Chapter 1

# Historical Aspects of Radar Atmospheric Dynamics

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## 1 Introduction

"Radar" stands for radio detection and ranging. It is well-known that radars were developed during World War II to detect aircraft for military purposes. However, the basic technique for radars was used for the first time by Sir Edward Victor Appleton in his ionosphere research in the 1920s. According to Robert Watson-Watt, "But for Appleton's scientific work, radar would have come too late to have been of decisive use in the Battle of Britain." (Nobel Lectures; Physics, 1964).

The scientific use began mainly after the war under the leadership of scientists working on radars during the war.

There are very many applications of radar techniques now in use. However, we shall below review the history of radar techniques which have been applied only for atmospheric observation. We start with the ionosphere observation by ionosonde symbolizing the earliest history of radar observation and proceed to later developments in the observation by other types of radars as partial reflection, meteor, incoherent scatter radars. As to lower atmosphere observation the historical development will be given mainly about MST radars.

## 2 Radar Technique Used for the Ionosphere Exploration in Early Days

The basic idea for radars was for the first time in 1924 put forward by Appleton who located the ionized upper atmosphere now known as the ionospheric E region. He worked on an experiment with Barnett who was the first graduate student under Appleton's
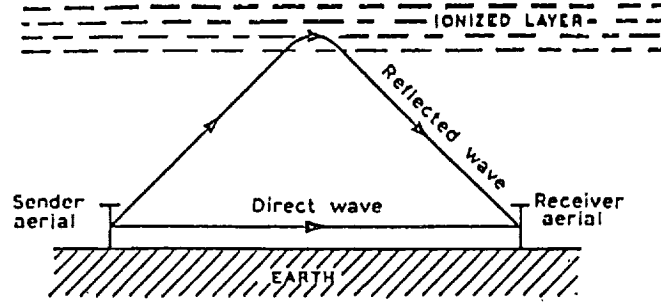
**Fig. 1.** Appleton and Barnett's experiment in 1924.

guidance at Cambridge (Appleton and Barnett, 1926). It was December 11 in 1924 that they attempted to receive at Oxford radio waves which were transmitted from BBC Station at Bournemouth, a coastal town south west of London. They found, as expected, that the fading pattern maximized repeatedly with the varying radar–wave frequency due to interference between those direct waves which arrived along the ground and those sky waves which were assumed to be reflected from the suspected ionosphere. It is straight forward to obtain the reflection height from the propagation path difference between the direct and sky waves, $D$, given as

$$m = \frac{D}{\lambda_1} - \frac{D}{\lambda_2} \tag{1}$$

where $\lambda_{1,2}$ are two wavelengths; between these two waves in variation we have $m$ maximum. The arrival direction was identified by a loop and a vertical antenna. This simple system (Fig.1) by Appleton's idea succeeded to determine the E region height as about 100 km, the success which remains as one of his great contributions to the study of upper atmosphere physics leading to his Nobel prize winning in 1947. We see in this Appleton's work the basic idea of radar techniques, especially of FM (Frequency Modulation) type. In 1925 in the U.S.A. Breit and Tuve invented the vertical sounding method which adopts pulse–modulated radio waves to be transmitted vertically, thereby simplifying the system and, since then, being widely used in the world. Thus, the pulsed radar system now in use was established. Appleton worked on theory of the ionized gas (1932). It was found that $f_0$ the frequency at which radio waves is totally reflected at each height of the ionosphere

is related to the electron density of the ionosphere $N$ at that height as

$$N = \frac{4\pi^2 \epsilon_0 m}{e^2} f_0^2 \qquad (2)$$

where $\epsilon_0$ is the vacuum dielectric constant and $m$ is the electronic charge and mass; $f_0$ was found to be 0.75 MHz before down in winter. We see that (2) is based on the refractive index $n$ changing relatively to vacuum with the sounding radio frequency $f$ as

$$n^2 = \frac{f^2 - f_0^2}{f^2} \qquad (3)$$

which is also applicable for understanding turbulent echoes from the mesosphere in MST radar observations.

Initially, the constant frequency sounding was used, giving the reflection height to vary with time. Note that the virtual height used in this sounding $h$'s is obtained as $h' = \frac{\Delta t}{2} c$ where $\Delta t$ is the time of the round trip for a radar pulse between the transmitting and the receiving stations, both at the same location and $c$ the light velocity; the pulse traversing the ionosphere on the way is retarded depending on $nc$, the group velocity, which depends on $N$ on the way given by (2) and (3). In 1930, Appleton initiated to sweep $f$ in order to obtain $h$'s versus $f$, namely, the electron density distribution with height $h$'s, the standard ionosphere observation which has routinely in use over the world even now. The ionosphere, however, is probed by this method only in its bottom side lower than the F region peak. The top side remained unknown before the rocket in situ sampling was introduced in the 1950's. The top side sounder on board satellite, based on usual ionosonde techniques, began to supply data of the ionosphere topside on global scale in the 1960's e.g. by the Alouette 1 Satellite as in Fig. 2 (Warren, 1962).

As shown below, in the 1960's novel radar systems were developed for ionosphere observation *i.e.* incoherent scatter radars which enable us to observe the top side ionosphere as well as the bottom side from the ground.

Application of ionosonde observation to ionosphere dynamics is very limited. Quantities available by the observation is the electron density which corresponds to the proving radio wave totally reflected at particular height by (2). We cannot choose certain height for observation unlike in the case of incoherent scatter and MST radars which choose the observing heights by gating the receiver so as to match the time at which echoes from the chosen height arrive. However, some indirect approaches to the dynamical study were attempted as in Fourier-analysing daily variation of ionospheric heights and electron density to find solar and lunar tides (e.g. Appleton and Weeks 1939, Martyn 1947, Rush et al, 1970). Note that the indirect approach depends often on ambiguous mechanisms which connect the dynamics and the observed electron density variation. Ionosphere networks
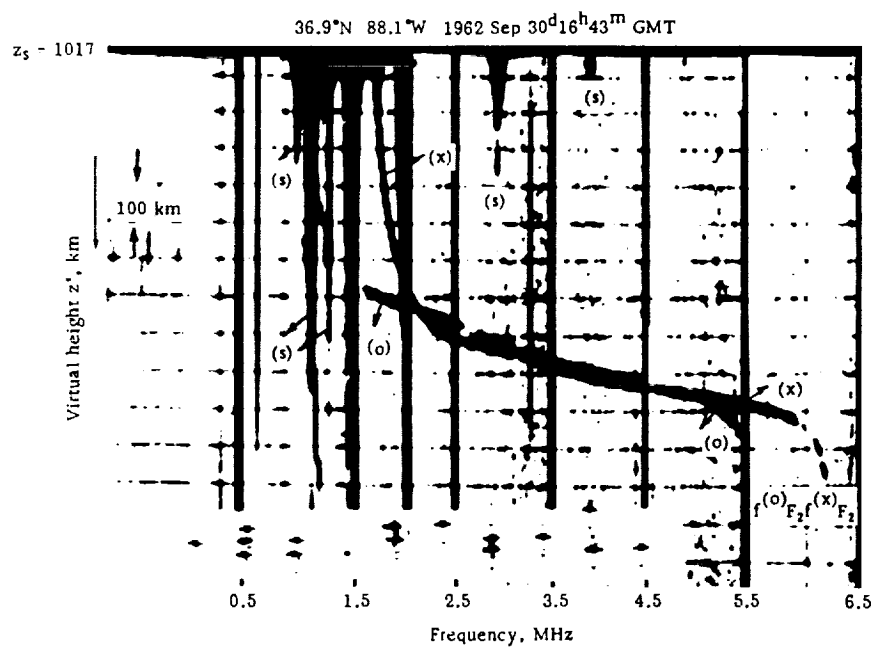
**Fig. 2.** A topside ionogram for the "quiet" outer ionosphere, obtained with the Alouette 1 satellite at a height $Z_s = 1017$ km.

local and global are, still now, useful as a source of information regarding the propagation of ionospheric disturbances.

# 3   Partial Reflection Radar Observation

In the late 1940's, weak echoes were found to be returned from the D region in the height range 75–90 km. Different from usual ionospheric echoes obtained by ionosonde, as mentioned above, the height appeared independent of the frequency range over 1.6—-4.0 MHz. In early times the sounding using the weak echoes, understood as partial reflection sounding, was used mainly to measure the D region electron density as based on different absorption between the magnets–ionic ordinary and extraordinary waves of the echoes. We know now that these radar echoes from the mesosphere are utilized for studying mesospheric dynamics. The echoes are now interpreted to be due to, beside partial reflection, the scattering by irregularities of the refractive index for radio waves (See (2)) irregularities which result from atmospheric turbulent mixing of the D region electron density with a height distribution.

Vincent and Belrose (1978) discussed the echoes with 2.66 MHz to vary around 80 km height above which the echoes are less aspect sensitive than those below this height; the echo power spreads in wider angle from zenith in the former than in the latter case. A similar feature was found later for much higher probing frequencies as 50 MHz by Fukao *et al.* in 1979 in their Jicamarca radar experiment. It is still open to question as to how the turbulent mixing of the D region electron density distribution (Fig. 3) can explain this difference around the mesopause. In the field of mesospheric dynamics RRD which stands for partial reflection drift techniques is now regarded as to be important especially for their stable operation for long periods and simple low–cost maintenance of the facility.

The principle of PRD technique is to receive the echo pulse around 2 MHz with its width as 20 $\mu s$ by several antennas. Correlations among echoes received at different antennas make it possible to decide the translation velocity of irregularities which cause the diffraction pattern ; the height resolution depending on the pulse width amounts to a few km.

The most sophisticated method, the Full Correlation Analysis, allows the diffraction pattern to be anisotropic changing with time and gives a so–called true velocity. There are many interesting observations of gravity wave and tides by PRD technique by Vincent (1984) and Manson and Meek (1986).

Vincent and Reid (1983) have developed a Doppler radar using MF frequency of this PRD technique, the antenna area having 1 km diameter to produce a 9 °beam-
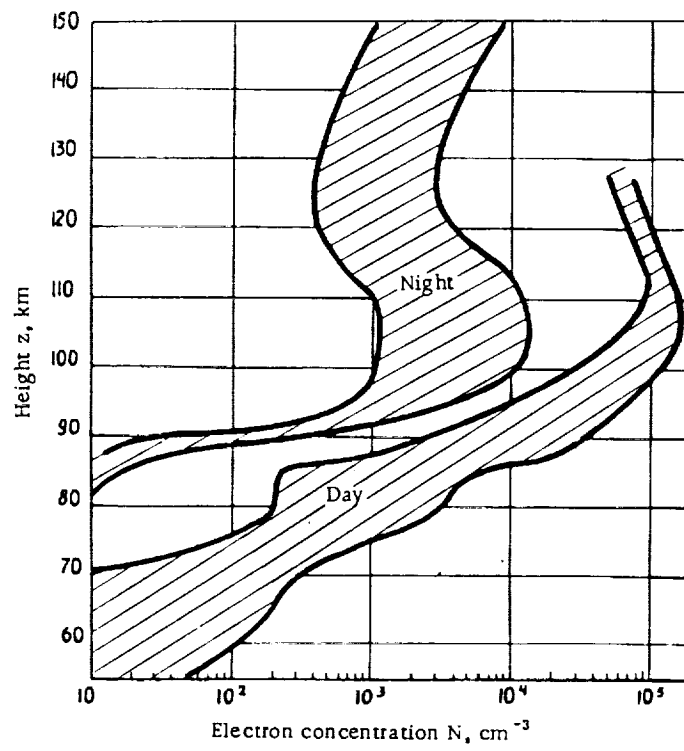
**Fig. 3.** D region electron density distribution (Al'pert, 1972).

width. They were successful to derive the vertical momentum flux of gravity waves on an interesting idea that two co–planar radar beams steered by an equal angle from zenith are used to measure continuously and simultaneously perturbed winds along the line of sight and the observed velocities squared after being averaged give the vertical momentum flux of horizontal velocity of gravity waves. The deduced flux variation with height seems to suggest a forcing which is consistent with gravity wave theory. This observation technique is now applied to MST radars to other regions of the atmosphere. Details will be discussed in other sessions of the present ISAR course and not be given.

# 4 Meteor Radar Observation

Meteors impinging on the earth's upper atmosphere produce ionization trails along their path in the height range between 80–100 km depending on their velocity as 10–70 km/s. Appleton in his early observation of the ionosphere has suspected the sudden appearance of the ionization around the E region to be due to meteors. Whilst meteors had been studied by radio methods for astronomical interests before 1960 (McKinley and Millman, 1949) meteor trail movement became a subject of study for observing winds at meteor heights in the 1950s (Manning et al., 1953).

The meteor trail is a column ionization with electron density as $10^{12}/m$; the effective diameter is much shorter than the probing radio–wave frequency, thereby producing coherently scattered echoes over the Fresnel zone along the meteor trail. Meteor trails, with a short life time ($\leq 0.1s$), were expected to move with the local wind. The meteor radar technique is based on this principle and first was used at Stanford, California by Manning who successfully measured winds at meteor heights in the early morning hours in the summer of 1949 to be on the average "125 km per hour with motion's from south–southwest and north the most common"(Manning et al., 1953). It seems interesting to know that he used a rotating radar beam along azimuth to increase the meteor detection frequency with an array of 4 antennas, each changing the phase of the transmitted wave. Later, many (more than 40) meteor radars have been constructed, contributing significantly to the study of winds, called meteor winds, over 80—110 km in heights centered at 95 km where the meteor trail occurs most frequently. The system has been much improved especially in the height resolution which is essential for the study of winds changing rapidly with heights. There are two important improvements; one is the establishment of radio interferometry system to increase the accuracy of the arrival direction of meteor echoes and the other is the use of computers to discriminate echoes on–line. The Kyoto Meteor Radar is one of the standard type of the facility adopting these improvements (Aso et al.,

1980). The resolution of elevation angle of the system is 1° averaged over 25°——70° of elevation angle of the echo arrival direction; this corresponds approximately to 3 km in height resolution.

An advantage of meteor radars over other radars, especially of the standard type, is to be handy in the operation i.e. in unattended fashion suitable for long period observation. The Kyoto Meteor Radar was in operation almost continuously for several years. As done by Meek and Manson (1987) by PRD, the accumulated data made it possible to deduce lunar tides at meteor heights (Tsuda et al., 1981). In general, the facility suits the climatological study of dynamics at meteor heights for atmospheric waves i.e. tides, planetary waves (Tsuda et al., 1988). For obtaining much more data with less height resolution as is required in these dynamical phenomena, the decay height method is used where the principle depends on the measurement of echo decay time i.e. meteor trail life time at each heights which as the molecular diffusion time is calculated using certain model atmosphere as CIRA.

A sophisticated observation of gravity wave was attempted by the Kyoto Meteor Radar. The area at meteor heights illuminated by the radar with an elliptical shape of 100 km in length and 50 km in width, is divided in five strips orthogonal to its major axis. Phase variation of winds from one strip to the next is measured by interferometry, thereby deducing the phase velocity of gravity waves passing in the area(Yamamoto et al., 1986).

The most powerful meteor radar used power as large as 1 MW, receiving tremendous number of echoes (Bowhill et al., 1978). But usual meteor radars receive fairly small number of echoes around dusk, resulting in the overall time resolution of a few hours.

Meteor echoes are also received by both main and side lobes of MST radars and a care must be taken to avoid the echoes which are erroneously detected by the side lobes in wind determination.

# 5   High Power Radar Observation

In 1958 Gordon pointed out the possibility that a powerful radar can be constructed to be able to detect incoherent scatter echoes by ionospheric free electrons in thermal motion, whereby measuring electron density and electron temperature. His idea was to realize the construction of a radar with "a megawatt transmitter, a 300 meter diameter dish (60 per cent efficiency), a bandwidth of 100 kilocycles matched to the expected Doppler spread, a noise figure of two, 20 decibel signal to noise improvement by averaging pulse, and cable losses of two decibels (Gordon, p.1827, 1958). He further went on saying "The

radar is powerful, but megawatt transmitters are available. The antenna is very large; but since the signal–to–noise does not depend on wavelength, the large area may be obtained with coarse mesh and moderate tolerances by selecting the longest wavelength (about 1.5 meters) consistent with cosmic noise limitations. The antenna may be fixed and pointed vertically". Gordon's idea has introduced in the 1960's the novel powerful ground–based tools called IS (Incoherent Scatter) radars for the study of ionospheric plasma structure and dynamics. The IS radar technique led us in the 1970's to a further development towards MST radar techniques for the study of Mesosphere Stratosphere and Tropospheric dynamics. Before referring to observations of these radars, we have to learn somewhat about how radio waves are scattered in these frequencies where the scatterers are refractive index irregularities, very weak, and filling the entire atmospheric volume illuminated by the radar beams.

We shall follow Villars and Weisskopf in their work on the scattering of electromagnetic waves by turbulent atmospheric fluctuations (1958). The scattered electric field amplitude $Es$ at a distance $R$ from the scattering volume $V$ $(R^3 \gg V)$ is

$$Es = \frac{\pi}{R\lambda^2} E_0 \mid \int_v \underline{dr} \Delta n(\mathbf{r}) e^{i2\mathbf{k}\cdot\mathbf{r}} \mid \tag{4}$$

for back–scattering; $\lambda$ and $\mathbf{k}$ the radar wavelength and wavenumber respectively; $E_0$ is the incident wave amplitude. Now $n$ includes neutral–atmospheric effects in addition to that of plasma by (3) as

$$n^2 = 1 + 0.74\frac{P'}{T^2} + 1.55 \times 10^{-4}\frac{P}{T} - \frac{f^2 - f_0^2}{f^2} \tag{5}$$

where $P$ and $P'$ are the atmospheric and water vapour pressure in the $mb$ and $T$ the temperature. The scattering cross section $\sigma$ per unit volume per solid angle is

$$\sigma d\Omega = \overline{\Delta n^2}\frac{\pi^2}{\lambda^4}C(2\mathbf{k})d\Omega \tag{6}$$

where $\Omega$ is the solid angle and

$$C(2\mathbf{k}) = (\frac{1}{2\pi})^3 \frac{1}{\overline{(\Delta n^2)}} \mid \int_v \Delta n(\mathbf{r}) e^{i2\mathbf{k}\cdot\mathbf{r}} \cdot d\mathbf{r} \mid^2 \cong (\frac{1}{2\pi})^3 \int_\infty C(\mathbf{r}) e^{i2\mathbf{k}\cdot\mathbf{r}} \cdot d\mathbf{r} \tag{7}$$

where $C(\mathbf{r})$ is the auto–correlation function of $\Delta n(\mathbf{r})$. Thus, by (4) $\sigma$ is proportional to the spectrum intensity of $\Delta n$ for $2\mathbf{k}$; the spectrum is the Fourier transform of the auto–correlation function. This implies intuitively that radars pick up as their targets only those irregularities whose size along the radar line of sight is $\frac{\lambda}{2}$ as called Bragg's law in crystal physics.

To ionospheric plasma (4) is given by (3) and (5)

$$< \overline{\Delta n^2} > = | \frac{\Delta N}{N} |^2 (\frac{f_0^2}{2f^2})^2 \approx \frac{1}{4} | \frac{\Delta N}{N} |^2 (\frac{f_0}{f})^4 \qquad (8)$$

for $f \gg f_0$ thus, by (6)

$$\sigma = (const)C(2\mathbf{k}) \qquad (9)$$

i.e. independent of $f$.

(7) is also applicable to mesosphere observation where free electrons are mainly responsible to the echo scattering.

To the stratosphere and troposphere, the third and second terms in (5) are mainly responsible, respectively. Then, we have by (6)

$$\sigma = (const)f^4 C(2\mathbf{k}) \qquad (10)$$

In (9) and (10) "const" is proportional to the mean square fluctuation of each tern in (5). Physics to produce refractive index irregularities is different between the regions we observe, i.e. the ionosphere and the lower neutral atmosphere.

In the case of the ionosphere, the scatterers are free electrons in random thermal motion which should produce incoherent scattering. It is expected then that $\sigma$ is $4\pi r_e^2$ where $r_e$ is the classical electron radius; $\sigma \approx 10^{-28} m^2$ as proved strictly by Fejer in 1960. Bowels (1958) has made for the first time the incoherent scatter experiment using a 41 MHz radio wave, 4–6 MW, 1024 antennas in a $(116 \times 140m)$ area etc. He received echoes as expected by the Gordon's idea in their intensity but not in the Doppler width which was to be due to electron thermal motion equivalent to the F region electron temperature as $10^3$ Kelvin in daytime i.e. as large as several ten KHz. What he really obtained was much less than that. Later it was found that if, as in the present case, the probing radar wavelength is much longer than the Debye shielding length which is less than 1 cm in the F region, the Doppler width is mainly due to ions which is in thermal motion of much lower temperature than that of free electrons; the observed Doppler width must be narrower by, at least, $10^{-2}$, the mass ratio between electrons and ions. This finding which had not been expected before the experiment opened much more possibilities for this technique so as to be able to observe physical states of ions as well as electrons in the ionosphere. Further, based on close physical coupling between ions and neutral particles due to their similar masses, the thermospheric gas dynamics has also been developed by IS radar observation.

IS radars are regarded in ability as to be rivals and also complements to in situ sampling by rockets and satellites (Evans, 1974). This type of radars was constructed at Arecibo in Puerto Rico and Jicamarca Peru and later at St. Santin in France and Milstone Hill in
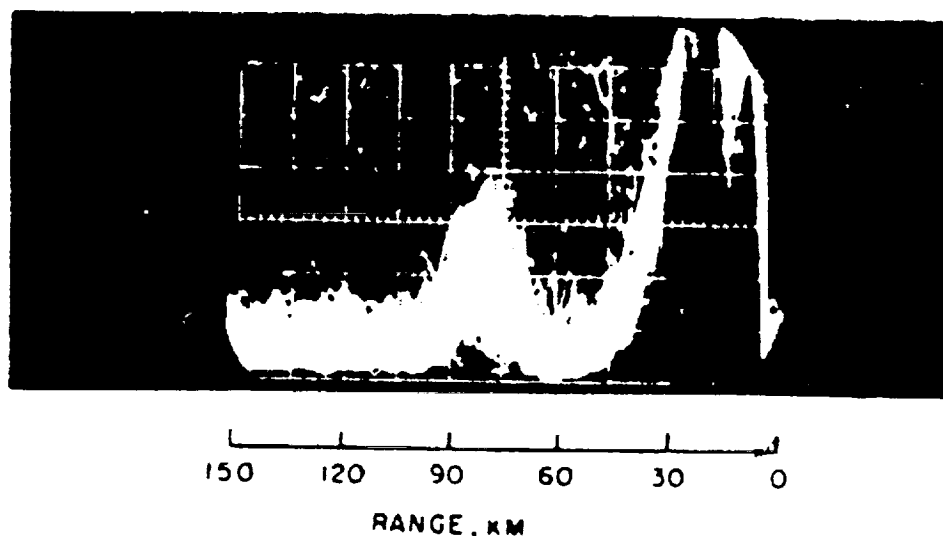
Fig. 4. Observation of a high power radar by Bowles 1958. Note that a strong echo is found around 75 km.

U.S.A. and recently in Scandinavian countries. Details of their contributions will learned in other sessions.

History shows that sciences enjoy often remarkable progresses through unexpected findings. This is true, as above-mentioned, for IS radars, detecting the observed wide Doppler broadening due to ions. Another finding came unexpectedly around 1970 when the Jicamarca radar, which usually obtained only IS echoes from the ionosphere, detected unknown echoes presumably from the mesosphere. Few seemed to believe Woodman's report on this finding at International Equatorial Aeronomy Conference in Nigeria in 1972. The echoes showed Doppler shifts corresponding to several ten meter per second in velocity. Soon, Woodman and Gullèn (1974) identified the echoes with those of scattering due to refractive index irregularities which are caused by turbulence moving with local winds in the mesosphere.

It seems impressive that as in Fig. 4 Bowles in his first IS experiment in 1958 found without noticing any significance intense echoes around a 80 km height. This is an example that scientific significance may vary with time! The finding by Woodman implies the beginning of a novel radar technique to be able to observe mesospheric winds, the MST

technique which enables us to observe the mesosphere, stratosphere and troposphere on the same principle i.e. due to "Clear Air Turbulence (CAT)" echoes in meteorological terms.

We call the mesosphere and stratosphere combined the middle atmosphere which had remained as ignorosphere before 1970, but were required immediate scientific elucidation in the 1970s. This was mainly because of the environmental assessment demanded by threatening pollution by artificial pollutants as Freon, NOx etc. Under the circumstance, Middle Atmosphere Program (MAP), an internationally cooperative scientific program for the purpose, was planned in the 1970s and realized between 1982–1985. MST radar techniques developed very rapidly just parallely along the MAP course and played a central role in the program. This is the case even beyond MAP to date.

Let us go back to (9) and (10), the base for MST radar techniques, where $C(2k)$ is now the spectrum of atmospheric turbulence which is known as

$$C(2\mathbf{k}) \propto \mathbf{k}^{-\frac{11}{3}} \quad \text{or} \quad \sigma = (\text{const})\mathbf{k}^{-\frac{11}{3}} \tag{11}$$

and

$$\sigma = (const)k^{\frac{1}{3}} \tag{12}$$

provided that the radar wavelength is within the turbulence inertia subrange; (11) and (12) are applicable, respectively, to the mesosphere, and the stratosphere; (12) is also for the stratosphere. Note that (11) and (12) show the basic principle for designing MST radars; in terms of the radar frequency, the lower the better for the mesosphere, whilst the reverse is true for the stratosphere and troposphere. However, the wave length must always be in the intertia subrange; otherwise, in the viscous range, the spectrum intensity is so weak. The minimum size giving the inertia subrange is approximately several meters in the mesosphere, decreasing monotonously down to 1 cm in the troposphere. Now, the radar wavelength of 5 m is of a fairly standard i.e. 50 MHz. The maximum output is usually 1 MW and the antenna area is $10^4$ $m^2$ or more. By (11) we know that PRD techniques as in Section 4 can use a very weak power as a few kW; the frequency used there ($\sim 2MHz$) is (1/20) which gives $6 \times 10^4$ times in the turbulent spectrum intensity to that for 50 MHz of MSP radars by (11). In (11) and (12) $\sigma$ contains a constant which depends on the height distribution of $n$ implying that as in (5) $\sigma$ depends on the height distribution of water vapour, air density and electron density. Their distributions are disturbed by turbulence; the turbulent diffusion is the basic process. Villars and Wisskap (1958) failed to notice this process assuming unrealistic air compression by turbulence. The pioneering Booker–Gordon theory (1950) was also unrealistic, resulting in such a $\sigma$ as virtually independent of $k$, unlike either (11) or (12).

Atmospheric gravity waves (GW's hereafter) had drawn little interests among meteorologists, say, before 1970. Ionospheric people showed some interests in those events in which GW cause remarkable disturbances named TID (Traveling Ionosphere Disturbance). GW's, which are produced mainly in the troposphere, are so weak that they play no significant role in tropospheric dynamics. However, GW's travel upwards, growing exponentially with the decreasing ambient air density and reaching tens of meters per second in velocity. In the 1970's people began to suspect that GW's may play an important role in the mesosphere. Around the end of the 1970's a theory by Matuno (1982), Holton (1981) and Lindzen (1981) predicted that GW's, after growing to certain degree, tend to break near the mesopause, whereby releasing their momentum against the local wind, working as a dynamic brake. This dynamical brake can explain why winds tend to weaken around a 80 km height as observed; Without this effect, winds should have been indefinitely increased with height. Thus, GW's are regarded as to play an important role in the middle atmosphere general circulation and became one of the most interesting subjects in MAP. Temperature observed by remote sensing techniques from satellite cannot be relevant because of inferior vertical resolution due to the technique and also inferior time resolution due to satellite motion. We need on many occasions 1 km in rolution along the vertical direction and a few minutes in time resolution which can be attained only by MST radars. Among various MST radars now in operation over the globe, that in Japan, named the MU radar to observe both middle and upper atmospheres, is outstanding because it can steer the beam so rapidly by electronic phase–shifting, a characteristics, which makes it possible to measure the GW structure instantaneously within the cone suspended by 30 °from zenith. There are many studies on peculiar GW behaviors by MST radars. The pioneering works around 1980 owes mainly to Balsley's group in Boulder and Röttger and Max Planck's group in Lindau(e.g. Balsley and Gage, 1980). These works will be discussed elsewhere through the present course.

We have now networks for global observation of the mesosphere dynamics consisting of both MST radars, PRD radars and meteor radars. One of the unique cooperative observations has been done between Kyoto and Adelaide which are located at geographically conjugate points at 35 °in lat. with respect to the equator. So far, tidal waves have been successfully studied by this cooperation.

There are radars smaller in size mainly for stratosphere and troposphere observation as at Sun–Set near Boulder constructed in the 1970's (e.g. Green *et al.*, 1979); they are ST radars which may replace the conventional routine meteorological balloon observations after distributed at many locations over the globe in future. They are fairly low in cost of construction and can operate continuously and almost unattended.

Rapid progress seen in radar atmospheric dynamics has been successful only by a good cooperation among people of different disciplines especially between ionosphere radio–physicists and meteorological dynamists. This cooperation will be essential for future advancement in this field.

# 6 Future Radar Observation

Now the atmosphere is found to be one large and complicated system, each part coupling with each others, both horizontally globally and vertically from the ground to the middle and, further, upper atmosphere. Anthropological pollution has become serious problems on atmospheric environments. Under the circumstance we need to understand the atmospheric dynamics increasingly accurately with time. For this purpose, radars will present useful and powerful techniques. These radars must be distributed globally making up an effective and comprehensive network relevant for the purpose.

At present we have none of powerful radars in the equatorial region which is receiving the maximum solar energy input driving almost the whole atmosphere in motion. Interaction of the atmosphere with the ocean there is also important but not well understood. For completing a global radar network the powerful radar construction there is essential. This is the Equatorial Radar Project which has been in planning mainly between Japan and Indonesia. The Indonesian district is the most intensively convecting region together with the equatorial Africa and the Amazon in South America. The MU radar, Adelaide radars (PRD radar), Chung–Li radar (ST radar) and some other radars to come in the Asian Sector will make up a very desirable network with this equatorial radar along the Asian longitude.

The planned system is very ambitious one (Fig. 5), able to measure the entire atmosphere from near the ground to the ionosphere with an excellent resolution with a 300 m diameter of the antenna area and one MW power, beam–steerable by 20 °from zenith. Beside the central radar, there will be meteorological radars together with other supporting facilities. This is the essence of the International Center for Equatorial Atmosphere Research which we desire to be realized in the future. Good Luck for our future!
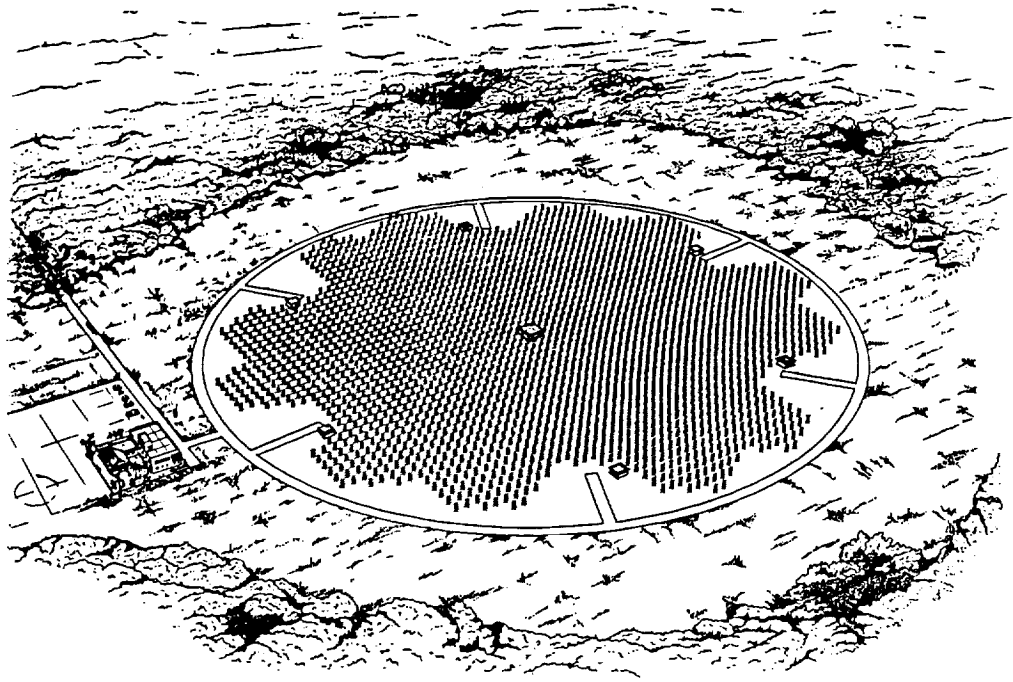
**Fig. 5.** Artistic view of the equatorial radar.

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