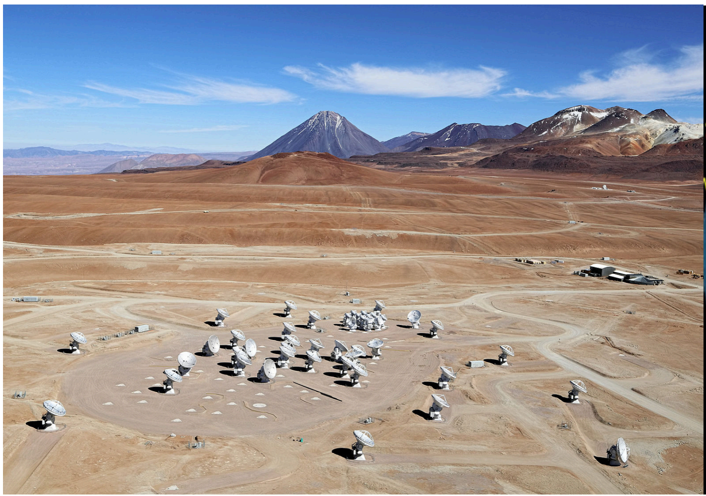
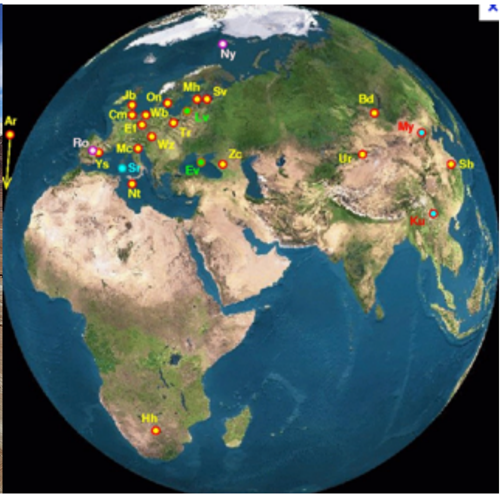
Onsala Space Observatory: Infrastructure Strategy 2020-2030





OSO Steering Group and Management
4th June 2019

ONSALA
SPACE OBSERVATORY

Goals of this Document. This document describes the strategic priorities of Onsala Space Observatory over the coming decade; the primary intended audiences are VR, Chalmers and other OSO stakeholders. This strategy will be updated periodically according to need. This OSO strategy complements the proposal submitted to VR in February 2019 for Swedish participation in SKA construction and operations. This strategy shows how OSO's future activities relate to SKA and OSO's other continuing roles in supporting millimetre wave astronomy, astronomical Very Long Baseline Interferometry and Geoscience.

Cover Images. Top-Left - The ALMA array in Chile. Top-Right- The distribution of telescopes of the European VLBI Network (EVN). Bottom-Left One of the two dishes of the Onsala Twin Telescope (OTT) for geodetic VLBI with the radome of the Onsala 20 m telescope in the background, Bottom-Right - Computer generated image of the completed SKA1-mid array in South Africa.

1. OVERVIEW

Onsala Space Observatory (OSO) is Sweden's centre of excellence for developing and operating radio/mm wavelength astronomy and geoscience infrastructure. Over more than half a century OSO has developed its cutting-edge expertise in receiver design/construction, in processing of complex radio/mm astronomy data and in providing user support. In recent years OSO has also developed increasing contacts with industry aimed at providing industrial return to Sweden from large radio/mm astronomy infrastructures. OSO innovates, operates and contributes to radio/mm astronomy telescopes that span five orders of magnitude in frequency and seven orders of magnitude in angular resolution. This broad engagement has enabled the Swedish astronomy community to deliver front-rank science in areas as diverse as evolved stars to the most distant galaxies.

This strategy document describes how in the coming decade OSO's key expertise and skills will be exploited to maximize scientific return to Sweden. Our strategy proposes concentrating OSO's future efforts towards supporting, for the use of Swedish scientists, the most important global radio/mm infrastructures. These four key infrastructures we identify as;

(a) The mm/submm wavelength telescope array ALMA in Chile to which OSO will continue to supply new hardware, software and give user support; the goal being to maintain the current very high scientific return of ALMA to Sweden.
(b) The metre/centimetre wavelength Square Kilometre Array (SKA) with elements located in South Africa and Australia; served by OSO by giving user and data processing support and via hardware/software contributions.
(c) The globally distributed astronomical Very Long Baseline Interferometry (VLBI[1]) telescope arrays; within which OSO will maintain its strong technical and scientific position.
(d) Globally distributed radio space geodesy and geoscience sensor networks; including participation by OSO in geodetic VLBI observations.

These four areas are not isolated activities but share many overlaps and synergies as illustrated in Figure 1; these synergies enable OSO to innovate by transferring knowledge from one infrastructure domain to another. An additional potential fifth infrastructure area concerns OSO supplying receivers to space-based radio astronomy missions, for both single-dish successors to Herschel and for Space-VLBI to image black holes. There are however significant uncertainties on the timelines of such missions, we therefore choose to base this core OSO strategy on the four listed ground-based infrastructures - while working toward OSO involvement in future space projects.

The astronomy infrastructures above will collectively contribute to answering some of the most important questions within the whole of the physical sciences. Within *Fundamental Physics* this includes testing general relativity using pulsar/black hole observations and

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[1] The VLBI technique involves combining the data from individual radio telescopes distributed around the world to synthesize a radio telescope whose angular resolution is the same as a single telescope with the Earth's diameter; a recent spectacular example of this technique involving OSO's APEX telescope and scientists at OSO is the first image of a black hole (see Fig 2).

probing the strong nuclear force by measuring the equation of state of nuclear matter within pulsars. Within *Cosmology* – key cosmological parameters will be measured and different hypotheses for the nature of Dark Energy tested. Within *Cosmogony* – concerning the origin of key components of the universe, such as galaxies, stars and planets, the three infrastructures will provide unique and critical information. The fourth key OSO infrastructure listed above, within geosciences, uses radio astronomy derived technology to contribute to efforts to monitor global change arising from our biggest societal challenge; that of climate change. More detail on the scientific impact of all four of the key OSO infrastructures is given in Sections 3 and 4 for astronomy and geoscience respectively. The prioritization of OSO's effort toward these key areas means that, assuming there is full Swedish participation in the major international astronomy infrastructures, OSO's involvement in smaller infrastructures, such as APEX and investments in 20 m telescope single dish capabilities will end.

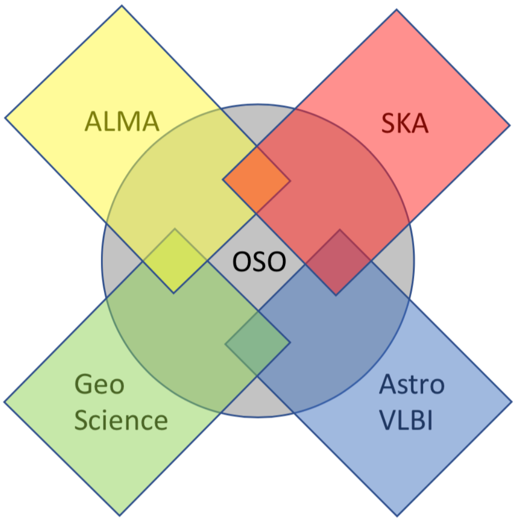

Fig 1. Illustration of the future key international infrastructures (coloured boxes) and their relation to OSO (grey circle). Within OSO Geoscience and Astronomical VLBI overlap via common use of the VLBI technique. Astro-VLBI and SKA overlap due to common receiver development and because SKA will observe as an element of future VLBI arrays. SKA and ALMA overlap due to similar data processing and user support requirements and also in the receiver area. ALMA and Geoscience overlap because radio methods to measure the atmosphere in geoscience are used to correct atmospheric effects.

Within the proposed strategy OSO will be a leading member of the global community of national radio astronomy observatories which supply hardware, software, data processing services and give user support to ALMA and to SKA. The other two infrastructure areas of astronomical VLBI and geoscience observations also involve observations made at Onsala. These observations exploit the strategic location of the site in Northern Europe which provides key North-South baselines to the global astronomy and geodesy radio telescope networks. In addition these Onsala based observations will continue one of the longest time-series of space-geodesy measurements in the world. In 2030 we envision that the Onsala OTT, 20 m, 25 m, and LOFAR telescopes, (see Sect 2) all equipped with greatly enhanced receiver systems, will operate as key elements of the global astronomical and geodetic VLBI networks. The advanced technology developed for broadband observations at Onsala for astronomical and geodetic VLBI will in turn strongly position OSO to make contributions to the expected extension/upgrade of SKA beyond 2030.

2. ONSALA SPACE OBSERVATORY TODAY

Below we briefly describe the present facilities and activities at OSO.

Radio telescopes at Onsala - OSO presently operates four radio telescopes at its Onsala site, namely; a 25 m diameter cm-wave dish, a radome-enclosed 20 m diameter cm/mm-wave dish, a LOFAR (Low Frequency Array) station for metre-wave studies and the Onsala Twin Telescope (OTT) for dedicated geodesy VLBI observations. The 25 m telescope is used for astronomical Very Long Baseline Interferometry (VLBI) observations. The 20 m telescope is used for astronomical VLBI and geodetic VLBI observations and for single dish observations (the latter activity funded only by Chalmers). The LOFAR station is mostly used as part of a European network, the International LOFAR Telescope, but is also used for a small fraction of its time in a standalone mode.

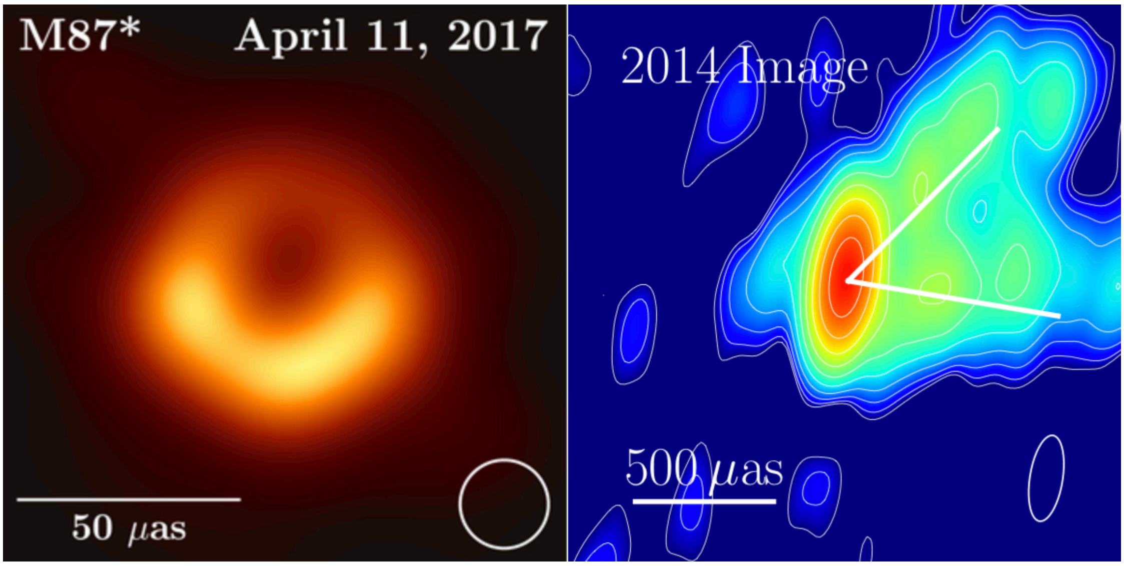

Fig 2. Left: First image of a Black Hole shadow (Akiyama et al 2019) via Event Horizon Telescope (EHT) global VLBI observations including OSO's APEX telescope and contributions of three OSO scientists. Right: Global 86 GHz VLBI observations including the Onsala 20m telescope (Kim et al 2018 as presented in Chael et al 2019) showing the base of the relativistic jet in M87. Future VLBI observations with intermediate resolution will connect the Black hole with the jet and reveal how this jet is launched

APEX – OSO shares in the operation of the APEX single dish submm wavelength telescope in Chile. This telescope is located on the same site as ALMA and is a collaboration with two other partners, the European Southern Observatory and the Max Planck Institute for Radio Astronomy in Bonn. For the current 2018 – 2022 partnership contract Sweden's share of APEX is 13%; reduced from its pre-2018 level of 23%. APEX principally conducts standalone single dish observations, which are low spatial resolution but allow for rapidly surveying large areas of the sky. In addition APEX also participates in extremely high resolution VLBI millimetre wave observations (see Fig 2).

Geoscience Instrumentation – In addition to using the OTT and 20 m telescopes for geodetic VLBI the Onsala sites operates a superconducting gravimeter, several Global Navigation Satellite System (GNSS) stations in cooperation with Lantmäteriet. two tide gauges (one of traditional design in collaboration with SMHI and our own based on GNSS-reflectometry), a seismometer (in cooperation with the Swedish National Seismic Network). Finally there are several aeronomy instruments at Onsala for making microwave observations of the composition of the atmosphere.

Millimetre and Terahertz Receiver Development – Millimetre and Terahertz wavelength receiver development is concentrated at the OSO’s Group for Advanced Receiver Development (GARD) located close to the clean room at Chalmers main campus. The GARD group has built numerous mm wavelength receivers for the Onsala 20 m telescope and APEX and has recently finished the delivery of a full set of Band 5 receivers to ALMA. The GARD group is working on new advanced technology for millimetre wavelengths and Terahertz frequencies.

SKA and VLBI receiver Development - At centimetre wavelengths the Onsala Electronics Laboratory, as well as maintaining the instrumentation at Onsala, leads the development of centimetre wavelength receivers for SKA and for VLBI. This group has designed and delivered the prototype Band 1 receiver for SKA.

ALMA and other Interferometry User Support - OSO hosts the Nordic ALMA support node whose role is to aid users in proposing and reducing ALMA data; members of the same group also provide assistance to Swedish users of other mm/radio interferometric telescopes such as LOFAR, VLBI etc.

Outreach – OSO maintains a modest outreach/media effort to explain the OSO’s results to the general public - and to help increase (especially younger) people’s interest in science. This activity is supported solely by Chalmers funding sources.

3. THE FUTURE RADIO ASTRONOMY INFRASTRUCTURE LANDSCAPE AND OSO’s ROLE

During the coming decade ALMA (front page - top left) and the SKA (front page- bottom right) will be the world’s dominant connected element array telescopes (with baselines <100km) for respectively sub-mm/mm and cm/metre wavelength observations. The construction of SKA and upgrade of ALMA are only possible via the technical contributions of numerous national centres of excellence such as OSO. In addition all countries with significant mm/radio astronomy communities already provide, or in the case of SKA plan, extensive national data processing and user support for these instruments. Going beyond the capabilities of ALMA and SKA there are numerous high impact radio/mm science cases requiring much higher angular resolution than is possible with ALMA or SKA alone. These science goals are addressed by a third distributed international infrastructure, astronomical VLBI (front page Top-Right), providing baselines up to 10 000 km in length and hence extremely high spatial resolution.

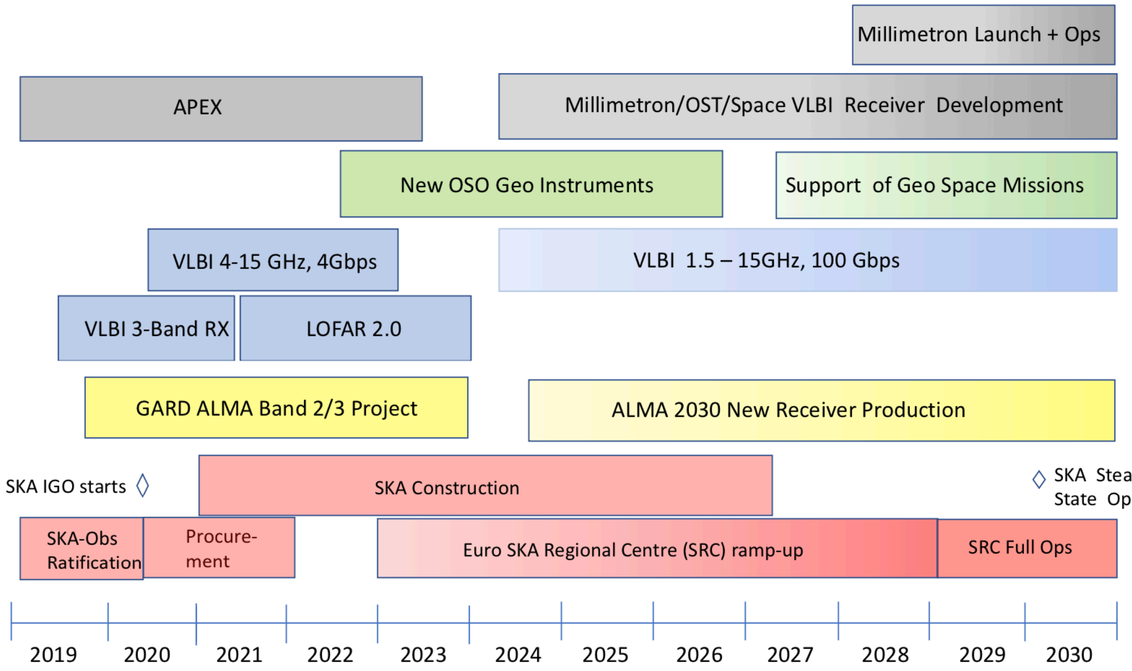

Fig 3 – Timeline of future OSO related infrastructure activities, Red (SKA), Yellow (ALMA), Blue (Astro VLBI), Green (Geosciences), Grey (Other).

In Sections 3.1 to 3.3 below we describe the science goals and development plans for each of the above astronomical infrastructures and OSO's expected key contributions to each. Section 3.4 describes other areas of interest for OSO astronomy involvement beyond these three core infrastructures

3.1 *ALMA* – The original technical design of ALMA, including a suite of receivers covering all millimetre wavelength atmospheric windows, is now close to completion. OSO's Group for Advanced Receiver Development (GARD) recently made the final delivery of a full set of 70 Band 5 receivers. GARD is now starting work as part of a consortium of three partners who will design and deliver the final receiver band according to the original ALMA specifications (Band 2).

ALMA is a highly successful project which already within its first six years of full operation has achieved all of its original primary astronomy design goals. In recent years ALMA has been considering its new science objectives and the technical requirements to achieve these goals, resulting in the *ALMA Development Plan*. The intention is that this plan will be fully implemented by 2030. One goal identified in this report, to develop the ALMA archive is already ongoing. The report's main future technical recommendation is to at least double the instantaneous bandwidth of all ALMA receiver bands. The signal path and correlator capacity will also be upgraded to be compatible with these wider bandwidths while, unlike the present system, also retaining very high spectral resolution when observing these wide bandwidths. These upgrades will provide observing speed-up factors of 2 for continuum observations and, depending on spectral resolution, between 2 and 64 for spectral line observations. The science goals of ALMA over the coming decade that will exploit the planned upgrade are described in Appendix A1.

OSO is extremely well placed to contribute to the proposed ALMA upgrade. The observatory's GARD mm receiver group is working on breakthrough technology to enable both wider instantaneous and tuning bandwidth for mm receivers. A new Band 7 receiver is also being built for APEX which already satisfies future ALMA requirements. On the user support side the ALMA support node at OSO is already working closely with the archive upgrade project. This work has a large overlap with future needs for SKA for user support and data support.

3.2 *SKA* -The Square Kilometre Array is planned to be the world's next huge step in cm/m wavelength astronomy and will consist of a low frequency array in Australia and a higher frequency array in South Africa. The two arrays will be up to 100 times faster for surveying the sky than existing telescopes. Sweden is already a member of the SKA Organisation which has designed the SKA. An international convention was recently signed in March 2019 by seven of the thirteen countries presently involved in the SKA project to form the SKA Observatory, a new intergovernmental organization that will build and run the SKA telescope. A proposal for Sweden to join the SKA Observatory and participate fully in SKA construction and operations was submitted to VR-RFI in February 2019 and is presently being evaluated. The construction of SKA is planned to start in 2021 and be completed by 2027. The SKA has a wide range of science goals which are more fully described in the above mentioned SKA proposal to VR-RFI but which are summarized in Appendix A2.

It is expected that an increasing fraction of OSO's activities in the decade ahead will be related to the support of SKA, including developing advanced receiver technology, managing industrial return to Sweden and supporting users. The later roll will involve an expansion of the scope of the current ALMA Regional Centre (ARC) node at Onsala to also support SKA. This expanded mission will involve managing the Swedish contribution to the European SKA Regional Centre. This together with other SKA Regional Centres around the world are vital components of the SKA project, collectively forming the data archive and processing interface between the SKA data and its users.

3.3 *Astronomical VLBI* - The international VLBI arrays at millimetre, centimetre and metre wavelengths provide the third major leg of observational radio/mm astronomy in the 2020's and beyond. The global VLBI array at centimetre wavelengths already has a total collecting area comparable to the SKA1-mid array in South Africa, with new VLBI antennas coming into operation around the world. During the next decade it is planned to increase VLBI observing bandwidths so that sensitivities increase by a factor of 7. This bandwidth expansion is made possible by new receiver technology, developed in part by OSO, combined with expected advances in digital sampling. By also including the phased-up SKA-mid in South Africa as one of the VLBI elements the sensitivity of future global VLBI arrays will be further enhanced by a factor of 2, giving an overall sensitivity increase of 14. The European VLBI Network (EVN) is presently completing a future Science Vision document which is expected to be finished by the end of 2019. The key future VLBI science areas identified in this draft document are listed in Appendix A3.

As well as providing Swedish users access to unique capabilities for scientific discovery the planned receiver technology for future VLBI goes significantly beyond that deployed on SKA; which is now frozen at approximately 2015 levels. VLBI technology therefore has the potential to feed back into future upgrades of SKA in the 2030's. Given the exciting scientific prospects for VLBI it is planned over the coming decade to upgrade the Onsala 20 m and 25 m telescopes to wider bandwidth. It is also planned, in synergy with geo-VLBI, to maintain OSO's special role as a station that develops and demonstrates new VLBI capabilities and therefore leads global VLBI forward. Operationally at cm wavelengths is expected that a subset of EVN telescopes, including the OSO 20 m and 25 m telescopes as core members, will operate for a high fraction of the year in order to locate and monitor transients. The increased tasks of the EVN's central correlator facility at the Joint Institute for VLBI in Europe, an ERIC in the Netherlands motivates a modest increase in its budget (paid directly by VR to JIVE) during the coming year. At longer wavelengths the International LOFAR Telescope, with its stations distributed around Europe including at Onsala provides a unique metre wavelength VLBI capability. This array plans to increase its bandwidth via the LOFAR 2.0 upgrade, which OSO plans to participate in, allowing many new scientific possibilities especially for transient detection and follow-up.

3.4 *Additional Space-Based and Single-dish Opportunities* - In addition to the above three infrastructures (ALMA, SKA and VLBI), which we see as forming the core of future global radio/mm astronomy (see Fig 3) there are other important facilities that OSO will seek to contribute toward during the 2020-2030 timeframe. These include the possibility of providing receivers to the Russian submm space VLBI mission Millimetron (projected launch date 2028). Somewhat further in the future is the possibility of supplying receivers to the NASA led Origins Space Telescope to be launched in the 2030's. There is also the possibility to provide new receivers to a new wavelength single-dish successor to APEX of at least 25 m diameter that is starting to be discussed. Such receiver contributions would in general result in the return of Guaranteed Observing time to Swedish astronomers. The above projects could be major opportunities for the observatory but all presently have high uncertainties; all will be carefully monitored in case opportunities develop for OSO involvement toward the late 2020's and early 2030's.

4. OSO's FUTURE ROLE WITHIN SPACE GEODESY AND GEOSCIENCE

OSO today contributes to global space geodesy and geosciences using technology that has developed in parallel with the needs of radio astronomy. A prerequisite for many aspects of geoscience research is a global set of Fundamental Geodetic Stations (FGSs), such as the one located at Onsala, that make observations contributing to the three pillars of geodesy, namely: *Earth rotation* – primarily using radio telescopes via geodetic VLBI. *Geometry* –using geodetic VLBI (see Fig 4) and Global Navigation Satellite System measurements, and *Gravity field* – using gravimeters. The global network of FGS provides a framework to investigate important aspects of the Earth system such as glacial isostatic adjustment, Earth interior dynamical processes, crustal motion, sea level rise, the hydrological cycle, ocean mass transport and the dynamics of the troposphere and ionosphere. The importance of an accurate Global Geodetic Reference Frame for geosciences and a sustainable global development of human society has been recognized by a 2015 United Nations resolution. An additional by-product of the geodesy observations made at Onsala is that they provide absolute measurements of water vapour in the atmosphere, a key parameter for both meteorology and climate change research.

Fig 4. In foreground is the new Onsala Twin Telescope for geodetic VLBI formed from two 13 m diameter dishes. Behind these is the 25 m diameter telescope used for astronomical VLBI.

The geodesy capabilities at Onsala have in recent years been greatly enhanced by the installation of the Onsala Twin Telescopes (OTT, see Fig 4), two fast-slewing 13 m diameter antennas compatible with the new dual-polarized broadband VGOS standard for global geodetic VLBI, a system designed to achieve 1 mm position accuracy on global baselines. The OTT, which was inaugurated in May 2017 and became operational in 2018 is an investment of over 40 Mkr financed jointly by the Knut and Alice Wallenberg foundation and Chalmers. The OTT is long-term project that requires observations over many decades to achieve its scientific goals. Achieving the designed 1 mm accuracy on global baselines will likely take most of the coming decade to understand all systematic effects. OSO plans to play a leading role in this global VGOS effort. It should also be noted that there is a very strong technical synergy effect between the OTT and astronomical VLBI (see Sect 3.1) since both applications use almost exactly the same receiver and data capture technology.

In order to further improve terrestrial reference frame accuracy and the assessment of local and global sea-level rise, the international geodetic research community is working on even more tightly combining together ground-based and satellite geodetic observations. One possibility, in addition to satellites having on-board GNSS receivers and Satellite Laser Ranging retro-reflectors, is that they could also transmit broadband signals to be observed by geodetic VLBI telescopes. The ultimate goal of these efforts is to achieve four-dimensional relativistic geodesy by combining geometry, gravity and time. This goal also requires time and frequency transfer between FGSs over intercontinental distances; a capability that will also open up the study of phenomena that are presently out of reach, e.g. related to general relativity. In order to integrate itself even more closely into the above geodetic goals OSO will investigate the possibility of adding additional geoscience equipment at its site (see Fig 3) using external investment funding from new partners (see below).

The geoscience work at OSO requires long term stable funding for its success. As a centrally scheduled observing activity which is part of a global network of observatories, the geoscience activities goes beyond the VR model of science infrastructure being utilized by distinct individuals or groups of scientific users. The VR funding of OSO's geodesy and geoscience work is an historical consequence of OSO's being a pioneer in geodetic VLBI already four decades ago, when this technique was applied as a new scientific discipline. Today, such observations are in many countries run by national mapping agencies. Over the last few years there has been discussions between OSO and Lantmäteriet, the Swedish mapping, cadastral and land registration authority, on taking over responsibility from VR for the geodetic operations (and potential investments) at OSO. Lantmäteriet is enthusiastic on taking on this this role given OSO data directly feeds into their geoscience research and also helps maintain global absolute reference frame solutions needed for navigation services to society. There are however administrative issues preventing such a transfer at government departmental level (VR and Lantmäteriet belong to different government departments). This strategy document assumes that these administrative hurdles will be overcome so that in the future Lantmäteriet replaces VR as the agency funding geodesy and related geoscience operations and investments at OSO.

5. SPECIFIC GOALS FOR OSO DEVELOPMENT AND USER SUPPORT

Below we describe the expected future role of different aspects of OSO's work, presented under similar headings to the description of OSO's present activities in Section 2.

Onsala Radio Telescopes - 25m and 20m - Wideband receiver upgrade projects for astronomical VLBI for these telescopes are already being designed (see Fig 3), including for the 20 m telescope a simultaneous triple-band receiver (22/43/86 -115 GHz) and a broad band (4 GHz-15 GHz) receiver recording 4 Gbps. Together with a future upgrade of the 25 m telescope to 1.5 GHz – 4 GHz the OSO telescopes will then together be able to simultaneously observe a decade of frequency. The OSO telescopes plan to closely follow the EVN technical roadmap based on its Science Vision, with an ultimate goal by 2030 of being able to capture and correlate a full decade of radio frequency (1.5 – 15 GHz) at data rates of 100 Gbps (see Fig 3). Such a broadband VLBI receiver will provide a prototype for the second generation of SKA receivers.

An important aspect of future receiver development at OSO is dealing with the effect of increasing levels of Radio Frequency Interference over the full range of frequencies observed at OSO (from metre to miilimetre wavelengths overlapping with ALMA). As well as being very active in radio astronomy frequency protection issues at national and European levels OSO is also very much involved in developing technical counter-measures. These activities include deploying superconducting frequency blocking filters, new types of interference resilient amplifiers and using digital filtering and data flagging techniques. Additional efforts must also be made to reduce interference from our own buildings (including our new visitor centre). LOFAR, including the station at Onsala, has already shown that it is possible to work at metre wavelengths in a very challenging interference environment and similar technology will in the future have to be deployed at cm and mm wavelengths. Although the SKA and ALMA sites have much lower terrestrial interference environments than Onsala they are equally susceptible to transmissions from the large constellations of low Earth orbit satellites that are expected to be deployed in the coming decade. The interference resistant technology prototyped at OSO to protect its own telescopes can therefore later be deployed at SKA and at ALMA – so helping protect the billions of Euro investment made in those infrastructures.

Onsala Radio Telescopes - LOFAR - The international LOFAR Telescope runs 50 stations for metre-wave astronomy concentrated in the Netherlands but also includes outrigger antennas located throughout Europe, including a station at Onsala. In the era of SKA the LOFAR telescope provides unique capabilities, especially with its international baselines which provide a metre-wave VLBI capability. The LOFAR community is working on an upgrade (LOFAR 2.0) to be accomplished by the mid-2020's. Phase 1 of this upgrade involves: (A) Upgrading LOFAR stations to form dual beams on the sky even at the High Band Array (110 – 250 MHz) aiding both calibration and allowing, during the day, for a beam to be placed on the Sun for solar monitoring. (B) Allowing simultaneous observations at High-Band and Low-Band (20 MHz to 80 MHz) so that ionospheric phase corrections derived at high band can be applied at Low Band, allowing noise-limited images to be made at Low Band. Phase 2 of the upgrade, which has not yet been decided upon, involves adding additional stations to provide more intermediate baselines between Dutch and the international baselines. Consistent with the strategy of continued OSO involvement in VLBI it is proposed that OSO takes part in the LOFAR 2.0 upgrade project, including the upgrade of the Onsala station costing approximately 6 Mkr.

APEX –This 12m single dish sub-millimetre wavelength telescope in Chile had an extensive upgrade in 2017/2018 and is highly productive scientifically both for single dish observations and via its participation in mm-VLBI. The latter observing mode includes participating in the VLBI observations giving the first image of a Black Hole (see Fig 2). APEX is also equipped with large formal pixel continuum cameras that can be thousands of times faster than ALMA for surveying the sky in continuum emission; acting as both a 'finder telescope' for ALMA and to address types of large sky area coverage science that cannot be addressed by ALMA. The ability to provide initial APEX continuum and spectral line observations continues to give Swedish users a competitive advantage in applying for highly competative ALMA time.

During the present 5-year operating contract for APEX (2018 – 2022) Sweden has a 13% share of APEX, reduced from the 23% it had previously. The status of the APEX project beyond the end of 2022 is unclear, with partner discussions just starting. If, as assumed in this strategy, Sweden decides to be a full partner in SKA construction and operations there will be understandable pressure on the VR budget for radio astronomy. Under such a circumstance savings must be made and it is proposed that OSO would in this case not request in its 2021 VR application any funding for participation in APEX beyond the end of 2022, so saving approximately 4 Mkr/yr. Assuming the APEX project continues beyond 2022 - OSO potentially could maintain a relationship with APEX as a supplier of receivers. Most of the cost of which is in existing OSO manpower, with the capital cost of such a receiver (approximately 4 Mkr) absorbed over three to four years of the OSO budget. In return for supplying such instrumentation Sweden could then receive APEX Guaranteed Observing Time.

Interferometer User Support - Building on the success of the OSO Nordic ARC node for ALMA the expert group at Onsala giving radio/mm interferometer support will be strengthened to also to also support SKA and contribute to the build-up of the European SKA Regional Centre. At present Interferometry support is provided at OSO by Support Scientists comprising 6.9 FTE (of which 70% is used for user support tasks and 30%, funded only by Chalmers, is free research time). This support effort is almost all directed toward ALMA support with only 1.1 FTE of this related at present to supporting SKA development and SKA precursors such as LOFAR. The ongoing EU H2020 AENEAS project charged with designing the European SKA Regional Centre estimates that a national SKA support node (scaled to a large European country such as Italy) requires at the national radio observatories 12 FTE of effort. This is in addition to manpower financed at national Data Centres, for which in the case of Sweden funding has been requested for SNIC as part of the SKA VR-RFI proposal. Assuming 2 FTE of observatory user support is required for each country as minimum and scaling the remainder according to the size of the Swedish astronomical community it is estimated that Sweden will require by 2030 at least 6 FTE for SKA user support at OSO, with this manpower comprising data achieve specialists and programmers in addition to support astronomers. It is expected that the requirements for ALMA support will gradually decline over the next ten years with 4 FTE assumed needed specifically for ALMA support in 2030 giving a total requirement for SKA+ ALMA support of 10 FTE. These figures are still uncertain; the planning of the SKA Regional Centres is ongoing and firmer estimates of total manpower requirements should be available by the time of the next OSO funding proposal in March 2021.

Millimetre Receiver Development - A main focus of the planned future work at OSO’s GARD group concerns increasing both the instantaneous bandwidth and tuning range of (sub)millimetre wavelength receivers. Wider observing bandwidth is one of the main goals of the ALMA 2030 upgrade plan. Likewise wider observing bandwidth is very important for the future development of the Event Horizon Telescope for imaging black holes including for future space-based VLBI projects. New substrates for millimetre receivers being developed by GARD also potentially allow the possibility to have very wide frequency tuning range, for instance making possible a single receiver that covers both Band 6 and 7 of ALMA. Such a development would allow when upgrading ALMA for two receiver bands to be replaced with a single band resulting in large financial savings. GARD also works with advanced technology to produce wideband receivers at frequency >1 THz using Hot Electron Bolometer techniques, which are of interest for future space missions such as the Origins Space Telescope (OST, see Fig 3). Finally at lower frequencies, work is on-going on wideband second stage amplifiers using new materials which promise increased linearity, protection against radio interference and lower cost.

Centimetre Receiver Development – OSO has been a key contributor to the development of ultra-wideband feeds for centimetre wave receivers both for SKA (with 3:1 frequency range) and for VLBI (with 10:1 frequency range). OSO will continue with these developments including building operational wideband receivers for the OSO 20m telescope for VLBI use. OSO is also the coordinator of the Advanced Single Pixel Feeds and Receivers (ASPFR) Advanced instrumentation Programme (AIP) for SKA within which as one of its work packages is looking at the design of a high frequency wideband (15 GHz- 50 GHz) receiver for SKA. Finally OSO is also involved with the SKA Phased Array Feed (PAF) AIP which designs multi-pixel receivers to increase the field of view of radio telescopes. OSO plans to test new technology that will significantly decrease PAF noise to help realize PAFs as an upgrade path for increasing the speed of SKA large sky area surveys.

Geodesy and Geosciences – A primary goal over the next ten years is to work with Onsala's OTT and with the global VGOS community in achieving the VGOS design goals of achieving 1 mm relative antenna position accuracy on global baselines. Achieving this goal will require a deep understanding of all issues of the observing system. This includes taking into account that the observed sources are not points but have internal structures that change with time. Increasing the observing efficiency of VGOS observations is also a challenge and may require investigation of novel methods of globally distributed software correlation. The addition of new geodetic equipment at OSO for observing satellites and determining their orbits is another possibility in order to even more closely integrate ground and satellite based geodesy observations.

Industrial Return – Assuming that the proposal for Swedish participation in SKA construction is successful OSO will in the coming years play an important role in the SKA procurement process for Swedish industrial return working in collaboration with the new Big Science Sweden organization. This will in particular be the case for OSO being the technical manager for the SKA Band 1 receiver project which is expected to be Sweden's largest industrial delivery to SKA. A separate funding request for procurement support is included in the Swedish SKA proposal to VR. In addition the upcoming ALMA 2030 upgrade will also provide additional opportunities for Swedish industry, in particular in the area of digital electronics.

Outreach - Outreach to the public we see as an important role of a facility such as OSO. Contributions in this area are important for maintaining public interest and understanding of science, in particular amongst young people. Outreach is accomplished at OSO activities such as organizing visits to the observatory and having good contacts with media. At present this activity at OSO is entirely supported by Chalmers though there is increasing interest in again supporting this activity at national level. Chalmers and its donating partners are at present contemplating investing 30 Mkr in a new visitor centre at Onsala which would provide an attractive modern exhibition space for schools and the public to visit.

6. IMPROVING STAFF DIVERSITY

Despite recent improvements the OSO infrastructure presently has a significantly uneven gender balance. OSO recognises the many benefits of diversity and is therefore committed to ensure excellent female applicants for every available position. This goal will be accomplished via careful consideration of the content of advertising and by ensuring that such advertising is spread to reach target audiences with significant female representation. We will also seek out and contact excellent individual female candidates to encourage their application. The goal of these efforts is in the decade ahead to reach as closely as possible a gender balanced workforce at OSO. We will also seek to promote a work environment in which everyone at all levels feels ownership and pride in the exciting and successful work of the infrastructure with careful monitoring on work-load to maintain a healthy work-life balance. OSO will argue within Chalmers for an attractive and fair career structure for all the staff that support the infrastructure.

APPENDIX: SCIENCE GOALS OF OSO RELATED ASTRONOMY INFRASTRUCTURES

A1 – ALMA – Below is a summary the expected main science goals of ALMA over the coming decade, highlighting those areas most enhanced by the planned ALMA 2030 upgrade.

- *Cosmology* - ALMA can improve our understanding of polarized mm wavelength galactic dust polarized emission - aiding foreground removal for dedicated experiments to detect the polarized Cosmic Microwave Background primordial 'B modes'. ALMA observations of the Sunyaev-Zeldovich effect in clusters can also be used to accurately estimate cosmological parameters.
- *High Redshift Galaxies* – Submm continuum observations of high z galaxies have the advantage that at larger distances brighter parts of a galaxy's spectrum are observed counteracting dimming due to distance. Continuum observations give dust masses and temperatures while spectral line observations trace evolution of key elements from the first galaxies ($z>10$) through the peak of star formation ($z=2$–4). Wider bandwidths will give more continuum detections, faster molecular spectra and more robust submm-only determinations of redshift.
- *Black Holes and Active Galactic Nuclei* - Continuing Event Horizon Telescope VLBI using ALMA as a key element (see Fig 2) will probe the conditions around the event horizon of the black holes in our Galaxy and in M87. ALMA working alone provides a powerful probe of the kinematics of circumnuclear gas that feeds black holes and provides an accurate means of measuring their masses.
- *Nearby Galaxies and Our Galaxy* – ALMA can make inventories of all the baryons contained respectively within dust, molecules, atoms and ions. The distribution of these phases can then be studied within galaxies, between galaxy types and versus cosmic time. Similar studies of different dust and gas phases can be carried out in our galactic plane and within galactic giant molecular clouds.
- *Origins of Stars and Planets* –Spectral line studies can connect the large scales of molecular clouds and star forming regions to the smaller scales of single star+disk/planets systems tracing the flow of mass and energy. Images of protoplanetary disks in nearby (150 pc) star formation regions can resolve the Earth forming zone (~ 1 AU) in the dust continuum at wavelengths shorter than 1 mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation.
- *Astrochemistry and Astrobiology* - Complex organic molecules can be observed at very low abundance in both pre-stellar cores and protoplanetary disks. The combination of wider bandwidth with very high spectral resolution allowed by the upgrade will give large speed-up factors for such observations.
- *Stellar Evolution* – *S*pectral scans can be used to understand the molecular content and dynamics of the winds from massive stars which distribute heavy elements and dust into the interstellar medium. Observations of supernova remnants can also assess the contribution of these objects to these processes.
- *Solar System* –Solar observations help understand the Sun's outer atmosphere and its heating sources. Observations of the solar system's planets, satellites, asteroids and comets help constrain molecular content of atmospheres and the sizes, shapes and rotation properties of smaller bodies. Molecular observations of comets probe the chemical make-up of the primordial material out of which the solar system formed.

A2 - SKA – A detailed science justification of the SKA is contained within the proposal submitted to RFI for Swedish participation in SKA construction/operations, below is a summary of the main areas of expected science impact.

- *Epoch of Reionization and Cosmic Dawn* - Detect and image highly redshifted atomic hydrogen which starts to radiate when the universe's first ionizing sources heat the intergalactic medium. These observations will trace the last great phase change in the universe, from neutral to ionized, and allow us to probe in detail the epoch of galaxy formation. Close synergies with ALMA and ELT observations of first galaxies exist.
- *Cosmology and Dark Energy* – Distinguish between cosmological models, including determine the equation of state for Dark Energy. This will be accomplished by tracing the angular scale versus redshift of the fixed linear scale of galaxy clustering and also via gravitational lens studies.
- *Galaxy Evolution traced by Spectral Lines and Continuum* – The SKA will use atomic hydrogen and other spectral line tracers to measure the build-up of gas and total dynamic mass of galaxies versus cosmic time, while using radio continuum emission to measure galaxy star-formation rates.
- *Strong-field Tests of Gravity using Pulsars* – General Relativity will be tested in the strong field limit by finding and monitoring Black Hole-Pulsar binaries, while the timing of large samples of non-binary pulsars will be used to detect the cosmic background of nano-Hz gravitational waves.
- *The Origins and Evolution of Cosmic Magnetism* - Approximately 10 million high redshift radio sources will be used to probe magnetic properties of objects along the line of sight including cosmic filaments, clusters and galaxies. These observations will trace how the energetic and dynamically important magnetic fields in the universe are initially generated an how they evolve through time.
- *The Cradle of Life*- Observations will examine the formation of centimetre sized particles in protoplanetary disks at AU scales and the formation of complex pre-biotic molecules in the interstellar medium. This science area overlaps closely with two of the three ALMA future science priorities.
- *Our Galaxy*- Galactic continuum and spectral line surveys will create a full inventory, free from dust obscuration, of supernova remnants, star-forming regions and probe the properties of evolved stars.
- *Transients* – Wide field of view SKA observations are ideal for detecting transients at radio wavelengths (i.e. Fast Radio Bursts) and for accurately locating and studying the structure of transients triggered by other wavebands/messengers (e.g. Black hole Tidal Disruption Events, Neutron Star – Neutron Star gravitational wave detections, Gamma Ray Bursts etc). Radio observations can constrain the material surrounding explosive transient events and along the line of site, and be used as cosmological probes.

A3 – Astronomical VLBI – The European VLBI Network is presently developing a Science Vision document for the coming decade, which is due to be finalized by the end of 2019, below is a summary of the main VLBI science areas identified in the current draft of that document.

- *Physics of Supermassive Black Holes*– Continued observations with the Event Horizon Telescope (using APEX with Swedish participation till 2022) – especially to measure the size shadow in the black hole at the centre of our galaxy (Sgr A*) so testing GR predictions in the strong limit at the 1% level (because for this black hole, unlike M87 the distance and mass are independently and accurately known).
- *Jet Formation from Supermassive Black Holes*.- Discriminate between different models for formation and initial propagation of relativistic jets emerging from supermassive Black holes (like M87*) at the centres of galaxies. Observations can also measure the total strength and three-dimensional structure of magnetic fields in regions within a thousand gravitational radii of the central black hole.
- *Co-evolution of Black Hole accretion and star formation* – Wide-field VLBI observations can distinguish emission from black hole accretion from circumnuclear star-formation, allowing studies of how star-formation and black hole accretion evolve together versus redshift.
- *Location and Evolution of Transient Sources* – Precisely locate extragalactic transients, such as Fast Radio Bursts, Black hole tidal disruption events and electromagnetic counterparts of gravitational wave detections within their host galaxies. Determine the structure of their radio emission to distinguish between jet and spherical interaction models and measure velocities and orientations of relativistic jets.
- *Astrometry of Galactic Objects*- Use VLBI astrometry to give parallax, proper motion and Doppler velocity observations to measure the structure and kinematics of our Milky Way's spiral arms and its inner region even in directions hidden by dust from optical/infra-red observations. A specific VLBI astrometry application is to measure the out of plane motion of the Solar System constraining the galactic disk matter distribution.
- *Formation of Massive stars* – Observation of masers with Doppler and proper motions can be used to probe the 3D dynamics of the collapse process around forming massive stars. Polarization of masers can be to get magnetic field orientations and Zeeman splitting observations to measure in-situ magnetic field strengths on accretion scales.
- *Radio Emission from Stars and Exoplanets* – At radio wavelengths exoplanets around other stars can be detected via direct radio emission from the planets themselves or via position wobbles induced in the radio emitting stars they orbit. In the former case the planetary orbit can be determined by the VLBI observations.