

# METSAT – a unique mission for weather and climate

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*The recent successful launch of METSAT (meteorological satellite), a dedicated satellite for meteorology, has been unique in many ways. With the heralding of the satellite era in the early 80s with the INSAT series, weather services received impetus in terms of operational meteorological data covering the Indian region. The operational products included cloud cover, sea surface temperature, cloud motion vectors, outgoing longwave radiation, quantitative precipitation estimation, etc. The satellite data also helped in improving the skills in forecasting using weather prediction models. The need for a dedicated satellite for meteorology spurred the Indian Space Research Organization to take up developmental efforts, and the launch of METSAT is the culmination of these efforts. The METSAT payload included water-vapour channel, which is a key parameter for monsoon studies. The future missions with advanced payloads such as atmospheric sounders and radiation budget etc. auger well for the meteorological services in the country.*

THE advent of satellite-based observations, over the past two decades, has added new dimensions to the study of atmosphere and weather systems. The synoptic coverage on a repetitive basis as provided by satellites, is ideally suited to study weather-related atmospheric processes on different scales. The recent advances in satellite sensing and parameter retrieval in terms of high resolution, multi-spectral bands covering visible, infrared and microwave regions with enhanced radiometry have made space data an inevitable component in weather monitoring and dynamic modelling. The satellite data play a critical role in improved definition of initial and boundary conditions for weather-prediction models. The impact of satellite data is phenomenal in certain areas of meteorological applications such as short-range forecasts, cyclone monitoring, and aviation forecasts, especially in the tropics.

Indian forays into satellite meteorology started with the launch of the Indian National Satellite (INSAT) in the early 80s. The INSAT series consists of multi-purpose satellites with payloads for communication, broadcasting and meteorology services, orbiting in geostationary orbit. INSAT-1 series consisted of four satellites and was followed by INSAT-2 series which was indigenously developed, with improved Very High Resolution Radio-

meter (VHRR). With the operational use of INSAT data and the growth of meteorological services and the emerging data requirements, the need for dedicated meteorological satellites has been projected by users. The Indian Space Research Organization (ISRO) initiated work in this direction and the recent launch of METSAT is the successful culmination of these efforts.

## Mission objectives

The METSAT mission objectives are:

- Round-the-clock synoptic images of weather systems, including severe weather conditions, cyclones, etc. and to provide operational geophysical parameters such as cloud cover, sea surface temperature, snow cover, cloud motion vectors, outgoing longwave radiation and quantitative precipitation estimation.
- Collection and transmission of meteorological, hydrological and oceanographic data from remote areas through data collection platforms.

With the successful launch of METSAT on 12 September 2002 and speedy operationalization, all essential steps towards realizing the above objectives have been realized.

## PSLV-C4/METSAT mission

Polar Satellite Launch Vehicle (PSLV), the operational launcher developed by ISRO accomplished its sixth successful mission in the C4 flight which took off on

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12 September 2002 from Satish Dhawan Space Centre, Sriharikota. The significance of this flight is that it was a Geosynchronous Transfer Orbit (GTO) mission performed for the first time by PSLV, which has proved itself as a reliable workhorse of ISRO through a string of six successful flights in a row. PSLV was essentially developed to carry out launch of Indian remote sensing satellites to polar orbit<sup>1</sup>.

While the basic vehicle configuration of this four-stage vehicle with six solid strapon motors has, by and large remained unaltered from PSLV-D1 to C4, the vehicle performance has steadily improved over the years through implementation of well thought out payload enhancement measures. Having enhanced the payload capability of PSLV for Sun Synchronous Polar Orbit (SSPO) mission to about 1350 to 1400 kg level, its potential to perform a GTO mission was assessed to be around 950 kg. However, based on the demand put forth for a minimum requirement of 1050 kg mass for an exclusive Meteorological Satellite (METSAT) to be deployed in GTO, several improvements were implemented on PSLV to achieve this target.

The major performance-enhancing element in C4 is the replacement of existing third stage motor (PS3) by a more powerful version called as High Performance PS3 (HPS3). Other elements are the 500 kg additional propellant loading in PS4 liquid upper stage and inert mass reduction in equipment bay/inner branch structures. The HPS3 motor is an optimized version which is comparable in performance and mass ratio to contemporary motors of its class, globally. The special features included:

- Optimized composite motor case.
- Optimized insulation.
- Reduced throat, increased area ratio, lighter nozzle of motor.
- Flex nozzle with 2° actuation.

To achieve the desired orbit, high performance of the vehicle was ensured through improved mass ratio, low burn-rate propellant and increased burn duration and payload gain through inert mass reduction, propellant increase and higher *Isp*.

Several new systems were introduced and changes made, such as new payload adapter for accommodating METSAT, propellant feed lines and circuits in PS4 modified for weight reduction, etc. Specific changes introduced to meet the GTO mission requirements are (i) launch azimuth set at 102° and a roll manoeuvre after lift-off; (ii) flight sequence changes such as delay in heat shield separation, PS2 cut-off based on guidance command; (iii) auto-pilot design tuned towards changes such as HPS3, L2.5 stages. All the above-mentioned changes made in PSLV-C4 went through rigorous reviews and testing. Figure 1 depicts the METSAT in the PSLV envelope.

Mission specifications of PSLV-C4 that deployed METSAT in a GTO in direct ascent mode are:

Perigee altitude	≥ 180 km
Apogee altitude	= 36,000 km
Inclination	= 17.8°
Argument of perigee	= 179°

The launch azimuth for PSLV-C4 was set at 102° compared to 140° for C3. Since the launch pad azimuth is 135°, it required a roll manoeuvre to align the flight path immediately after lift-off.

After METSAT separation from PSLV vehicle, the stage was manoeuvred in yaw by 60°, and the passivation function was initiated by sequentially opening the tank ullage to the ambient by firing pyro valves. This was implemented for the first time in PSLV-C4 to vent out and remove all energetics from the spent PS4 so as to avoid an explosion and generation of debris in orbit. The mission design of PSLV-C4 was thus aimed at meeting two major constraints of maximizing the payload capability and managing the impact of the spent stages, especially the PS3 stage within the safe corridor.

#### *Unique aspects of METSAT*

The development and realization of METSAT spacecraft bus with a lift-off mass of 1055 kg and mission life of 7 years was a challenging task. This new 1000 kg class bus has been configured around a new Carbon Fibre Reinforced Plastic (CFRP) cylindrical structure with use of indigenously developed propellant tanks, optimized con-

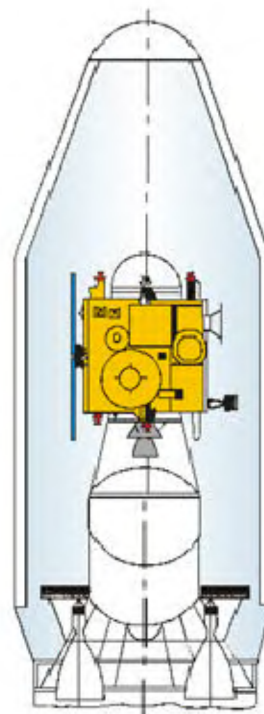


Figure 1. METSAT in PSLV-C4 envelope.

trol thrusters, bus sub-systems with proven flight heritage and meteorological payload derived from earlier INSAT-missions, inclusive of modifications for reliable operation. METSAT spacecraft has several novel features imple-



Figure 2. Spacecraft under dynamic testing.

mented in its configuration due to the lift-off mass constraints imposed by PSLV launch vehicle.

The spacecraft structure was configured with CFRP design to achieve a structure that is light and meets various design requirements. Aluminum honeycombs have been used to a minimum extent. CFRP structure is coated with electrically conductive black paint to meet electrical grounding requirements.

In order to de-couple the uncertainty in VHRR radiative cooler performance associated with the solar sail/boom configuration in earlier missions, METSAT configuration has been simplified with no sail/boom the north side of the spacecraft and with one solar array deployed on other side of the spacecraft. METSAT uses linear, controlled, higher capacity-sized magnetic torques to take care of solar radiation pressure imbalances exerted on solar panel. The METSAT spacecraft under dynamic test is shown in Figure 2.

The solar panel is 2.15 m × 1.8 m in size using GaAs/Ge technology and generates 640 W of power at BOL equinox season. Power available at EOL summer solstice is about 500 W against a requirement of 460 W. The Solar Array Driver Assembly (SADA) slip rings and drive mechanism are modified to meet the power transfer and drive requirements, and it is mass-optimized (Figure 3).

Some of the unique factors of the spacecraft are:

- A new element called planar array antenna is used to transmit VHRR and Data Relay Transponder (DRT) data.

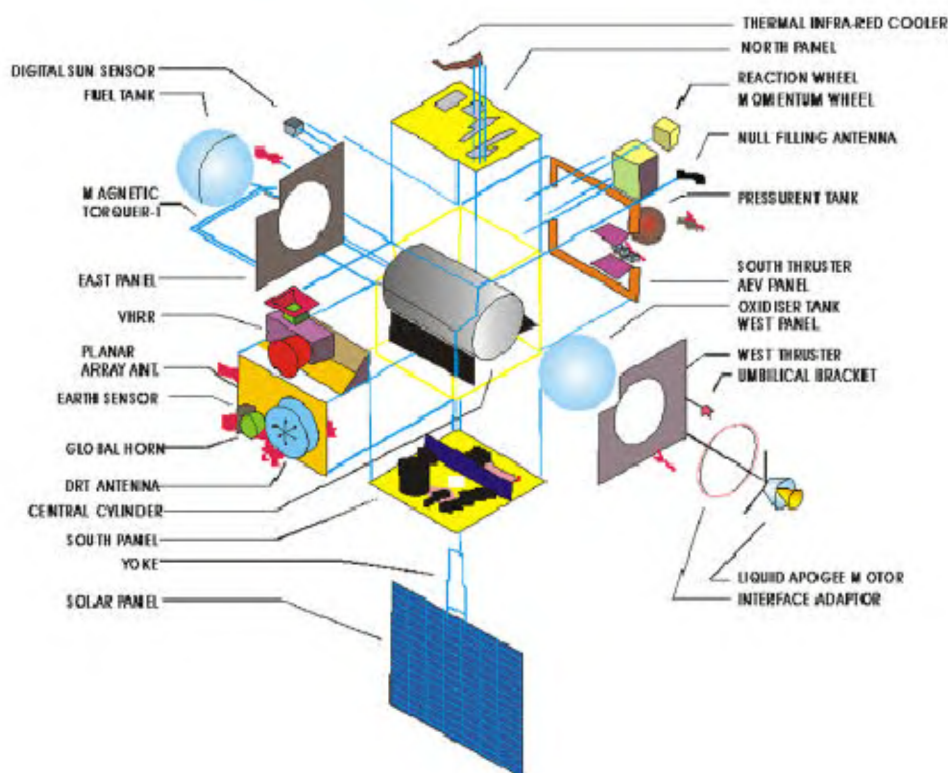


Figure 3. Disassembled view of METSAT.

- It has a 440 N apogee motor and only twelve RCS thrusters with a distribution of a set of four each on east, west and south faces, compared to earlier INSAT missions with 16 RCS thrusters.
- It has a single power bus and 18 AH battery for optimizing the weight.

### Payloads on-board METSAT

The payloads on the dedicated meteorological satellite consist of VHRR and DRT. The VHRR has three bands comprising visible operating in  $0.55\text{--}0.75\ \mu\text{m}$ , water vapour (WV) in  $5.7\text{--}7.1\ \mu\text{m}$  and thermal infrared (TIR) in  $10.5\text{--}12.5\ \mu\text{m}$ , to provide both day and night coverage. The radiometer employing a bi-axial scan mechanism for coverage in the east–west and north–south direction is designed to operate from body-stabilized geostationary satellite. The ground resolution of VHRR at the sub-satellite point is nominally  $2\text{ km} \times 2\text{ km}$  in the visible and  $8\text{ km} \times 8\text{ km}$  in the WV/TIR bands. The operational elements of the VHRR payload are shown in Figure 4.

The incoming solar radiation is reflected onto an 8-inch aperture R-C telescope by a beryllium scan mirror mounted at  $45^\circ$  to the optical axis. The optical system includes a gold-film dichroic beam-splitter that transmits visible light energy and reflects WV/TIR energy, so that the radiation from the earth is channelized to the visible and IR focal planes simultaneously. The visible band detector configuration consists of two staggered arrays of four silicon photodiodes each; while two sets of mercury–cadmium telluride detector elements operating nominally at  $100\text{--}110\text{ K}$  sense the WV/thermal radiation.

The scan mirror is mounted on a two-axis, gimbaled scan mechanism system to generate a two-dimensional image by sweeping the detector instantaneous field of

view across the earth's surface in east to west (fast scan) and north to south (slow scan). The three modes of operation are given in Table 1.

The visible and WV/TIR detector outputs are individually amplified, band-limited and digitized to ten bits. The digitized data along with housekeeping information and calibration data are transmitted in the extended C-band. Some of the unique characteristics of the VHRR performance are given in Table 2.

The DRT is configured in METSAT payload to receive signal in circular polarization in UHF. The DRT system is designed to receive the data from unattended data collection platforms.

### METSAT mission: Launch and early orbit phase

The launch window was selected based on the spacecraft requirements like avoiding VHRR radiative cooler directly looking at the sun, and the favourable geometry for calibrating on-board Gyros. The lift-off of PSLV occurred at  $10:23:40\text{ h}$  from Satish Dhawan Space Centre, Sriharikota and the satellite was separated after reaching orbit-injection conditions at  $10:44:31\text{ h}$ . The spacecraft was injected into an orbit of  $216.4\text{ km}$  perigee,  $34641.5\text{ km}$  apogee and at an inclination of  $17.67^\circ$ .

The most important activities during the early orbit phase operations are:

- Orienting the solar panel towards the sun for providing necessary power.
- Calibration of on-board Gyros.
- Perigee raising and inclination correction to achieve near Geo-Synchronous Orbit (GSO).
- Station acquisition manoeuvres to reduce the drift and to bring the satellite to GSO at its intended orbital slot.

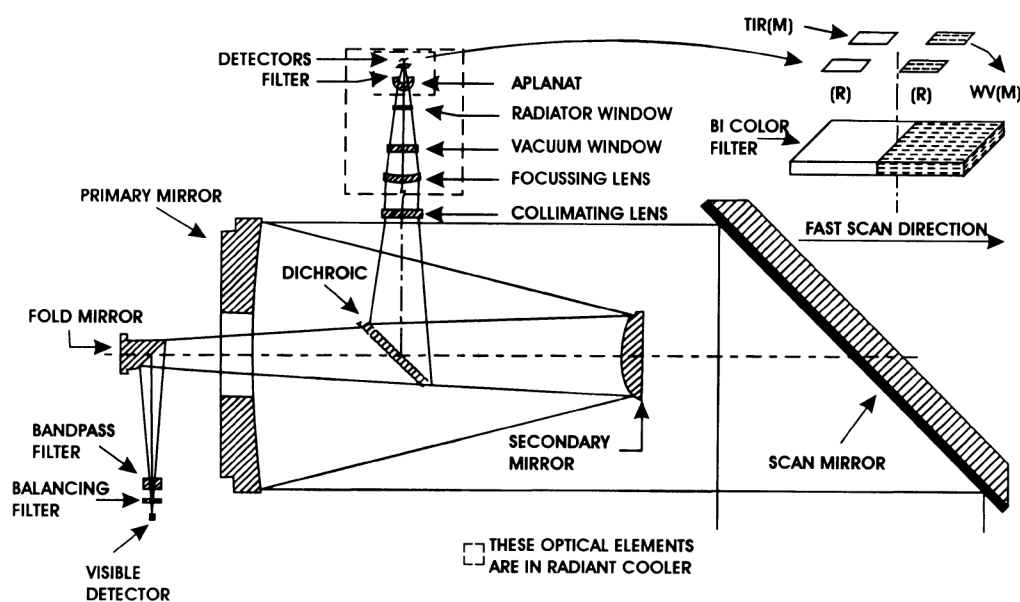


Figure 4. Schematic of the VHRR payload.

- Establishing normal on-orbit earth lock mode in three-axis stabilized configuration.
- Payload turn-on, and the scan operations for earth-imaging.

The deployment of on-board solar panel was completed within 29 s after separation of the satellite by an automatic sequencer initiated by separation signal. Telemetry data from the spacecraft were received by the Ground Station, ISRO at Biak for 9 min, which covered 5 min after separation of the satellite. The data confirmed separation of the spacecraft and deployment of the solar panel.

All the early orbit mission operations were carried out from Master Control Facility (MCF), Hassan. As the period of revolution of the injection orbit was 10 h 09 min, MCF did not have continuous visibility in the GTO. To have continuous data for satellite operations, INMARSAT Network Stations in Lake Cowichan (Canada), Fucino (Italy), Beijing (China) were utilized for telemetry, tracking and command (TTC) operations.

### Orbit-raising operations

Firing of the on-board Liquid Apogee Motor (LAM) was planned to be carried out at second apogee, fourth apogee and fifth apogee in three stages. MCF had clear visibility for all the three critical operations. Table 3 gives the details of the Apogee Motor Firing (AMF) operations.

A total velocity of 1690 m/s was imparted to the spacecraft after the three AMF operations, for raising the spacecraft to geosynchronous orbit. The orbits before and

after each AMF are shown in Figure 5 (orbits are drawn to scale).

### Three-axis stabilization

In the transfer orbit, METSAT attitude was maintained using thrusters. In this phase the spacecraft was in sun-oriented attitude to ensure power generation. On 16 September 2002, momentum wheels were turned on and selected as actuator in the control-loop to maintain the attitude. Magnetic torquers were used for fine control of yaw. In this configuration the spacecraft is earth-oriented, and the solar array configured to track the sun. After appropriate station acquisition manoeuvres, by the evening of 21 September 2002, nine days after its launch, METSAT was positioned to its orbital slot of 74° E longitude.

The propellant consumption for the operations was optimal, leaving 105 kg on-board, which will ensure 7 years design-life of METSAT.

### Payload turn-on and initial scans

METSAT VHRR works in three spectral bands; visible, WV and TIR. The patch on which IR detectors were placed had to be carefully controlled at 100 K for proper functioning of IR channel. VHRR patch area, which is exposed to the space on the northern face of the spacecraft, was heated from 12 to 19 September (approximately for 168 h), so that the contaminants from the spacecraft outgassing do not condense and settle in the IR detector area. In addition to the VHRR, METSAT also carries a DRT for collection of meteorological data from the unattended data collection platforms to Meteorological Data Utilization Centre (MDUC), India Meteorological Department, Delhi.

The first VHRR scan was commanded on 19 September at 07 : 14 GMT to take full earth disk imagery in the visible spectral band. The quality of the imagery at MCF

**Table 1.** Imaging modes of METSAT VHRR payload

Imaging mode	Coverage	Repeatability (min)
Full scan	20° N–S and 20° E–W	33
Normal scan	14° N–S and 20° E–W	23
Sector scan	4.5° N–S and 20° E–W	23 (3 times)

**Table 2.** VHRR specifications

Channel	Number of detectors	Modulation transfer function	Dynamic range	Noise performance
Visible	Four with four redundant	> 0.23 approx.	0–100% albedo	6 : 1 min at 2.5% albedo
Water vapour	One with one redundant	> 0.21 approx.	4–340 K	0.25 K at 300 K
Thermal	One with one redundant	> 0.21 approx.	4–320 K	0.5 K at 300 K

**Table 3.** Apogee Moptor firing operations

Operation	Date	Delta V imparted (m/s)	Orbit (perigee and apogee altitudes)	Period
Pre AMF 1	–	–	219.5 × 34483.1 km at $i = 17.67^\circ$	10 h 09 min
AMF 1	13 September 2002	939.6	12144 × 34492.1 km at $i = 4.68^\circ$	14 h 08 min
AMF 2	14 September 2002	702.2	34441.1 × 34535.2 km at $i = 0.44^\circ$	22 h 50 min
AMF 3	15 September 2002	22.5	34486.8 × 35676.4 km at $i = -0.495^\circ$	23 h 20 min



met all the specifications. Detailed in-orbit tests on VHRR and DRT payloads were carried out from 20 to 24 September 2002, and the results matched fully with the specifications. The mission operations could be completed in 11 days as all the sub-systems performed optimally.

### *Potential applications of METSAT data*

The METSAT data are received and processed at the MDUC. Reception facility also exists at MCF, Hassan and Space Applications Centre, Ahmedabad for sensor health monitoring, satellite housekeeping and in-house R&D activities.

Figure 6 shows the first image from METSAT VHRR in visible channel.

### *Operational applications of METSAT data*

The foremost application of data from METSAT will be towards operational services in terms of the following<sup>2</sup>:

- i. Watch and monitor the growth of weather phenomena like cumulonimbus cells, thunderstorm, fog, etc. and their decay.
- ii. Track movements of migrating systems such as tropical cyclones, monsoon depressions, western disturbance, etc.
- iii. Identify and locate primary synoptic systems like surface lows, troughs/ridges, jet streams, regions of intensive convection, inter-tropical convergence zones, etc.
- iv. Monitor onset and progress of monsoon systems.
- v. Detect genesis and growth of tropical cyclones and monitor their intensification and movement till land-fall.

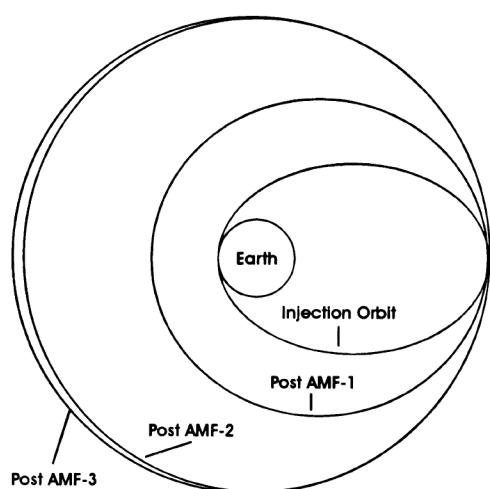


Figure 5. Pre- and post-AMF orbits of METSAT.

In this context, the capability of METSAT payload to provide data in three imaging modes is found to be of relevance. These special imaging modes permit scanning of intense weather systems frequently, to get insights into the dynamics of the atmosphere. The higher resolution of 2 km in visible and 8 km in thermal IR permits study of mesoscale events.

Besides the monitoring capability through imageries, the METSAT payloads are capable of providing several operational parameters for assimilation in weather prediction models and atmospheric research. Some of the key parameters derived from METSAT VHRR data are:

- i. Cloud Motion Vectors (CMV) derived using three half-hourly images by analysing movement of cloud tracers through a detailed pattern-matching process. The CMVs are derived for two layers, viz. lower troposphere and upper troposphere using visible/thermal images, and with the availability of WV channel, wind vector is also derivable for the mid-troposphere. The CMVs derived thrice daily besides being disseminated to the global data system, are used to study monsoon flow, formation of eddies, cross-equatorial flow, offshore vortices, etc.
- ii. Outgoing Longwave Radiation (OLR) derived from thermal infrared data using physical and statistical algorithms, based on radiative transfer principles. The OLR derived using 3 hourly data on daily/weekly/monthly time-scales is an important indicator of convective activity, and has direct bearing to weather development. The OLR is a key parameter in monsoon onset assessment and has been well correlated with rainfall patterns.



Figure 6. First image from METSAT VHRR visible band, 19 September 2002.

- iii. Quantitative Precipitation Estimation (QPE) based on the Arkin's method<sup>3</sup> using 3 hourly cloud-top temperature accumulated over  $2.5^\circ \times 2.5^\circ$  latitude/longitude grids and correlated to rainfall. The QPE over the oceans fills up an important gap in rainfall measurements and is a key input to numerical weather models.
- iv. Sea Surface Temperature derived from TIR band data. Though of coarse resolution (estimated accuracy of about 1.5 K), it is found to be well correlated with thermal fronts and upwelling associated with monsoon currents.
- v. WV channel data ( $5.7\text{--}7.1\ \mu\text{m}$ ) providing information on mid-tropospheric WV and flow patterns associated with incursion of WV during monsoon onset. A combination of visible/thermal and WV data is found to be useful in cloud characterization and identification of convective regions.

### Applications of WV band data

Imaging in the WV channel greatly enhances insight into atmospheric circulation and humidity in the middle atmosphere<sup>4</sup>. The physical basis of WV band is the strong absorption of emitted terrestrial radiation by atmospheric WV. Regions of high upper tropospheric humidity appear as cold (bright) and low humidity as warm (dark). The WV channel peaks at 400 mb and the radiance is used for computation of mid-tropospheric moisture content<sup>5-7</sup>. The cloud patterns which appear as separated from each other in visible and thermal images can be recognized as part of the same air mass based on WV image. WV structure also correlates well with atmospheric motion and thus can be used to delineate jet cores. Thick cumulonimbus clouds with anvil appear prominently in both WV and thermal data. WV appearing as plumes indicates heavy rainfall regions, leading to flash floods.

Other applications of WV data are:

- Forecasting track of cyclones, such as recurvature indicated by the moisture envelope around the cyclone field<sup>8</sup>;
- WV plumes appearing as a tongue or stream of moisture, indicating cyclonic circulation leading to heavy rainfall;
- Filling of gap in upper air observations (low density of radiosonde stations in tropics).

### Monsoon studies using METSAT data

Considering the studies in the past using INSAT data, the data from METSAT are expected to contribute to several aspects of monsoon research. The addition of WV channel in the VHRR payload is useful in studying (i) inter-tropical convergence zone dynamics, (ii) large-scale moisture build-up prior to monsoon onset, (iii) low frequency modes such as the 40-day oscillations<sup>9</sup> in monsoon circulation. The parameters such as cloud-motion vector, SST and OLR are used for initial fields in models with improved forecasts.

### Future meteorological missions

Several satellite missions have been planned globally as well as by India to support the operational needs and ongoing research efforts. The future METSAT missions will carry improved VHRR and vertical sounders for temperature/humidity profiles. The Megha-Tropiques mission slated for launch in 2004 will be a joint project by ISRO and CNES, France with the objective of studying the water cycle and energy exchanges in the tropics. With an equatorial inclined orbit, the satellite will have high repetitivity over tropical areas, thus providing frequent sampling. The Megha-Tropiques payloads consist of Sca Rab for radiation budget measurements in short

**Table 4.** Future missions for meteorology

Satellite/country	Sensors	Parameters
INSAT 3D/India	VHRR (Vis/TIR/WV) Sounder (multi-ch)	Cloud Motion Vectors, SST, temperature/humidity profiles, OLR, QPE
Megha-Tropiques/ India-France	Sca Rab, SAPHIR, MADRAS	Radiation budget, humidity profile, precipitation, cloud ice particles, convection
NOAA-N/USA	AVHRR, ATOVS, AMSU	Radiation budget, temperature/humidity profile
EOS-PM/Europe	AIRS, MODIS, ALT	Humidity profile, ozone column, vegetation index, sea level
METOP-1/Europe	IASI, AVHRR-4, ASCAT, GOME-2	Temperature/humidity profile, ozone profile, SST, sea-ice cover
ADEOS-2/Japan	MHS, IMG, ILAS-2	Temperature profile, ozone profile
GIFTS/USA	Fourier Transform Spectrometer	High resolution, 3D observations of meteorological parameters
SMOS/Europe	MIRAS (microwave imaging)	Soil moisture, ocean salinity
CALIPSO/USA	LIDAR (3-channel Radiometer)	Cloud properties, aerosol, radiative flux
CLOUDSAT/USA	Radar (94 GHz)	Radiative properties, cloud properties, precipitation
GPM/USA-Japan	Precipitation Radar, Microwave Radiometer	Global precipitation, rainfall structure

and longwavelengths, SAPHIR with six channels for atmospheric WV distribution and MADRAS operating in microwave region (89 and 157 GHz) for study of convective systems. The data from this mission are expected to provide better insights into the convective processes in the tropical regions. Table 4 summarizes the future space missions of direct relevance to our region.

With several advanced missions planned in the near future providing operational meteorological parameters, efforts will be focused towards assimilation of the space data in prediction models and to achieve improved forecasts in short, medium and long ranges.

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## Fields Medals and Nevanlinna Prize: 2002

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*John Charles Fields, a Canadian mathematician who was Secretary of the ICM (International Congress of Mathematicians) held at Toronto in 1924, mooted in 1931 the idea of two medals to be awarded at successive ICMs (held once in four years) for outstanding achievements in mathematics, intended at the same time to be an encouragement for further achievement. When he passed away in 1932, in his will he had left his estate for the prizes. Fields apparently felt strongly about the lack of Nobel Prize in mathematics, which he tried to make up for with his limited means, and the prizes, though modest in monetary value, have held great prestige and emotional appeal to the mathematical community, similar to the Nobel Prizes.*

*Two to four medals are now awarded at each ICM, to mathematicians under the age of 40 (keeping in view the twin objectives). At the latest ICM held in Beijing in August this year, the medals were awarded to Laurent Lafforgue and Vladimir Voevodsky.*

*The IMU (International Mathematical Union) which operates the Fields Medal awards, and also organizes the ICMs, established in 1981, a medal and prize similar to the Fields Medal, for outstanding achievements in mathematical aspects of information science. The prize is named after the Finnish mathematician Rolf Nevanlinna who was President of the IMU, and is awarded along with the Fields Medals. This time the award went to Madhu Sudan.*

*We present here glimpses of the work of the three awardees: the notes are prepared by Rajan on Lafforgue, Nitsure on Voevodsky, and Radhakrishnan on Madhu Sudan.*

### Laurent Lafforgue

Laurent Lafforgue was awarded the Fields Medal for the proof of the Langlands conjectures for the case of the general linear group over function fields. The conjectures

of Langlands represent a vast generalization of the classical quadratic reciprocity law. These conjectures envisage an intricate relationship between arithmetical objects on the one hand and analytical data on the other.

Reciprocity laws can be traced back to the observation of Fermat that a prime number  $p$  can be expressed as a sum of two integral squares, i.e.  $p = x^2 + y^2$ , where  $x$  and  $y$  are natural numbers, if and only if  $p - 1$  is divisible by 4; a well-known identity which goes back to Brahmagupta then shows that a general natural number is a sum

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