Estimation and validation of the radiation pattern of the Middle Atmosphere Alomar Radar System (MAARSY)

Toralf Renkwitz, Gunter Stober, Jorge L. Chau, and Ralph Latteck

Leibniz-Institute of Atmospheric Physics at the Rostock University, Schloss-Str. 6, 18225 Kühlungsborn, Germany, renkwitz@iap-kborn.de

Summary - The Middle Atmosphere Alomar Radar System (MAARSY) is a radar with a large aperture active phased array antenna designed for studies of atmospheric phenomena in the mesosphere and lower thermosphere. Its design in particular the flexible beam forming and steering capability makes it to a powerful instrument to perform observations with high angular and temporal resolution. The knowledge of the actual radiation pattern and radar parameters is crucial to configure and analyze experiments carried out with the radar. For this purpose the simulated radiation pattern is evaluated by the observation of cosmic radio emissions which are compared to a Global Sky temperature Map Model. Additionally to these passive receive-only experiments active two-way experiments are presented, which corroborate the findings of the passive experiments.

The Middle Atmosphere Alomar Radar System was built in 2009/2010 by the Leibniz-Institute of Atmospheric Physics (IAP) on the island Andøya in Northern Norway (69.30°N, 16.04°E) as the successor of the ALWIN radar, which was operated for almost ten years continuously. The flexibility and performance of MAARSY allows improved studies of the arctic atmosphere in the troposphere/lower stratosphere and the mesosphere/lower thermosphere with high spatial and temporal resolution. The radar operates at 53.5 MHz with an active phased array antenna consisting of 433 Yagi antennas as well as additional separate antenna groups. Each individual antenna of the main array is connected to its own transceiver delivering up to 2 kW peak power with independent phase control. These properties give the radar a very high flexibility of beam forming and beam steering. Several model studies have been carried out in order to estimate the radiation pattern for various combinations of beam forming and steering during both the design phase of MAARSY and the successive commissioning. However, some impacts can hardly be measured or included into the model, like exact ground parameters, the nearby terrain surrounding the radar (hills and the Atlantic ocean) and mutual coupling of the array elements resulting in active impedances. The actual radiation pattern may be inflicted by these parameters, which requires experimental methods to verify the model results.

For this purpose, various passive experiments, observing cosmic noise radiation, and active experiments, scattering off the moon, satellites and rocket payloads, have been carried out to gather information on the performance of the radar and especially the radiation pattern of the antenna array, which are subsequently introduced briefly. During the first experiments the radar has occasionally been used in passive mode, monitoring the noise power originating from both distinct galactic radio sources like e.g. the Supernova remnant Cassiopeia A (RA: 23h 23.4m, Dec: +58° 48.9'), radio galaxy Cygnus A (RA: 19h 59.473m, Dec: +40° 44.035') and the complete diffuse radio background radiation. The analysis of this receive-only mode data enables us to verify beam forming and steering attempts, mainly focussing on the beam position and its width. These results document the current status of the radar and provide valuable information for quality control and further improvements.

In the passive experiments we typically performed a scan between 0 and 34° zenith angle pointing in southern directions. The simulated radiation pattern of MAARSY343 antenna array with an overlay of the trajectory of Cygnus A is depicted in figure 1. In this scan range, we were able to identify two distinct cosmic radio sources, Cassiopeia A, Cygnus A, and the signature of the Milky Way. Lately, we expanded the scan range to declinations between 9 to 69°, which allowed to monitor additional radio source like the supernova remnant Taurus A (RA 05 h 34.53 m, Dec. +22° 0.87') and the largely extended nebula 3C400 (RA 19 h 22.92 m, Dec. +14° 11.46'). To validate our observations we use the Global Sky temperature Maps Model (GSM) by de Oliveira-Costa et al. (2008). This model is comprised of the eleven most accurate radio sky surveys and allows the generation of Quiet Day Curves for a user specified frequency, which is convolved with the simulated radiation pattern of MAARSY. Recently, we created 2D GSM maps matching to the scan experiments we performed with MAARSY for further comparisons. Figure 2 shows the detected incident power in the upper panel, succeeded by the deviation of the GSM map model to the observations. For the parts of the sky originating lower temperatures the largest discrepancies are found between the GSM map and our observation, which is likely caused by the ideal

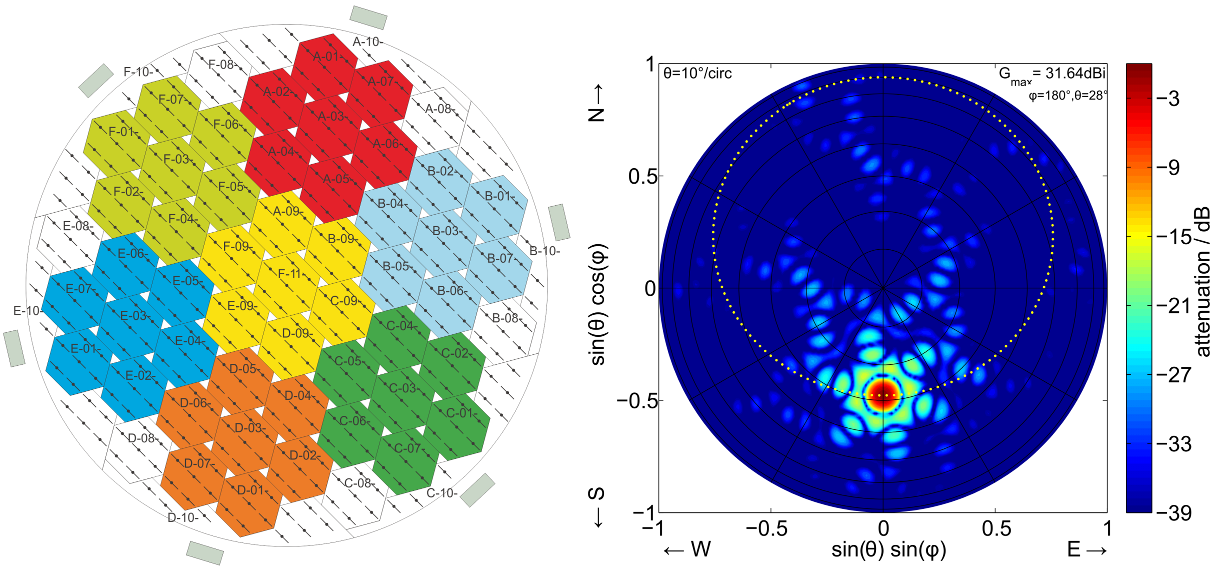

Figure 1: Left: Sketch of the MAARSY VHF radar antenna array. The colored subgroups mark the MAARSY343 subarray. Right: Simulated radiation pattern of the MAARSY antenna array in top view, using 343 array elements pointing to Cygnus A ($\phi = 180°, \theta = 27.5°$ - right side). The corresponding trajectory of the radio source is depicted with yellow dots. The radiation pattern is depicted relative to the maximum gain with an overlay of equidistant rings of each 10° zenith angle.

pattern used to generate the GSM maps.
With the same observations we furthermore derived the apparent beam pointing and beam width for the culmination of Cassiopeia A and Cygnus A. The apparent mispointing can be derived from the exact positions of the sources, well known from various radio astronomy observations. The azimuthal mispointing may be derived from the temporal offset, while the zenithal mispointing along the zenith angle may be taken directly from the scan observations. Doing so, the beam pointing accuracy could be estimated to be better than 1°, which is reasonably good for 3.6° minimum beam width.
Additionally, the radio sources are used to derive absolute phases for the individual receiver groups connected to array subgroups of various size. These phase calibration experiments incorporate the total receiving system, from the antenna down to the A/D-converter and are compared to a daily hardware phase test performed for the components excluding the antennas and their feeding cables.
In the beforehand depicted experiments the radar was used exclusively in reception mode, however there is a significant interest in the validation of the transmit radiation pattern of MAARSY. For this purpose we arranged experiments where we used the Earth's moon, satellites and the payload of an atmospheric sounding rocket as backscatter targets.
To gain information about the transmitting pattern of MAARSY we prepared scan experiments with beam positions corresponding to the individual trajectories of the individual targets. Similarly to the passive cosmic noise experiments we performed a declination scan pointing southwards to see the passage of the moon. The backscatter of the moon was found at the predicted time and zenith angle as shown in figure 3. The range slope of the backscatter agrees well to the calculated distance of the moon and thus supporting the echos origin. The intensity of the moons echo is characterized by high fluctuations, which is likely related to Faraday rotation, absorption and scintillation effects as the radar signal travels along a considerable long path through the atmosphere, pointing 48° off-zenith. As denoted before, another way to verify the beam pointing capability of a radar is the use of satellites. For this purpose we have chosen the GRACE and ENVISAT satellites as these have high inclination orbits and represent a significantly large targets for our observation frequency. In figure 3 are depicted height-time-intensity plots for one passage of the two GRACE satellites. The time of passage through the individual radar beams and the detected range are in good agreement to simulations of the trajectory. Equivalent results have been found for the observation of ENVISAT, where we additionally placed two beam positions each 4° next to the satellites trajectory to see potential beam mispointing and to verify the side lobe suppression. With these two satellite experiments we were able to verify our beam pointing on 18 individual positions for up to 30° zenith angle with an accuracy better than ±1°. This is especially valuable as due to the polar position of MAARSY the observation of galactic radio emissions is generally restricted to

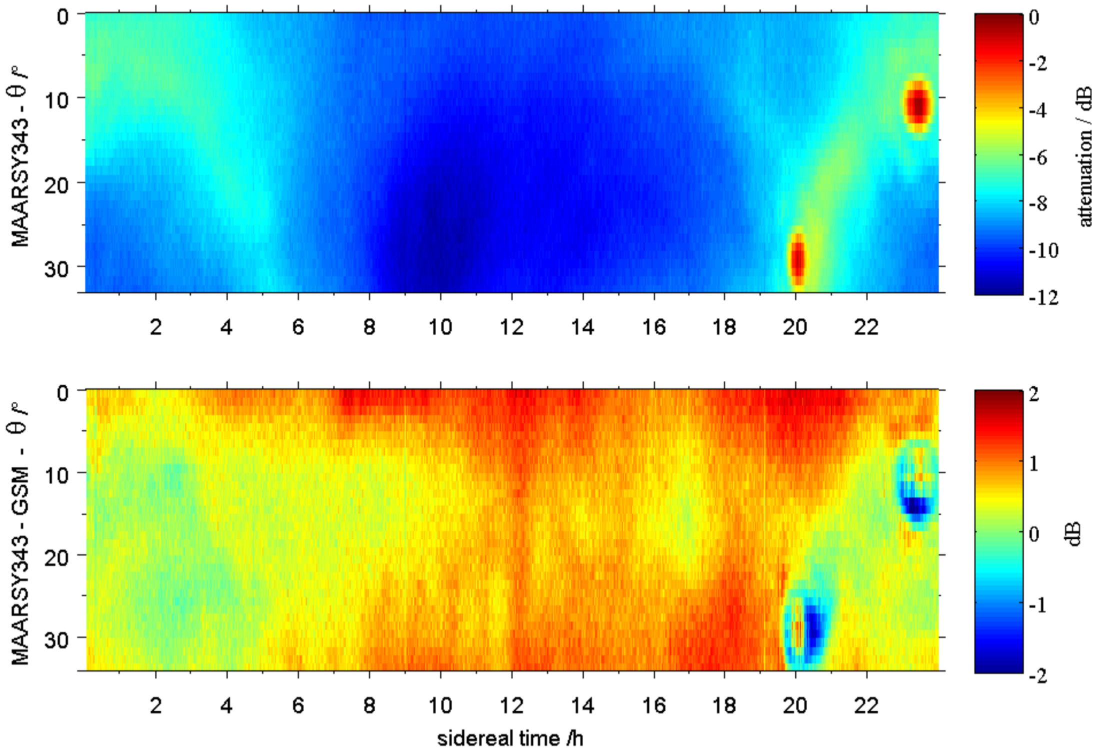

Figure 2: Distribution of incident noise power over local sidereal time and zenith angle θ for a scan within $\phi = 180°$, θ = 0-34° received with MAARSY343. The highlighted point-like radio sources are Cassiopeia A ($\theta = 10.5°$) and Cygnus A ($\theta = 27.5°$). The middle and bottom panel show the generated GSM map for the equivalent scan and the deviation from the observation.

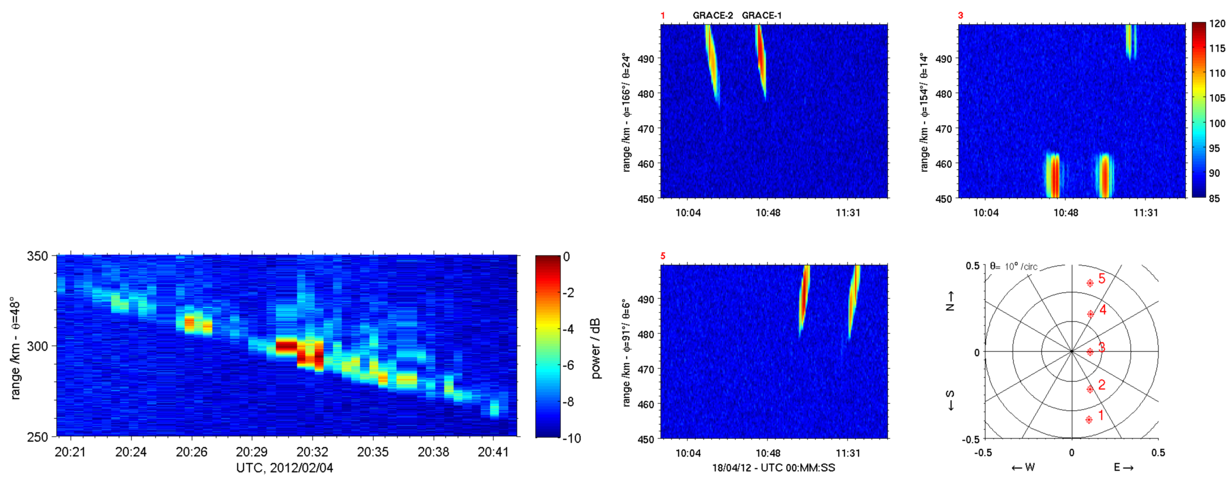

Figure 3: Left: Incident backscatter power received during the moon experiment depicted over range and time. Right: Received backscatter power from the GRACE-satellite experiment for three of five beam positions depicted over range and time. The beam positions used in this experiment are shown in the lower right panel, depicted in spherical coordinates.

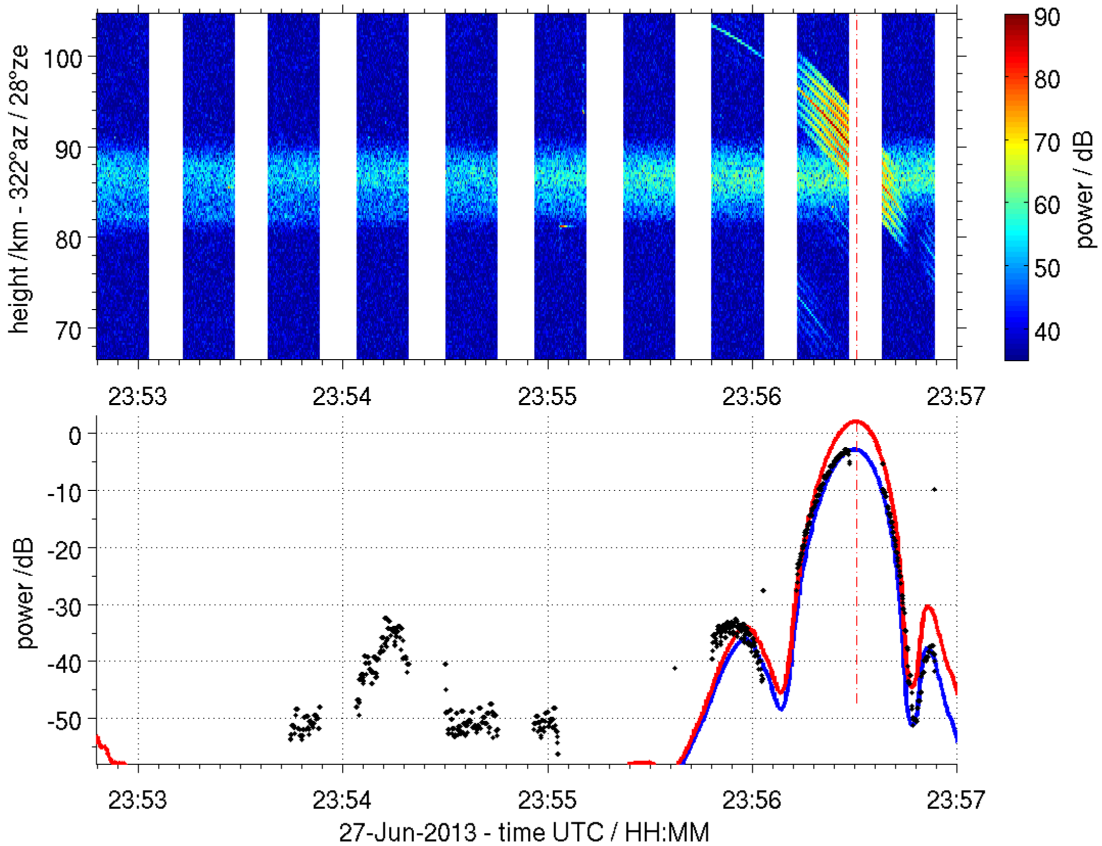

Figure 4: left: Incident backscatter power received during the WADIS rocket campaign. Top: HTI-distribution of backscatter originating from the WADIS payload and PMSE structures around 85 km height. Bottom: Simulated intensity from the MAARSY radiation pattern (red and blue, see text) and the detected power along the payloads trajectory (black dots).

southern directions.

Additionally, a statistical approach for meteor head echo observations is introduced to derive the radiation pattern by the angular distribution of detected events. The main focus for this experiment is the estimation of the position of the main and first side lobes, where the majority of events is seen.

Lately, we analyzed data from experiments observing Polar Mesosphere Summer Echoes (PMSE) during the WADIS rocket campaign, where also the payload have been observed with MAARSY. Performing a scan experiment during the rocket flight the strong backscatter off the approximately 3 m long payload enabled us to validate the beam pointing, main lobe width and side lobe attenuation for partially large off-boresight pointing angles. In the top panel of figure 4 are depicted the detected Height-Time-Intensity distribution during the flight of the WADIS payload for one beam pointing direction. The detected power corresponding to the trajectory of WADIS is plotted in the bottom panel (black dots) comparing the simulated radiation pattern with and without range and angle of attack correction (red an blue respectively). This experiment highlights the performance of the MAARSY radar, indicated by accurate beam pointing ($<0.5°$ pointing error), extraordinary good agreement to the simulated radiation pattern including the appropriate side lobe attenuation (two-way >30 dB).

[0]Talk to be presented in the session *Recent Advances in Antenna Measurement Techniques. AB01/02* at the 31st URSI General Assembly, 16-23 August 2014, Beijing, China.