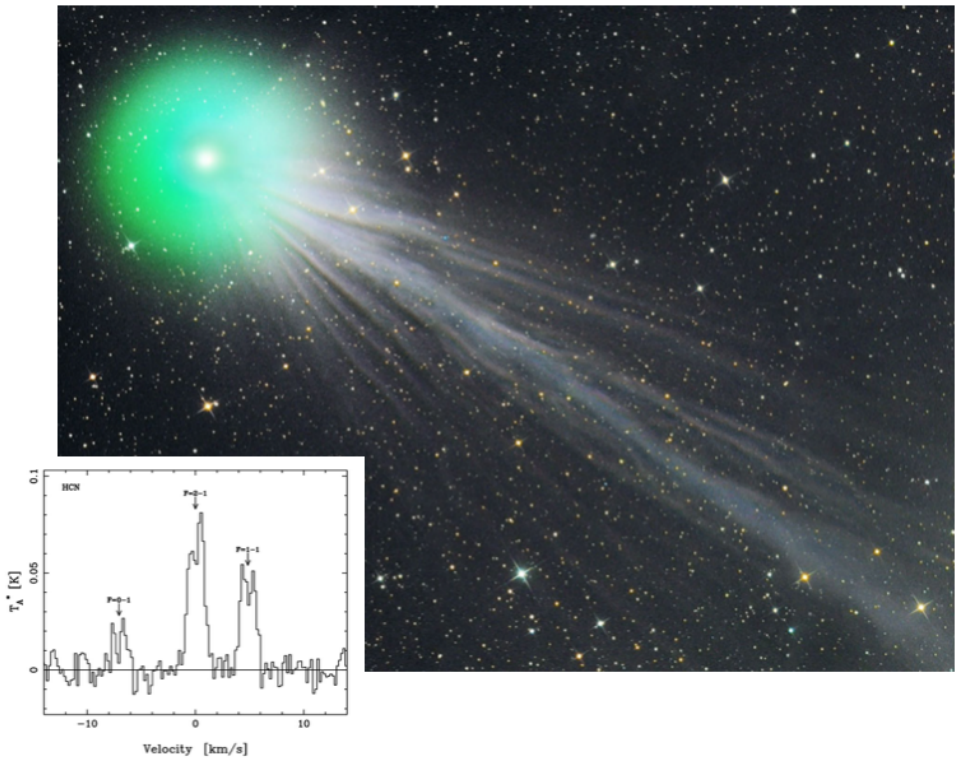
ONSALA RYMDOBSERVATORIUM
CHALMERS TEKNISKA HÖGSKOLA

ONSALA SPACE OBSERVATORY
CHALMERS UNIVERSITY OF TECHNOLOGY

Dnr: RoG 2016-0026-4.7

Report on the activities in 2015 of Onsala Space Observatory The Swedish National Facility for Radio Astronomy

This report presents the activities at Onsala Space Observatory (OSO) during 2015; including the usage of the instruments for scientific purposes, according to the contract for operation of OSO between the Swedish Research Council (VR) and Chalmers.



Cover figure. *Detection of the HCN(J=1-0) line towards the comet C/2014 Q2 (Lovejoy) using the Onsala 20 m telescope (Wirström et al., in press). (Optical image credit: Velimir Popov & Emil Ivanov, IRIDA Observatory)*

Onsala, 15th March 2016

John Conway
Director, Onsala Space Observatory

Contents

This report is divided into the following sections:

1 Operations

During 2015 Onsala Space Observatory (OSO) operated the following facilities:

– The Onsala 20 m telescope for astronomical Very Long Baseline Interferometry (VLBI), geodetic VLBI, and single-dish astronomy
– The Onsala 25 m telescope for astronomical VLBI
– The Onsala LOFAR station as part of the International LOFAR Telescope (ILT) and in stand-alone mode
– The Atacama Pathfinder Experiment telescope (APEX) for single-dish astronomy and astronomical VLBI

– The Nordic ARC node (the Atacama Large Millimeter/sub-millimeter Array Regional Centre node for the Nordic, and Baltic, countries)

– The Onsala aeronomy station for observations of atmospheric H_2O, CO, and O_3
– Two water vapour radiometers (WVRs) to support space geodesy
– The Onsala gravimeter laboratory for absolute and relative gravimetry
– The tide gauges at Onsala
– The Onsala GNSS stations
– The Onsala seismometer station
– The Onsala time & frequency laboratory

Operations using the above facilities are described in more detail below under Telescopes (Sect. 1.1), Nordic ARC node (Sect. 1.2), and Geophysical instruments (Sect. 1.3), respectively.

1.1 Telescopes

In general, all telescopes have operated according to the 2015 activity plan without any major problems, more details are given below:

- **Onsala 20 m telescope:** The 20 m telescope was used in accordance with the 2015 activity plan without any major divergence. This included 45 geodetic campaigns, 18 astronomical SingleDish projects, participation in 4 extended astro-VLBI sessions, 3 teaching and outreach observations, and a number of shorter special campaigns in collaboration with international telescopes. Maintenance (incl. technical observations) occurred at anticipated levels. Significant time in the autumn was spent on the commissioning of a new 4 mm receiver and of a spectrometer bandwidth upgrade.

- **Onsala 25 m telescope:** The Onsala 25 m telescope has operated according to the 2015 activity plan without any major problems during the year.

- **APEX:** A total of 53 days, organized in four runs, of Swedish APEX observations were carried out in 2015. To perform service mode observations, which are organized as three observing shifts per day (afternoon, night, morning), OSO typically sent four observers per run.

  A version of an ALMA Band 5 receiver cartridge (163 – 211 GHz) integrated into a 3-cartridge cryostat was installed on APEX during February/March of 2015. Shortly afterwards, a call for science verification proposals for the new Swedish-ESO PI receiver for APEX for Band 5 (SEPIA-B5) receiver went out to the Swedish community. Accepted proposals were carried out during Swedish runs in the first half of 2015, and subsequently, in the call for proposals for the P96 period, SEPIA-B5 was offered as a regular PI instrument. During April and May, the 64-pixel 345 GHz heterodyne camera SuperCam, with an improved efficiency after parts of the optical system had been replaced, was again available in the Cassegrain cabin at APEX and was used during both Swedish and ESO time.

- **LOFAR:** In International LOFAR Telescope (ILT) mode, the station is controlled centrally by ASTRON. In Local mode, the station is controlled by OSO, and this observing time is partially allocated via an open Call-for-Proposals basis and partially via ILT Call-for-Proposals. In both cases the time is devoted to pulsar research.

- **VLBI:** Very Long Baseline Interferometry observations were conducted using the Onsala 25 m and 20 m telescopes as part of international networks of telescopes. The astronomical VLBI observations were scheduled based on recommendations from time allocation committees [the European VLBI Network TAC and the Global Millimetre VLBI Array (GMVA) TAC]. The International VLBI Service (IVS) scheduled the geodetic VLBI observations for Astrometry and Geodesy.

The usage of the above telescopes was distributed in the following ways:

– The Onsala 20 m telescope:	73 days of single-dish astronomy
	17 days of astronomical VLBI
	45 days of geodetic VLBI
– The Onsala 25 m telescope:	64 days of astronomical VLBI
– The LOFAR station	207 days (ILT), 155 days (local)
– APEX telescope	53 days of single-dish astronomy

Note that time for "normal" technical service, pointing, etc. are not included in the above figures. These service activities amounted to about 25 and 12 days on the 20 m and 25 m telescopes, respectively. There were a number of upgrades to the 20 m telescope in 2015 (e.g., new 4 mm receiver, broader spectrometer), in addition to normal maintenance activities (pointing etc.), which reduced the amount of time available for scientific observations. The time for geodetic VLBI includes 45 regular IVS-sessions in the R1-, RD-, RDV-, T2- and EUR-series. In the autumn, a student team of the University of Applied Sciences in Frankfurt (Germany) visited the observatory and carried out a survey of the reference point of the 20 m radio telescope and the local tie to the reference point of the ONSA GNSS station.

1.2 Nordic ARC Node

In 2015, the Nordic ARC provided support to the Nordic ALMA communities for data reduction and analysis of ALMA data from all observing cycles. Additionally, proposal preparation workshops were organized for the Cycle 3 call for proposals. Basic two-day ALMA proposal preparation tutorials were held at Onsala Space Observatory, Uppsala University (in collaboration with Stockholm University) and the University of Helsinki.

In Cycle 3, more than 50 % of all (62) Swedish co-I/PI were awarded time. Swedish co-I/PI are represented at 117 out of a total of 636 accepted ALMA proposals. The Nordic ARC provided contact scientists for each project with a Nordic PI or leading Nordic co-I. In 2015, contact scientists were assigned for 22 projects. The contact scientists serve as the point of contact between the user and the ALMA project during the phase 2 scheduling block (SB) generation and afterwards. Nordic ARC staff also supported several face-to-face visits for data reduction of 14 Cycle 1, 2, and 3 ALMA proposals (with Nordic PIs or co-Is). Each project has taken an average of two weeks full-time support and so far at least 75 % of all Nordic projects with delivered data have benefited from Nordic ARC face-to-face support.

The Nordic ARC performed quality assessment on more than 80 European ALMA Scheduling Blocks (SB). The majority (>90 %) of these processed SBs were for Nordic projects. Thus, the Nordic ARC performed quality assessment for approximately one fifth of all European delivered data sets.

In January, an international panel reviewed the functioning of the European ARC network, including the Nordic ARC node. The evaluation was highly positive and the report can be found at: http://bele.oso.chalmers.se/nordicarc/outgoing/eu_arc_review_final.pdf. In September, the ARC node organized the annual all-hands meeting of the European ARC node members in Smögen. At these annual meetings, all issues related to e.g. quality assessment, face-to-face support, ALMA operations and data reduction, which are of relevance for functioning of the ARC network, were discussed. In October, the Nordic ARC staff was heavily involved in tutoring at the North-European Radio Astronomy school organised in Finland.

The ARC node continued their development of advanced data analysis tools. These tools are published at the Nordic ARC webpage (www.nordic-alma.se). This year saw updates of the uv-fitting code UVMULTIFIT, and the uv-stacking code STACKER, and the release of several visualization tools. A member of the node staff also further refined the scripts he wrote and designed, which are being used by ALMA to package the data for delivery to the PIs, in order to accommodate the delivery of ALMA total power observations and pipelined data.

In May, the ARC node manager attended the annual ARC node coordinating committee meeting in Leiden. An ARC member of staff also gave (invited) presentations about developments for phasing up the ALMA antennas and the software tools developed within the node at workshops and conferences in Leiden, Tenerife, and Paris.

1.3 Geophysical Instruments

The geodetic VLBI days include regular IVS-sessions in the R1-, RD-, RDV-, T2- and EUR-series. All sessions were recorded with the modern DBBC/Mark5B+ system. Some of them were recorded in parallel on the Flexbuff and both data sets were sent to the Bonn correlator for correlation to evaluate the Flexbuff recordings. The general experience is that the Flexbuff recordings and Mark5B+ recordings are equivalent.

For the other geophysical facilities the activities can be summarised as follows:

- **Aeronomy station:** The aeronomy station performed continuous observations of mesospheric CO, O_3, and H_2O (except for maintenance periods). Mesospheric H_2O profiles from 2014 were delivered to the Network for the Detection of Atmospheric Composition Change (NDACC). The first combined CO and O_3 data from the double-side-band 3mm frontend has been processed and compared to satellite data. A new software defined radio spectrometer has replaced the old auto-correlator system, giving both larger bandwidth and higher resolution.

- **Water Vapour Radiometers:** The two water vapour radiometers Astrid and Konrad measure the amount of water vapour in the atmosphere. Astrid was operating continuously as from May 2015 after replacement of the control unit for azimuth and elevation. Konrad was operating continuously during the first seven months of 2015. During the second half of the year Konrad suffered from problems in the azimuth control system.

- **Gravimeter laboratory:** The main purpose of the gravimeter laboratory at Onsala is to maintain a gravity reference and calibration facility co-located with space geodetic techniques. The facility is one component of the Fundamental Geodetic Station. The laboratory is furnished with platforms for visiting absolute gravimeters, which happens on average one to three times per year. Its primary instrument is a superconducting gravimeter (SCG, model GWR 054). This instrument has been operated with very few breaks in recording (less than 10 days) since its installation in June 2009. Since January 2012 the system delivers one-second data online with two minutes latency at maximum. See http://holt.oso.chalmers.se/hgs/SCG/monitor-plot.html. The records are submitted to the archive of IGETS (International Geodynamics and Earth Tide Service, former Global Geodynamics Project, GGP) at GeoForschungsZentrum (GFZ) Potsdam (Germany), on a monthly routine.

- **Tide gauges:** During 2015 a station using established modern sea level sensors (based on the principles of radar and differential pressure measurements) in order to secure sea level data continuously, also during rough sea surface conditions. The sea level data are fundamental for the geodynamic application of ocean loading effects on the Earth's crust. This new station calls for the highest possible accuracy and is sometimes referred to as the super tide gauge. It is further described in Sect. 7 (Instrument development and upgrades). The GNSS-based tide gauge was operated throughout the year. Data of both GPS and GLONASS were received and analysed with different analysis strategies. Additionally, a dedicated USRP-based GNSS-R sensor for sea-level monitoring focussing on GLONASS signals was developed and operated for several months. An evaluation of the various GNSS-R sensors was performed. A high precision spirit-levelling to the bench marks at the super tide gauge was performed in the autumn by a student team of the University of Applied Sciences in Frankfurt (Germany). The successful GNSS-R tide gauge at Onsala has raised interest of international colleagues working on similar topics. As part of a collaboration with the GeoForschungsZentrum Potsdam in Germany, GFZ's reflectometry instrumentation was operated for validation purposes side-by-side with the Onsala GNSS-R installation throughout the year 2015. The collected data are currently analysed at GFZ.

- **GNSS stations:** OSO's primary GNSS station, called ONSA, is also a part of the SWEPOS network operated by Lantmäteriet. Additionally, it is one of the fundamental reference sites used in the global IGS network, as well as in the European EUREF network. During the period from May 22 to July 8 the ONSA station was out of order due to a failure of pre-amplifiers in the GNSS antenna. During this time, the backup station ONS1 was the primary GNSS station at OSO. Throughout the year, four of the six stations of the dense network were operated in the area of the construction site for the Onsala Twin Telescope, in collaboration with Lantmäteriet. In the autumn, a student team of the University of Applied Sciences in Frankfurt (Germany) visited the observatory and carried out a 3D-survey of this dense GNSS-network.

- **Seismometer station:** OSO hosts a seismograph station of the "Svenska nationella seismiska nätverket" (SNSN) at Uppsala University. We have data access to the local seismometer and keep a continuous archive of its recordings. The station's waveform files are used in delay calibration of the SCG and for noise reduction in absolute gravity measurements.

- **Time and frequency laboratory:** The time and frequency laboratory hosts the hydrogen maser, necessary for VLBI observations, which contributes to the universal atomic time. OSO also collaborates with SP Technical Research Institute of Sweden on a Swedish time-keeping system using a second hydrogen maser and a cesium clock installed at Onsala.

2 Quantitative Measures of Reliability

The reliability of the OSO instruments (telescopes and geoscience equipment) is in general very high. For instance, the downtime of the telescopes due to technical failures is well below an average of 10 %. Most periods of downtime are instead caused by weather effects (rain, wind, etc). The observing efficiency is particularly high for the Onsala 20 m telescope because of the radome enclosure, which makes the telescope operations immune to most weather conditions.

In general, an exact efficiency value for each instrument is difficult to define. In particular, this is the case of the astronomical observations where data quality must be taken into account. The quality is for instance sensitively dependent on the (varying) weather conditions, particularly at mm and sub-mm wavelengths. In addition, the efficiency varies strongly with the complexity of the observations. This is particularly noticeable for sub-mm observations at APEX where the overhead for getting data may be a factor of three even in good weather conditions with no technical issues. In the list below, efficiency is therefore defined as the ratio between the amount of time delivering data (of acceptable quality), including overhead because of telescope movement, pointing, and calibration, and the amount of time allocated to the activity.

– Efficiency of 25 m telescope for astronomical VLBI 93 %
(time lost mainly due to weather)

– Efficiency of 20 m telescope for astronomical VLBI 97 %

– Efficiency of 20 m telescope for cm- and mm-wave single-dish 92 %
(time lost mainly due to weather)

– Efficiency of LOFAR station ILT observations 99 %
stand-alone mode 99 %

– Efficiency of APEX during Swedish time 83 %

– Efficiency of 20 m telescope for geodetic VLBI 97 %

– Efficiency of superconducting gravimeter 100 %

– Efficiency of seismometer 94 %

– Efficiency of aeronomy station, 22 GHz system 90 %
110 – 115 GHz system 70 %

– Efficiency of water vapour radiometers, Astrid 65 %
(no data acquired from Jan.–May, due to problems with the unit for azimuth and elevation control)
Konrad 58 %
(no data acquired from Aug.–Dec., due to problems in the azimuth control system)

– Efficiency of GNSS station 100 %
Based on how many days of data that have been acquired. On the other hand, individual observations, especially at low elevation angles, may be lost or suffer from low signal-to-noise ratio. Typical values are: more than 80 % of all possible observations above the horizon (0 degrees) and more than 95 % of the observations above 15 degrees have an acceptable quality. As mentioned above (Sect. 1.3) the antenna site ONSA was replaced by ONS1 during the spring.

3 User Statistics

In this compilation of user statistics below ‘user’ means an author or co-author of a proposal granted observing time during 2015 on an OSO instrument:

- Onsala 20 m telescope, single-dish: 57

  Of these investigators 22 had a Swedish affiliation, 18 had not used the telescope before; Notably, the number of proposals submitted in 2015 was 18 (about 50% for the 4mm receiver, showing the considerable interest in this less-explored frequency range). During 2015, the over-subscription rate was slightly above 1.

- APEX (Swedish time), single dish: 185

  Of these users 34 had a Swedish affiliation (note most projects with a Swedish affiliated user also had several non-Swedish co-Is). Of the total number of users 61 had not used APEX before on Swedish time. The oversubscription factor on Swedish time was 1.7.

- ALMA/Nordic ARC Node 68

  This is the number of unique Nordic users who were awarded time on ALMA in Cycle 3 (with proposal deadline in 2015). Of these 68, 36 had a Swedish affiliation. The number of unique Swedish PI or co-I on submitted proposals were 62 (so 58 % got ALMA time). In total, there were 117 ALMA proposals with a Swedish PI or co-I.

- Astronomical VLBI: 283

  The handling of proposals, scheduling, etc. is done centrally, mainly through the EVN. OSO does not have direct access to all statistics but we have been informed that in 2015, there were 283 individual users of the EVN (including e-VLBI) and GMVA (The Global mm-VLBI Array). Fifteen of these had a Swedish affiliation. Most VLBI projects included at least one of the Onsala telescopes. The EVN oversubscription rate was 2.6.

- LOFAR: 41 ILT projects (number of users unknown)
  3 users in stand-alone mode

  The Onsala LOFAR station spends the majority of its time operating as part of European network of antennas and a small amount of time operating as a stand-alone station. For the former proposals are submitted centrally to the ILT (International LOFAR Telescope) with headquarters at ASTRON in the Netherlands. Within this time the Executive committee of the LOFAR-Sweden consortium (freely open to membership to all Swedish scientists, see http//lofar-se.org) allocates the Swedish guaranteed time (4.5 % of the total).

Geoscience instruments — contributions to various archives and external projects:

- Geodetic VLBI: Observations are performed as a service to the global geodesy community, i.e., the observations are not primarily performed for particular scientific projects. Given this operational mode it is hard to give the number of users. Geodetic VLBI defines the global geodetic reference system, which is used by a very large number of research projects (e.g., in remote sensing). It can be noted though, that at least 11 refereed publications in 2015 were using geodetic VLBI data acquired with the Onsala 20 m telescope.

- The Onsala Aeronomy Station: Mesospheric water vapour data from 2015 is under processing to be delivered to the international Network for the Detection of Atmospheric Composition Change (NDACC).

- Gravimeter Laboratory: Through an http address, gravimeter data with one-second samples and maximum two-minutes latency is publically available. On a monthly basis, one-minute data is transferred to the IGETS archive at GFZ Potsdam (Germany). IGETS is a service under the auspices of the International Association of Geodesy (IAG). During 2015, three visits with absolute gravimeters have taken place, a two-instrument campaign with a novel quantum gravimeter (GAIN) from Humboldt-University Berlin, Germany and a traditional Micro-g FG5X instrument from Leibniz University Hannover, Germany, in February, and thirdly a visit by Lantmäteriets FG5 in June.

- The GNSS data are available through the SWEPOS archive (http://swepos.lmv.lm.se/), and the International GNSS Service (IGS) (http://igscb.jpl.nasa.gov/) archives.

- Since 2002 OSO provides a computing service for ocean tide loading effect in application to surface displacements and gravity (http://holt.oso.chalmers.se/loading). Being endorsed by the IERS, its main purpose is to provide consistent reduction of these effects to VLBI, GNSS and SLR analysis centres in their preparation of products that maintain the ITRF. Apart from this, the service's logbook hints at a large number of users peripheral or outside the ITRF community in their analysis of GNSS observations. Loading-induced displacements are computed from a range of global ocean tide maps, using 25 sources featuring 8 to 11 tide species each. In 2015, the web site had 1041 different users having placed 16,722 requests for a sum of 57,555 geographic locations—probably non-unique, but many users compare a range of models for their observing stations. The original paper detailing the computation of tide displacements and the oceanic loading effects (Scherneck, Geophys. J. Int. 106, 677, 1991) has been cited 168 times.

4 Peer-reviewed Papers

The list below give the number of papers in refereed journals based on the OSO instruments appearing in 2015 (the numbers are minimum, publications may have been missed):

– Onsala 20 m telescope, single-dish:	5
– APEX, single dish[1]:	64
– SEST, single-dish[2]:	8
– ALMA[3]	13
– Astronomical VLBI:	17
– LOFAR[4]:	25
– Odin aeronomy[5]:	3
– Geodetic VLBI[6]:	11
– GNSS, tide gauge, gravimeter, radiometers[7]:	18

1) Includes Swedish, ESO and MPI time; because OSO contributes to the full APEX operations and because the Swedish SHeFI instrument is used by all partners.
2) The Swedish-ESO Submillimetre Telescope (SEST), an equal collaboration between ESO and OSO was taken out of operation in 2003.

3) These are the ALMA papers in which the Nordic ARC node helped the authors with observation preparation or with data reduction.
4) In addition, there is a large number of publications discussing future observations with LOFAR.
5) Odin aeronomy is mentioned here since OSO played a technically important role in this satellite project.
6) Additionally, one of the main goals for geodetic VLBI is to define the global geodetic reference system, which is used by a very large number of research projects (e.g., in remote sensing accurate positioning is often a necessity both from the ground and from space).
7) The data are found in international data bases and are often used without our knowledge. Especially GNSS reference data are used in numerous analyses and are sometimes not even referenced to the specific station. GNSS data also define the geodetic reference frames for regional scales (land surveying).

In addition, there are papers by OSO staff on R&D within the areas of mm/sub-mm instrumentation and radio-astronomical methods and techniques:

– Technical R&D: 5

5 Selected Scientific Highlights

Below follows a list of scientific highlights selected to illustrate the different instruments and science areas covered by OSO.

Astronomy

Especially highlighted in this section are papers from Swedish astronomers using OSO facilities plus some international results of high science impact that make use of OSO telescopes and/or instrumentation.

5.1 Onsala 20 m telescope single dish

Yun et al. (MNRAS 452, 1523, 2015) reported the discovery of a new young stellar cluster in the outer Galaxy located at the position of an IRAS Point Source Catalog source that was previously misidentified as an external galaxy. Near-infrared imaging and archival Spitzer images confirm the young stellar nature of the sources detected. Near- and mid-infrared photometry indicates that the stars exhibit colours compatible with reddening by interstellar and circumstellar dust and are likely to be low- and intermediate-mass, young stellar objects (YSOs) with a large proportion of Class I YSOs. ^{12}CO, ^{13}CO, and CS lines were detected with the Onsala 20m telescope, with the CO emission well centred near the position of the richest part of the cluster, Fig. 1. The velocity of the molecular lines indicates that the gas is Galactic and located at a distance of about 5.5 kpc, in the outer Galaxy.

The study of pre-stellar cores is essential to understanding the initial stages of star formation. Parikka et al. (A&A 577, 69, 2015) selected 21 cold clumps, as a follow-up on original Planck and Herschel detections, and mapped these in the ^{13}CO(1-0), C^{18}O(1-0), and N_2H^+(1-0) lines using the Onsala 20m telescope, to find out if these cold clumps are pre-stellar. They calculated the clump masses and densities from the dust continuum and molecular line observations and compared these to each other and to the virial and Bonnor-Ebert masses calculated for each clump. They also examined two of the fields with radiative transfer models to estimate CO abundances. The results indicate that most cold clumps in their sample, with dust temperatures of less than 15 K, are not necessarily pre-stellar.

In January 2015, the new dual-polarisation, sideband-separating 3mm receiver system was used to observe HCN emission from comet C/2014 Q2 (Lovejoy) only 16 days before its perihelion. All three hyperfine components were clearly detected in just above 6 hours of observation time, Fig. 2. Analysis presented in Wirström et al. (2016, in press, arxiv:1602.07078) implies a global HCN abundance relative to water of 9×10^{-4}, very similar to what was obtained from observations at the IRAM 30 m telescope. This demonstrates the excellent performance of the available receiver system at the Onsala 20 m telescope for comet observations.

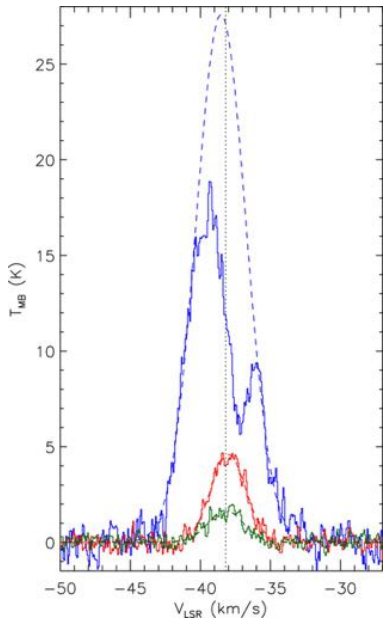


Figure 1. *Spectra of the three observed lines towards the centre position of the CO map, corresponding to the location of the IRAS source. Blue: ^{12}CO(1–0); red: ^{13}CO(1–0); green: CS(2–1).*

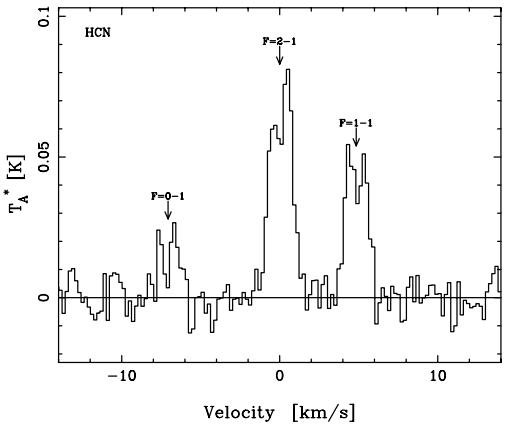


Figure 2. *HCN (J=1-0) spectrum for comet C/2014 Q2 (Lovejoy) on January 14, 2015. The three hyperfine components are marked with arrows. (Wirström et al., in press, arxiv:1602.07078).*

Lundquist et al. (ApJ 806, 40, 2015) conducted a ^{13}CO survey of a sample of 128 infrared colour-selected intermediate-mass star-forming region (IM SFR) candidates. They utilized the Onsala 20 m telescope to observe ^{13}CO(1–0) toward 67 northern IM SFRs, the 12 m APEX telescope to observe ^{13}CO(2–1) toward 22 southern IM SFRs, and incorporated an

additional 39 sources from the Boston University Five College Radio Astronomy Observatory Galactic Ring Survey which observed ^{13}CO(1–0). They detected ^{13}CO(1–0) in 58 of the 67 northern sources and ^{13}CO(2–1) in 20 of the 22 southern sources. The mean molecular column densities and ^{13}CO line widths in the inner Galaxy are higher by factors of 3.4 and 1.5, respectively, than in the outer Galaxy. They attribute this difference to molecular clouds in the inner Galaxy being more massive and hosting star-forming regions with higher luminosities on average than in the outer Galaxy. IM SFRs have a mean molecular column density of 8×10^{21} cm^{-2}, a factor of 3.1 lower than that for a sample of high-mass regions, and have a mean ^{13}CO line width of 1.84 km/s, a factor of 1.5 lower than that for high-mass regions. They demonstrate a correlation between ^{13}CO line width and infrared luminosity as well as between molecular column density and infrared luminosity for the entire sample of intermediate-mass and high-mass regions. IM SFRs appear to form in distinctly lower-density environments with mean line widths and beam-averaged column densities a factor of several lower than in high-mass star-forming regions.

The ratio of the two stable isotopes of nitrogen, ^{14}N and ^{15}N, varies greatly among solar system bodies. The origin of this isotopic anomaly is still an unsolved puzzle. Insight can be gained from measurements of the nitrogen isotopic composition in the gas around protostars in different evolutionary stages. Wampfler et al. (in prep.) used the 3mm receiver to study the nitrogen isotopic composition in a sample of 6 protostars in Perseus using several molecular tracers, Fig. 3. For instance, they can derive the ^{14}N/^{15}N isotopic ratio from the integrated intensities of H^{13}CN(1-0) and HC^{15}N(1-0). An important advantage of using the J=1-0 rotational transitions in the 3mm band is that the hyperfine structure splitting of H^{13}CN is resolvable. From the resolved hyperfine pattern, they can estimate the optical depth, which is a crucial parameter in the derivation of the ^{14}N/^{15}N ratio. The broad instantaneous bandwidth of the new receiver allows one to observe both isotopologues simultaneously and hence reduce the calibration uncertainty from the absolute calibration uncertainty (usually around 10-20 %) to the relative calibration uncertainty across the band, which is normally within just a few percent. In this way, Wampfler et al. obtained much more precise isotopic ratios. The derivation of the isotopic ratios is currently work in progress, but even the faint ^{15}N-bearing isotopologues are well detected at a signal to noise of more than 5 for the majority of the protostars in their sample.

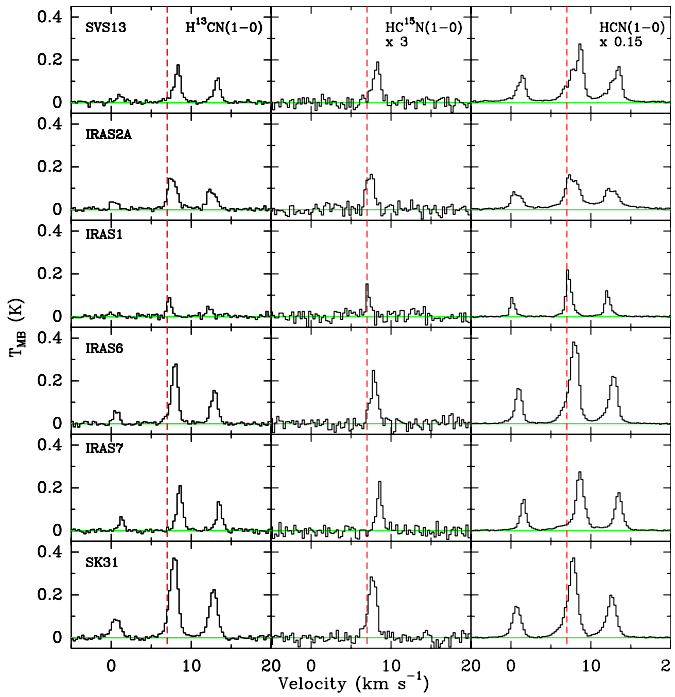


Figure 3. *An overview of the isotopologues of HCN ($H^{13}CN$, $HC^{15}N$, and HCN from left to right) for the mini-survey of six protostars in Perseus (Wampfler et al., in prep.).*

5.2 Astronomical VLBI

Extending the time baseline from two years to more than ten years, Kirsten et al. (A&A 577, 111, 2015) measured the parallax and the proper motion for the three isolated pulsars B1929+10, B2020+28, and B2021+51 in a global VLBI experiment including the OSO 25 m telescope. Combining their 5 GHz data with that from Brisken et al. (ApJ 571, 906, 2002) and Chatterjee et al. (ApJ 604, 339, 2004) their data on B1929+10 indicates a distance of 360 +/- 7 pc, Fig. 4. In combination with the measured proper and inferred transverse velocity the authors trace the pulsar's trajectory back in time through the Galactic potential. They conclude that the previously made claim that the pulsar once formed a binary system with the runaway O-star z Oph is very unlikely. They also conclude that the putative common binary origin of B2020+28 and B2021+51 in the Cygnus Super-bubble is very unlikely.

Since 2009, Surcis and collaborators have been running a large VLBI project with the EVN, including the OSO 25 m telescope, to measure the magnetic field at AU scales around 31 massive young stellar objects (YSOs). By observing the polarised emission of 6.7 GHz methanol masers the structure of the magnetic fields for 19 sources have been obtained so far, an example is shown in Fig. 5. A first statistical analysis of these sources reveals that the magnetic field around the YSOs is preferentially oriented in the same way as the molecular outflows ejected from the sources (Surcis et al., A&A 578, 102, 2015). For several sources it was possible to obtain a detailed description of the magnetic field.

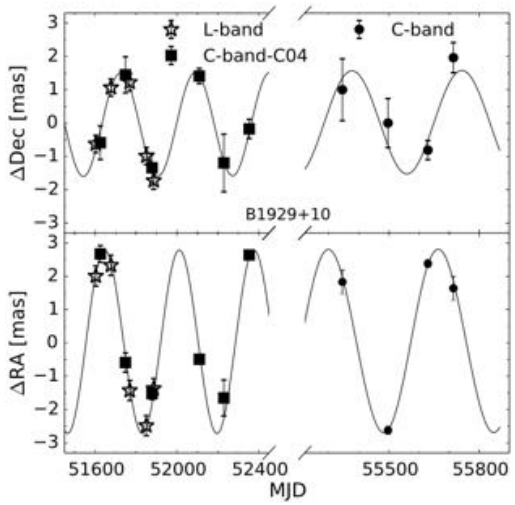


Figure 4. *Relative measured positions of B1929+10 with the best fit proper motion removed. The solid line is the best fit parallax from all available data combined. Solid dots show the most recent measurements at 5 GHz, open stars are the data from Brisken et al. (ApJ 571, 906, 2002), and squares are the data from Chatterjee et al. (ApJ 604, 339, 2004). (Kirsten et al., A&A 577, 111, 2015)*

Frey et al. (MNRAS 455, 2058, 2016) observed four hot dust-obscured galaxies (hot DOGs) with the EVN, including the OSO 25 m telescope, at 18 cm. Hot DOGs are a rare class of hyper-luminous infrared galaxies identified with the WISE satellite. The majority of them is at a redshift of z=2–3. Their observations support that an Active Galactic Nucleus (AGN) residing in a hot DOG may be a genuine young radio source where starburst and AGN activities coexist.

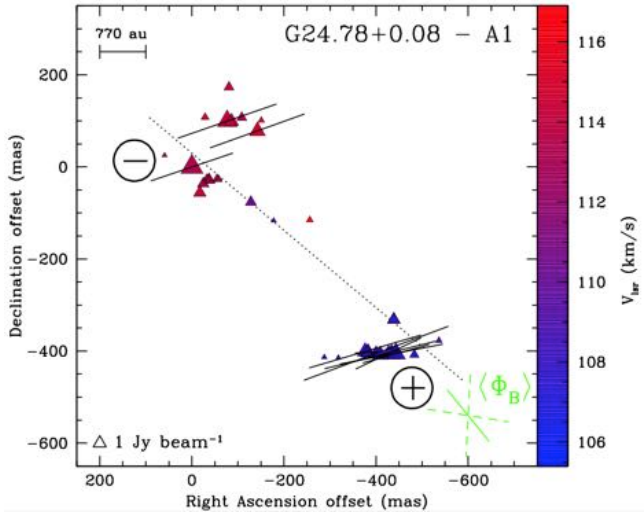


Figure 5. *A view of the methanol maser features detected in the massive star-forming region G24.78+0.08. The black segment represents the linear polarisation vectors of the methanol maser feature. The magnetic field is perpendicular to the linear polarisation vector. (Surcis et al., A&A 578, 102, 2015)*

Using a combination of archival radio and Chandra X-ray data, together with new observations, such as EVN data at 18 cm (including data from the OSO 25 m telescope), Argo et al. (MNRAS 452, 1081, 2015) have investigated a spectacular radio outburst in the

polar-ring galaxy NGC660. The EVN data reveal a new, bright radio source at the location of the black hole with a typical core-jet structure associated with nuclear activity.

5.3 LOFAR

An important milestone for LOFAR is the imminent public release of the Multifrequency Snapshot Sky Survey (MSSS). Heald et al. (A&A 582, A123, 2015) presents this unique, extensive survey of the low-frequency northern sky, Fig. 6. MSSS provides information on the spectral properties of the detected sources in the frequency range 30 to 160 MHz. The broad frequency coverage, in combination with the fast survey speed generated by LOFAR's multi-beaming capabilities, make MSSS the first survey of the sort anticipated to be carried out with the forthcoming Square Kilometre Array (SKA).

Shulevski et al. (A&A 583, A89, 2015) used LOFAR for a study of the steep spectrum source VLSS J1431.8+1331. Steep spectrum radio sources associated with AGNs may contain remnants of past AGN activity episodes. Studying these sources gives us insight into the AGN activity history. Analysis suggests that VLSS J1431.8+1331 is an intriguing, two-component source, Fig. 7. The larger component seems to host a faint radio core, suggesting that the source may be an AGN radio relic.

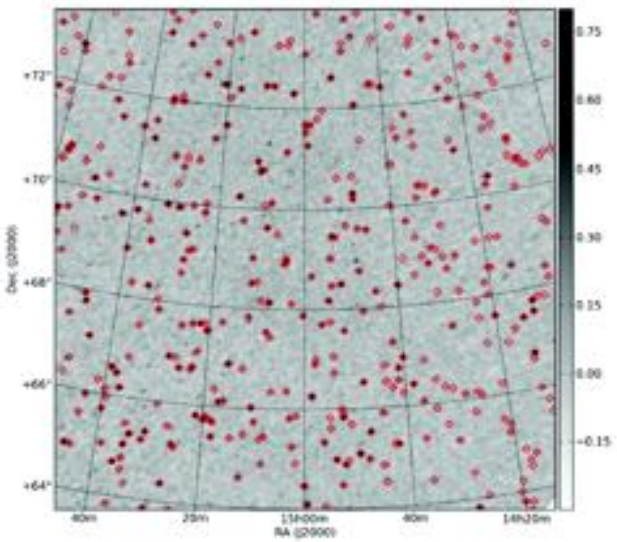


Figure 6. *The MSSS Verification Field (MVF) for LOFAR LBA. Diamonds mark the positions of catalogued VLA Low-Frequency Sky Survey sources. (Heald et al., A&A 582, A123, 2015)*

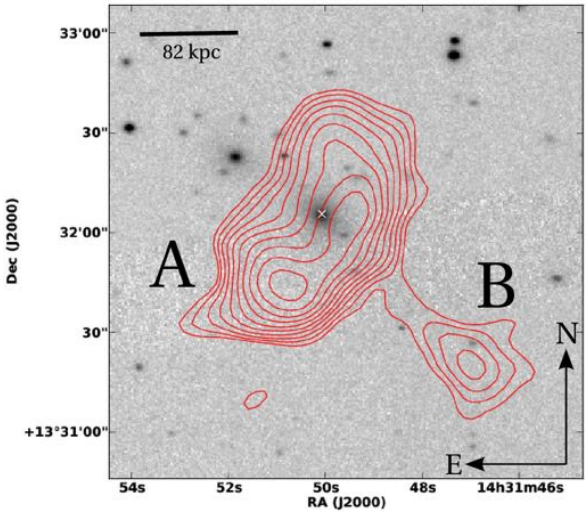


Figure 7. *LOFAR HBA image contours (red) of VLSS J1431.8+1331 (centred on 148 MHz and with a bandwidth of 48 MHz) superposed on a Sloan Digital Sky Survey (SDSS) greyscale image of the galaxy cluster maxBCG J217.95869+13.53470. (Shulevski et al., A&A 583, A89, 2015)*

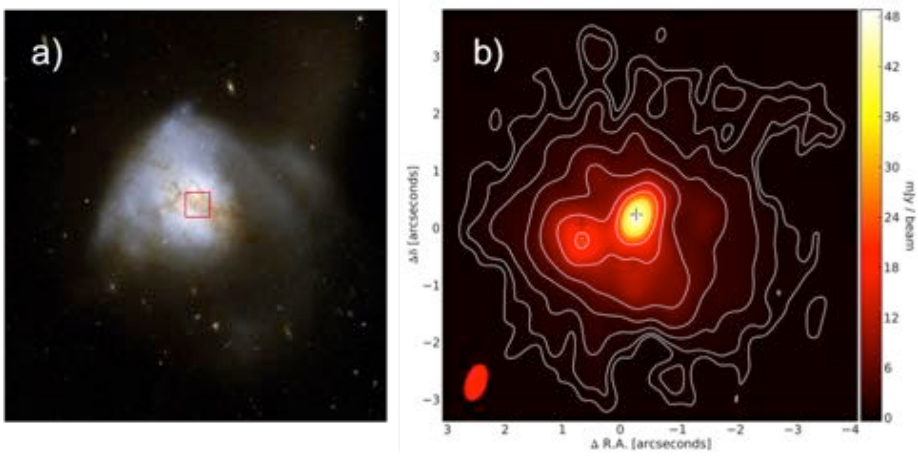


Figure 8. *a) Arp 220 at optical wavelengths. The box indicates the extent of the LOFAR image. b) A zoom into the centre of the merging galaxy Arp 220, obtained with LOFAR at 150 MHz. The crosses indicate the position of the merging nuclei as seen at GHz frequencies. (Varenius et al. 2016, in prep.)*

The galaxy Arp 220 is a fascinating object. At 77 Mpc distance it is the prototypical nearby Ultra Luminous Infrared Galaxy (ULIRG), an optical image can be seen in Fig. 8a. ULIRGs are extremely intense sources of emission at many wavelengths, and thus are examples of extreme astrophysical environments. Many ULIRGs are thought to be powered by very intense star formation, or an AGN, or a mix of both. Arp 220 is also a merging system of two galaxies with two compact nuclei about 1" apart on the sky, Fig. 8b. Studies of the two nuclei, with active star formation and possible AGN activity, thus require high spatial resolution. Although Arp 220 has been studied extensively for decades, it has not been possible to image this galaxy with high enough resolution at meter wavelengths to study the two nuclei in detail. By using the experience from the record-breaking LOFAR imaging of the galaxy M82 by Varenius et. al (A&A 574, A114, 2015), the group has now for the first time obtained an image of Arp 220 at 150 MHz with sub-arcsecond resolution, using the International LOFAR telescope (Varenius et al., 2016, in prep.). Preliminary conclusions reveal a surprisingly low amount of thermal gas in the two nuclei. Another new result is the

relatively weak but extended (5", Fig. 9b) synchrotron emission surrounding the two nuclei. Because of its steep spectrum, this extended emission is very challenging to detect at higher frequencies. Last but not least, the LOFAR image shows offsets between the peaks of emission at 150 MHz and the position of the nuclei at GHz frequencies, Fig. 8b. This may be evidence for outflows in the nuclei, which could be direct evidence for AGN activity. However, strong winds driven by massive star formation could also give rise to similar outflows, as seen in the previous LOFAR images of M82.

5.4 APEX

Using mapping observations of the very dense ρ Oph A core, Liseau et al. (A&A 578, A131, 2015) examined standard 1D and non-standard 3D methods to analyse data of far-infrared and sub-mm continuum radiation. The resulting dust surface density distribution, obtained from LABOCA/SABOCA observations with APEX, can be compared to that of the gas. The latter was derived from the analysis of molecular line emission, observed with Herschel from space and with APEX from the ground, Fig. 9. They found that the gas-to-dust mass ratio is varying across the map. The exponent of the power-law description for the dust opacity, β, exhibits a clear dependence on evolutionary stage, with high values of 2 for the envelope-dominated emission in starless Class-1sources to low values close to 0 for the disk-dominated emission in Class-III objects, and intermediate values for evolutionary classes in between. Since β is primarily controlled by grain size, grain growth mostly occurs in circumstellar disks.

Liseau & Larsson (A&A 583, A53, 2015) extended their search for HOOH, believed to be correlated with O_2, to Orion, after the previous successful detection of this molecule in ρ Oph A. Line emission at the appropriate LSR-velocity and at the level of >4σ was found for two transitions, with lower signal-to-noise ratio (2.8-3.5σ) for another two transitions, whereas for the remaining transition, only an upper limit was obtained. The extremely high spectral line density in Orion makes the identification of HOOH much more difficult than in ρ Oph A. As a result of having to consider the possible contamination by other molecules, the current detection status is undecided.

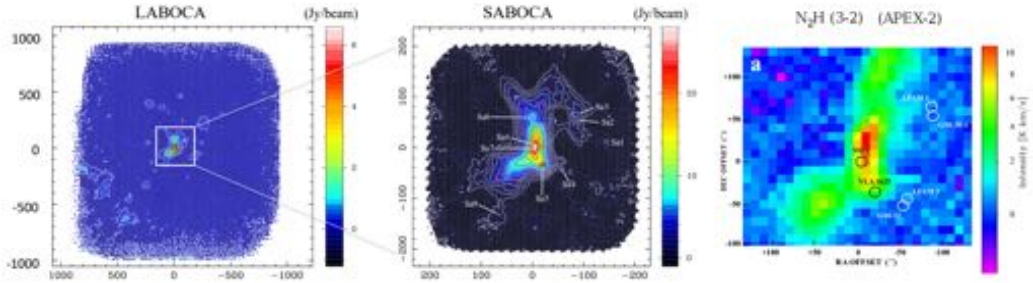


Figure 9. *ρ Oph A observed at 870 μm with LABOCA, at 350 μm with SABOCA, and with APEX-2 in the N_2H^+(3-2) line at 280 GHz. (Liseau et al., A&A 578, A131, 2015)*

CI line emission at 492 GHz was detected by Olofsson et al. (A&A 582, A102, 2015) towards R Scl, Fig. 10. The line intensity is dominated by emission from the detached shell surrounding the star, presumably as a result of a recent thermal pulse. The detection is at a level consistent with the neutral carbon coming from the full photo-dissociation of all species except CO, and with only limited photo-ionisation of carbon. The best fit to the observed ^{12}CO and ^{13}CO line intensities, assuming a homogeneous shell, is obtained for a shell mass of ≈ 0.002 M_{sun}, a temperature of ≈ 100 K, and a CO abundance with respect to

H_2 of 10^{-3}. The estimated CI/CO abundance ratio is ≈ 0.3 for the best-fit model. However, a number of arguments point in the direction of a clumpy medium.

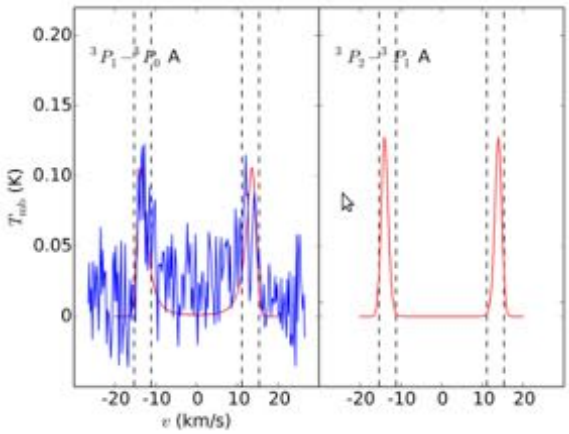


Figure 10. *Left: The CI($^3P_1$–$^3P_0$) observed (blue; APEX-3) and model (red) line spectrum of R Scl. Right: The CI($^3P_2$–$^3P_1$) model line spectrum of R Scl. (Olofsson et al., A&A 582, A102, 2015)*

Wallström et al. (A&A 574, A139, 2015) used APEX CO data and optical spectroscopy to investigate the properties of the Fried Egg nebula, which surrounds the putative yellow hypergiant IRAS 17163-3907. CO(2-1, 3-2) line emission was detected for the first time from its circumstellar medium, Fig. 11. The CO lines show a multi-component asymmetrical profile, and an unexpected velocity gradient in the east-west direction, suggesting a bipolar outflow. This is in contrast with the apparent symmetry of the dust envelope as observed in the infrared. The optical and radio data supports the classification as a yellow hypergiant.

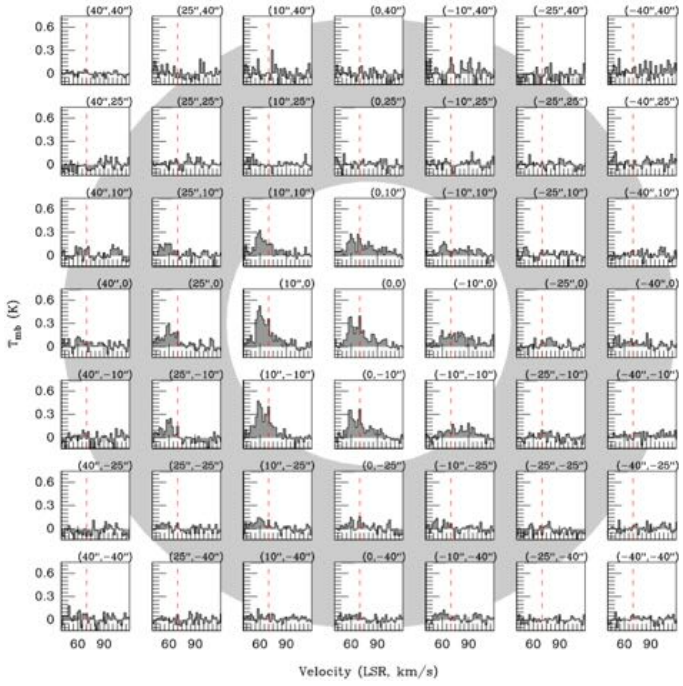


Figure 11. *Map of the CO 2−1 emission from the Fried Egg nebula, with the star at (0, 0). The grey background ring shows the location and extent of the 25" dust ring seen in the far-infrared. Most of the CO emission is found inside this dust ring. (Wallström et al., A&A 574, A139, 2015)*

Moor et al. (ApJ 814, 42, 2015) used the APEX and IRAM 30m telescopes to search for CO gas in 20 bright debris disks. In one case, around the 16 Myr old A-type star HD131835, they discovered a new gas-bearing debris disk, where the CO(3-2) line was successfully detected, Fig. 12. No other individual system exhibited a measurable CO signal. Herschel Space Observatory far-infrared images of HD131835 marginally resolve the disk at both 70 and 100 μm, with a characteristic radius of ≈ 170 AU. While in stellar properties HD131835 resembles β Pic, its dust disk properties are similar to those of the most massive young debris disks. With the detection of gas in HD131835 the number of known debris disks with CO content has increased to four, all of them encircling young (< 40 Myr) A-type stars. Based on statistics within 125 pc, we suggest that the presence of a detectable amount of gas in the most massive debris disks around young A-type stars is a common phenomenon.

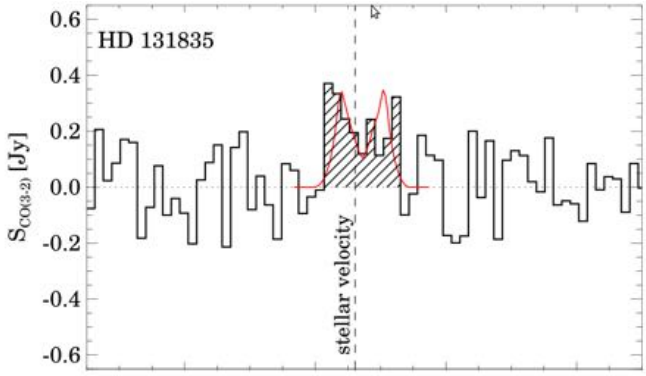


Figure 12. *APEX CO(3–2) spectrum of HD131835. The dashed line marks the radial velocity of the star. The best-fit model spectra are plotted by red lines.(Moor et al., ApJ 814, 42, 2015)*

Hacar et al. (2016, in press, arxiv:1511.06370) investigated the kinematic properties of the Musca cloud, in order to characterize the internal dynamical properties of filaments. They sampled the main axis of this filamentary cloud in the ^{13}CO and C^{18}O (2–1) lines using APEX-1, Fig. 13. The different line profiles show that this cloud presents a continuous and quiescent velocity field along its ≈ 6.5 pc of length. With an internal gas kinematics dominated by thermal motions (i.e., $\sigma_{NT}/c_s \approx 1$) and large-scale velocity gradients, these results reveal Musca as the longest velocity-coherent, sonic-like object identified so far in the ISM. The transonic properties of Musca present a clear departure from the predicted supersonic velocity dispersions expected in Larson's velocity dispersion-size relationship, and constitute the first observational evidence of a filament fully decoupled from the turbulent regime over multi-parsec scales.

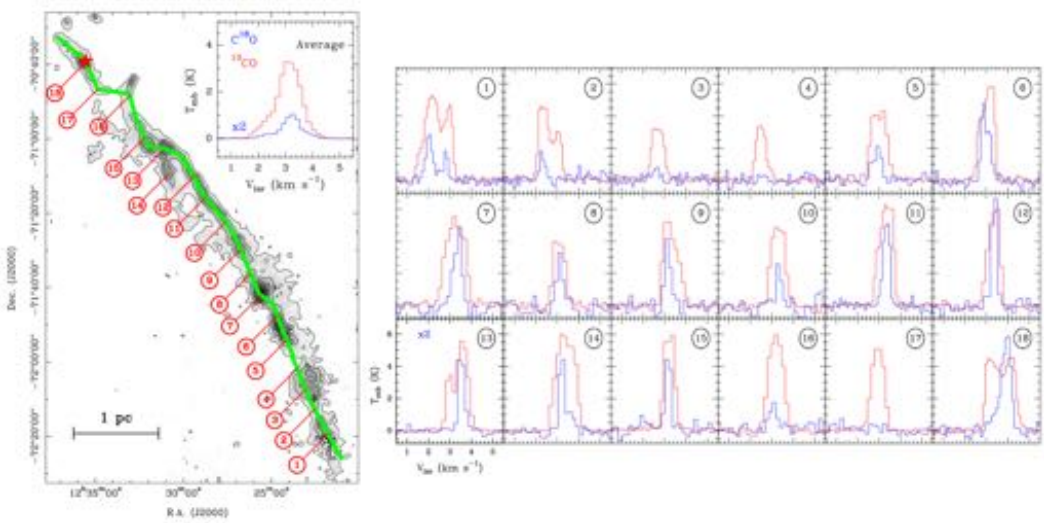


Figure 13. *Left: Total column density map derived from NIR extinction measurements. The contours are equally spaced every 2 magnitudes in A_V. The 300 positions surveyed by the APEX observations in both the ^{13}CO and $C^{18}O$ (2–1) lines are marked in green following the main axis of this filament. The red star in the upper left corner denotes the position of the T Tauri source IRAS12322-7023. Right: ^{13}CO(2–1) (red) and $C^{18}O$(2–1) (blue; multiplied by 2) line profiles found in different representative positions along this cloud (spectra 1-18), all labeled on the map. The averaged spectra of all the data available inside this region are also shown in the upper right corner of the extinction map. (Hacar et al., 2016, in press, arxiv:1511.06370)*

The first VLBI publication including APEX was published in 2015. Fringes at 230 GHz were found towards the blazar 3C279 between APEX, the phased submillimeter array (SMA) on Hawaii, and the Submillimeter Telescope (SMT) of the Arizona Radio Observatory (ARO) by Wagner et al. (A&A 581, A32, 2015). The baseline lengths varied between 2800 Mλ to 7200 Mλ and a fringe spacing of 28.6 micro-arcseconds was achieved. The visibility data suggest an emission region ≲ 38 micro-arcseconds in size, and at least two components. A lower limit to the brightness temperature of the inner jet region of 10^{10} K is obtained. The angular resolution achieved here allows one to resolve the last-photon ring around the Galactic Center black hole event horizon, expected to be about 40 micro-arcseconds in diameter, and to probe radio jet launching at unprecedented resolution, down to a few gravitational radii in galaxies like M 87.

5.5 ALMA observations supported by the Nordic ARC node.

Using the combined high-z sensitivity of ALMA thermal dust emission from a redshift z=7.5 galaxy was detected for the first time (Watson et al., Nature 519, 327, 2015), Fig. 14. The data was initially reduced and optimised at the Nordic ARC node at OSO, providing the best possible results. A1689-zD1 has one of the highest known redshifts, which was determined using the VLT, and it is located behind the massive galaxy cluster A1689, which is magnifying the light of A1689-zD1 by a factor ≈9. The galaxy is a "normal" starburst galaxy in the sense that it is not a quasar or a bright sub-mm galaxy (SMG), which are otherwise the only other early-universe sources with dust continuum detections. A1689-zD1 is estimated to have a stellar mass of $2x10^9$ M_{sun}, a star formation rate of 12 M_{sun}/yr, and a dust mass of $4x10^7$ M_{sun}. Discovering this relatively large amount of dust has been a surprise and the result implies that there is still a lot to learn about how dust is produced during the

early stages of galaxy formation. The discovery is published in Watson et al., 2015, Nature 519, 327.

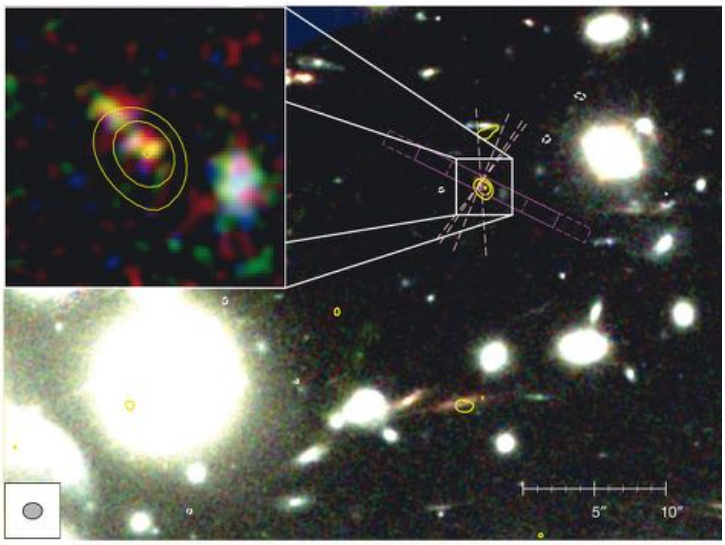


Figure 14. *HST image of the galaxy cluster Abell 1689. The zoomed box shows A1689-zD1. Contours indicate the far infrared dust emission detected by ALMA at 3, 4 and 5σ. (Watson et al., Nature 519, 327, 2015)*

Applying a novel analysis technique to ALMA observations of the gravitationally-lensed blazar PKS1830-211, Marti-Vidal et al. (Science, 348, 311, 2015) reported the highest polarization rotation measure (RM) ever detected in the Universe at sub-mm wavelengths, Fig. 15. This RM (of the order of tens of millions of radians per square meter, in the frame of the source) is originating very close to the base of the relativistic blazar's jet, and encodes information about the physical conditions (plasma density and magnetic-field geometry and strength) at a few tens of milliparsec from the event horizon of the central engine. The new analysis technique (called "dual differential polarimetry") has been developed by the team, and can eventually be used even in interferometric observations where the cross-hand polarisation products are missing.

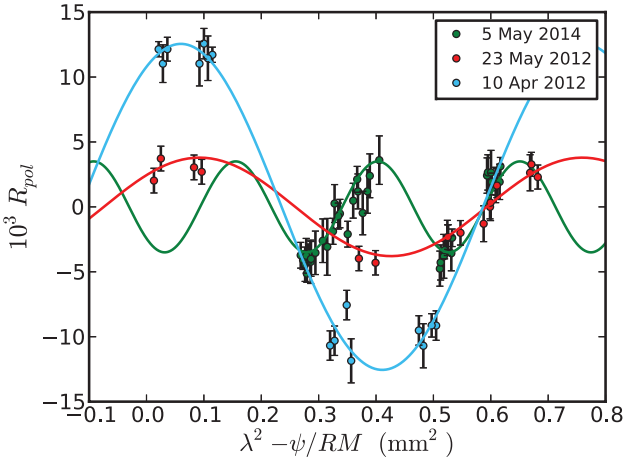


Figure 15. *Fits to the polarization ratio between the two components of the lensed blazar PKS 1830-211 for three epochs at 250 GHz and 300 GHz. The sinusoidal pattern directly reveals the large rotation measure. (Marti-Vidal et al., Science, 348, 311, 2015)*

Using ALMA Science Verification data reprocessed, and analysed with tools developed at, the Nordic ARC, the first resolved sub-mm image was made of an evolved star (Vlemmings et al., A&A 577, L4, 2015), Fig. 16. The observations revealed what seems to be a gigantic flare on the surface of Mira A, one of the closest and most famous red giant stars in the sky. Activity like this in red giants – similar to what we see in the Sun – comes as a surprise to astronomers. The discovery could help explain how winds from giant stars make their contribution to our galaxy's ecosystem. Not only was Mira A itself resolved, but the observations also revealed the size of the ionized wind around its companion, a white-dwarf called Mira B. The size of Mira B's ionized region places limits on the accretion of the material expelled by Mira A and captured by Mira B.

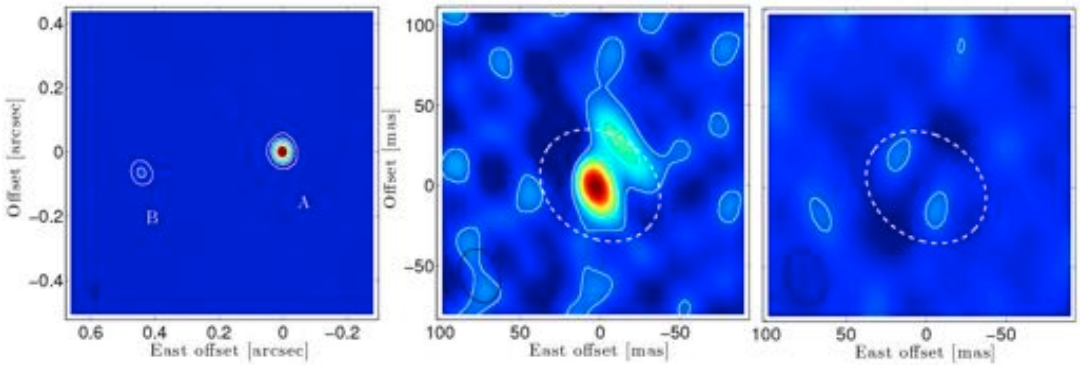


Figure 16. *Continuum image of the Mira AB binary at Band 6 (left). Residuals in Band 6 at the location of Mira A after subtracting the best-fit stellar-disc model (middle) and the disc model including a compact Gaussian hotspot (right) from the visibilities. The dashed ellipse indicates the size of the fitted stellar disc. (Vlemmings et al., A&A 577, L4, 2015)*

HD101584 is a bright object in the sky, but its true nature has been a matter of some considerable debate. It is now believed to be a binary stellar system where the primary has just left its evolution as a red giant and is evolving to become a white dwarf. It is further believed that the red giant evolution was terminated when the companion was captured by the red giant (the companion nevertheless survived and is now found at a distance of about 0.7 AU from the primary). The object shows some remarkable emission lines from CO molecules in the circumstellar environment. This emission has now been mapped using ALMA (Olofsson et al., A&A 576, L15, 2015), Fig. 17. The data outlines a high-velocity (150 km/s) molecular jet, almost along the line of sight, which has excavated an hour-glass shaped structure in the circumstellar gas. The age of this phenomenon is estimated to be about 500 years, and it is suggested that it is the effect of the capture of the companion. The released orbital energy has contributed to the ejection of the jet, but the data shows that it is not enough. Another process must help in the ejection, e.g. an accretion disc around the companion. In addition to this high-velocity gas, the data shows that about a solar mass of material rests in an unresolved (by ALMA) region centered on the stars. This is presumably left-over material from the red giant that has now assembled in the form of a circum-binary disc.

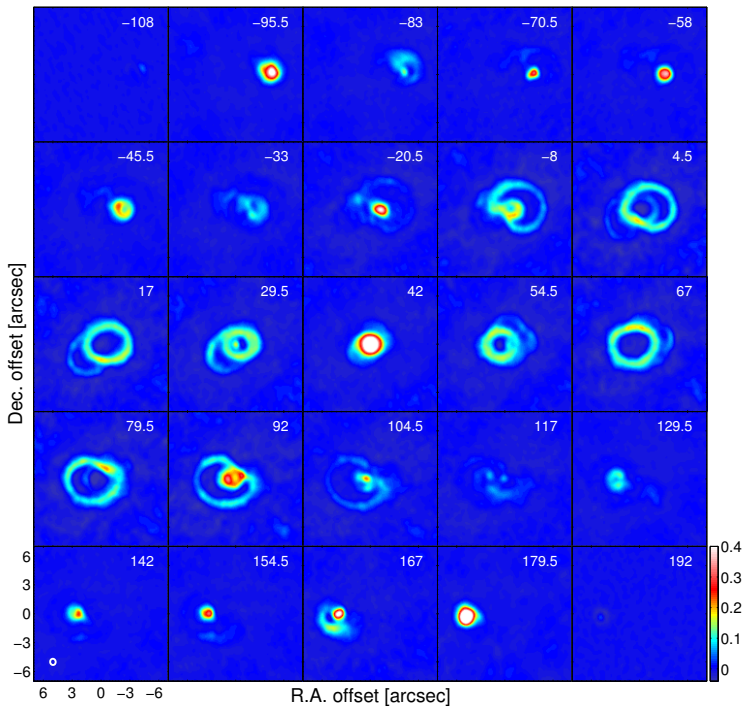


Figure 17. *Velocity-channel maps (Δv=12.5 km s−1) of the 12CO(J = 2–1) emission obtained with ALMA towards HD101584 (synthesized beam in the lower left corner). The intensity scale unit is Jy/beam (noise rms 2 mJy/beam). (Olofsson et al., A&A 576, L15, 2015)*

Geosciences

5.6 Inter-continental frequency transfer with VLBI and GPS

Hobiger et al. (Metrologia 52, 251, 2015) showed that the combination of GPS and VLBI on the observation level using the multi-technique software c5++ allows to achieve frequency-link instabilities that are better than corresponding results from individual analysis of only VLBI or GPS data. The test-bed for this study was the CONT11 VLBI campaign observed in 2011, where OSO contributed. Individual analyses of VLBI and GPS data with independent technique-specific analyses give frequency link instabilities at the level of 10^{-14} to 10^{-15} (MDEV) on inter-continental baselines for averaging times of one day. The combination approach leads to small but consistent improvements for frequency transfer of up to 10 %, in particular for averaging periods longer than 3000 s.

5.7 Local-tie determination with GPS on the 20 m radio telescope

Two gimbal-mounted GNSS antennas were installed on each side of the Onsala 20 m telescope. GPS data with a 1 Hz sampling rate were recorded for five semi-kinematic and four kinematic observing campaigns. These GPS data were analysed together with data from the IGS station ONSA with an in-house Matlab-based GPS software package, using the double-difference analysis strategy. The coordinates of the GNSS antennas on the telescope were estimated for different observation angles of the telescope, at specific epochs, and used to calculate the geodetic reference point of the telescope. The local tie vector between the VLBI and the ONSA GNSS reference points in a geocentric reference frame was hence obtained. The two different types of observing campaigns gave consistent results of the estimated local tie vector and the axis offset of the telescope. The estimated local tie vector obtained from all nine campaigns gave standard deviations of 1.5, 1.0, and 2.9 mm for the

geocentric X, Y, and Z components, respectively. The result of the estimated axis offset of the VLBI telescope shows a difference of 0.3 mm, with a standard deviation of 1.9 mm, with respect to a reference value obtained by two local surveys carried out in 2002 and 2008. The results presented by Ning et al. (J. of Geodesy, 89, 711, 2015) show that the presented method can be used as a complement to the more accurate but more labour intensive classical geodetic surveys to continuously monitor the local tie at co-location stations with an accuracy of a few millimetres.

5.8 Geodetic VLBI

Nilsson et al. (Earth, Planets and Space, 67, 136, 2015) showed that the application of Kalman filtering in the analysis of geodetic VLBI data leads to improvements compared to traditional least-squares analysis. Results for baseline-length repeatability, Earth-orientation parameters, radio-source positions, and tropospheric delays are improved by using a Kalman filter analysis. Baseline repeatabilities improve on the average by 10 %.

5.9 Quantum interferometric gravimeter visit at Onsala

A novel type of instrument for absolute gravimetry has been tested at Onsala Space Observatory in February 2015. Its design is based on interferometry of neutral Rb-atoms in free flight. This gravimeter, baptised GAIN, has been developed at the Humboldt University Berlin, Germany. The campaign at OSO was the second after a first test at the gravity station of Wettzell. In each case, SCGs have served for comparison and reduction of local effects due to earth tides, atmospheric and oceanic attraction and loading, and for monitoring the micro-seismic background noise. In Onsala data from the SNSN seismograph was added. GAIN operated from Feb. 7 to 12 and 19 to 25. During the first period a traditional falling corner-cube gravimeter (FG5X 220 from Leibniz University Hannover) recorded in parallel. The experiment thus was able to demonstrate precision and noise rejection in GAIN as clear advantages with respect to FG5 (Freier et al., 2016, in press, arxiv:1512.05660), Fig. 18.

The SCG is – deliberately – susceptible to micro-seismics, peaking in the band between 0.1 and 0.5 Hz. Cross-correlation of pairs of instruments shown in Fig. 19 reveal patterns that help qualify instrument performance. In fact, the upper-left diagram in Fig. 19 can be used to verify the time delay of the SCG's anti-aliasing filter (used in the preparation of the standard 1 sample/s recording). The pattern of the FG5 shows a similarly clear correlation; the irregularity with respect to time stems from the drift of the clock controlling the drop times. Drops are usually performed at 10 s intervals. Thus, the micro-seismic noise is aliased into temporal averages. The GAIN instrument, on the other hand shows a much lower cross-correlation level, practically vanishing after an adjustment of the vibration isolator after segment 18. The typical 1.5 s interval of measurements with GAIN provides a series that is less critical of micro-seismic aliasing and, owing to continuous operation during many days, a more profound statistical basis, despite a raw-data scatter close to that of the FG5.

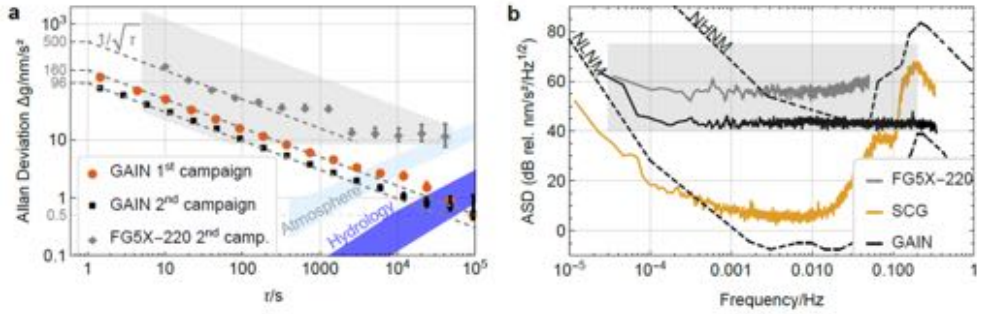


Figure 18. *Gravimeter comparison. a) Allan std. deviation of GAIN and FG5X-220 gravity data reduced by SCG signals. The continuous operation of GAIN allows shorter integration time and improved long-term stability compared to the FG5X. The blue-shaded areas highlight common gravity signals due to air-pressure and hydrological effects. b) Amplitude spectral density of GAIN during the 2nd campaign, showing a noise level better than the FG5X but worse than SCG. The FG5X noise level was increased due to elevated micro-seismic vibrations as depicted by high- and low-noise models (NHMM and NLMM, respectively). The grey area thus denotes the expected noise under quiet and noisy conditions. (Freier et al., 2016, in press, arxiv:1512.05660)*

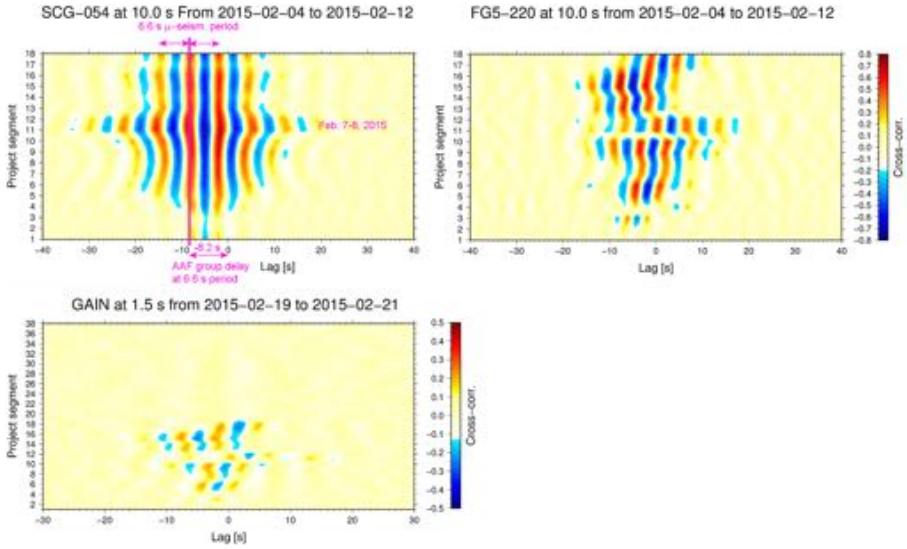


Figure 19. *Sliding cross-correlation of AG drop series with vertical acceleration obtained from the Onsala seismograph. Time progresses from the bottom to the top in each diagram. The pairing in cross-correlation is: SCG to seismometer (upper left), SCG to falling corner-cube gravimeter FG5 (upper right), and SCG to quantum interferometric gravimeter GAIN (lower left). (Freier et al., 2016, in press, arxiv:1512.05660)*

5.10 Mesospheric CO and O_3

The first time series of mesospheric CO and O_3 from the DSB 110–115 GHz radiometer has been compared to data from the Aura/MLS satellite sensor (Forkman et al., Geosci. Instrum. Method. Data Syst. 5, 27, 2016), Fig. 20. The data from the two instruments show the same general features in both sporadic events and in the overall variation. Microwave radiometry is the only ground-based remote-sensing technique that can monitor the mesosphere day and night even during cloudy conditions. Simple and reliable microwave radiometers measuring

in the frequency range below 150 GHz are very valuable for mesospheric research since they can be operated at almost every ground-based site. This new instrument shows the potential of a double-sideband, and frequency-switched, radiometer system for simultaneous measurements of mesospheric CO and O_3.

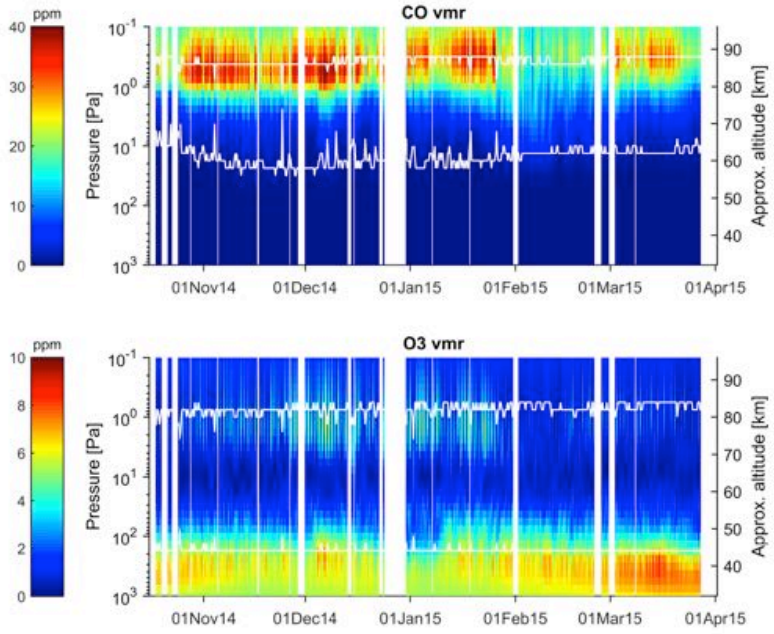


Figure 20. *The retrieved volume mixing of CO and O_3. The x-axis and the y-axis show time and altitude respectively and the volume-mixing ratios, vmr, are given by the colour code in ppm. The white lines mark where the a priori profiles affect the result with 20 % (< 20 % between the lines). (Forkman et al., Geosci. Instrum. Method. Data Syst. 5, 27, 2016)*

6 Technical R&D

6.1 Millimetre/sub-millimetre devices

The Group for Advanced Receiver Development (GARD) at OSO carries out research and development work on mm and sub-mm technology that is further implemented into receivers and their components in order to maintain the observatory at the forefront of instrumentation. These technological developments are directly incorporated into the receivers that GARD builds for the Onsala 20 m telescope, APEX, and ALMA.

From June 2012 GARD has been involved in the three-year EU-funded RadioNet3 Joint Research Activity AETHER (Advanced European TeraHertz Heterodyne Receivers) to work on advanced IF components for sideband-separating SIS (Superconductor-Isolator-Superconductor) mixers and balanced HEB (Hot Electron Bolometer) mixers for array receivers. This work is successfully completed (Fig. 21, left) and GARD is involved in preparation of the new RadioNet4 JRA AETHRA under EC Program Horizon 2020.

Another important component of mm receiver systems is the RF-waveguide hybrid. This component can have a high impact on the receiver sideband rejection, and hence the final receiver sensitivity and performance. Based on the work performed in 2013, when the

innovative RF hybrid design was introduced by GARD, this solution was implemented in the production of the ALMA Band 5 receiver cartridge, Fig. 21 (right).

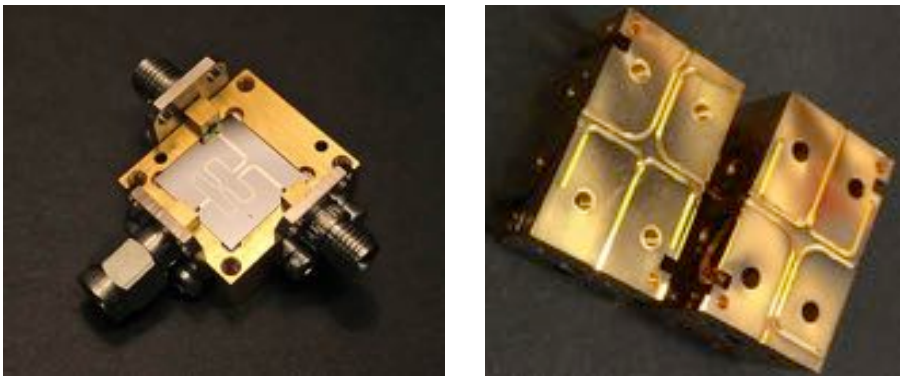


Figure 21. *Left: The superconducting Wilkinson power combiner used in balanced HEB THz mixer. Right: The waveguide part of the separating sideband ALMA Band 5 mixer with the implemented novel RF hybrid.*

GARD continued to work on the previously demonstrated new approach to construct THz HEB mixers, where the active element is micro-machined using a so-called π-frame, and the waveguide is micro-machined using a moulding technique with thick photoresist. Another important component of the HEB mixer is ultra-thin, 4-5 nm, NbN films. GARD has made advances in the fabrication of these films and currently has demonstrated state-of-the-art quality. The summary of properties for ultra-thin NbN films are presented in Fig. 22.

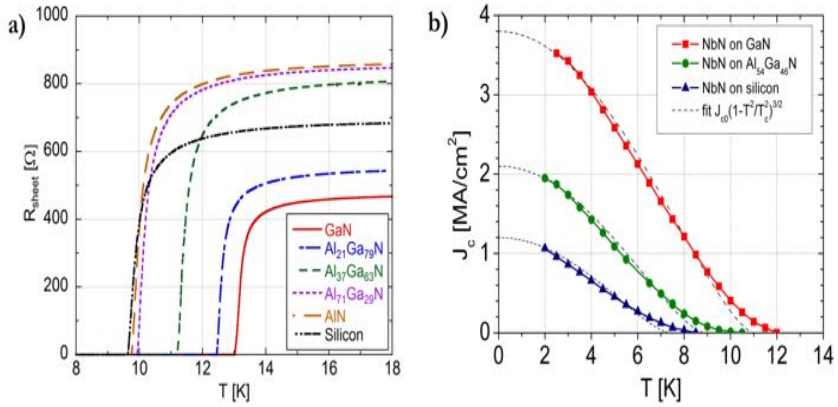


Figure 22. *a) Resistance versus temperature behaviour of ultra-thin NbN films with 5 nm thickness, deposited on the AlGaN buffer layer in comparison with Si substrates. b) Critical current density versus temperature for NbN grown onto GaN Al54Ga46N and Si substrates.*

In addition to the above projects GARD has been investigating several new areas of development, each of which is at an early stage: i) work to demonstrate parametric amplification in a superconducting transmission line using the Kerr effect, ii) work to make accurate characterizations of the specific capacitance of superconducting tunnel junctions using a novel method, and involving direct measurements at microwave frequencies at 4 K (Yadranjee Aghdam et al., IEEE Trans. on Terahertz Science and Technology (2156-342X). Vol. 5, 3, 464, 2015; J. of Applied Physics (0021-8979), Vol. 119, 5, 0545021, 2016), and

iii) work on demonstrating effective multiplication on an SIS-based multiplier with resonant-type superconducting tunnel junctions (several articles are submitted and are under reviewing). These technologies open up possibilities to design a new generation of mm and sub.mm receivers for current telescopes (ALMA, APEX, OSO 20 m) and future ground-based and space telescopes.

6.2 LOFAR

The Swedish LOFAR station was the first to exploit a new type of interferometric imaging. LOFAR stations see the entire celestial hemisphere, but traditionally interferometry can only image on tangent planes. However, Carozzi (MNRAS 451, L6, 2015) showed how genuinely spherical images can be made with ordinary interferometers such as the LOFAR station in Onsala, Fig. 23. This technique will be of great importance for future, space-based low-frequency radio interferometers, such as planned epoch-of-reionization projects.

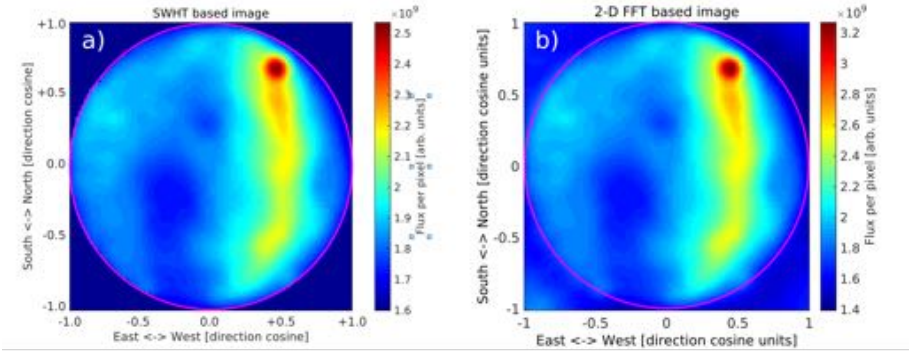


Figure 23. *The truly spherical image a) compared with traditional, flat Fourier transform based image b) of the celestial hemisphere based on a snapshot from the Onsala LOFAR station. The images are similar except for the unphysical emissions beyond the horizon (shown as a magenta circle) in the FFT image, demonstrating that traditional interferometric images are approximations of the spherical imaging method. (Carozzi, MNRAS 451, L6, 2015)*

6.3 VLBI

During 2015, personnel from OSO have been very much involved in introducing both new observational methods as well as technical upgrades of the EVN. A new e-VLBI mode was introduced in 2015, automated generic e-VLBI trigger observations. It is an observation mode to be scheduled automatically during an e-VLBI observation if a specific set of triggering criteria (e.g., through a VOEvent or other form of automated/manual trigger response) is met. The expected response time to execute a new program is about 10 minutes.

Successful tests were also done in e-VLBI mode at 2 Gb/s with participation of telescopes from Sweden (Onsala), Germany (Effelsberg), Italy (Medicina), Spain (Yebes) and South-Africa (Hartebeesthoek). In order to achieve this the digital backend (DBBC2) at the stations were connected to a piece of equipment called FILA10G. The FILA10G reformats and packetizes the data and sends it over its 10 GbE network interface directly onto the internet to JIVE. There the data is fed into the SFXC software correlator, which runs on a 400-core computer cluster, that processes the data in, real-time. The intention is to offer 2 Gb/s e-VLBI to the user community in 2016.

EVN is moving towards a disk-shipping-less model where VLBI data is buffered locally at the station and e-shipped to the correlator at JIVE. OSO has been very much involved in the development during the last years and will be one of the first EVN stations introducing this concept in 2016. Turning to disk-less operations will have many significant advantages. Stations, such as OSO, would not need to bother with conditioning, changing and shipping disk packs, and no recording media would need to be sent out before each session. Furthermore, transfers could be done practically automatically, and the results of a significant sub-set of the EVN network will be available in real-time.

OSO continued the work within the EU RadioNet3 Joint Research Activity DIVA (Developments for VLBI in Astronomy) during 2015. This project has two parts, and OSO is involved in both. The first part concerns the development of a broadband feed and low-noise amplifier (LNA) package for VLBI, in collaboration with MPfR (Germany), ASTRON (the Netherlands), and IAF Fraunhofer (Germany). MPIfR and ASTRON are developing the design of state-of-art LNAs, and the MMIC (Monolithic Microwave Integrated Circuit) chips for the LNAs will be processed at IAF Fraunhofer. OSO has the responsibility of integrating the LNAs with a broadband feed and performing the sensitivity tests. The prototype cryostat with the integrated QRFH and the DIVA LNAs can be seen in Fig 24. The RF chain consists of two DIVA LNAs directly connected to the corresponding ports of the feed, coaxial semi-rigid cables connected to vacuum feed-throughs at the back plate of the cryostat, and a room temperature amplifier model LNF-LNR1_15A.

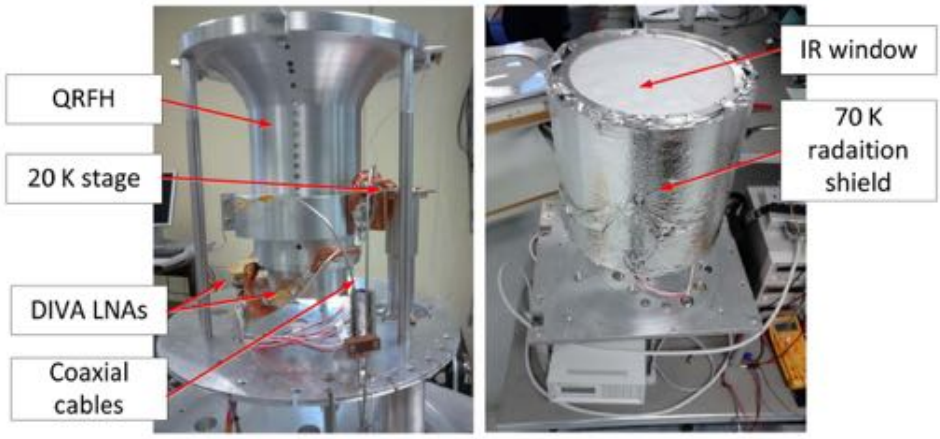


Figure 24. *The prototype QRFH integrated in the prototype cryostat with the DIVA LNAs (left) and with mounted 70 K radiation shield (right).*

The measured receiver noise (T_{rec} in K) and gain (dB) as a function of frequency can be seen in Fig. 25. T_{rec} values are calculated using a sky temperature of 7 K. The physical temperature of LNA and horn was 16 K. As can be seen from the figure the receiver noise drops between 1.5 and 3 GHz from about 50 to 20 K. The ripples in this frequency range are due to impedance mismatch between the feed and LNA input impedances. From 3 to 5.5 GHz the receiver noise has an average value of about 15 K which is a very good result.

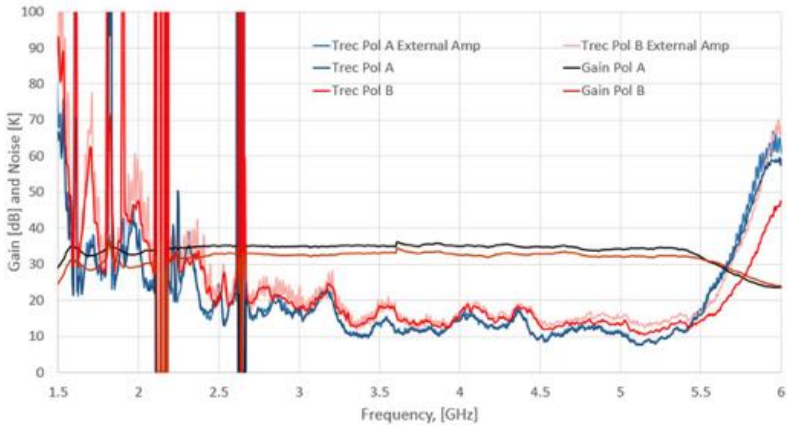


Figure 25. *The measured receiver noise (K) and Gain (dB) as a function of frequency with the integrated prototype containing QRFH Horn and Diva LNA 01 and LNA 02.*

The second part of DIVA involves the design and testing of the third generation of a digital backend system (DBBC3 + FILA40G). The FILA40G, which has been designed at OSO, combines four individual 8 Gb/s data streams from the DBBC3, performs some processing on them as needed before either transmitting the resulting streams via a 40 GbE interface or writing to disk, or a combination of both. Observations at 16 Gb/s were successfully recorded during two test sessions this year, and subsequent modifications enabled a test to be performed in which 282 TB of data was recorded over a period of 21 hours at a sustained data rate of 32 Gb/s with no data lost. The aim is to fully implement digitally all the functionality required of a complete 32 Gb/s VLBI backend for the EVN and for the future geodetic VLBI system VGOS (VLBI2010 Global Observing System).

6.4 ALMA Phasing project

The ALMA phasing project (APP) has reached the stage where it will be offered in ALMA Cycle 4 (proposal deadline in April 2016). Inclusion of ALMA in a VLBI network would not be possible without the PolConvert code developed at OSO which converts the linear polarization base of ALMA into the circular polarization base needed for correlation in the VLBI network (Marti-Vidal et al., 2016, in press, arxiv/1601.04266). Staff of the Nordic ARC node has extensively tested the code using actual phased-up ALMA data. The PolConvert code itself will also be useful for inclusion of other telescopes with linearly polarized receiver feeds in a VLBI network.

7 Instrument Development and Upgrades

7.1 A new 3 mm/4 mm receiver system for the Onsala 20 m telescope

The project to build a new multi-channel 3 mm/4 mm receiver for the Onsala 20 m telescope as outlined in the 2012 – 2016 observatory strategic plan is completed, Fig. 26. The mechanical, cryogenic and optical parts of both wavelength channels are built and installed on the telescope. Furthermore, the 3 mm receiving channel is now fully commissioned and has been brought into use (see Science highlights and Fig. 28). For single-dish operation, the receiver uses an innovative on-source/off-source optical switch. Within the same optical

layout this switch, in combination with additional optical components, provides two calibration loads (for the 3 and 4 mm channels respectively), sideband rejection measurements, and tuning possibilities. The 3 mm channel employs a sideband-separating dual polarization receiver with OMT and 4–8 GHz IF bandwidth. The performance and design of the 3 mm channel has been reported in the Belitsky et al. (A&A 580, A29, 2015). The work on the 4mm channel (which uses a broadband Low Noise Amplifier has been completed during 2015, and the 4 mm channel was installed and commissioned during the fall of 2015. The performance was seen to meet or exceed expectations in terms of noise, stability, and sideband rejection, Fig. 27. Science verification observations with the 4 mm receiver (67-87 GHz) will begin in January 2016 as planned.

Figure 26. *A new 3 mm/4 mm receiver for the Onsala 20 m telescope during the technical commissioning tests in the laboratory.*

During winter/spring 2015, a new spectrometer was put into regular use for single-dish observations, which corresponded to a vast improvement in instantaneous bandpass coverage (2x2.5 GHz versus the previous 2x0.5 GHz at comparable channel spacings). Also the best spectral resolution was significantly improved (from 12 kHz to 5 kHz). In October 2015 two additional spectrometer modules were added to the existing pair in order to reach the goal of covering the maximum bandpass available in our current IF design: 4 GHz in dual polarisation mode. The technical and on-sky commissioning of this new mode was largely complete by December 2015.

On the software side we note that, as previously, the control system is being gradually updated and 2015 saw improvements in e.g. efficiency and flexibility in the startup and tuning procedures (apart from developing the code to support the new hardware discussed above).

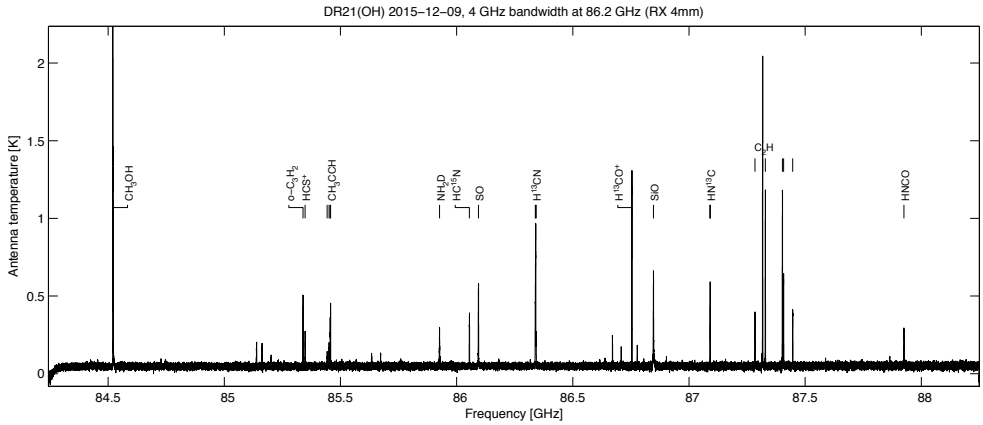


Figure 27. *A 4 GHz wide spectrum of the star-forming region DR21(OH) obtained with the Onsala 20 m telescope using the new 4 mm receiver and the new broader spectrometer. Some detected lines are indicated.*

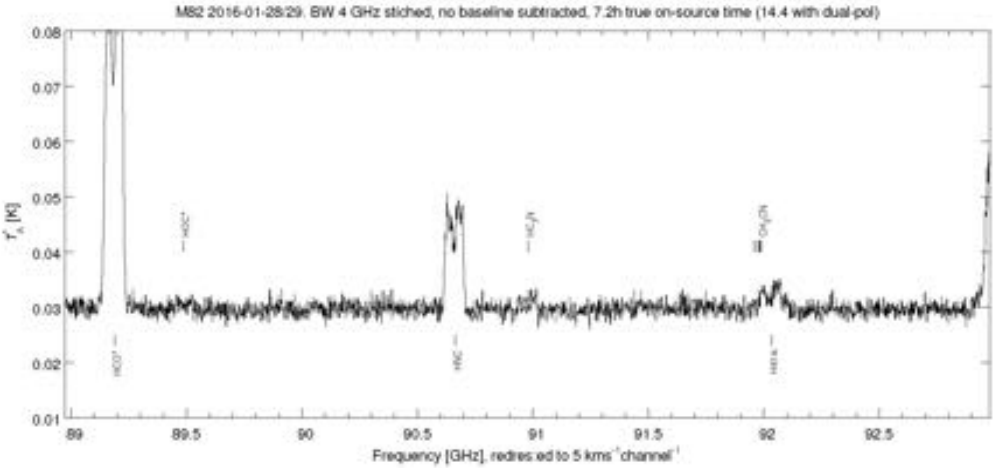


Figure 28. *A 4 GHz wide spectrum of the galaxy M82 obtained with the Onsala 20 m telescope using the new 3 mm receiver and the new broader spectrometer. Detected lines are indicated.*

7.2 VLBI Equipment

In order to improve the sensitivity of the EVN the maximum data rate has been increased from 1 Gb/s (corresponding to an observing bandwidth of 128 MHz, dual polarization, 2-bit sampling) to 2 Gb/s (corresponding to an observing bandwidth of 256 MHz, dual polarization, 2-bit sampling) for disk recording. The first 2 Gb/s user projects were offered from session 3, 2015.

7.3 APEX Swedish Heterodyne Facility Instrument (SHeFI)

GARD developed mixers, designed, and built the Swedish Heterodyne Facility Instrument (SHeFI), which is in operation at the APEX telescope since 2008. Observations with SHeFI produces the majority of the APEX publications employing heterodyne technology. During 2015, GARD performed two SHeFI-related service missions to APEX. The missions dealt with the malfunctioning of the SHeFI Band 1 mixer, which was removed from the receiver, returned to Sweden, repaired, installed back, and then successfully commissioned. During

the entire 2015, SHeFI performed faultless and served as the only facility heterodyne instrument on APEX.

7.4 Sweden-ESO PI Instrument for APEX (SEPIA)

Following a mutual agreement between ESO and OSO, GARD designed, built, and shipped to Chile a 3-cartridge cryostat, which is compatible with the ALMA receiver cartridges, the Sweden-ESO PI Instrument for APEX (SEPIA). It encompasses an ALMA-style cryostat, optics, control system, and supporting electronics, Fig. 29. The first receiver cartridge installed into SEPIA is an ALMA Band 5 receiver cartridge (163 – 211 GHz). SEPIA-B5 was installed on APEX in January 2015. This gave APEX the ability to make Band 5 observations prior to operations with this band being available for users on ALMA. The first receiver installed in this cryostat is the pre-production version of the ALMA Band 5 receiver cartridge built by GARD during the EC FP6 Project. The local oscillator and warm cartridge for this band were delivered to the SEPIA project from the National Radio Astronomy Observatory (US) via ESO. The performance of the SEPIA Band 5 receiver significantly exceeds the ALMA specifications. Science verification observations were done, and the receiver is now in regular use (for an example see Fig. 30).

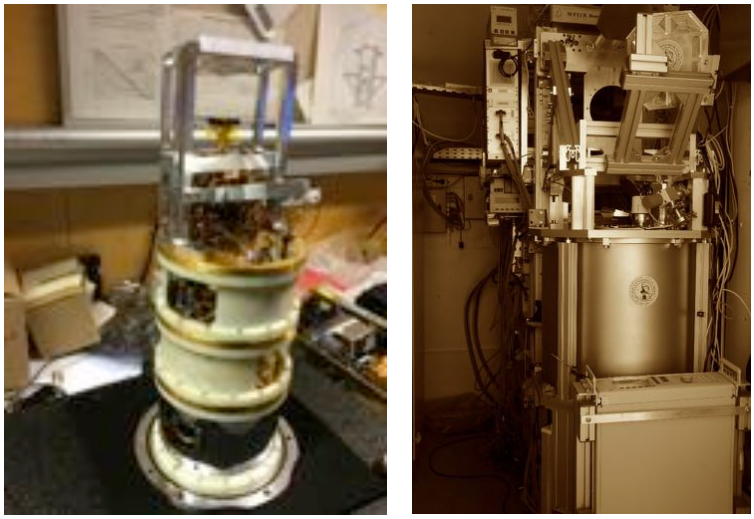


Figure 29. *Left: The ALMA Band 5 cold receiver cartridge before installation into the cryostat in the GARD laboratory. Right: SEPIA receiver installed into APEX Nasmyth Cabin A.*

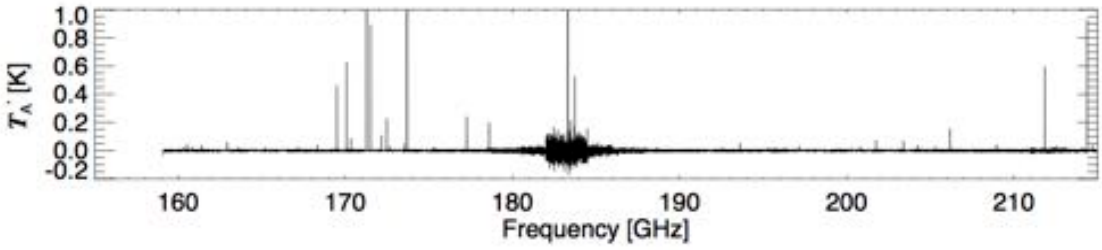


Figure 30. *A spectral scan of the AGB star R Dor covering the full frequency range of SEPIA-B5. Note the substantially higher noise at the location of the atmospheric H_2O line at 183 GHz. (De Beck et al., in prep.)*

During 2015, OSO, ESO and NOVA (the Netherlands Research School for Astronomy), the Dutch group that provided ALMA with Band 9 receiver cartridges, reached an agreement to install ALMA Band 9 receiver cartridge into SEPIA at APEX. The receiver will be installed in February 2016.

7.5 ALMA Band 5 Full Production project

The ALMA Band 5 receiver covers the frequency range 163–211 GHz and is centred on the para-H_2O (3_{13}–2_{20}) line at 183 GHz; one of the few H_2O lines that can be observed from the Earth's surface (at the high-altitude ALMA site under good weather conditions the atmospheric transmission can approach 50 % at the line peak). The ALMA Observatory Board decided in Spring 2012 to finance the full deployment of Band 5 receivers on ALMA. In the full production project GARD collaborates with NOVA. A contract was signed in February 2013 to produce 67 Band 5 cartridges of a slightly modified design compared to those made for an earlier EU project (in which GARD produced Band 5 receiver cartridges). This project brings in a total of ≈ 43 Mkr of ALMA central upgrade funding to OSO/GARD in the period ending at the end of 2017. So far, GARD, together with NOVA, has built and delivered to ALMA 17 Band 5 production receiver cartridges. The measured noise performance significantly exceeds specifications.

7.6 Laser-scanning of the main reflector of the Onsala 20 m radio telescope

In autumn a project was performed together with colleagues from the University of Bonn (Germany) to determine the reflector surface and the focal length of the Onsala 20 m telescope with a laser-tracking system. A laser tracker was mounted on of the quadrupod legs and the tracking measurements in various elevation angles were performed. These data are currently analysed and the results will be used to e.g. develop an improved delay model for geodetic VLBI, and for modelling the instrumental delay due to thermal and mechanical distortions of the radio telescope itself.

7.7 Real-time monitoring of focal length changes of the Onsala 20 m radio telescope

Together with SP Technical Research Institute of Sweden, a laser-based system was installed on the Onsala 20 m radio telescope that allows monitoring focal length changes in real time. Small laser-distance devices monitor the distance from the centre of the main reflector to the subreflector and to the quadrupod legs.

7.8 Reference point and local-tie determination in VLBI networks

Together with collaborators from the University for Applied Sciences in Frankfurt (Germany), the Finnish Geodetic Institute (FGI) and SP Technical Research Institute of Sweden, a project was performed to monitor the reference points and local-ties in a VLBI network simultaneously. Similar equipment was used, and measurements were performed, simultaneously at the Onsala 20 m telescope and the Metsähovi 14 m radio telescope, while they were involved in the same geodetic VLBI session

7.9 Gravimeter laboratory

A ground-water-level sensor was installed in the bore hole underneath the Gravimeter laboratory in September 2015. Its measurements are collected in the OSO sensor network at 5 s sampling interval.

7.10 The new tide gauge station

A goal for the observations at a fundamental geodetic station is to measure and model variations in the Earth's crust at the mm level. This implies, for example, that loading effects on the crust due to varying masses in the atmosphere and in the ocean must be measured and understood. The amplitude and phase variations in the local sea level are too complicated to be interpolated using data from the existing nearby tide gauge stations in Ringhals and in Gothenburg. The long-term goal is to have continuous time series of sea-level observations with an accuracy of a few mm. This called for the construction of a new tide gauge station at the observatory with four independent sensors for reliability and redundancy. The principle is illustrated in Fig. 31. In the well there are two pneumatic sensors (bubbler 1 and 2) and one radar sensor. Bubbler sensor 3 is mounted just outside of the well. The well is insulated and the water in the well is heated when the water temperature goes below 0 °C. The Swedish Meteorological and Hydrological Institute (SMHI) now takes an active role in the data quality check and archiving, thereby securing that the data are suitable for use in future geodynamic research as well as being a high-quality station in the Swedish observational network of the sea level. The tide gauge is shown in Fig. 32.

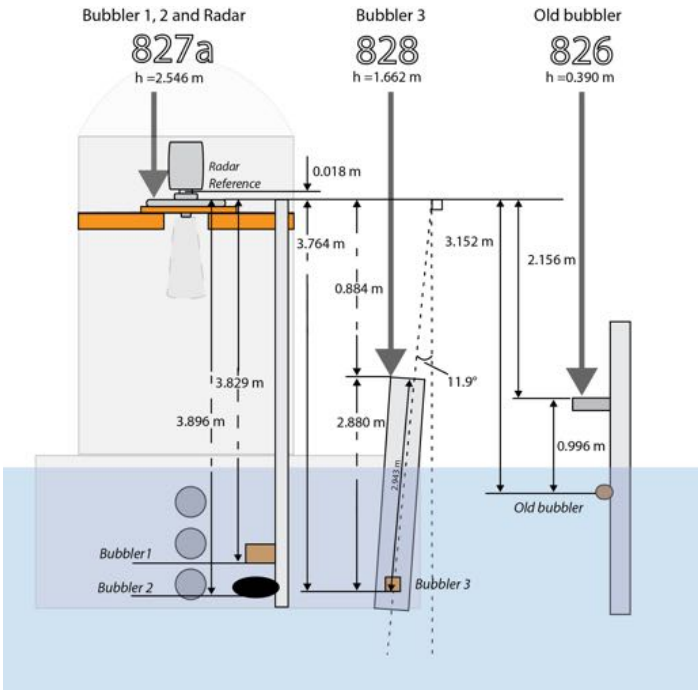


Figure 31. *The location of the sensors. Note that the objects in the graph are not in correct scale (relative to each other). The Old bubbler was operational from August 2013 to June 2015.*

Figure 32. *The new tide gauge station developed in collaboration with SMHI. The station has acquired continuous data since the summer 2015. It was officially inaugurated on 17 September.*

7.11 Aeronomy station

A cost-effective replacement for the old auto-correlator spectrometer for the 110-115 GHz radiometer has been developed. The new FFT spectrometer is based on software-defined radio, and the USRP X310 unit from Ettus, together with the free GNU radio package has been used. This new spectrometer is now fully implemented in the receiver system and gives both larger bandwidth and higher resolution than the old auto-correlator.

8 SKA Design Activities

During 2015 OSO continued its technical involvement in The Square Kilometre Array (SKA), an international project aiming to build a new astronomical facility serving the radio waveband at metre and centimetre wavelengths. SKA will be built in two phases with phase 1 (SKA1) planned to be fully operational in 2023 and phase 2 likely to be built in the 2030's at the earliest. In June 2013 contracts were awarded to 11 multi-national design consortia that (managed by the central SKA Office) will accomplish the final detailed engineering design of SKA Phase 1. Sweden, represented by OSO is part of two such design consortia, the Dish and the Wide Band Single Pixel Feed consortia (SKA-DC and SKA-WBSPF).

During the SKA preconstruction phase individual countries pledge their own resources to support design activities within these consortia; i.e., contributions to the design phase are in-kind. In total, integrated over all design consortia, 120 M€ of in-kind contributions have been pledged worldwide to the design phase (including an estimated 2.6 M€ from OSO as the Swedish contribution). During 2015, OSO has about 5.7 FTEs working for the SKA project. This includes management support (0.7 FTE), support from the mechanical workshop and electronics laboratory (0.5 FTE), and a permanent PhD-level member of staff who leads the integration design of the wideband feed and receivers (1 FTE). Finally, the project also has a (self-funded) manpower contribution of 0.55 FTE from the Chalmers Microelectronics laboratory which has a clean-room process that makes the world's best low noise amplifiers for the higher frequency bands of SKA. The total value of the above OSO/Chalmers contributions over the period 2014–2016 will be 12 Mkr, which is estimated to be about half of the total needed to complete all allocated work tasks. The rest of the resources necessary to accomplish the design activities were made possible via two VR planning grants awarded in 2012 and 2014. These grants have made it possible to employ temporary project resources.

8.1 Band 1 in SKA-DC

OSO is work package (WP) leader for the Band 1 Single Pixel Feed (SPF) WP within SKA-DC. Within this WP, OSO has the overall responsibility to design, prototype and characterize a feed and low-noise receiver package that covers 350–1050 MHz frequency range. According to the SKAO prioritization this receiver band will be one of the first implemented on the SKA together with Bands 2 and 5. Partners in this WP are the National Research Council (NRC) of Canada, providing state of the art LNAs, Omnisys Instruments AB (Sweden) working on the design of the control system and the final design for mass production, and Low Noise Factory (Sweden) providing on-shelf world-class LNAs.

During 2015 OSO worked on the preliminary design of the cryostat and feed assembly, Fig. 33. This design was reviewed in February 2015, and, with some small modification, was approved for future development towards the Detailed Design phase. A scaled version of the QRFH was designed, fabricated, and tested during 2015, Fig. 33 (right). The measured beam pattern agreed well with the simulation results. This cross validation was an important milestone that allowed OSO to continue further with the detailed design of the QRFH for the Detailed Design Review.

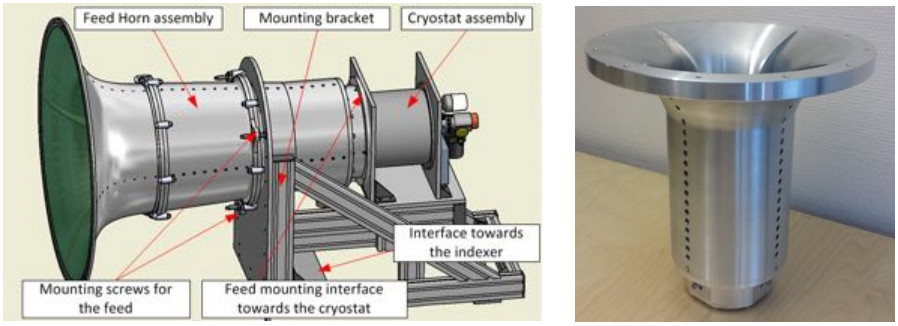


Figure 33. *Left: SKA Band 1 feed horn and cryostat assembly. Right: Scaled Band 1 feed prototype.*

During the first half of 2015, extensive work was done on the design, prototyping and characterization of the cryogenic receiver for Band 1. Figure 34 shows the manufactured and assembled cryostat and it's interior. The performed RF tests confirmed the theoretical predictions for the receiver noise.

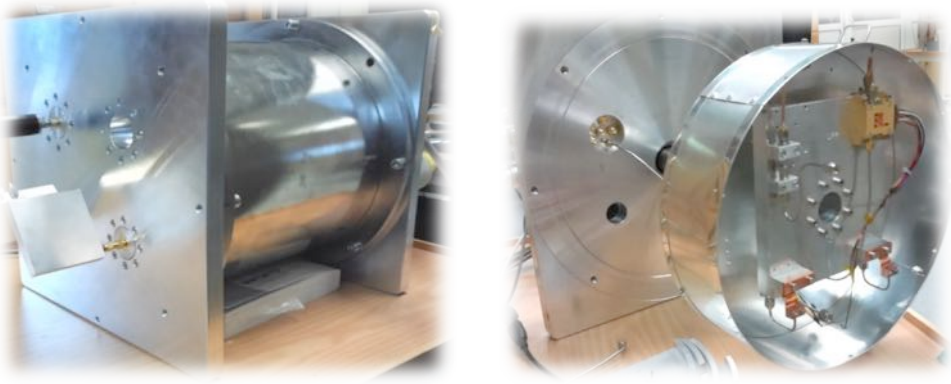


Figure 34. *Left: Fully assembled Band 1 prototype cryostat. Right: The interior of the cryostat with LNAs and heat sinks visible.*

During the second half of 2015 the work was focused on improving the design and adapting it for manufacturability and reliability. The detailed mechanical design of the cryostat was transferred to Omnisys Instruments AB. The electromagnetic design of the feed horn was successfully accomplished. Due to its big size, the feed horn was manufactured using sand-molding. Figure 35 shows the assembled Band 1 feed horn. After some testing at OSO in the beginning of 2016, the feed horn will be sent to Canada for tests on an SKA prototype antenna.

Figure 35. *Front and back view of the assembled SPF Band 1 QRFH.*

8.2 SKA-WBSPF

OSO leads the WBSPF consortium that is part of the Advanced Instrumentation Program (AIP) for SKA. The AIP is intended to develop technology that would be employed as a second-generation SKA-1 receiver or on SKA Phase 2. The scope of work for the WBSPF includes the activities necessary to develop a broad spectrum single-pixel-feed, LNAs, and digitizers. Specifically, WBSPF seeks to greatly expand the frequency range covered by present radio astronomy receiver systems. While conventional (‘octave’) radio astronomy receivers only cover approximately a factor of two in frequency, WBSPF technology can cover ranges of 4 to 8 in frequency. As consortium leader, OSO has overall management and coordination responsibility to deliver the work according to the time plan and specification. In addition, OSO provides system engineering for the consortium, where the main work is to derive low-level requirements, write specifications for various sub-systems, develop ICDs and Compliance Matrices, and write verification programs. During April 2015, OSO organized a consortium meeting, hosted by the SKAO at Jodrell Bank (UK), with more than 30 participants. During that period regular bi-weekly management telecons were conducted to discuss details on work distribution and technical issues. A WBSPF Requirement Specification document was written and approved by the SKAO during a formal meeting in September 2015. OSO’s technical involvement in the WBSPF concern the design of a feed

for the 4.5–24 GHz range, also referred to as Band B. The work during 2015 was focused on the concept design of the Eleven Feed and the Quad-Ridged Feed Horn (QRFH) for Band B, Fig. 36. This activity will culminate when the choice of the preferred feed technology is done at the Concept Design Review in 2016.

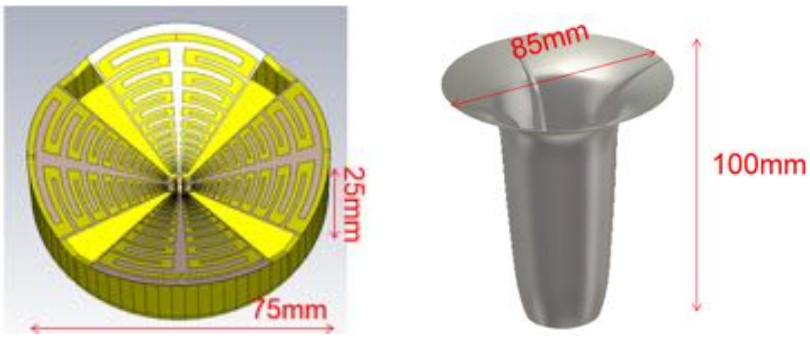


Figure 36. *CAD model of the feed alternatives for Band B: Left: Eleven Feed. Right: QRFH.*

The most challenging in the design of the QRFH for this frequency is to maintain the thickness of the ridges such that integrating the feeding line into the ridge is possible from a manufacturing point of view. Band B (Feed and LNA) will be installed at cryogenic temperature in order to provide the ultimate sensitivity needed for SKA. This implies significant challenges for the integration: a vacuum window transparent for the electromagnetic waves and also an infrared window decreasing the heat via infrared radiation. In addition, the feed must be constructed such that it has low thermal mass. During 2015, possible manufacturing techniques satisfying those criteria were investigated, and preparations for starting prototyping work for both feed alternatives are ongoing.

9 Twin-Telescope System for Geodetic VLBI at Onsala

OSO obtained funding in 2011 from the Knut and Alice Wallenberg (KAW) foundation to build a next-generation double-telescope for geodetic VLBI (the so-called Onsala Twin Telescopes or OTT; the project has been delayed because of an extended building-permit process, and because of the complicated telescope procurement process). These twin telescopes (parabolic dishes with diameter 13.2 m) will follow the new geodetic VGOS standard, and will enable position measurements with a precision 10 times better than existing geodetic VLBI observations. This improved accuracy opens up the possibility of discovering, and understanding, new global geodynamic effects.

During the autumn the two telescope foundations for the future Onsala twin telescopes were constructed, Figs 37 and 38. The two foundations are octogonal concrete towers of 7.6 m in height and a ground base of 6.7 m in diameter. The towers are at a distance of about 75 m from each other, and they are mounted directly in solid bed rock with 8 deep drilled metal bars each. Further infrastructure, like roads, concrete mounting pads for the telescope reflectors, fibre cables for data transfer and cables for electric supply were also installed.

The telescopes will be delivered in the summer of 2016. Receivers, data handling and transmission systems will thereafter be built and installed. The first VLBI test observations are expected during 2017. The complete twin telescope system is expected to be fully operational by the end of 2019.

Figure 37. *The concrete foundation of the southern telescope on December 28, 2015. The 25 m telescope is seen in the background.*

Figure 38. *The concrete foundation of the northern telescope on December 28, 2015.*

10 Memberships of International Committees

During 2015, OSO was involved in the following international boards and coordinating committees. The observatory director serves on many of these boards.

- *The European VLBI Network (EVN) for* astronomical VLBI (the Director is a board member. Michael Lindqvist is chairman of the Technical Operations Group (TOG) and member of the Observing Programme Committee).
- *The Joint Institute for VLBI ERIC (JIVE),* a European Research Infrastructure Consortium that operates the EVN correlator in Dwingeloo (NL) and supports the EVN activities (The Director is a board member).
- *The APEX project* where three partners operate a 12 m sub-mm telescope in northern Chile (the Director is a board member).
- *The International LOFAR Telescope (ILT)* Board, which oversees the operation of the

ILT (the Director is a board member).
- *RadioNet3,* an EU-financed I^3 project, which coordinates all of Europe's leading radio astronomy facilities (The Director is a board member, Michael Lindqvist represents the EVN TOG and CRAF)
- *The SKA Organisation (SKAO),* the British company that is responsible for the SKA project in its pre-construction phase (the Director and Lars Börjesson, Chalmers, are board members). In addition Hans Olofsson is a member of the Finance Committee.
- *SKA Dish Design Consortium* (the Director is a board member)
- *SKA Wide-Band Single Pixel Feed Design Consortium* (the Director is the leader of the Consortium)
- *International VLBI Service for Geodesy and Astrometry (IVS*), which operates geodetic VLBI (Rüdiger Haas is board member)
- *International Earth Rotation and Reference Frame Service (IERS*) (Rüdiger Haas is board and committee member)
- *Nordic Geodetic Commission (NKG)* through the *Working Group of Positioning and Navigation* (Rüdiger Haas is committee member)
- *The European VLBI Group for Geodesy and Astrometry (EVGA*) (Rüdiger Haas is chair person)
- *Global Geodetic Observing System (GGOS) Inter Agency Committee (GIAC)* (Rüdiger Haas is committee member)
- *ESF Committee on Radio Astronomy Frequencies (CRAF)* for the protection of the radio band for radio astronomical use (Michael Lindqvist is a committee member)

11 RadioNet3 EU Project

The EU-funded RadioNet3 project (Advanced Radio Astronomy in Europe) began in 2012 and finished at the end of 2015. RadioNet3 is an EU Integrated-Infrastructure-Initiative-funded network of all the major radio astronomical observatories in Europe (and some beyond). RadioNet3 follows on from a number of successful similar activities over the years. Its aim is to support the use of the radio astronomical facilities as well as to support R&D on new radio astronomical instrumentation and methods. From this activity OSO gets TransNational Access (TNA) funding for its operation of APEX and its contribution to astronomical VLBI. It also takes part in two Joint Research Activities: AETHER (Advanced European TeraHertz Heterodyne Receivers) and DIVA (Developments in VLBI Astronomy) and, described respectively in Sects 6.1 and 6.3.

12 Workshops, Schools, etc.

In March and April, the Nordic ARC node organized ALMA Cycle 3 proposal preparation tutorials in Onsala, Helsinki (together with the University of Helsinki) and Uppsala (with Uppsala University). The tutorials were attended by astronomers from PhD to permanent staff level, and were aimed at helping the Nordic community prepare for the Cycle 3 ALMA proposal deadline. Presentations of the ALMA status and new ALMA capabilities were followed by hands-on simulator and observing tool tutorials as well as face-to-face proposal support. Following the tutorial in Onsala, ARC staff also organized a Radionet-funded Evolved Stars Proposal Preparation workshop with 35 international attendees, including several PhD students.

In September, the ARC node organized, supported by ESO, the annual all-hands meeting of

the European ARC node members in Smögen. At these annual meetings, issues related to the functioning of the ARC network, were discussed, i.e., quality assessment, face-to-face support, ALMA operations and data reduction. The meeting was attended by 52 European ALMA ARC network astronomers.

13 Education

The OSO staff does not generally take part in the academic teaching at Chalmers (except for, e.g., a few guest lectures on specialized radio astronomy observing techniques). The national facility does however support teaching by making a small fraction of the time on the telescopes available for exercises by students on Chalmers and other Swedish academic courses. The staff are also sometimes involved in teaching and providing exercises at specialised graduate level schools that are organised from time to time at the Observatory. Specifically at Chalmers, the 20 m telescope and SALSA are used in astronomy courses, the 25 m telescope in a satellite-communication course, GNSS equipment in a satellite-positioning course, and laboratory equipment in courses on microwave, millimetre wave, and THz technology. Additionally, students from the universities in Stockholm and Lund visited the Observatory to carry out observations and/or to learn about radio astronomy.

14 Outreach

In our outreach programme we have engaged with the public in order to communicate the excitement and importance of science to people of all ages, share our research results, and make it possible for the public to experience our telescopes and instruments first-hand. Half of our outreach effort during 2015 was carried out by astronomy PhD students at Chalmers.

During 2015 people discovered both our telescopes and our international projects through visits to the observatory in Onsala and through other arrangements. We count a few special events. 50 invited guests and local media representatives attended the inauguration of the super tide gauge in September. During the Gothenburg Science Festival and on Sweden's Day and Night of Astronomy in October, we organised and co-organised many talks and other events in Gothenburg and, for the first time, in Kungsbacka. But most visitors came on a total of 70 guided tours, led primarily by students, of which school groups of all ages accounted for 27 tours. A few school visits, and skype conversations with school classes, complemented this program. In October, two work-experience (prao) students visited the observatory. Many visitors to Onsala came as part of two public open days, during the Gothenburg Science Festival in April and at the end of May. All these activities provided direct contact with scientists, most often astronomy Ph.D. students, for hundreds of people of all ages. The Onsala site was also visited by a South-African science delegation (Fig. 39) and by a group of local politicians, including the county governor in Halland (Fig. 40).

The observatory's SALSA radio telescopes were booked for an average of 24 hours every week, on average 4.5 hours per booking, by students, teachers and amateur astronomers from Sweden and from as far away as the US, Bangladesh, and Honduras. Most users study the movements of interstellar gas in the Milky Way. We provided support and supervision for a number of Swedish high school projects using SALSA.

News from OSO facilities and research by Chalmers scientists were communicated to the media in collaboration with Chalmers press office and with ESO. News media in Sweden,

and around the world, reported on the super tide gauge, LOFAR's image of galaxy M82, ALMA's discovery of strong magnetic fields near a supermassive black hole, a surprisingly dusty galaxy in the early universe, evidence of activity on the red giant star Mira, and the installation of SEPIA on APEX. The staff handled many media enquiries on astronomical topics and were regularly quoted in news media.

Support was provided to the SKA Key Science meeting in Stockholm in August 2015, and during the year news about SKA was communicated in Swedish via the project's Swedish minisite and in social media. In October, a meeting of the EU-funded network Radionet3's outreach project was hosted. OSO helped finalise two of the project's outcomes, a comic book for young people ("*Eagle View Network*") about the history of the European VLBI Network and the Swedish version of *Invisible Universe*, a workbook on radio astronomy for primary schools.

Figure 39. *Several groups of important people visited the observatory during 2015. Here a scientific delegation from South Africa is flanking director John Conway.*

Figure 40. *In August a group of local politicians accompanied Lena Sommestad, county governor in Halland (3rd from right), on a visit to the observatory.*

15 Changes in Organisation

During 2015, the members of the Steering Committee served the second year of their three-year term. The OSO Time Allocation Committee continued its work without change of personnel. The memberships of the Steering Committee and the Time Allocation Committee can be found at http://www.chalmers.se/en/centres/oso/about-us/Pages/Organization.aspx.

16 Importance to Society

OSO supports basic research within astronomy and geoscience. Both astronomy and geoscience research have a strong appeal to the curiosity of people of all ages, and this is used in our outreach activities as described above. In addition, geoscience is of importance for understanding the system "Earth", and therefore of importance for e.g. climate applications, such as monitoring of ozone in the atmosphere and determining changes in the absolute sea level. Geodetic VLBI provides the fundamental terrestrial reference frame, which is the basis for all navigational applications. As a by-product of its VLBI activities, the observatory also contributes to establishing the official Swedish time and international time, through two hydrogen maser clocks and one cesium clock. The OSO staff and instruments are also involved in education at all levels from bachelor to graduate studies at Chalmers, and through organised schools.

17 Importance to Industry

The major industrial impact of OSO's work is connected with the SKA project. The SKA is on such a scale that its components must be provided by industry. It is expected that the SKA will have a large financial payback to Swedish industry especially if Sweden fully joins the SKA construction phase. OSO is working closely with industrial partners (Omnisys Instruments AB and Low Noise Factory) in developing Wide Band Single Pixel Feeds for SKA-mid bands 1 and 5. Similar technology has possible commercial applications for geodetic and astronomical VLBI.

18 Financial Account

OSO gets most of its operation funding from the Research Council (VR) and Chalmers. There is in addition a small contribution to operations funding within the EU-financed RadioNet3 project via its Trans National Access (TNA) element, which supports international access to APEX and the use of the OSO telescopes in EVN VLBI. The income and expenditure on the VR account for 2015 are as follows:

VR income, operation	*38 000* kkr
Expenditures on VR grant:	
Salaries	24 735 kkr
APEX central operation	5 485 kkr
LOFAR, central operation	729 kkr
JIVE, central operation	1 044 kkr
SKA, membership fee	2 506 kkr
ESF, Frequency manager	179 kkr
Data fibre links to Stockholm/Netherlands	399 kkr
Travel	1 262 kkr
Equipment	2 868 kkr
Supplies	1 654 kkr
Services	1 674 kkr
Buildings	51 kkr
Total	42 586 kkr
Chalmers income, operation	*19 343* kkr

Project funding

In addition to its operations funding the Observatory is involved in a number of multi-year projects, the total values and periods of these projects are given below.

VR Planning Grant (SKA), 2015-2016	6 593 kkr
Chalmers, EU support, 2015	190 kkr
EU, RadioNet3, 2012 – 2015	704 k€
ESO ALMA Band 5, 2013 – 2017	41 397 kkr

Acronyms

AETHER	Advanced European TeraHerz Heterodyne Receivers
ALMA	Atacama Large Millimeter/submillimeter Array (Chile)
ARC	ALMA Regional Centre
APEX	Atacama Pathfinder Experiment (Chile)
DBBC	Digital Base Band Converter
DIVA	Developments In VLBI Astronomy
eMERLIN	upgraded Multi-Element Radio Linked Interferometer Network (UK)
ESO	European Southern Observatory
EVN	European VLBI Network
FFT	Fast Fourier Transform
FFTS	Fast-Fourier-Transform Spectrometer
FGI	Finnish Geodetic Institute
FTE	Full Time Equivalent
GARD	Group for Advanced Receiver Development
GGOS	Global Geodetic Observing System
GGP	Global Geodynamic Project
GIAC	GGOS Inter Agency Committee
GLONASS	Global Navigation Satellite System (translated from Russian)
GMVA	Global Millimetre VLBI Array
GPS	Global Positioning System
GNSS	Global Navigational Satellite Systems
HEB	Hot Electron Bolometer
IAG	International Association of Geodesy
IGETS	International Geodynamics and Earth Tide Service
IGS	International GNSS Service
ILT	International LOFAR Telescope
IRAM	Institut de Radioastronomie Millimetrique
IVS	International VLBI Service for Geodesy and Astrometry
ITRF	International Terrestrial Reference Frame
JIVE	Joint Institute for VLBI in Europe (NL)
KAW	Knut and Alice Wallenberg foundation
LOFAR	Low Frequency Array
LNA	Low Noise Amplifier
NKG	Nordic Geodetic Commission
NOVA	Netherlands Research School for Astronomy
MMIC	Monolithic Microwave Integrated Circuit
NRAO	National Radio Astronomy Observatory (USA)
NDACC	Network for the Detection of Atmospheric Composition Change
OSO	Onsala Space Observatory
OTT	Onsala Twin Telescope
RadioNet3	Advanced Radio Astronomy in Europe
SALSA	Such a Lovely Small Antenna
SEPIA-B5	Swedish-ESO PI receiver for APEX (Band 5)
SEST	Swedish-ESO Submillimetre Telescope (Chile)
SHFI	Swedish Heterodyne Facility Instrument for APEX
SIS	Superconductor-Insulator-Superconductor (receiver technology)
SKA	Square Kilometre Array
SKADC	SKA Dish Consortium
SMHI	Swedish Meteorological and Hydrological Institute
SNSN	Swedish National Seismic Network

SP	SP Technical Research Institute of Sweden
SWEPOS	Lantmäteriet's support system for satellite positioning in Sweden
TAC	Time Allocation Committee
TNA	Trans National Access
ToO	Target of Opportunity
VLBA	Very Large Baseline Array (US)
VLBI	Very Long Baseline Interferometry
VGOS	VLBI2010 Geodetic Observing System
WBSPF	Wideband Single Pixel Feed Consortium
WVR	Water Vapour Radiometer