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THE SOUSY-VHF-RADAR
FOR TROPO-, STRATO- AND MESOSPHERIC SOUNDING

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1. INTRODUCTION

The development of a VHF-radar in the Harz mountains (F.R.G.) for the study of the dynamics at tropospheric, stratospheric and mesospheric heights was motivated mainly by the question to what extent dynamic processes in the thermosphere and ionosphere are generated at lower atmospheric heights (SOUSY, 1974). Earlier work on thermospheric acoustic-gravity waves, in particular, indicated that part of the observed wave spectrum originates from tropospheric sources (Schödel et al., 1973; Klostermeyer, 1976; Röttger, 1976). Figure 1, for instance, shows the strong correlation between oscillations of the ground-level pressure, the Faraday rotation angle and the maximum electron concentration of the F2-layer observed on 1 July 1973 at Tsumeb in southern Africa. The oscillations were caused by acoustic-gravity waves with periods of the order of 1 h which were generated by a geostrophic adjustment process in the lower troposphere (Klostermeyer, 1976).

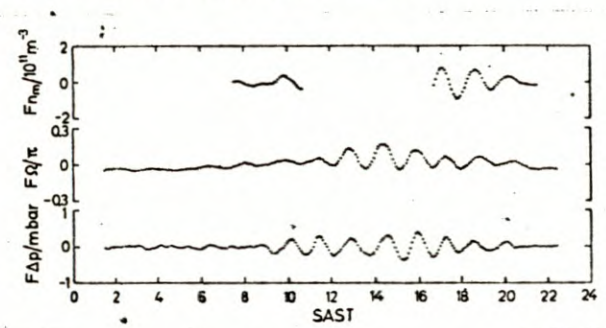

Figure 1. Filtered records of ground-level pressure, Faraday rotation angle (∝ total ionospheric electron content) and maximum electron density. The applied filter is characterized by a center period of 90 min and a half power width of 38 min (from Klostermeyer, 1976).

The investigation of the propagation of acoustic-gravity waves from their tropospheric sources to thermospheric heights is severely restricted because of the almost total lack of continuous wind measurements at the intermediate layers. Recent results (Rastogi and Woodman, 1974; Woodman and Guillen, 1974; Green et al., 1975; Rastogi and Bowhill, 1975; VanZandt et al., 1975) demonstrate, however, that high power radar systems in the VHF-range are appropriate tools to obtain the required information about the background winds and also the wave-induced motions. The principle of the VHF-radar technique is based on the scattering of electromagnetic waves by fluctuations of the refractive index. These fluctuations can be described by the radar cross section of the scattering medium which at heights greater than some kilometers depends on the turbulent temperature fluctuations as well as the background temperature gradient (Hardy, 1972). Since the cross section is proportional to the air density, the backscattered power decreases rapidly with height as is shown in Figure 2. At mesospheric heights, however, the radar cross section increases again because the scattering is now caused by irregularities of the electron density which increases at lower ionospheric heights. Because of the high collision frequency at these heights, the electron density fluctuations directly correspond to turbulent fluctuation in the neutral air.

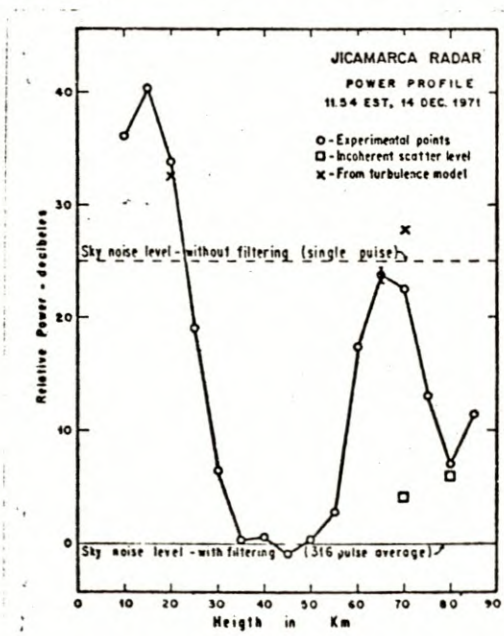

Figure 2. Backscatter power profile observed with the 50 MHz Jicamarca radar (from Woodman and Guillen, 1974).

The echo amplitudes from the tropospheric and lower stratospheric regions are relatively constant with time of day whereas the mesospheric echoes depending on the ionization density can normally not be observed at night. In addition to the measurement of the power profile, the radar method allows us to observe the Doppler shift and the shape of the frequency spectrum of the echoes which are related to the velocity of the scattering volume and the distribution of turbulent velocities within the scattering volume, respectively (Woodman and Guillen, 1974).

We expect therefore that the VHF-radar technique can be successfully used to investigate turbulence and related subjects like eddy diffusion and eddy viscosity coefficients as well as atmospheric-gravity waves, tides, planetary waves and the global circulation pattern from tropospheric to upper mesospheric heights. Preliminary measurements which were carried out using the Jicamarca radar in Peru to investigate mainly the spatial coherence of turbulence echoes are presented in the following paper (Rüster and Woodman, 1976) of this issue.

2. VHF-RADAR SYSTEM

From the results of Woodman and Guillen (1974), Rastogi and Bowhill (1975) and VanZandt et al. (1975) we concluded a radar to be a very appropriate tool to fill the research gap existing in the sounding-system of the Max-Planck-Institut für Aeronomie (SOUSY, 1974).

Some preliminary considerations had to be performed in order to fit the technical parameters of the system most properly to the scientific demands of our research work. Essential parameters, which mainly base on the objectives to measure the power spectrum of the radar echoes at a most high accuracy and high resolution as well as to cover a most wide height range, shall be treated shortly in the following section. It is understood that these conditions can be provided only by a self-consistent, real-time controlled, high-power radar system.

2.1 Operational Frequency

An essential question to be answered is the choice of an appropriate frequency for the radar operation. To decide what frequency for a tropo-strato-mesospheric radar sounder would be most suitable, the following considerations are made.

The optimum frequency is expected to be in the range between several MHz, normally used for ionospheric sounding, and several GHz, used for weather radar systems to investigate processes at tropospheric and lower stratospheric heights. Assuming a Kolmogorov spectrum and volume scattering of turbulences (Ottersten, 1969), the radar equation yields the received scatter power to be proportional to $\lambda^{-1/3}$ (λ is the radar wavelength) if one uses an antenna system with constant aperture. For an antenna system with constant gain, which can be achieved by extending the antenna aperture proportional to λ^2 and keeping the aperture efficiency constant, the received power increases with $\lambda^{5/3}$. Since, in praxi, this latter condition can at least partially be fulfilled, a low rather than a high frequency should be used for the projected type of radar operation. This result is supported by the decrease of atmospheric attenuation with decreasing frequency which, on the other hand, has to be considered only at frequencies greater than 3 GHz. However, since the sky-noise temperature increases with λ^2 at frequencies lower than some GHz (Berkowitz, 1965), a deterioration of the signal-to-noise ratio is expected using low frequencies. This difficulty can be reduced by coherent signal integration which was shown by Woodman and Guillen (1974) to be an appropriate method detecting a coherent radar signal even covered by strong noise. The efficiency of this method improves with integration time, which can be made longer for lower frequencies because the signal coherence time is proportional to λ (Battan, 1973).

These considerations lead to a preference of rather low frequencies. However, a more striking condition urges us to operate on low frequencies to receive echoes not only from the tropo- and stratosphere but also from the mesosphere. The latter condition has to be assured by the projected radar for middle atmospheric research. Due to increasing kinematic viscosity at mesospheric heights, the inner scale of the inertial subrange of the turbulence spectrum is at a length of about several meters (Cunnold, 1975). At smaller wavelengths, in the viscous subrange, the spectral power of the turbulences and, as a consequence, also the radar backscatter power decays much faster than assumed in the Kolmogorov spectrum. According to Cunnold (1975), frequencies smaller than 100 MHz should be used for mesospheric radar investigations since higher frequencies are in the viscous subrange. On the one hand, the upper limit of wavelengths to be used for mesospheric radar operations is determined by the length of about 100 m at which turbulence becomes anisotropic. On the other hand, it is determined by the increasing influence of ionospheric scatter and reflection at lower frequencies as well as by the bandwidth and antenna size limitations. Since furthermore administrative frequency allocations must be considered, we have to operate the radar on 54 MHz, which incidently is close to the Jicamarca radar frequency of 50 MHz. Since these frequencies are in the lower portion of the VHF-band, we prefer the name VHF-radar to be used for tropo-strato-mesospheric radar sounding.

2.2 Radar Transmitter-Receiver

To provide a range resolution of around 100 m, which is the expected thickness of turbulent layers estimated by Woodman and Guillen (1974), the radar must have a considerably high bandwidth. After careful considerations we decided to use the pulsed radar technique instead of the FM/CW-technique (SOUSY, 1974). To fit about 100 m range resolution, the minimum pulse length will be 0.8 µs. The pulse length, the pulse shape and the pulse repetition frequency will be adjustable by automatic control in order to match them to the properties of the scattering medium. Since the scattered signals from the upper stratosphere and the mesosphere are expected to be partially very weak, the radar will operate at a maximum pulse output power of 600 kW. The transmitter (Figure 3) is designed as a linear amplifier with a bandwidth of about 5 MHz. There are two reasons

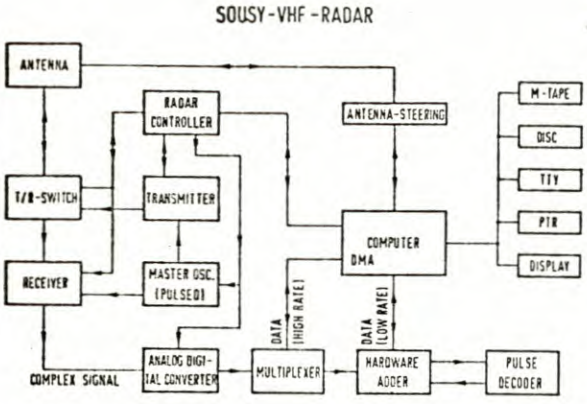

Figure 3. Block diagram of the SOUSY-VHF-Radar.

for this broad-band linear amplification: (1) the suppression of harmonic generation, (2) the fact that the pulse shaping depends only on the input from the pulse shaping master oscillator. The first condition is necessary because of administrative regulations in Germany. The second condition assures the advantage of easy pulse-shape matching in the receiver and transmitter path. The transmitter can handle pulse-coded signals up to a maximum duty cycle of 4 %, so that a considerable improvement of the signal-to-noise ratio of at least 10 dB can be expected, as compared to single pulse operation. The power supply is capable to handle the maximum length of a coded pulse-train to be 100 µs, which is necessary for mesospheric sounding. Phase and amplitude jitter caused by the high power amplification, which may influence the accuracy of the power spectrum analysis of the received scatter signals, is kept at minimum. The driver and the final amplifier are screen-grid modulated in order to keep shot noise generation during the receiving phase at a low level so that the limiting receiver sensitivity is not influenced. The transmitter final stage operates at grounded grid using two watercooled tetrodes Siemens RS 1084 in push-pull mode. The radar transmitter and the receiver can be tuned in the wide frequency range from 48 MHz to 67 MHz without any complicated mechanical reconstruction.

The high-sensitive, solid-state radar receiver (4 kT_0) is capable of linear amplification within the dynamic range of 70 dB at 1 MHz video bandwidth. The deviation from linearity throughout the 70 dB range is smaller than ±1 dB. This high linearity is necessary because of the hardware coherent integration procedure which has to be applied to improve the signal-to-noise ratio during the signal processing. The output signal amplitude of the receiver can be controlled by fast-switched attenuators which are set by the computer, depending on the signal strength as a function of range. Thus, an overloading of the receiver and the analog-digital converter is avoided and the dynamic range is increased considerably so that, for instance, ground-clutter problems can be reduced. The receiver IF-bandwidth is 2 MHz and shall be adjustable to different low-pass filters in the video path which properly match the transmitted pulse shape. Of course, all reference frequencies in the transmitter and receiver are coherent to assure Doppler measurements of the radar echoes. The complex video signals from the quadrature receiver outputs, which have a phase stability better than 1° throughout the entire dynamic range, are fed to the analog-digital converter for further processing.

2.3 Transmit-Receive Switch and Antenna System

The transmit-receive switch (TRS) connecting the same antenna to transmitter and receiver has to handle the maximum power of 600 kW transmitted in the VHF-band at the rather fast response time matching the minimum pulse length of 0.8 µs. To fit the properties of the transmitter and receiver which are tunable in a rather broad-band fashion, a broad-band balanced duplexer is applied for TRS (Unitrode, 1968). In this duplexer, two hybrids are used and the switching is performed by 2 × 6 high-power pin-diodes. The only frequency-dependent part is a tunable stub to compensate the diode capacities. It is estimated that the decoupling of transmitter and receiver during the transmitting phase will be at least 66 dB. The hybrids perform an additional decoupling between transmitter and receiver even during the receiving phase so that shot noise generated in the transmitter is expected not to limit the receiver sensitivity. A fast diode-switching control shall assure a maximum recovery time of the TRS around 15 µs, which defines the shortest radar range of the facility to be around 2 km.

The VHF-radar antenna, which has to point almost in vertical direction, was designed keeping in mind two basic conditions. These are a high-gain main-lobe and an extreme suppression of side-lobes in order to decrease clutter from ground and low-angle tropospheric turbulences.

To observe the propagation of atmospheric-gravity waves at a minimum horizontal wavelength of some ten kilometers, a beam-width of about 10° is sufficient. The beam must be tilted off the zenith direction in order to measure vertical as well as horizontal wave and background velocities. However, in case of a considerable large beam-width the structures of small-scale turbulences are smeared, the Doppler spectrum is broadened due to background velocities and the height resolution is diminished (SOUSY, 1974).

Sophisticated calculation methods using for example statistical optimization procedures (Czechowsky, 1976) as well as analytical considerations led us to the following parameters of the VHF-radar antenna. In order to keep the antenna size practicable, the width of the antenna main lobe was chosen to be 10°, which corresponds to a gain of 25 dB. The main lobe which is approximately rotational symmetric is tilted to the east by 10° off the zenith. The side lobe next to the main lobe is suppressed by 20 dB with respect to the main lobe. All side lobes at elevation angles from 0° - 15° are smaller than 30 dB. To keep the interference level minimal for special directions

(the operating frequency 54 MHz is in a TV-channel), the suppression of radiation at very low elevation angles shall even exceed 40 dB. These parameters can be accomplished by a phased antenna array of about 40 m diameter (taking 54 MHz as operational frequency) packed with 76 single Yagi-antennas. The chosen field site is capable of doubling the original antenna area so that eventually a gain improvement of 3 dB can be achieved.

The full antenna aperture which has approximately an octagonal shape is spatially weighted. This is provided by the spacing of the single Yagis becoming slightly larger at outermost positions. In east-west and north-south direction, the spacing of the Yagi-antennas, which are positioned in straight lines, increases from 0.77 λ in the innermost part to 1.17 λ in the outermost part. Looking at 45° with respect to E-W or N-S direction, the position of the antennas is on slightly outward-bent lines, since also the distance between the E-W and N-S lines increases (from 0.38 λ to 0.60 λ) with distance from the center of the antenna field. The mean package density in the antenna field is given by the mean separation of 0.7 λ between the single Yagi-antennas.

These antennas of the phased array are 4-element Yagis with 7 dB gain, which are normally used for TV-reception but modified to handle more than 10 kW peak pulse power. Since these Yagis introduce a front-to-back ratio of 16 dB, a reflecting ground screen beneath the antennas is not required. The phasing between different antennas is provided by different lengths of the feeding cables. The Yagis with the feeding point about 1 m above ground point straight up to the zenith and the axes of the Yagi-feeding elements are parallel to the E-W direction for interference reduction.

In addition to the spatial weighting, the antenna aperture is weighted electrically by feeding the outermost antennas with half of the power of the inner ones. The split of the 600 kW power from the transmitter to the antennas is performed by a seven-level cascading network of 75 broad-band hybrids which additionally provide a strong decoupling of the single antennas. The decoupling is a necessary condition if the beam shall be steered by phase controlling the single antennas with pin-diode switches. This is intended to be carried out in the succeeding development phase of our radar facility. Alternatively, for beam-steering, circularly polarized antennas could be used whose phases are adjustable by rotation of the antenna axes so that no electrical switching of the VHF-signal will be necessary.

The antenna field site is in the Sperrlutter valley (10.5° E, 51.7° N) in the Harz mountains 25 km east of Lindau. The mountains surrounding the valley provide a considerable shielding up to elevation angles of 5° - 25° up to distances of 2.8 km, which is expected to be the maximum ground-clutter range.

2.4 Computer

The computer represents an essential unit of the radar facility. It will not only be used for data acquisition and preprocessing but shall be more feasible to provide a real-time control of the radar. This shall assure that the system operations can be optimally adjusted to the varying characteristics of the backscatter returns. A real-time decision derived from a test-set of data, thus, is a necessary condition for optimized radar operation.

After coherent detection at the receiver output, the two quadrature signals (real and imaginary part of the video signal) undergo an analog-digital conversion. The two-channel analog-digital converter will have a high conversion rate of more than $2 \cdot 10^6$ words/s, which matches the 1 MHz video bandwidth. Each word has 10 bits sufficiently fitting to the linear dynamic range of the receiver. The digital data are either directly transferred to the computer memory via the high-rate channel or to the hardware adder. This device shall be capable to integrate the data coherently. This shall be done for height intervals down to 120 m within a height range of several ten kilometers. The signal coherence time should be checked by the computer as a function of height so that the integration time of the hardware adder can be set to an optimum value. A hardware pulse-decoding can be directly accomplished after hardware adding. The data then are transferred via the low-rate channel into the computer. After further preprocessing, the data (e.g. power and velocity as function of range) can be displayed for quick look and will be used for real-time decisions of the radar control. For further more sophisticated processing and analysis, the data will additionally be recorded on magnetic tape.

The steering of the antenna-beam will be controlled by the computer. The radar controller, manually or computer-controlled, generates for example the transmitter pulse sequences for the master oscillator, the control pulses for the transmitter and receiver amplifier, the transmit-receive switch and the analog-digital converter. A fast response transmitter (VSWR, duty cycle, overloading etc.) and receiver (TRS) protection is not only provided by direct-access control but also will be done by the radar controller and computer. For these purposes, an HP 21 MX computer will be used which provides the ability for real-time executing.

3. CONCLUSION

The high-power, high-resolution VHF-radar promises the observation of the development of turbulence in tropo-, strato- and mesospheric heights. Besides the investigations of turbulence, the profile of the eddy diffusion coefficient shall be deduced. This is a problem at least to be solved for the height regions near the tropopause and the turbopause. The VHF-radar can essentially help to describe the life history, including sources, propagation characteristics and decay of gravity waves and turbulence in the middle atmosphere.

Since the VHF-radar equipment is installed in three big containers, the facility is self-consistent and transportable. It is anticipated to operate the system not only in the midlatitude Harz mountains. Supported by recommendations for the Middle Atmosphere Program (MAP, 1976), the facility shall also contribute to investigations at lower latitudes.

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