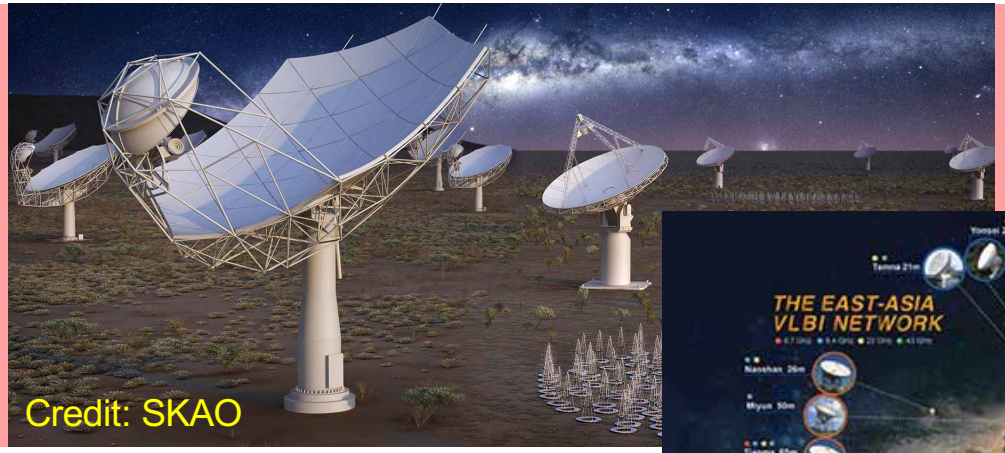
SKA-VLBI Concept



Credit: An, Sohn, Imai et al.2018

SKA-JP
Square Kilometre Array Japanese Consortium

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鹿児島大学 総合教育機構共通教育センター
大学院理工学研究科天の川銀河研究センター

国立大学法人 鹿児島大学 KAGOSHIMA UNIVERSITY

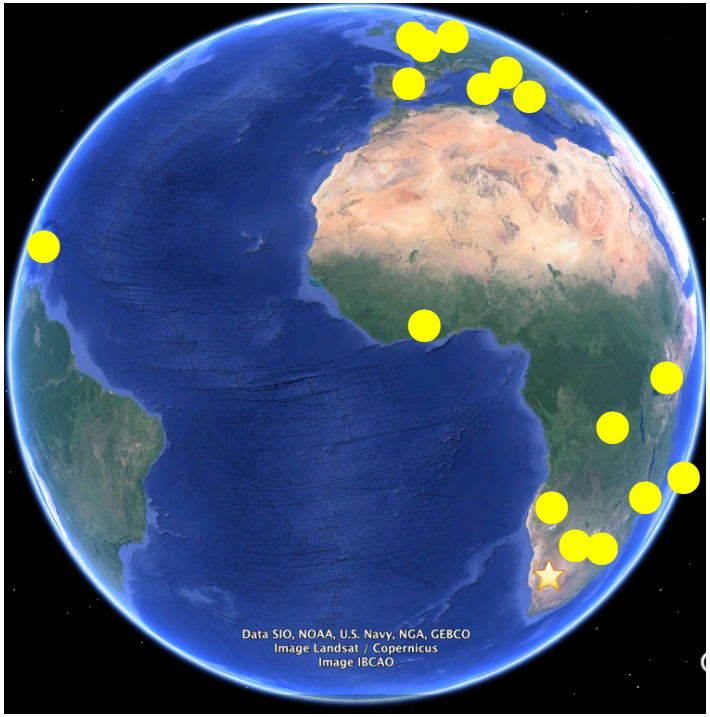
SKA時代のVLBIサイエンス検討会

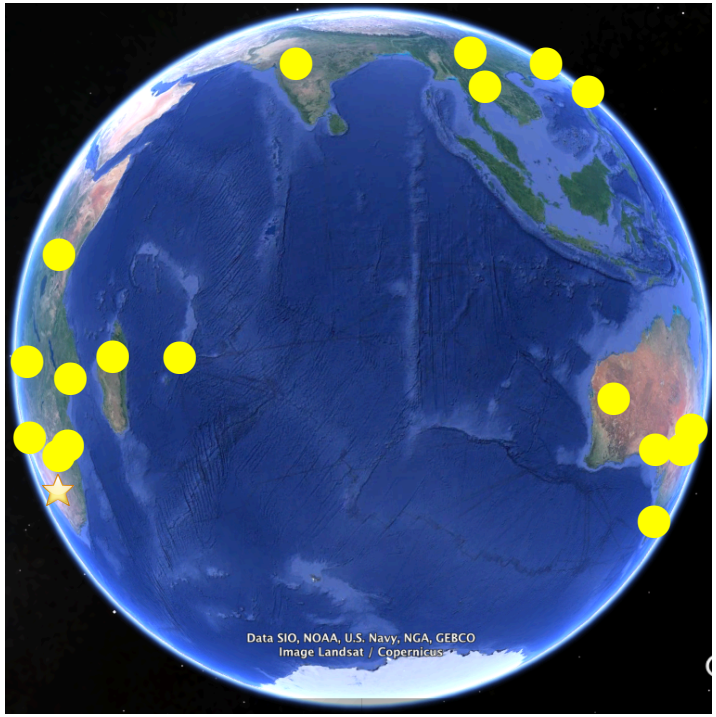
2018年7月22日

SKA-VLBI Concept

❖ SKA2: 最長基線長 2000—3000 km → VLBIそのもの
（光結合された干渉計かも）2030年代後半実現？

❖ **SKA1+VLBI:　2020年代以降現存する**
電波望遠鏡群との組み合わせ





European VLBI Network
African VLBI Network
- **Hartebeethoek, Ghana,**
- **Kenya, Mozanbique**
- **Bostwana, Madagascal**
- **Namibia, Zambia, Mauritius**

Band 1&2 VLBI
(350—1800 MHz)
+ FAST + Arecibo
+ ASKAP + GMRT

SKA-VLBI 仕様参考資料

VLBI懇談会ホームページよりリンクあり

http://www2.nict.go.jp/sts/stmg/vcon/Event/2018/SKA-VLBI/SKA-VLBI-Specification-2018.pdf

SKA-VLBI 性能諸元

2018 年 7 月 9 日

今井 裕（鹿児島大学）、赤堀卓也（国立天文台）、青木貴弘（山口大学）

概要 この文書では SKA 計画の外観をまとめた上で、SKA-VLBI の感度、角度分解能、視野などの性能諸元を示す。末尾には、本検討に用いた情報をまとめる。

1 VLBI素子としての SKA1

❖全アンテナの7割程度 (数km以内)をphase up

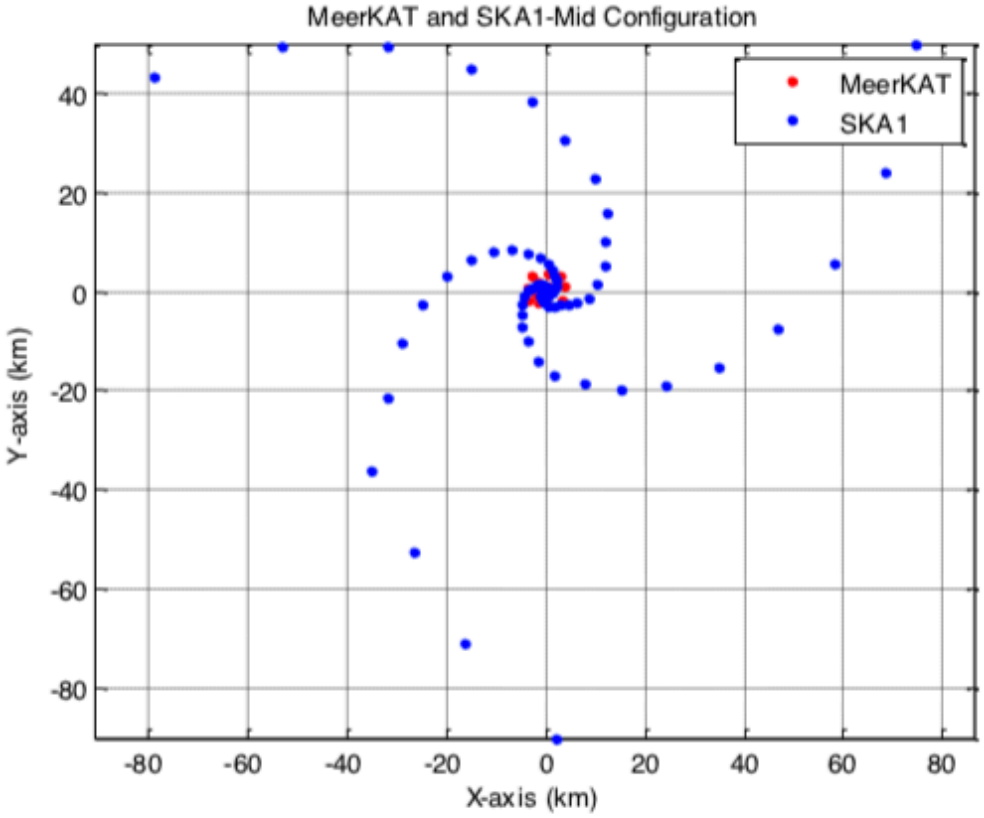


Figure 1 MeerKAT and SKA1_MID Antenna Configuration

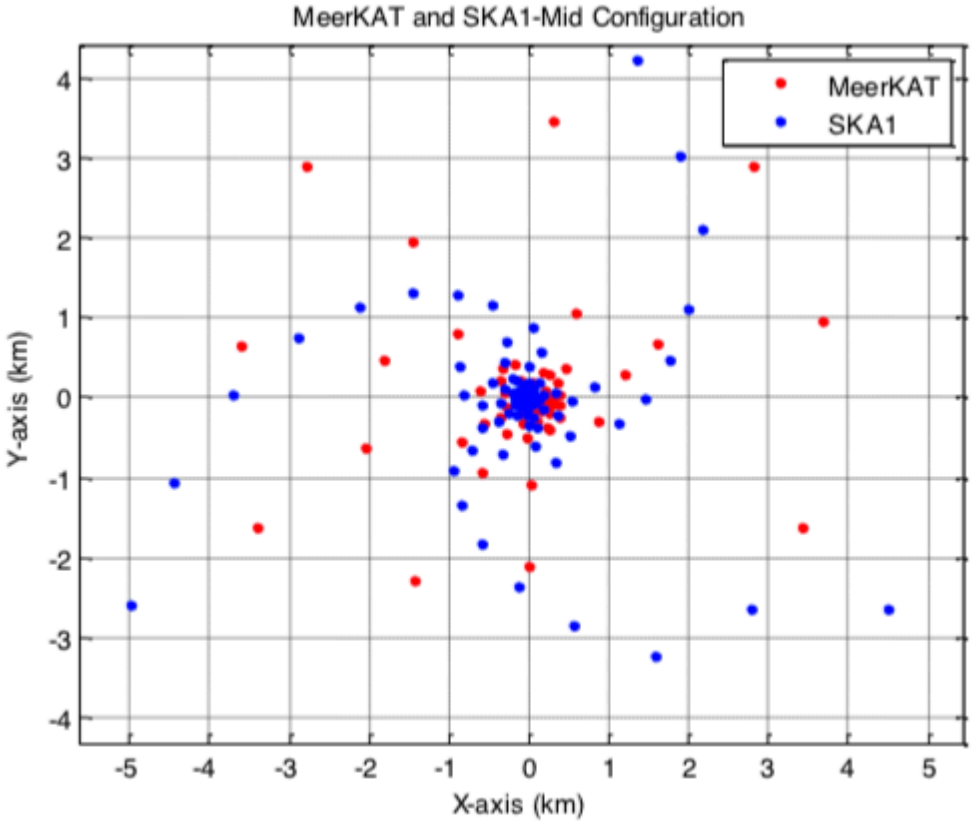
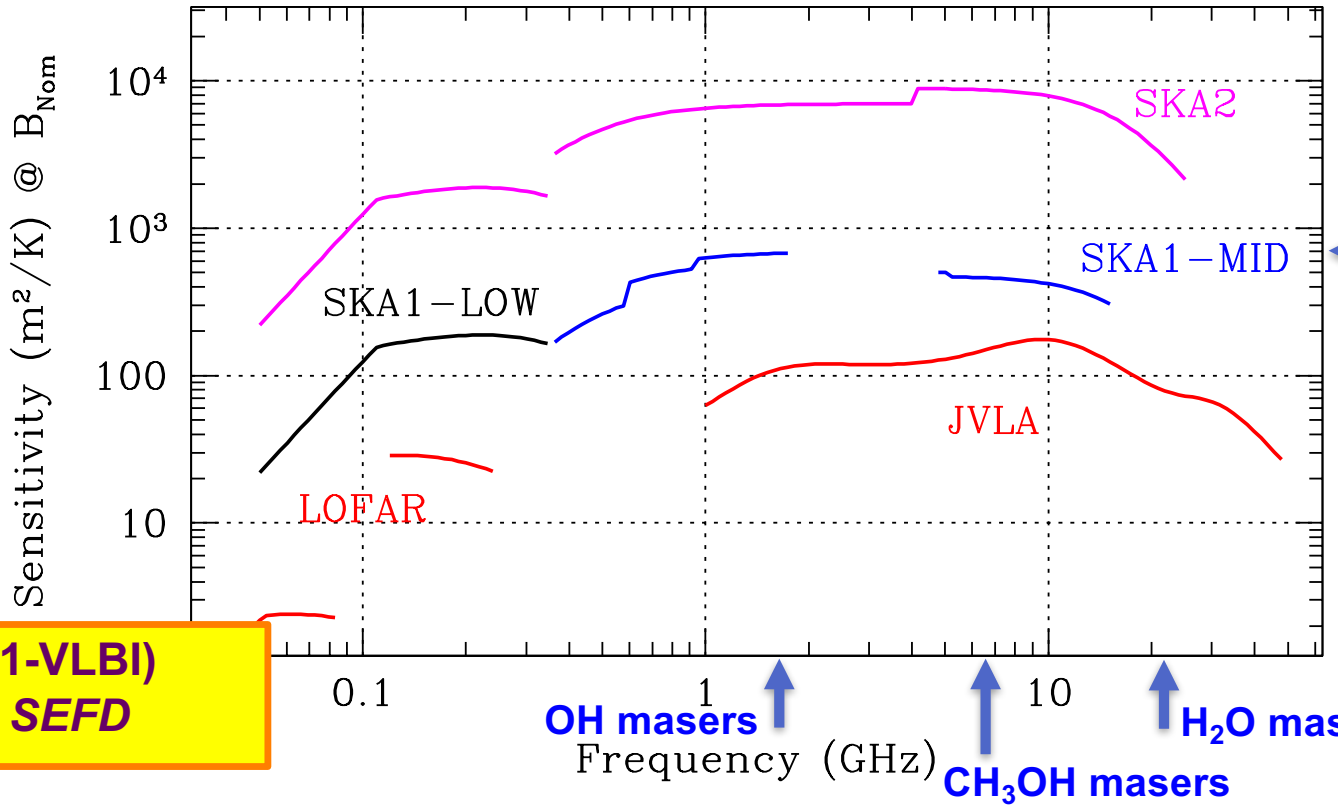


Figure 2 Enlarged MeerKAT and SKA1_MID Configuration

Sensitivity

$$sensitivity \propto \frac{1}{\sigma} \propto \frac{A_{\mathrm{eff}} N_{\mathrm{ant}} \sqrt{\Delta \nu \tau_{\mathrm{int}}}}{T_{\mathrm{sys}}}$$

σ: noise level
T_{sys}: system temperature
A_{eff}: effective antenna aperture
N_{ant}: number of antennas
Δv: band width
τ_{int}: integration time



133 15 m dishes
η_A~ 0.8
T_{sys}~25 K
→ *SEFD*~3.6 Jy

c.f. FAST
~300 m, η_A~ 0.3?
T_{sys}~30 K
→*SEFD*~3.9 Jy

***SEFD* (SKA1-VLBI)**
~ 1/0.7 ✖□ *SEFD* (SKA1)

Baseline sensitivity in SKA1

❖ **Baseline sensitivity (for calibration)**

mJy-level continuum calibrators useful (~10 mJy at present)

$$\sigma_{i,j} = \frac{\sqrt{SEFD_i SEFD_j}}{\sqrt{2\Delta\nu t_{\rm int}}} \approx 63\ [\mu{\rm Jy}] \frac{\sqrt{(SEFD_{\rm core}/5.0\ {\rm Jy})(SEFD_{\rm remote}/40\ {\rm Jy})}}{\sqrt{(\Delta\nu/0.5\ {\rm GHz})(t_{\rm int}/100\ {\rm s})}}$$

c.f. SEFD=40 Jy @Parkes 64-m L-band

Array sensitivity in SKA1

❖ **Image sensitivity for continuum (core-remote baselines only)**

mJy-level continuum calibrators useful (~10 mJy at present)

$$\sigma_{\rm image} \leq \frac{\sigma_{\rm baseline}}{\sqrt{\Delta t / t_{\rm int}}} \approx 7.9\ [\mu{\rm Jy}] \frac{1}{(N_{\rm station}/4)\sqrt{(\Delta\nu/0.5\ {\rm GHz})(\Delta t/400\ {\rm s})}}$$

c.f. SEFD=40 Jy @Parkes 64-m L-band

❖ **Image sensitivity for line (core-remote baselines only)**

10 mJy-level OH masers as astrometry targets (~1 Jy)

$$\sigma_{\rm image} \leq \frac{\sigma_{\rm baseline}}{\sqrt{\Delta t / t_{\rm int}}} \approx 2.4\ [{\rm mJy}] \frac{1}{(N_{\rm station}/4)\sqrt{(\Delta v/1\ {\rm km\ s^{-1}})(\Delta t/400\ {\rm s})}}$$

Baseline and array sensitivity in SKA2 (~10xSKA1)

❖ **Baseline sensitivity (for calibration)**

e.g. *SEFD*(SKA2)~ 0.25 *SEFD* (SKA1)

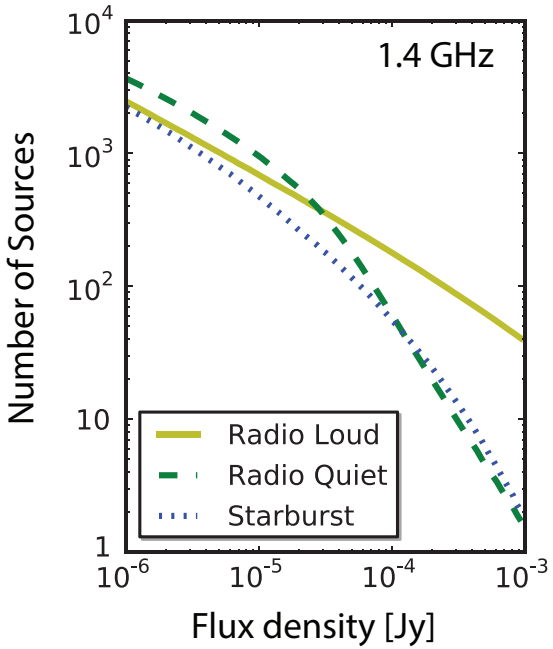
SEFD (SKA2-remote)~ 0.43 *SEFD* (SKA1) (25 remotes)

$$\sigma_{i,j} = \frac{\sqrt{SEFD_i SEFD_j}}{\sqrt{2\Delta\nu t_{\rm int}}} \approx 18\ [\mu{\rm Jy}] \frac{\sqrt{(SEFD_{\rm core}/0.9\ {\rm Jy})(SEFD_{\rm remote}/18\ {\rm Jy})}}{\sqrt{(\Delta\nu/0.5\ {\rm GHz})(t_{\rm int}/100\ {\rm s})}}$$

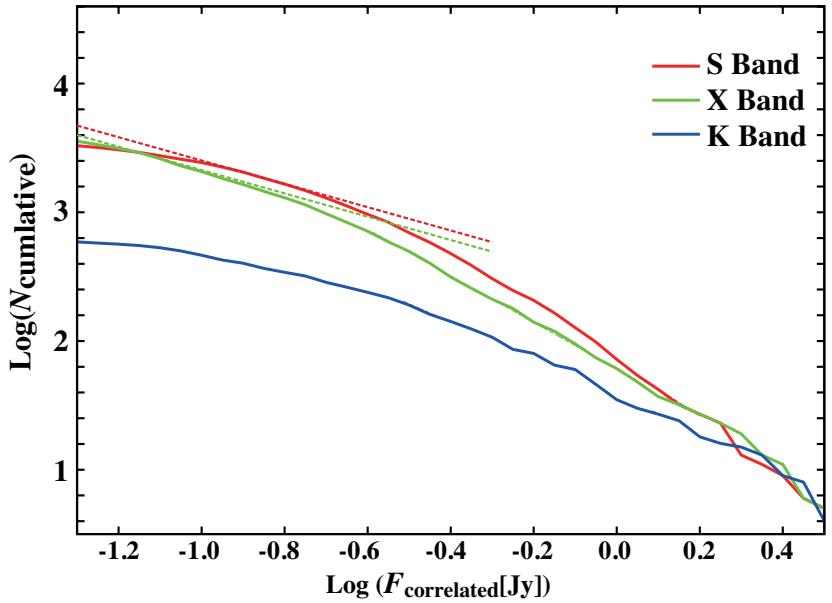
❖ **Image sensitivity (core-remote baselines only)**

$$\sigma_{\rm image} \leq \frac{\sigma_{\rm baseline}}{\sqrt{\Delta t/t_{\rm int}}} \approx 180\ [{\rm nJy}] \frac{1}{(N_{\rm station}/25)\sqrt{(\Delta\nu/0.5\ {\rm GHz})(\Delta t/1600\ {\rm s})}}$$

Increasing radio sources
(including those used as astrometric reference)



Radio sources in FoV (SKA Memo 135)



Total number of references sources on the Sky
(Imai & Orosz et al. 2016)

160 000 calibrators at 2.2 GHz → 2.9 sources/SKA-MID beam
→ for OH masers, pulsars **Multi-beams (in a single FoV)**
130 000 calibrators at 8.4 GHz → 0.05 source/SKA-MID beam
→ for CH_3OH masers **Multi-views (or FoVs)**

SKAアストロメトリ: 位置決定精度

❖ 熱雑音で決まる統計的位置誤差(Moran et al. 1993)

$$\sigma_\theta \approx 0.5\frac{\theta_{\rm beam}}{R_{\rm SN}} \approx 1000\frac{[\lambda/10{\rm cm}]}{[B_{\rm max}/1000{\rm km}][R_{\rm SN}/10]}[\mu{\rm as}]$$

6000 km の基線、波長18cm、信号雑音比300⇒ 誤差10 μas

SKA1の測量対象 (10分積分)
- 1000 mJy 以上のOHメーザー源
- 120 mJy 以上のCH_3OHメーザー(6.7 GHz)源

c.f.
VERAアストロメトリ対象(σ≲100μas)
(H_2Oメーザー源) >5000 mJy

SKA2の測量対象 (10分積分)
- 200 mJy 以上のOHメーザー源
- 24 mJy 以上のCH_3OHメーザー(6.7 GHz)源

SKA1: 1桁増える測量対象
SKA2: 2桁増える測量対象

熱的放射源のアストロメトリもテーマ視野へ (誤差1mas程度から)

Sensitivity of SKA1-VLBI for thermal emission

❖ Continuum sensitivity

10 μJy-level continuum source detectable

$$\sigma_{\rm image} \leq \frac{1\ \mu{\rm Jy}}{(N_{\rm station}/5)\sqrt{(\Delta\nu/0.5\ {\rm GHz})(\Delta t/10000\ {\rm s})}}$$

❖ Image sensitivity (core-remote baselines only)

Stellar winds from OB stars detectable

$$\sigma_T \leq \frac{c^2\sigma_{\rm image}}{2k_{\rm B}\nu^2\theta_{\rm beam}^2} \approx 5000\ {\rm K}\,\frac{\left(\sigma_{\rm image}/1\mu{\rm Jy}\right)(\lambda/18\ {\rm cm})^2}{(\theta_{\rm beam}/10\ {\rm mas})^2}$$

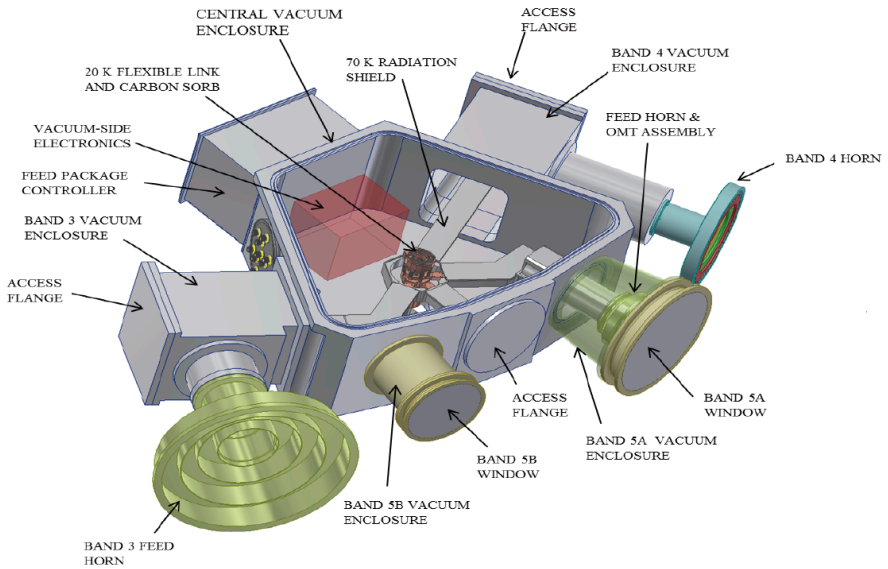
Let's consider to map thermal absorption lines in front of non-thermal sources!

SKA-MID Band 5

❖ **2017年7月時点： PDRの継続 →ΔPDRへ**
- MID Band 2 に比べて優先度が格段と下がっている
- PDR(per-CDRではない)の報告
- Band 3, 4, 5用冷却器： 充分に冷却できないのでは？

5.5.2	Reduce MID Band 5 feeds: A, from 130 to 67	MID	Placement to be determined based on full community consultation.	2

❖ **Band 5 開発参加状況**
- 共同開発の相手
(7/12 by Phil Diamond)
Oxford (UK)、スペイン
- 搭載試験に使用するDISH prototype
中国（2017年10月）
ドイツ@MeerKAT（2018年3月）
- **役割分担交渉が必要**
Band 5 全体について考慮する必要がある



Courtesy of Prof Angela Taylor

日本国内にSKA素子アンテナを持つこと

- Asian-Pacific Telescope (APT)
  - + ASKAP (L-band) +LBA (ATCA, Parkes, …) + Tianma (65 m) + QTT (110m)
  - + FAST (~300 m effective diameter, L-band) + GMRT (30 x 45 m, λ>20 cm)
  - + Thailand VLBI Network
  - 日本が最北東端
- SKA-VLBIと双璧を成す (L帯)
  - 大きく異なるLST（経度）帯 …. SKAと同じ仕様であることに意義がある
- P(350 MHz)帯は？
  - MWA以外のAPT partners?

SKA仕様の受信・信号記録系
→SKAを絡めた多様なVLBI連携

SKA VLBIの検討状況

- SKA1 System Requirements Specification Level 1 revision 11
  (2017年8月）
- SKA1-LOW及びMIDを用いたVLBIの要求仕様
  それぞれ5.1.8章と5.3.5章
- SKA1-CSPにおけるbeam forming
- SKA1-DSPにおけるdata buffer →仕様は不明, VDIF準拠
- 相関処理はJIVEで？

ひとまずここまで

SKA-JP
Square Kilometre Array
Japanese Consortium

SKA-VLBI Concept

SKA時代のVLBIサイエンス検討会　2018年7月22日

SKA1_LOW tied array beamforming

❖SKA1-SYS_REQ-3540 Coherence of SKA1_Low tied-array beams

SKA1_Low shall form pulsar search, pulsar timing, and VLBI tied-array beams that each have a coherence within 5% of that allowed by the current atmospheric conditions.

SKA1_LOW VLBI

❖SKA1-SYS_REQ-3578 SKA1_Low VLBI time stamping

Each SKA1_Low VLBI data sample shall be directly traceable to the time at the common delay centre of the SKA1_Low telescope, with an accuracy of better than 2 nanoseconds.

❖SKA1-SYS_REQ-3579 SKA1_Low S/N Performance

The SKA1_Low, when forming VLBI beams, shall have a signal-to-noise performance better than 90% of that achievable by an ideal signal chain, given the same inputs, instrumental calibration and excluding RFI.

SKA1_LOW VLBI

❖ SKA1-SYS_REQ-3580 SKA1_Low VLBI beams sampling rate

SKA1_Low, when forming VLBI beams, shall output them with a sampling rate selectable between Nyquist and at least a factor of two oversampling for the selected bandwidth.

❖ SKA1-SYS_REQ-3581 SKA1_Low Beamforming weights

SKA1_Low shall weight the Field Station beams, which are inputs into the VLBI tied-array sums, based on relative sensitivity and coherence losses.

❖ SKA1-SYS_REQ-3582 SKA1_Low Configurability

SKA1_Low, when commanded, shall change the pointing, centre frequency, and bandwidth of each VLBI tied-array beam independently, on scan boundaries.

SKA1_LOW VLBI

❖ **SKA1-SYS_REQ-3583 Independently configurable beams**

SKA1_Low shall provide, through configuration, 1, 2, 3, or 4 separate VLBI specific beams, each with independently selectable centre frequency, bandwidth, frequency resolution and pointing.

❖ **SKA1-SYS_REQ-3584 SKA1_Low VLBI configurability**

SKA1_Low shall, reconfigure the centre frequency, frequency band, and bandwidth for each VLBI beam, in less than 30 seconds.

❖ **SKA1-SYS_REQ-3585 SKA1_Low VLBI spectral resolution**

SKA1_Low shall generate VLBI beams with a spectral resolution different from the spectral resolution used for imaging within the same subarray.

❖ **SKA1-SYS_REQ-3586 SKA1_Low VLBI channel width**

SKA1_Low shall be able to generate VLBI beam data with a selectable channel width of: 256, 128, 64, 32, 16, 8, 4, 2, or 1 MHz TBC.

SKA1_LOW VLBI

❖SKA1-SYS_REQ-3587 SKA1_Low VLBI imaging and beamforming

SKA1_Low shall simultaneously generate both VLBI beams and SKA1_Low imaging data for all polarization products and all baselines (including autocorrelations) with a spectral resolution no worse than 1 MHz, covering at least the larger of 100 MHz TBC or the frequency range(s) covered by the VLBI beam(s) within the associated subarray.

❖SKA1-SYS_REQ-3588 SKA1_Low VLBI out-of-channel rejection

SKA1_Low shall generate VLBI beams with a transition band that is monotonically decreasing from -3dB at the channel edge, to -60dB at a frequency offset from the centre frequency by the channel bandwidth.

❖SKA1-SYS_REQ-3589 SKA1_Low VLBI beams and subarrays

SKA1_Low shall be able to allocate individual VLBI beams to different subarrays.

❖SKA1-SYS_REQ-3590 SKA1_Low VLBI reference position

The SKA1_Low VLBI array phase centre shall be within 100km (TBC) of one of the SKA1_Low stations.

SKA1_LOW VLBI

❖ SKA1-SYS_REQ-3591 SKA1_Low VLBI: spectral purity

Spectral distortion, after calibration, for SKA1_Low VLBI shall be below:
-30dB in amplitude, 0.01 radians in phase.

❖ SKA1-SYS_REQ-3606 SKA1_Low VLBI number of beams

The SKA1_Low correlator shall have the capability of producing 4 dual polarisation tied-array VLBI beams TBC for one SKA1_Low sub-array.

❖ SKA1-SYS_REQ-3607 SKA1_Low VLBI array diameter

The SKA1_Low correlator shall be capable of forming 4 beams TBC across all stations within the VLBI sub-array to a distance of up to 100,000 TBC metres from the sub-array centre.

❖ SKA1-SYS_REQ-3608 SKA1_Low VLBI beam centre frequency

The SKA1_Low VLBI beams shall have a centre frequency selectable anywhere within the SKA1_Low observing band.

❖ SKA1-SYS_REQ-3609 SKA1_Low VLBI beam bandwidth

The SKA1_Low VLBI beams shall have a contiguous processing bandwidth up to the full bandwidth of the SKA1_Low array.

SKA1-SYS_REQ-2968 SKA1_Mid zoom windows

- **Maximum zoom window bandwidtgh: 256 MHz + 35%**
- **Zoom windows configurable: 1, 1/2, 1/4, 1/8, 1/16, 1/32 or 1/64**
- **14000—16384 linearly spaced frequency channels**

- **Dependent on other simultaneous observation allocations**
  - Standard imaging: bandwidth 5 GHz
  - 1500 pulsar search beams
  - 8 pulsar timing beams with 2.4 GHz
  - 4 VLBI beams with 2.4 GHz

ECP-170017 (CSP Mid.CBF) 1/2

Correlator and Beam Former 中の Frequency Slice Architecture (FSA) が実現する同時処理モード:
バンド数・モード数・subarray数・処理帯域幅の組み合わせの例

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	5	5000.0	0	0	0.0	0		

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	2	810.0	8	1500	810.0	16		
2	5	2500.0						

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	5	0.0	26					

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	2	810.0	3	1500	810.0	16	810.0	2

VLBI BF単独の場合：BW=2500 MHz, 4 beams

SKA-JP
Square Kilometre Array
Japanese Consortium

ECP-170017 (CSP Mid.CBF) 2/2

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	5	5000.0						
2	1	700.0	22					
3	2	810.0	21					
4	3	1400.0	19					
5	4	2380.0	14					

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams	Subarray N_imag_FSPs	Subarray N_PSS_FSPs	Subarray N_PST_FSPs	Subarray N_VLBI_FSPs
1	1	700.0	5	500	700.0	4	600.0	2	9	2.604	4	3
2	2	810.0	5	1000	810.0	4	600.0	2	10	5.208	5	3
3	3	1400.0	3						10	0.000	0	0
4	5	2000.0			1000.0	4			10	0.000	5	0
5	5	2000.0			1000.0	4			10	0.000	5	0
6	5	2000.0					600.0	2	10	0.000	0	3
7	5	2000.0					600.0	2	10	0.000	0	3
8	5	1000.0	5						10	0.000	0	0
9	4	2000.0							10	0.000	0	0
10	4	2000.0							10	0.000	0	0
11	4	2000.0							10	0.000	0	0
12	3		10				600.0	2	10	0.000	0	3
13	3		10				600.0	2	10	0.000	0	3
14	3		10				600.0	2	10	0.000	0	3
15	2		10						10	0.000	0	0
16	2		10						10	0.000	0	0
						16			Note: Total number of PST beams can't exceed 16--the PST sub-element limit			
				1500					Note: Total number of PSS beams can't exceed 1500--the PSS sub-element limit			

ECP-170017 (CSP Mid.CBF) 1/2

Correlator and Beam Former 中の Frequency Slice Architecture (FSA) が実現する同時処理モード:
バンド数・モード数・subarray数・処理帯域幅の組み合わせの例

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	5	5000.0	0	0	0.0	0		

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	2	810.0	8	1500	810.0	16		
2	5	2500.0						

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	5	0.0	26					

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	2	810.0	3	1500	810.0	16	810.0	2

VLBI Band 5 BF単独の場合： BW=2500 MHz, 4 beams

SKA1_MID VLBI

❖ SKA1-SYS_REQ-3292 SKA1_Mid VLBI time stamping

Each SKA1_Mid VLBI data sample shall be directly traceable to the time at the common delay centre of the SKA1_Mid telescope, with an accuracy of better than 2 nanoseconds.

❖ SKA1-SYS_REQ-2689 SKA1_Mid VLBI number of beams

SKA1_Mid shall produce a total of up to four VLBI beams, spread across one or more subarrays.

❖ SKA1-SYS_REQ-2759 SKA1_Mid VLBI: beamforming

SKA1_Mid, when commanded, shall generate VLBI beams from any or all receptors within a subarray which are separated by at most 100km.

❖ SKA1-SYS_REQ-2762 SKA1_Mid S/N Performance

The SKA1_Mid, when forming VLBI beams, shall have a signal-to-noise performance better than 90% of that achievable by an ideal signal chain, given the same inputs, instrumental calibration and excluding RFI.

SKA1_MID VLBI

❖ SKA1-SYS_REQ-2849 SKA1_Mid VLBI beams sampling rate

SKA1_Mid, when forming VLBI beams, shall output them with a sampling rate selectable between Nyquist and at least a factor of two oversampling for the selected bandwidth.

❖ SKA1-SYS_REQ-2851 SKA1_Mid Beamforming weights

SKA1_Mid shall weight the dish inputs into the VLBI tied-array sums based on relative sensitivity and coherence losses.

❖ SKA1-SYS_REQ-2852 SKA1_Mid Configurability

SKA1_Mid, when commanded, shall change the pointing, centre frequency, and bandwidth of each VLBI tied-array beam independently, on scan boundaries.

SKA1_MID VLBI

❖ **SKA1-SYS_REQ-2853 Independently configurable beams**

SKA1_Mid shall form up to at least 4 separate VLBI tied- array beams up to a beams-bandwidth product of 10 GHz, distributed across one or more subarrays, each beam having independently configurable sky coordinates.

❖ **SKA1-SYS_REQ-2854 SKA1_Mid VLBI configurability**

SKA1_Mid shall, reconfigure the centre frequency, frequency band, and bandwidth for each VLBI beam, in less than 30 seconds.

❖ **SKA1-SYS_REQ-2855 SKA1_Mid VLBI spectral resolution**

SKA1_Mid shall generate VLBI beams with a spectral resolution different from the spectral resolution used for imaging within the same subarray.

❖ **SKA1-SYS_REQ-2856 beam channel sampled bandwidth**

SKA1_Mid shall generate VLBI beam channel data with a selectable channel width of: 128, 64, 32, 16, 8, 4, 2, 1 MHz, or a single wideband option, with channel width greater than (128 + 2n + 2m MHz) and less than or equal to 512MHz. Where n and m are non-negative integers.

SKA1_MID VLBI

❖SKA1-SYS_REQ-2857 SKA1_Mid VLBI imaging and beamforming

SKA1_Mid, when commanded, shall simultaneously generate both VLBI beams and VLBI imaging data for the same subarray. VLBI imaging data shall include all polarization products and all baselines (including autocorrelations), with a spectral resolution no worse than 1 MHz, covering a bandwidth of at least 100 MHz, and spanning the full frequency range(s) covered by the VLBI beam(s) generated within the same subarray.

❖SKA1-SYS_REQ-2859 SKA1_Mid VLBI out-of-channel rejection

SKA1_Mid shall generate VLBI beams with a transition band that is monotonically decreasing from -3dB at the channel edge, to -60dB at a frequency offset from the centre frequency by the channel bandwidth.

❖SKA1-SYS_REQ-3469 SKA1_Mid VLBI reference position

The SKA1_Mid VLBI array phase centre shall be within 100km of one of the SKA1_Mid stations.

SKA1_MID VLBI

❖ **SKA1-SYS_REQ-3474 SKA1_Mid VLBI: spectral purity**

Spectral distortion, after calibration, for SKA1_Mid VLBI shall be below:

-30dB in amplitude, 0.01 radians in phase.

SKA1_MID VLBI

❖ **SKA1-SYS_REQ-2760 SKA1_Mid VLBI beam centre frequency**

For each VLBI beam, SKA1_Mid shall tune the centre frequencies of each of its derived beam channels independently with:

1. **1. Beam channels of 128 MHz bandwidth or less, to an accuracy of 0.01 MHz or better, such that their bandwidth falls entirely within the fixed boundaries of beam channels greater than 128 MHz.**
2. **2. Beam channels of greater than 128 MHz bandwidth having fixed offset centre frequencies within the processed bandwidth of the observing Band.**

※ Mark 5 recorder limiting to the bandwidth of 512 MHz.

❖ **SKA1-SYS_REQ-2761 SKA1_Mid VLBI beam bandwidth**

The bandwidth for each SKA1_Mid VLBI beam shall be independently configurable, with a contiguous processing bandwidth up to the full bandwidth of the selected Band. For Band 5 this applies to each of the two 2.5 GHz streams, and not across streams -- that is, a single Band 5 VLBI beam can produce two 2.5 GHz -wide outputs.