1. An Eye in the Sky

Satellite meteorology is the youngest branch of the science of meteorology, because before 1960 there were no weather satellites, except in science fiction. On 1 April 1960, the U.S. launched TIROS-1, and the meteorologists got their first view of the sky from space. Until then, they had been observing the sky mostly from the ground. TIROS-1 offered a vantage point to get glimpses of the earth and its atmosphere from the sky. That was a watershed event that changed the world of meteorology forever. The greatest advantage of weather satellites was that they could observe the great expanse of the oceans and inaccessible areas like mountains and deserts, where it had not been possible to establish observatories.

TIROS-1 was followed by more satellites, each one different from and better than the previous one. The early satellites carried television cameras, but they were soon replaced by radiometers which measured the radiation reaching the satellite from the earth, clouds and the atmosphere. All information that satellites provide us today is quantitative and even the familiar satellite pictures that we see on television or the internet are actually reconstructed from numerical data.

A weather satellite can surely be called an eye in the sky but it surely sees much more than what the human eye is capable of seeing. First of all, that depends on where the satellite is, or in what kind of orbit it is revolving around the earth. If it is near the earth, it sees a small area. If it is high up, it sees a wider area. The region of the earth that a satellite can view or cannot view depends upon the inclination of the orbit. In a polar orbit, the satellite sees all latitudes, while in a tropical orbit, it sees only the tropical belt. In a geostationary orbit, the satellite remains relatively stationary over a point on earth at a height of 36,000 km, from where it can keep a continuous watch on the earth's disc.

The satellite radiometer measures the radiation falling upon it in a narrow wavelength band or spectral region, which is called a channel. Higher the number of channels, greater is the information that can be obtained about the clouds, sea and atmosphere. If the spectral channel is narrow, less radiation falls on the satellite and the resulting image has less sharpness or poor resolution. Visible channels can make measurements only during daytime. Infrared channels can work at all times.

Designing and launching a weather satellite is a trade-off between science requirements and available resources, both technological and financial. Satellites can be launched in polar orbits with smaller rockets. Heavier satellites in geostationary orbits need advanced launch vehicles.

1.1 Electromagnetic Spectrum

By the term spectrum, we traditionally mean the seven colours of visible light, such as those seen in a rainbow. Nowadays, the term has come to be associated more with mobile communications. In scientific parlance, however, it refers to the entire range of wavelength or frequency of electromagnetic radiation, visible light or the microwave region being just small parts of it (Table 1.1). The characteristic spectrum of a given object is the pattern of electromagnetic radiation that it absorbs, transmits and emits.

Table 1.1 Electromagnetic Spectrum.

<table>
<tr><th>Wavelength</th><th></th><th>Wavelength</th><th></th></tr>
<tr><td>10^{-6} nm</td><td rowspan="5">Gamma Rays
(MeV)</td><td>1 mm</td><td>Millimetre
Waves (mm)</td></tr>
<tr><td>10^{-5} nm</td><td>1 cm</td><td rowspan="3">Microwaves
(cm, GHz)</td></tr>
<tr><td>10^{-4} nm</td><td>10 cm</td></tr>
<tr><td>10^{-3} nm</td><td>1 m</td></tr>
<tr><td>10^{-2} nm</td><td>10 m</td><td rowspan="8">Radio Waves
(MHz, kHz)</td></tr>
<tr><td>10^{-1} nm</td><td rowspan="3">X-Rays (Å)</td><td>100 m</td></tr>
<tr><td>1 nm</td><td>1 km</td></tr>
<tr><td>10 nm</td><td>10 km</td></tr>
<tr><td>100 nm</td><td rowspan="2">Ultra-Violet (nm),
Visible, Near Infra-Red (μ)</td><td>100 km</td></tr>
<tr><td>1 μ</td><td>10^3 km</td></tr>
<tr><td>10 μ</td><td>Thermal Infra-Red (μ)</td><td>10^4 km</td></tr>
<tr><td>100 μ</td><td>Far Infra-Red (μ)</td><td>10^5 km</td></tr>
</table>

Note: 1 nm (nanometre) = 10^{-9} m and 1 μ or micrometre or micron) = 10^{-6} m

The region of the electromagnetic spectrum with which we are most concerned in real life is the region of visible light, to which the human eye is very sensitive and in which the sun and stars emit the strongest radiation. In recent times, we are getting familiar with other wavelength regions as FM radio stations, mobile phones, satellite television or microwave ovens become more and more a part of our daily life.

The seven colours of the visible spectrum are identified by their wavelengths (Table 1.2). Radiation of wavelengths shorter than violet is called ultra-violet (UV) radiation. This has very high energy that can break chemical bonds, ionize molecules, damage skin cells or cause cancer. However, most of the UV radiation coming from the sun is absorbed by the layer of atmospheric ozone which resides in the higher atmosphere, and shields life on earth from its harmful effects.

Table 1.2 Wavelength Range of Visible Colours.

Colour	**Wavelength**	
	(nm)	**(μ)**
Violet	380-430	0.38-0.43
Indigo	430-500	0.43-0.50
Blue	500-520	0.50-0.52
Green	520-565	0.52-0.565
Yellow	565-590	0.565-0.59
Orange	590-625	0.59-0.625
Red	625-740	0.625-0.740

X-rays have wavelengths that are even shorter than UV, which are expressed in Å (Angstrom Units or 10^{-10} m). Gamma rays have wavelengths that could be as short as 10^{-15} m and it is more convenient to express their magnitude in terms of their energy levels which are of the order of KeV (Kilo electron volts) or MeV (Million electron Volts). X-rays and gamma rays have great penetration power and have applications in astronomy, radioactivity and other fields.

Towards the other end of the visible spectrum, radiation which has wavelength higher than red is called infra-red (IR). The IR region of the spectrum can be further sub-divided into near (NIR), short-wave (SWIR), middle (MIR), and thermal (TIR) with increasing wavelength.

Radiation with still longer wavelengths are called millimetre waves, followed by microwaves and radio waves. These again are further classified with respect to their frequency as given in Tables 1.3 and 1.4.

Table 1.3 Nomenclature of Microwave and Radio Wave Frequencies.

Abbreviation	Full Form	Frequency	Wavelength
EHF	Extremely high frequency (Microwaves)	30-300 GHz	1 mm-1 cm
SHF	Super high frequency (Microwaves)	30-3 GHz	1 cm-10 cm
UHF	Ultra-high frequency	3 GHz-300 MHz	10 cm-1 m
VHF	Very high frequency	300-30 MHz	1 m-10 m
HF	High frequency	30-3 MHz	10 m-100 m
MF	Medium frequency	3 MHz-300 kHz	100 m-1 km
LF	Low frequency	300-30 kHz	1-10 km
VLF	Very low frequency	30-3 kHz	10-100 km
VF	Voice frequency	3 kHz-300 Hz	100-10^3 km
ELF	Extremely low frequency	300-30 Hz	10^3-10^4 km

Table 1.4 Microwave Bands.

Band	Wavelength	Frequency
mm-Band	1-7.5 mm	40-300 GHz
Ku-K-Ka- Band	0.75-2.5 cm	12-40 GHz
X-Band	2.5-4 cm	8-12 GHz
C-Band	4-8 cm	4-8 GHz
S-Band	8-15 cm	2-4 GHz
L-Band	15-30 cm	1-2 GHz

1.2 Satellite Orbits

The design of an optimum orbit around the earth for a meteorological satellite is a complex process. There are two main classes of orbits, polar orbiting and geostationary, and they are complementary to each other. However, tropical and other new types of orbits have now come into use or are being considered.

There are certain classical laws that were originally formulated to explain the motion of planets in the solar system and their orbits around the sun. They are, however, very fundamental and general in nature and we now know that they are equally applicable to the orbits of artificial satellites placed around the earth and other planets or moons in the solar system. Weather satellites therefore follow the same physical laws as planets in the solar system.

The time period, speed and acceleration of an artificial satellite orbiting the earth are not dependent upon its mass. So theoretically speaking we can put into orbit as big a satellite as we wish, the only practical constraint being that of lifting it into space with the rockets that we have.

For a height of 1000 km, the period of revolution is 105 min, and this is a popular choice for meteorological satellites. If the time period is set at 24 hr, the height of the satellite will work out to be about 35,840 km above the earth's surface. Such an orbit is called geosynchronous as the satellite matches the angular velocity of the earth at this height.

Figure 1.1 shows the relative orientations of polar, geostationary and tropical orbits around the earth. A satellite in a polar orbit crosses the equator twice a day, but views the poles in every orbit. With every orbital revolution, a new region of the earth comes under its view because of the earth's rotation. A global picture thus emerges over a period of time.

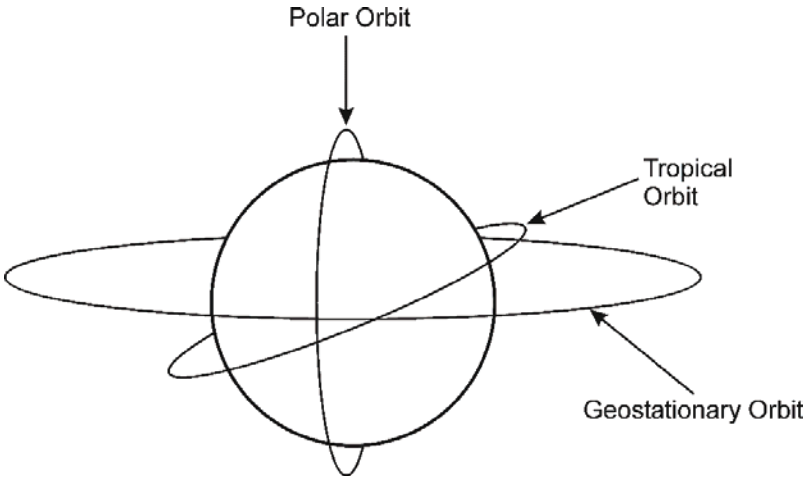

Figure 1.1 Relative orientations of polar, geostationary and tropical orbits around the earth.

A polar orbiting meteorological satellite is typically in a circular orbit with an altitude of about 850 km and a period of 100 minutes. This results in the satellite scanning a 3000-km wide swath on the earth's surface which can fully cover the polar regions. The satellite completes 14 orbits in a day, and every point on the earth is viewed at least twice a day.

When a satellite is placed in a circular orbit with a radius of 42,400 km or a height of 36,000 km above the earth’s surface, it will circle round the earth with the same angular velocity as that of the earth. At that specific height, it will complete one orbital revolution around the earth in 24 hours. Such a satellite is called a geosynchronous satellite. A special case of a geosynchronous satellite is one in which its orbit is in the equatorial plane. In a relative sense, it will appear to remain stationary above a given point on the equator. Such a satellite is called a geostationary satellite and it can provide a continuous earth view from about 80º N to 80º S, but not the polar regions. Practically, however, the useful view is limited to about 60º around the sub-satellite point, as the image outside it gets distorted. A constellation of 5 or 6 geostationary satellites spaced around the equator can together give a near-global picture. Geostationary satellites are ideal for communications purposes and continuous monitoring of the weather over the region within their view. Considerations of orbit stability demand that a geostationary satellite be placed only over a point on the equator and not above any other latitude.

1.3 Weather Satellite Payloads

The basic payload carried by the TIROS-1 satellite in 1960 was just a television camera that relayed to the ground whatever it saw of land, ocean and clouds. With every successive meteorological satellite launched over the last four decades by different countries, there have been rapid advances in satellite instrumentation and technology, serving various areas of application.

After the end of the TIROS satellite series, TV cameras were given up as a means of observing the earth’s cloud cover and replaced by scanning radiometers which have become more and more advanced as time went by. Scanning radiometers do not give snapshot pictures but images are constructed from the digital data transmitted by them over a span of time required to complete the scan. In brief, a meteorological satellite measures only radiation. What you see in the satellite image depends upon the spectral band in which the satellite radiometer has received radiation, the sensitivity and response of the sensor, the height from which the satellite is viewing the earth, the time of the scan and such other factors.

While the use of Charge Coupled Devices (CCDs) has been common in remote sensing satellites for land resources applications, India was the first country to fly a 3-band CCD-based imager in geostationary orbit on its INSAT-2E satellite to complement the VHRR. A similar instrument was also flown on the INSAT-3A satellite. It provides co-registered images of the earth in VIS 0.62-0.68 μ, NIR 0.77-0.86 μ and SWIR 1.55-1.69 μ regions of the spectrum. The ground resolution of these images at the sub-satellite point is 1 × 1 km for all the three bands.

Microwave remote sensing has always been recognized as a powerful tool for meteorological and oceanographic applications, because of its ability to measure water vapour and liquid water even in the presence of most clouds. However, it did not come into popular use due to the poor ground resolution of microwave images and because land surface emissivity in the microwave region is high and variable. Moreover, microwave sensors have to be flown on low earth orbiting satellites and it has not been possible so far to place them on geostationary platforms because of the weak microwave signal strength.