MODULE 8
WEATHER RADAR

Project
Strengthening Meteorological Information Service and Early Warning System (Component A)

BANGLADESH METEOROLOGICAL DEPARTMENT

LOCAL TRAINING

Prepared by:
Grant Thornton Consulting Bangladesh Ltd.

AIMS AND OBJECTIVES

- Participants will become familiar with issues associated with the weather radar system including the function of the controls; analysis and interpretation of the radar display; weather hazards; and weather avoidance.
- They can demonstrate critical and analytical skills to interpret and predict weather systems using weather products (model results, maps, satellite imagery, etc.).
- Participants can demonstrate knowledge of the Weather Radar.
- Participants can demonstrate skills for communicating their technical knowledge.

DELIVERY AND DESCRIPTION

Methodology

This module is designed in such a way that the participants get explicit idea regarding the Weather Radar and its terms and concepts. Besides, we also wish that the participants will be enhance their official works. To achieve this objective, we have made the sessions based on the most important topics of Weather Radar that are used in everyday life.

Key learning outcomes

By the end of the course, delegates will have a knowledge and understanding of:

- Define range, bearing, and altitude as they relate to a radar system.
- Discuss how pulse width, peak power, and beam width affect radar performance.
- Describe the factors that contribute to or detract from radar accuracy.
- Using a block diagram, describe the basic function, principles of operation, and interrelationships of the basic units of a radar system.
- Explain the various ways in which radar systems are classified, including the standard classification system.
- Explain the basic operation of cw, pulse, and Doppler radar systems

Disclaimer

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CHAPTER 1 : WEATHER RADAR

1.0 Radar

The word "radar" means "Radio Detection and Ranging", signifies a means of employing radio waves to detect and locate material objects. Location of an object is accomplished by determining the distance and direction from the radar equipment to the object and requires, in general, the measurement of three coordinates –usually range and angles of azimuth and elevation.

Radar detection depends upon the reflection of radio waves from an object. A radar set may be compared with a searchlight and an observer stationed beside the light. A small portion of the light wave from Microwave radar is only one of many available techniques for remote sensing of the atmosphere. Radar has been defined as "the art of detecting by means of radio echoes the presence of objects, determining their direction and range recognizing their character.

In radar meteorology the term "object" is construed to mean anything in the atmosphere which returns to a receiver a detectable amount of power. Thus, in the study of radar meteorology one must consider the reflections by – Raindrops, Cloud droplets, Ice particles, Snowflakes, Atmospheric nuclei, insects, birds, and regions of large index-of-refraction gradients.

The implementation and operation of primary radar systems involve a wide range of disciplines such as -

- Building works
- Heavy mechanical and electrical engineering
- High power microwave engineering
- Advanced high-speed signal and data processing techniques

Some laws of nature have greater importance here. Radar measurement of range or distance is made possible because of the properties of radiated electromagnetic energy. Basic rules are-

- Reflection of electromagnetic waves: The electromagnetic waves are reflected if they meet an electrically leading surface. If these reflected waves are received again at the place of their origin, then that means an obstacle is in the propagation direction.
- Constant speed of Electromagnetic waves: Electromagnetic energy travels through air at a constant speed, at approximately the speed of light 300,000 kilometers per second. This constant speed allows the determination of the distance between the reflecting objects and the radar site by measuring the running time of the transmitted pulses.

- Travels through straight lines: This EM wave energy normally travels through space in a straight line and will vary only slightly because of atmospheric and weather conditions. By using of special radar antennas this energy can be focused into a desired direction. Thus, the direction (in azimuth and elevation) of the reflecting objects can be measured.

These principles can basically be implemented in radar system, and allow the determination of the distance, the direction, and the height of the reflecting objects.

Advantages:

Radar has many advantages compared to an attempt of visual observation:

- Radar is able to operate day or night over a long range.
- It can operate in all weather-in fog and rain; it can even penetrate walls or layers of snow.
- Radar has very broad coverage, it is possible to observe the whole hemisphere
- Radar detects and tracks moving objects, a high-resolution imaging is possible, and that results in object recognition.
- Radar can operate unmanned, 24 hours a day, 7 days a week.

1.1 History of Radar

Neither a single nation nor a single person says that the discovery and development of radar technology was his (or its) own invention. One must see the knowledge about "Radar" than an accumulation of many developments and improvements, in which any scientists from several nations took part in parallel. In the past, there are nevertheless some milestones, with the discovery of important basic knowledge and important inventions:

- Development of Radar as a full-fledged technology did not occur until World War II.
- The basic principle of radar detection is almost as old as the subject of electromagnetism itself.
- Heinrich Hertz in 1886 experimentally tested the theories of Maxwell and demonstrated the similarity between radio and light waves.
- Hertz showed that radio waves could be reflected by metallic and dielectric bodies.
- In 1900 Nicola Tesla suggested that the reflection of electromagnetic waves could be used for detecting for detecting of moving metallic objects.
- In 1903 a German engineer by the name of Hulsmeyer experimented with the detection of radio waves reflected from ships. He obtained a patent in 1904 in several countries like Germany, France and the United Kingdom for an obstacle detector and ship navigational device. His methods ware demonstrated before the German navy, but generated little interest. This is the first practical Radar.

- 1921 The invention of the Magnetron as an efficient transmitting tube by the American Physicist Albert Wallace Hull.
- Marconi recognized the potentialities of short waves for radio detection and strongly urged their use in 1922 for this application.
- Although Marconi predicted and successfully demonstrated radio communication between continents, he was apparently not successful in gaining support for some of his other ideas involving very short wave. One was the radar detection and the other was –the very short waves are capable of propagation well beyond the optical line of sight-a phenomenon now known as tropospheric scatter.
- In 1922 A.H. Taylor and L. C. Young detected a wooden ship using a CW wave-interference radar with separated receiver and transmitter-inspired by Marconoi's idea.
- The first application of the pulse technique to the measurement of distance was in the basic scientific investigation by Breit and Tuve in 1925 for measuring the height of the ionosphere. However, more than a decade was to elapse before the detection of aircraft by pulse radar was demonstrated.
- The first experimental radar systems operated with CW (Continuous wave) and depended for detection upon the interference produced between the direct signal received from the transmitter and the Doppler-frequency-shifted signal reflected by a moving target.
- The first detection of aircraft using the wave interference effect was made in June, 1930; by L. A. Hyland of the Naval research Laboratory (NRL). It was made accidentally while he was working with a direction-finding apparatus located in an aircraft on the ground.
- In Britain the first known proposal for radar system came from William A. S. Butement and P.E. Pollard in January 1931. They equipped a ship with radar. As antennas were used parabolic dishes with horn radiator. Although their equipment produced short-range results the work was abandoned for lack of government support.
- By 1932 the equipment was demonstrated to detect aircraft at distances as great as 50 miles from the transmitter. The NRL work on aircraft detection with CW wave interference was kept classified until 1933, when several Bell Telephone Laboratories engineers reported the detection of aircraft during the course of other equipment.
- The early CW wave interference radars were useful only for detecting the presence of the target
- The limitations to obtaining adequate position information could be overcome with pulse transmission

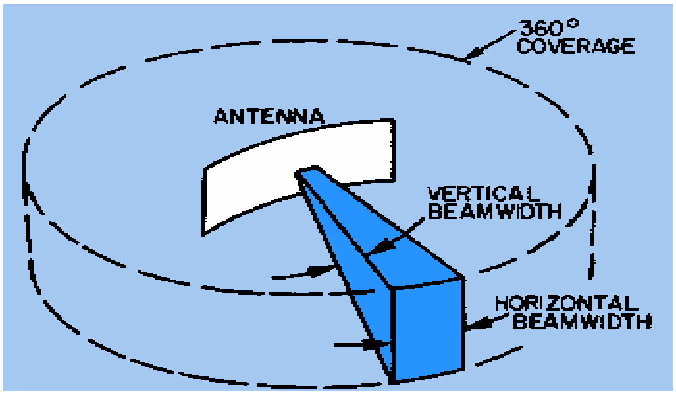
- In 1935 Robert Watson-Watt suggested that radio waves might be used to detect aircraft at a distance. Intensive research began and by 1939 Britain possessed a defensive chain of highly secret Direction Finding (RDF) stations.
- In 1936 development of the Klystron by the technicians George F. Metcalf and William C. Hahn, both General Electric. This will be an important component in radar units as an amplifier or an oscillator tube.
- In 1939 two engineers from the university in Birmingham, John Turton Randall and Henry Albert Howard Boot built a small but powerful radar using multicavity-Magnetron. The B-17 airplanes were fitted with this radar. Now they could find and thus combat the German submarines in the night and in fog.
- The term "RADAR" was officially coined as an acronym by U.S. Navy Lieutenant Commander Samuel M. Tucker and F. R Furth in November 1940. The acronym was by agreement adopted in 1943by the allied powers of the World War II and thereafter received general international acceptance.

1.2 Radar Types

The preceding paragraphs indicated that radar systems are divided into types based on the designed use. This section presents the general characteristics of several commonly used radar systems. Typical characteristics are discussed rather than the specific characteristics of any particular radar system.

1.2.1 Search Radar

Search radar, as previously mentioned, continuously scans a volume of space and provides initial detection of all targets within that space.



Search radar systems are further divided into specific types, according to the type of object they are designed to detect. For example, surface-search, air-search, and height-finding radars are all types of search radar.

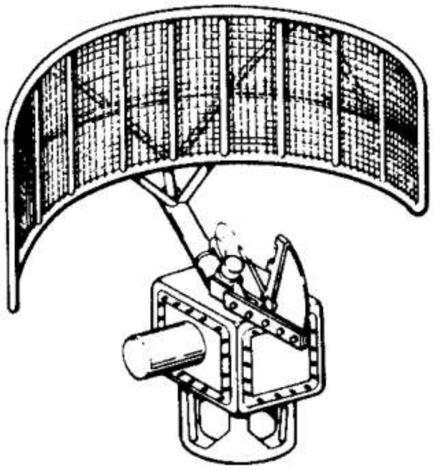
1.2.1.1 Surface-Search Radar

A surface-search radar system has two primary functions: (1) the detection and determination of accurate ranges and bearings of surface objects and low-flying aircraft and (2) the maintenance of a 360- degree search pattern for all objects within line-of-sight distance from the radar antenna.

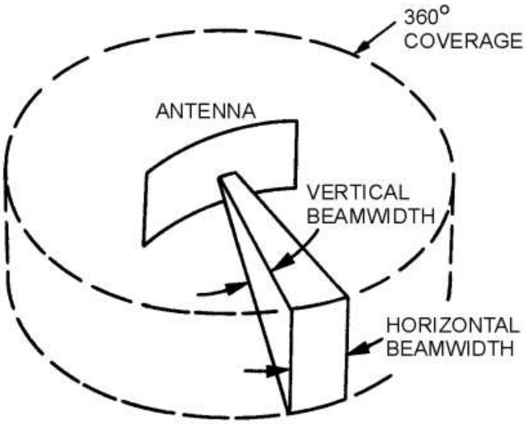
The maximum range ability of surface-search radar is primarily limited by the radar horizon; therefore, higher frequencies are used to permit maximum reflection from small, reflecting areas, such as ship masthead structures and the periscopes of submarines. Narrow pulse widths are used to permit a high degree of range resolution at short ranges and to achieve greater range accuracy. High pulse-repetition rates are used to permit a maximum definition of detected objects. Medium peak power can be used to permit the detection of small objects at line-of-sight distances. Wide vertical-beam widths permit compensation for the pitch and roll of own ship and detection of low flying aircraft. Narrow horizontal beam widths permit accurate bearing determination and good bearing resolution. For example, a common shipboard surface-search radar has the following design specifications:

- Transmitter frequency 5,450-5,825 MHz
- Pulse width .25 or 1.3 microseconds
- Pulse-repetition rate between 625 and 650 pulses per second
- Peak power between 190 and 285 kW
- Vertical beam width between 12 and 16 degrees
- Horizontal beam width 1.5 degrees

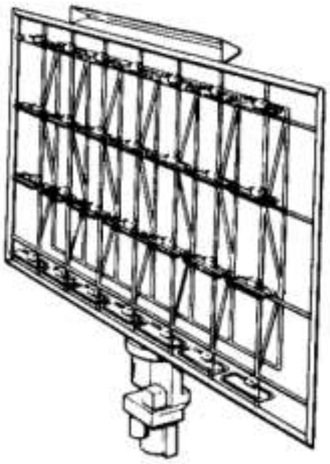
Surface-search radar is used to detect the presence of surface craft and low flying aircraft and to determine their presence. Shipboard surface-search radar provides this type of information as an input to the weapons system to assist in the engagement of hostile targets by fire-control radar. Shipboard surface search radar is also used extensively as a navigational aid in coastal waters and in poor weather conditions. A typical surface-search radar antenna is shown in figure



1.2.1.2 Air-Search Radar



Air-search radar systems initially detect and determine the position, course, and speed of air targets in a relatively large area. The maximum range of air-search radar can exceed 300 miles, and the bearing coverage is a complete 360-degree circle. Air-search radar systems are usually divided into two categories, based on the amount of position information supplied. As mentioned earlier in this chapter, radar sets that provide only range and bearing



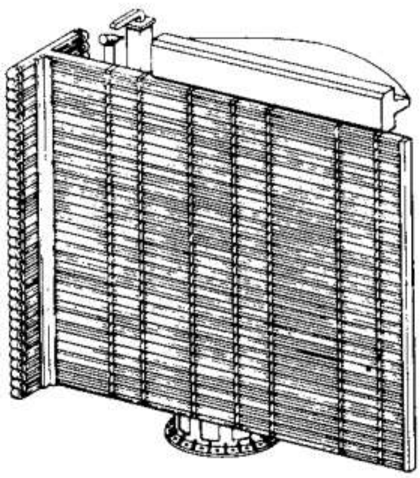
information are referred to as two-dimensional, or 2D, radars. Radar sets that supply range, bearing, and height are called three-dimensional, or 3D, radars. (3D radar will be covered in the next section.) The coverage pattern of a typical 2D radar system is illustrated in figure. A typical 2D air-search radar antenna is shown in figure.

Relatively low transmitter frequencies are used in 2D search radars to permit long-range transmissions with minimum attenuation. Wide pulse widths and high peak power are used to aid in detecting small objects at great distances. Low pulse-repetition rates are selected to permit greater maximum range. A wide vertical-beam width is used to ensure detection of objects from the surface to relatively high altitudes and to compensate for pitch and roll of own ship. The output characteristics of specific air-search radars are classified; therefore, they will not be discussed.

Air-search radar systems are used as early-warning devices because they can detect approaching enemy aircraft or missiles at great distances. In hostile situations, early detection of the enemy is vital to a successful defense against attack. Antiaircraft defenses in the form of shipboard guns, missiles, or fighter planes must be brought to a high degree of readiness in time to repel an attack. Range and bearing information, provided by air-search radars, used to initially position a fire-control tracking radar on a target. Another function of the air-search radar system is guiding combat air patrol (CAP) aircraft to a position suitable to intercept an enemy aircraft. In the case of aircraft control, the guidance information is obtained by the radar operator and passed to the aircraft by either voice radio or a computer link to the aircraft.

1.2.1.3 Height-Finding Search Radar

The primary function of a height-finding radar (sometimes referred to as a three-coordinate or 3D radar) is that of computing accurate ranges, bearings, and altitudes of aircraft targets detected by air search radars. Height-finding radar is also used by the ship's air controllers to direct CAP aircraft during interception of air targets. Modern 3D radar is often used as the primary air-search radar.
This is because of its high accuracy and because the maximum ranges are only slightly less than those available from 2D radar.



The range capability of 3D search radar is limited to some extent by an operating frequency that is higher than that of 2D radar. This disadvantage is partially offset by higher output power and a beam width that is narrower in both the vertical and horizontal planes.

The 3D radar system transmits several narrow beams to obtain altitude coverage and, for this reason, compensation for roll and pitch must be provided for shipboard installations to ensure accurate height information.

Applications of height-finding radars include the following:

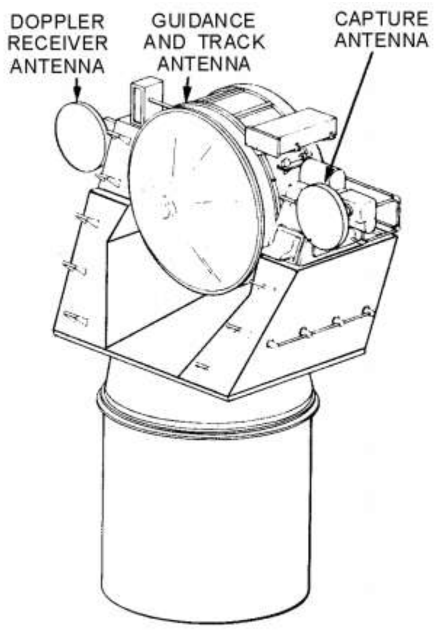
- Obtaining range, bearing, and altitude data on enemy aircraft and missiles to assist in the control of CAP aircraft
- Detecting low-flying aircraft
- Determining range to distant land masses
- Tracking aircraft over land
- Detecting certain weather phenomena
- Tracking weather balloons
- Providing precise range, bearing, and height information for fast, accurate initial positioning of fire-control tracking radars.

1.2.2 Tracking Radar

Radar that provides continuous positional data on a target is called tracking radar. Most tracking radar systems used by the military are also fire-control radar; the two names are often used interchangeably.

Fire-control tracking radar systems usually produce a very narrow, circular beam.

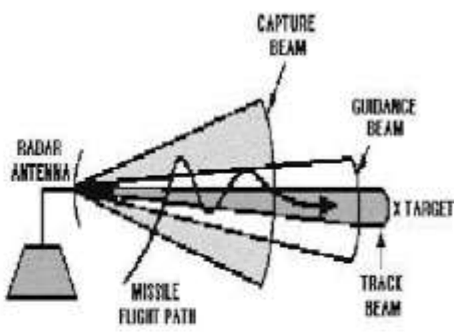
Fire-control radar must be directed to the general location of the desired target because of the narrow-beam pattern. This is called the DESIGNATION phase of equipment operation. Once in the general vicinity of the target, the radar system switches to the ACQUISITION phase of operation. During acquisition, the radar system searches a small volume of space in a prearranged pattern until the target is located. When the target is located, the radar system enters the TRACK phase of operation. Using one of several possible scanning techniques, the radar system automatically follows all target motions. The radar system is said to be locked on to the target during the track phase. The three sequential phases of operation are often referred to as MODES and are common to the target-processing sequence of most fire control radars.



Typical fire-control radar characteristics include a very high prf, a very narrow pulse width, and a very narrow beam width. These characteristics, while providing extreme accuracy, limit the range and make initial target detection difficult. A typical fire-control radar antenna is shown in figure. In this example the antenna used to produce a narrow beam is covered by a protective radome.

1.2.3 Carrier-Controlled Approach (CCA) And Ground-Controlled Approach (GCA) Radar

CARRIER-CONTROLLED APPROACH and GROUND-CONTROLLED APPROACH radar systems are essentially shipboard and land-based versions of the same type of radar. Shipboard CCA radar systems are usually much more sophisticated systems than GCA systems.



This is because of the movements of the ship and the more complicated landing problems. Both systems, however, guide aircraft to safe landing under conditions approaching zero visibility. By means of radar, aircraft are detected and observed during the final approach and landing sequence. Guidance information is supplied to the pilot in the form of verbal radio instructions, or to the automatic pilot (autopilot) in the form of pulsed control signals.

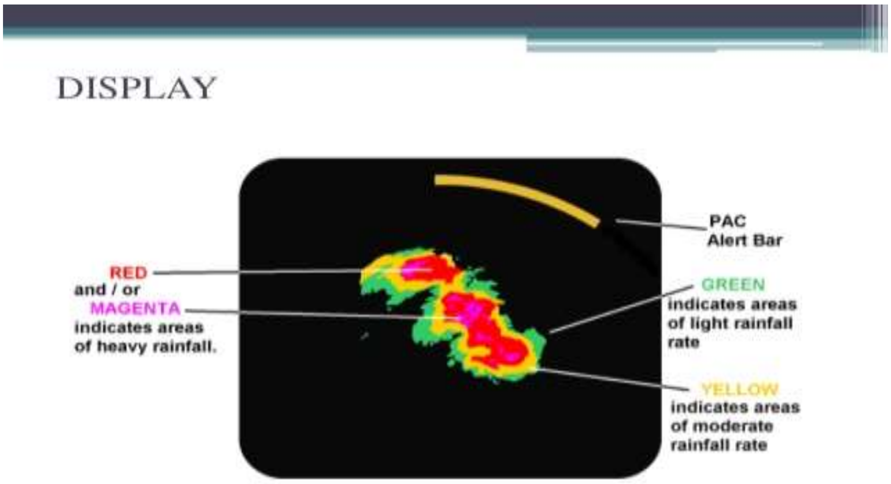
Ground-controlled approach is the oldest air traffic technique to fully implement radar to service a plane. The system was simple, direct, and worked well, even with previously untrained pilots. It requires close communication between ground-based air traffic controllers and pilots in approaching aircraft. Only one pilot is guided at a time (max. 2 under certain circumstances). The controllers monitor dedicated precision approach radar systems, to determine the precise course and altitude of approaching aircraft. The controllers then provide verbal instructions by radio to the pilots to guide them to a landing. The instructions include both descent rate (glidepath) and heading (course) corrections necessary to follow the correct approach path.

A U.S. Navy Sea King makes a ground-controlled approach, 1964. Two tracks are displayed on the Precision Approach Radar (PAR) scope:

- Azimuth, showing the aircraft's position relative to the horizontal approach path.
- Elevation, showing vertical position relative to the published glidepath.

1.2.4 AIRBORNE RADAR

Airborne radar is designed specially to meet the strict space and weight limitations that are necessary for all airborne equipment. Even so, airborne radar sets develop the same peak power as shipboard and shore-based sets.



As with shipboard radar, airborne radar sets come in many models and types to serve many different purposes. Some of the sets are mounted in blisters (or domes) that form part of the fuselage; others are mounted in the nose of the aircraft.

In fighter aircraft, the primary mission of a radar is to aid in the search, interception, and destruction of enemy aircraft. This requires that the radar system have a tracking feature. Airborne radar also has many other purposes. The following are some of the general classifications of airborne radar: search, intercept and missile control, bombing, navigation, and airborne early warning

CHAPTER 2 : USAGE AND PRINCIPLES OF RADAR

2.1 Application of Radar

Radar has been employed on the ground, in the air, and on the sea and undoubtedly will be used in space.

Avionics weather radar

Aircraft application of radar systems include weather radar, collision avoidance, target tracking, ground proximity, and other systems. For commercial weather radar, ARINC 708 is the primary specification for weather radar systems using an airborne pulse-Doppler radar.

Antennas

Unlike ground weather radar, which is set at a fixed angle, airborne weather radar is being utilized from the nose or wing of an aircraft. Not only will the aircraft be moving up, down, left, and right, but it will be rolling as well. To compensate for this, the antenna is linked and calibrated to the vertical gyroscope located on the aircraft. By doing this, the pilot is able to set a pitch or angle to the antenna that will enable the stabilizer to keep the antenna pointed in the right direction under moderate maneuvers. The small servo motors will not be able to keep up with abrupt maneuvers, but it will try. In doing this the pilot is able to adjust the radar so that it will point towards the weather system of interest. If the airplane is at a low altitude, the pilot would want to set the radar above the horizon line so that ground clutter is minimized on the display. If the airplane is at a very high altitude, the pilot will set the radar at a low or negative angle, to point the radar towards the clouds wherever they may be relative to the aircraft. If the airplane changes attitude, the stabilizer will adjust itself accordingly so that the pilot doesn't have to fly with one hand and adjust the radar with the other.

Receivers/transmitters

There are two major systems when talking about the receiver/transmitter: the first is high-powered systems, and the second is low-powered systems; both of which operate in the X-band frequency range (8,000 – 12,500 MHz). High-powered systems operate at 10,000 – 60,000 watts. These systems consist of magnetrons that are fairly expensive (approximately $1,700) and allow for considerable noise due to irregularities with the system. Thus, these systems are highly dangerous for arcing and are not safe to be used around ground personnel. However, the alternative would be the low-powered systems. These systems operate 100 – 200 watts, and require a combination of high gain receivers, signal microprocessors, and transistors to operate as effectively as the high-powered systems. The complex microprocessors help to eliminate noise, providing a more accurate and detailed depiction of the sky. Also, since there are fewer irregularities throughout the system, the low-powered radars can be used to detect turbulence via the Doppler Effect. Since low-powered systems operate at considerable less wattage, they are safe from arcing and can be used at virtually all times.

Thunderstorm tracking

Digital radar systems now have capabilities far beyond that of their predecessors. Digital systems now offer thunderstorm tracking surveillance. This provides users with the ability to acquire detailed information of each storm cloud being tracked. Thunderstorms are first identified by matching precipitation raw data received from the radar pulse to some sort of template preprogrammed into the system. In order for a thunderstorm to be identified, it has to meet strict definitions of intensity and shape that set it apart from any non-convective cloud. Usually, it must show signs of organization in the horizontal and continuity in the vertical: a core or a more intense center to be identified and tracked by digital radar trackers. Once the thunderstorm cell is identified, speed, distance covered, direction, and Estimated Time of Arrival (ETA) are all tracked and recorded to be utilized later.

Doppler radar and bird migration

Using the Doppler weather radar is not limited to determine the location and velocity of precipitation, but it can track bird migrations as well as seen in the non-weather targets section. The radio waves sent out by the radars bounce off rain and birds alike (or even insects like butterflies). The US National Weather Service, for instance, have reported having the flights of birds appear on their radars as clouds and then fade away when the birds land. The U.S. National Weather Service St. Louis has even reported monarch butterflies appearing on their radars. Different programs in North America use regular weather radars and specialized radar data to determine the paths, height of flight, and timing of migrations. This is useful information in planning for windmill farms placement and operation, to reduce bird fatalities, aviation safety and other wildlife management. In Europe, there has been similar developments and even a comprehensive forecast program for aviation safety, based on radar detection.

Meteorite fall detection

According to the American Meteor Society, meteorite falls occur on a daily basis somewhere on Earth. However, the database of worldwide meteorite falls maintained by the Meteoritical Society typically records only about 10-15 new meteorite falls annually.

Meteorites occur when a meteoroid falls into the Earth's atmosphere, generating an optically bright meteor by ionization and frictional heating. If the meteoroid is large enough and infall velocity is low enough, surviving meteorites will reach the ground. When the falling meteorites decelerate below about 2–4 km/s, usually at an altitude between 15 and 25 km, they no longer generate an optically bright meteor and enter "dark flight". Because of this, most meteorite falls occurring into the oceans, during the day, or otherwise go unnoticed.

It is in dark flight that falling meteorites typically fall through the interaction volumes of most types of radars. It has been demonstrated that it is possible to identify falling meteorites in weather radar imagery by different studies. This is especially useful for meteorite recovery, as weather radar are part of widespread networks and scan the atmosphere continuously. Furthermore, the meteorites cause a perturbation of local winds by turbulence, which is noticeable on Doppler outputs, and are falling nearly vertically so their resting place on the ground is close to their radar signature.

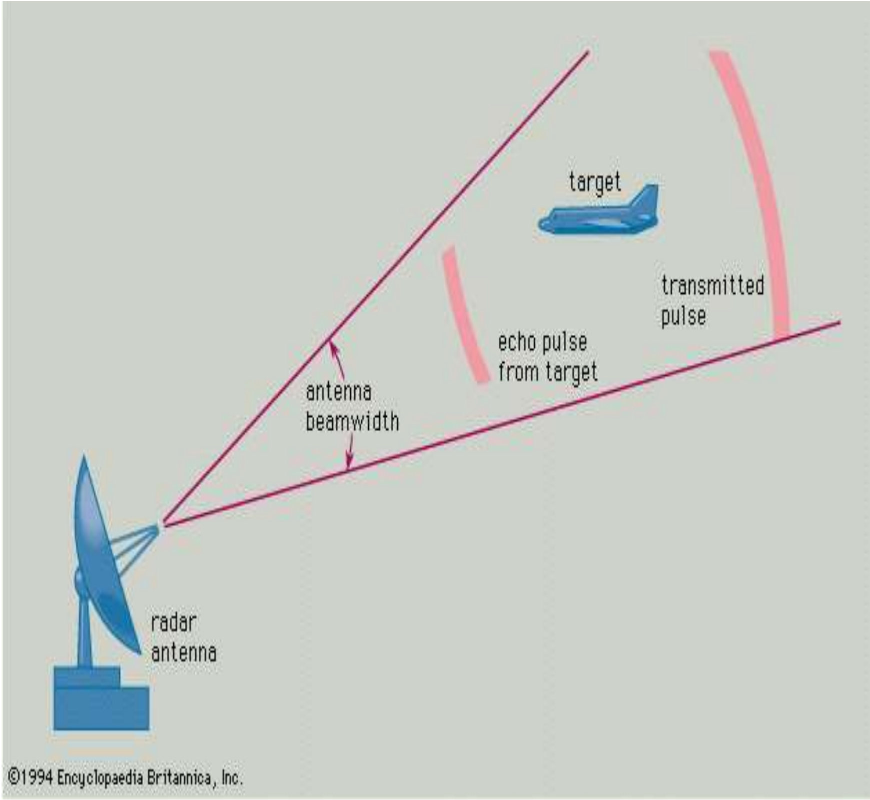
In a brief,

- Ground based radar has been applied chiefly to the detection and location of aircraft or space targets.
- Shipboard radar may observe other ships or aircrafts or space targets or it may be used as a navigation aid to locate shore lines or buoys.
- Airborne radar may be used to detect other aircrafts, ships, or land vehicles or may be used for storm avoidance and navigation.
- Air traffic-control radar monitors air traffic in the vicinity of airports and en route between air terminals.
- One of the more important applications of radar is in the detection and tracking of weather disturbances, especially tornadoes and hurricanes.
- Radar has also been used as an aid in surveying over very large distances.
- Speed measuring radar used by many of the highway police.

2.2 Radar Principle

The basic principle of radar operation is simple to understand. A radar system transmits electromagnetic energy and analyzes the energy reflected back to it (by an object). ... If these reflected waves are received again at the place of their origin, then that means an obstacle is in the propagation direction.

The electronic principle on which radar operates is very similar to the principle of sound-wave reflection. If we shout in the direction of a sound-reflecting object we will here an echo. If we know the speed of sound in air, we can then estimate the distance and general direction of the object. The time required for an echo to return can be roughly converted to distance if the speed of sound is known.



Radar uses electromagnetic energy pulses in much the same way. The radio frequency energy is transmitted to and reflected from the reflecting object. A small portion of the reflected energy returns to the radar set. This returned energy is called an echo, just as it is in sound technology. Radar uses the echo to determine the direction and distance of the reflecting object.

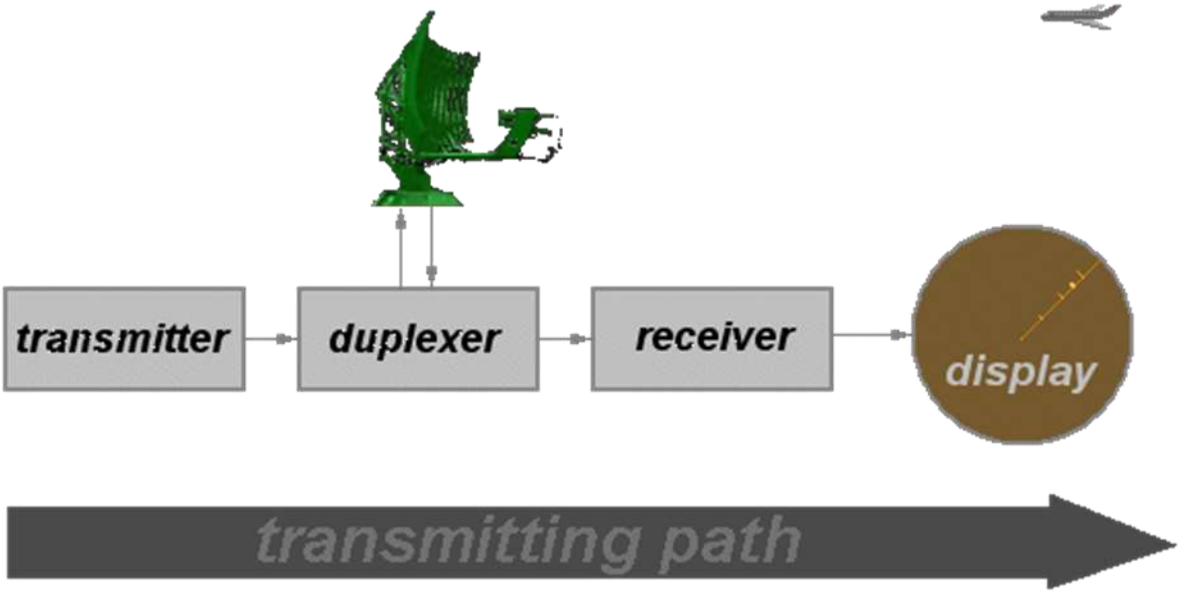
Now Radar refers to electronic equipment that detects the presence of objects by using reflected electromagnetic energy. Under some conditions, radar system can measure the direction, height, distance, course and speed of these objects. The frequency of electromagnetic energy used for radar is unaffected by darkness and also penetrates fog and clouds. This permits radar systems to determine the position of airplanes, ships or other obstacles that are invisible to the naked eye because of distance, darkness or weather. Modern radar can extract widely more information from a target's echo signal than its range. But the calculating of the range by measuring the delay time is one of its most important functions.

The basic principle of on which RADAR operates is similar to that of sound wave reflection. RADAR uses electromagnetic energy pulses for detection and location of the objects. In short, its operation can be summarized as below:

- The RADAR transmits electromagnetic waves through the antenna in all the directions.
- Reflecting objects (targets) intercept these radiated waves and reflect back in all the directions.
- Some of the reflected signal is received by the receiver in RADAR system.

- The received signal is processed further through digital signal processing and amplification thereby a decision is made at the reception output for determining the presence of reflected signal from the target. If the target is present, its location and other information are obtained.

2.3 Basic Design of a Radar System



The above figure shows the operating principle of primary radar. The Radar antenna illuminates the target with a microwave signal, which is then reflected and picked up by a receiving device. The electrical signal picked up by the receiving antenna is called echo or return. The radar signal is generated by a powerful transmitter and received by a highly sensitive receiver.

From target received signal is reflected in a wide number of directions. The reflected signal is also called scattering. Backscatter is the term given to reflections in the opposite direction to the incident rays.

Radar signals can be displayed on the traditional plan position indicator (PPI) or other more advanced radar display systems. A PPI has a rotating vector with the radar at the origin, which indicates the pointing direction of the antenna and hence the bearing of targets.

Transmitter: The radar transmitter produces the short duration high-power rf (radio frequency) pulses of energy that are into space by the antenna. It can be a power amplifier like a Klystron, Travelling Wave Tube or a power Oscillator like a Magnetron. The signal is first generated using a waveform generator and then amplified in the power amplifier.

Waveguides: The waveguides are transmission lines for transmission of the RADAR signals.

Duplexer: The duplexer alternately switches the antenna between the transmitter and receiver so that only one antenna needs to be used. This switching is necessary because the high-power pulses of the transmitter would destroy the receiver if energy were allowed to enter the receiver. It can be a gaseous device that would produce a short circuit at the input to the receiver when transmitter is working.

Receiver: The receivers amplify and demodulate the received RF-signals. The receiver provides video signals to the output. It can be super heterodyne receiver or any other receiver which consists of a processor to process the signal and detect it.

Antenna: The antenna transfers the transmitter energy to signals in space with the required distribution and efficiency. This process is applied in an identical way on reception. It can be a parabolic reflector, planar arrays or electronically steered phased arrays.

Display/ Indicator: The indicator should present to the observer a continuous, easily understandable, graphic picture of the relative position of radar targets. The radar screen (PPI Scope) displays the produced from the echo signals. The longer the pulses were delayed by the runtime, the further away from the center of this radar scope they are displayed. The direction of the deflection on this screen is that in which the antenna is currently pointing.

CHAPTER 3 : WORKING METHODOLOGY OF RADAR

3.1 Range or distant measurement

The radar transmits a short radio pulse with very high pulse power. This pulse is focused in one direction only by the directivity of the antenna and propagates in this given direction with the speed of light.

If in this direction is an obstacle, for example an airplane, then a part of the energy of the pulse is scattered in all directions. A very small portion is also reflected back to the radar. The radar antenna receives this energy and the radar evaluates the contained information. The distance we can measure with a simple oscilloscope. On the oscilloscope moves synchronously with the transmitted pulse a luminous point and leaves a trail. The deflection starts with the transmitter pulse. The luminescent spot moves to scale on the oscilloscope with the radio wave. At this moment, in which the antenna receives the echo pulse, the pulse is also shown on the oscilloscope. The distance between the two shown pulses is a measure of the distance of the aircraft.

Since the propagation of radio waves happens at constant speed the distance is determined from the runtime of the high-frequency transmitted signal. The actual range of a target from the radar is known as slant range. Slant range is the line of sight distance between the radar and the object illuminated. While ground range is the horizontal distance between the emitter and its target and its calculation requires knowledg of the targets elevation. Since the waves travel to a target and back, the round trip time is dividing by two in order to obtain the time the wave took to reach the target. Therefore the following formula arises for the slant range:

$$R=\frac{C_o}{2}t$$

C_o = Speed of light

t=measured runtime

R=Slant range of antenna

The distances are expressed in kilometers or nautical miles (1 NM=1.852km)

3.2 Direction Determination

The angular determination of the target is determined by the directivity of the antenna. Directivity, sometimes known as the directive gain, is the ability of the antenna to

concentrate the transmitted energy in a particular direction. An antenna with high directivity is also called a directive antenna. By measuring the direction in which the antenna is pointing when the echo is received, both the azimuth and elevation angles from the radar to the object or target can be determined. The accuracy of angular measurement is determined by the directivity, which is a function of the size of the antenna.
Radar units usually work with very high frequencies. Reasons for this are-

- High resolution –the smaller the wavelength, the smaller the objects the radar is able to detect
- Higher the frequency, smaller the antenna size at the same gain
- Quasi-optically propagation of these waves

The True Bearing (referenced to the true north) of radar target is the angle between the true north and a line pointed directly at the target. The angle is measured in the horizontal plane and in a clockwise direction from true north.

The antennas of most radar systems are designed to radiate energy in a one directional lobe or beam that can be moved in bearing simply by moving the antenna. The shape of the beam is such that the echo signal strength varies in amplitude as the antenna beam moves across the target.

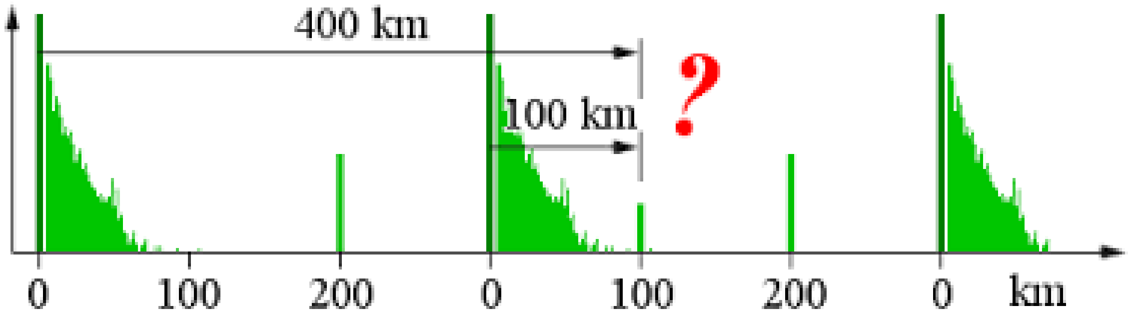
In order to have an exact determination of the bearing angle, a survey of the north direction is necessary. Therefore, older radar sets must expensively be surveyed. More modern radar sets take on this task with the help of the GPS satellites.

3.3 Maximum Unambiguous Range

The maximum ambiguous range is the longest range to which a transmitted pulse can travel out to and back again between consecutive transmitted pulses. In other words, this is the maximum distance radar energy can travel round trip between pulses and still produce reliable information.

The relationship between the PRF or their reciprocal value inter-pulse period T (PRT-Pulse Repetition Time) and Rmax determines the unambiguous range of the radar. Suppose the radar emits a pulse that strikes a target and returns to the radar in round trip time t:

- If $t<T$, then the return signal arrives before the next pulse has been emitted
- If $t=T$, then the return signal arrives exactly when the next pulse has been emitted.
- If $t>T$, then the return signal arrives after the next pulse has been emitted and there is an ambiguity, that is the radar cannot tell whether the return signal has come from the first or second pulse.



In the above figure, the first transmitted pulse, after being reflected from the target in 200km, is received by the radar before the second pulse is transmitted. There will be no ambiguity here as the reflected pulse can be easily identified as a reflection of the first pulse. But in the same figure, we notice that the reflection of a target of the first pulse is received after the second pulse has been transmitted (in the range of a 400km). This causes some confusion since the radar, without any additional information, cannot determine whether the received signal is a reflection of the first pulse or of the second pulse. This leads to an ambiguity to determining the range, the received echo signal be mistaken as a short-range echo of the next cycle.

Therefore, maximum unambiguous range $\boldsymbol{R_{max}}$ is the maximum range for which $\boldsymbol{t}$ is smaller than T (**t<T**).

$$R_{max}=\frac{C_o\ (T-\tau)}{2}$$

R_{max}=Unambiguous Range

C_o= Speed of the light

T=Pulse repetition Time

τ= Length of the transmitted pulse

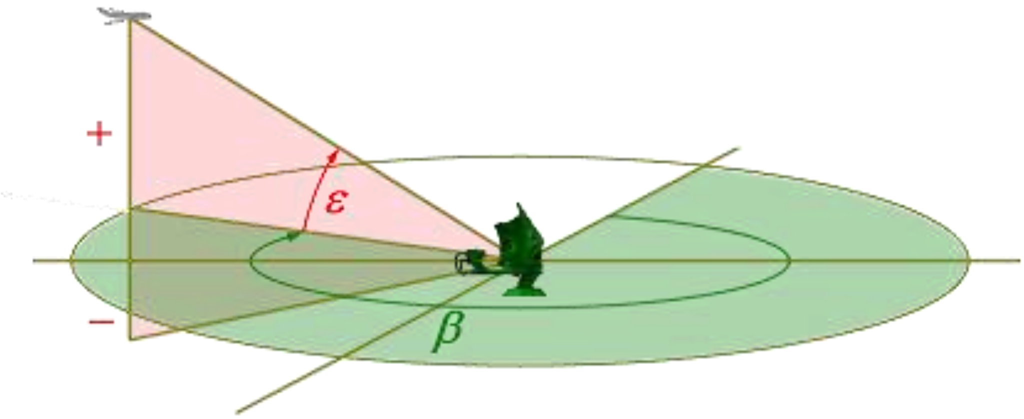
Minimal Measuring Range:

Monostatic pulse radar sets use the same antenna for transmitting and receiving. During the transmitting time the radar cannot receive. The radar receiver is switched off using an electronic switch, called duplexer.

The minimum measuring range is the minimum distance which the target must have to be detected. Therein, it is necessary that the transmitting pulse leaves the antenna completely and the radar unit must switch on the receiver. The transmitting time and the recovery time should be as small as possible, if targets shall be detected in the local area. Targets at a range equivalent to the pulse width from the radar are not detected.

3.4 Elevation Angle

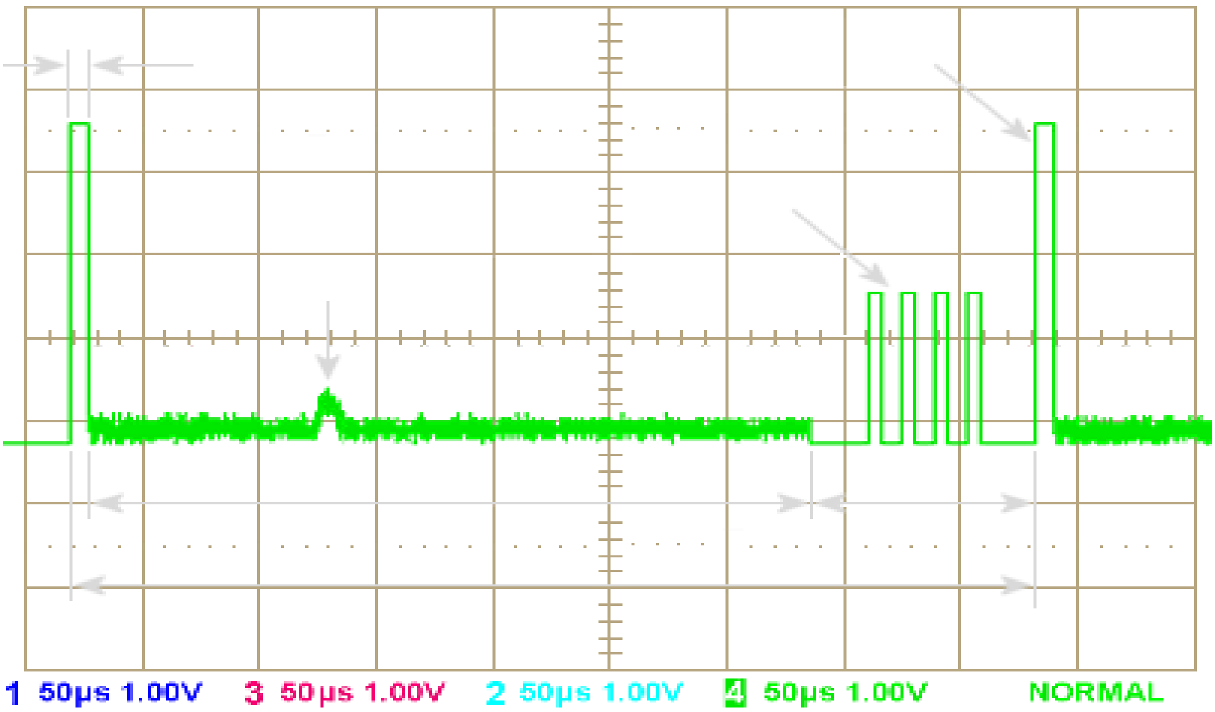
Elevation angle is the angle between the horizontal plane and the line of sight, measured in the vertical plane. The reference direction (i.e. an elevation angle of zero degree) is a horizontal line in the direction to the horizon, starting from the antenna.



Elevation angle is positive above the horizon but negative below the horizon.

3.5 Pulse Repetition Frequency (PRF)

Pulse Repetition Frequency (PRF) of the radar system is the number of pulses that are transmitted per second.



Radar systems radiate each pulse at the carrier frequency during transmit time, wait for returning echoes during listening or rest time, and then radiate the next pulse as shown in the figure. The time between the beginning of one pulse and the start of the next pulse is called pulse –repetition time (PRT) and is equal to the reciprocal of PRF as follows-

$$PRT=\frac{1}{PRF}$$

Generally, the receiving time is the time between the transmitter's pulses. The receiving time is always smaller than the difference between the pulse repetition periods. It is sometimes also limited by a so-called dead time, in which the receiver is already switched off just before the next transmitting pulse.

In some radar between the transmitting pulse and the receiving time, there is a short recovery time of the duplexer. This recovery time occurs when the duplexer must switch off the receiver response to the high transmitting power.

Radar signals should be transmitted at every clock pulse. The duration between the two clock pulses should be properly chosen in such a way that the echo signal corresponding to present clock pulse should be received before the next clock pulse.

Radar transmits a periodic signal. A typical radar wave form is having a series of narrow rectangular shaped pulses. The time interval between the successive clock pulses is called Pulse Repetition Time, Tp.

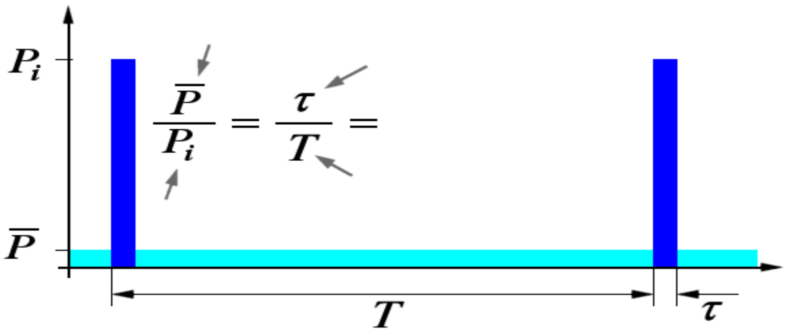
The reciprocal of pulse repetition time is called Pulse Repetition Frequency, f_p. Mathematically, it can be represented as

$$f_p=\frac{1}{T_p}$$

Therefore, Pulse Repetition Frequency is nothing but the frequency at which Radar transmits the signal. That means PRF of the radar system is the number of pulses that are transmitted per second.

Peak and Average Power:

The energy content of a continuous-wave radar transmission may be easily figured because the transmitter operates continuously. However, pulsed radar transmitters are switched on and off to provide range timing information with each pulse. The amount of energy in this waveform is important because maximum range is directly related to transmitter output power. The more energy the radar system transmits, the greater the target detection range will be. The energy content of the pulse is equal to the peak (maximum) power level of the pulse multiplied by the pulse width.



However, power is measured in radar system over a period of time that is longer than the pulse width. For this reason, pulse-repetition time is included in the power calculations for transmitters. Power measured over such a period of time is referred to as average power.

$$D=\frac{P}{p_i}=\frac{\tau}{T}$$

Where,

P=Average Power

P_i=Pulsed Power

τ= Pulse width

T=Pulse repetition Time (PRT)

Peak power must be calculated more often Than average power.
The product of pulse width (τ) and pulse-repetition frequency (prf) as the reciprocal of the pulse period (T) in the above formula is called the duty cycle of radar system. Duty cycle is the fraction of time that a system is an "active state". In particular, it is used in the following contexts: Duty cycle is the portion of time during which a component, device or system is operated.
Suppose a transmitter operates for 1 microsecond, and is shut off for 99 microseconds, then is run for 1 microsecond again, and so on. The transmitter runs for one out of hundred microseconds, and its duty cycle is therefore 1/100, or 1 percent. The duty cycle is used to calculate both the peak power and average power of radar system.

<u>Electric Field: *********</u>
<u>Magnetic Field: ********</u>
<u>Frequency and wavelength: **********</u>

Electromagnetic wave:

Electromagnetic waves or EM waves are waves that are created as a result of vibrations between as electric field and a magnetic field. In other words, EM waves are composed of oscillating magnetic and electric fields. Electromagnetic waves are formed when an electric filed comes in contact with a magnetic field.

Polarization of Electromagnetic Wave:*********
Radar Frequencies:*********

Continuous Wave Radar:

Continuous-wave radar (CW Radar) is a type of radar system where a known stable frequency continuous wave radio energy (electromagnetic wave) is transmitted and then received from any reflecting objects. Individual objects are detected using the Doppler Effect, which causes the received signal to have a different frequency that the transmission, allowing to be detected by filtering out the transmitting frequency.

At this process also filters out slow or non-moving objects, it renders the radar immune to interference from large stationary objects and slow-moving clutter. This makes it particularly useful for looking for objects against a background reflector, for instance, allowing a high-flying aircraft to look for aircraft flying at low altitude against the background of the surface.

Pulse Radar:

Pulse radar emits short and powerful pulses and in the silent period receives the echo signal. In contrast to the continuous wave radar, the transmitter is turned off before the measurement is finished. This method is characterized by radar pulse modulation with very short pulses typically 1µs. Between the transmit pulses are very large pulse pauses, which are referred to as the receiving time.

Monostatic Radar:

Whether transmitter and receiver are at the same site.

Bistatic Radar:

Transmitter and receiver both components are deployed at completely different locations.

MTI RADAR:

If the radar is used for detecting the movable target, then the radar should receive only the echo signal due to the movable target. This echo signal is desired one. However, in practical applications, radar receives the echo signals due to stationary objects in addition to the echo signal due to the movable target. The echo signals due to stationary objects (places) such as land and sea are called clutters because these are unwanted signals. Therefore, we have to choose the radar in such a way that it considers only the echo signal due to movable target but not the clutters.

For this purpose, radar uses the principle of Doppler effect for distinguishing the non-stationary targets from stationary objects. This type of radar is called Moving Target Indicating Radar or simply MTI Radar.

3.6 Clutter

Clutter is a term used for unwanted echoes in electronic systems. Such echoes are typically returned from ground, sea, rain, animals/insects, chaff and atmospheric turbulences, and can cause serious performance issues with radar systems.

What one person considers to be clutter, another may consider to be a target. However, targets usually refer to point scatterers and clutter to extended scatterers (covering many range, angle, and Doppler cells). The clutter may fill a volume (such as rain) or be confined to a surface (like land). In principle, all that is required to estimate the radar return (backscatter) from a region of clutter is a knowledge of the volume or surface illuminated and the echo per unit volume, η, or per unit surface area, $\sigma°$ (the backscatter coefficient).
In addition to any possible clutter there will also always be noise. The total signal competing with the target return is thus clutter plus noise. In practice there is often either no clutter or clutter dominates and the noise can be ignored. In the first case the radar is said to be Noise Limited, in the second it is Clutter Limited.

In principle, all that is required to estimate the radar return (backscatter) from a region of clutter is knowledge of the volume or surface illuminated and the echo per unit volume or per unit surface area.

There are a number of problems in calculating the signal to clutter ratio. The clutter in the main beam is extended over a range of grazing angles and the backscatter coefficient depends upon grazing angle. Clutter will appear in the antenna sidelobes, which again will involve a range of grazing angles and may even involve clutter of a different nature.

The general significant problem is that the backscatter coefficient cannot in general be calculated and must be measured. The problem is the validity of measurements taken in one location under one set of conditions being used for a different location under different conditions. Various empirical formulae and graphs exist which enable an estimate to be made but the results need to be used with caution.

3.7 Derivation of RADAR Range Equation

Radar range equation represents the physical dependences of the transmit power, which is the wave propagation up to the receiving of the echo signals. Radar range equation is useful to know the range of the target theoretically. The standard form of radar range equation is also called as simple form of Radar range equation. Let's derive-

Our derivation of the range equation starts with a simple spherical scattering model of propagation for a point source antenna (i.e. an isotropic antenna). Isotropic means equally in all directions. Thus, an isotropic radiator is one which radiates equally in all directions.

The concept can be understood by imagining the transmitting antenna to be at the center of a sphere and the power flux density is the power flow per unit surface area. We know that power density or power flux density is nothing but the ratio of power and area.

The surface area of a sphere is a function of its radius:

$$A_s = 4\pi r^2$$

A_s=Area of Sphere

R=Radius of sphere

By imagining the isotropic radiator to be at the center of a sphere of radius r, the power flux density (Ψ), which is the power flow through unit area, is

$$\Psi_i = \frac{Pt}{4\pi r^2}$$

P_t=Amount of power transmitted by the radar transmitter in watts,

Ψ_i=Power flux density for an isotropic antenna

Now the flux density from a real antenna will vary with directions, but with most antennas a well-defined maximum occurs. Since Radar systems use directive antennas to focus radiated energy onto a target, the equation can be modified to account for the directive gain G of the antenna. This is defined as the ratio of power directed toward the target compared to the power from an ideal isotropic antenna. (The gain of the antenna is the ratio of this maximum to that for the isotropic radiator at the same radius r.)

$$G_t = \frac{\Psi m}{\Psi i}$$

G_t= Gain of the directive Antenna

Ψ_m= Maximum transmitted Power flux density

A very closely related gain figure is the directivity. Therefore, the power density due to directional antenna will be-

$$\Psi_m = G_t \Psi_i$$

$$\Psi_m = G_t\left(\frac{Pt}{4\pi r^2}\right)$$

So the maximum power flux density at some distance r from a transmitting antenna of gain G_t is

$$\Psi_m = \frac{GtPt}{4\pi r^2} \quad \text{(Transmitted power density)}$$

An isotropic radiator with an input power equal to Gt Pt would produce the same flux density. Hence this product GtPt is referred to as the Equivalent Isotropic Radiated Power (EIRP).

EIRP=Gt P_t

This equation describes the transmitted power density that strikes the target. A target radiates the power in different directions from the received Input power. Some of that energy will be reflected in various directions and some will be radiated back to the radar system. The amount of incident power density that is radiated back to the radar is a function of the Radar Cross Section (RCS) or σ (Sigma) of the target. (The amount of power which is reflected back towards the radar depends on its (target) cross section.)

With this information, the equation can be expanded to solve to solve for the power density returned to the radar antenna. This is done by multiplying the transmitted power density by the ratio of the RCS and area of the sphere:

$$\Psi_R = \Psi_m \frac{\sigma}{4\pi r^2}$$

Ψ_R =Power density returned to the radar, in watts per square meter

σ =RCS (Radar Cross Section) in square meters

$$\Psi_R = \left(\frac{\mathrm{Gt}\ P_t}{4\pi r^2}\right)\left(\frac{\sigma}{4\pi r^2}\right)$$

So, the power density of echo signal (incoming wave) at radar can be mathematically represented as

$$\Psi_R = \left(\frac{\mathrm{Gt}\ P_t}{4\pi r^2}\right)\left(\frac{\sigma}{4\pi r^2}\right)$$

An important concept used to describe the reception properties of an antenna is that of Effective Aperture $A_{eff.}$

With the receiving antenna aligned for maximum reception, the received power will be proportional to the power density of the incoming wave (Ψ_R)-

$$P_{rec} \propto \Psi_R$$

The constant of proportionality is the effective aperture, A_{eff} ., which is defined by the equation

$$P_{rec} = A_{eff} . \Psi_R$$

$$\Rightarrow P_{rec} = A_{eff} \left(\frac{\mathrm{Gt}\ P_t}{4\pi r^2}\right)\left(\frac{\sigma}{4\pi r^2}\right)$$

$$\Rightarrow P_{rec} = \frac{P_t.\mathrm{Gt}.\sigma\ .\ A_{eff}\,.}{(4\pi)^2.r^4}$$

Thus, the radar antenna will receive a portion of this signal reflected by the target. This signal power is equal to the return power density at the antenna multiplied by the effective area,

A_{eff} of the antenna.

P_{rec} = Signal power received at the receiver in watts

P_t=Transmitted power in watts

G_t=Gain of the transmit antenna

σ =RCS (Radar Cross Section) in square meters

r= Radius of distance to the target in meters

$A_{eff} = Effective$ area of the receive antenna square meters

Antenna theory allows us to relate the gain of an antenna to its effective area as follows:

$$A_{eff} = \frac{G_r \lambda^2}{4\pi}$$

G_r = Gain of the receiving antenna;

λ=Wavelength of the radar signal in meters;

The equation for the received signal power can now be simplified. For a monostatic radar the antenna gain G_t and G_r are equivalent. $G_t = G_r$.

$$P_{rec} = \frac{P_t.\text{Gt}.\sigma}{(4\pi)^2.r^4} \; A_{eff}$$

$$\Rightarrow P_{rec} = \frac{P_t.\text{Gt}.\sigma}{(4\pi)^2.r^4} \left(\frac{G_r \lambda^2}{4\pi}\right)$$

$$\Rightarrow P_{rec} = \frac{P_t.G_t.G_r\lambda^2 .\sigma}{(4\pi)^3.r^4} \qquad (G_t = G_r = G)$$

$$\Rightarrow P_{rec} = \frac{P_t.G^2.\lambda^2 .\sigma}{(4\pi)^3.r^4}$$

$$\Rightarrow r = \left[\frac{P_t.G^2.\lambda^2 .\sigma}{(4\pi)^3.P_{rec}} \right]^{1/4}$$

If the echo signal is having the power less than the power of the minimum detectable signal, then Radar cannot detect the target since it is beyond the maximum limit of the radar range. Therefore, we can say that the range of the target is said to be maximum range when the received echo signal is having the power equal to that of minimum detectable signal.

$$\Rightarrow r_{max} = \left[\frac{P_t . G^2 . \lambda^2 . \sigma}{(4\pi)^3 . P_{rec-min}} \right]^{1/4}$$

This is one of the standard forms of radar range equation. If we count effective aperture then the equation becomes

$$\Rightarrow r_{max} = \left[\frac{P_t . \mathrm{G} . \sigma\ A_{eff} .}{(4\pi)^2 . P_{rec-min}} \right]^{1/4}$$

And this is another standard forms of radar equation.

All considerations, when calculating the radar equation, were made assuming that the electromagnetic waves propagate under ideal conditions without disturbing influences. In practice, a number of losses should be considered since they reduce the effectiveness of the radar considerably.

$$\Rightarrow r_{max} = \left[\frac{P_t . G^2 . \lambda^2 . \sigma}{(4\pi)^3 . L_{ges} . P_{rec-min}} \right]^{1/4}$$

This factor includes the following losses:

$$L_{ges} = L_D + L_f + L_{atm}$$

L_d= Internal attenuation factors on the transmitting and receiving paths

L_f=Fluctuation losses during the reflection

L_{atm}=Atmospheric losses during propagation of the electromagnetic waves to and form the target

Free Space path loss: ********
Relation between Effective Aperture and Directivity: *******

3.8 Effective Area of an Antenna

Antenna Aperture, effective area or receiving cross section, is a measure of how effective an antenna is at receiving the power of electromagnetic radiation. The aperture is defined as the area, oriented perpendicular to the direction of an incoming electromagnetic wave, which would intercept the same amount of power from that wave as is produced by the antenna receiving it.

The power received by an antenna is equal to the power density of the electromagnetic energy, multiplied by its aperture. The larger an antenna's aperture, the more power it can collect from a given electromagnetic field.

The polarization of the incoming waves must match the polarization of the antenna and the load (receiver) must be impedance matched to the antenna's feed-point impedance.

Due to reciprocity, an antenna's gain in receiving and transmitting are identical. Therefore, A_e can be used to compute the performance of a transmitting antenna also. Capture area or effective aperture (A_e), is a direct function of antenna gain and operating wavelength. In simple terms if the antenna is placed in a electromagnetic field of a certain intensity, a certain amount of power will appear in the load at the antenna terminals. The area of space around the antenna that provided this amount of power is the effective aperture.

Many people confuse physical area with effective aperture. They are not the same. Physical size only affects the gain of an antenna. Gain and wavelength determines capture area, but capture area itself has nothing to do with actual physical size or physical area of the antenna.

3.9 Directivity

Directivity is a fundamental antenna parameter. It is a measure of how "directional" an antenna's radiation pattern is. An antenna that radiates equally in all directions would have effectively zero directionality, and the directivity of this type of antenna would be 1 (or 0 dB).

3.10 Relation between Directivity and gain

Directivity is a measure of the concentration of radiation in the direction of the maximum. Gain of an antenna (in a given direction) is defined as "the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotopically. The gain is related to the directivity by the relation

$$G = \eta D$$

Where η is the efficiency factor of the antenna and is equal to 1if the antenna has no copper, dielectric or mismatch losses.

For many types of antenna systems, the losses are very low and the value of gain is essentially equal to the directivity. For this reason, the two terms are often used interchangeably. However, it must be remembered that the gain is the important quantity when evaluating the systems performances of an antenna and that the value of directivity may be misleading if an antenna has substantial dissipative or mismatch losses.

The directivity figure can be evaluated theoretically from the computed radiation patterns of an antenna or evaluated experimentally by graphical integration of the measured radiation patterns.

3.11 Relationship between effective area and directivity of an antenna

The effective aperture of an antenna is uniquely related to its directivity. By using the directivity and effective aperture of a short diploe, which are relatively easy calculated, a general interrelation between effective aperture and directivity, valid for any antenna.

Consider a two-antenna communication system. Where system 1 may be the transmitter and system 2 is receiver, or the other way around. The antennas are displaced a distance R and are assumed to be lined up with respect to polarization and directivity. Where
D_T= Directivity of antenna 1 (Transmitter)

A_{eT}= Effective aperture of Transmitter

D_R= Directivity of antenna 2 (Receiver)

A_{eR}= Effective aperture of Receiver

P_T=Totally radiated power by antenna 1 (Transmitter)

We start by considering that antenna 1 is transmitting and antenna 2 is receiving. If antenna 1 is an isotropic radiator, the power density, S_0, at distance R from antenna 1 would be

$$S_0=\frac{P_T}{4\pi R^2}$$

Since in real field the antenna is not an isotropic antenna, it has directive properties so the power density, S_T , at distance R is

$$S_T = S_0 D_T$$

$$\Rightarrow \; S_T=\frac{P_T D_T}{4\pi R^2}$$

The antennas are displaced a distance R and are assumed to be lined up with respect to polarization and directivity.

The power received by antenna 2 is P_R is then

$$P_R = S_T A_{eR}$$

$$\Rightarrow P_R = \frac{P_T D_T A_{eR}}{4\pi R^2}$$

Where A_{eR} is the effective aperture of antenna 2. Rearranging the above equation gives-

$$D_T A_{eR} = \frac{P_R}{P_T}(4\pi R^2)$$

If we now let antenna2 transmit P_T and we look at the received power at antenna 1, which by virtue of reciprocity is equal to P_R, we find

$$D_R A_{eT} = \frac{P_R}{P_T}(4\pi R^2)$$

From above two equations we can write-

$$D_T A_{eR} = D_R A_{eT}$$

$$\frac{D_T}{A_{eT}} = \frac{D_R}{A_{eR}}$$

If we now assume that in the two antenna system, the transmitting antenna is an isotropic radiator, then D_T=1 and the above equation transforms into

$$A_{eTiso} = \frac{A_{eR}}{D_R}$$

Which means that, the effective aperture of an isotropic radiator is equal to the ratio of effective aperture and directivity of any antenna.

If we take, for example , a short dipole, we may relatively easy calculate the effective area and directivity as

$$A_e = \frac{3}{8\pi}\lambda^2$$

$$D = \frac{3}{2}$$

where λ is the used wavelength. Therefore the effective area of an isotropic radiator is

$$A_{eTiso} = \frac{\frac{3\lambda^2}{8\pi}}{\frac{3}{2}}$$

$$A_{eTiso} = \frac{3\lambda^2}{8\pi} x \ \frac{2}{3}$$

$$A_{eTiso} = \frac{\lambda^2}{4\pi}$$

Thus for any antenna-

$$\frac{A_e}{D} = \frac{\lambda^2}{4\pi}$$

$$\Rightarrow D = \frac{4\pi}{\lambda^2} \ A_e$$

This is the desired relation between effective aperture and directivity of an antenna.

3.12 Radar Reflectivity

Reflectivity is the amount of transmitted power returned to the radar receiver after hitting precipitation, compared to a reference power density at a distance of 1 meter from the radar antenna.

As transmitted pulse within the radar beam encounter targets, energy will be scattered in all directions. A very small portion of the intercepted energy will be backscattered (termed reflectivity) toward the radar and referred to as an echo. The degree or amount of backscatter is determined by target-

- Size (radar cross section)
- Shape (round, oblate, flat, etc)
- State(Liquid, frozen, mixed, dry, wet)
- Concentration (number of particles per unit volume)

Meteorologists are concerned with two types of scattering, Rayleigh and non-Rayleigh. Rayleigh scattering occurs with targets whose diameter (D) is much smaller than the wavelength of the transmitted energy. Rayleigh scattering occurs with the targets whose diameters are less than or equal to about 7 mm or ~ 0.4 inch. Raindrops seldom exceed 7mm so all liquid drops are Rayleigh scatters.

Nearly all hailstones are non-Rayleigh scatters due to their larger diameters.

3.12.1 Base Reflectivity

Taken from the lowest ($^{1}/_{2°}$) elevation scan, base reflectivity is excellent for surveying the region around the radar to look for the precipitation. However, remember the radar beam increases in elevation in elevation as distance increases from the radar. This is due, in part, to the elevation angle itself but is more because the earth's surface curves away from the beam. This can lead to underestimating the strength and intensity of distant storms. For this reason, it is wise to always check the radar images from different locations to help provide the overall picture of the weather in any particular area.

Also, thunderstorms can contain hail which is often a good reflector of energy. Typically a hailstone is coated with a thin layer of water as it travels through the thunderstorm cloud. This thin layer of water on the hailstone will cause a storm's reflectivity to be greater, leading to a higher dBZ and an over estimate the amount of rain received.

Value of 20 dBZ is typically the point at which light rain begins. The values of 60 to 65 dBZ are about the level where ¾" hail can occur.

3.12.2 Radar Reflectivity Factor

A quantity determined by the drop-size distribution of precipitation, which is proportional to the radar reflectivity if the precipitation particles are spheres small compared with the radar wavelength.

3.12.3 Radar Cross-Section

Radar cross section, σ, is a specific parameter of a reflective object that depends on many factors, and which has units of m2. The calculation of the radar cross-section is only possible for simple objects. The surface area of simple geometric bodies depends on the shape of the body and the wavelength. If absolutely all of the incident radar energy on the target were reflected equally in all directions, then the radar cross section would be equal to the targets cross-sectional area as seen by the transmitter. In practice, some energy is absorbed, and the reflected energy is not distributed equally in all directions.

Therefore, the radar cross section is quite difficult to estimate and is normally determined by measurement. The target radar cross section depends on the:

- Physical geometry and exterior features
- Direction of the illuminating radar
- Transmitters frequency
- Used material types.

CHAPTER 4: DOPPLER RADAR

4.1 Basic Observation Data and Products

A Doppler radar is a specialized radar that uses the Doppler effect to produce velocity data about objects at a distance. It does this by bouncing a microwave signal off a desired target and analyzing how the object's motion has altered the frequency of the returned signal. This variation gives direct and highly accurate measurements of the radial component of a target's velocity relative to the radar. Doppler radars are used in aviation, sounding satellites, Major League Baseball's StatCast system, meteorology, radar guns, radiology and healthcare (fall detection and risk assessment, nursing or clinic purpose), and bistatic radar (surface-to-air missiles).

Partly because of its common use by television meteorologists in on-air weather reporting, the specific term "*Doppler Radar*" has erroneously become popularly synonymous with the type of radar used in meteorology.

Most modern weather radars use the pulse-Doppler technique to examine the motion of precipitation, but it is only a part of the processing of their data. So, while these radars use a highly specialized form of *Doppler radar*, the term is much broader in its meaning and its applications.

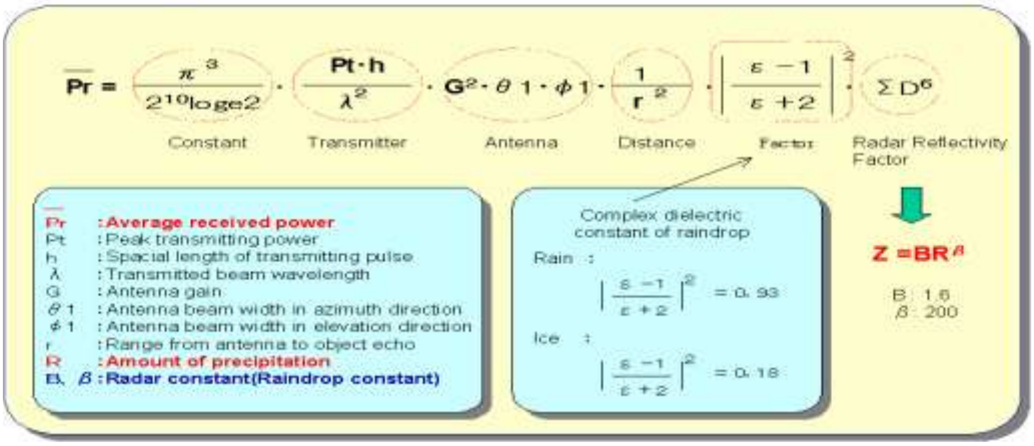
4.1.1 Basic Data

Table 1 shows the basic data observed by Doppler radar.

Symbol	Units	Description
T	dBz	Total power that shows the reflection intensity including the ground clutter power.
Z	dBz	Radar reflectivity factor that is determined from the received power by the radar equation.
V	m/s	Doppler velocity that shows the speed of the moving target measured from the radar radial direction.
W	m/s	Fluctuation of Doppler velocity (=Spectrum Width)

4.1.1.1 Radar Equation and Z-R Relation

The received power information observed by the radar is derived as the radar reflectivity factor (dBz) in the following equation.



The radar observes the radar reflectivity factor. However, since there is considerably regularity in the particle size distribution of the weather drop in the air, the relation between the reflectivity (Z) and the rainfall rate (R) is statistically expressed by $Z = BR^{\beta}$. This is called Z-R (reflectivity-rainfall rate) Relation.

B and β

I: Scattered but somewhat heavy portion of thunderstorm echo, or high isolated, convective echo in dry atmospheric air (water drops evaporate considerably).

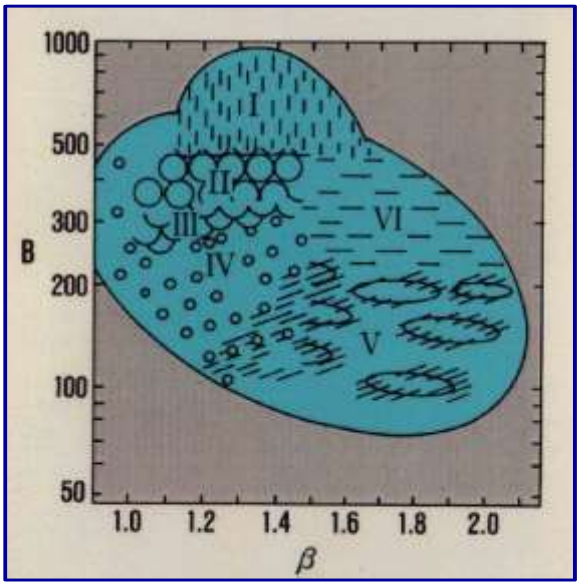
II: Center portion where thunderstorm echo is dominant, or strong, massive echo with slightly scattered shape

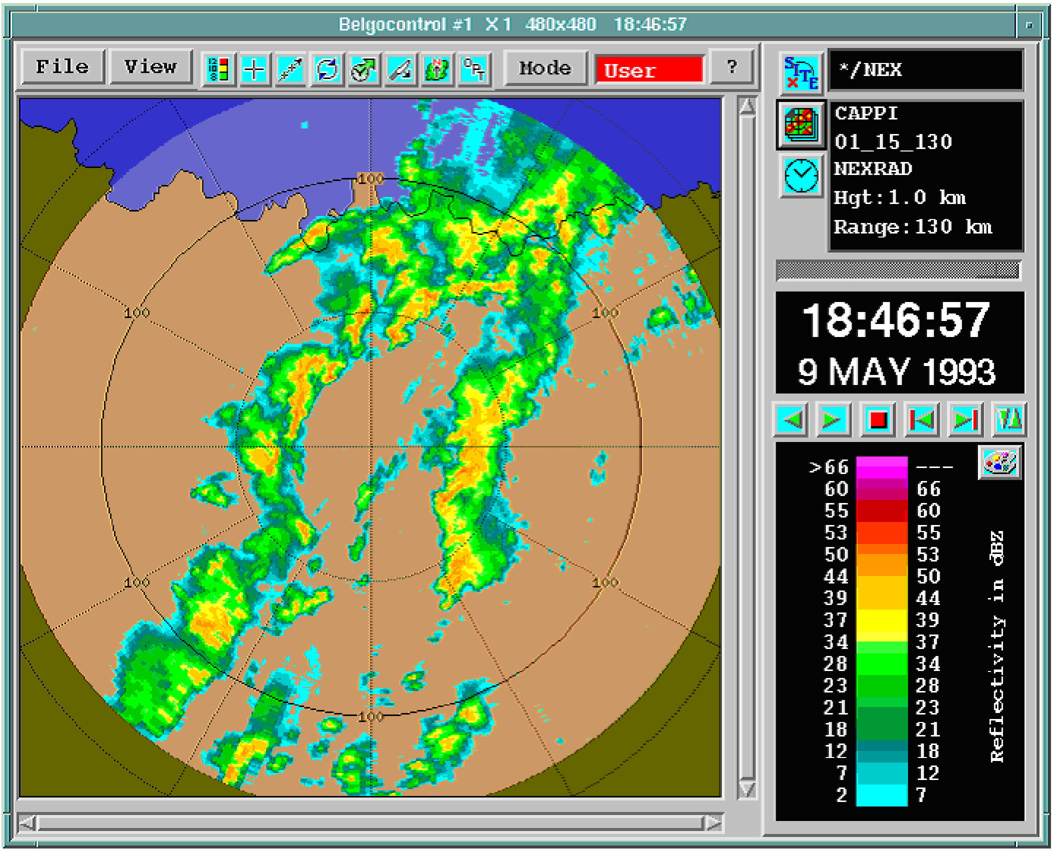
III: Breaking out or growing stage of the convective cells.

IV: Small, solid-like, convective echoes scattered or aligned.

V: Stratiform echoes uniformly spread, or scattered weak echoes.

VI: Final stage of thunderstorm completely scattered, or scattered portions.

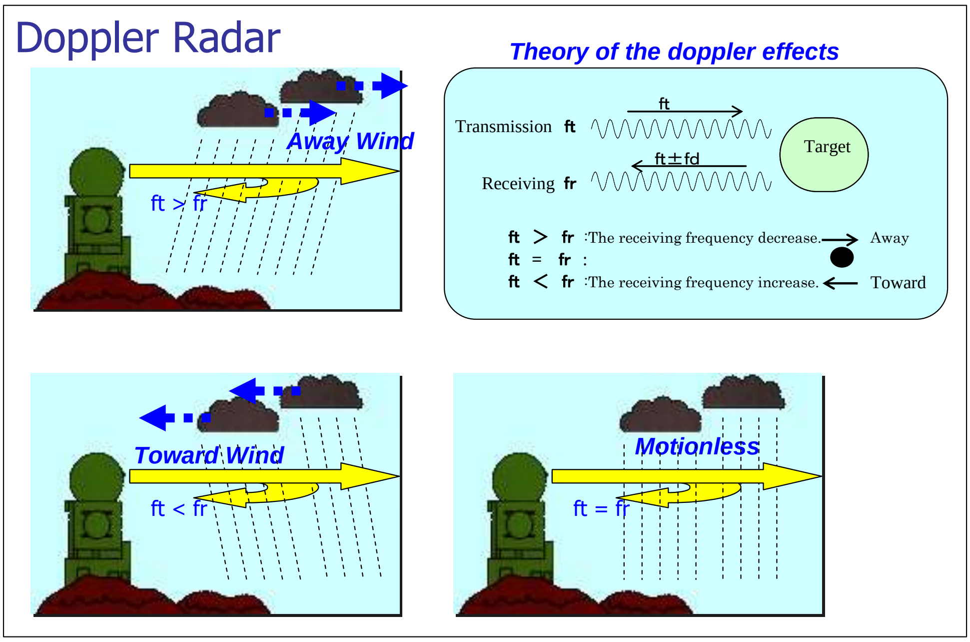




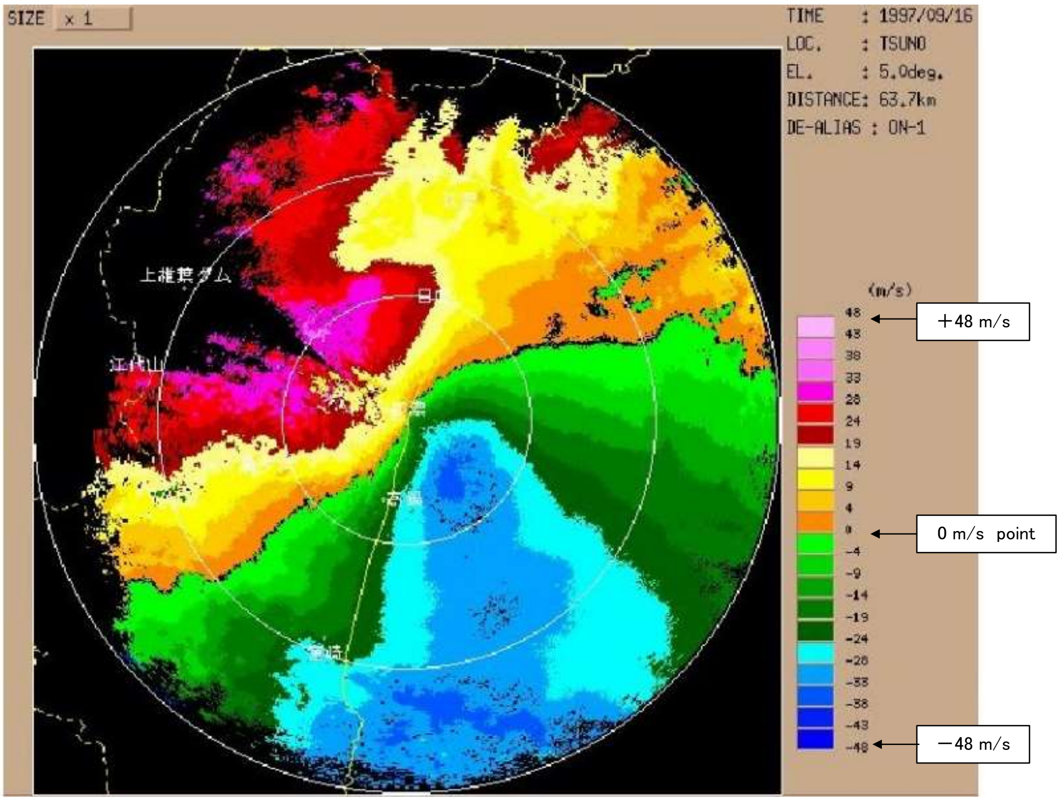
Example of Reflection Intensity

4.1.1.2 Doppler Velocity

The moving speed of the precipitation in radial direction can be measured using the Doppler effects.



The observed result is displayed as below. Generally, the window toward to radar is cool-colored and the window away from radar is warm-colored.



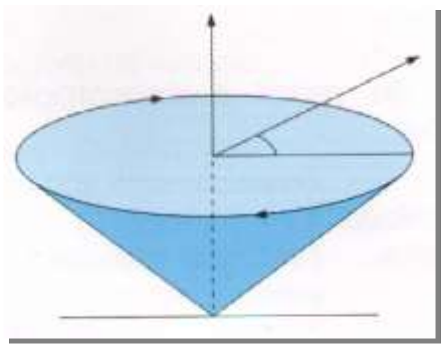
Example of Doppler Velocity Data Display

4.1.2 Various Products

IRIS can generate the useful products for the weather report, flood forecast, and the meteorological research from the observed basic data with the various algorithms.

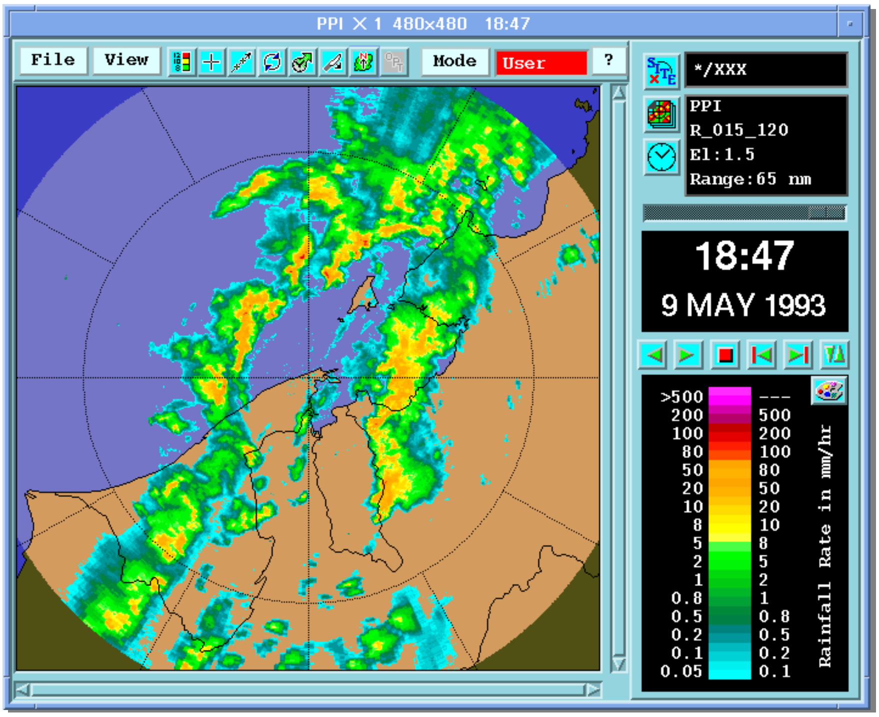
4.1.2.1 PPI: Plan Position Indicator Product

The PPI product shows the distribution of the selected data parameter on a constant elevation angle surface rotating the antenna to the horizontal direction. This is the essential base product of the radar observation. For more information on this product, refer to the IRIS Product & Display Manual, 2.8 PPI: Plan Position Indicator.



PPI Scan Conceptual Diagram

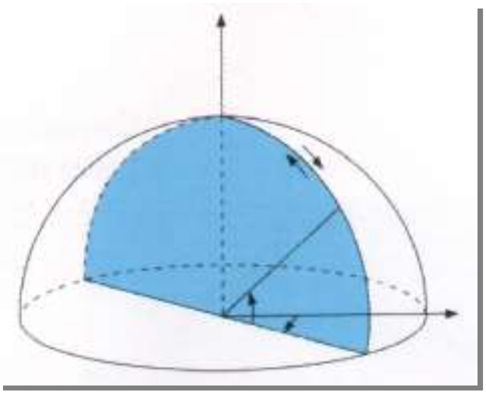
Note: In this product, the longer range, the higher the beam height (the observation point) will be.



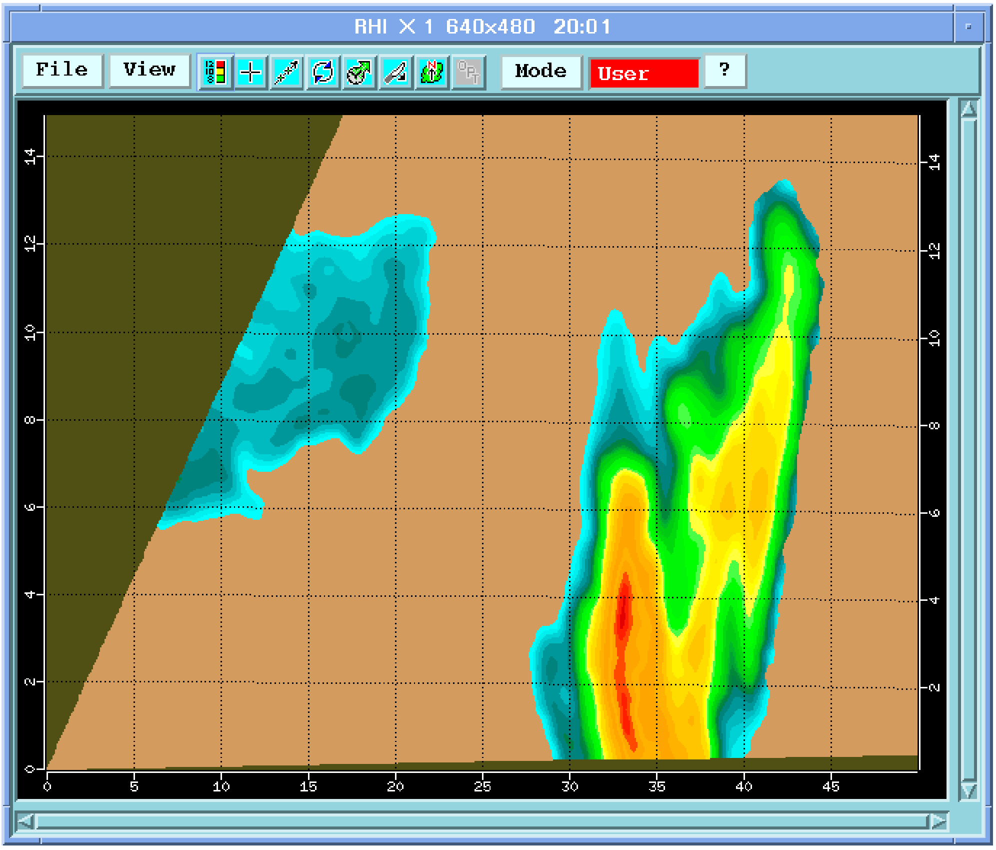
Example of PPI Product Display

4.1.2.2 RHI: Range Height Indicator

The RHI product is excellent for viewing the detailed vertical structure of a storm. During RHI scanning, the antenna azimuth is fixed and the elevation is swept. In the following display, the horizontal axis is the range, and the vertical axis is the height from the radar. For more information on this product, refer to the IRIS Product & Display Manual, 2.12 RHI: Range Height Indicator.



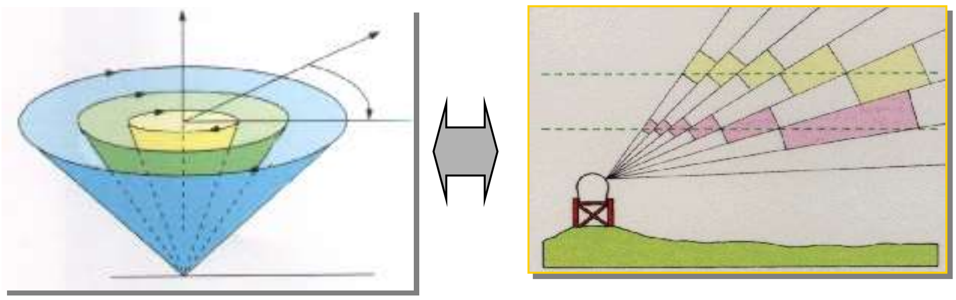
RHI Scan Conceptual Diagram



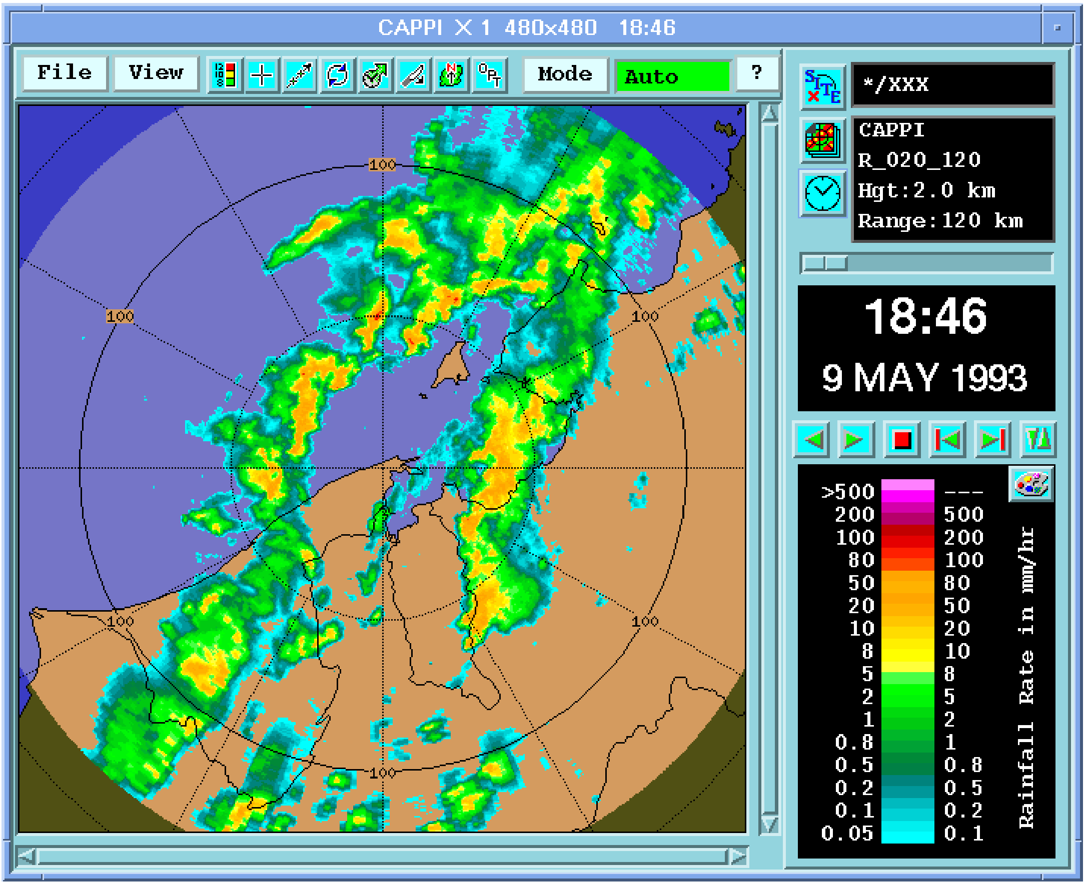
Example of RHI Product Display

4.1.2.3 CAPPI: Constant Altitude Plan Position Indicator

The CAPPI gathers the three-dimensional data changing slightly the azimuth angle of the antenna per rotation to the upper side and displays the equal altitude precipitation distribution using the data. It also supports calculation of SHEAR data. For more information on this product, refer to the IRIS Product & Display Manual, 2.4 CAPPI: Constant Altitude Plan Position Indicator.



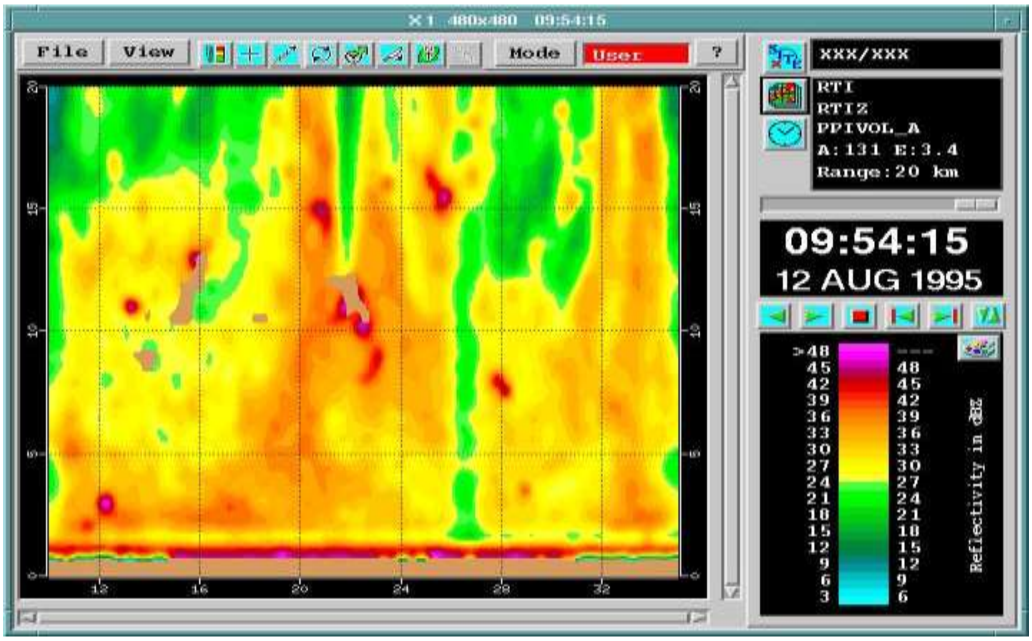
CAPPI Scan Conceptual Diagram



Example of CAPPI Product (Phase at 2km height)

4.1.2.4 RTI: Range Time Indicator

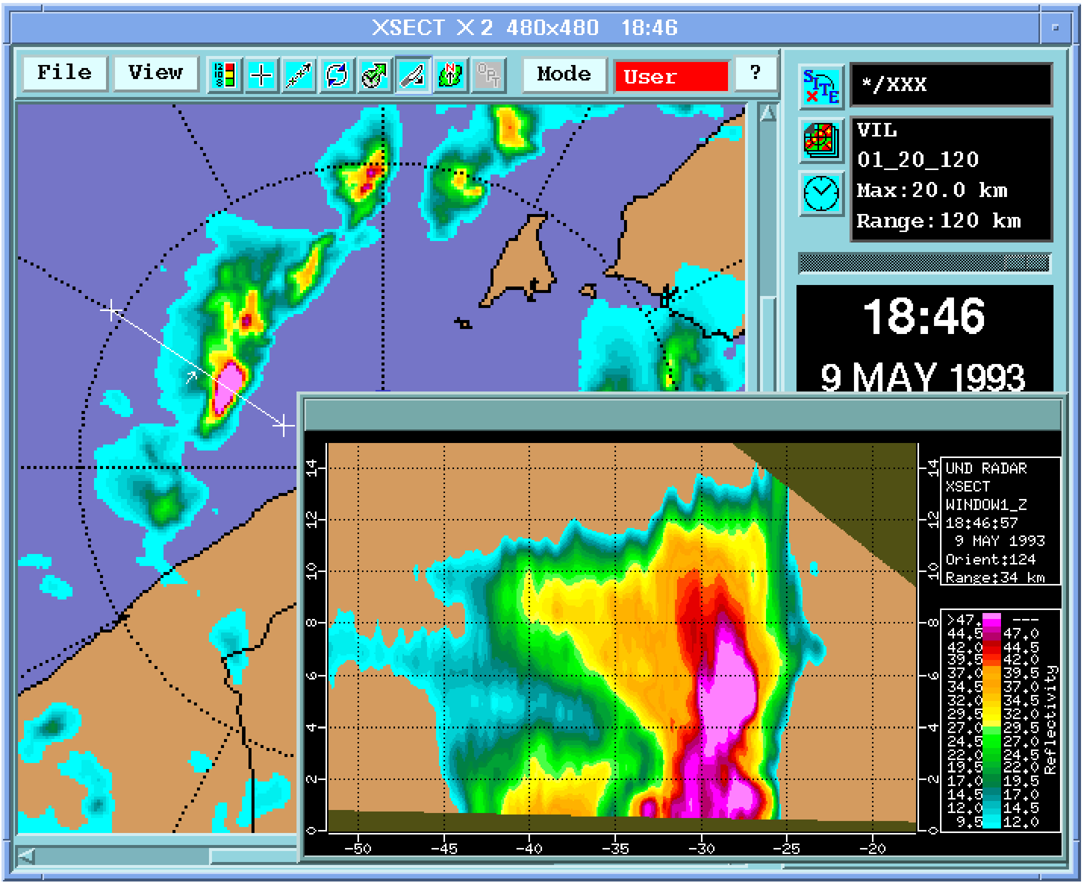
The RTI is most useful for manual scans or “searchlight” scans, which are manual, scan at a fixed position. The horizontal axis is the time (seconds after the beginning of the scan), and the vertical axis is the range from the radar. Also, it is called B-Scope. For more information on this product, refer to the IRIS Product & Display Manual, 2.13 RTI: Range Time Indicator.



Example of RTI Product Display

4.1.2.5 XSECT: Cross Section

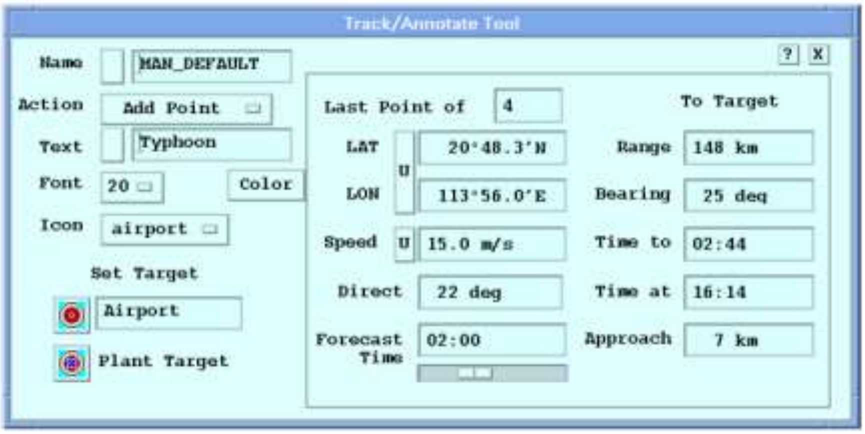
The XSECT product (cross section) is constructed from the CAPPI data. This product lets you make a cross section at any point and along any line – in effect letting you move the radar wherever you want. For more information on this product, refer to the IRIS Product & Display Manual, 5. The Quick Look Window.



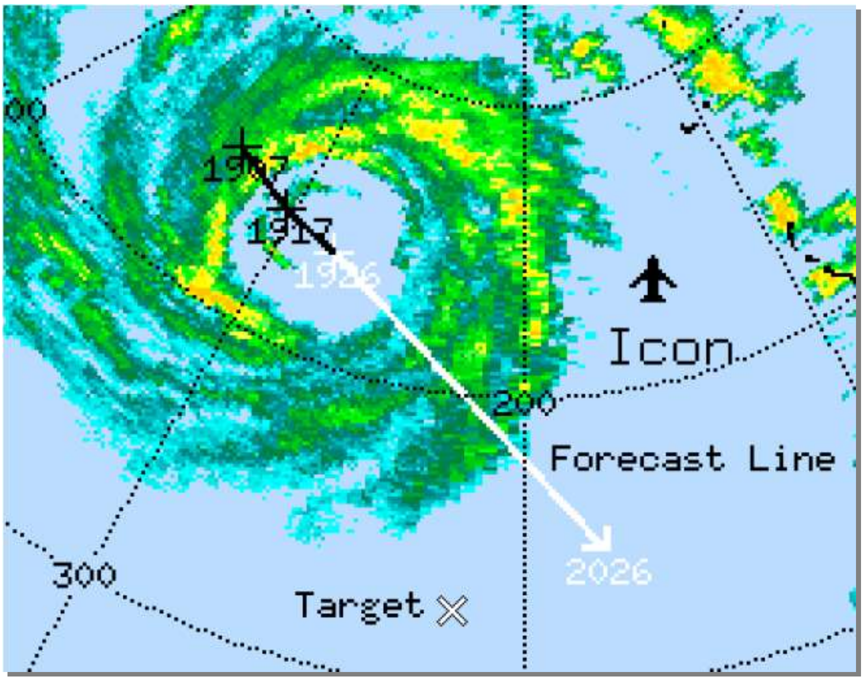
Example of XSECT Product Display

4.1.2.6 TRACK: Tracking/Forecast

TRACK products show the projected motion for storm features (centroids) based on a series of input products from different time. You define the threshold level and size of the centroids, below which weather features are ignored. When new data comes in the TRACK product compares the previous one to the new data to obtain a motion vector of the weather target. Warnings are issued if a centroid hits, or is forecast to pass through, a protected area. For more information on this product, refer to the IRIS Product & Display Manual, 5. The Quick Look Window5. The Quick Look Window.



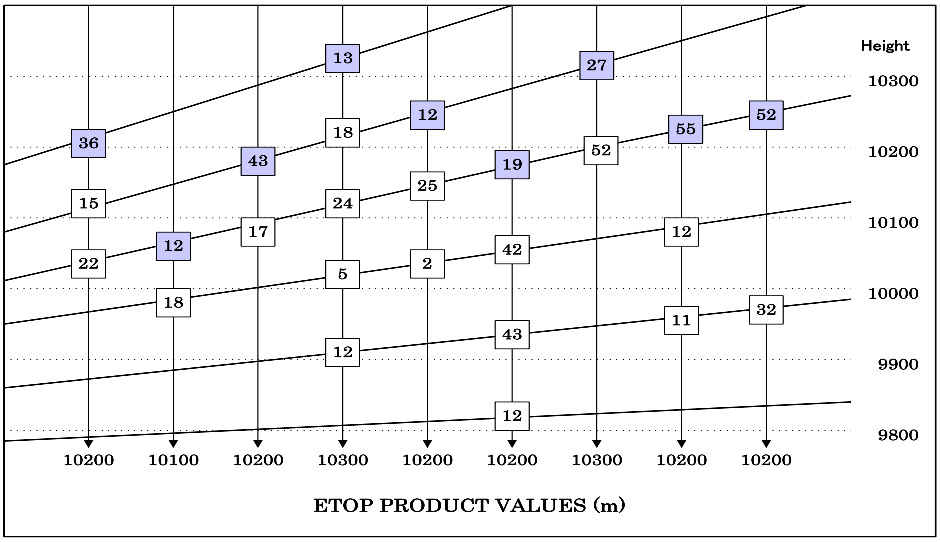
Track/Annotate Tool Window



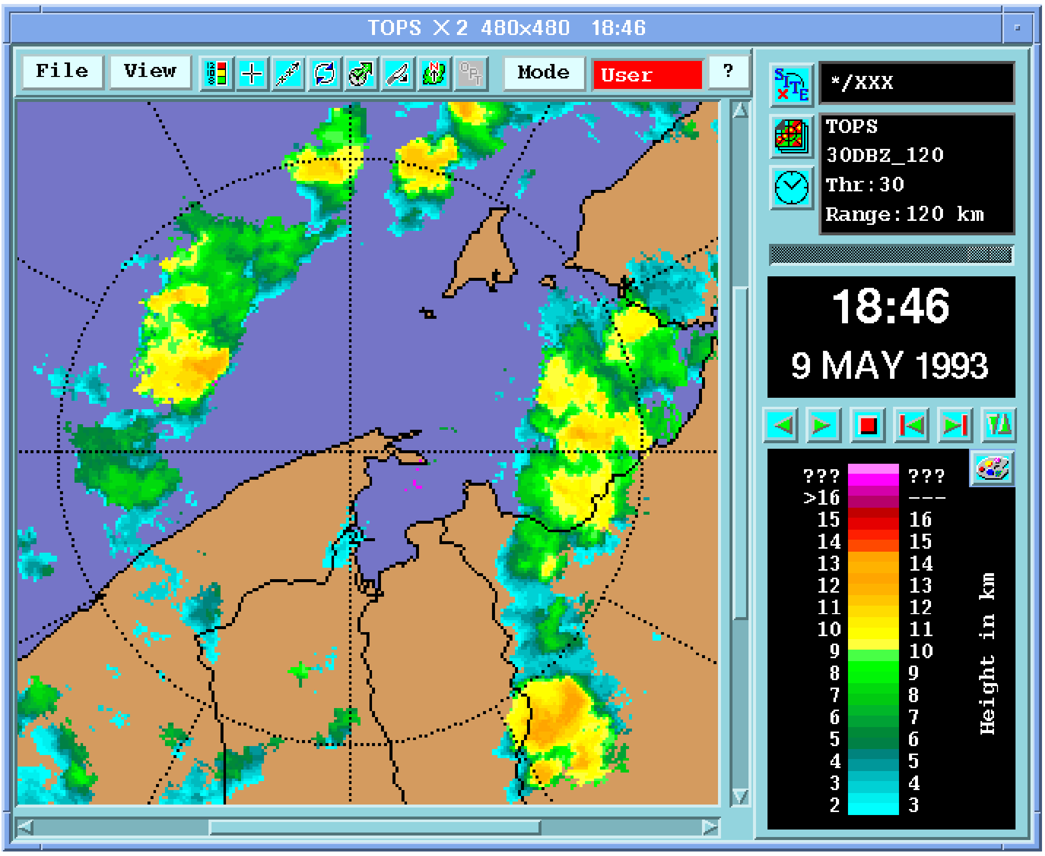
Example of TRACK Product Display
(In this example, the position of the cyclone centroid in an hour later is shown.)

4.1.2.7 TOPS: Echo Tops

The TOPS product is an excellent indicator of severe weather and hail. It is a display image of the height of the highest occurrence of a selectable threshold dBZ contour. For more information on this product, refer to the IRIS Product & Display Manual, 2.16 TOPS: Echo Tops.



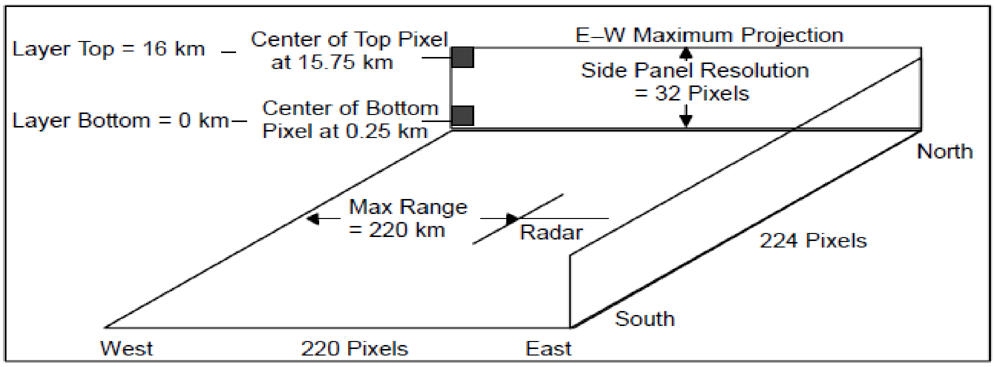
Echo Top Detection Conceptual Diagram



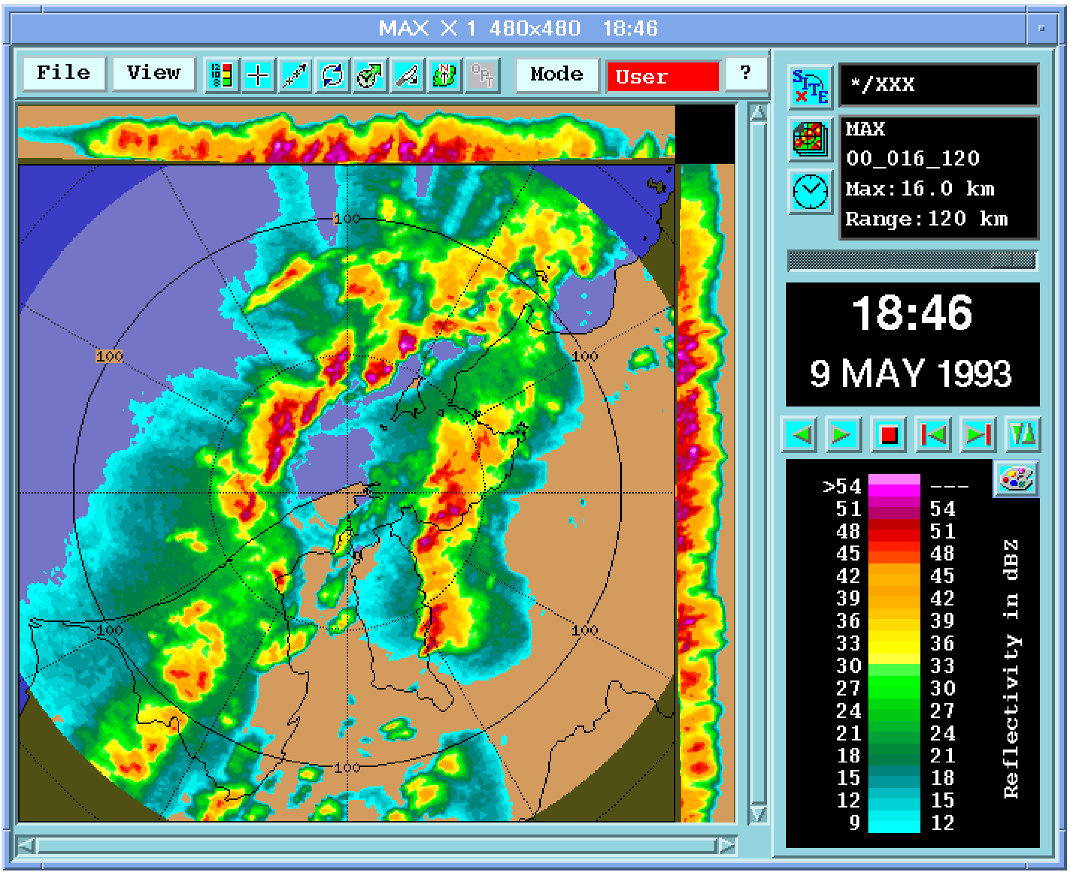
Example of TOPS Display

4.1.2.8 MAX: Maximum Reflectivity

The MAX product provides an easy-to-interpret presentation of the echo height and intensity in a single display. It is useful for intuitive understanding of the precipitation structure. For more information on this product, refer to the IRIS Product & Display Manual, 2.7 MAX: Maximum Reflectivity.



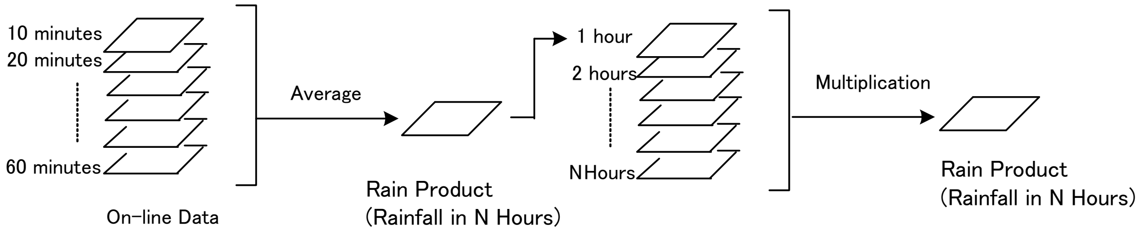
Example of MAX Geometry



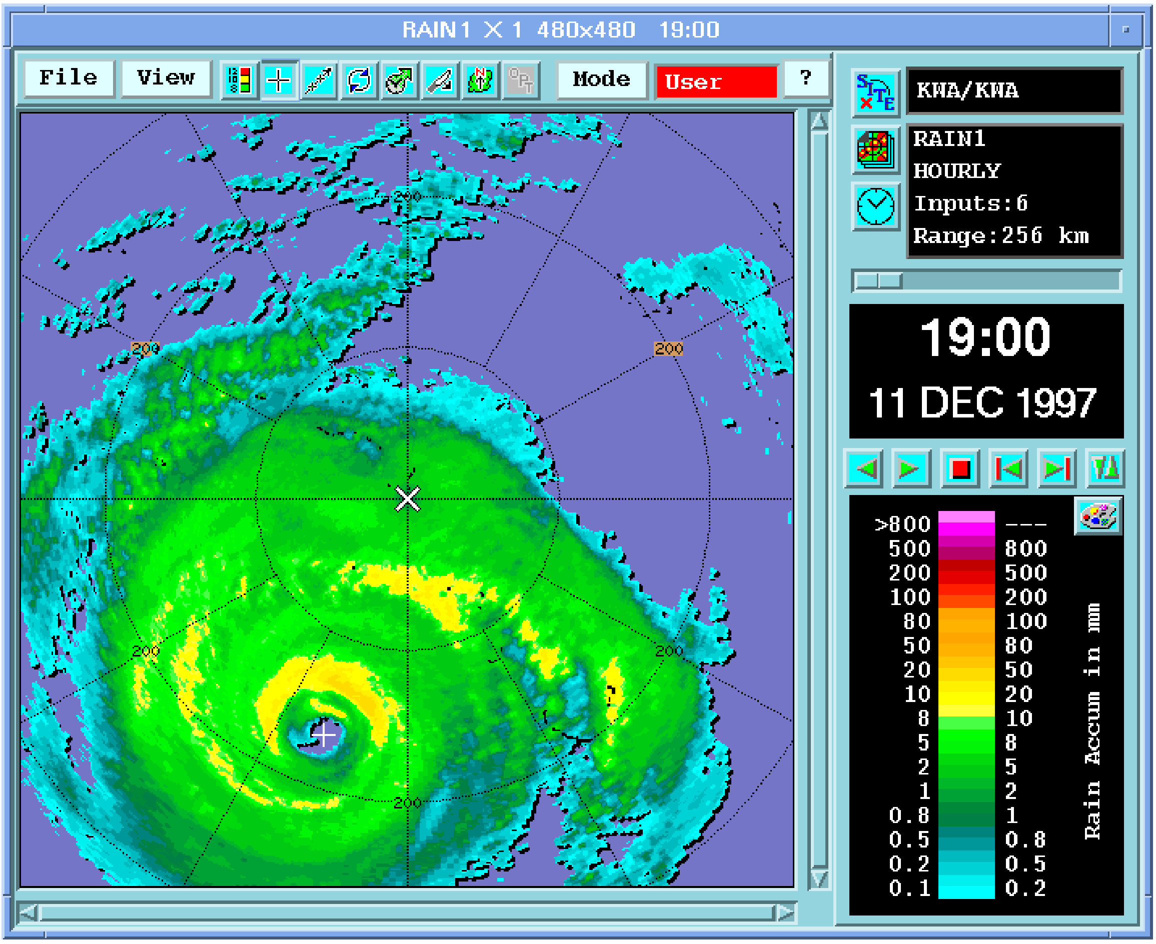
Example of MAX Display

4.1.2.9 RAIN1 and RAINN: Hourly and N-Hour Rain Accumulation

The RAIN1 product uses the previous hour's CAPPI or SRI data to obtain an estimate of the rainfall that fell within that hour. The RAINN is a product of a product: you can sum any number of hours of individual RAIN1 products. The product output shows the last N hours of accumulation. For more information on this product, refer to the IRIS Product & Display Manual, 2.9 RAIN1: Hourly Rain Accumulation and 2.10 RAINN: N-Hour Rain Accumulation.



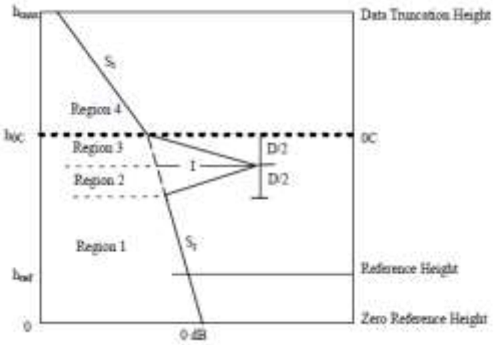
RAIN Product Conceptual Diagram



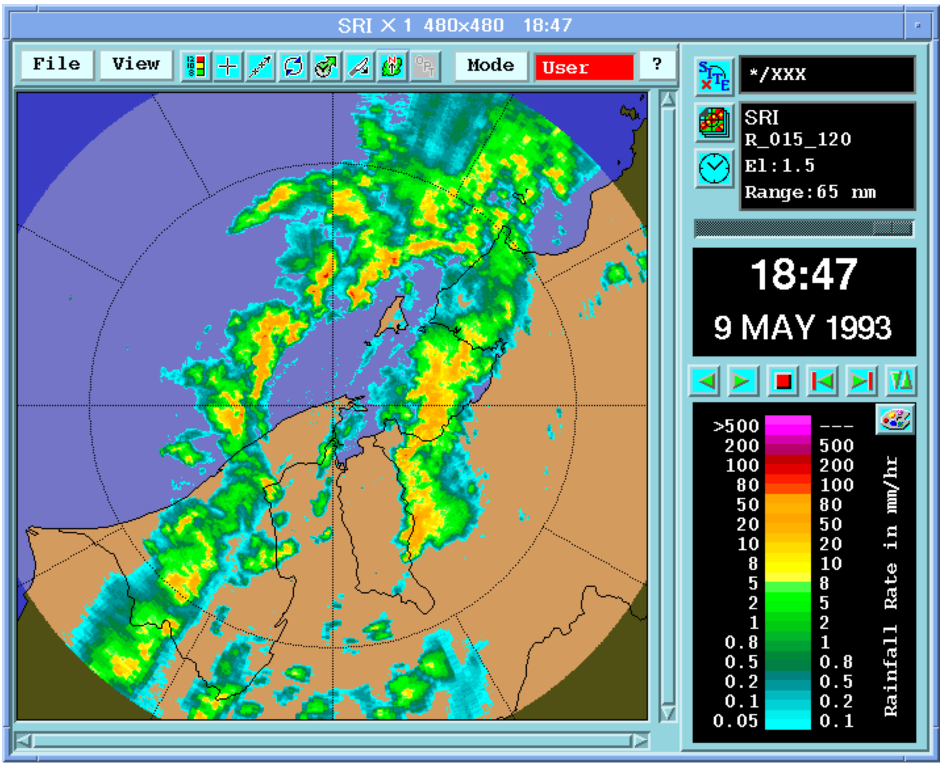
Example of RAIN1 (Hourly Rain) Product Display

4.1.2.10 SRI: Surface Rainfall Intensity

The SRI is mainly used of as input into the RAIN1 product to get the best possible estimates of accumulated precipitation even at longer ranges from the radar. Upper parts of precipitating clouds give typically weaker echo than the cloud base, except near melting layer where the echo is much stronger. Thus, a correction is needed to estimate surface rainfall intensity. This product allows the user to apply their knowledge and provides several ways to input information of the actual reflectivity profile using the bright band. The following figure shows the method for obtaining the correction by recoding monthly the information of the melting layer. For more information on this product, refer to the IRIS Product & Display Manual, 2.14 SRI: Surface Rainfall Intensity.



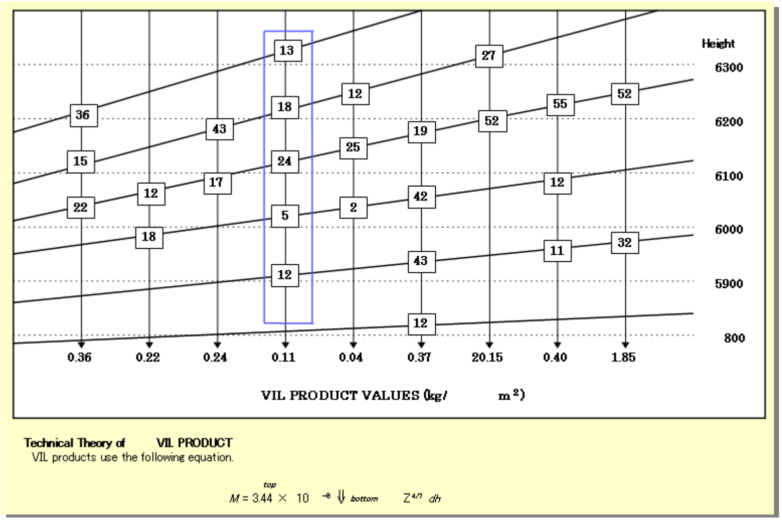
Example Reflectivity Profile



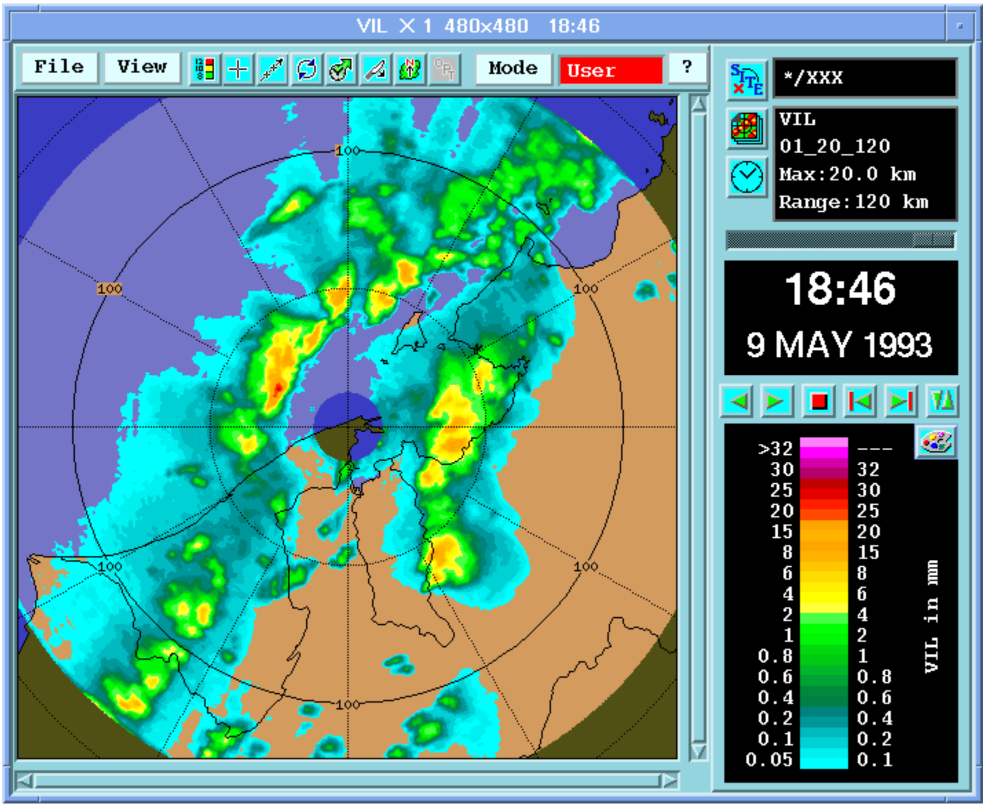
Example of SRI Product

4.1.2.11 VIL: Vertically Integrated Liquid

The VIL product is another excellent indicator of severe storms and hail. It shows the vertically integrated liquid by accumulating vertically the CAPPI data per each cell as below figure. It also can serve a forecasting guide that how much precipitation is likely to fall during the next few minutes. For more information on this product, refer to the IRIS Product & Display Manual, 2.18 VIL: Vertically Integrated Liquid.



VIL Product Algorithm Conceptual Diagram



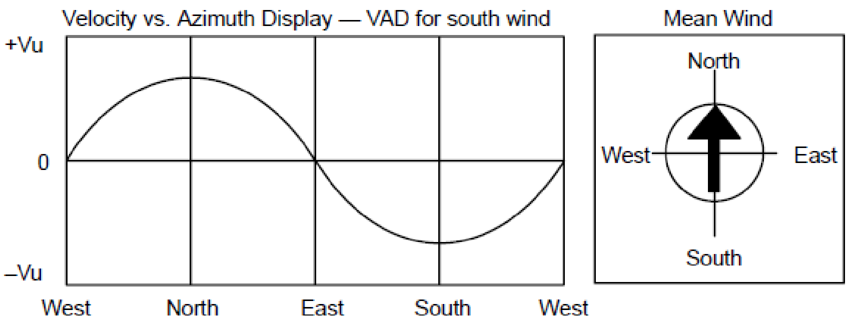
Example of VIL Product Display

4.1.2.12 VVP: Velocity Volume Processing

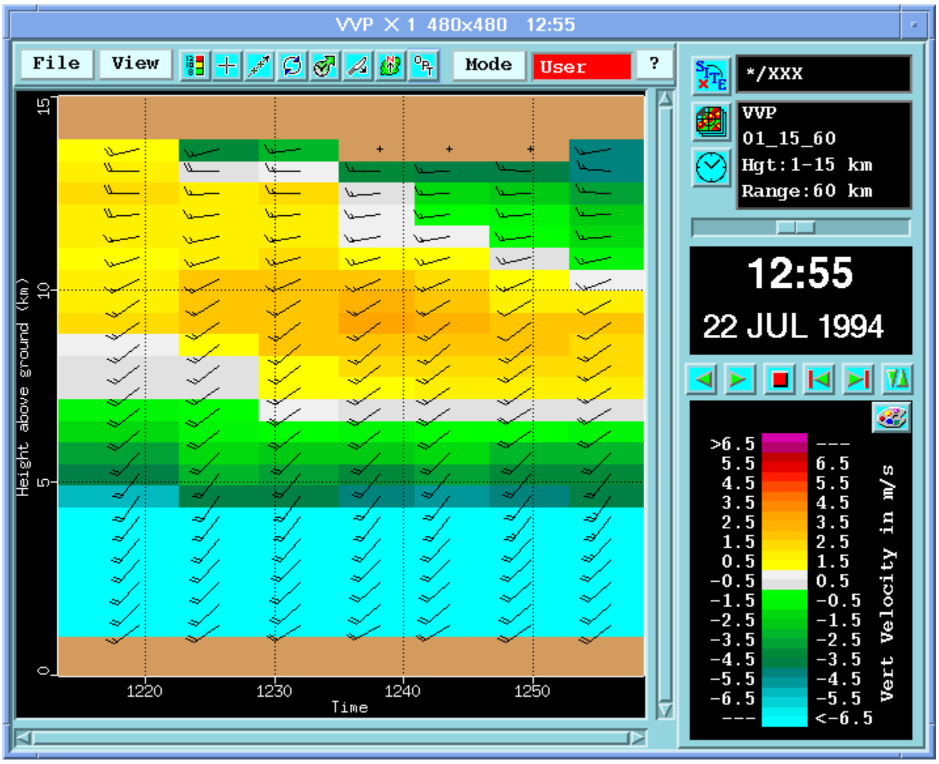
The VVP Volume Processing algorithm (VVP) obtains the following parameters averaged over a volume centered about the radar.

- Horizontal wind speed and direction
- Horizontal divergence (related to vertical air motions)
- Particle vertical velocity (airspeed and particle fall-speed combined)
- Horizontal deformation and axis of dilatation (related to frontal forcing)
- Average reflectivity

It is similar to the so-called VAD technique, except that it is an improved analytical approach. The weather parameters are often used for the aviation weather information. For more information on this product, refer to the IRIS Product & Display Manual, 2.19 VVP: Velocity Volume Processing.



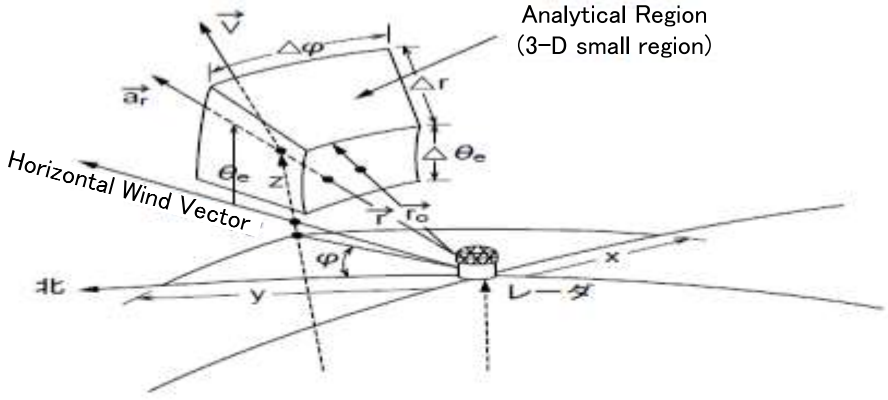
Example of Radial Velocity vs. Azimuth Display



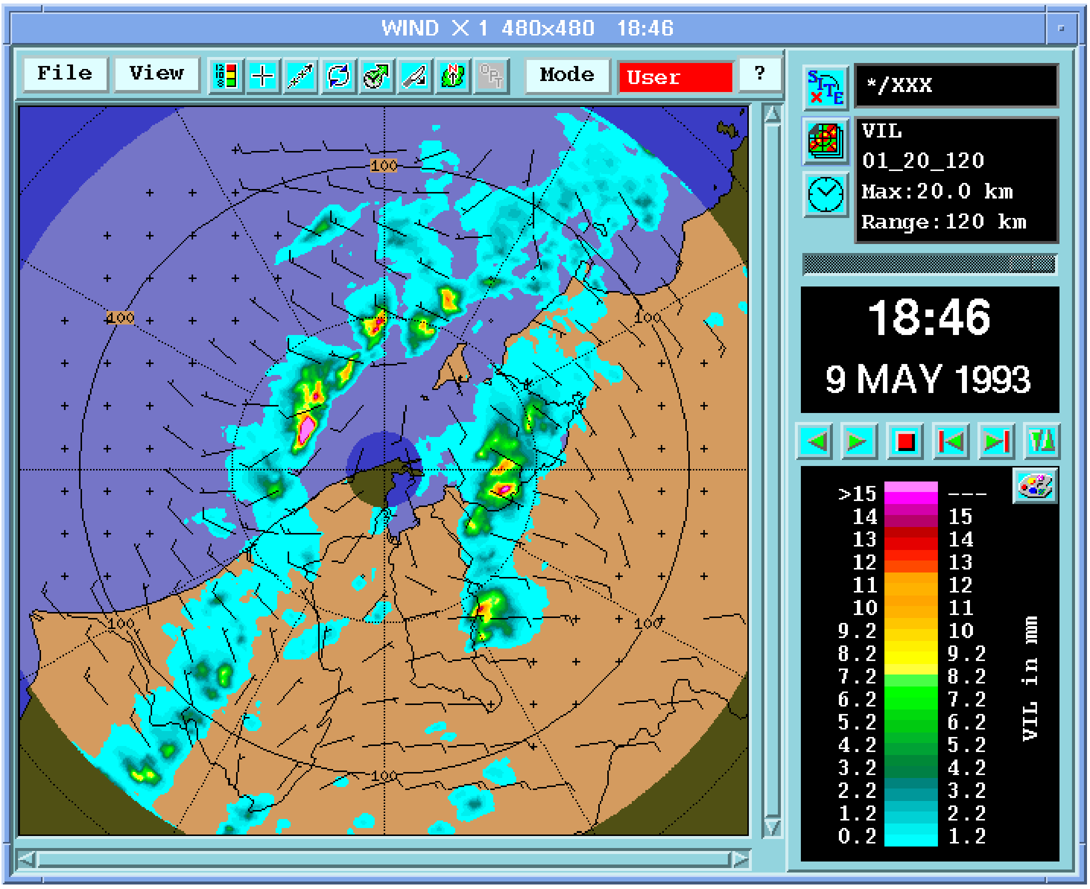
Example of VVP Product Display

4.1.2.13 WIND: Wind Speed and Direction

The WIND product computes a 2-D array of horizontal wind vectors (the horizontal wind field) using the radial velocity information and the assumption that the wind is uniform over a limited sector. For more information on this product, refer to the IRIS Product & Display Manual, 2.21 WIND: Wind Speed and Direction.



WIND Algorithm Conceptual Diagram



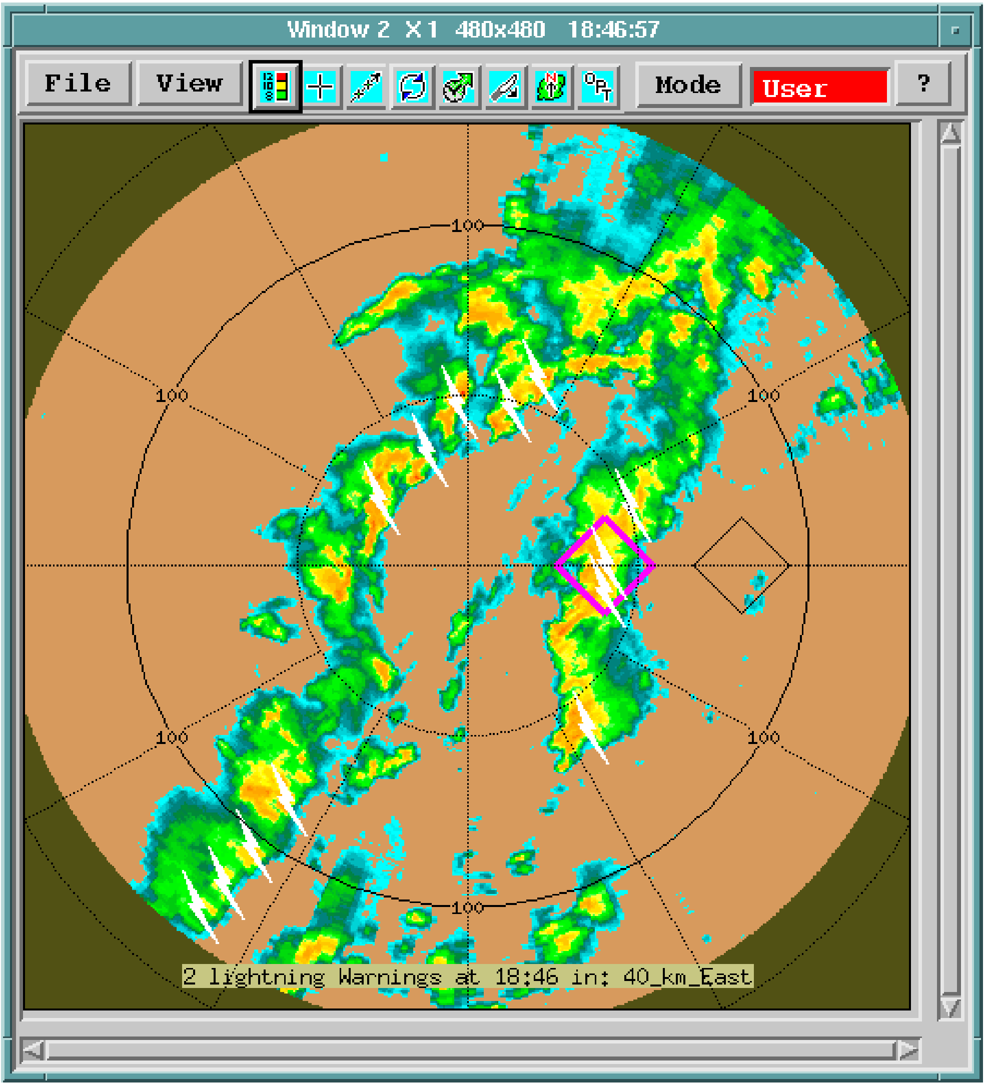
Example of WIND Product (Overlay product with VIL) Display

4.1.2.14 WARN: Warning/Centroid Product

The WARN product looks at other IRIS products to detect significant weather and monitors all of the various displays and parameters in real time, then alerts the operator when an event is detected. The following are the various alarms.

- Hail Warning
- Thunder Warning
- Storm Warning
- Microburst Warning
- Window-shear Warning

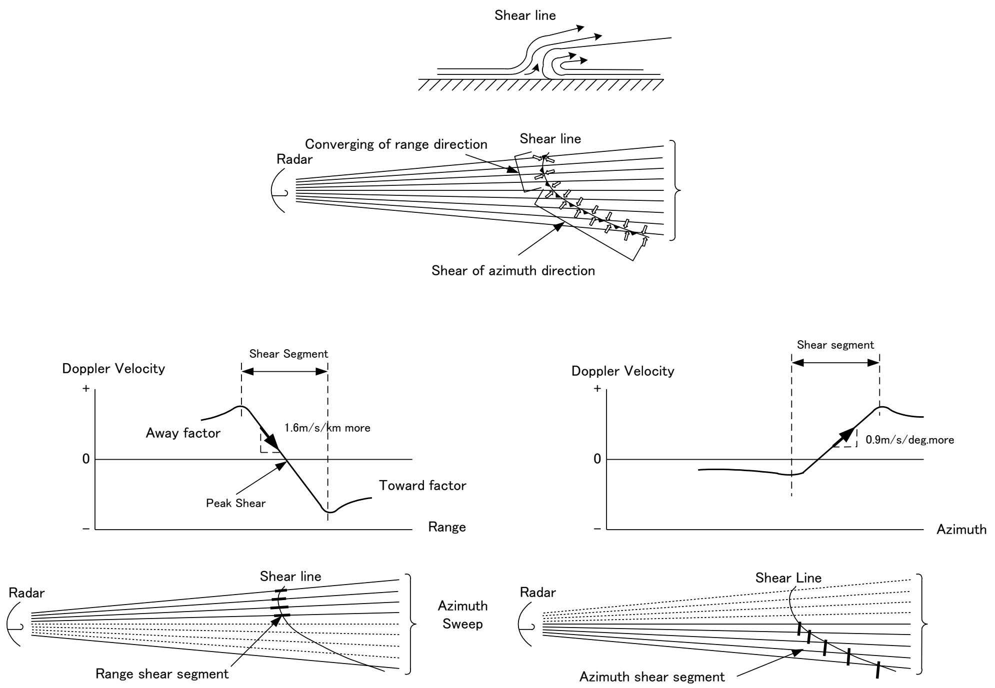
This product is effective on the on-going weather report or the storm forecast. For more information on this product, refer to the IRIS Product & Display Manual, 2.20 WARN: Warning/Centroid Product.



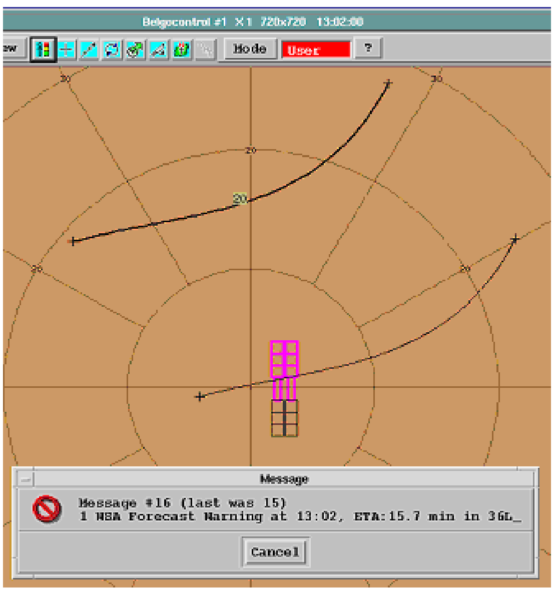
Example of WARN Product (Overlay product with PPI reflectivity) Display

4.1.2.15 SHEAR: Wind Shear

The optional SHEAR product can detect wind shear in the atmosphere. Wind shear is associated with a variety of phenomena: Microburst, Gust Fronts, Mesocyclones, Cold Fronts and Atmospheric Waves. The shear line is outputted by detecting the information of the range shear, azimuth shear and elevation shear, then combining them. This is used for the aviation weather information. For more information on this product, refer to the IRIS Product & Display Manual, 3.5 SHEAR: Wind Shear.



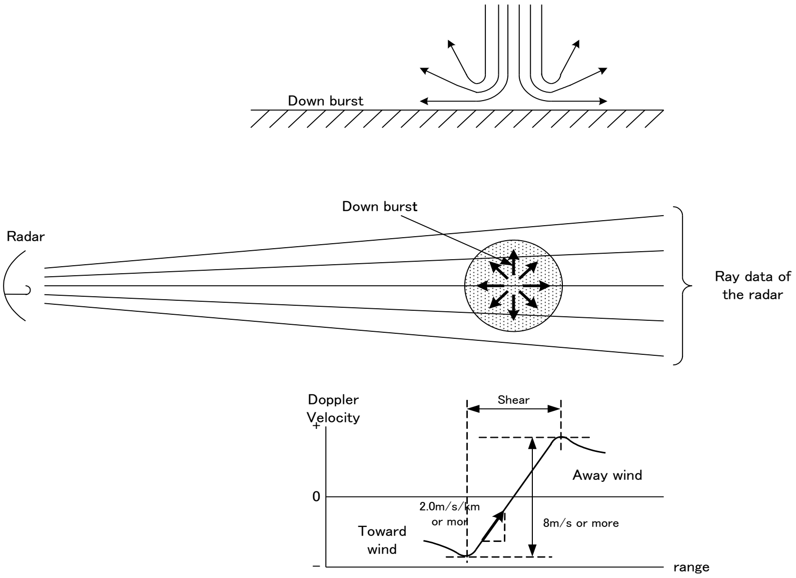
Wind Shear Detection Conceptual Diagram



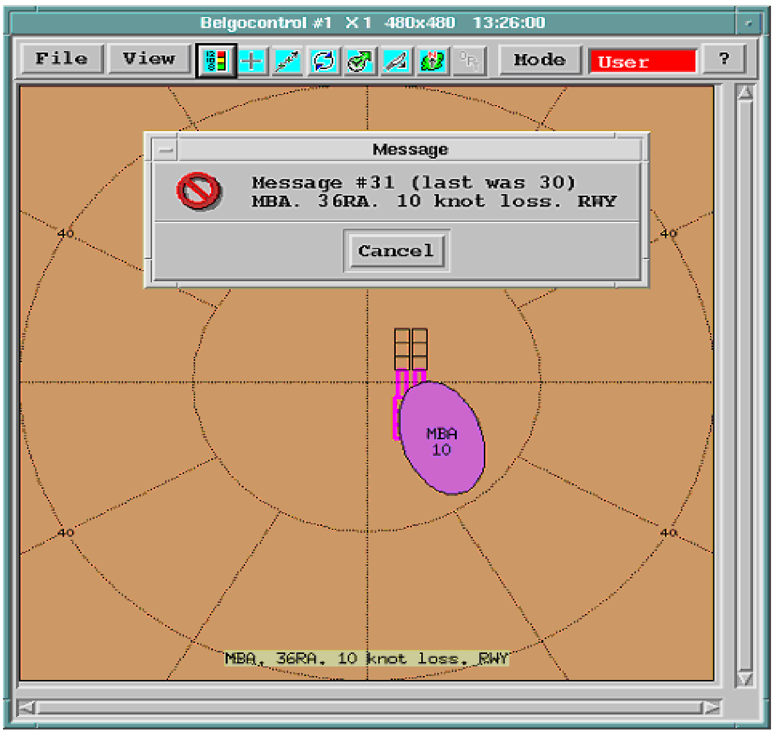
Example of Wind Shear Line Product Display (including Forecast Warning Time)

4.1.2.16 Microburst Warning

Microbursts are characterized by positive values of the radial shear (strongly divergent outflow) in a roughly circular region, typically less than 3 km in size. Microbursts are associated with the convective storms and extremely hazardous to aircraft during landing or takeoff.



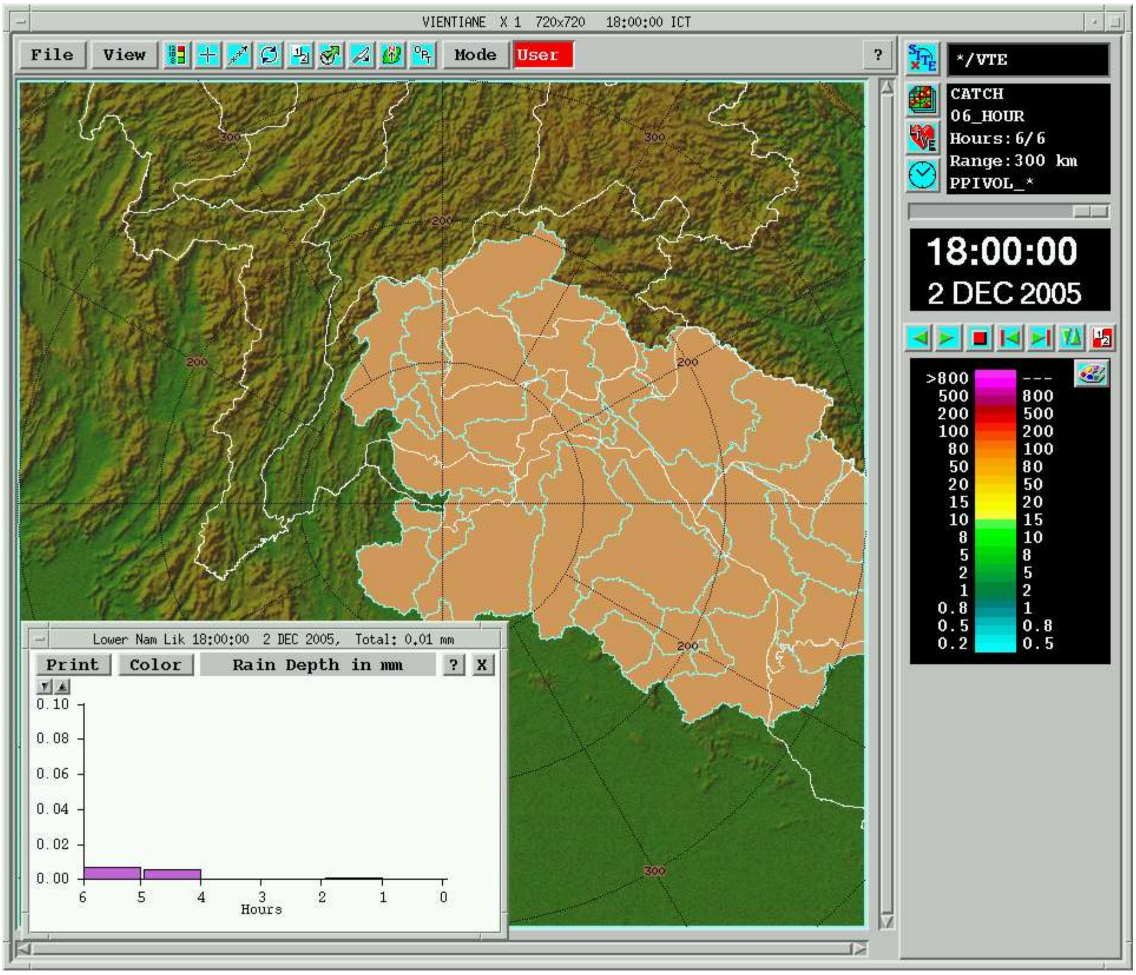
Microburst Detection Conceptual Diagram



Example of Microburst Detection Product Display

4.1.2.17 CATCH: Subcatchments Precipitation Accumulation

The CATCH product calculates the precipitation accumulation in subcatchment regions such as a watershed area. It is used for hydrometeorological applications such as estimating the total rainfall in a river basin for the purpose of flood forecasting. Both the time of the integration and the subcatchment areas can be selected. It can also issue warnings if the precipitation in a subcatchment region exceeds a threshold value. For more information on this product, refer to the IRIS Product & Display Manual, 3.1 CATCH: Subcatchments Precipitation Accumulation.



Example of CATCH Product Display

CHAPTER 5 : BASIC RADAR METEOROLOGY

5.1 Observation Sequence and Generating Products

The observation sequence is intimately related with the generating products. Thus, the observation sequence should be appropriate to the operational purpose of radar.

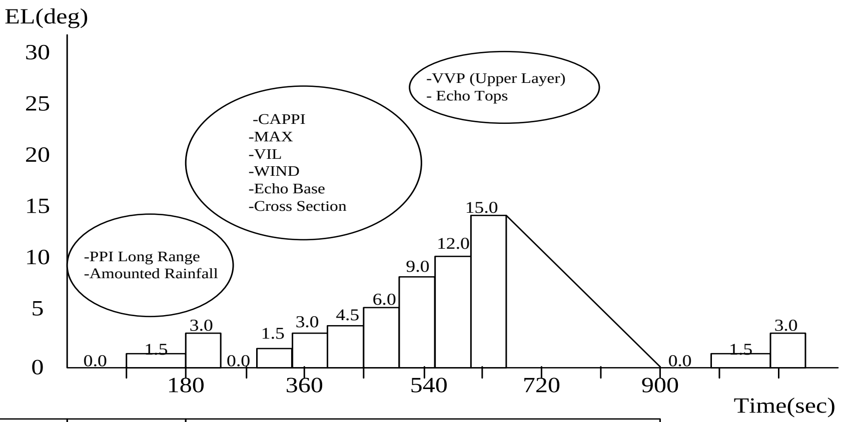
<u>Examination Items</u>

Observation purpose	: Weather Forecast, Aviation Weather Forecast, Management of River and Flood
Observation performance	: Observation Range and Elevation Angle (Height)
Observation interval	: Time Interval of observation
Generating product	: Kind of products in accordance with the operational purpose
Distribution interval and Amount of product	: Distribution interval and number of products in accordance with the network capacity.

An example of the observation sequence is shown below.
The observation time interval is set in fifteen minutes.

- During the first six minutes, the observation is done with low azimuth angle.
- Continuously, the observation is done increasing gradually the angle until fifteen degrees.

Note that Echo Tops and VVP products can obtain the accurate data with the high elevation angle of fifteen degrees.



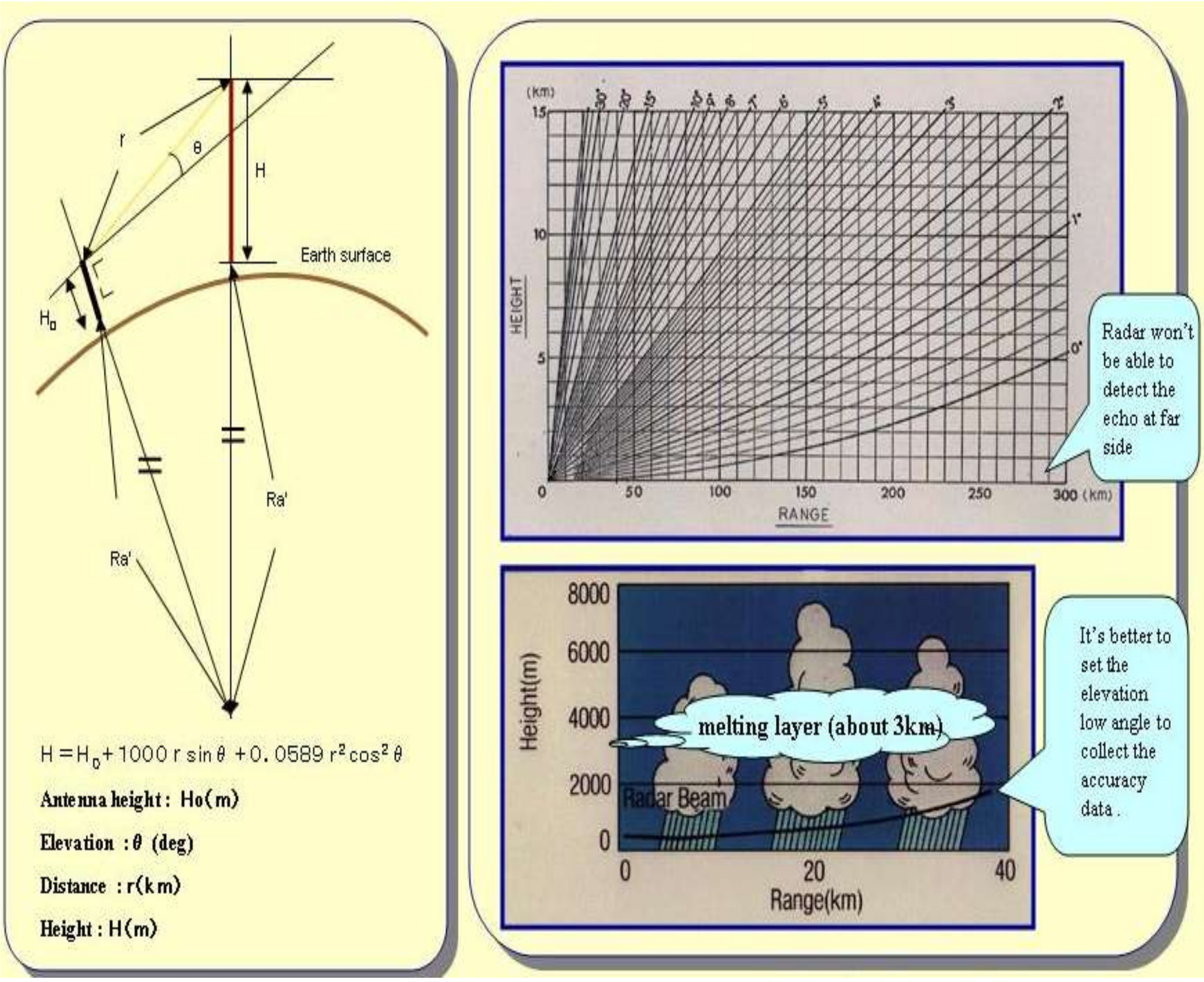
Mode	Intensity	Doppler
Rotation	1.5rpm	1.5rpm
PRF	320Hz	576/720Hz
Range	440km	200km

Example of Relation of Observation Sequence and Generating Products

5.2 Basic Radar Meteorology

5.2.1 Propagating Beam Height

The radar uses the straightness of the microwaves, however, in actual, the radar beam bend down a bit, at a radius of 4/3 the earth because of the atmospheric optics, air pressure, temperature, or water vapor. Thus, the horizon by the radar is about 16% farther than the geometrical horizon.

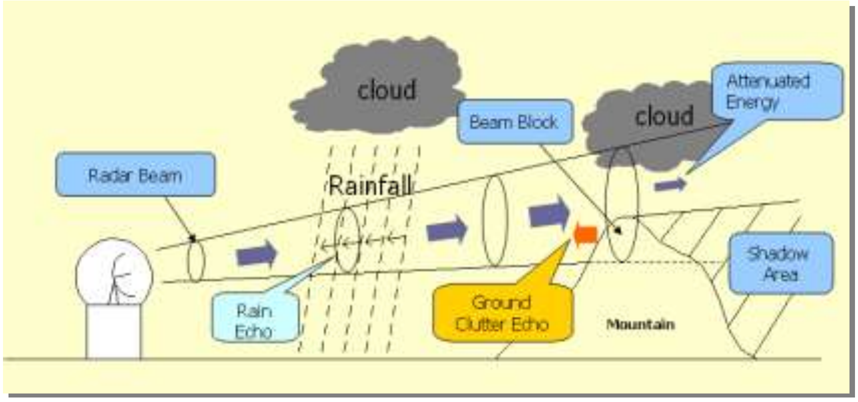


Propagating Beam Height vs. Range

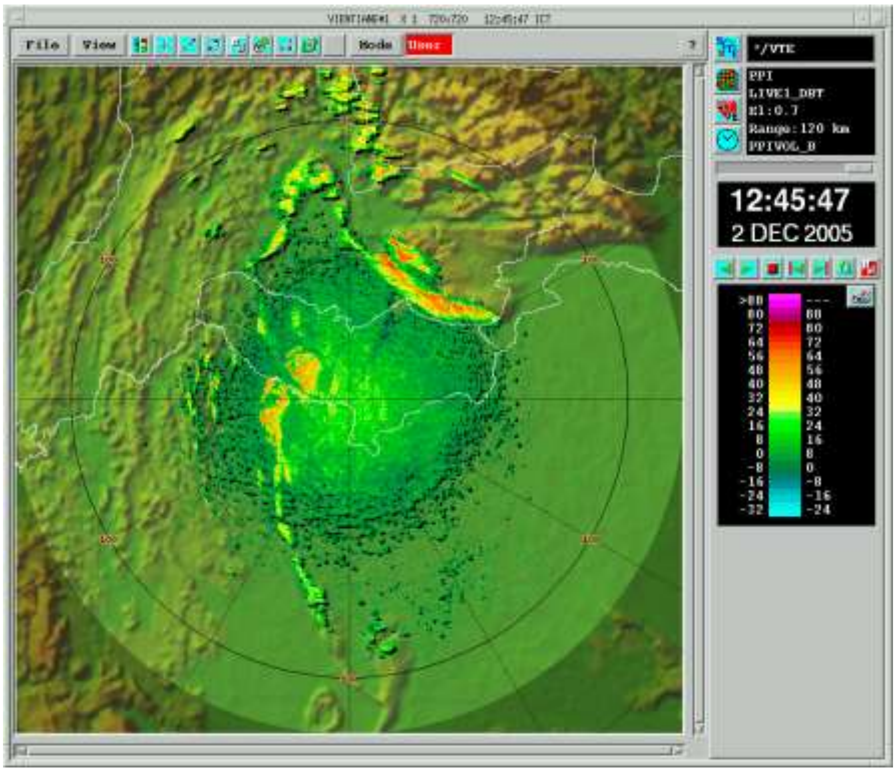
5.2.2 Ground Clutter and Shadow Area

The radar beams cannot bypass. Consequently, if there is any shielding on the propagation path, they cannot propagate to the back of the shielding so that the area that cannot be observed will appear. This area is called “Shadow Area (or Blind Area)”.

Also, if some part of the transmitted beam hits mountains or buildings, the total energy of it is attenuated in proportion to the blocked area so that the echo intensity from weather targets should be weak. That is called “Beam Blocking”.



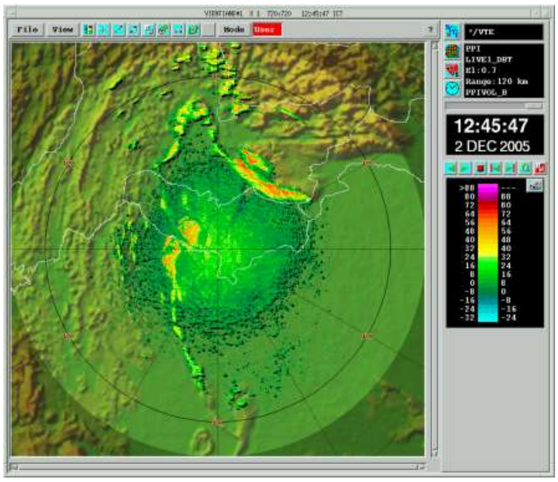
The echo from mountain or building (ground clutter) is usually much stronger than the weather clutter. The following figure shows an example of the ground clutter.

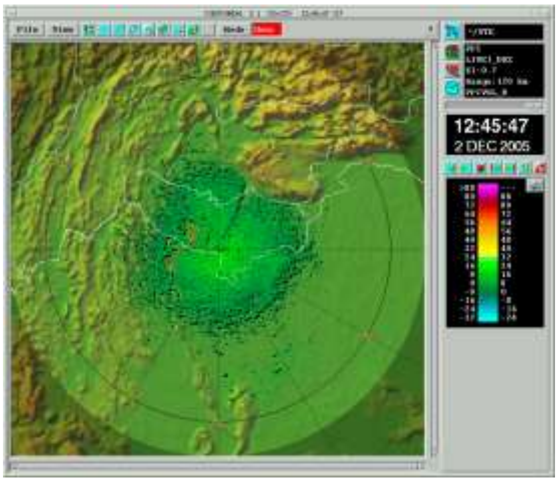


Example of Ground Clutter Observation Data Display

Clutter Filter

The ground clutter information is not necessary for the weather forecast or the river management, so that the ground clutter signal is removed by the clutter filter (FFT Clutter Filter is very common.) on the signal processing. The following two displays show the non-filtered and filtered images.



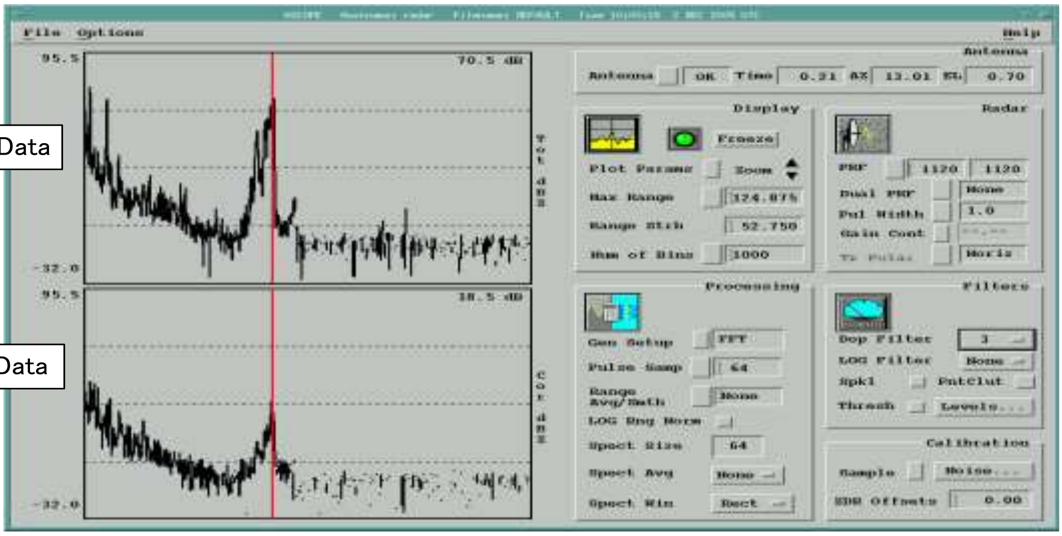


Unfiltered Data Display

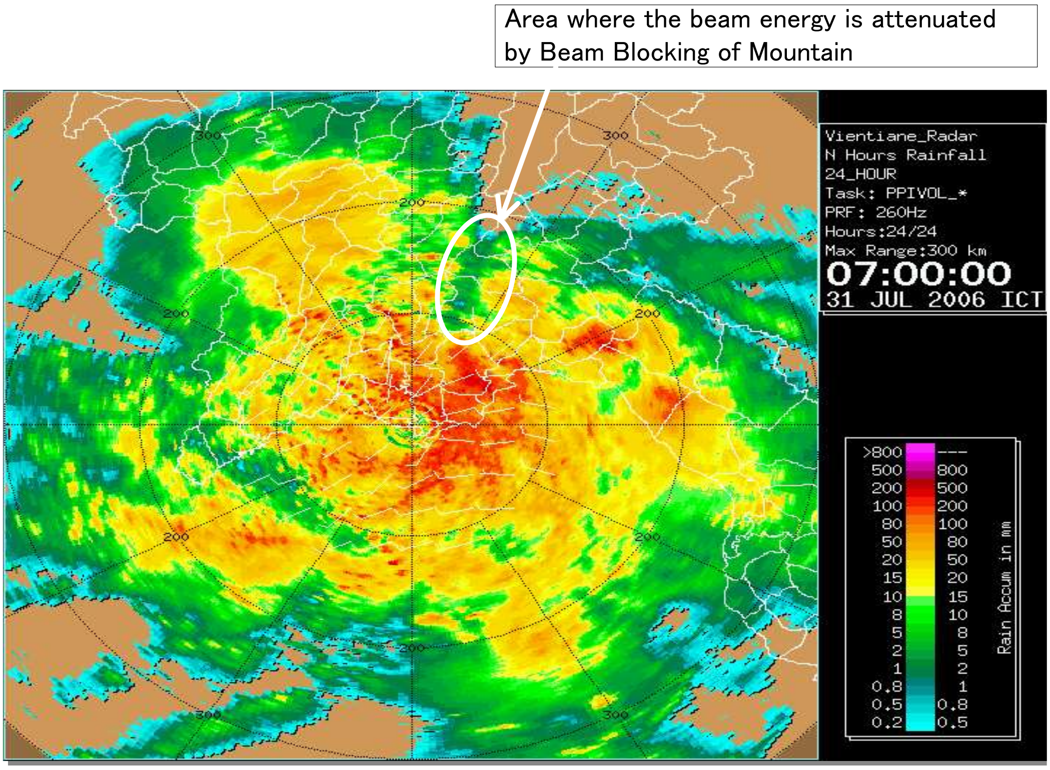
Filtered Data Display

Unfiltered Data

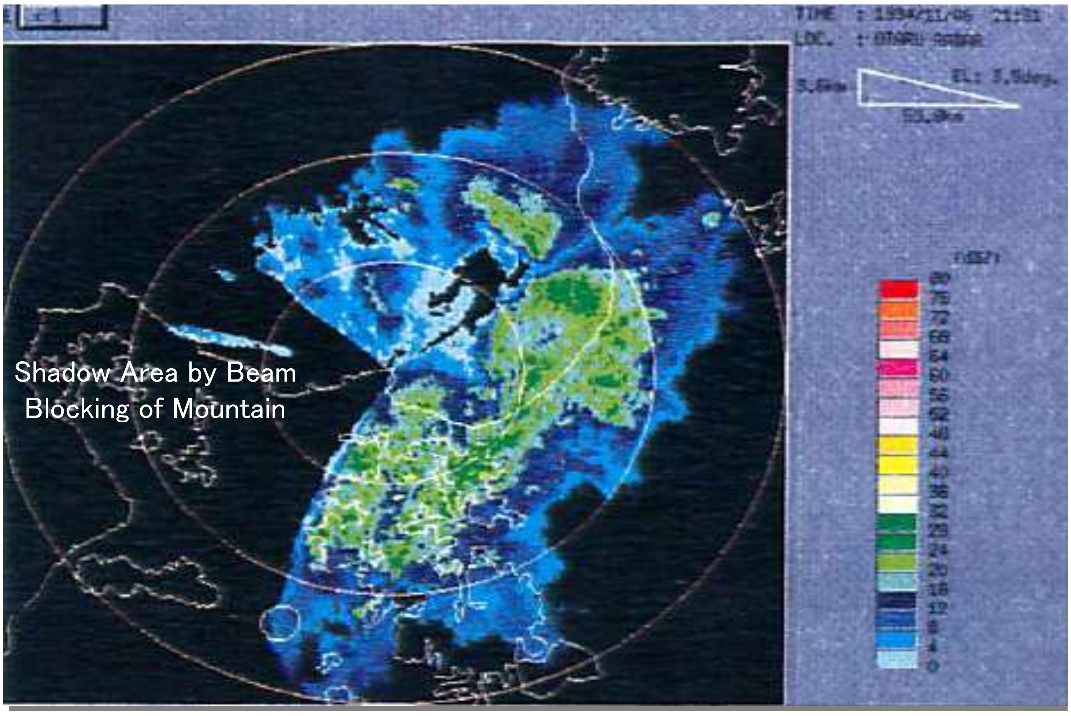
Filtered Data



Unfiltered and Filtered Data Comparison by A-Scope



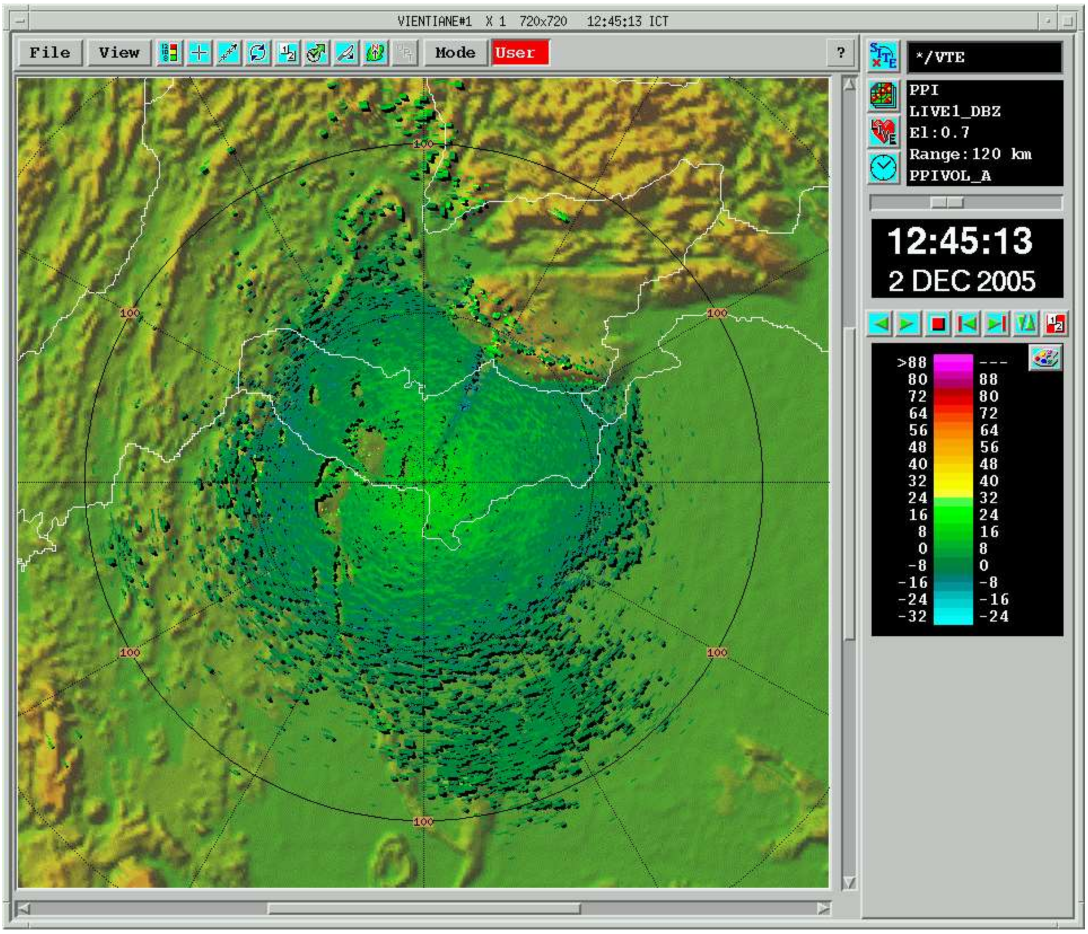
Example of Attenuated Data by Beam Blocking



Example of Shadow Area by Beam Blocking

5.2.3 Clear Air Echo

The high sensitive radar may receive some reflected wave from dust, powder dust or insects in the clear air. The following example image shows the echoes of 0 to 16dBz from dust or others.



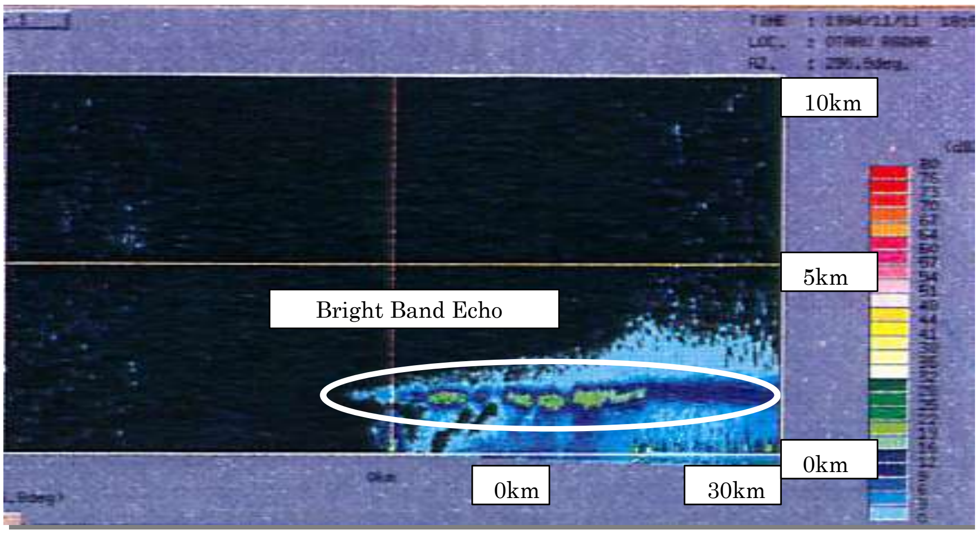
Example of Clear Air Echo Data Display

5.2.4 Bright Band

When snow melts into rain (the temperature is 0℃ in the sky), the region where this melting occurs often has a stronger reflectivity than snow above or rain below; this region was hence given the name of "bright band" (or Melting layers). On the display by PPI observation, it will appear with the shape of hydrometeors around the radar. When snowflakes start melting, snowflakes get covered by water and look like large raindrops so they reflect a lot. This will cause the fault data of the precipitation amount much larger than the actual amount.

The height of the bright band depends on the regions or seasons; in Japan, it is generally more than 3km in summer and less than it in winter.

The following display shows the example image of the bright band at 2km height.



Example of Bright Band Echo Data by RHI Scan

IRIS software corrects the effect by the bright band using the SRI product.

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