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MeerKAT interferometric pointing

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Introduction

MeerKAT needs an all-sky blind pointing model which is accurate to a small fraction of the Full Width Half Maximum, so that all antennas when given a requested position will have their maximum sensitivity very close to that position. For most practical antennas (whose beams are very approximately gaussian for the primary lobe) the slope of the received intensity against offset varies most rapidly with the angular offset near the half power beamwidth[1], so we need an accuracy of order a few percent of the Full Width Half Maximum (FWHM) beamwidth. For MeerKAT at L-band the FWHM is about 1°, so we want to be within about 1 arcminute to keep losses in sensitivity below 2% at the half-power point. Peter Napier says that the pointing accuracy for interferometers wanting to image sources at the half power point must be better than FWHM/17 (or 3.5 arcminutes for MeerKAT at L-band)[2]. Pointing accuracy is also vital for mosaicing so that the overlapping regions can be calibrated correctly.

If we need higher accuracy than this procedure can provide, we will need to do reference pointing.

We use a set of parameters 'P1-P8' that are the same as in the VLBI Field System, and their meaning which can be found at https://drive.google.com/open?id=0B2-Tk_jh20nha2JoUWt2V3hYcTQ

The first 7 parameters (P1-P8) parameters are enough to get within 1.5 arcminutes at L-band (P2 is zero for alt-az mounted dishes) . If more parameters are needed it suggests a problem with that antenna. There are direct equivalents in the ALMA pointing system (see appendix)

- Interferometric pointing will need at least a first-order single-dish pointing to work adequately. If the error in the single dish pointing is larger than about 1° at L-band we will probably not find a good fit with this procedure.
- Interferometric pointing will also need the interferometry part to be stable enough to run scans on many point source targets to give good sky coverage.
    - Delay tracking needs to be reliable for most of the sky, so geometrical delays should be known for all dishes involved.
    - Delay offsets should be small enough to have a small number of wraps across the band, so we should do a delay calibration before starting. We do not need phase-ups, as are used for beamforming, but they can be used to diagnose bad pointing parameters.
- Although there will be some overlap with the single-dish point source list, the interferometric list will be different because
    - With the longer MeerKAT baselines some sources will no longer look like points
    - Confusing sources around some earlier candidate targets may be resolved out, so in many cases weaker sources can be used.
- Each observation needs a large "plus sign" scan around the nominal target position.To adequately get an all-sky fit we will need a *minimum* of 60 points spread fairly evenly in azimuth and elevation. (The area of sky from 15-90 degrees is 4.6 steradians, we

[1] If the beam is *exactly* gaussian the maximum slope is slightly closer to the pointing centre than the half-power point. It is of course not exactly gaussian.
[2] In Synthesis Imaging in Radio Astronomy, Napier quotes FWHM/20, or about 3 arcminutes

should aim at 10-15 points per steradian to get good sky coverage, and provided we have enough points we can use subsets to estimate errors). If we only have points in a small patch of sky we cannot extrapolate to an all sky fit. At best we can find erroneous fits.
- Whenever possible we should use 2 second dumps and 20 seconds per point of the "plus" so that we can get adequate coverage in 2-3 hours. If we only need a check on a currently known pointing don't need 60 points, we just need more than the number of parameters to fit (7). If we use the default 8 second dump rate then each of the ten points making up the "plus" takes about 64 seconds; to get adequate sky coverage would take about 8 hours for a full interferometric pointing if we include time for slews and firing the noise diodes.
- As the output is a simple text file multiple observations can be combined if we find that a pointing model in use is a poor fit.
- We can run the tests in parallel for dishes under test, provided the some have reliable pointing.
- Preferred correlator mode would be 4k, to keep datasets small. 1k channels will also work, but do not use 32k as the datasets get cumbersome for no added benefit.
- A good RFI mask is also needed so that we avoid fitting to interference, which is often much stronger than the celestial sources we want. There is a selection of masks available in the reduction notebook directory.

For estimated errors see https://drive.google.com/?id=0B2-Tk_jh20nhTjFVUV9UbnBfQkE

Applicable and Referenced Documents

Applicable Documents

Single dish pointing (KAT-7 version)

https://docs.google.com/document/d/1zQQp4Ynhb85HtNE6b6Dy8QCfu1YsURYZiyfX_bZkMe8/edit

The procedure for single dish pointing for MeerKAT is identical except that it was found that 2 second dumps were adequate

Referenced Documents

http://www.aoc.nrao.edu/events/synthesis/2006/lectures/TuesdayJune13/Napier.pdf

Synthesis Imaging in Radio Astronomy II, ASP Conference Series, Vol. 180, 1999, G. B. Taylor, C. L. Carilli, and R. A. Perley (eds), p51

Comm Task Title

JIRA ticket link

https://skaafrica.atlassian.net/browse/MKAIV-202

Purpose

1. Refine the pointing model produced by RTS
2. Optimize calibration routines and source lists.
3. Determine appropriate avoidance cone at zenith.
4. Evaluate stability over the full parameter space.
5. Determine maximum wind speeds for accurate pointing.
6. Verify blind pointing accuracy.
7. Verify referenced pointing accuracy.

Observations

Frequency range: 856-1712 MHz
centre frequency: 1284 MHz
Observing script used: */home/kat/katsdpscripts/observation/interferometric_pointing.py*
Source list for L-band: */home/kat/katsdpcatalogues/gaincal_l_5jy.csv*
see the appendix for script details

Two of the sources initially used (0410-752 and 0637-752) were severely resolved for the long baselines (>4km) of MeerKAT but, unfortunately, these were the two furthest to the south, so a region near the South Celestial Pole (azimuth 180°, elevation 30.7° for MeerKAT) is poorly sampled.

Data reduction

jupyter notebooks

http://imgr-com-4.sdp.mkat.chpc.kat.ac.za:8888/tree/Pointing/Interferometric

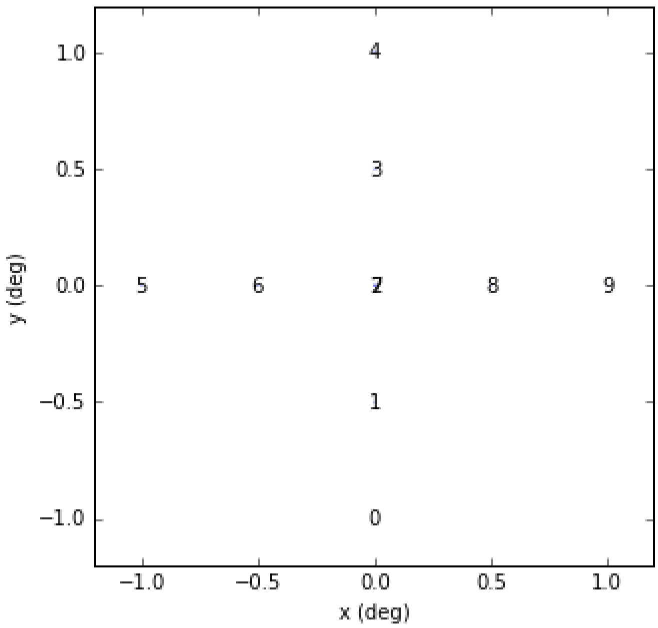
Reduction script used:
/var/kat/katsdpscripts/reduction/analyse_interferometric_pointing.py

Software versions:
Scape version: 0.1.dev616+master.e836eb2
katdal version: 0.10.2.dev826+master.be5c992
katpoint version: 0.8.dev362+master.b075d72
katsdpscripts version: 0.1.dev2870+master.d7e88db

Method

The current method[3] is to have many short pointings in an ‘plus sign’. They alternate between patterns as to which is the initial pointing, but all have repeats to the nominal position (2 and 7 which are superimposed in the plot below). We reduce the data with a *jupyter notebook* (see above), and the output is a comma separated variable (.csv) file for each antenna that was processed and plots of new and old solutions.

[3] There was a previous method which involved scans to make a six-pointed star through the nominal position. The results were as good, but it took much longer to observe and reduce



Pointing diagram for L-band

Given a '.csv' file with the pointing offsets (for many azimuths and elevations) for a given antenna we may then run 'fit_pointing_model.py' interactively in exactly the same way it was done for KAT-7 data, but this is also done in the jupyter notebook for the (typically small) amount of data for that observation.

For UHF point we use a different list of sources (*point_UHF.csv*) and a larger span on the sky (±1.5°) to correspond to the larger primary beam.

Results

The current interferometric pointing system is more liable than the old one for the per-source fits to be bogus, but these can easily be spotted as they will give values many (>20) degrees away from the source, and so cannot possibly be physical. These extremely bad fits have estimated infinite beamwidths (marked 'inf' in the csv file), so they are automatically removed with a *sed* script. Similarly fits without a clear source fit (labelled ' Nothing') are automatically removed. Other bad solutions can usually be spotted in the listing as they give low values of 'valid solutions'. A line for a good solution gives "*16 valid solutions out of 16 for m0..*" at the start, so we must discard lines that give far fewer than 16 solutions for most dishes. These Others can also be removed with other '*sed*' lines for that source and time.

If there is not enough good data in any single pointing observation, it is possible to combine the data by simply concatenating the '.csv' files and removing the header lines after the first one. This will work provided that the pointing of the telescope was stable. There is a simple '*bash*' script to do this (see appendix).

Note that any major work on the dishes (particularly adjusting encoders, changing sub-reflector, major changes to reflector panels, changes in receiver indexer) will need new pointing observations.

Recent results are kept in the configuration files in https://github.com/ska-sa/katconfig/tree/karoo/user/pointing-models/mkat

and some (not so recent) examples are avialable on https://docs.google.com/document/d/10kyRLAADASUNCTKZUaWc7MTCWhgmuByken0-bG5TaLI/edit

Comparison with requirements

One requirement is that after reference pointing we should be able to achieve a pointing accuracy 5 arcseconds under optimal conditions (7 arcseconds under normal conditions), but in order to be close enough to achieve that we need an all-sky blind pointing to about 1 arcminute. The guidelines from the NRAO (HPBW/20) gives us 3 arcminutes. These can be met.

Discussion:

What has and has not been included:

Included:

- Tropospheric refraction model (based on that used by the field system) which can be about 160 arcseconds at 20°elevation for typical site conditions). The model used is the same as the one used by VLBI, which agrees with several other refraction models (astropy, palpy, tpm,SOFA) to within 5 arcseconds down to an elevation of 15°. Their major dependencies are on ground atmospheric pressure and precipitable water vapour (estimated from relative humidity at ground level). The lapse rate has a much smaller effect. Provided these are measured accurately this model should be adequate except when there are major gradients caused by an approaching weather front.
- Tilts caused by differential heating from solar illumination (depending on the weather up to about 50 arcseconds) and wind. However some of these were set up incorrectly before February 2018 (some with scale factor errors, others wired up incorrectly). *The tilt meters are still under active investigation.*

Not included:

- Ionospheric refraction. This is a small effect at the top of the L-band, but should be noticeable at the bottom of the band and **will be needed for UHF.** It can in principle be in any direction (depending on gradients in the ionosphere) but - because the Total Electron Content (TEC) is lower at night the effects should be least then. Conversely at dawn the gradients will be highest. Ionospheric corrections (and a model of the local magnetic field) will be needed in any case to correct for Faraday rotation.
- Diurnal aberration (about 0.3 arcseconds). This is because the current version of katpoint is based on the *ephem* astrometric library (which is no longer being updated and whose accuracy was set to 1 arcsecond). We will probably need this for Ku band observation, so we may need to update to a more recent library, such as *skyfield* or *astropy*, where sub-arcsecond effects are included.

Conclusion/Recommendations

The current interferometric pointing system is adequate for L-band all-sky blind pointing but will need upgrading to be able to cope with Ku-band (diurnal aberration) and UHF band (inclusion of ionosphere).

References:

ALMA memo 366 http://legacy.nrao.edu/alma/memos/html-memos/alma366/memo366.pdf

Appendices:

Observing Scripts:

L-band: assuming 2 second dump rate and for a duration of 14400 seconds

obs.sb.description = "MKAIV-202 Interferometric Pointing Calibration"

obs.sb.instruction_set="run-obs-script /home/kat/katsdpscripts/observation/interferometric_pointing.py '/home/kat/katsdpcatalogues/gaincal_l_5jy.csv' --horizon=20 -t 20 -m 14400"

obs.sb.controlled_resources_spec="cbf,sdp"

obs.sb.proposal_id= "MKAIV-202"

UHF: assuming 2 second dump rate and for a duration of 14400 seconds

obs.sb.description = "MKAIV-202 Interferometric Pointing Calibration"

obs.sb.instruction_set="run-obs-script /home/kat/katsdpscripts/observation/interferometric_pointing.py '/home/kat/katsdpcatalogues/point_UHF.csv' --horizon=20 -t 20 --max-extent=1.5 -m 14400"

obs.sb.controlled_resources_spec="cbf,sdp"

obs.sb.proposal_id= "MKAIV-202"

Names and meanings

Comparing terms in ALMA and MeerKAT pointing; see ALMA memo 366

MeerKAT Name	ALMA name	Correction form	Meaning
P1	IA	ΔAz fixed offset	Azimuth encoder offset
P2			not used
P3	NPAE	ΔAz tan(el)	Non-perpendicularity between Az and El axes
P4	CA	ΔAz sec(el)	Collimation error
P5	AN	ΔAz tan(el)sin(az) ΔEl cos(az)	Az axis offset/misalignment North-South
P6	AW	ΔAz tan(el)cos(az) ΔE sin(az)	Az axis offset/misalignment East-West

P7	IE	ΔEl fixed offset	Elevation encoder offset
P8	ECEC	ΔEl cos(el)	Gravitational flexure correction at horizon

Note that for secondary mirrors there is also (in ALMA terms)
ΔAz1 =IA1 + CA1.sec(el)
ΔEl1 = IE1 + ECEC1.cos(el)

Other terms can be added to account for warps in bearings or scale errors in encoders.

Orders of magnitude

Any of the parameters may be positive or negative, but there is a 'normal' range for each of them

Parameter	Absolute value	Comment
P1	<2 degrees	Largest range
P2	identically zero	not used
P3	<15 arcminute	most < 10 arcmin
P4	<15 arcminute	most < 10 arcmin
P5	<3 arcmin	most < 2 arcmin
P6	<3 arcmin	most < 2 arcmin
P7	<1 degree	most < 30 arcmin
P8	<10 arcmin	most < 2 arcmin

Solutions where the parameters lie outside these ranges may be valid, but should be treated with caution and preferably another pointing observation made to confirm them before changing the configuration files.

Non-orthogonality

Given the limited range in elevations (20-90°) the parameters P1,P3 and P4 are not orthogonal. To a fair approximation you can replace a 'true' P4 with

$P1_{false} = P1_{true} + 0.4213 \times P4_{true}$

$P3_{false} = P3_{true} + 0.9706 \times P4_{true}$

and a true P3 with

$P1_{false} = P1_{true} - 0.4299 \times P3_{true}$

$P4_{false} = P4_{true} + 1.0290 \times P3_{true}$

so a large range in elevations is needed to separate these.

Extra script

to Combine 'csv' files

first parameter is the antenna name 'm0xx'

```
#!/bin/bash
echo "Doing" $1
cat `ls -r 1*${1}.csv` > $1.tmp
cat $1.tmp | gawk '/# ant/&&c++>0 {next} 1' |  gawk '/dataset/&&c++>0 {next} 1' > $1.csv
echo "done" $1.csv
```