Conduct Lightning Current	The dish site is expected to experience ground flash densities of 1-3 strikes per km² per year. The dish mount and TMA system shall be designed to conduct the lightning current to earth in accordance to IEC 62305 LPL III.	C	

Number	Element	Description	Category (C=Compulsory, Ma=Major, Mi=Minor, N/A=Not Applicable)	Comment
TMA.616	Dish surface deviations due to operational conditions	The deformation of each TMA dish surface under the combined effect of the following normal operating conditions: 1) Windspeeds up to 13.5 m/s; 2) Thermal gradients induced by the specified solar irradiance of 1120 W/m², including the effect of parts of the dish masking sunlight from other parts (shadows); 3) Differential thermal expansion due to the use of materials with different thermal expansion coefficients, and with the dish saturated at a steady thermal condition, i.e. at a fixed temperature; shall adhere to the following: 1) Dish accuracy shall be better than or equal to the accuracy requirements as defined in TMA.202. 2) Dish precision shall be better than or equal to the precision requirements as specified in TMA.204. 3) Dish vertex maximum absolute positional deviation (dX_V, dY_V, dZ_V) relative to the center of the elevation axis shall be better than or equal to the accuracy and precision requirements as specified in TMA.206. 4) The orientation of the Dish reference surface relative to the main (vertex to focal point) axis of each TMA dish shall be better than or equal to the accuracy and precision requirements as specified in TMA.205, 5) Orthogonality of the boresight vector relative to the dish elevation axis of each TMA dish shall be better than or equal to the accuracy and precision requirements as specified in TMA.301. These requirements shall be verified by means of a combination of Thermal FEA, Structural FEA and CFD, whichever is applicable. Note on differential thermal expansion: The differential thermal expansion shall be evaluated at any given temperature with the dish at steady thermal ("saturated") condition in the operational temperature range between the minimum and maximum, as defined in TMA.602 and TMA.604.	Ma	Deformations due to gravity are specified earlier in TMA.202 and TMA.204.

Number	Element	Description	Category (C=Compulsory, Ma=Major, Mi=Minor, N/A=Not Applicable)	Comment
TMA.616.1	Receiver support deviations due to operational conditions	The deformation of each TMA dish receiver support under the combined effect of the following normal operating conditions: 1) Windspeeds up to 13.5 m/s; 2) Thermal gradients induced by the specified solar irradiance of 1120 W/m², including the effect of parts of the dish masking sunlight from other parts (shadows); 3) Differential thermal expansion due to the use of materials with different thermal expansion coefficients, and with the dish saturated at a steady thermal condition, i.e. at a fixed temperature; shall adhere to the following: 1)The position of the TMA receiver relative to the dish focus shall be better than or equal to the accuracy and precision requirements as defined in TMA.109. 2) The TMA receiver orientation perpendicular to the Dish boresight vector shall be better than or equal to the accuracy and precision requirements as defined in TMA.110. This requirement shall be verified by means of a combination of Thermal FEA, Structural FEA and CFD, whichever is applicable. Note on differential thermal expansion: The differential thermal expansion shall be evaluated at any given temperature with the dish at steady thermal ("saturated") condition in the operational temperature range between the minimum and maximum, as defined in TMA.602 and TMA.604.	Ma	Relevant to receiver Support Deformations due to gravity are specified earlier in TMA.107.2.
TMA.616.2	Dish mount deviations due to operational conditions	The deformation of each TMA dish mount under the combined effect of the following normal operating conditions: 1) Windspeeds up to 13.5 m/s; 2) Thermal gradients induced by the specified solar irradiance of 1120 W/m², including the effect of parts of the dish masking sunlight from other parts (shadows); 3) Differential thermal expansion due to the use of materials with different thermal expansion coefficients, and with the dish saturated at a steady thermal condition, i.e. at a fixed temperature; shall adhere to the following: 1) The absolute alignment error (angle alpha) of the TMA elevation axis with respect to the X axis (Global East-West line) in array coordinates shall be better than or equal to the accuracy and precision requirements as defined in TMA.303. 2) The accuracy and precision of the manual elevation mechanism shall be better than or equal to the accuracy and precision requirements as defined in TMA.305. This requirement shall be verified by means of a combination of Thermal FEA, Structural FEA and CFD, whichever is applicable. Note on differential thermal expansion: The differential thermal expansion shall be evaluated at any given temperature with the dish at steady thermal ("saturated") condition in the operational temperature range between the minimum and maximum, as defined in TMA.602 and TMA.604.	Ma	Relevant to Dish mount Deformations due to gravity are specified earlier in TMA.303.

Number	Element	Description	Category (C=Compulsory, Ma=Major, Mi=Minor, N/A=Not Applicable)	Comment
TMA.616.3	Provision of the partial derivative of dish accuracy with respect to dish temperature.	The Dish supplier shall provide the partial derivative of dish assembly accuracy to dish temperature, using simulations. This partial derivative shall be evaluated with the dish at steady thermal (“saturated”) condition, similar to the case of differential thermal expansion mentioned above. The partial derivative shall be evaluated at temperatures of 0ºC, 10ºC, 20ºC, 30ºC and 40ºC. See V.TMA.616 for the method.	Ma	Relevant to the entire dish assembly, i.e. mount and dish surface
TMA.617	Dish Transient Surface Deviations	Transient deformations during survival or operating conditions that exceed the maximum accuracy requirements on the dish, must not be permanent. Upon return of the environmental conditions from survival to normal, each TMA dish must return to a state that meets those requirements without any manual intervention. This requirement shall be verified by analysis and test. Test will be done by perturbing the dish in a manner that simulates extreme conditions.	C	
TMA.701	Dish Number	The total TMA shall consist of an initial number of 256 dishes, extendable to 1024.	C	
TMA.801	Trench Compliance	All trenches between dishes, carrying electrical conductors, shall adhere to SANS 10198:2016 Edition 2.2.	N/A	
TMA.802	Trench Covers	All trenches between the dishes that carry cables and fibre shall be closed and the cover able to withstand loads from vehicles up to 2000 kg.	N/A	
TMA.803	Interchangeability	The following parts of the TMA shall be interchangeable and replaceable when damaged during the lifespan of the system: 1) Dish 2) Dish Support Structure 3) Receiver Electronics assembly or parts (Cloverleaf, Balun and main board) 4) Receiver Support (including enclosure mentioned in TMA.106) 5) RFoF Housing and Electronics 6) RFoF Cabling	C	
TMA.804	Identical Configuration	The physical configuration of the TMA components shall be identical to each other, within manufacturing tolerances, for the sake of manufacturing, assembly on-site, maintenance, logistics and quality.	C	

Table 9: TMA requirements

6. Telescope Mechanical Assembly Requirements Verification

Nominal tests to be performed by the Client and the Dish supplier are indicated in the table below. The Client nevertheless reserves the right to perform any of the tests listed in the table below at the installation site as well as witness tests at the factory to ensure that the requirements are met. In any case that the contents of this paragraph conflicts with the content of the verification column, the contents of this paragraph will take preference.

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.101	Mounting of Receiver Support to Dish	It shall be verified by Inspection that the TMA receiver is attached to the dish vertex by means of a hollow cylindrical tube. It shall be verified by test, or reference to material information that the receiver support structure is made entirely from non-conductive material.	Test, Analysis & Design Review	Design	Dish Supplier: at Factory
VTMA.102	Diameter of Receiver Support Structure	It shall be verified by Inspection that the diameter of the support structure shall not be more than 350 mm.	Inspection	Design	Dish Supplier: at Factory
VTMA.103	Axial circular symmetry of Receiver Support Structure	It shall be verified by measurement that the cylindrical part of the Receiver support structure is axisymmetric in form to within 1 mm.	Inspection (measurement)	Design	Dish Supplier: at Factory
VTMA.104	Receiver Support Structure RF Attenuation	It shall be verified by test, or by analysis, that the RF attenuation of the receiver support structure is less than 0.05 dB.	Test or Analysis & Design Review	Design	Dish Supplier: at Factory
VTMA.105	Mounting of RFoF Electronics on Receiver Support	The contractor shall show in a design review, and demonstrate on the first prototype, the provision made to mount the RFoF electronics behind the receiver (i.e. behind the mounting point for the feed Can).	Demonstration & Design Review	Design & Prototype	Dish Supplier: at Factory
VTMA.106	Protection of RFoF Electronics by Receiver Support	The contractor shall show in a design review by referring to an appropriate analysis, and demonstrate by test on the first prototype, the provision of protection to the RFoF Electronics (RFoF Housing) from the elements, with IP rating IP65.	Test, Analysis & Design Review	Design & Prototype	Dish Supplier: at Factory
VTMA.107	Allow for Power & Signal to/from RFoF Electronics	The contractor shall demonstrate that the receiver support structure provides means of routing power to the RFoF electronics.	Demonstration	Design	Dish Supplier: at Factory
VTMA.107.1	Routing of Power & Signal to/from RFoF Electronics	It shall be verified by Inspection that the nominal routing path for fibre bundles and electrical conductors through the receiver support structure is along the central axis of the receiver support structure. It shall be verified by demonstration that the fibre bundles and electrical conductors is routed in such a way that the relative movement of the fibre bundles and conductors to the receiver support structure is less than 2 mm RMS in the lateral direction.	Inspection & Demonstration	Design, Prototype & Production	Dish Supplier: at Factory Client: on Site
VTMA.107.2	Rigidity of Receiver Support Structure	It shall be verified by analysis that the mounting of the receiver to the dish vertex is sufficiently rigid so that the receiver shall not move by more than 1.0 mm in the xy-plane and 0.5 mm along z-axis in dish coordinates, when the dish elevation is changed from Zenith to the extreme angles of ±30º. Movement in the x-y plane due to gravity may be verified by measuring the movement of the receiver mount when the dish elevation is changed from Zenith to the extreme angles of both +30º and -30º.	Test & Analysis	Design & Prototype	Dish Supplier: at Factory Client: on Site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.107.3	Rigidity of Receiver Support Structure During Survival Conditions	It shall be verified by test that the transient deformations during survival or operating conditions that exceed the maximum absolute deviation requirements on the receiver support structure, shall not be permanent. A force equivalent to the drag force experienced by the receiver support structure as a result of 1.5 times the maximum operational wind shall be applied to the midpoint of the receiver support structure, perpendicular to the boresight vector, and the deviation in receiver support structure position measured before and after the application of the Force. It shall be verified by test that, after return of the environmental conditions from survival to normal, each TMA receiver support structure shall return to a state that meets the normal operational requirements without any manual intervention. A force equivalent to the drag force experienced by the receiver support structure as a result of 1.5 times the maximum survival wind shall be applied to the midpoint of the receiver support structure, perpendicular to the boresight vector, and the deviation in receiver support structure position measured before and after the application of the Force. No plastic deformation shall be detected.	Test	Design & Prototype	Dish Supplier: At Factory
VTMA.107.4	Mechanical Interface between Receiver Support Structure & Receiver Hardware	The Dish supplier shall adhere to the supplied interface drawing. The Dish supplier shall inspect and scrutiny the interface drawing and **shall clarify any and all uncertainties beforehand.**	Design review, inspection, measurement	Design & Prototype	Dish Supplier: At Factory Client: on Site
VTMA.107.5	Receiver Hardware Adjustability	It shall be verified by demonstration that it shall be possible to service, adjust and replace the feed hardware in situ, i.e. without removing the receiver support structure from the dish.	Demonstration	Design, Prototype	Dish supplier: at Factory
VTMA.108	RFoF Housing Size	The Dish Supplier shall demonstrate by appropriate analysis, with supporting calculations, that the receiver support structure accommodates the RFoF transmitters in such a way that no part of the support structure protrudes by more than 200 mm beyond the dish aperture.	Demonstration	Design & Prototype	Dish Supplier: at Factory

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.109	Position of TMA Receiver relative to the Focus Position	A receiver housing unit with precisely located photogrammetry or laser tracker targets will be provided. The unit will be mounted in the dish, and the target positions will be measured simultaneously with the dish surface, using photogrammetry or laser tracking. The position of the receiver will be determined relative to the best-fit paraboloid of the dish surface. The accuracy and precision of the measured position of the receiver relative to the ideal position (using the best fit paraboloid) in the xy-plane shall be better than or equal to the requirements as specified in TMA.109. The same applies to the measured position of the receiver relative to the ideal position (using the best fit paraboloid) along the z-axis (in dish coordinates). Measurements will be performed both at the factory and on site to ensure that the receiver position does not shift by more than the above specified tolerances after the dish is attached to the mount. Measurements on site shall include allowance for thermal effects. Refer to TMA.616.1 and VTMA.616.1 for the effect of environmental conditions.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site
VTMA.110	Orientation of TMA Receiver Relative to Dish Boresight Vector	A receiver housing unit with precisely located photogrammetry or laser tracker targets will be provided. The unit will be mounted in the dish, and the target positions will be measured simultaneously with the dish surface, using photogrammetry or laser tracking. The orientation angles of the receiver will be determined relative to the best-fit paraboloid of the dish surface. The accuracy and precision of the reconstructed polar angle (delta) relative to the reference orientation of the receiver shall be better than or equal to the requirements as specified in TMA.110. The same applies to the reconstructed azimuthal angle (gamma) relative to the reference orientation. Measurements will be performed both at the factory and on site to ensure that the receiver orientation angles do not shift by more than the specified tolerances after the dish is attached to the mount.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site
VTMA.201	Dish Diameter	In Factory: Laser tracker measurements of at least 30 equi-distant targets on the dish edge. On site: Photogrammetry (with scale bar calibration) or laser tracker measurements of at least 16 equidistant targets on the dish edge. Diameter accuracy must be 6 m ±3 mm. Diameter precision must be calculated from the mean of measurements on dish.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.202	Dish Shape Accuracy	Factory: Measure dish shape with laser tracker and calculate best-fit paraboloid. There will be a minimum of 500 measurement points/targets, roughly equally spaced across the dish surface. The best-fit paraboloid, p(x,y), will be compared against the ideal paraboloid, q(x,y). The maximum deviation from the ideal paraboloid shall be calculated (i.e. MAX(|p(x,y) - q(x,y)|) < 5 mm). On site: Measure dish shape with photogrammetry or laser tracker and calculate best-fit paraboloid. There will be a minimum of 200 measurement points/targets, roughly equally spaced across the dish surface. The best-fit paraboloid, p(x,y), will be compared against the ideal paraboloid, q(x,y). The maximum deviation from the ideal paraboloid shall be calculated (i.e. MAX(|p(x,y) - q(x,y)|) < 5 mm). Verification shall be done with the dish at Zenith, as well as for the two cases where the dish elevation is at the extreme angles of +30º and -30º from Zenith. Note: This verification will be performed both at factory and on site to confirm the dish integrity after transport.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site
VTMA.203	Embedment of conductive layer (if applicable)	If applicable (i.e. optically reflective surface is not the same as the RF reflective surface), the precision of the difference between the optically reflective surface and the RF reflective surface of each dish of the TMA shall be tested by a calibrated reflectometer at a minimum of 20 locations on the dish.. The Reflectometer shall be calibrated using a reference sample of the dish surface of which the embedment of the conductive layer is known to be within a variance of 1.0 mm. The Dish Supplier shall provide the reference sample of the dish surface.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.204	Dish Static Surface RMS	At Factory: Measure dish shape with photogrammetry or laser tracker and calculate best-fit paraboloid. There will be a minimum of 500 measurement points/targets, roughly equally spaced across the dish surface. The measured target positions, P(x,y), will be compared against the best-fit surface, averaged over the array elements p(x,y) as specified in the supporting documentation "guideline to precision and accuracy" which defines the calculation and application of accuracy and precision. HIRAX requires RMS[P(x,y) - p(x,y)] < 1 mm. On Site: Measure dish shape with photogrammetry and calculate best-fit paraboloid. There will be a minimum of 200 measurement points/targets, roughly equally spaced across the dish surface. The measured target positions, P(x,y), will be compared against the best-fit surface, averaged over the array elements p(x,y) as specified in the supporting documentation "guideline to precision and accuracy" which defines the calculation and application of accuracy and precision). HIRAX requires RMS[P(x,y) - p(x,y)] < 1 mm. Verification shall be done with the dish at Zenith, as well as for the two cases when the dish elevation is at the extreme angles of +30º and -30º from Zenith. These verifications will be performed both at factory and on site to confirm the dish integrity after transport.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.205	Dish Reference Surface	At Factory during design: The presence of the inclinometer reference surface shall be verified by demonstration; the accuracy and precision requirements shall be verified by analysis of information contained in the drawings. At Factory and on-site test: After the dish is integrated with the mount, photogrammetry or laser tracker targets will be placed on: 1) the dish surface, and 2) inclinometer reference surface. The inclinometer reference surface shall have at least four marked locations/attachment points, preferably at each corner of the inclinometer reference surface, to serve as precise mechanical references for deriving the position and orientation of the inclinometer reference surface. The dish shape and inclinometer reference surface position will be measured with photogrammetry or laser tracking at a minimum of 10 elevation angles equally spaced throughout the elevation range. The best-fit paraboloid for the dish surface will be used to define the coordinate system and origin. From this, the main (vertex to focal point) axis of the dish shall be determined. The accuracy and precision of the perpendicular orientation of the inclinometer reference surface relative to the main (vertex to focal point) axis of the dish shall be better than or equal to the values as specified in TMA.205, at all measured elevation angles. Refer to VTMA.301.	Demonstration	Design, Prototype & Production	Dish Supplier: At Factory Client: On Site
VTMA.206	Dish Vertex Position Deviation	After the dish is integrated with the mount, photogrammetry or laser tracker targets will be placed on: 1) the dish surface, and 2) elevation axis. The axis must have at least two marked locations/attachment points, preferably at each end, to serve as precise mechanical references for deriving the position and orientation of the axis. The dish shape and elevation axis position will be measured with photogrammetry or laser tracking at a minimum of 10 elevation angles equally spaced throughout the elevation range. The best-fit paraboloid for the dish surface will be used to define the coordinate system and origin. The accuracy and precision of the dish vertex position relative to the center of the elevation axis, both measured in dish coordinates, shall be better than or equal to the values as specified in TMA.206, at all measured elevation angles.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.207	Inter-Dish Separation	The maximum separation of 2 m (soft limit) to 3 m between the edges of neighboring dishes shall be verified by inspection and measurement on site.	Inspection	Production	Client: On Site
VTMA.208	Dish Electrical Connectivity	Measure mesh hole size on material samples, and visual inspection of the dish to ensure that there are no gaps or open seams. All gaps must have a maximum linear dimension of 5.0 mm and total maximum filling fraction (open area) of 80%.	Inspection & Demonstration	Prototype & Production	Dish Supplier: at Factory
VTMA.209	Dish Surface Conductivity	The contractor shall demonstrate, by analysis and test of at least one prototype and one production dish, that the entire surface of the dish paraboloid is conductive with a conductivity of no less than 1x10^6 S/m at all measured location. This will be done using a calibrated reflectometer to measure local conductivity at a minimum of 20 locations on the dish. See also VTMA.203.	Test & Analysis	Prototype & Production	Dish Supplier: at Factory
VTMA.210	Dish Protective Layer	The Dish contractor shall, at the Dish design review, demonstrate with reference to appropriate analysis, that the protective layer, covering the dish and receiver assembly, does not attenuate the reflection of radio waves from the dish by more than 0.02 dB. The presence of the protective layer shall be verified at the factory for each Dish and Receiver assembly.	Analysis	Design	Dish Supplier: at Factory
VTMA.301	Orthogonality of the Dish Boresight Vector	Measure dish shape with photogrammetry or laser tracker at a minimum of 5 elevation angles, evenly spaced between 60° (or the lowest possible elevation angle) and 90°. There will be a minimum of 500 measurement points/targets, roughly equally spaced across the dish surface, as well as stationary targets either on the mount or on the ground to provide common reference points between measurements. The best-fit paraboloid and corresponding vertex-focus vector will be calculated for each elevation angle. The derived rotation axis, calculated from the measurements at the different elevation angles, must be orthogonal to the vertex-focus vector within the accuracy and precision requirements as specified in TMA.301.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site
VTMA.302	Elevation Axis Center Position Accuracy	Photogrammetry or laser tracker targets will be placed on: 1) the dish foundation to serve as absolute reference points for the array, and 2) elevation axis. The axis must have at least two marked locations / attachment points, preferably at each end, that serve as precise mechanical references for deriving the position and orientation of the axis. The central position of the axis must lie within 1mm of the desired absolute position in the X-Y direction and within 2 mm in the Z direction relative to the nominal (Xi, Yi, Zi) coordinates. The nominal (Xi, Yi, Zi) coordinates will be specified by the HIRAX team.	Test	Prototype & Production	Dish Supplier: at Factory for at least one prototype and on site for prototypes and production, using onsite Client equipment and (optional) personnel

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.303	Elevation Axis Alignment	Photogrammetry or laser tracker targets will be placed on: 1) the dish foundation to serve as absolute reference points for the array, and 2) elevation axis. The axis must have at least two marked locations / attachment points, preferably at each end, that serve as precise mechanical references for deriving the position and orientation of the axis. The accuracy and precision of the orientation angle of the axis relative to the desired absolute orientation angle (Global East-West line in array coordinates) within the array shall be better than or equal to the accuracy and precision requirements specified in TMA.303.	Test	Prototype & Production	Dish Supplier: at Factory for at least one prototype and on site for prototypes and production, using onsite Client equipment and (optional) personnel
VTMA.304	Mount Elevation Range	The dish mount shall have a precise mechanical reference surface as specified in TMA.205, for mounting an inclinometer to measure the elevation or zenith angle. These angles will be recorded as the mount is tilted across the full elevation range. The measured zenith angles from the inclinometer must span the full ±30° range.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site
VTMA.305	TMA Elevation Adjustment	The dish mount shall have a precise mechanical reference surface as specified in TMA.205, for mounting an inclinometer to measure the elevation or zenith angle. Measurements shall be conducted using an inclinometer with an accuracy and precision at least 10 times better than the values as specified in TMA.305 These angles will be recorded as the mount is tilted from -30° to +30° in zenith angle in 2.5° increments. This tilting/measuring process will be repeated at least three times. For all zenith angles, the accuracy and precision of the measured values must better than or equal to the values as specified in TMA.305. This will also include the accuracy to which the increments are equispaced. The measurements will be performed at both the factory and on site to ensure that the mount elevation adjustment still meets the requirements after the dish is attached.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site
VTMA.306	TMA Elevation Lock	It shall be verified by test that, after being adjusted to the preferred elevation position, the TMA shall remain locked in position. This locking action shall not result in the TMA deviating from the adjusted elevation position by more than 40 arcsec. This shall be verified by measuring the elevation angle before and after the locking action, and the deviation in adjusted elevation position measured.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.306.1	TMA Elevation Lock Rigidity	It shall be verified by test that, after locking to the correct elevation angle, the dish locking mechanism shall withstand maximum operational wind and other external effects as specified, and not move permanently from the adjusted position. To verify this, a force equivalent to the drag force experienced by the dish as a result of the maximum survival wind shall be applied to the dish rim, perpendicular to the boresight vector, and the deviation in adjusted elevation position measured before and after the application of the force shall be measured.	Test	Prototype & Production	Dish Supplier: at Factory Client: on Site
VTMA.307	Mount Setting Adjustment	On Site: The contractor shall first install the dish mount onto the foundation, and compensate for the inaccuracies and out of flatness of the dish foundation, using compensation means of his choice. Verification of compensation for the inaccuracies and out of flatness of the dish foundation may be done using photogrammetry or laser tracking, or use of an inclinometer of commensurate accuracy, mounted on a reference surface of sufficient accuracy. Once the verification of compensation for the inaccuracies and out-of-flatness of the dish foundation is done, the range of the adjustments may be verified. For the verification of the range of adjustments, Photogrammetry or laser tracker targets will be placed at enough locations on the mount to fully determine its position and orientation angle. Additional targets will be placed on the foundation to serve as common reference points between measurements. The mount will be moved/tilted through the full range allowed by the fine adjustment mechanisms, with a minimum of 2 intermediate values for all adjustments. Photogrammetry or laser tracker measurements will be taken at all adjustment values. The mount position and orientation angle will be calculated for each photogrammetry/laser tracker measurement. Once installed, and after compensating for the inaccuracies and out-of-flatness of the dish foundation, the maximum absolute value of the angular adjustment shall be no less than ±5 arc minutes, and the maximum absolute value of the translation adjustment shall be not less than ±5 mm, determined by evaluation of the data, and/or the results of external measurements (such as an inclinometer). Note: A reference surface may have to be provided for on the mount, to ensure ease of measurement. The decision of providing a reference surface, or using other means, is left to the Contractor.	Test & Analysis	Prototype & Production	Dish Supplier: at Factory for at least one prototype and on site for prototypes and production , using onsite Client equipment and (optional) personnel

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.308	Locking of Dish Mount	It shall be verified by test that, once the dish mount is locked into place after it is adjusted to the correct position and orientation, the locking action does not result in the misalignment of the dish elevation axis or the dish elevation angle deviating from the adjusted orientations by more than 40 arcsec, and the positions deviation by more than 0.2 mm. This shall be verified by measuring the dish mount position and orientation angle before and after the locking action, and the deviation in adjusted elevation position and orientation measured. Measurements shall be taken with appropriate test equipment, used to align the dish. A reference surface may have to be provided for on the mount, to ensure ease of measurement. The decision of providing a reference surface, or using other means, is left to the Contractor.	Test	Prototype & Production	Dish Supplier: At Factory Client: On Site
VTMA.309	Mount Fixation to Foundation Under Normal Operating Conditions	It shall be verified by test that the dish mounting is fixed to the foundation in such a way that the fixation of the mounting to the foundation shall withstand the maximum operational wind and other operational effects as specified, and not permanently deform. A force equivalent to the drag force experienced by the dish as a result of 1.5 times the maximum operational wind shall be applied to the dish rim, perpendicular to the boresight vector, and the deviation in adjusted elevation position measured before and after the application of the force.	Test	Prototype & Production	Dish Supplier: at Factory for at least one prototype and on site for prototypes and production, using onsite Client equipment and (optional) personnel
VTMA.310	Mount Fixation to Foundation Under Abnormal Operating Conditions	It shall be verified by test that the dish mounting shall be fixed to the foundation in such a way that the fixation of the mounting to the foundation shall survive the maximum survival wind as specified, and not fail to fix the mount to the foundation (plastic deformation is allowed). A force equivalent to the drag force experienced by the dish as a result of 1.5 times the maximum survival wind shall be applied to the dish rim, perpendicular to the boresight vector, and the deviation in adjusted elevation position measured before and after the application of the Force.	Test	Prototype & Production	Dish Supplier: at Factory for at least one prototype and on site for prototypes and production, using onsite Client equipment and (optional) personnel
VTMA.401	Foundation Height	The Civil contractor shall demonstrate that the foundation of the dishes is not higher than 0.5 m above ground. In the event that this is not true, the Civil contractor shall affix a protective frame around the specific foundation.	Inspection	Prototype & Production	On Site (civil contractor)
VTMA.402	Dish Height	It shall be verified by demonstration on site that the maximum height of any part of the dish above the foundation shall not exceed 4.0 m in any configuration, including the ±30° elevation case.	Demonstration	Prototype & Production	Dish Supplier: at Factory Client: on Site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.501	TMA Operational Life	Dish Supplier to conduct an age analysis on all materials used in the construction of the TMA to ensure an expected lifespan of 10 years with at least one-year margin. Contractor to provide documented specification on materials used. The full spectrum of environmental conditions shall be considered, and the worst-case combination of environmental conditions for aging shall be selected as basis.	Analysis and Analogy	Design, design review	Dish supplier: At Factory
VTMA.502	Mobile Maintenance Structure	The successful Dish Supplier shall supply, as part of the special equipment accompanying the first prototype dishes, a structure that will allow technicians to do onsite maintenance on the receiver without stepping on the dish. The design of the structure shall be reviewed as part of the Design Review. The successful operation and use of the structure shall be demonstrated on site.	Inspection & Demonstration	Design, Prototype & Production	Dish Supplier: at Factory Client: on Site
VTMA.503	Dish Water Drain	The Dish Supplier shall demonstrate, by demonstration on the first prototype dish at the factory as well as on site on the first dish, that the dish can drain excess water from the dish in the event of a water load equivalent to precipitation of 15 mm/min or 50 mm/hr over a period of 4 hours. The Dish Supplier shall demonstrate Drainage of excess water to be completed within 5 minutes after precipitation has stopped.	Test	Prototype & Production	Dish Supplier: At Factory Client: On Site
VTMA.504	Cleaning of Dish Drainage Holes	The Dish Supplier shall, for the first prototype dish, specify and demonstrate the method to inspect and clean the drainage holes from debris, without damaging the protective layer.	Demonstration	Prototype	Dish Supplier: At Factory Client: On Site
VTMA.505	Cleaning of Dish & Receiver	The Dish Supplier shall, at the Dish design review, with reference to appropriate analysis, specify the cleaning agent and/or the equipment to be used and the method of cleaning of the dish surface, and for the first prototype dish, demonstrate the method to clean the protective layers, without damaging the protective layer.	Inspection	Design	Dish Supplier:At Factory
VTMA.506	Drainage of Excess Water from Foundation	The Civil contractor shall demonstrate, by demonstration on site on the first dish foundation, and all subsequent dish foundations, that the dish foundation design and the site civil preparation is adequate so that excess rainwater from water load equivalent to precipitation of 15 mm/min or 50 mm/hr over a period of 4 hours, is routed away from the foundations and do not enter or affect the cable and fibre trenching.	Demonstration	Prototype & Production	Not applicable to Dish supplier. Civil Contractor or Client: on Site
VTMA.507	Dish Surface Quality (precision)	After the construction of each dish, the measured surface of the dish, relative to the mean best-fit paraboloid of revolution, (averaged over all dishes being assessed up to date of manufacture) shall be measured. The precision of this dish shall be calculated based on the data of all the dishes previously manufactured. This data shall be used to trend the conformance of all the dishes to the requirements as specified in TMA.204 to indicate process stability. If trending shows non-conformance is approached, or shows clear trending towards non-conformance to the requirements as specified in TMA.204, the contractor shall take the necessary steps to rectify the problem, before manufacturing subsequent dishes. The verification process as specified in VTMA.204 shall be used.	Test	Prototype & Production	Dish Supplier: at Factory

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.507.1	Dish Surface Quality (accuracy)	After the construction of each dish, the measured surface of the dish, relative to the mean best-fit paraboloid of revolution, (averaged over all dishes being assessed up to date of manufacture) shall be measured. The accuracy of this dish shall be calculated based on the data of all the dishes previously manufactured. This data shall be used to trend the conformance of all the dishes to the requirements as specified in TMA.202 to indicate process stability. If trending shows non-conformance is approached or shows clear trending towards non-conformance to the requirements as specified in TMA.202, the contractor shall take the necessary steps to rectify the problem, before manufacturing subsequent dishes. The verification process as specified in VTMA.202 shall be used.	Test	Prototype & Production	Dish Supplier: at Factory
VTMA.508	Dish Protrusions	The Dish Supplier shall ensure that the Dishes do not have sharp protrusions, burrs or corners that could injure personnel. This shall be verified by Inspection at the Factory before release to the Site.	Inspection	Prototype & Production	Dish Supplier: at Factory
VTMA.509	Mount Elevation Locking	The Dish Supplier shall demonstrate that the locking mechanism that lock dishes in place shall be designed such that dishes shall not be able to dislodge from the locked-in elevation position and resulting in injury of personnel working on the dishes or in the vicinity of the dishes in the event of: 1. Wind loading up to 1.1 times the maximum allowed wind speed; 2. Unbalance loads due to the accumulation of hail stones, water or debris; 3. Collapse of the measurement frame; 4. A person with the mass of less than or equal to 120 kg standing on or hanging off any edge of the dish. Verification of the requirement shall be done by calculating the appropriate load cases by a combination of Finite Element analysis and CFD analysis, and applying the associated loads onto the first prototype dish.	Test & Analysis	Prototype & Production	Dish Supplier: at Factory Client: on Site
VTMA.510	Access to RFoF Electronics via Receiver Support	The Dish Supplier shall demonstrate that the receiver support structure provides easy access (i.e. opening/dismantling or closing within 10 minutes) for maintenance to the RFoF Electronics.	Demonstration	Prototype	Dish Supplier: at Factory Client: on Site
VTMA.511	Mount Elevation Repointing	Perform the repointing procedure with a maximum of 3 people and time the process. The repointing procedure should be easily manageable with the 3-person team and should take no longer than 10 minutes using minimal auxiliary equipment.	Demonstration	Prototype	Dish Supplier: at Factory Client: on Site
VTMA.512	Mount Setting Repositioning	The Dish Supplier shall perform the fine adjustment process with 4-5 people and time the process. The fine adjustment procedure should be easily manageable with the 4- or 5-person team and should take no longer than 1 hour using auxiliary equipment.	Demonstration	Prototype	Dish Supplier: at Factory Client: on Site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.601	TMA Minimum Ambient Temperature Survival	Dish Supplier to conduct analysis on all materials used in the construction of the TMA to ensure the TMA will survive under a minimum ambient temperature of -7°C. Dish Supplier to provide documented specifications on materials used. The project will monitor receiver support health in all weather conditions over the duration of the experiment.	Analysis or (Analogy/Similarity)	Design @ design review	Dish Supplier: at Factory
VTMA.602	TMA Minimum Ambient Temperature Operations	Dish Supplier to conduct analysis on all materials used in the construction of the TMA to ensure normal operation under the site environmental parameter of a minimum ambient temperature of -5°C. Manufacturer to provide documented specification on materials used.	Analysis or (Analogy/Similarity)	Design @ design review	Dish Supplier: at Factory
VTMA.603	TMA Maximum Ambient Temperature Survival	Dish Supplier to conduct analysis on all materials used in the construction of the TMA to ensure the TMA will survive under a maximum ambient temperature of 45°C. Manufacturer to provide documented specifications on materials used. The project will monitor receiver support health in all weather conditions over the duration of the experiment.	Analysis or (Analogy/Similarity)	Design @ design review	Dish Supplier: at Factory
VTMA.604	TMA Maximum Ambient Temperature Operations	Dish Supplier to conduct analysis on all materials used in the construction of the TMA to ensure normal operation under the site environmental parameter of a maximum ambient temperature of 40°C. Manufacturer to provide documented specifications on materials used.	Analysis or (Analogy/Similarity)	Design @ design review	Dish Supplier: at Factory
VTMA.605	TMA Solar Radiation Operations	Dish Supplier to conduct accelerated life cycle testing for UV exposure in a UV chamber on all materials used in the construction of the TMA, to ensure normal operation under the site environmental parameter of solar radiation of 1120 W/m^2 from twilight to dawn. The project will accept prior testing of materials, if certified by an appropriate authority. Dish Supplier to provide documented specifications on materials used.	Test or (Analysis and Analogy/Similarity)	Design @ design review	Dish Supplier: at Factory
VTMA.606	TMA Humidity Operations	Dish Supplier to conduct analysis on all materials used in the construction of the TMA to ensure normal operation for life without degradation under the site environmental parameter of 95% Relative Humidity. Manufacturer to provide documented specifications on materials used.	Analysis or (Analogy/Similarity)	Design @ design review	Dish Supplier: At Factory
VTMA.607	TMA Precipitation Rate Survival	The Dish Supplier will perform a test to demonstrate water drainage from the constructed dish to ensure survival at a rate of precipitation of 50 mm/hr over 4 hours.	Test	Prototype	Dish Supplier: at Factory
VTMA.608	TMA Windblown Particle Survival	Dish Supplier to conduct analysis on all materials used in the construction of the TMA to ensure will survive windblown dust and grit. Manufacturer to provide documented specifications on materials used.	Analysis or (Analogy/Similarity)	Design @ design review	Dish Supplier: at Factory
VTMA.609	TMA Wind Blown Particle Operations	Dish Supplier to conduct analysis on all materials used in the construction of the TMA to ensure normal operation under the normal site environmental parameter of windblown dust and grit. Manufacturer to provide documented specifications on materials used.	Analysis or (Analogy/Similarity)	Design @ design review	Dish Supplier: at Factory

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.610	TMA Hail Survival	Dish Supplier to test all materials used in the construction of the TMA to ensure that it will survive hail up to an energy of 11 J. The project will accept prior testing of materials, if certified by an appropriate authority. Manufacturer to provide documented specifications on materials used. Tests and material sample size shall be i.a.w. Internationally accepted standards.	Test on material samples and (Analysis or Analogy/Similarity)	Design @ design review	Dish Supplier: at Factory
VTMA.611	TMA Ice Survival	Dish Supplier to conduct analysis on the TMA to ensure the TMA shall survive an ice loading of 5.4 kg/m^2 on all exposed surfaces (which corresponds to a glaze ice thickness of 6.0 mm with a density of 900 kg/m^3 - i.a.w. MIL-STD-810F Method 521.2). Dish Supplier to provide documented specifications on materials used.	Analysis or (Analogy/Similarity)	Design @ design review	Dish Supplier: at Factory
VTMA.612	TMA Wind Speed Survival	Dish Supplier to conduct Finite Element Analysis with load cases from Computational Fluid Dynamics (FEA/CFD) analysis to ensure the TMA shall survive the following (with a nominal air density of 1.05 kg/m^3 at 20°C): 1) Peak wind speed: 20 m/s (3 second gust). 2) Peak survival wind speed: 44.4 m/s (instantaneous gust). Dish Supplier to provide documented specifications on materials used.	Analysis	Design @ design review	Dish Supplier: at Factory
VTMA.613	TMA Wind Speed Operations	Contractor to conduct Finite Element Analysis, with load cases from a Computational Fluid Dynamics (FEA/CFD) analysis to ensure normal operation of the TMA under the following conditions (with a nominal air density of 1.05 kg/m^3 at 20°C): 1) Average wind speed: 4.2 m/s; 2) Maximum average wind speed (10 min averages): 13.5 m/s. Dish Supplier to provide documented specs on materials used.	Analysis	Design @ design review	Dish Supplier: at Factory
VTMA.614	TMA Earthquake Survival	The Dish Supplier shall show, by using appropriate analysis, that the TMA system shall survive an earthquake with a maximum peak acceleration of 1 m/s^2.	Analysis	Design @ design review	Dish Supplier: at Factory
VTMA.615	Conduct Lightning Current	The Dish Supplier shall show, by using appropriate analysis with reference to IEC 62305 LPL III, that the dish mount and TMA system shall be designed to conduct the lightning current to earth. Compliance to IEC 62305 LPL III shall be verified by inspection on each dish.	Analysis & Inspection	Design, Prototype & Production	Dish Supplier: at Factory Client: Inspection on Site

VTMA.616	Dish Operational Surface Deviations	Analysis: Dish Supplier to perform several multi-case combined Thermal FEA, Structural FEA and CFD, to demonstrate that the dish surface deviations meet requirements as stated in TMA.616, due to the combined effects of 1) Windspeeds up to 13.5 m/s, including the effects of wind direction; 2) Thermal gradients induced by the specified solar irradiance of 1120 W/m², including the effect of parts of the dish masking sunlight from other parts (shadows); 3) Differential thermal expansion due to the use of materials with different thermal expansion coefficients, and with the dish saturated at a steady thermal condition, i.e. at a fixed temperature; The dish surface shall meet stated requirements as defined in TMA.616 under all stated test conditions. Tests The tests suggested below are intended as a rough test to validate or supplement analysis. Wind conditions Step 1: Determine the equivalent distributed mechanical loads on the dish surface due to the wind loading in 1) above, using the abovementioned CFD analysis. Standalone aerodynamic calculations may also be used in conjunction or as an alternative. When used as an alternative, the results shall be verified against the results of the CFD analysis. Step 2: Apply an equivalent distributed loading (to within 30% accuracy) to the Dish or Dish surface. Step 3: Measure the Movement of the Dish surface due to the applied loads using the methods as stated in VTMA.202 and VMA.204. Step 4: Compare these deflections to the requirements as stated in TMA.202 and TMA.204. Movement of the dish surface due to thermal gradients induced by solar irradiance, may be tested by comparing the measured movement of the receiver support in the shade, to that measured at noon in full sun, and comparing the difference with the specification values to the requirements as stated in TMA.202 and TMA.204. Measurements shall use the methods as stated in VTMA.202 and VMA.204. Movement of the dish surface due to differential thermal expansion induced by temperature differences across the dish (at a fixed temperature) may be tested comparing the measured movement of the receiver support at low temperatures, to that measured at normal room temperatures, and comparing the difference with the specification values to the requirements as stated in TMA.202 and TMA.204.	Analysis and Test	Design @ design review and Prototype	Dish Supplier: at Factory Client: at site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
		This can be repeated for any temperature in the operational temperature range between the minimum and maximum, as defined in TMA.602 and TMA.604. Measurements shall use the methods as stated in VTMA.202 and VMA.204. Note on differential thermal expansion: The differential thermal expansion shall be evaluated at any given temperature with the dish at steady thermal ("saturated") condition in the operational temperature range between the minimum and maximum, as defined in TMA.602 and TMA.604. Note: If it is practical, the tests on the dish surface as defined in VTMA.616, may be done concurrently with the tests on the dish mount as defined in VTMA.616.2.			

VTMA.616.1	Receiver support Operational Deviations	Analysis: Dish Supplier to perform several multi-case combined Thermal FEA, Structural FEA and CFD, to demonstrate that the receiver support meets requirements as stated in TMA.616.1, due to the combined effects of 1) Windspeeds up to 13.5 m/s, including the effects of wind direction; 2) Thermal gradients induced by the specified solar irradiance of 1120 W/m², including the effect of parts of the dish masking sunlight from other parts (shadows); 3) Differential thermal expansion due to the use of materials with different thermal expansion coefficients, and with the dish saturated at a steady thermal condition, i.e. at a fixed temperature; The receiver support shall meet stated requirements as defined in TMA.616.1 under all stated test conditions. Test: For the receiver support integrated with the dish: Wind conditions Step 1: Determine the equivalent distributed mechanical loads on the receiver support due to the wind loading in 1) above, using the abovementioned CFD analysis. Standalone aerodynamic calculations may also be used in conjunction or as an alternative. When used as an alternative, the results shall be verified against the results of the CFD analysis. Step 2: Apply a force equivalent to the drag force experienced by the receiver support structure due to the wind conditions defined above, to the midpoint of the receiver support structure, perpendicular to the boresight vector to the receiver support. Step 3: Measure the Movement of the receiver support due to the applied loads using the methods as stated in VTMA.109 and VMA.110. Step 4: Compare these deflections to the requirements as stated in TMA.109 and TMA.110. Movement of the receiver support in the x-y plane and along the z- axis due to thermal gradients induced by solar irradiance, may be tested by comparing the measured movement of the receiver support in shady conditions, to that measured around noon in full sun, and comparing the difference with the specification values as stated in TMA.109 and TMA.110. (rough test only). Measurements shall use the methods as stated in VTMA.109 and VMA.110. Movement of the receiver support in the x-y plane and along the z- axis as a result of movement of the dish surface due to differential thermal expansion induced by temperature differences across the dish (at a fixed temperature) may be tested comparing the measured movement of the receiver support at low temperatures, to	Analysis and Test	Design @ design review and Prototype	Dish Supplier: at Factory Client: at site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
		that measured at normal room temperatures, and comparing the difference with the specification values as stated in TMA.109 and TMA.110. This can be repeated for any temperature in the operational temperature range between the minimum and maximum, as defined in TMA.602 and TMA.604. Measurements shall use the methods as stated in VTMA.109 and VMA.110. Note on differential thermal expansion: The differential thermal expansion shall be evaluated at any given temperature with the dish at steady thermal ("saturated") condition in the operational temperature range between the minimum and maximum, as defined in TMA.602 and TMA.604.			

VTMA.616.2	Dish Mount Operational Deviations	Analysis: Dish Supplier to perform several multi-case combined Thermal FEA, Structural FEA and CFD, to demonstrate that the dish mount assembly meets requirements as stated in TMA.616.2, due to the combined effects of 1) Windspeeds up to 13.5 m/s, including the effects of wind direction; 2) Thermal gradients induced by the specified solar irradiance of 1120 W/m^2, including the effect of parts of the dish masking sunlight from other parts (shadows); 3) Differential thermal expansion due to the use of materials with different thermal expansion coefficients, and with the dish saturated at a steady thermal condition, i.e. at a fixed temperature; The dish mount shall meet stated requirements as defined in TMA.616.2 under all stated test conditions. Tests For the dish integrated onto the mount: The tests suggested below are intended as a rough test to validate or supplement analysis. Wind conditions Step 1: Determine the equivalent distributed mechanical loads on the dish mount due to the wind loading in 1) above, using the abovementioned CFD analysis. Standalone aerodynamic calculations may also be used in conjunction or as an alternative. When used as an alternative, the results shall be verified against the results of the CFD analysis. Step 2: Apply an equivalent distributed loading (to within 30% accuracy) to the Dish. Step 3: Measure the Movement of the Dish mount due to the applied loads using the methods as stated in VTMA.303 and VMA.305. Step 4: Compare these deflections to the requirements as stated in TMA.303 and TMA.305 Movement of the dish mount due to thermal gradients induced by solar irradiance, may be tested by comparing the measured movement of the dish mount in the shade, to that measured at noon in full sun, and comparing the difference with the specification values as stated in TMA.303 and TMA.305. Measurements shall use the methods as stated in VTMA.303 and VMA.305. Movement of the dish mount due to differential thermal expansion induced by temperature differences across the dish (at a fixed temperature) may be tested comparing the measured movement of the receiver support at low temperatures, to that measured at normal room temperatures, and comparing the difference with the specification values as stated in TMA.303 and TMA.305. Measurements shall use the methods as stated in VTMA.303 and VMA.305.	Analysis and Test	Design @ design review and Prototype	Dish Supplier: at Factory Client: at site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
		This can be repeated for any temperature in the operational temperature range between the minimum and maximum, as defined in TMA.602 and TMA.604. Note: If it is practical, the tests on the dish surface as defined in VTMA.616.2, may be done concurrently with the tests on the dish mount as defined in VTMA.616. Note on differential thermal expansion: The differential thermal expansion shall be evaluated at any given temperature with the dish at steady thermal ("saturated") condition in the operational temperature range between the minimum and maximum, as defined in TMA.602 and TMA.604.			
VTMA.616.3	Provision of the partial derivative of dish accuracy with respect to dish temperature.	The Dish supplier shall provide the partial derivative of dish assembly accuracy to dish temperature, using simulations. The partial derivative shall be evaluated at temperatures of 0ºC, 10ºC, 20ºC, 30ºC and 40ºC. The method used shall be to calculate the partial derivative shall be to determine the dish assembly accuracy at temperatures of 2 degrees less and two degrees more than the applicable temperatures stated above and calculate the partial derivative using these values.	Analysis	Design	Dish Supplier: at Factory Client: on Site
VTMA.617	Dish Transient Surface Deviations	The Dish Supplier shall use the analysis as defined in VTMA.616, to determine the load cases that represent the limiting survival conditions. The survival of the dish under these extreme conditions shall be verified by the appropriate analysis. The Dish Supplier shall also determine mechanical (i.e. perturbation) load cases that can be applied to the dish on-site to determine survival. After the dish is integrated with the mount, the Dish Supplier shall perturb the dish in accordance with the perturbation load cases that will test survival of the dish. The dish, receiver support, and mount shall meet all requirements under all attempted test conditions.	Test & Analysis	Design & Prototype	Dish Supplier: at Factory and on Prototypes on Site Client: on Site
VTMA.701	Dish Number	Dishes will be counted at delivery.	Inspection	Production	Client: on Site
VTMA.801	Trench Compliance	The Civil contractor shall demonstrate, by analysis and reference to the standard SANS 10198:2016 Edition 2.2, that all trenches between dishes carrying electrical conductors, adheres to SANS 10198:2016 Edition 2.2. Verification of this shall be done by Inspection on site and by appropriate analysis shared at the Dish design review.	Analysis & Design Review, Inspection	Design, Prototype & Production	Not applicable to Dish Supplier. Civil contractor: on Site
VTMA.802	Trench Covers	The Civil contractor shall demonstrate, by inspection, that the trenches between dishes that carry cables and fibre are closed with a protective cover. Verification that the cover does withstand loads from vehicles of up to 2000 kg shall be done by appropriate analysis.	Analysis & Design Review, Inspection & Design Review	Design, Prototype & Production	Not applicable to Dish Supplier. Civil contractor: on Site

Number	Element	Description	Verification Method	Verification Level	Revised Verification Location and responsibility
VTMA.803	Interchangeability	The Dish Supplier shall demonstrate that the parts applicable to their scope of supply of the TMA, mentioned in TMA.803 i.e. 1), 2) and 4), shall be interchangeable and be replaceable. This demonstration shall be done on the first prototype dish.	Demonstration	Design @ Design review, Prototype	Dish Supplier: at Factory
VTMA.804	Identical Configuration	The Dish Supplier shall, at the Dish design review, demonstrate that the physical configuration of each specimen of the individual TMA components are identical to each other, within manufacturing tolerances.	Demonstration	Design @ Design review, Prototype	Dish Supplier: at Factory

Table 10: TMA Verification requirements

7. Appendix

7.1. Supporting Requirements and Traceability

Higher-level requirements are listed in the *System Description Document* along with traceability information.

7.2. Acronyms and Abbreviations

AGN	Active Galactic Nuclei	LSST	Large Synoptic Survey Telescope
ANLY	Analysis	NRF	National Research Foundation
BAO	Baryon Acoustic Oscillation	OH&S	Occupational Health and Safety
CHPC	Centre for HIgh Performance Computing	PHY	Physical Requirement
CON	Project Constraints	PSR	Pulsar
DEM	Demonstration	REF	Reference
DER	Derived Requirement	RF	Radio Frequency
DREV	Design Review	RFI	Radio Frequency Interference
FoV	Field of View	RFoF	Radio Frequency over optical Fibre
FRB	Fast Radio Bursts	SARAO	South African Radio Astronomy Observatory
FUN	Functional Requirement	SCI	Science-level Requirements
HartRAO	Hartebeesthoek Radio Astronomy Observatory	SKA	Square Kilometer Array
HI	Hydrogen	SYS	System-level Requirements
HIRAX	Hydrogen Intensity and Real-time Analysis eXperiment	TMA	Telescope Mechanical Assembly
INCOSE	International Council on Systems Engineering	UKZN	University of KwaZulu-Natal
KSG	Key Science Goals	TBC	To Be Confirmed

7.3. Assumptions

Number	Assumption
A1	Weather: similar to SKA mid-site
A2	Site location: accessibility, RFI quiet, available infrastructure
A3	Lifetime: 10 year lifetime of array, not multi-decade lifetime
A4	Technique: probe BAOs and dark energy with 21cm intensity mapping technique
A5	Cost: mount (not mechanised), on-axis dish (vs off-axis), receiver design/materials, RfoF vs Coax, FPGA digitiser/channeliser, GPU correlator, data processing & storage
A6	Dish: dish subsystem requirements completely driven by the 'Dark energy with 21cm intensity mapping' science case.

A7	Dish: dish vs cylinder or tiled array
A8	Receiver: redshift range corresponds to octave bandwidth for high efficiency receiver
A9	Receiver: active feeds (over passive feeds)
A10	RF chain: RfoF advantages over coaxial cable
A11	Modelling: theoretical assumptions about level of signal and foregrounds
A12	The plane of dish foci, which will be largely determined by the slope of the land, will lie within 5 degrees of horizontal