

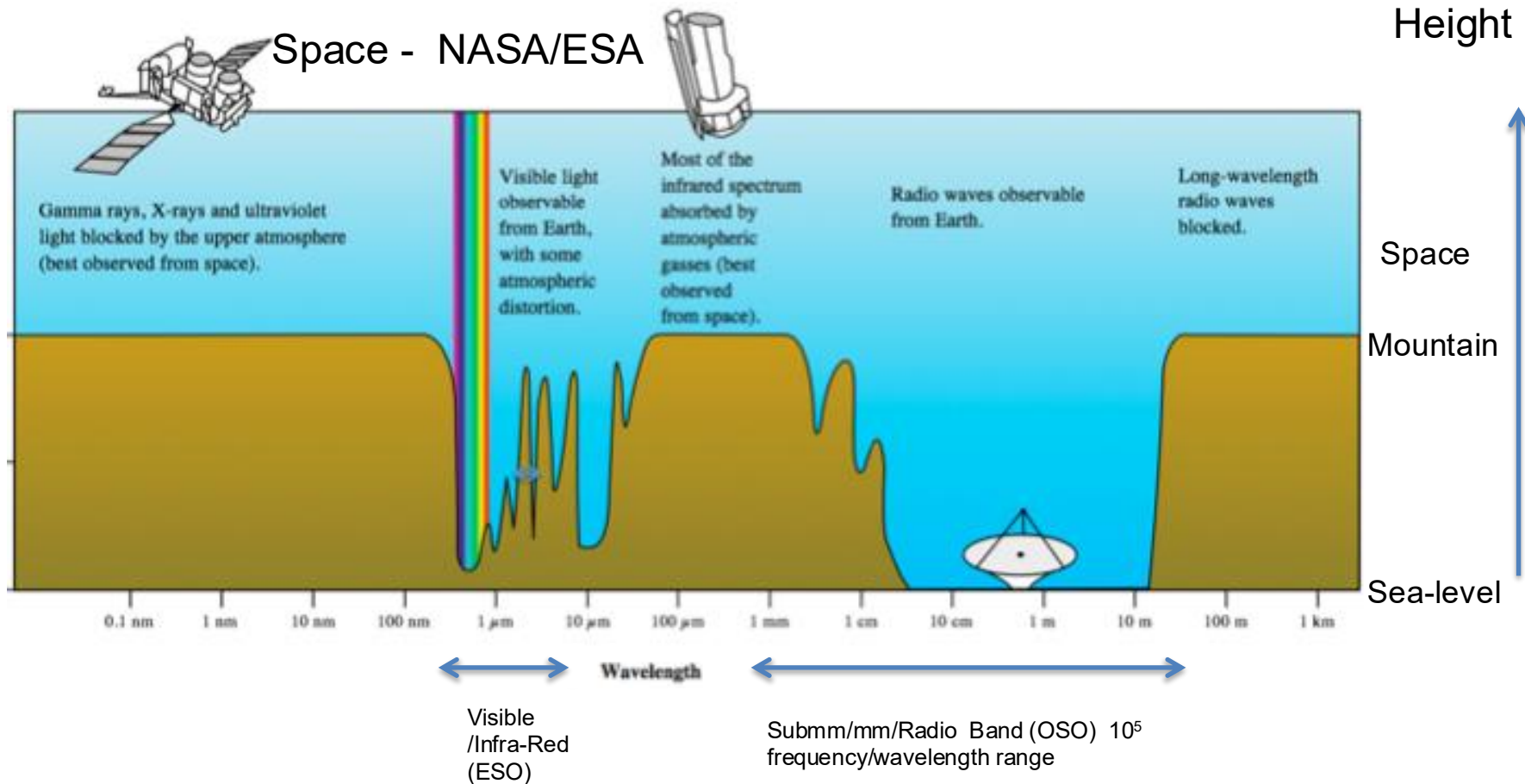
Onsala Space Observatory

John Conway



RÅG-B Visit to OSO - 2026-09-24

OSO - Radio/mm Astronomy Mission

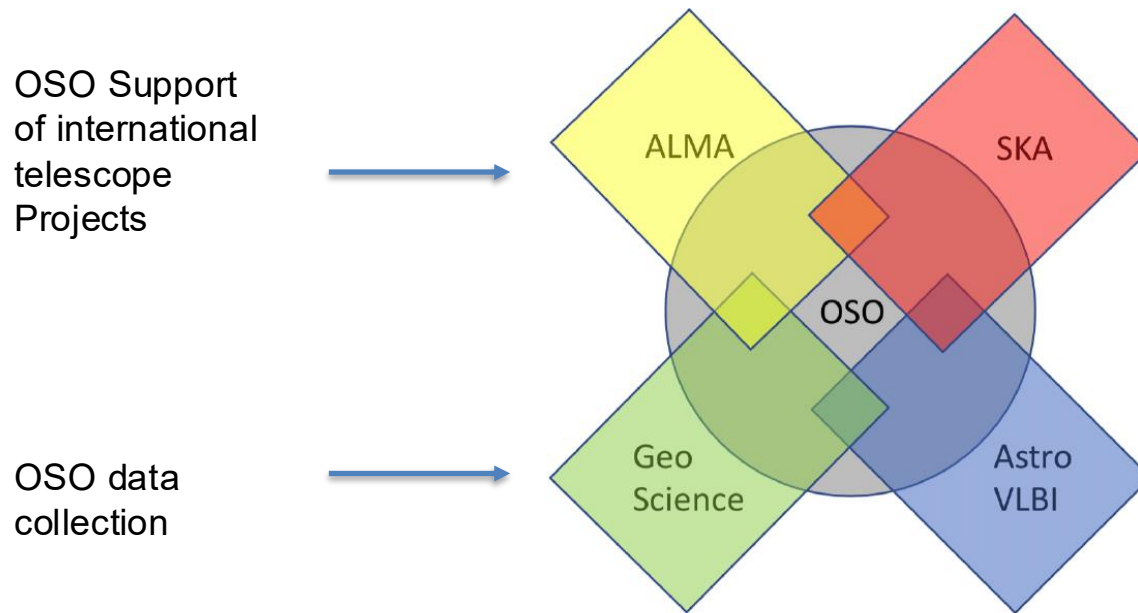


OSO mission in astronomy to support Swedish astronomer use of the radio window (mm, cm, m wavelengths) - funded by VR and Chalmers.

OSO Geoscience mission in Space Geodesy measuring shape/orientation of Earth (using radio astronomy techniques) - funded by Lantmäteriet. Will spend less time on this since not VR funded but of high impact and importance and synergy with astronomy activities is vital.

Part 1 - OSO radio astronomy telescopes and geoscience instruments

OSO Infrastructure Strategy



Four OSO strategy cornerstones. 3 for Astronomy (financed by VR + Chalmers) + 1 for Geoscience (financed by Lantmäteriet). Each cornerstone supports the others via numerous scientific and technical links.

Note - Other smaller but important OSO goals include: single dish/station observations, working toward new space-based radio astronomy projects (similar but larger than past Odin), and public Outreach.

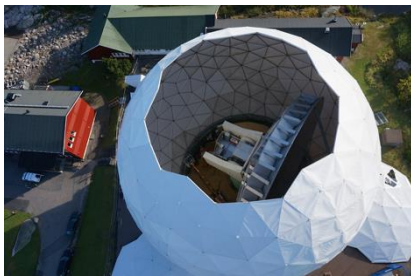
OSO National Facility Telescopes



25m telescope cm



Onsala Twin Telescope (OTT)
cm-geo



20m telescope cm/mm wave

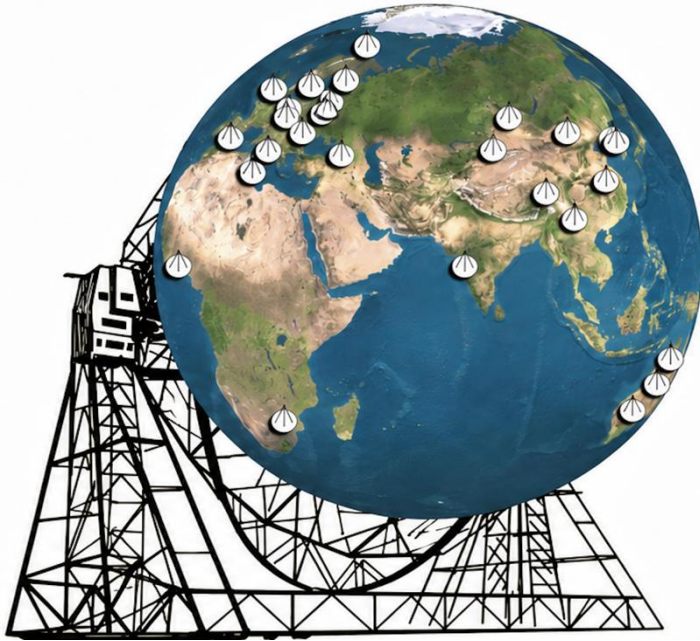


APEX in Chile –
mm/sub-mm -wave



LOFAR station – m -wave

VLBI Onsala creates a global radio telescope - 1968

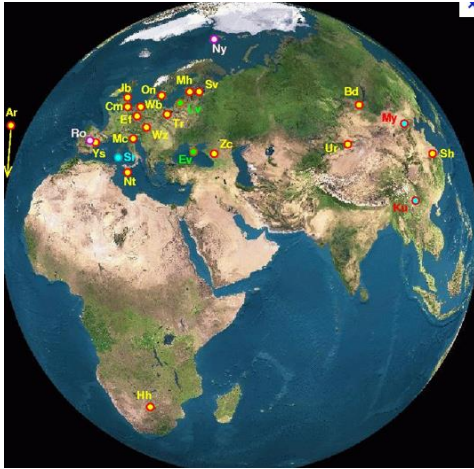


Very Long Baseline Interferometry (VLBI) – technique that combines signals to form a virtual radio telescope the size of the Earth - Allows very sharp images + Also gives location of telescopes to up to mm accuracy

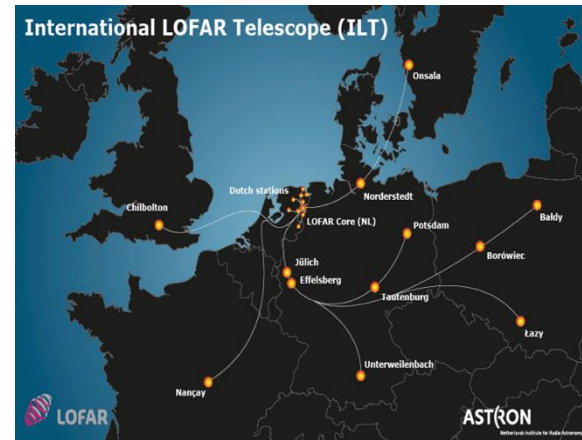
Control room of 25 m telescope Onsala in 1968. First Transatlantic VLBI to Westford Massachusetts

Today OSO's telescopes take part in state-of-the-art **mm**, **cm** and **m** wave VLBI, made more sensitive by inclusion of the huge ALMA and (in future) SKA arrays

Astro VLBI Cornerstone - VLBI telescope networks from mm to metre wavelengths with Onsala telescope participation



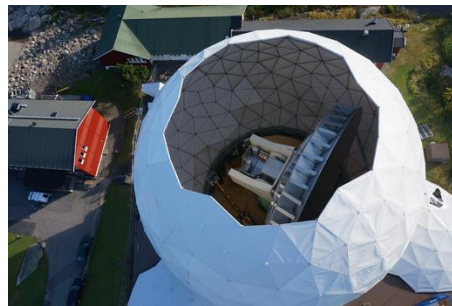
European VLBI Network milliarcsecond resolution at cm wavelengths



European LOFAR Network at metre wave



OSO 25m dish (cm- wave)

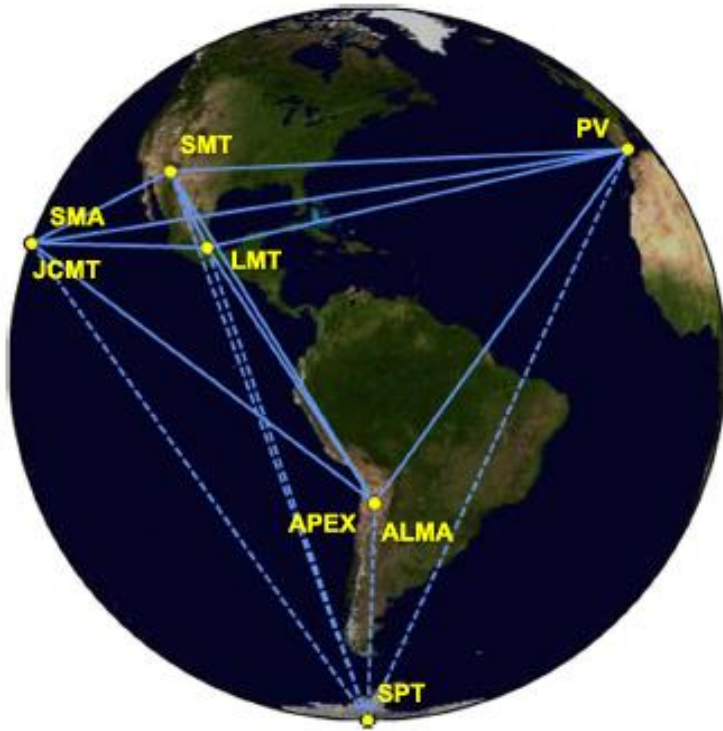


OSO 20m (cm+mm)



OSO LOFAR station (m-wave)

VLBI at mm wavelengths - Event Horizon Telescope for black hole imaging - observing 1.3 mm wavelength

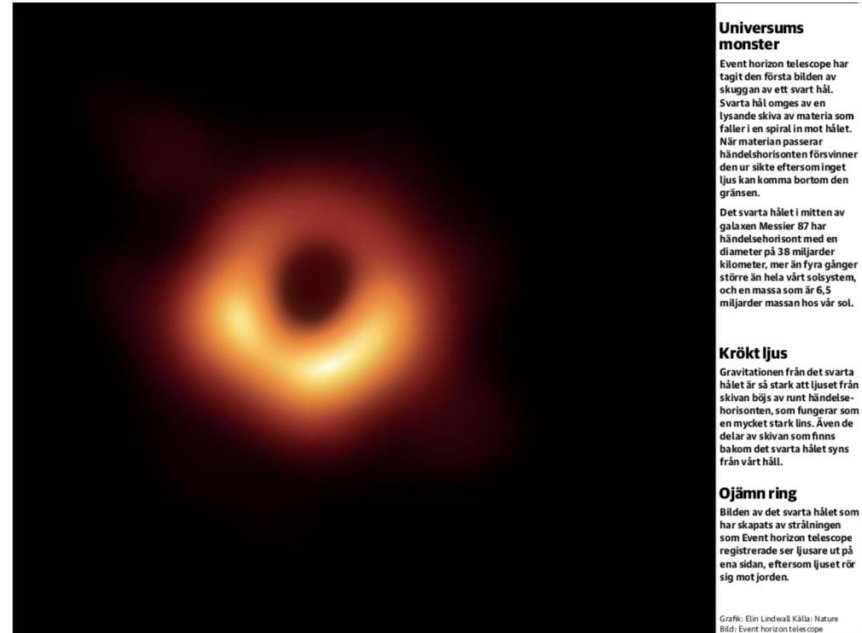


Black hole images made with a **virtual radio telescope** the size of the Earth – formed from connecting dishes



Used the APEX radio telescope in Chile, in which Onsala is a partner. Operates at 1 mm wavelength and is located at 5000 m altitude in the Atacama desert.

Rymden.

 $42 \pm 3 \mu \text{ arcsec}$ 

Universums monster

Event horizon telescope har tagit den första bilden av skuggan av ett svart hål. Svarta hål omges av en lysande skiva av materia som faller i en spiral in mot hålet. När materian passerar händelsehorisonten försvinner den ur sikte eftersom inget ljus kan komma bortom den gränsen.

Det svarta hålet i mitten av galaxen Messier 87 har händelsehorisont med en diameter på 38 miljarder kilometer, mer än fyra gånger större än hela vårt solsystem, och en massa som är 6,5 miljarder massan hos vår sol.

Krökt ljus

Gravitationen från det svarta hålet är så stark att ljuset från skivan böjs av runt händelsehorisonten, som fungerar som en mycket stark lins. Även de delar av skivan som finns bakom det svarta hålet syns från vårt håll.

Ojämn ring

Bilden av det svarta hålet som har skapats av strålningen som Event horizon telescope registrerade ser ljusare ut på ena sidan, eftersom ljuset rör sig mot jorden.

Grafik: Elin Lindwall Källa: Nature
Bild: Event horizon telescope

Den suddiga bilden är bara början

Bilden från Event horizon telescope, EHT, föreställer inte Sagittarius A* utan det svarta hålet i mitten av galaxen Messier 87, 55 miljoner ljusår bort i Jungfruns stjärnbild. Men EHT har även samlat data från Sagittarius A* och det är troligt att de snart också kommer att presentera en bild därifrån.

Att svarta hål existerar är en förutsägelse av den allmänna relativitetsteori, Albert Einsteins teori om gravitationen från 1915. Enligt teorin kan det finnas områden i rymden med så stark dragningskraft att ingenting, inte ens ljuset, kan lämna dem. Gränsen runt hålet kallas för händelsehorisonten, eller event horizon på engelska. Allt som

och starkt lysande skiva innan den antingen sugs in i hålet eller slungas i väg i två smala strålar.

Gravitationskraften från ett svart hål är så stark att den böjer hela rumtiden omkring sig. Den fungerar som en kraftig lins, så att även den del av den lysande skivan som finns bakom det svarta hålet kommer att synas från vårt håll, eftersom ljuset från den böjs av. "Det går inte att glömma sig bakom ett svart hål", som Event horizon telescopes ledare Shep Doeleman uttryckte det när DN pratade med honom för två år sedan.

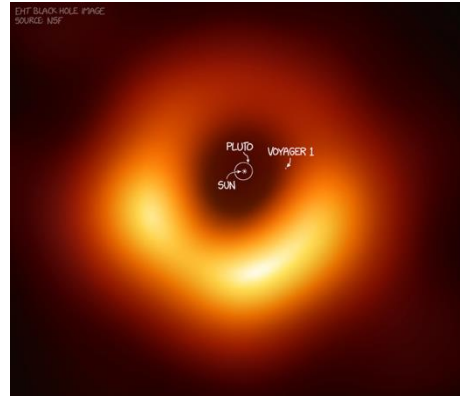
Alla tidigare illustrationer av svarta hål och området runt dem grundar sig på beräkningar utifrån den allmänna relativitetsteorins

2019 Svenska Dagbladet – 'This fuzzy image is only the beginning'
...describing the highest resolution astronomy observation ever made...
For comparison $1 \mu \text{ arcsec}$ equals about 1 m at the distance of Mars

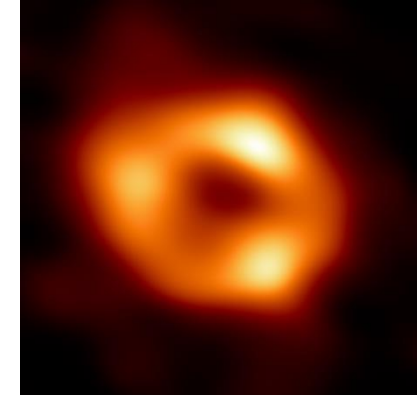
Black Hole Imaging with mm VLBI



Event Horizon Telescope (EHT)
including APEX in Chile (see below)



M87 galaxy Black
hole image - April
2019



Galactic centre Black
hole image -May
2022

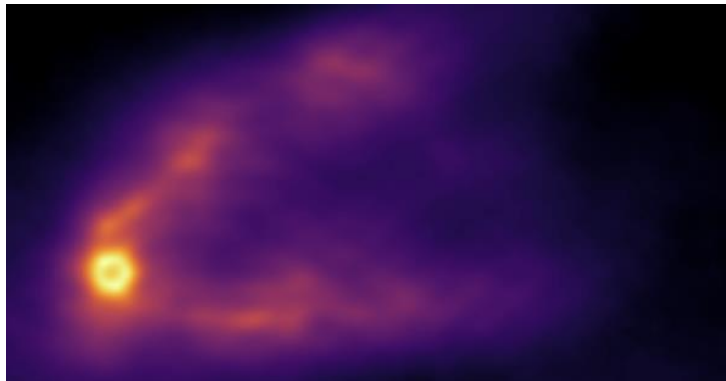


Chalmers EHT consortium members 2022 – John
Conway, Michael Lindqvist, Chiara Ceccobello

The Onsala 20 m telescope joins the fun

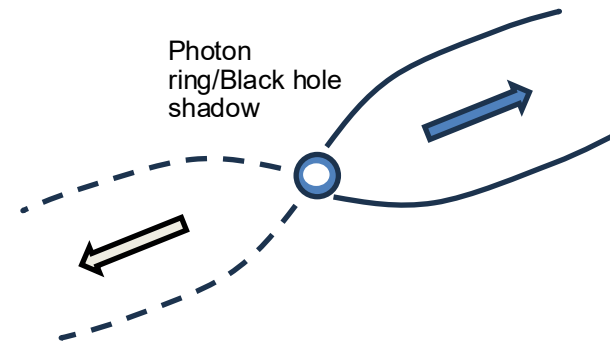


Data were observed using a global VLBI network (GMVA) including the Onsala 20m telescope. at **3 mm** wavelength



Kim et al 2025

First image of Black hole ring connecting to and launching a relativistic jet in the nucleus of galaxy M87- Observations at 3mm wavelength.



Relativistic jet
point away from
us

Weak

Relativistic jet
pointing toward us

Bright

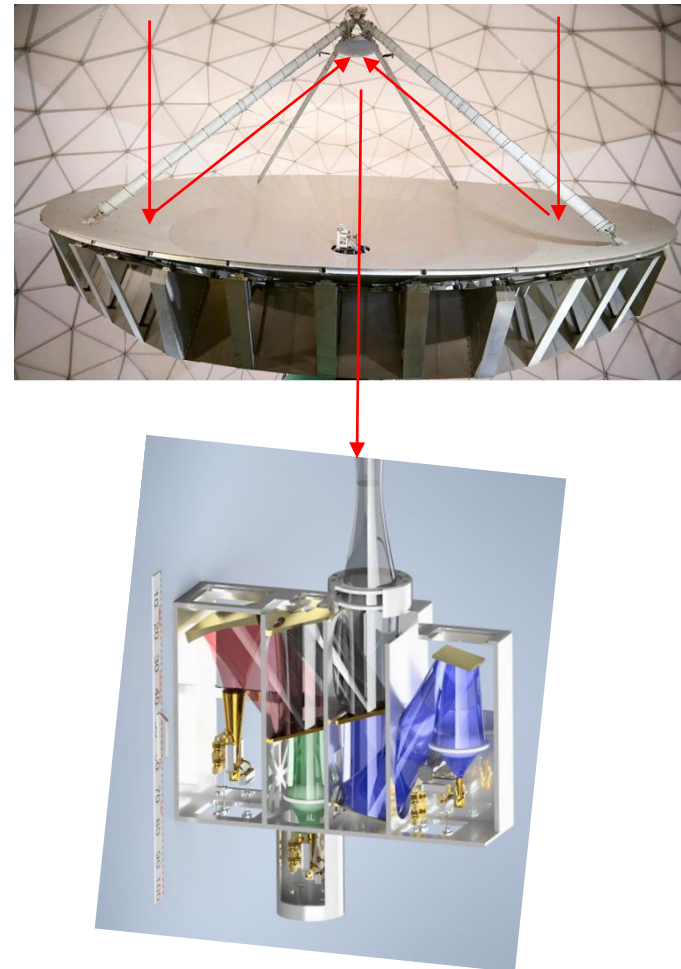
New Triband camera Project – part of VR successful VR 2027-2030 infrastructure proposal – secured via additional financing (13 Mkr) from Hasselblad Foundation.

The Triband camera will be placed in the 20 m telescope's 'focus cabin' room located just below the dish surface.

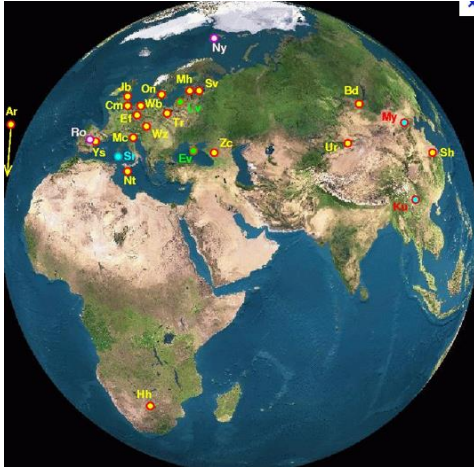
The three-band camera separates the radio light concentrated by the dish into three wavelengths i.e. 3 mm (blue), 7 mm (green) and 13 mm (red) using a pair of 'two-way' mirrors.

Three colours allows for correction of atmosphere effects equivalent to moving telescope to 2300 m altitude. → More sensitive colour movies of black hole accretion and jet formation, and many other targets (like forming massive stars).

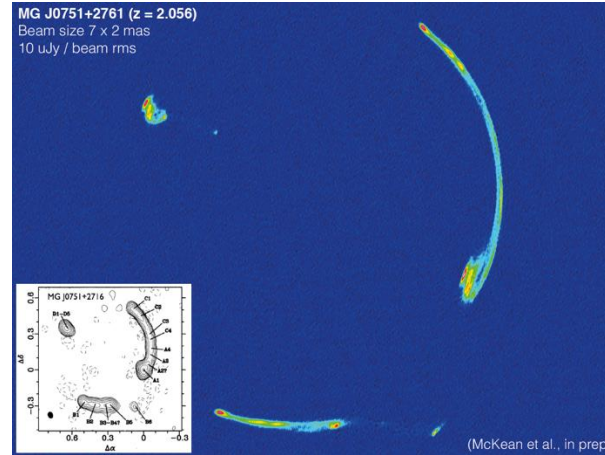
Although the 20 m telescope is 50 yrs old, metal doesn't stop reflecting... what matters is the state-of-the-art instrumentation installed at the telescope focus.



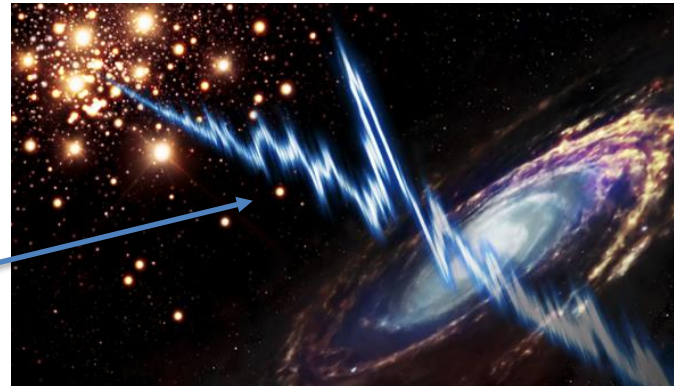
Centimetre VLBI Results



European VLBI Network (EVN)



Gravitational Lens Observations



An artist's depiction of fast radio bursts coming from galaxy M81. (Image credit: Chalmers University of Technology/Daniëlle Futselaar, artsource.nl)

Fast Radio Bursts - Mysterious flashes of radio radiation lasting < 10 ms – first precise location and identification to a galaxy at $z=0.3$ – Involving Onsala 25m telescope were made in 2017. Recent detection and precise location using VLBI of the nearest FRB in galaxy M81 – led by Chalmers PI Kirsten et al 2022

SKA will revolutionize cm –VLBI

- The breakthrough allowing Black Hole imaging via 1.3 mm and 3mm wavelength VLBI was made possible by the addition of ALMA as a huge sensitive anchor station.
- The creation of SKA-mid in South Africa as similar anchor station at 2cm – 30 cm wavelength is expected to similarly revolutionize cm wavelength VLBI, increasing sensitivity for i.e. Fast Radio Burst, Gravitational lens observations, Gravitational wave and Neutrino sources.
- The advent of SKA greatly increases the science value of the global array of radio telescopes including those at Onsala.
- This global array is a platform allowing innovation toward increased bandwidth and new techniques (i.e. Triband Cameras) beyond the technology on SKA (whose design was frozen 10 years ago) – Which can then be deployed for future SKA upgrades and give new industrial return to Sweden.

LOFAR – metre wave VLBI



LOFAR Station at Onsala, Upgraded to LOFAR 2.0 May 2026



LOFAR European network including three to-be-constructed stations in Italy-Bologna, Bulgaria and Czech Republic (plus another station in Italy-Sicily is funded).

LOFAR has baselines of 2000 km probing unique high-resolution science inaccessible to SKA-low with its 70 km maximum baselines.

LOFAR sees 30 times finer detail than SKA and so will remain a unique and complimentary instrument in the SKA era.

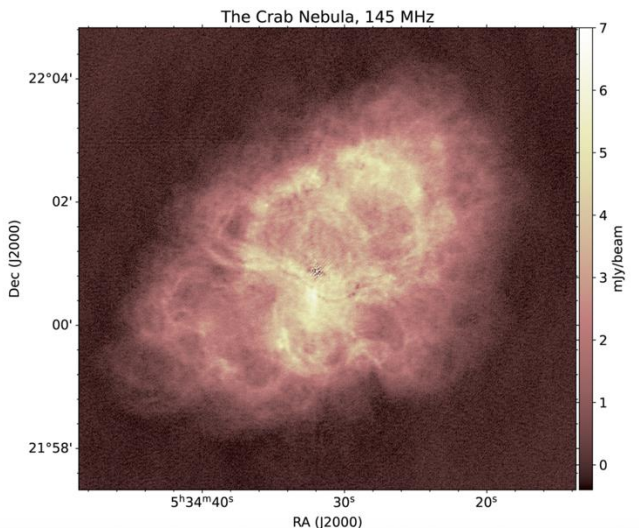
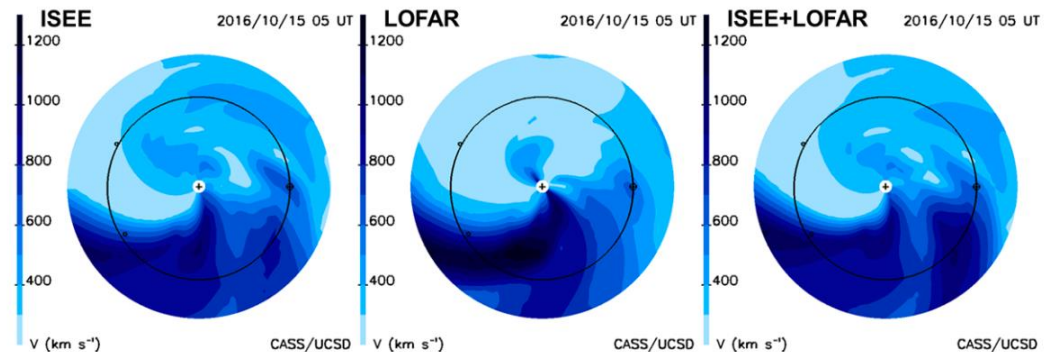


Image of Crab Nebula using LOFAR international stations (Arias et al 2025)

LOFAR Space Weather Observations

- LOFAR4SW EU H2020 project design completed- Goal of dual beam at HBA - so that every LOFAR station can have both a LBA + HBA station beam in solar direction during day.
- Ultimate goal is to help predict path of Coronal Mass Ejections- early warning for Earth.
- Also International LOFAR array currently studies interplanetary medium via Interplanetary Scintillation (IPS)



Maps of Solar wind velocity on Solar System, using combined Japanese array and LOFAR Interplanetary Scintillation (IPS) observations

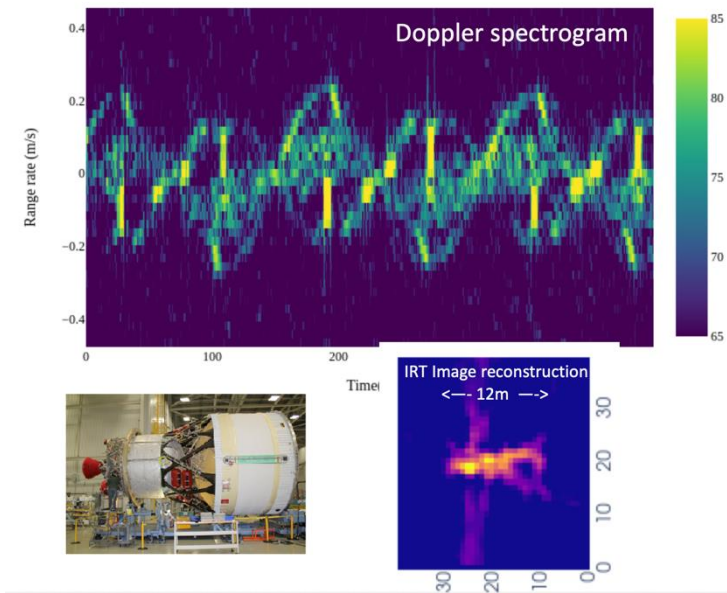
Radio telescope dual use for astronomy and society

Beyond traditional radio astronomy the telescopes at Onsala can also be used for:

- Space weather monitoring (see previous slide)
- Space geodesy (see coming slides)
- Space Situational Awareness (LOFAR can via radar echos to detect majority of orbiting satellites) - and our short wavelength dishes can image them via bistatic radar ---→ (getting up to 5cm resolution at Geostationary orbit)
- Space Communications (cis-Lunar and Solar system)

China recognizes the above strategic multi-disciplinary applications and is building numerous radio telescopes both at home in China and in countries around the world (especially in Africa and South America, see US House of Representative committee report - Feb 2026).

Recognising and supporting the multidisciplinary use of radio astronomy facilities is something Sweden could do better. Unlike China which takes a holistic view we are in part hampered by having different funding agencies, VR, Lantmäteriet, Defence, SNSA etc potentially involved in funding and not recognizing the large potential synergy savings they have.



Tumbling Delta 4 rocket Body, Illuminated by cooperating Pulsed radar and using radio Telescope to receive (Garrington et al 2023), The received range-Doppler signal is shown at the top, while bottom left is the ground truth,

Geoscience Cornerstone

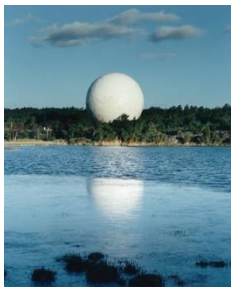
Onsala is one of only a handful of fundamental geodetic stations in the world



GPS network



Gravimeter to
measure
gravity
variations



Geodetic VLBI

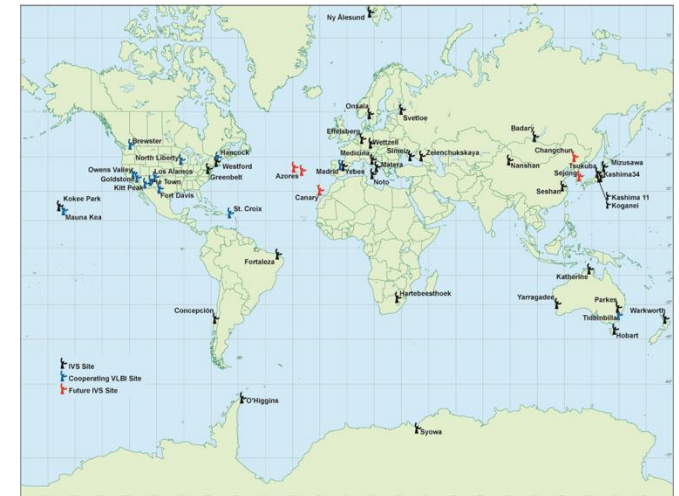
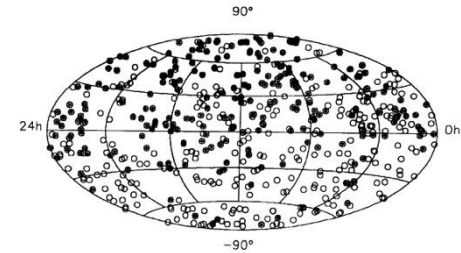


Two Tide gauges for sea level
+ Seismometer
+ Aeronomy station (atmospheric composition change)
+ Time and frequency laboratory

Onsala telescopes are used to get Earth orientation for navigation - a practical use of Black Holes.

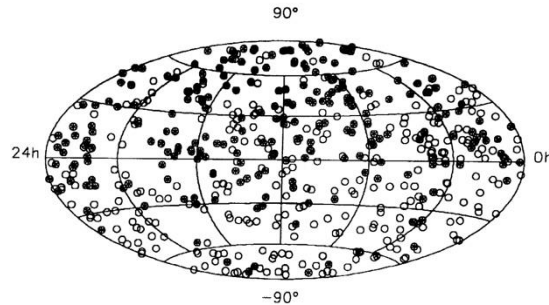


Onsala Twin Telescopes (OTT) inaugurated 2017. Construction financed by KAW and Chalmers, operations Lantmäteriet – Part of a global network regularly observes 250 black holes as part of a global network- to get accurate 1mm positions and Earth orientation in space.

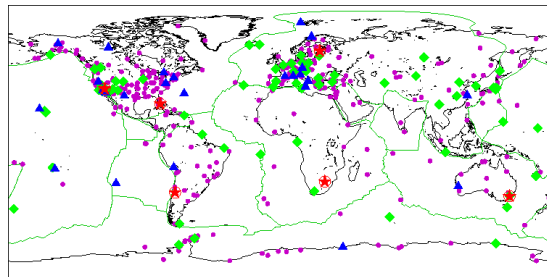


Geodetic VLBI Outputs

ICRF
International
Celestial
Reference
Frame

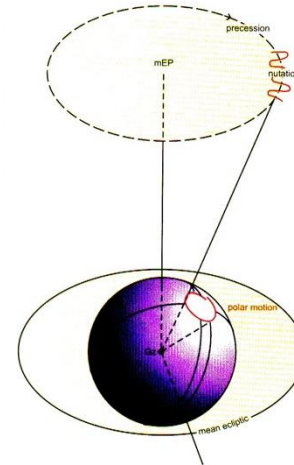


ITRF –
International
Terrestrial
Reference
Frame



1 Collocated techniques > 70
2 Collocated techniques > 70
3 25
4 6

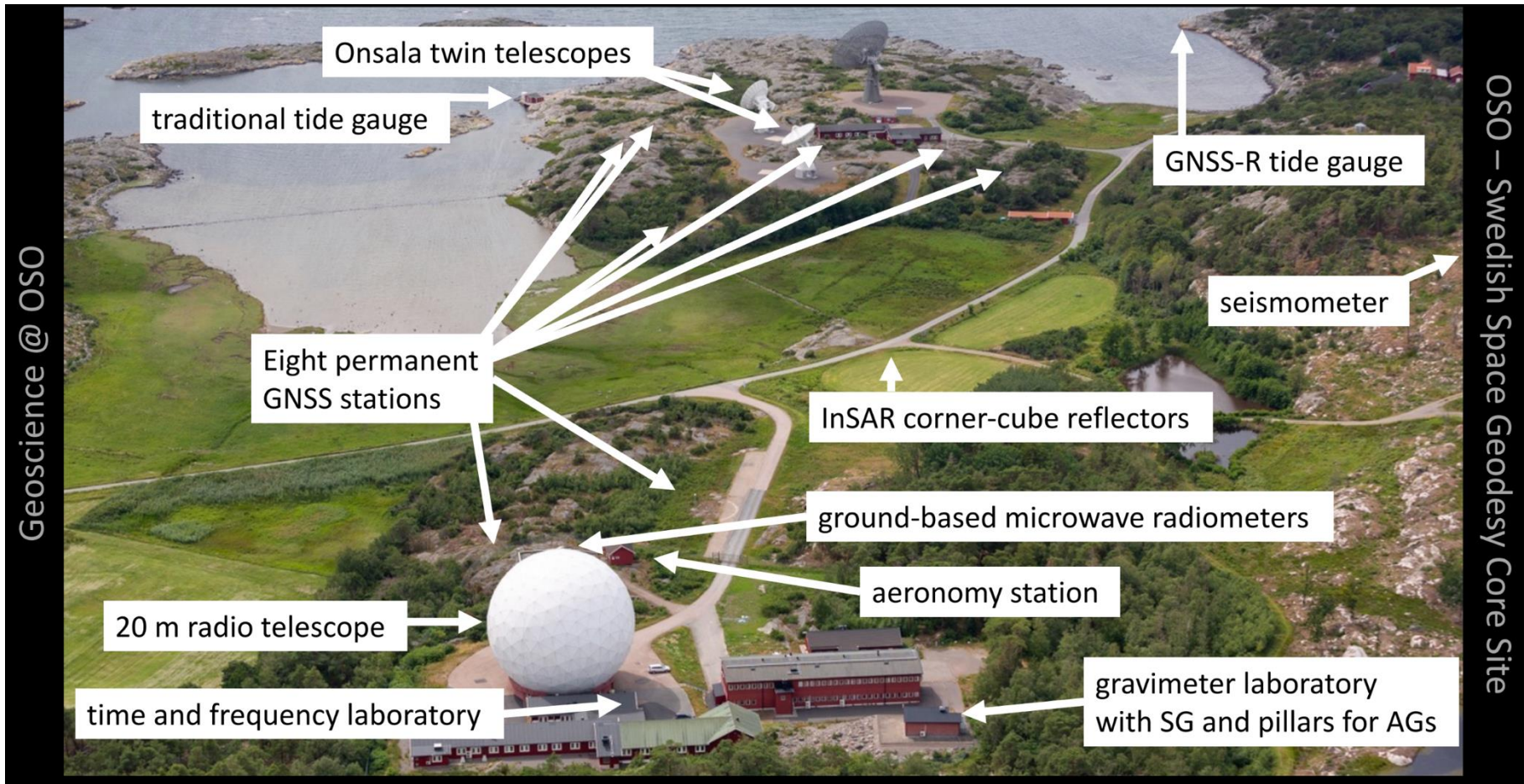
EOP Earth
Orientation
Parameters



- **ICRF:**
 - Radio Source Positions
- **ITRF:**
 - Station Positions
 - Velocities
- **EOP's:**
 - Celestial Pole ($d\epsilon$, $d\psi$)
 - Polar Motion (x_P , y_P)
 - UT1-UTC (DUT1)
- Importance documented:
coming up IAG Project **IGGOS** with demand for
 - mm-accuracy
 - consistent for decades
 -

Observations provide undamental information for Geoscience and give important practical input for **navigation services** (GPS, phone location) and **Geophysics**. Geo-location service worth worldwide 10's Billions of Euro (NOTE a practical use of black holes !). Also defines celestial reference frame for astronomers and other side products (monitor long term increase in atmospheric water vapour that forces global warming). Of strategic importance for Europe to independently measure EoP to calibrate Galileo satellites

OSO Geoscience instruments



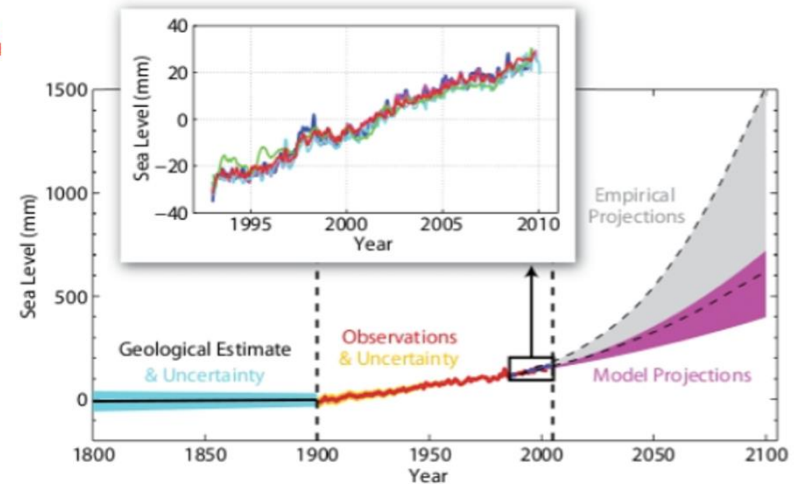
Sea-level rise measurements



OSO has VLBI
to measure land
uplift + tide
gauges to
measure sea
level wrt land,



Challenge: Sea level change



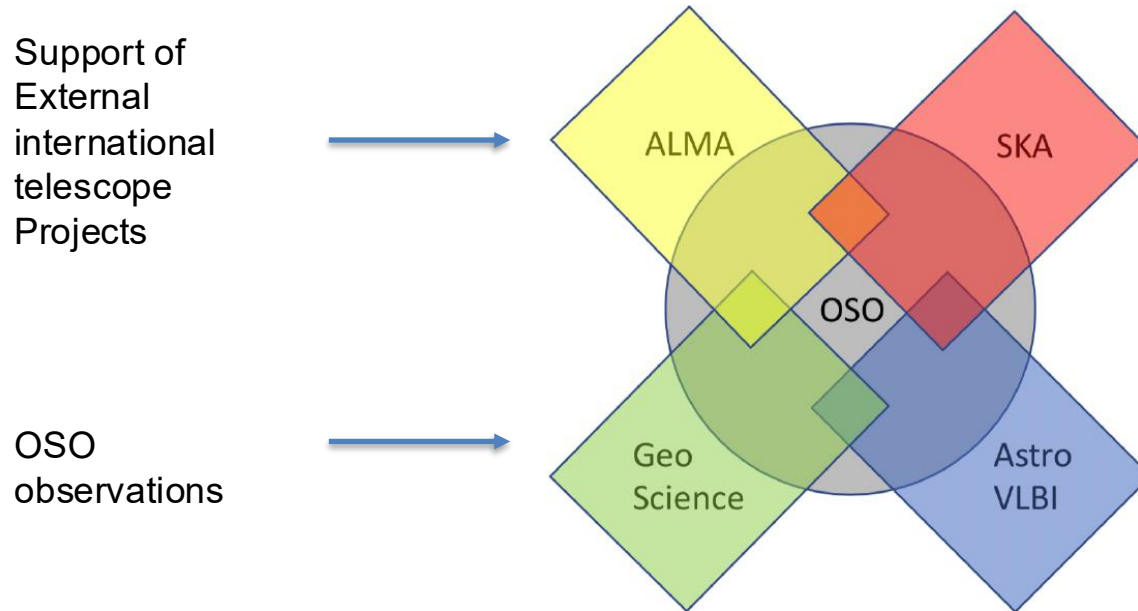
OSO twin telescope geodetic VLBI observations vital to measure and correct effects of land uplift on our sea level measurements.

Black holes contribute to global change studies as well as navigation!

OSO's two tide gauges – measure sea-land. Geo-VLBI measures land relative to centre of Earth

Part 2 - OSO involvement in the international projects ALMA and SKA

OSO Infrastructure Strategy



Four OSO strategy cornerstones. 3 for Astronomy + 1 Geoscience (Financed by Lantmäteriet) Each cornerstone supports the others via numerous scientific and technical links.

Note - Other important goals include: single dish operation, Space based radio astronomy projects, and public Outreach,

ALMA Cornerstone - Atacama Large Millimetre Array



ALMA site in the Atacama Desert in Chile at altitude 5000m. OSO has played a significant role in forming, designing (J Conway planned the antenna layout) and building ALMA via supplying Band 5 and 2 receivers etc.

ALMA has been operating and has cost >2 B€. It has produced transformational science at mm/sub-mm wavelengths in multiple areas of astrophysics,

OSO currently supports Nordic ALMA users and is prototyping ALMA's next generation receivers.



ALMA organization – via three regional ‘Executives’ plus host country

Europe (37.5%)

- [European Southern Observatory](#) and the European Regional Support Centre (Sweden one of 16 members)

North America (37.5%)



- [National Science Foundation](#) via the [National Radio Astronomy Observatory](#) and the North American ALMA Science Center
- [National Research Council of Canada](#)

East Asia (25%)



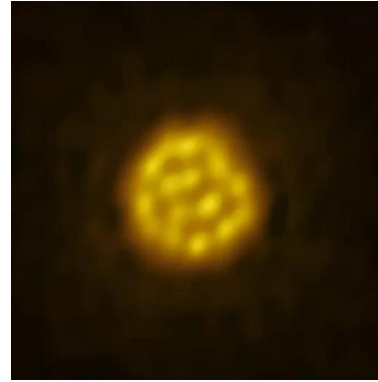
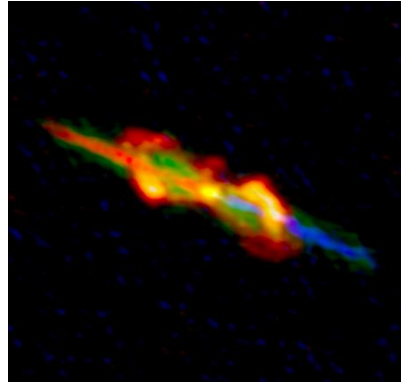
- [National Astronomical Observatory of Japan](#) (NAOJ) under the National Institutes of Natural Sciences (NINS)
- ALMA-[Taiwan](#) at the [Academia Sinica](#) Institute of Astronomy & Astrophysics (ASIAA)

Chile (10% ‘avskalning’)

- Republic of Chile

Overall Sweden pays about 1% of the ALMA running costs as part of its membership fee to ESO.

Nordic ARC Node – ALMA user support



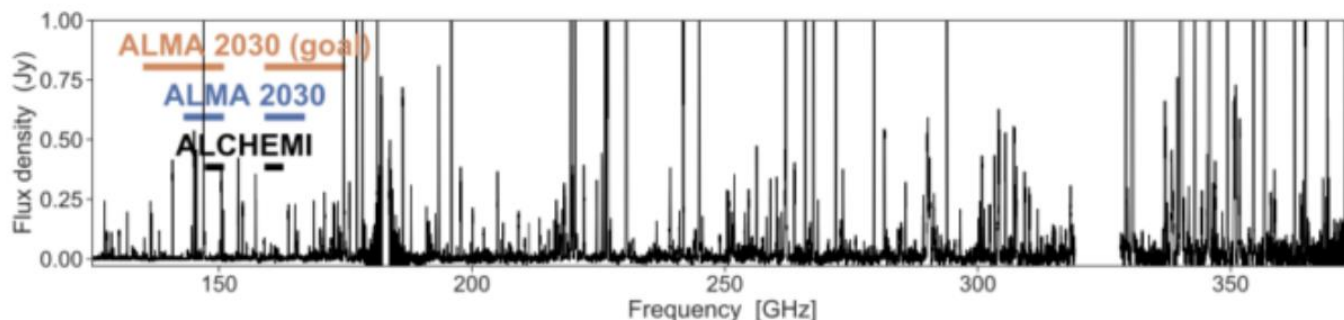
ALMA results via Swedish Authors Left–Jets from a dying star (Tafoya et al 2020) Right- Convection cells on a stellar surface (Vlemmings et al 2024). **ALMA gives the largest Swedish astronomy science output from OSO supported telescopes, and this is likely to remain the case through 2030's.**



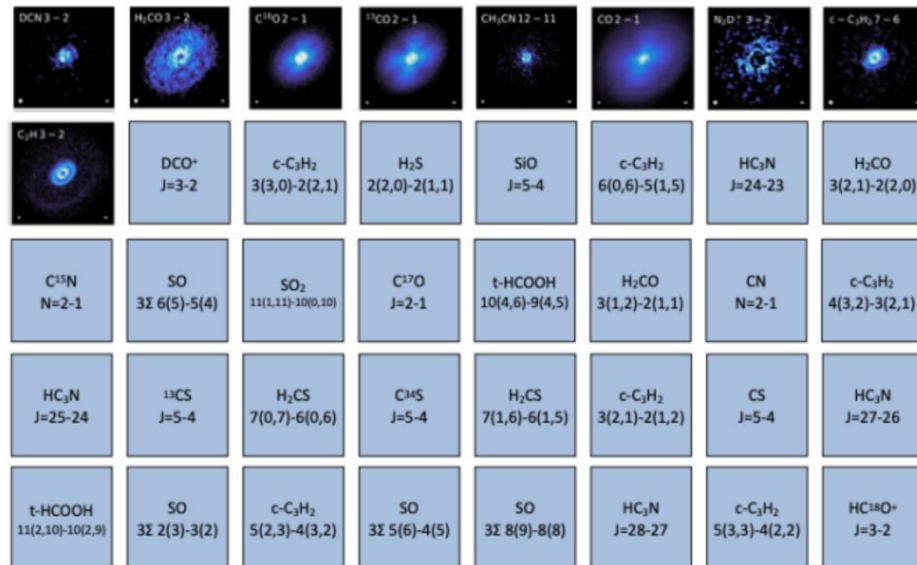
Onsala hosts the Nordic node of the distributed European ALMA Regional Centre (ARC) to support ALMA users. In terms of success in getting ALMA observing time per active astronomer Sweden is second only to Japan.

ALMA Wide Band Sensitivity (WSU) Upgrade

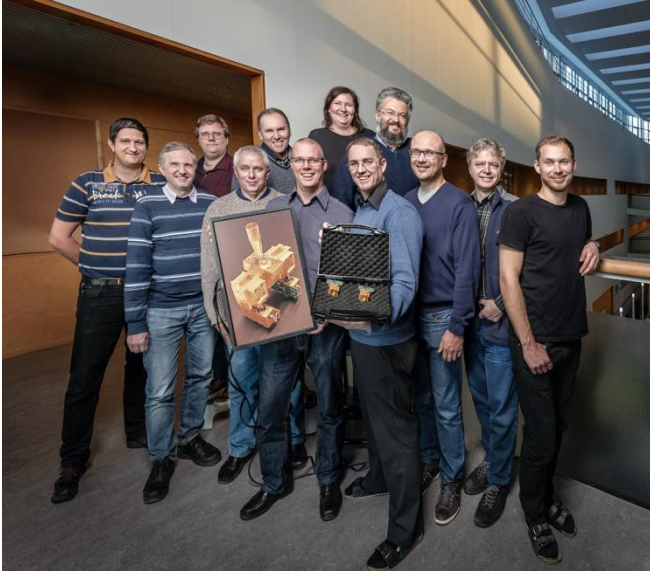
Project to increase bandwidth of ALMA receivers by factor of 4, improve sensitivity, and allow finer spectral resolution, due for completion in early 2030's. Below is a typical rich spectrum of spectral lines observed by ALMA with current frequency range for one tuning in black and ALMA 2030/WSU goal of 4 x bandwidth in orange, giving a speed up factor of 4.



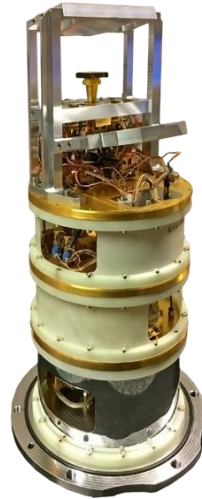
Imaging example, bandwidth improvement allows simultaneous imaging of protoplanetary disks in 40 spectral transitions from different molecules instead of 9 as now.



OSO Group for Advanced Receiver Development (GARD) ALMA receivers



GARD celebrating completion (circa 2017) of contract to supply 75 Band 5 receivers to ALMA. Recently delivered first Band 2 cartridges to ALMA.



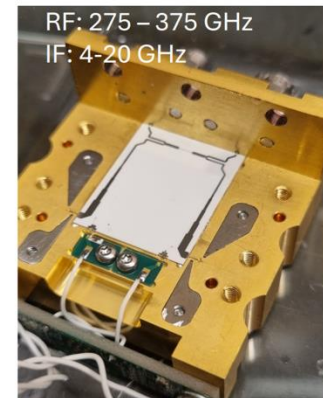
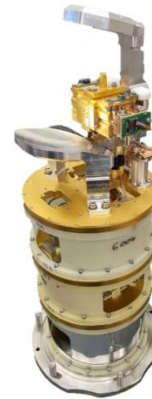
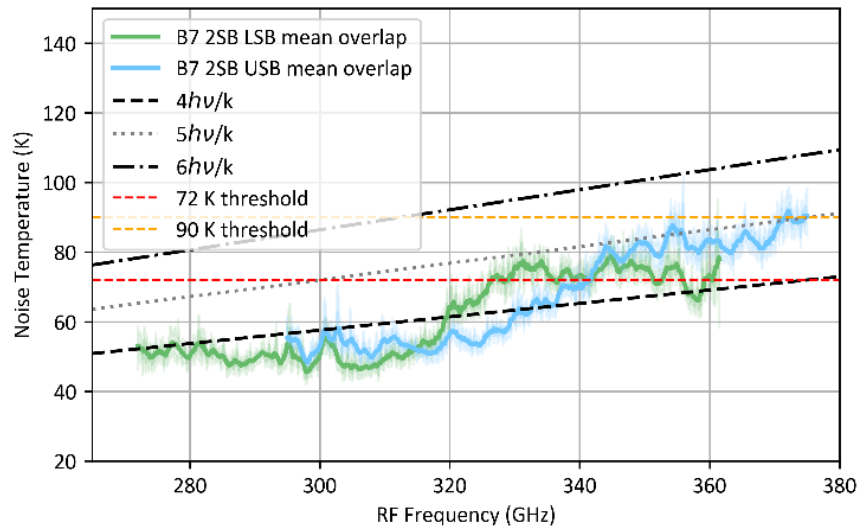
Presently GARD finalizing Band 7 WSU prototype for demonstration on APEX – plan to ship end of June 2026.

Also working higher frequency receivers for LETO M-class proposal to ESA

View below of Chalmers MyFab clean room, one of the largest university clean rooms in Europe supporting GARD's receiver leadership.



ALMA Band 7 WSU receiver prototype



GARD prototype achieves (figure top-left) the WSU goal of 4x bandwidth of existing ALMA receivers while simultaneously getting 10% lower noise than existing receivers (!)

This prototype to be installed on APEX in January to demonstrate on-sky performance; and allow sharper black hole imaging using mm VLBI.

OSO/GARD expected to get contract to supply new Band 7 to ALMA – based on generous VR funding in our new 2027-2030 grant this Swedish financing this will bring back extremely valuable Guaranteed Time Observing (GTO) from the European ALMA partner ESO

Estimated as 130 hrs back in GTO. ALMA is the most oversubscribed telescope on Earth; factor of 10 (!) in recent call.

SKA Cornerstone – Square Kilometre Array



South Africa (cm-wave)

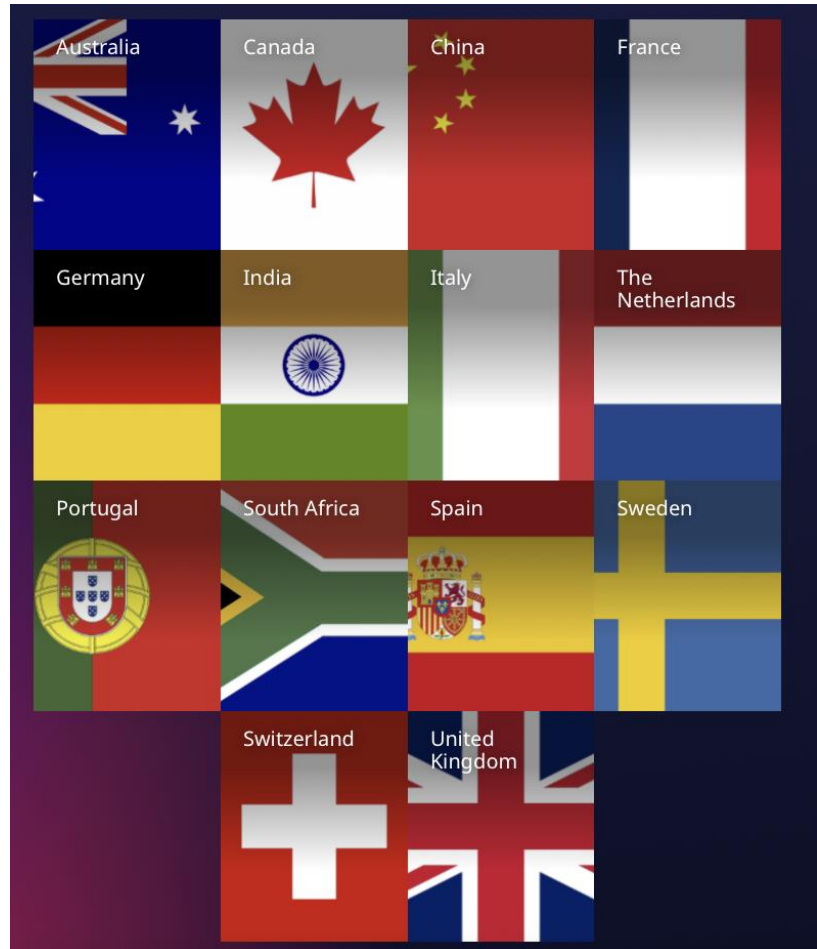
Australia (m-wave)

Construction began December 2022. The AA* array is scheduled for completion 2032. Goal to provide transformational science at cm/m wavelengths. SKA and ALMA complement each other. Initial funding schedule (Jan 2021 – Dec 2030) cost of 2 B€,

SKA Observatory

Latest Inter-governmental Organization (IGO) for science- alongside ESO for astronomy.

Currently SKAO has 14 members with discussion ongoing to finalize South Korea membership.



AASKAII: an astounding array of science...

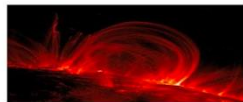


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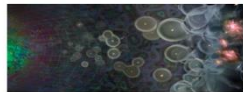
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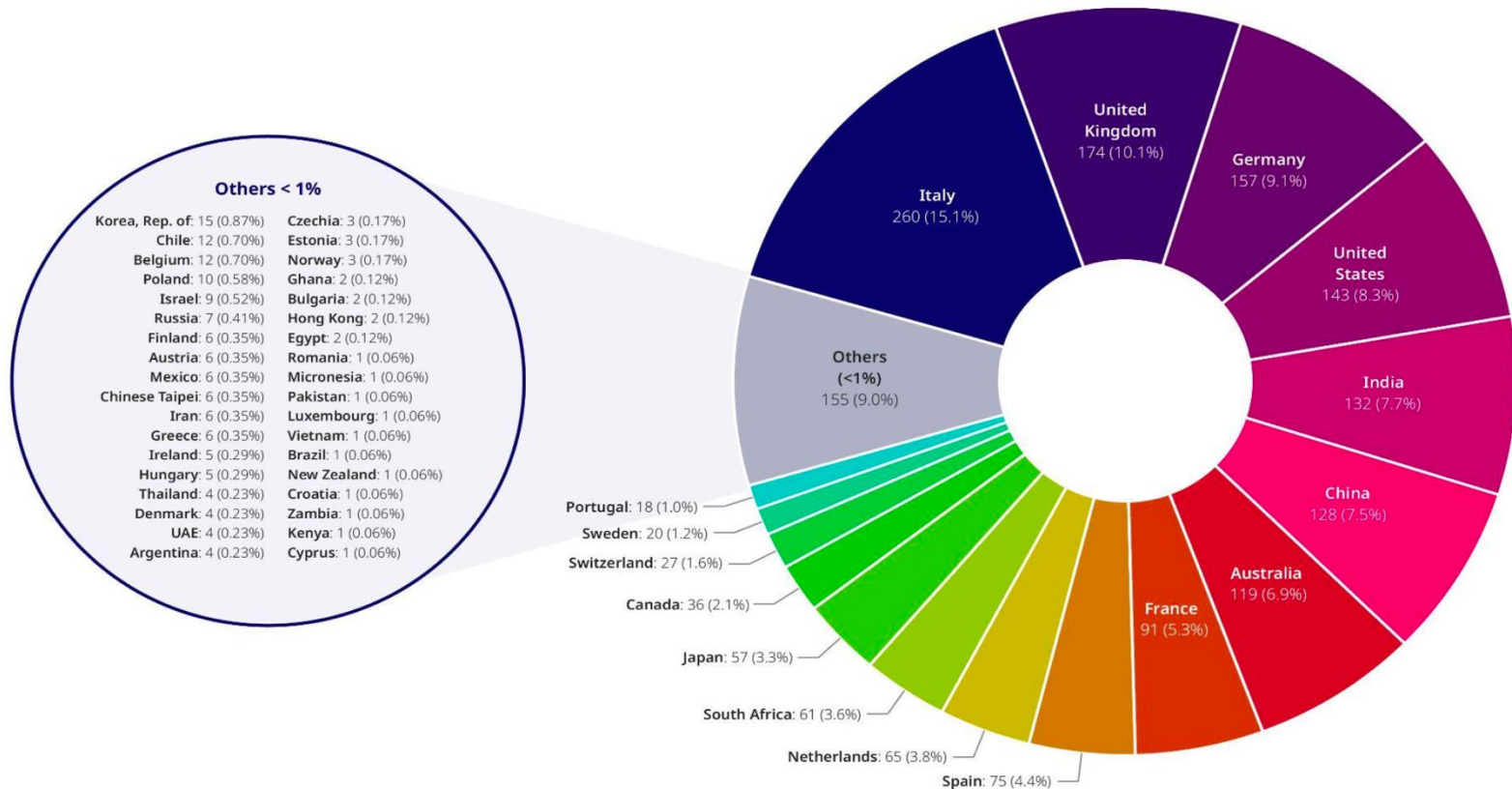
- **Methods and techniques**

- *Interferometry, VLBI, Imaging, Calibration, Scientific Inference for SKA Science, Citizen Science, AI*

New Science Book for SKA since summer available online

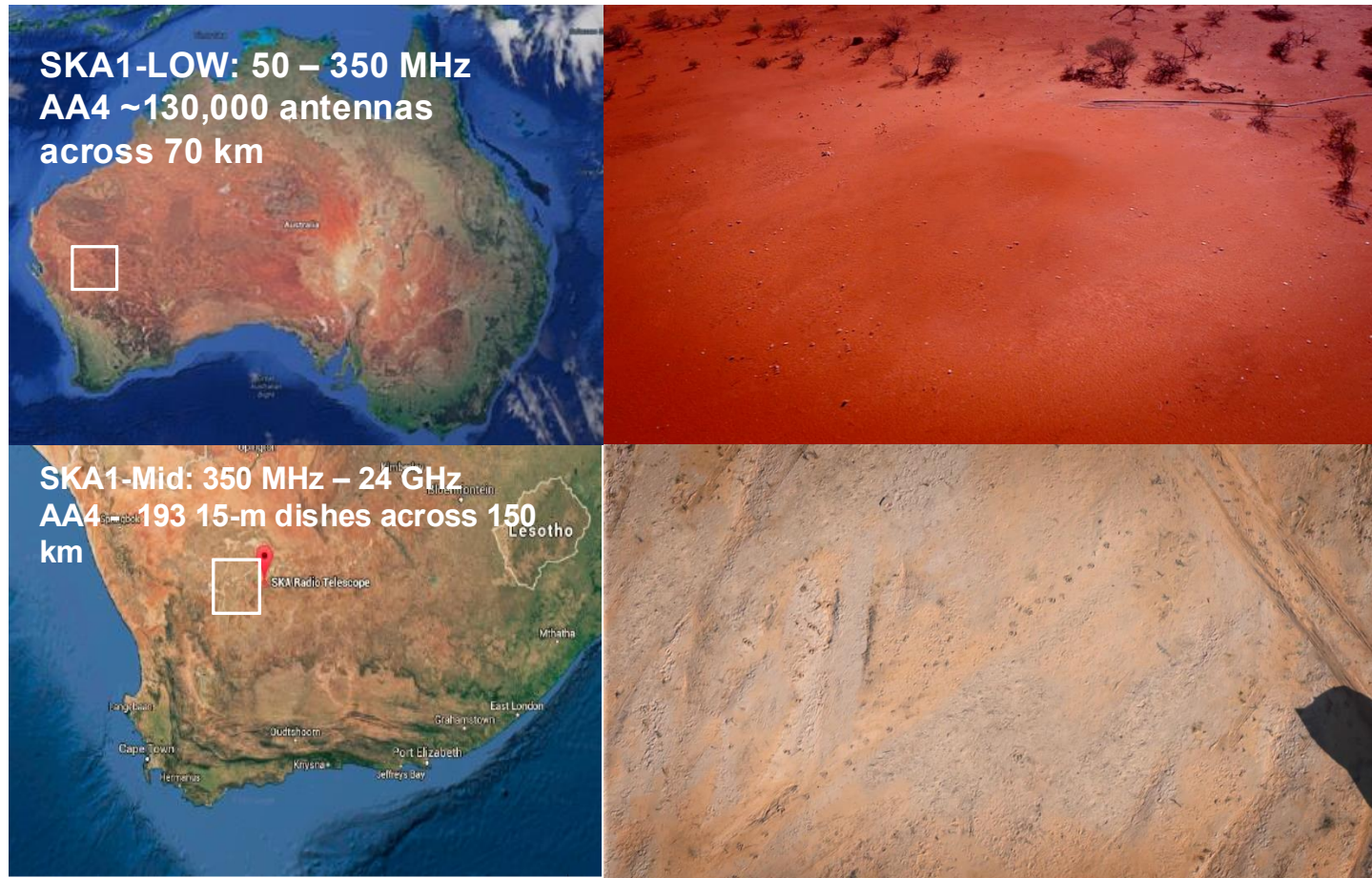
Contributors to the SKAO science book

Total: 1,718 unique authors · 52 countries



Sweden has 1.2% of authors or 1.5% of the authors from SKA member countries - which is exactly our current (and anticipated future) project share.

SKA: Telescopes in Australia & South Africa

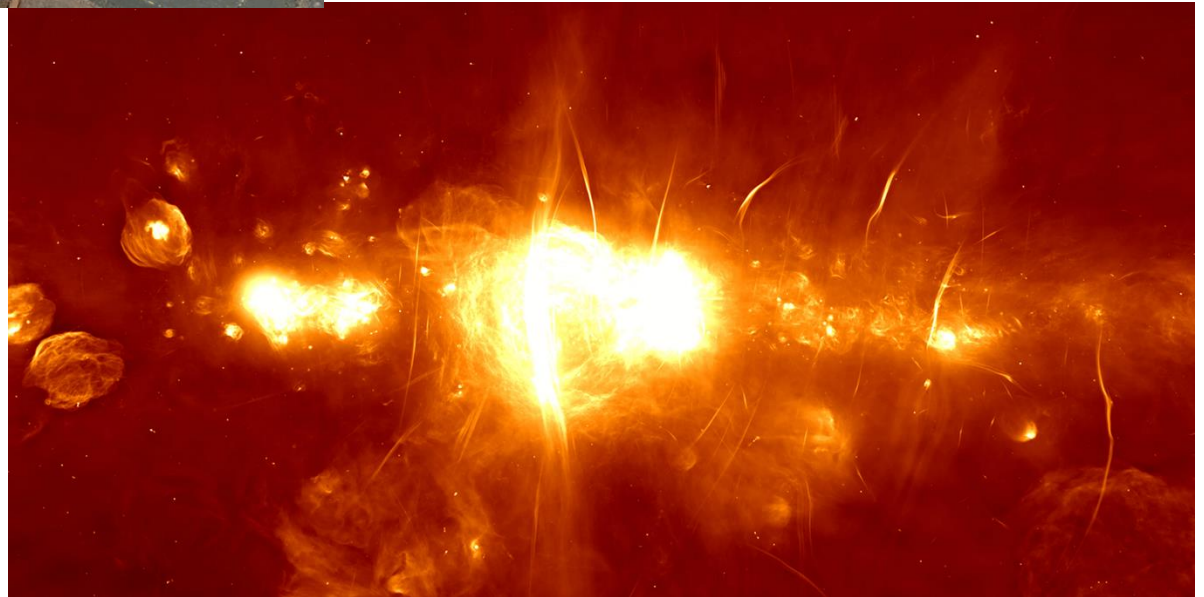


MeerKAT SKA Precursor - South Africa



64 x 13.5 m diameter dishes in South Africa already in operation, for last 10 years, to these will be added 133 x 15m dishes to form AA4 SKA1-mid.

First MeerKAT results from 2018 – Galactic Centre image



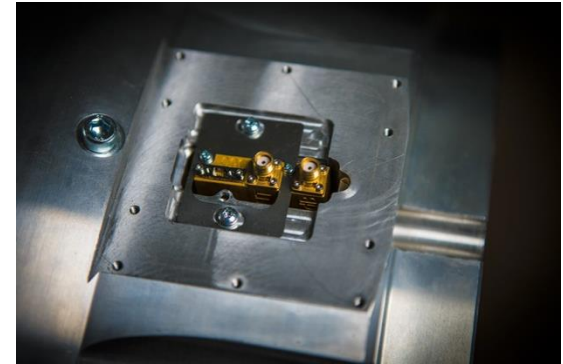
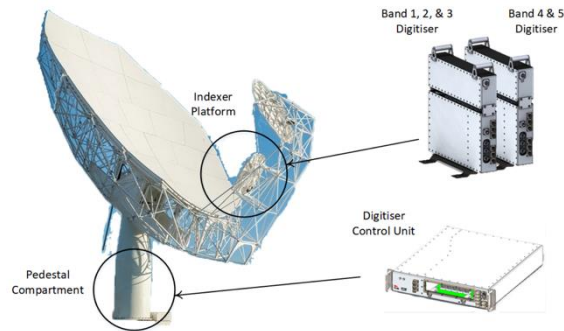
Overview of assigned Swedish SKA Industrial Returns – contracts worth 31 M€ to Swedish industry

These contracts exceed the total Swedish spending on SKA 2021-2030 from VR+VINNOVA construction funding + membership payments of 26.7 M€ (!) – Of the membership fee component 4.0 M€ was paid VR→OSO→SKAO

SKA1-mid Digitizer

Sweden Tier 1 lead and delivering digitizers for bands 1,2,3.

Quamcom company.

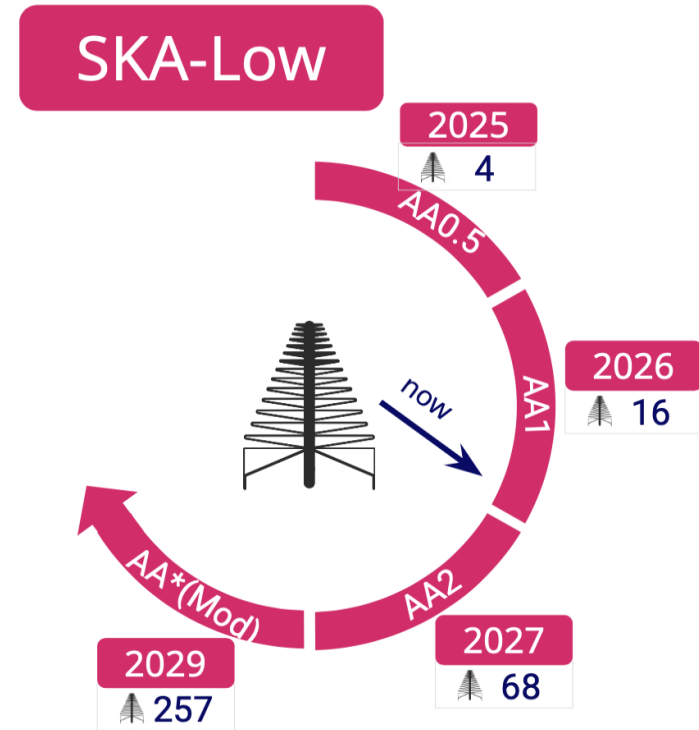
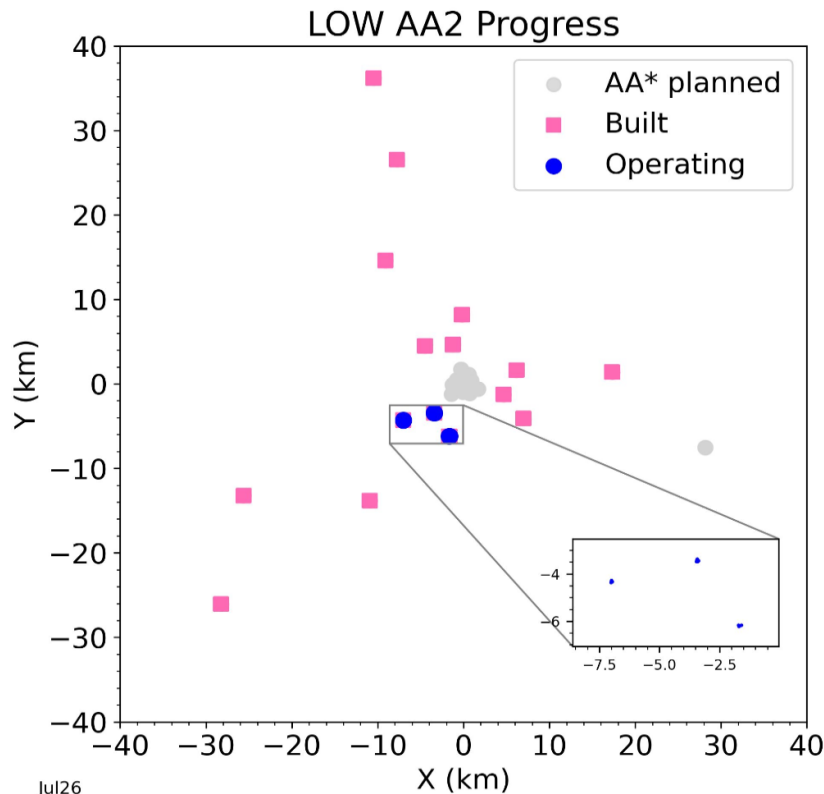


Ultra sensitive Low Noise Amplifiers (LNAs) – Detectors of radio waves – from the Gothenburg **Low Noise Factory** company (world leader for LNA's for radio astronomy and quantum computing) fabricated in Chalmers clean room to be used for SKA1-band Bands 1, 5a, 5b



SKA1-mid Band 1 Receiver – OSO designed prototype - Now in full production by **Omnisys** company.

SKA-Low construction status (July 2026)



AA stands for Array Assembly and releases of different partial array will be in stages AA0.5, AA1, AA2, AA*(mod), full SKA design is AA4.

SKA-low progress – July 2026

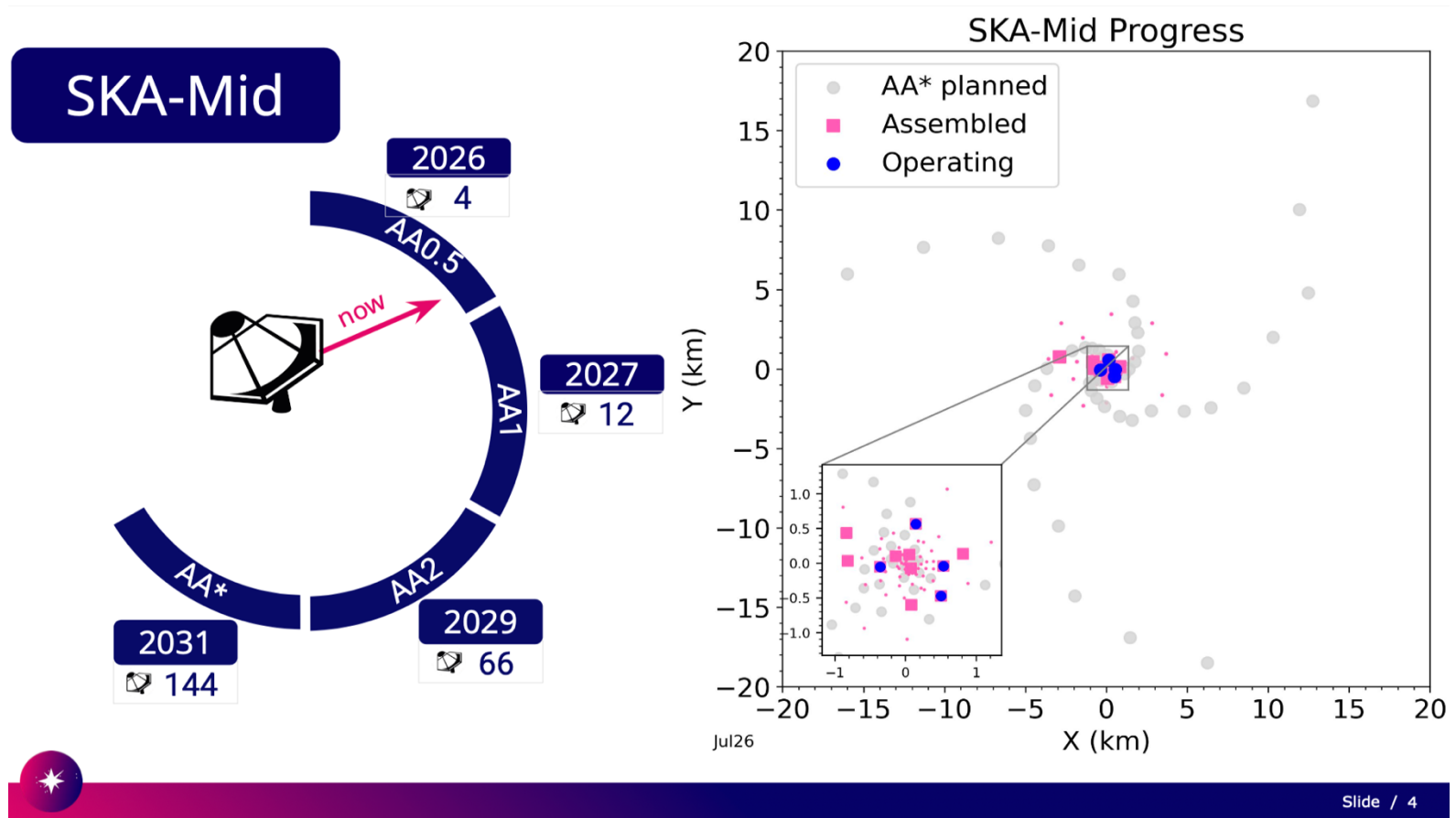
First major milestone AA0.5 achieved!



SKA Observatory reaches first construction milestone in Australia



SKA-Mid construction status –July 2026

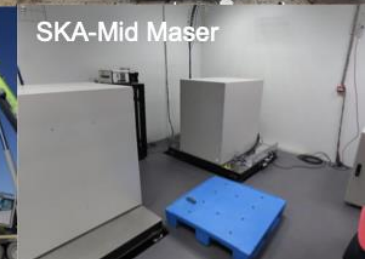


SKA-mid progress – July 2026

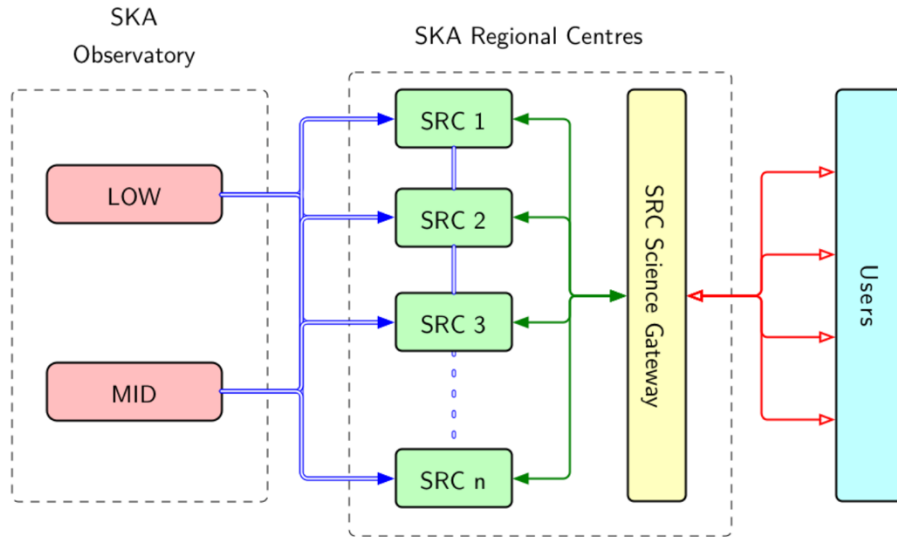
SKA-Mid

Juggling construction, science, and the weather

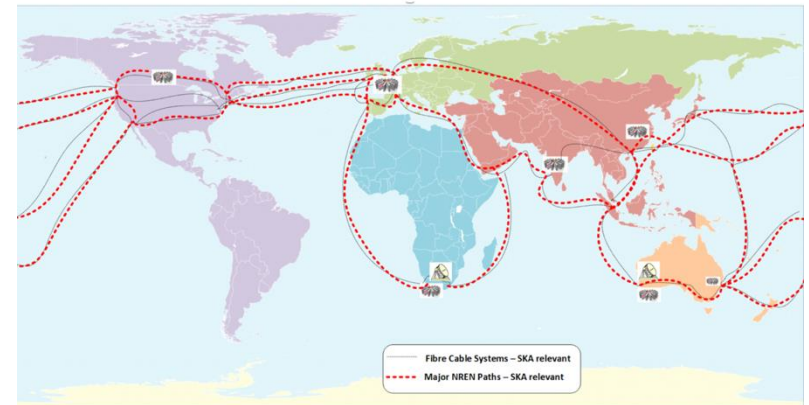
- **Dish Deployment – building towards 3-4 dishes per month in 2026**
 - 7 “big lifts” have taken place
 - 15 dish structures on site, and 4 more dishes underwent Factory Acceptance Tests in China last week.
 - Dish structure performance testing activities continuing at pace, and all indications are good
- **Radio frequency feeds**
 - Band 1 - Pre-production units under construction
 - Band 2 - Manufacturing of feeds well advanced, first units delivered
 - Band 5 – Design underway
- Civil infrastructure will be completed by March 2026
- Power and fibre on site forecasted to complete by July 2026
- High bandwidth long haul data links are partially complete and on track for completion in 2026



SKA Regional Centre Network



SRC Networking



- access to support using the SKA and its data products
- a platform for collaborative science
- transparent and **location agnostic** interface for users
- access to project data for all SKA users
- a place for development of software tools: analysis, modelling, visualisation

Working toward distributed storage and process of 700 PB/year

Swedish SRC node

SRCNet 0.1 was a huge milestone!

Proof of concept established across many sites

**SRCNet 0.1
2025**



Milestone passed!

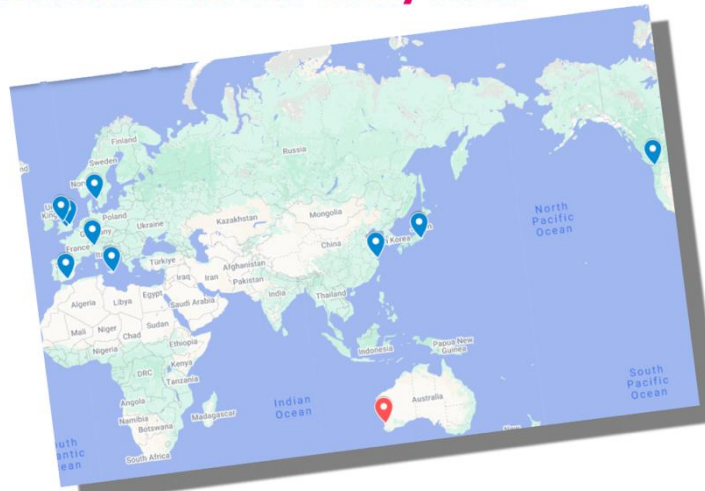
9 nodes

Test campaigns
performed in 2025

Data movement between
sites centrally managed

Data ingestion at SDP
location in Perth

**Internal version,
testing architecture**



**Millions of global
data transfers
made in test
campaigns**

- **Centrally managed** data archive of > 3 PBytes
 - **Ingestion of data from an SDP site (Pawsey) on SKAO resources**
 - **Trust between sites** allowing resources to be integrated
- Map Key: 0.1 nodes (Spain, Switzerland, SKAO, Sweden, UK, China, Japan, Canada, Italy) SKAO ingestion site (Pawsey)

Swedish node since first establishment last year has been one of the most reliable – Now preparing for SKA-low user Science Verification in mid/late 2027

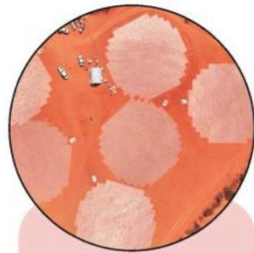
The SKA Science Timeline

Evolution of SKAO operational modes

SKAO milestones

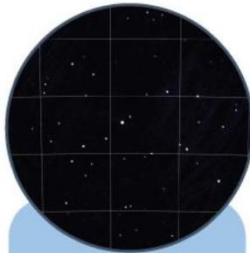
Community involvement starts

Credit: I. Heywood, SARAO



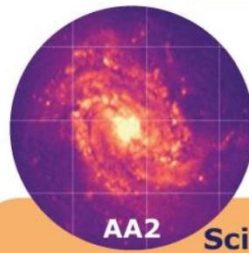
Construction

- Building antennas, dishes, roads...
- Followed by Assembly, Integration and Verification



Commissioning

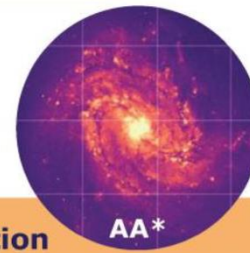
- SKAO activity
- Collaborative across system verification and science commissioning



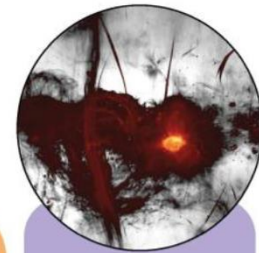
AA2

Science Verification

- **Primary purpose of SV is verification of the scientific capability, overall workflow and usability of the system** → science is a bonus, not guaranteed.
- Provide an end-to-end test of the system for each mode/ODP
- Must not place unnecessary burden on the SKA user community
- Build trust in operational model and excitement on our way to science



AA*



Cycle 0

- Shared-risk PI projects
- SRCNet resources ready for user
- proprietary periods



Now

Now

Mid 2027

First half 2029

2030



Now

Now

First half 2029

First half 2031

2032



Last Update: 31 March 2026

SKA AA* and SKA AA4

Fully operational respectively 2030/2032 will be the AA* versions of the SKA-low and SKA-mid telescopes, whose scope is constrained by available funding. The full SKA design (designated AA4) will then follow (discussions on-going whether to pause and operate AA* for some years or more likely have a seamless transition to AA4). Discussions are ongoing in the Funding Working group on funding for the next 10-year period 2031 – 2040.

SKA-mid **AA*** 144 dishes (80 new dishes + potentially 64 MeerKAT)
max baseline 36 km (with one test outlier at 108 km)

AA4 197 dishes (133 new dishes + 64 MeerKAT)
max baseline 160 km

SKA-low **AA*(mod)** 257 stations, max baseline 73 km

AA4 512 stations, max baseline 73 km

OSO 2027-2030 and beyond

- We at OSO thank VR for their confidence in OSO in granting us 154 Mkr of funding for the next funding period 2027 – 2030
- We are working hard on recruitment and other actions to fulfil the grant plan through 2030.
- The next proposal infrastructure proposal from OSO is due February 2029 (just over 2 years from now, when I will be turning 66) – covering the period after 2031 and onward.
- The OSO management + Steering Committee is starting to prepare a new OSO strategic plan for 2031-2036, outlining future options for OSO's development.
- An advert will soon appear for a new OSO Director; with the baseline plan that I step down by end of 2027 after 14 years in the role. I will continue doing research and be available to help the new Director till I retire about 5 years from now. Following the above recruitment schedule the new Director will have a full year (2028) in post as Director before leading the submission of the new proposal in February 2029.