SDP Memo 041: Calibration and imaging context

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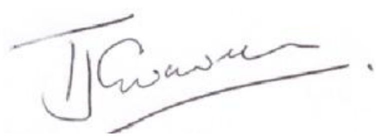
Signature & Date:		2018-02-06

SDP Memo Disclaimer

The SDP memos are designed to allow the quick recording of investigations and research done by members of the SDP. They are also designed to raise questions about parts of the SDP design or SDP process. The contents of a memo may be the opinion of the author, not the whole of the SDP.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

1. Introduction

This SDP internal document describes the context in which we expect SDP will operate. Context provides typical processing steps and parameters. The context drives SDP in two ways: functionality and performance. These two are not entirely separate and so the functionality may be limited to certain performance limitations. For example, while we will have the functionality required for calibrating the bandpass every second, we will not (usually) have sufficient SNR. This limitation is important because the context determines the required performance in a helpful way. In general, this document errs on the side of defining functionality without too much reference to performance.

This memo is informed from VLA experience [RD7] for MID and LOFAR experience [RD3] for LOW, as well as informal communications.

This document covers what we know now about SKA1 calibration and imaging, based on experience with existing telescopes. Since we are building two telescopes with considerably enhanced scientific performance, we should expect that the actual processing required when the telescopes are fully operating will be significantly different from prior in some key areas. The consequences are that for both telescopes flexibility of processing is vital, and continuing investment in SDP will be required during operations.

2. References

2.1 Reference Documents

Reference Number	Reference
RD1	Perley, R.A., (1999) “Synthesis Imaging in Radio Astronomy II” eds. G B Taylor, C L Carilli, and R A Perley, pp 275.
RD2	VLA calibration, https://science.nrao.edu/facilities/vla/data-processing/pipeline/scripted-pipeline
RD3	Rau, U., Bhatnagar, S., Voronkov, M.A., and Cornwell, T.J., "Advances in Calibration and Imaging Techniques in Radio Interferometry", Proc IEEE, 97, 1472-1481, (2008)
RD4	Sanaz Kazemi, Sarod Yatawatta, and Saleem Zaroubi (2013), “Clustered Calibration: An Improvement to Radio Interferometric Direction Dependent Self-Calibration”, Monthly Notices of the Royal Astronomical Society, Volume 430, Issue 2, p.1457-1472
RD5	R. J. van Weeren, W. L. Williams, M. J. Hardcastle, T. W. Shimwell, D. A. Rafferty, J. Sabater, G. Heald, S. S. Sridhar, T. J. Dijkema, G. Brunetti, M. Brüggen, F. Andrade-Santos, G. A. Ogrean, H. J. A. Röttgering, W. A. Dawson, W. R. Forman, F. de Gasperin, C. Jones, G. K. Miley, L. Rudnick, C. L. Sarazin, A. Bonafede, P. N. Best, L. Birzan, R. Cassano, K. T. Chyzy, J. H. Croston, T. Ensslin, C. Ferrari, M. Hoeft,

	C. Horellou, M. J. Jarvis, R. P. Kraft, M. Mevius, H. T. Intema, S. S. Murray, E. Orru, R. Pizzo, A. Simionescu, A. Stroe, S. van der Tol, and G. J. White, “LOFAR Facet Calibration,” ApJS, vol. 223, no. 1, p. 2, Mar. 2016.
RD6	Intema, H T and Van der Tol, S and Cotton, W D, “Ionospheric calibration of low frequency radio interferometric observations using the peeling scheme-I. Method description and first results”, A&A, 501, 1185–1205 (2009)
RD7	S. Bhatnagar, T. J. Cornwell, K. Golap, and J. M. Uson, “Correcting direction-dependent gains in the deconvolution of radio interferometric images,” *Astron. & Astrophys.*, vol. 487, pp. 419–429, 2008.
RD8	S. Bhatnagar, T. J. Cornwell,, “The Pointing Self Calibration algorithm for aperture synthesis radio telescopes”, https://arxiv.org/abs/1709.08681

3. Common requirements for all calibration and imaging

The core requirements are:

1. The calibration and imaging formalism is required to be the extension of Hamaker-Bregman-Sault to imaging (RD6), (SDP-REQ-765).
2. Both telescopes are calibrated using a Local Sky Model consisting of both images and compact components. The LSM is derived from a Global (i.e. all-sky) Sky Model (SKA1-SYS-REQ-2322).
3. Both telescopes must support real-time closed loop calibration. The time for closing the loop is not specified but we will assume a 30s time-scale (not 1s as specified by SDP-REQ-663) (SKA1-SYS_REQ-2319).
4. Calculation of the visibilities corresponding to this LSM shall be performed by any means that allows meeting the system performance budget.
5. Flagging for known effects such as non-operational equipment, elevation limits, loss of tracing, and also shadowing is performed by the Telescope Manager and passed via meta-data to SDP.
6. The telescope calibration is applied in two places: in the beam-formers for time-series processing, and at ingress to the SDP pipelines (including both RCAL and ICAL).
7. Both telescopes must support iterative self-calibration using wide-band models of the continuum sky. No limits on number of iterations is given.
8. Both telescopes must support imaging with correction for wide-field effects.
9. Correction for the w-term is needed for both telescopes. The strength of the effect is measured by the Fresnel scale (see Figure 1) and the processing scales as the square of the Fresnel term.
10. Wide field algorithms are in rapid development. We can expect this to continue until well into scientific operations. Because of the ever increasing sophistication of the wide field algorithms, the successful algorithms will almost certainly need auto-tuning to context. The SDP Performance Model can serve this purpose. At the moment, an optimal choice would be a combination drawn from w projection, w stacking/slicing, w snapshots, and faceting. Improvements in performance from e.g. Image Domain Gridding should be tracked.
11. In addition to correction for the w-term, support for the following DDE's is required: Aperture Array, Dish, Faraday Rotation. It is not specified how detailed or time-variable these need be. (See SKA1-SYS_REQ-2321, SKA1-SYS_REQ-2724, SKA1-SYS_REQ-2727, SKA1-SYS_REQ-2725).
12. Frequency dependent sky models must be used over entire bandwidth: SDP use of MSMFS in sub-bands is in conflict with this unless boundary conditions across sub-bands are imposed.
13. A continuum imaging pipeline must be available and should be able to make noise-limited images for 1000h out to the third null of the primary beam. This is a system requirement, and SDP does not yet have an allocation. Part of this capability has been moved to SRCs and therefore verification will require coordination between SDP and SRC.
14. A spectral line pipeline must be available. The deconvolution of the spectral line channel images shall be out to the first zero. SDP expects that there will be two different pipelines:

with continuum left in, and with continuum removed. The method of continuum removal is not specified, but we will plan for three approaches: removal of the LSM, linear fitting to the visibilities across the band, and linear fitting to the image pixels across the band. The latter can also be performed after the science product image has been created.

15. Deconvolution of wide-band continuum models (as required for calibration and some science) will be done using the Multi-scale-multi-frequency-synthesis (MSMFS) algorithm. Deconvolution of spectral line planes will be done using the MS algorithm. It is possible that these may be replaced by superior algorithms such as Compressive Sampling but this is not likely soon. The quite uncertain details of the processing (numbers of scales and numbers of frequency terms) drive our processing performance required.
16. Estimation of compact sources will be necessary for high dynamic range imaging (see section 8).

The above constitute a set of requirements that drive the overall processing. Other requirements are in addition to the core:

1. Solution for pointing errors both from specially designed observing sequences or from the field being observed (see e.g. RD5). SKA1-SYS_REQ-2328
2. Peeling of bright sources (see e.g. RD4) SKA1-SYS_REQ-233 is necessary for LOW and MID. Extended sources must be accommodated.
3. Glass box calibration implies some responsibility for SDP. Most probably in comparing with SDP-derived estimates (e.g. for LOW Beam calibration). SKA1-SYS_REQ-3045, SKA1-SYS_REQ-3044, SKA1-SYS_REQ-3034, SKA1-SYS_REQ-3033, SKA1-SYS_REQ-3042, SKA1-SYS_REQ-3043.
4. A global (i.e. all sky) TEC model is available in real time from GPS systems. This should be used to correct for Faraday Rotation, using a DIE approximation. DDE correction may also be required.
5. RFI (known and unknown) must be flagged using the AOflagger (or presumably a work-alike). Time, Frequency flagging can constrain the architecture so it is necessary to constrain the range of time-frequency products, time range, and frequency range separately. VLA practice is to iterate the calibration and RFI excision.
6. Nonlinear joint mosaicking will not be available in SDP. Instead, the individual pointings will be processed separately and passed to the SRCs for combination. For this to work a sensitivity image must be produced for subsequent combination into a large mosaic. The sensitivity image can be calculated in two ways: either directly using the known primary beam models, or by gridding and transforming the weights using the convolution function, including the Primary beam A-term.
7. Correction for strongly varying primary beams will be required for high dynamic range. This may either be to a flat signal sky or to a reference frequency.
8. The uncertain details of the imaging (field of view, image spatial sampling, numbers of scales and numbers of frequency terms) drive the processing performance required.

https://docs.google.com/spreadsheets/d/1fk1QSlxP2kwKww2SCaJBM9ses7C4SpcFvHFiAhsX2sM/edit#gid=1243781794

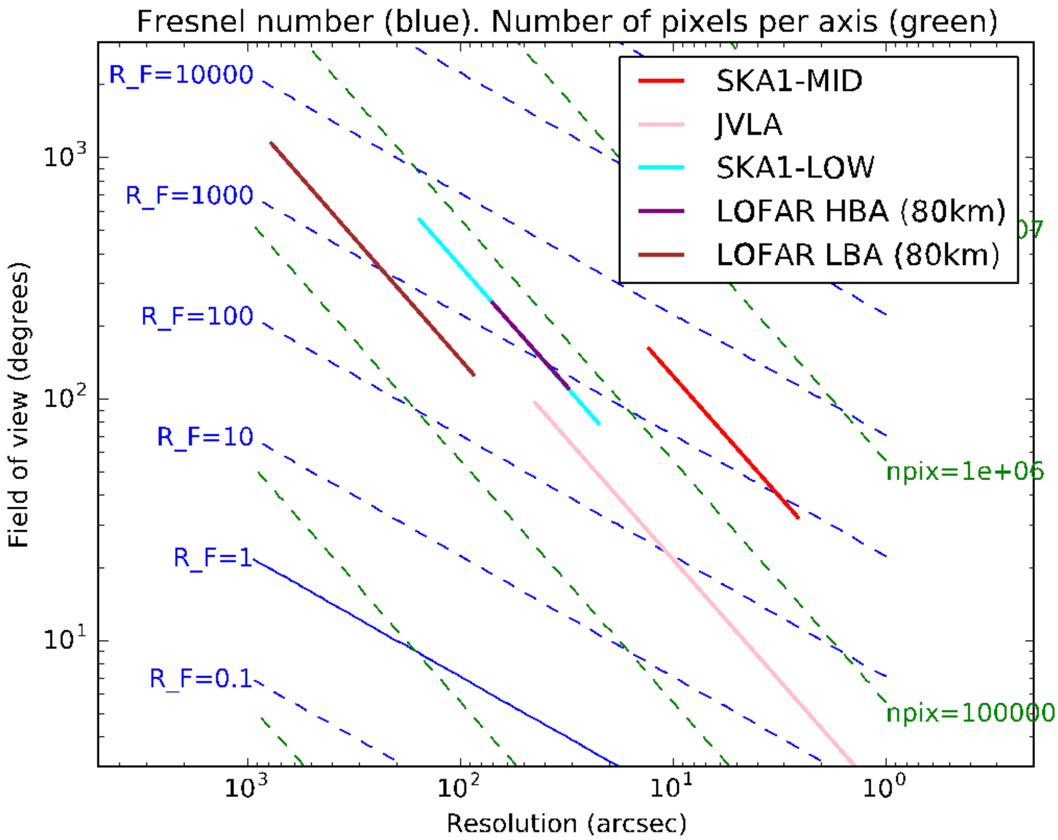


Figure 1: Fresnel number for SKA1-MID and SKA1-LOW. The lines trace out the effect over the full frequency range. The field of view is as required for continuum imaging (i.e. 2.8 x FWZ)

On exit from the ICAL pipeline, the full calibration of the DIE has been applied, and the calibration parameters for the DDE effects are available. The DIE effects can be applied to the visibilities directly, but the DDE effects must be applied when constructing the image. This can either be done using a collection of facets spanning the field of view, or via AWProjection in Fourier space. These capabilities are required for both MID and LOW imaging.

3.1 Science data products

To obtain the science products post-calibration, images must be formed using the DDE effects, and then deconvolved. Multiple major cycles of cleaning will be required for both continuum projects and spectral line projects.

The image sizes for ICAL vary between about 60,000 pixels on a side (for SKA1-LOW) to 200,000 pixels on a side (for SKA1-MID). Assessing image quality visually will require special capabilities.

MSMFS Deconvolution in the ICAL loop produces the following: A clean map image, dirty beam image, clean component map image, and residual map image same weighted by fractional frequency offset, up to the maximum number of Taylor terms used (5 currently). In addition, for mosaicking a sensitivity cube must be produced for subsequent linear mosaicking. The calculation of the sensitivity cube is a significant computation burden not yet included in the SDP Performance Model.

MultiScale Clean (MSClean) Deconvolution in the spectral image pipeline produces the following: A clean map cube, dirty beam cube, clean component cube, and residual cube. For mosaics a sensitivity cube must be produced.

In addition to these image-based scientific data products, the results for compact objects in the field of view must be included (see section 8). This will include bright sources for which more exact processing was necessary.

4. MID

4.1 Calibration

The basics of calibration of Mid are well-known from the EVLA and other ~ 1 GHz telescopes.

The main source of phase errors will be the troposphere for high frequencies (>1GHz) and ionosphere at low frequencies (<1GHz). The troposphere will be non-isoplanatic at all frequencies. At 350 MHz, the ionospheric phase varies over the field by about 5 radians and will require estimation and correction for high dynamic range using the same techniques as used for SKA1-LOW.

We can expect the electronic gain to be very stable. Since the antennas are statically located the continual re-establishment of baselines and pointing models is not needed. Most calibration effects are direction-independent (DIE) and can be treated prior to imaging. The exceptions are ionosphere (as noted above), and antenna pointing errors. Self-calibration of the pointing errors may be necessary at very high dynamic range. Peeling of very bright sources may be necessary in some scientific contexts.

The core required calibration operations are given in Table 1 . Note that the operations needed are more clearly defined than who is responsible. We have used SDP to represent both SDP in both pre- and post-construction. The two pipelines concerned with calibration (RCAL and ICAL) are always run. RCAL provides real time calibration with feedback to the Telescope Model. ICAL is run at the end of observing. In addition, there are specialized pipelines that have not yet been defined but will be need to support Operations. Fast Imaging may require a specialised pipeline.

Table 1: Operations required for SKA1-MID calibration

Action	Pipeline	Lead
Physical survey antennas after installation		OPS
Calibrate antenna locations and delays (initially on installation and then monthly?) (SDP_REQ-774)	Special	OPS
Interferometric aperture plane holography of the antennas should be a regular task until the antennas are known to be stable. This will require tailored aperture plane holography software packaged as a pipeline. (SDP_REQ-775)	Special	OPS
Calibrate antenna pointing model (initially weekly)	Special	OPS
initially Calibrate antenna polarization (P Jones) (weekly and then as needed weekly) (SDP_REQ-776)	Special	OPS
Calibrate absolute flux scale (G) by observations of a set of known or reference sources (weekly)	Special	OPS

(SDP_REQ-777)		
Calibrate G with respect to absolute flux scale by using short observations of a set of known or reference sources (SDP_REQ-777)	ICAL	SDP
Calibrate bandpass (Jones B) as often as possible. Bandpass calibration will depend on having either a strong calibrator or the field itself. SDP will have to support both. Solution for G and B will be limited to the same time-bandwidth product and so a typical time-scale here would be 4-6 hours for B.	ICAL	SDP
Calibrate/monitor antenna gains (G Jones) (1 min - 1 hour)	RCAL	SDP
Calibrate/monitor incremental antenna gains (G Jones) (0.5 - 1 hour)	ICAL	SDP
Calibrate autocorrelation spectra using the interferometric spectra. Timescale for this is not specified. SKA1-SYS_REQ-3047, SDP_REQ-778	Autocorrelation pipeline	SDP
Calibrate atmospheric phases (T Jones) (~1 minute)	RCAL	SDP
Calibrate incremental atmospheric phases (T Jones) (1s - 1 minute)	ICAL	SDP
Derive DIE Faraday Rotation from GPS and apply as needed. (SDP_REQ-772)	ICAL	SDP
Self-calibrate everything again (P, B, G, T) as possible. This is the ICAL pipeline. For low frequencies, non-isoplanatic calibration of the ionosphere may be necessary.	ICAL	SDP
Peeling of bright sources will be necessary in some situations. (SDP_REQ-392)	ICAL	SDP
Reference pointing will be required, with the timescale depending on well-behaved the antennas actually are. At low frequencies, fields can be complex with many sources. For this reason, reference pointing should take advantage of the full processing power of the SDP to return pointing offsets expeditiously (SDP-REQ-839). Thus there needs to be a reference pointing pipeline. Pointing	RCAL	SDP

offsets may warrant feedback to observing. (SDP_REQ-836, 837, 838)		
Self-calibration of the receptor primary beam is limited to a shared global model, together with pointing offsets.	ICAL	SDP

4.2 Mid imaging

Mid imaging requires imaging with DDE for ionosphere (at low frequencies) and pointing errors.

5. Low

5.1 Low calibration

SKA1-LOW will require calibration of direction dependent effects: primarily the behavior of the antenna/station beams with phase centre direction, and ionosphere. SKA1-LOW will be beset with direction dependent effects (DDEs). Once these are known, they can be applied in imaging using AW Projection or faceting/cluster calibration. Both are expensive computationally. DDE correction can only be done during the imaging process. Thus the ICAL pipeline will have to provide correction for large first order problems such as the zenith-angle-dependent polarized primary beam.

The core required operations for calibration are:

Action	Pipeline	Lead
Physical survey antennas and stations after installation		OPS
Calibrate station locations and delays (initially on installation and then monthly?)		OPS
Calibrate each station using antenna cross correlation (10 min to 1 month?)	In station	OPS
Calibrate up to 8 independent station beams for all steps below, with possibly different bandwidths	RCAL, ICAL	SDP
Calibrate up to four zoom modes SKA1-SYS_REQ-2975, simultaneously with full band observations	RCAL, ICAL	SDP
Calibrate autocorrelation spectra using the interferometric spectra. Timescale for this is not specified. SKA1-SYS_REQ-3047, SDP_REQ-778	Autocorrelation pipeline	SDP
Calibrate absolute flux scale (weekly) SKA1-SYS_REQ-2824	Special	OPS
Calibrate station polarization (P Jones) (initially weekly and then as needed) (SDP_REQ-776)	Special/ICAL	OPS/SDP
Calibrate/monitor station gains (G Jones) (1 min - 1 hour)	RCAL	SDP
Calibrate/monitor incremental station gains (G Jones) (0.5 - 1 hour)	ICAL	SDP
Calibrate atmospheric phases (T Jones) (~1 minute)	RCAL	SDP

Calibrate incremental atmospheric phases (T Jones) (1s - 1 minute)	ICAL	SDP
Calibrate bandpass (Jones B) as often as possible (6 hours?). Bandpass calibration will depend on having either a strong calibrator or the field itself. SDP will have to support both. SKA1-SYS_REQ-2811, SDP_REQ-417	ICAL	SDP
Self-calibrate everything again (P, B, G, T) after updating the LSM.	ICAL	SDP
The ionosphere (I Jones) requires special treatment (see e.g. RD1 for a state-of-the-art example from LOFAR). The ionospheric phase changes on 10s timescales and varies substantially across the field of view (at 100MHz, this corresponds to roughly 60km at the ionosphere). [1]	ICAL	SDP
An ionospheric monitoring pipeline will be required.	RCAL	SDP

5.2 Low imaging

Imaging with SKA1-LOW is complicated by the variation of the effective primary beam with zenith angle. As the source rises and sets, the stations are each seen from the source with different projections. This effect also affects the polarization. The consequence is that the Mueller matrix for the station beam must be recalculated often. Also there is a differential effect across the field of view than must be accounted for.

[1] There are multiple techniques that provide high dynamic range imaging for a non-isoplanatic ionosphere. The two leading contenders are cluster (RD4) and facet imaging (RD5). These are very similar in concept. Both break the field of view up into small regions over which the antenna phase is the same. The framework for these applications should be agnostic as to which of these two algorithms will be required. Physically the total electron content (TEC) of the ionosphere integrated along the line of sight perturbs the phase with a λ2 behavior. Thus observations across a range of frequencies can be used to track the TEC with time. Once the TEC is known, the data can in principle be averaged in Frequency but this is likely to require MSMFS imaging because the source structure will change over larger bandwidths (e.g. 10MHz)

6. POSSIBLE INCOMPLETE OR MISSING L1 REQUIREMENTS

1. There will be a fast imaging pipeline capable of imaging every integration time after removal of the LSM. The L1 requirements are particularly undeveloped in this area (SKA1-SYS_REQ-2345, SKA1-SYS_REQ-2346). Based on work at ASKAP, MWA, and AARTFAAC, we should expect that construction of a catalog will be performed for a geometric series of timescales of 1, 2, 4, 8, … integration times. In addition, it should be possible to specify the time-averaging filter.
2. From MWA experience, it may also be that for compact baselines subtraction of a previous observation at the same LST might be necessary as well or instead of subtraction of the LSM. The latency requirement is likely to be difficult to meet. Compromises in the quality of the image may have to be made.

7. L2 REQUIREMENTS AWAITING SYSTEM PERFORMANCE BUDGETS

- SDP_REQ-681: Continuum imaging astrometric error
- SDP_REQ-667: Imaging transient search astrometric error
- SDP_REQ-664: Imaging transient search compute performance
- SDP_REQ-703: Continuum imaging independent directions
- SDP_REQ-702: Continuum imaging facet imaging
- SDP_REQ-692: Continuum imaging direction dependant solving performance
- SDP_REQ-686: Spectral line imaging frequency-dependant flux density
- SDP_REQ-680: Continuum imaging frequency-dependant flux density
- SDP_REQ-424: Polarisation purity

8. QUESTIONABLE L2 REQUIREMENTS

- SDP_REQ-663: When doing real-time calibration, the SDP shall compute calibration solutions for the Jones matrices: G_troposphere, G_ionosphere (Direction Independent Part) and G_electronics. These solutions may be on different timescales for each matrix and will have a maximum cadence of 1s. JIRA Tickets: SE-386, TSK-1426
- SDP_REQ-691: "The SDP shall be able to subtract up to 10^5 point sources using continuous 772Fourier transform (or another technique with the same practical accuracy). The remainder of known sources shall be subtracted using Fourier transforms of their pixelated representation or other techniques with equivalent or better imaging performance." Surely the point is driven by system performance budgets rather than an arbitrary number. JIRA Ticket SE-183 (still open).

9. DYNAMIC RANGE LIMITATIONS

Numerous effects can limit the dynamic range of synthesis images. Here we provide a comprehensive list and the responsive L2 requirements. We do not estimate whether these are likely to be significant in any given observational scenario. This list is provided to ensure that all likely known causes of dynamic range limitations have been accounted for.

Cause of dynamic range limitations	Comments	Responsive L2 requirements	Actions in response
Limited Fourier plane coverage	Addressed by deconvolution algorithms	SDP_REQ-684 SDP_REQ-685 SDP_REQ-693	Add more to match ws-imager capabilities.
Inadequate synthesised beam sampling	Point source between pixels forces sinc-like pattern		New L2 (SDP_REQ-691)
Inadequate antenna/station calibration	Limitations due to direction, time, frequency, polarisation variations.	SDP_REQ-765 SDP_REQ-766 SDP_REQ-772	None
w-term		SDP_REQ-769	None
Primary beam	Known and unknown	SDP_REQ-401 SDP_REQ-771	None
Spectral effects across the bandwidth	Includes sub-band MFS and bandpass calibration	SDP_REQ-386 SDP_REQ-387 SDP_REQ-388	None
Sidelobes from known sources with unknown calibration	Peeling of known sources	SDP_REQ-392	None
Sidelobes from steep-spectrum sources	Extreme spectrum sources (alpha ~ -2) may strain the MFS tolerances	Not addressed	New L2 (SDP_REQ-849)
Sidelobes from time-variable sources	A time-variable source will leave uncleaned sidelobes of strength related to the duty cycle	Not addressed	New L2 (SDP_REQ-849)

Non-isoplanatic phase screens	Different phase errors across the field of view	SDP_REQ-692	None
Non-isoplanatic Faraday rotation screens	Different approaches being developed in community. Not yet clear which should be supported.	SDP_REQ-770	Await RT report
Poor modelling of compact objects	Leads to poor dynamic range around bright sources.	No L2 requirement	New L2 (SDP_REQ-846, 847, 848, 849)
Antenna/station pointing errors	i.e. a phase slope across the aperture. This is required for both MID and LOW.	SDP_REQ-771	None
Antenna/station beam changes	The higher order version of solution for pointing errors.	Not yet addressed. SDP_REQ-771 is for first order effects only. Needs scientific analysis as to feasibility.	None
Poor modelling of station or antenna beam polarisation	Likely to be more pressing for LOW than MID. Update rates and granularity requirements are not known	Actually an unknown performance requirement	None
Closure errors	Assumed not to exist for specified observational scenarios, particularly time and frequency sampling	Not addressed	None
Aberrant sensors	Errors found only via calibration or data inspection	SDP_REQ-773	None

Radio Frequency Interference	Unknown and known	SDP_REQ-773	None

This analysis thus identifies five areas requiring additional definition:

1. Compact source identification and lifecycle in processing. This is an area that is implicit in current L2 requirements.
2. Anomalous sources in the field of view, having unusual time and/or frequency behaviour.
3. High accuracy deconvolution adapted to compact sources against an image-based representation. Compressive sampling algorithms are being developed for this case.
4. Self-calibration of higher order parametric primary beam models.
5. CLEAN capabilities reflecting WS-IMAGER.

Items 1 and 2 are related. Item 3 is new. As with other effects, some system performance budgets are needed to determine importance. Failing a budget, all three should be represented in the L2's.

The suggested changes are:

Table 2: New L2's arising from dynamic range analysis

Number	**Comment**	**Suggested L2 text**
SDP_REQ-846	This should be explicit in the L2's	The sky brightness distribution shall be represented by compact components and regularly pixelated images.
SDP_REQ-847	Also needs to be explicit	Imaging pipelines shall iteratively improve the sky brightness representation, including both compact components and regularly pixelated images.
SDP_REQ-848	The division between LSM and science product needs better definition	Science products shall include both compact components and regularly pixelated images.
SDP_REQ-849	e.g. polynomial and tabulation i.e. components can be slowly varying functions of time and frequency.	Compact components shall allow decomposition in both time and frequency
SDP_REQ-850	The life-cycle of the GSM should be sufficiently well-defined that the LSM for any	The SDP shall have a well-defined process governing changes to the GSM triggered

	given epoch can be unambiguously determined.	by the results of an observation.

Table 3: New L2's arising from WS-IMAGER comparison

Number	Comment	Suggested L2 text
SDP_REQ-??? (L3 ?)	Auto-masking: maintains and updates scale-dependent masks. Local RMS is calculated by robust statistics over O(25 x 25) beams	SDP shall calculate and use scale-dependent cleaning masks based on thresholds calculated by robust statistics.
SDP_REQ-??? (L3 ?)	Automatic determination of scales relative to synthesised beam	SDP shall allow automatic determination of cleaning scales relative to synthesised primary beam.
SDP_REQ-862	These are standard but worth making explicit.	SDP shall support natural, uniform, briggs weighting in both single grid pixel and multiple grid pixel (super-) variants
SDP_REQ-863		SDP shall support calculation of visibility weights based on frequency-integrated density
SDP_REQ-864	See WS-IMAGER for definitions	SDP shall support Gaussian and Tukey tapering of visibility weights

10. Required Definition documents

Some topics are sufficiently complicated to warrant an SKA-level definition document. The absence of these documents and the corresponding L1 requirements means that the set of L2 requirements cannot be considered complete. These topics include:

- Ionospheric monitoring pipeline
- Fast Imaging/Slow transients, including calibration
- Self-calibration of primary beam parametric models
- Drift scan observing

- EOR interface
- Mosaicking
- Calibration of autocorrelation spectra
- VLBI using SKA telescopes

11. Special topics

In this section, we collect various bits of information on specific calibration procedures, corrections to be applied, or other processing steps / pipelines. In most cases this means that more work is needed to get the specifics in place.

11.1 Near field visibility correction

The L1 requirement SKA1-SYS_REQ-3555 is broken down into 2 L2 requirements: SDP_REQ-796 Near field visibility corrections, SDP_REQ-797 Near field imaging. An initial analysis can be found in JIRA ticket TSK-1418, including supporting documents. Below, comments from that ticket are copied.

There are two cases of interest for near-field effects.

- The source is near enough that the delay across the array is not linear. In this case the delay commanded to each antenna/station must be set correspondingly. This can be done either online via TM or, provided the frequency sampling is good enough, in the SDP processing.
- The source is near and large enough that the delay corrections vary across the object. A w-projection-like algorithm has been developed for this case. See nearfield_NRL.pdf attached to TSK-1418.

If the source is dominant in flux over the rest of the field then self-calibration will automatically correct the near field term.

From nearfield.xlsx attached to TSK-1418

- Taking the limit to be 0.1 rad on the longest baseline, LOW must use near-field corrections out to the distance of the Moon.
- For MID the near field ranges from the Moon out to the nearest parts of the asteroid belt.
- If imaging the surface of the Moon over more than ~ 30 - 50km, corrections of the sort described in nearfield_NRL.pdf must be accommodated.

The phase error is: $\frac{\pi B^2}{(\lambda D)}$ where B is the baseline and D is the distance to the object. The coherence size limit on the field of view for a single correction is $\sqrt{\lambda D}$. The correction in the visibilities is just the delay to the object. There is therefore a possible L2 requiring calculation of delays to objects inside the solar system and very close to the earth.

Table 4: New L2 requirements for near-field imaging

	Rationale	Text
SDP_REQ-796	Objects closer than the nearside of the Asteroid Belt for MID and the Moon for LOW will lead to phase errors of more than 0.1 radian on the longest baselines.	SDP shall apply near-field delay corrections to visibilities measured towards celestial objects whose distance present phase errors on the longest baseline, due to wave-front curvature, of more than 0.1 radians.
SDP_REQ-797	A near-field source will require different delay corrections than the background sky. These terms must be kept separate during the calibration and imaging process.	SDP shall image a near-field source against a far-field sky.
SDP_REQ-855		SDP compact source representation shall support near-field calculations, i.e, the position along the line of sight of the compact components shall be described to sufficient accuracy for the corrections.

11.2 Measurements and update of the antenna pointing model

In Table 1, we describe the need for regular updates of the antenna pointing model.

The following L1 requirements refer to On-line Pointing for MID: **SKA1-SYS_REQ-3209**, SKA1-SYS_REQ-3210, SKA1-SYS_REQ-3211, SKA1-SYS_REQ-3212, SKA1-SYS_REQ-3213, SKA1-SYS_REQ-3214. This requires a process for measuring the pointing. JIRA ticket TSK-1787 gives the following description that needs to be elaborated.

- The basic procedure is the same for global pointing model evaluation and reference pointing. It will be necessary to scan (a subset of) antennas in a 5-point or cross-scan pattern while keeping the rest tracking the nominal position during an interferometric observation of a bright calibrator.
- The scan is typically +/- primary beam FWHM at the frequency of the measurement. Fits to the amplitudes of the scanned antennas on baselines to reference antennas then gives the offsets from the currently implemented pointing model.
- The process can then be repeated interchanging scanned and reference antennas.

For a global pointing model evaluation, the measurements (50-100) would be done for a grid of calibrators distributed over the entire accessible sky. The resulting offsets are sent to Telescope Manager which will fit to a geometrical + flexure model using the TPOINT package (or equivalent). For reference pointing, the offsets are used directly to correct the pointing for the subsequent observations.

The responsibility of SDP is to perform the fit to the observed interferometric amplitudes and return the corresponding offsets in Elevation and Cross-elevation to TM. It is the responsibility of TM to set up and control the scan pattern and to analyse and apply the pointing offsets.

Table 5: L2 requirements arising from pointing calibration

	Rationale	Text
SDP_REQ-662	Modify existing L2 to be more specific about the trigger	When doing real-time calibration the SDP shall send the calculated calibration coefficients no later than 15s after the receipt of the last of the relevant visibility data
SDP_REQ-836	An ensemble across large range in antenna-local coordinates is needed for robust solution.	When performing global pointing model calibration, the SDP shall deliver offsets to Telescope Manager for fitting using TPOINT package (or equivalent) for fitting to ensemble pointing measurements.
SDP_REQ-838	Single observation is needed to track direction-dependent or time-varying departures from global pointing model	When performing reference pointing calibration, the SDP shall derive updates to a subset of the antenna pointing model from a single 5-point observation.
SDP_REQ-839	Should be commensurate with other RTC latencies	SDP shall calculate and return reference pointing solutions to TM with a latency of no more than 30s (TBC-086).

11.3 Pointing self-calibration

The very highest dynamic range may require self-calibration of the antenna pointing to supplement both the global antenna pointing model and reference pointing. This would occur in the ICAL pipeline, most probably at the last few iterations. Self-calibration of a small number of parameters of the antenna pointing model using an optimisation algorithm that essentially does the trial pointing offsets via either gridding (RD7, RD8) or a component-based least-squares fitting (MeqTrees). The LSM is held fixed during this search but in principle it could be iterated. Pointing self-calibration is only in occasional use at the JVLA.

The TRL of pointing self-calibration is low. It is not in common use at the VLA.

Table 6: L2 requirements arising from pointing self-calibration

	Rationale	Text
SDP_REQ-840	Agnostic as to approach	SDP shall derive pointing parameters (two offsets from the global and reference models) during the self-calibration process.
SDP_REQ-841	Probably only A projection is appropriate	SDP shall apply pointing parameters, derived from self calibration, during imaging.

11.4 Application of primary beam model

Correction for the primary beam during imaging may be needed for various reasons:

- To counter artificially high spectral index for sources close to the half-power point of the primary beam. If not corrected this effect may limit the effectiveness of multi-frequency synthesis
- To correct substantially varying primary beams, such as occurs for LOW with azimuth and zenith angle (see e.g. Tasse et al, 2016)

This includes both images and discrete components.

Linear mosaicing including combination of drift scans is to be performed at SRCs. This requires that SDP calculates the sensitivity as a function of sky direction, polarisation, and frequency.

Table 7: L2 requirements arising from application of primary beam model

	Rationale	Text
SDP_REQ-842	Agnostic as to approach: in image space or in uv space via the weights	SDP shall calculate a sensitivity image as function of direction, frequency, and polarisation
SDP_REQ-843	Necessary for LOW high	SDP shall be able to use the transform

	dynamic range imaging. May be necessary for MID as well.	of the primary beam (the A-term) in imaging.
SDP_REQ-844	Required so that the prediction of visibilities is correct.	SDP shall apply primary beam models to the discrete components of the LSM
SDP_REQ-845	Required to correct the derived discrete components for the primary beam	SDP shall correct fitted discrete components for the primary beam at the position of the component