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Network of Automatic Weather Stations : Pseudo random burst sequence type

M. R. RANALKAR, R. P. MISHRA, ANJIT ANJAN and S. KRISHNAIAH

INSAT AWS Laboratory, India Meteorological Department, Pune

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e mail : mr.ranalkar@imd.gov.in

सार – भारत मौसम विज्ञान विभाग (आई.एम.डी.) द्वारा वर्ष 2006–07 के समूचे भारत में 125 स्वचालित मौसम स्टेशनों (ए.डब्ल्यू.एस.) का संजाल स्थापित किया गया। प्रत्येक स्टेशन को वायु तापमान, घंटावार अधिकतम तापमान, घंटावार न्यूनतम तापमान, सापेक्षिक आर्द्रता, स्टेशन का दाब, घंटावार वर्षा और पूरे दिन की संचयी वर्षा पवन गति एवं पवन की दिशा मापने के समनुरूप बनाया गया है। इन प्रचालों के अलावा 25 स्टेशन ऐसे हैं जो भूमंडलीय और सौर विकिरण और मृदा तापमान के आँकड़े उपलब्ध कराते हैं। पाँच स्टेशन मृदा के अलावा मृदा की नमी के आँकड़े भी उपलब्ध कराते हैं।

प्रत्येक स्टेशन आँकड़ों को एक–एक घंटे के अंतराल पर छद्म यादृच्छिक लहर अनुक्रम (पी.आर.बी.एस.) रूप से समर्पित मौसम उपग्रह कल्पना–1/इन्सैट–3ए. के यू. एच. एफ. ट्रांसमीटर के माध्यम से केन्द्रीय स्वचालित मौसम स्टेशन के आँकड़ा संग्रहण अर्थ स्टेशन को भेजता है। यह सुविधा भारत मौसम विज्ञान विभाग, पुणे में स्थापित की गई है। इस आँकड़ा संग्रहण अर्थ स्टेशन से समुद्र तल का औसत दाब, ओसांक तापमान, तेज धूप की अवधि और दैनिक अधिकतम एवं न्यूनतम तापमान प्राप्त किए जाते हैं। इन आँकड़ों को वैश्विक दूर संचार प्रणाली के माध्यम से निकटतम वास्तविक समय पर डब्ल्यू. एम. ओ. कोड के रूप में प्रसारण भी किया जाता है।

इस शोध पत्र में पी. आर. बी. एस. टाइप के भारतीय स्वचाालित मौसम स्टेशन संजाल के विभिन्न उप–प्रणालियों का तकनीकी विवरण दिया गया है। जिसमें उपकरण, उपग्रह संचारण तकनीक, संवेदक की विशेषताएँ, स्थान एव उच्छादन की स्थितियाँ और एक प्रतिनिधि स्टेशन की कार्य प्रणाली शामिल है।

ABSTRACT. A network of 125 Automatic Weather Stations (AWS) has been set up by India Meteorological Department (IMD) during the year 2006-07 across India. Each station is configured to measure air temperature, hourly maximum temperature, hourly minimum temperature, relative humidity, station level pressure, hourly rainfall and cumulative rainfall for the day, Wind speed and Wind direction. In addition to these parameters, 25 stations provide data for global solar radiation and soil temperature. Five stations also provide soil moisture in addition to soil temperature.

Each station transmits a data stream at an interval of an hour in a Pseudo Random Burst Sequence (PRBS) manner *via* UHF transmitter and a dedicated meteorological satellite KALPANA-1/ INSAT-3A to the central AWS data receiving Earth Station facility established at IMD, Pune. Mean sea level pressure, dew point temperature, duration of bright sunshine and daily maximum & minimum temperature are derived at the receiving Earth Station. Data archival in near real time is done at the receiving Earth Station. Data dissemination in WMO code form is also done in near real time through Global Telecommunication System.

This paper provides technical description of various sub-systems of PRBS type Indian Automatic Weather Station network including instrument, satellite transmission technique, sensor characteristics, siting and exposure conditions and performance of a representative station.

Key words – AWS, PRBS, Earth Station.

1. Introduction

The concept of automation of meteorological observations and their dissemination is not new to the meteorological fraternity. The automation began way back in 1877 when Dutch meteorological instruments designer Olland developed telemeteograph on suggestion of Buys Ballot. Similar attempt was made in Belgium but the

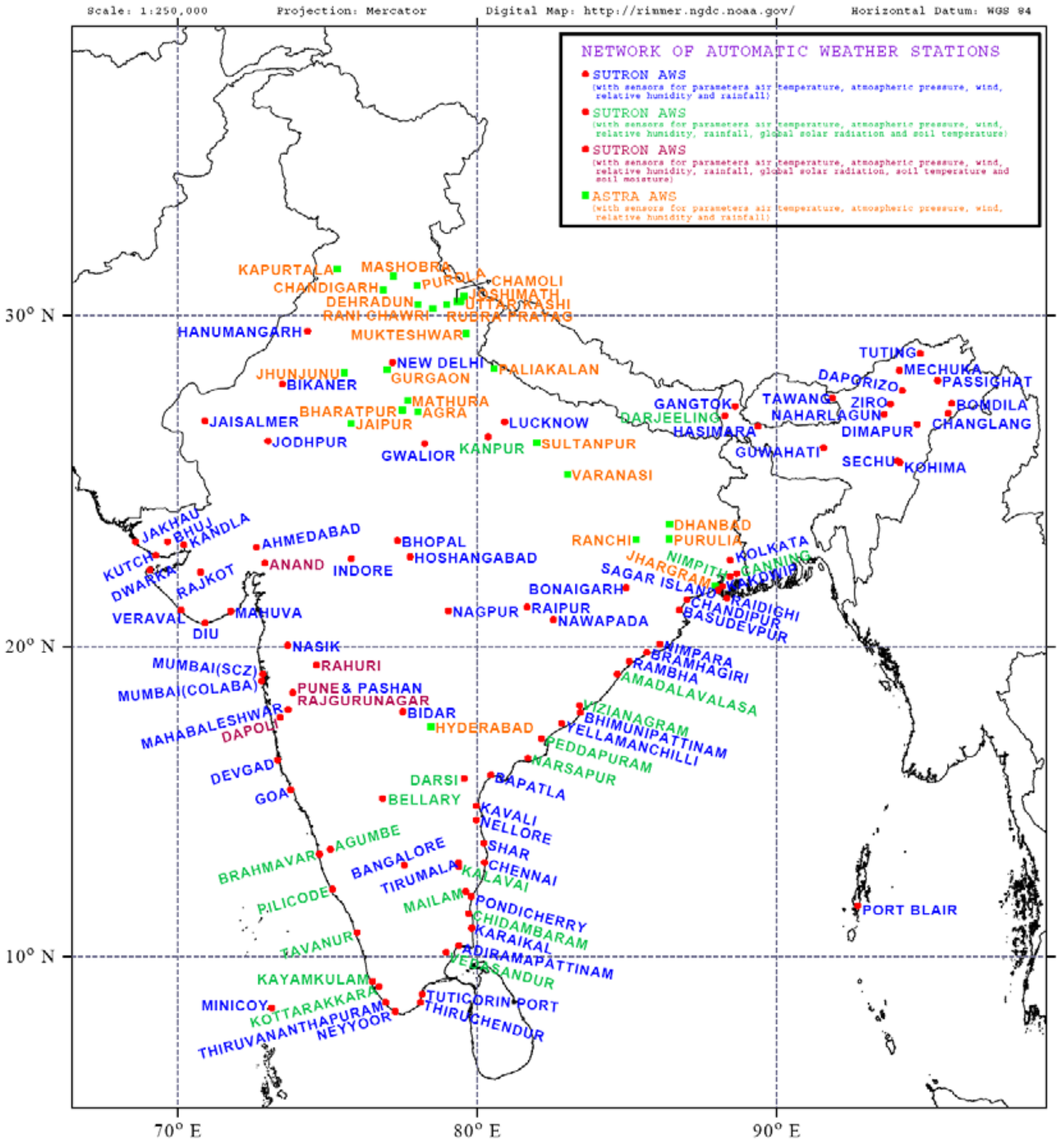


Fig. 1. Map depicting locations of automatic weather stations

concept could not flourish at that time due to high production and maintenance cost involved (Höhne, 1986). U. S. Navy sponsored development of Automatic Weather Station (AWS) with radio communication in 1940's. This AWS was developed by the U. S. National Bureau of Standards (Diamond and Hinman, 1940; Wood, 1946). This perhaps was the first AWS in operation. Since then, development of AWS has undergone phenomenal changes. With the advancement in technology especially with the advent of microprocessor technology in 1960ies the concept of AWS in its modern form brought revolution in meteorological observations.

The history of AWS in India can be traced back to 1974-75 when first experiment was carried out to relay meteorological data through India's first polar orbiting satellite "Aryabhatta". In the year 1979-80, India Meteorological Department (IMD) conducted a pilot experiment with Indian Space Research Organization (ISRO) to operate a small network of Data Collection Platforms (DCP) *via* polar orbiting satellite "Bhaskara" (SEO). The data transmitted were received at the Earth Station located at Shriharikota Rocket Range (Datar *et al*., 1983). These initial experiments though more of academic interest helped IMD to get insight into the technical details

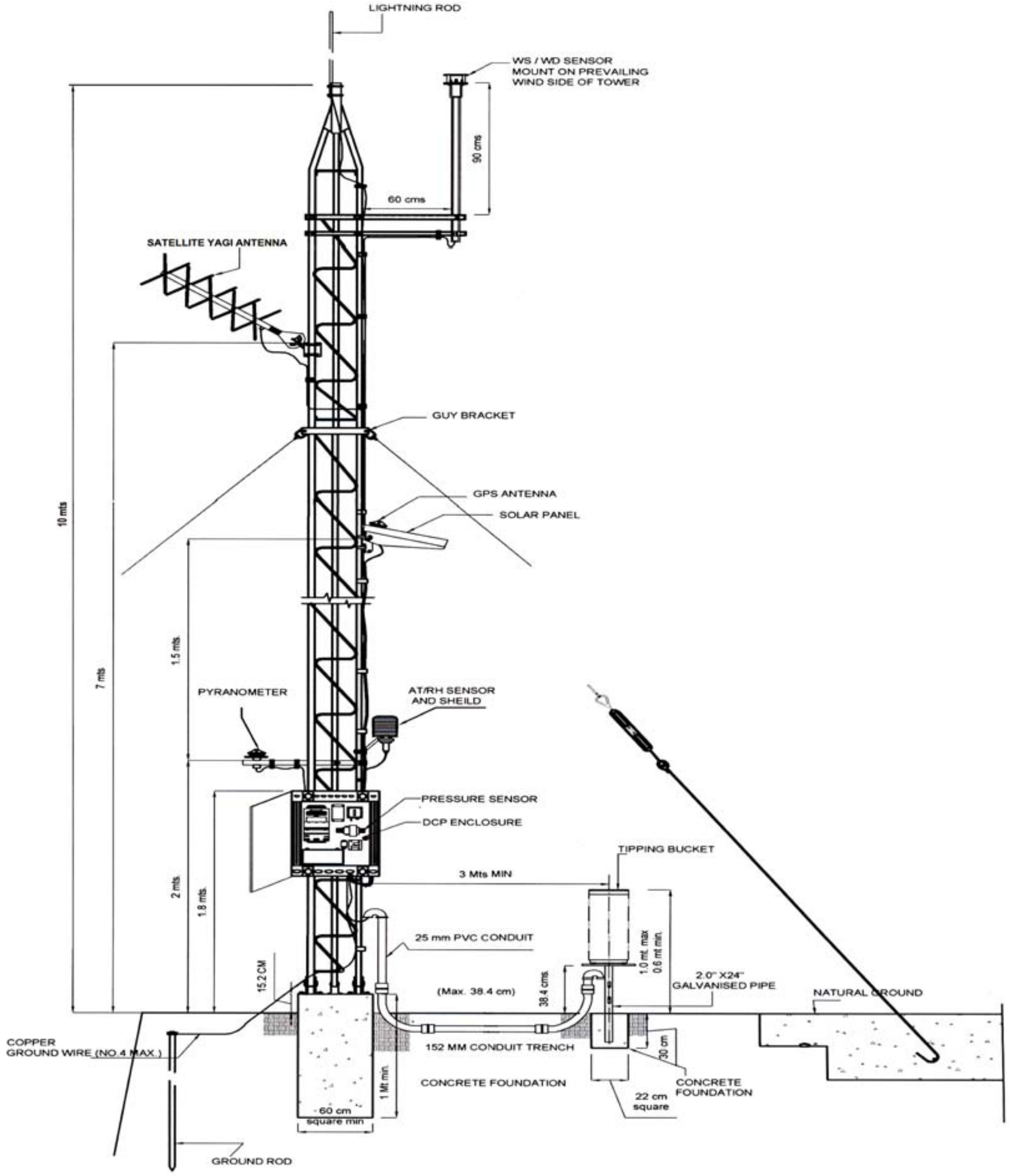


Fig. 2. Typical site layout of automatic weather station

of DCPs and experience of operating the network of DCPs in hostile environment. Subsequently, IMD established a network of 100 DCPs across India. Apte and Bhaskara Rao (1988) reported satisfactory performance of DCP installed in oppressive weather conditions. However, due to system design limitations overall network performance was unsatisfactory both in terms of data reception and quality. In 1997, the network of 15 state-of-the-art microprocessor/ microcontroller based AWS was established in Test and Evaluation mode. Gupta (2001) developed the algorithms for computerized monitoring of performance of this AWS network. Vashistha *et al*. (2005) have reported that during 1998-2005, deviations of AWS data from the co-located synoptic surface observatory data were within acceptable limits and thus AWS network performance was satisfactory.

It was therefore decided to expand and upgrade the network of AWS under the project "Replacement of obsolete DCP network with AWS and establishment of

TABLE 1

AWS sensor details and characteristics

Parameter	Type and Make	Height	Accuracy	Range & Resolution
Air temperature	Thermistor (Sutron make)	2 m	± 0.2 °C	- 40 °C to + 60 °C, Resolution: 0.1 °C
Relative humidity	Capacitive type (Sutron make)	2 m	± 3%	0% to 100%, Resolution: 1%
Atmospheric pressure	Accubar solid state (Sutron make)	1.5 m	0.2 hPa	600-1100 hPa (100 hPa above datum value), Resolution: 0.1 hPa
Rainfall	Tipping Bucket (Sutron make)	0.6 to 1 m	2% at 240 mm/hr	Resolution: 0.5 mm
Wind speed	Ultrasonic (Gill Instruments)	10 m	1.2 m/s	0-60 m/s Resolution: 0.1 m/s
Wind direction	Ultrasonic (Gill Instruments)	10 m	1°	0° - 360° Resolution: 1°
Global solar radiation	Silicon photo-diode Licor-200SZ	2 m	5% against Eppley lab	0.3 - 4 μm
Soil temperature	Campbell Scientific	-20 cm	±0.4 °C	- 40 °C to + 50 °C Resolution: 0.1 °C
Soil moisture	Stevens Hydra Probe	-20 cm	±0.03 wfv	0 to 0.45 wfv Resolution: 0.01 wfv

data receiving Earth Station at Pune". In the year 2006-07, the network of 125 AWS has been established across India as depicted in Fig. 1. The objectives of AWS network are: (*i*) To establish network of 125 AWS for measurement of about 8 to 12 meteorological parameters and transmission of these data *via* UHF transmitter. (*ii*) To receive the data at receiving Earth Station *via* a dedicated meteorological satellite and data process, archive and disseminate the data. (*iii*) To enhance surface observational network of IMD and augment the manned observatory network by providing high temporal resolution data in a cost effective manner.

The AWS network has diverse applications in operational meteorology such as agro-meteorology (McNew *et al*., 1991; Hubbard *et al*., 1983), flash flood forecasting (Mc Culloch and Strangeways, 1966) and NWP models etc. In view of these potential applications, expansion of network of AWS is recommended by the steering committee constituted by the Ministry of Earth Sciences. Network of about 1000 AWS and 3600 Automatic Rain Gauge (ARG) stations will be established across India in phased manner through implementation of modernizaion programme. A network of 550 AWS and 1350 ARG stations is being established in first phase of the programme (Ranalkar *et al*., 2010).

In this paper we describe the features of three components of the network of 125 AWS, *viz*., (*i*) Remote station (*ii*) Telemetry system and (*iii*) Data Receiving Earth Station. The comparison of AWS data with co-located surface observatory is also presented for Pune station.

2. Remote stations

The network consists of 100 AWS procured from M/s. Sutron Corp. USA and 25 AWS procured from Astra Microwave Products Ltd., India. The system includes a data logger, UHF transmitter, sensors, crossed Yagi antenna, GPS antenna, NEMA 4 standard enclosure, 10 m tower and 12V/65 AH Sealed Maintenance Free (SMF) battery float charged through a 30 W solar panel. Out of 125 AWS, 43 AWS are co-located with the manned surface observatories and remaining 82 AWS are installed at remote locations.

The network is planned to meet operational needs of IMD especially Cyclone Warning. It can be seen from Fig. 1 that significant number of stations have been installed along the coastline hence uniform distribution of AWS could not be maintained in this project.

2.1. *Site layout*

The station layout is shown in Fig. 2. A 10 m galvanized iron tower with red oxide coating is used to mount the system enclosure and sensors. The tower is erected on a concrete foundation of 3-5 feet depth depending on site requirement. In addition the tower is supported by three guy ropes. The NEMA 4 standard enclosure is fixed on the tower at a height of about 1.8 m. Wind sensor is mounted on a shaft; at least 3 feet from the tower. The shaft for pyranometer is kept to the south to minimize the effect of tower shadow. The crossed Yagi antenna is installed on a tower at an approximate height of 6-7 m. The antenna elevation and azimuth angle depends on latitude and longitude of the field site and the satellite longitude. For the AWS network the azimuth angle is greater than170°. The antenna is therefore mounted on the tower facing the South. The tipping bucket rain gauge is installed at a minimum distance of 3 m from the tower.

2.2. *Site requirements*

The guidelines for selection of sites for installation of AWS have been framed by the project team in consultation with IMD's Regional Meteorological Centres. Each AWS is established in a fenced piece of land admeasuring 12 m × 15 m with good exposure conditions. The norms for site selection are: (*i*) There shall be no obstruction to the transmitting antenna in south-west direction (170° - 230°) for azimuth orientation and for 50° to 75° or elevation of the antenna. (*ii*) The site shall be free from nearby tall buildings, trees, large water bodies, industrial heat source and high tension cables (both overhead and underground). (*iii*) The distance between the fencing and the AWS tower shall be at least 5 m. This is to minimize the effect of the fence as horizontal obstruction to the sensors. (*iv*) The site shall not have steep slope, high vegetation and also should not be low lying place holding water after rain.

In order to ensure measurement of unperturbed wind, the guidelines required that distance between wind sensor and any obstruction shall be at least 10 times the height of the obstruction (WMO 2008). AWS have been installed preferably at National Research Institutes, Universities, Agricultural Research Centres, Defence Establishments and District Collectorates etc. All institutes were requested to provide suitable land to IMD for installation of AWS. In return IMD agreed to share the data with the concerned institute. Security of equipments was also considered before finalization of site as most of the AWS are installed at remote unmanned locations. There have been sporadic instances of vandalism/theft of the system accessories. No AWS has become unserviceable due to natural hazard, such as cyclonic winds, lightning strikes, hailstorm, dust storm etc.

Although a few sites failed to meet the stringent site requirement criteria, the exposure conditions of AWS sites are in general good. The metadata of each AWS has been documented including site photographs.

2.3. *Sensors*

Sensors for the parameters such as atmospheric pressure, air temperature, relative humidity, rainfall, wind speed and wind direction, global solar radiation, soil temperature and soil moisture are interfaced with AWS in the network. The meteorological parameters for which sensors are interfaced with each station are given in Fig. 1 and the sensor characteristics are listed in Table 1.

2.3.1. *Wind sensor*

Wind Sonic sensor (an ultrasonic sensor with no moving parts) of Gill Instruments, U. K. is used for wind measurement. The hourly wind speed and wind direction are obtained after taking vector average of samples taken every second starting from three minutes prior to full hour UTC (180 samples starting from 57th minute to full hour UTC). Three minute wind averaging is in conformity with the IMD standard being followed at all conventional synoptic observatories.

2.3.2. *Air Temperature and Relative Humidity sensor (AT/RH probe)*

Rotronic make Air Temperature/ Relative Humidity probe mounted in naturally ventilated radiation shield is used for measurement. Thermistor is used as temperature sensor and relative humidity is measured based on change in capacitance. The hourly air temperature and relative humidity along with hourly maximum and minimum temperature based on samples taken at every minute (60 samples) are transmitted from field station.

2.3.3. *Tipping bucket rain gauge*

The collector diameter of rain gauge is 20 cm. Thus, 15.7 cm^3 (product of collector area and resolution) of rain water corresponds to 0.5 mm of rainfall. The large collector area helps to prevent the loss of rainfall due to evaporation. Each bucket is calibrated to tip when 15.7 cm^3 of rain water is collected in it. At any given time one bucket is always in collection mode. As the bucket tips, it causes a magnet to pass by a ruggedized mercury switch, momentarily closing the switch. This initiates count accumulation in the data logger. Hourly rainfall (count reset at every full hour UTC) and daily rainfall (count reset everyday at 0300 UTC) is transmitted to the satellite.

TABLE 2

Specifications of UHF transmitter

Parameter	Specifications
Carrier frequency band	402.0 MHz to 403.0 MHz Carrier Frequency: 402.75 MHz
Carrier settability	In steps of 100 Hz
Modulator	BPSK
Data bit rate	4.8 KBPS (user selectable)
Data coding	NRZ (M)
Frequency stability	
(a) Long term	Better than ±1 ppm/year
(b) Over temperature range	Better than ±1 ppm
Signal Bandwidth	6.0 KHz
Output power	3-10 Watt (user selectable)
Power stability	±1 dB
Spurious	-60 dB or better
Harmonics	-55 dB or better
Environmental operating temperature	-40 °C to +55 °C

TABLE 3

AWS data transmission protocol

Carrier and Bit Time Recovery	Frame Synchronization $(D8E2)_{16}$	BCH Address	Data for Met. Parameter	End of Transmission	Total Bits
160 bits (100 zeros & 60 ones)	16	31	199	16	422

2.3.4. *Atmospheric pressure sensor*

Sutron make barometric pressure sensor (ACCUBAR) is interfaced with all 125 AWS. It is a solid state pressure transducer suitable for meteorological applications. The sensor is interfaced with the data logger in Serial Data Interface-1200 (SDI-12) port.

2.3.5. *Solar radiation sensor*

LI-COR make silicon photodiode type pyranometer LI-200SZ is used for measurement of global solar radiation. The pyranometer is mounted on a shaft about 1 m away from 10 m tower to minimise the effect of reflection. The duration of bright sunshine is derived from global solar radiation.

2.3.6. *Soil temperature sensor*

Campbell Scientific model CS 107 temperature probe is used for soil temperature measurement. This is a thermistor designed to be buried in soil or submerged in water. The probe accuracy is a combination of thermistor’s interchangeability specification, the precision of the bridge resistors and the polynomial error.

2.3.7. *Soil moisture sensor*

The Stevens Hydra Probe is used for soil moisture and soil temperature measurement at five stations, *viz*., Anand, Rahuri, Dapoli, Pune and Rajgurunagar. The sensor determines soil moisture by making a high frequency (50 MHz) complex dielectric constant measurement. Soil temperature is also determined using a calibrated thermistor incorporated into the probe head.

3. Data logger, transmitter and antenna system

The data loggers used in AWS systems have been procured from M/s. Sutron Corp., USA and M/s. Astra Microwave Products Ltd., India and hence they differ in their functional capabilities. However, both are configured with same sampling and measurement schemes.

Both data loggers have sufficient analog and digital channels for interfacing of sensors and they support varied transmission modes such as telephone, satellite, GSM/GPRS, radio modem etc. It is possible to execute customized programs at scheduled interval in Sutron make data logger. UHF satellite transmitter is used for transmission to INSAT series of satellites. The real time clock of the system is synchronized to UTC *via* GPS at least once in a day. The features of UHF transmitter are given in Table 2.

Crossed Yagi antenna is interfaced to satellite transmitter to transmit data from stations. The antenna polarization is field configurable and can be set either to LHCP or RHCP depending upon the satellite. The mounting arrangements are such that 360° azimuth and 180° elevation angle adjustment are possible. High beamwidth (40°) permits easy pointing of antenna and high gain (minimum 11 dBi) allows operation with AWS transmitting in the range of 3 to 10 Watt.

4. Telemetry system design

A dedicated geo-stationary meteorological satellite is used for data transmission to the central receiving Earth Station. According to Brock *et al.* (1995) this telemetry system is most cost-effective and reliable for a nation-wide network though it has limitation of being one way communication.

Since its inception in 2006-07 to May 2010 the network was operated through Data Relay Transponder (DRT) on board the KALPANA-I located at 74° E. The KALPANA-I satellite has reached its expected End of Life (EoL) and is now in inclined orbit. In view of this, the DRT traffic on KALPANA-I has been switched over to INSAT-3A (93.5° E) in the year 2010. The use of DRTs on board the satellites is regulated by ISRO and IMD. The regulations include transmission of data on assigned frequency channel (within a band of 402.65 to 402.85 MHz) and time window at a baud rate of 4800 with 0 and 180 degree Phase-Shift Keyed Non Return to Zero-Manchester (PSK NRZ-M) encoded modulation. The transmission protocol is based on the National Environmental Satellite, Data, and Information Service (NESDIS) protocol. The protocol used for AWS data transmission is given in Table 3.

TABLE 4

AWS data frame

Number of bits	Data
5	Time (UTC)
11	Battery Voltage
11	Hourly Rainfall
11	Hourly Soil Moisture
11	AWS Health
15	Sensor - I
15	Sensor - II
15	Sensor - III
15	Sensor - IV
15	Sensor - V
15	Sensor - VI
15	Sensor - VII
15	Sensor - VIII
15	Sensor - IX
15	Sensor - X

In this protocol transmitter is required to transmit 160 bits (first 100 bits are zeros and remaining 60 bits are ones) for carrier and bit time recovery. This facilitates bit synchronization in the demodulator. This is followed by a frame synchronization message which is a minimum autocorrelation sequence of 16 bits (Frame sync: 1101100011100010_2, *i.e.*, $D8E2_{16}$) with number of ones equal to number of zeros.

Thirty one bits followed by frame synchronization constitutes station identification and error correction. These 31 bits are referred to as Bose, Chaudhuri, Hocquenghem (BCH) Code. The first 21 bits of this code provide information in respect of user identification, priority of data transmission and platform index. These 21 bits are called information matrix for the platform. Last 10 bits are known as check bits. These bits provide means for error correction and are generated by multiplying the (1×21) information matrix with a well known (21×31) BCH matrix. The product is 1×31 matrix which is known as 31/21 BCH code. This 31/21 bit code provides 2^{21} unique addresses as defined in NOAA Technical Memorandum (NOAA, 1979). The 21 bit information matrix consists of 9 bits for user identification, 2 bits for

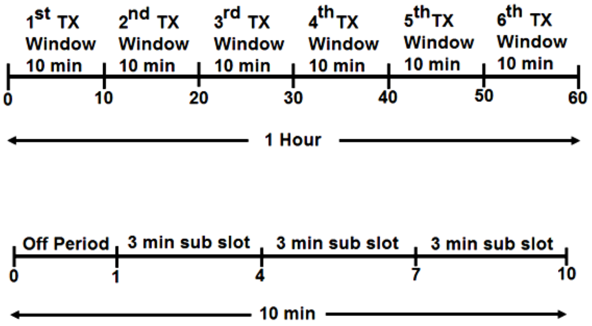


Fig. 3. Time windows and sub-windows for transmission in pseudorandom manner

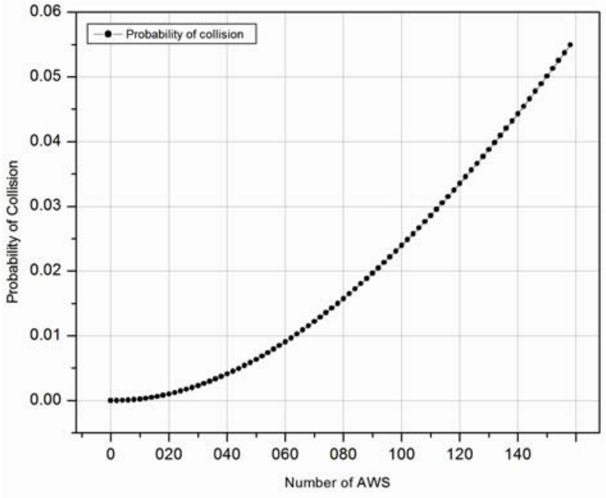


Fig. 4. Probability of loss of AWS data during transmission due to burst collision

priority and 10 bits for platform index. The BCH check bits matrix and procedure to use it is given in Appendix 1.

The priority bits are used to categorize the platform as test and evaluation (00), cyclone warning (01), flood warning (10) or snow survey (11). Next 199 bits constitutes AWS data frame which consists of time code, calibration voltages, AWS health and data from 10 sensors as given in Table 4. Five bits are provided for transmission of time in full hour UTC (from 0000 to 2300). Each of the calibration voltages and AWS health has 11 bits arranged in 10 data bits + 1 parity bit form. In 10 data bits the extreme right (last) bit is least significant (LSB). The slots for calibration voltages are now used to transmit sensor data. All health bits are not used extensively. Each sensor data consists of 15 bits arranged in the form of 10 bits (sensor output) + 1 bit (Parity) + 4 bits (sensor identification). Out of the 10 sensor output bits, the bit on extreme right (last) is least significant (LSB).

The transmission is concluded with 16 bit End of Transmission code 1111101011011110_2, *i.e.*, FADE_{16}. The total time for transmission of 422 bits is 87.9 msec (422 bits at the rate of 4800 bits sec^{-1}).

Each AWS automatically takes measurement of meteorological parameters once every hour at full hour UTC and stores it in system memory. System transmits this data in a self timed Pseudo Random Burst Sequence (PRBS) manner in its allotted time slot within the next 60 minutes before the next measurement. This random multiple access technique is known as ALOHA technique (Abramson, 1977) in which the station neither has assigned time stamp as in TDMA nor narrow frequency band as in FDMA. Each station is assigned a time window in which it transmits in pseudo random manner. All the AWS are divided into 6 groups each of 10 minutes duration. These transmission windows are 0-10 min, 10-20 min, 20-30 min, 30-40 min, 40-50 and 50-60 min. Each 10 min transmission window is further divided into 4 sub-slots as shown in Fig. 3.

First slot of 1 min duration is off period and 3 sub slots each of 3 minutes duration are for repeat transmission. Every AWS transmits hourly data 3 times within the allotted transmission window once in each 3 min. sub-slot in burst mode. This follows from the optimum number of transmission attempts needed to transmit the burst successfully in ALOHA system (Abramson, 1977). Thus, we do know that a station will transmit data in allotted 10 min time window but we do not know the exact time of transmission hence, the name Pseudo Random Burst Sequence. An hourly message is repeated 3 times in order to preclude the loss of data due to (*i*) satellite communication errors (*ii*) collision of messages transmitted simultaneously by any two AWS.

5. Probability of loss of data due to collision

Let N AWS transmit in a time window ω such that there is one transmission in each sub-window T. Each AWS transmits a data of duration t in a sub-window. Let, AWS1 transmits a data burst at time t_i then data burst transmitted by any AWS in time interval $t_i - t < t < t_i + t$, *i.e.*, over an interval $2t$ will collide with that transmitted from AWS1 and none of the bursts will be received correctly. The interval $2t$ is therefore known as vulnerable period. The probability of successful transmission from

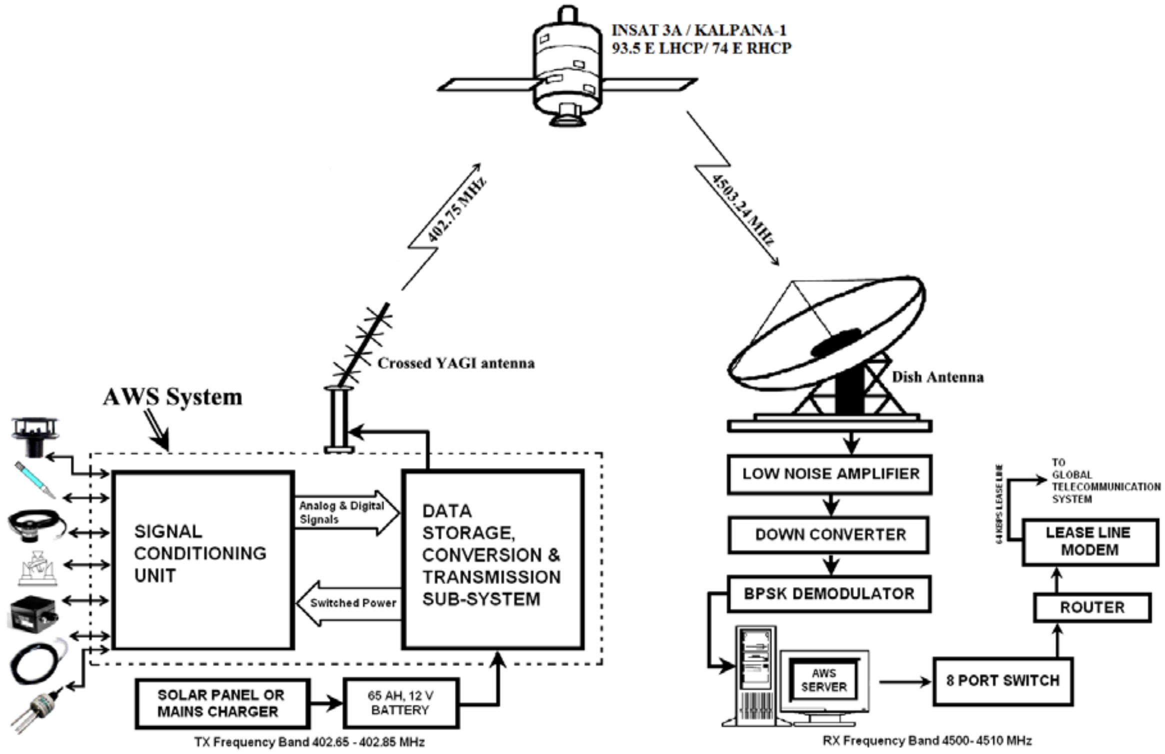


Fig. 5. Telemetry link of network of AWS

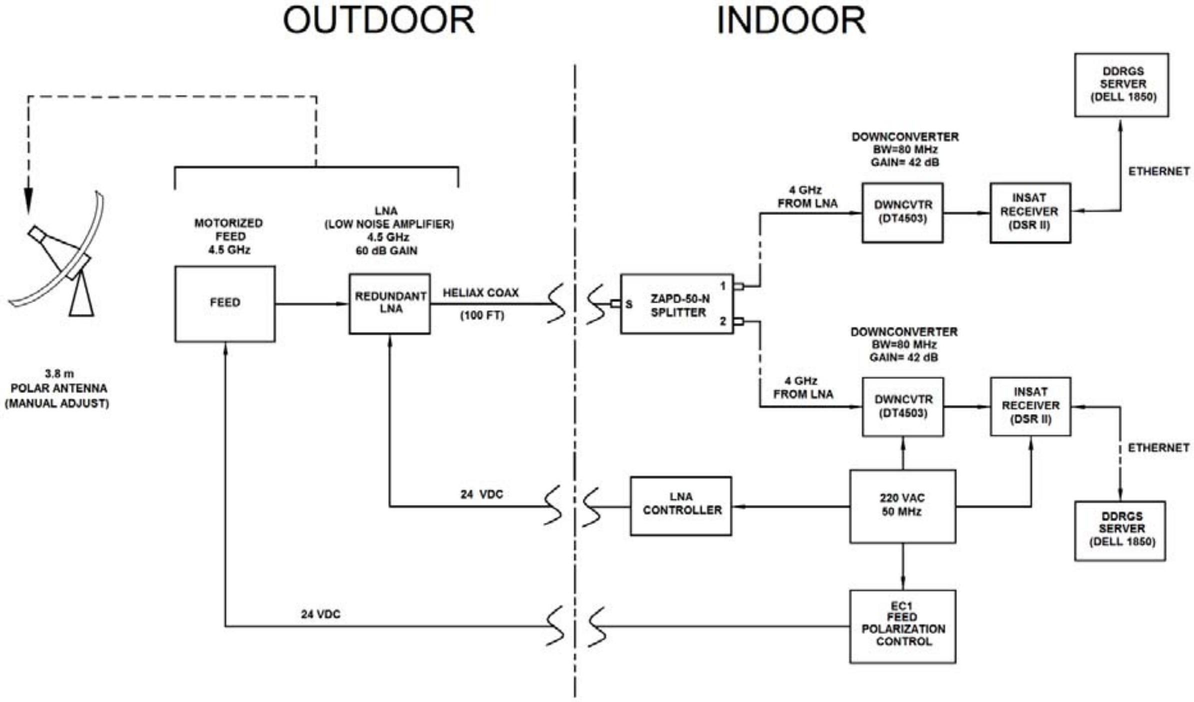


Fig. 6. Block diagram of indoor and outdoor components of receiving Earth Station

an individual AWS without collision with remaining N-1 AWS transmitting randomly in sub-window T is given by

$$p = \left(1 - \frac{2t}{T}\right)^{N-1}$$

$$\text{where, } \frac{2t}{T} << \frac{1}{N-1} \qquad (1)$$

Each AWS transmits a data burst thrice to overcome collision with bursts being simultaneously transmitted by two or more AWS. The features of PRBS technique are given in Appendix 2. We assume that the transmission from an AWS is successful if at least two bursts are received correctly without collision within time window ω. The probability that all three bursts are received correctly without collision is p^3. The probability that two bursts are received successfully without collision is $3p^2(1\text{-}p)$. Thus, overall probability of successful transmission from an AWS is given by

$$p_s = p^3 + 3p^2\,(1\text{-}p) \qquad (2)$$

The probability of loss of data due to collision is therefore given by

$$p_c = 1\text{-}\ p_s \qquad (3)$$

The probability of collision is plotted against the number of AWS (transmitting in given time window) in Fig. 4. In order to ensure the probability of collision of data bursts to be about 0.01 or less for the characteristics described above, approximately 70 AWS need to transmit in each time window. The overall probability of data burst reception is thus 99% or better. The IMD guideline requires that not more than 67 AWS shall be transmitting in any 10 min. time window. Thus, approximately 400 AWS can be accommodated per satellite channel to meet the requirement of burst collision probability. A different treatment of probability of collision is available in the literature (Datar *et al.*, 1983; Muthuramlingam *et al.*, 2006).

6. Data receiving Earth station

Every station transmits data to INSAT 3A at an interval of one hour at uplink carrier frequency of 402.75 MHz and transmitted output power in the range of 3 to 10 Watt. The DRT onboard the satellite receives the data burst at an uplink frequency. It then down converts it to 28 MHz, filters and up converts to a down link frequency of 4503.246 MHz.

The signal from the satellite is very weak when it is received at the antenna front end. The power of the signal is of the order of pico watts. Once received, it has to be amplified without adding noise. This function is done by Low Noise Amplifier (LNA). LNA has a minimum gain of 60 dB. LNA Noise Temperature has a major contribution to the system noise. Hence LNAs should have less Noise Temperature in order for the system to have good G/T. The system has redundant LNAs. If one LNA fails second automatically takes over.

The RF signal received through the antenna is amplified by LNA. The signal is splitted at the indoor unit of the Earth Station and fed to the redundant down converters. The signal in the frequency range 4.5 to 4.8 GHz is received at the input end of the Down converter. Processing of the signal at such higher frequencies requires costly and sophisticated equipments. Hence the signal is down converted to an intermediate frequency of 140 MHz. This value in general depends upon the mixing stages incorporated in the down converter.

The down converted signal of 140 MHz is fed to Digital Satellite Receiver (DSR) which is further down converted to 10 MHz suitable for A/D conversion and then it is digitized and demodulated (4 channels can be simultaneously demodulated). Raw data is then extracted and sent on demand to the central processing computer.

The processing software decodes the raw data to engineering values of meteorological parameters and archives the data in the database. Various data and diagnostic reports and graphical representation of data can be generated and scheduled. Finally the hourly data are encoded into the WMO code format and are disseminated through GTS for operational utilization. The complete telemetry link is shown in Fig. 5 and the block of diagram of Earth Station is shown in Fig. 6.

7. Quality objectives and Link budget of INSAT 3A

The telemetry link calculations are based on specified quality objectives. At the receiver the modulated carrier is subjected to band pass filter to limit the input noise. For polar NRZ baseband signal and for Binary Phase Shift Keying modulation, the probability of the detector making an error (also known as bit error rate) as a result of noise is given by

$$P_e = \frac{1}{2}\,erfc\left(\sqrt{\frac{E_b}{N_o}}\right) \qquad (4)$$

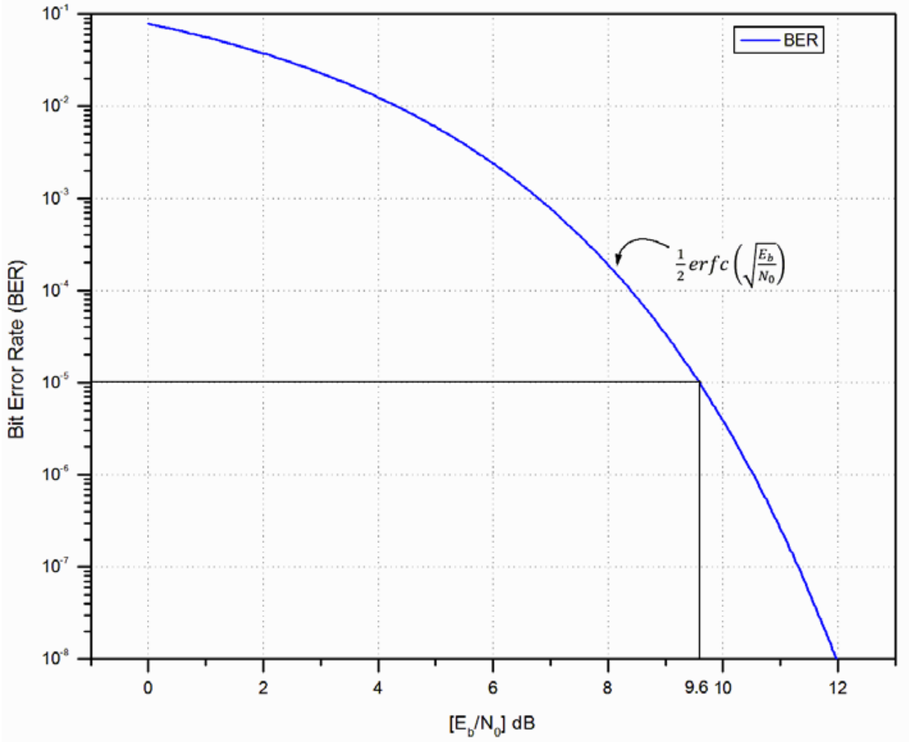


Fig. 7. Bit error rate *Vs.* (E_b/N_0)

Where, *erfc* is a complementary error function, E_b is average bit energy in joule, N_o is noise power spectrum density in joule (Roddy, 2001).

The bit error rate is specified to be 10^{-5}. The corresponding ratio of bit energy to noise density is 9.6 dB as shown in Fig. 7. Once the theoretical value of $\frac{E_b}{N_o}$ is known an implementation margin of 1.0 dB is added to allow for imperfections in the filtering. The effective $\frac{E_b}{N_o}$ is thus 10.6 dB. With the data rate R_b = 4800 bit sec^{-1} the required $\frac{C}{N_o}$ is therefore given by:

$$\left[\frac{C}{N_o}\right]=\left[\frac{E_b}{N_o}\right]+\left[R_b\right]=10.6+10\log_{10}(4800)=47.41\text{dBH}_z$$

With these quality objectives the link budget of INSAT 3A is given in Table 5.

8. Processing, archival and dissemination of data

The processing software decodes the raw data received at the Earth Station server at scheduled time interval and archives it in a database. Past data can be accessed trough the application software. Reports on data reception, transmission quality etc can also be generated at scheduled time.

The Dew Point Temperature and Mean Sea Level Pressure are derived at the Earth Station using basic meteorological parameters. Dew point temperature is derived from hourly values of air temperature, Relative Humidity and Station level pressure using Tetan's formula for vapour pressure

$$e_s = 6.11\exp\frac{a(T-273.16)}{(T-b)} \tag{5}$$

Where, 'a' and 'b' are constants which take different values depending upon whether saturation occurs over water or ice. Following Krishnamurti and Bounoua (1996) the flowchart for algorithm is given in Fig. 8.

Depending on the elevation of the station, the mean sea level pressure and gpm height of the nearest isobaric level is derived using temperature, station level pressure, latitude, mean vapour pressure (V_p) and mean pressure of the air column between station level and mean sea level (P_m). For stations with elevation less than 800 m, mean sea level pressure is derived and for stations with elevation greater than 800 m gpm height of the nearest

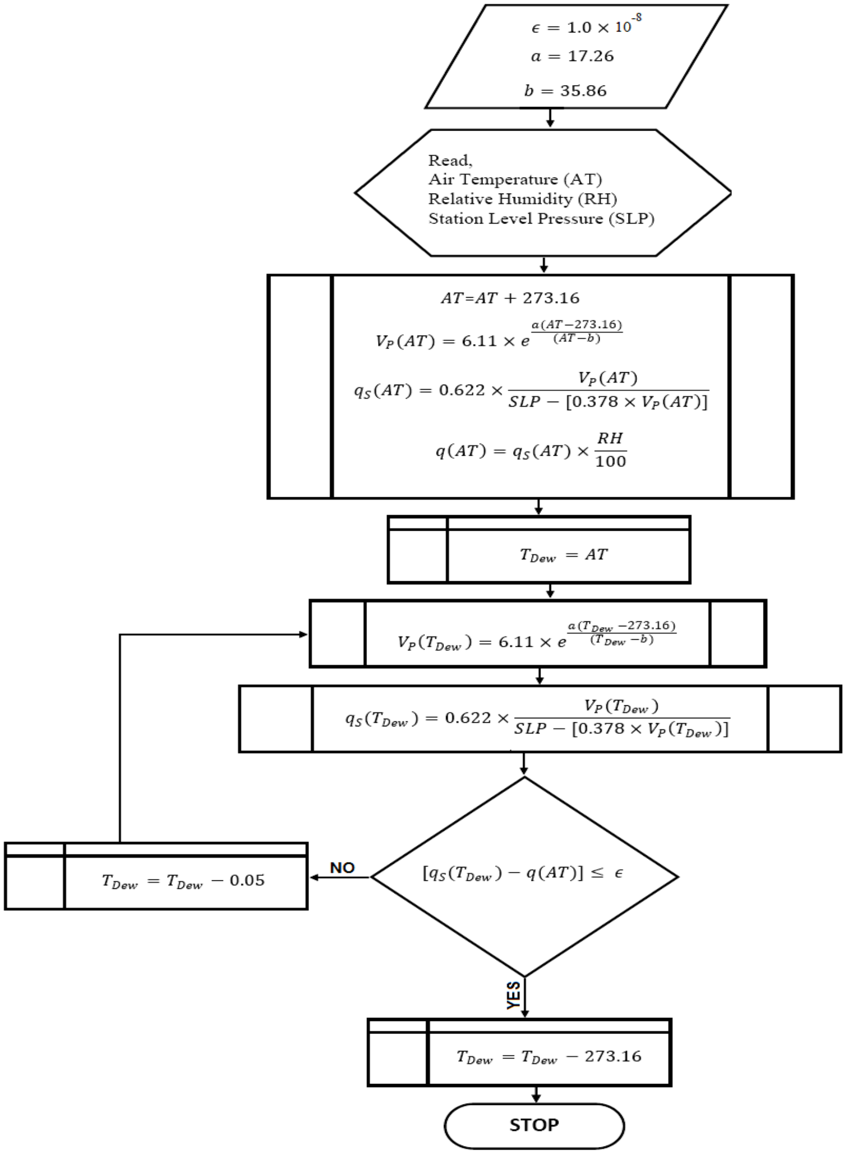


Fig. 8. Flowchart of algorithm to derive dew point temperature at the receiving Earth station

isobaric level is reported (Ranalkar *et al.*, 2008a). The flowchart of the algorithm is shown in Fig. 9.

Hourly AWS data being received at the receiving Earth Station is encoded into WMO FM 14-XIV SYNOP MOBIL format. It is presumed that by 58th minute of an hour all stations have reported at least two burst at the Earth Station. Synop message generator is therefore scheduled to generate a message at the 58th minute of an hour to ensure that data of all stations are encoded. As soon as the message is generated it is uploaded to the server at Automated Message Switching System (AMSS) Mumbai through ftp *via* 64 kbps dedicated lease line for onward transmission to Global Telecommunication System (GTS) and utilization in forecasting. The data is also available at www.imd.gov.in and www.imdpune.gov.in. In order to ensure timely maintenance of the network the data is monitored in near real time at www.imdaws.com.

9. Performance of the network

The factors that have bearing on the performance of AWS are (*i*) malfunctioning of sensors (*ii*) generation of

TABLE 5

AWS Telemetry link budget for INSAT 3A satellite

Uplink		Downlink	
Frequency	402.75 MHz	Downlink Frequency	4503.24 MHz
Antenna Gain [G_t]	11 dB	Satellite gain (G_s)	160 dB
Transmitted output power [P_t]	10 Watt	Downlink EIRP = [G_S] + [P_R]	4.36 dBW
[EIRP]$_{uplink}$ = [G_t]+[P_t]	21 dBW	Down link free space loss	197.38 dB
Slant Range	38000 km	Down link misc. loss	0.50 dBW
[Free Space Loss]$_{uplink}$	176.14 dB	Antenna gain	43.47 dB
Absorption loss	0.50 dB	System noise temperature	20 dB
Power Flux Density at the I/P of satellite (-105 dBWm^{-2} max.)	-141.588 dBWm^{-2}	Hub station $\frac{G}{T}$	19.20 dBK
Carrier power at the I/P of satellite antenna [P_R]	-155.64 dBW	$\frac{C}{N_0}$	54.28 dBHz
Satellite $\frac{G}{T}$	-17 dBK		
$\frac{C}{N_0}$	55.96 dBHz		
Effective $\frac{C}{N_0}$ =52.03 dBHz			
Required $\frac{C}{N_0}$ =47.41 dBHz			
Link margin (clear LOS)= 4.62 dBHz			

parity errors at source (*iii*) loss of data during transmission etc. The performance of AWS can be improved with periodic preventive and corrective maintenance. The loss of data due to burst collision can be minimized by ensuring repeat transmission. It is, however, impossible to control loss of data due to parity errors. For assessing operational utility of AWS data it is desirable to know deviation of AWS data from that recorded at conventional manned observatory.

Amudha *et al.* (2008) have examined the performance of the network during Indian summer monsoon 2007 and reported it to be satisfactory. Though there were initial hiccups, performance of AWS in oppressive weather of Antarctica is also reported to be satisfactory (Ranalkar *et al.*, 2008b).

Comparison of AWS data with conventional observatory is a debatable issue as techniques used for measurement of parameters at AWS and surface observatory are different. For example, mercury in glass thermometer is used in observatory whereas thermistors/Pt100 sensor is used in AWS, wind vane, moving cup anemometer is used in observatory for wind measurements and ultrasonic wind sensor is used in AWS. The inherent instrument biases would also affect the reliability of data. Similarly, different averaging intervals are employed at surface observatory and AWS. For example, at AWS, wind is sampled for every second starting from three minutes prior to full hour UTC and vector average is taken over the samples collected (180 samples). On the other hand, at the conventional observatories scalar average is taken for measurement of wind.

The logged data of Pune AWS for the year 2008 is compared with the observatory data for eight synoptic hours. Figs. 10(a-c) show scatter plot for the parameters Air Temperature, Relative Humidity and Atmospheric Pressure. Though there are few outliers in general the

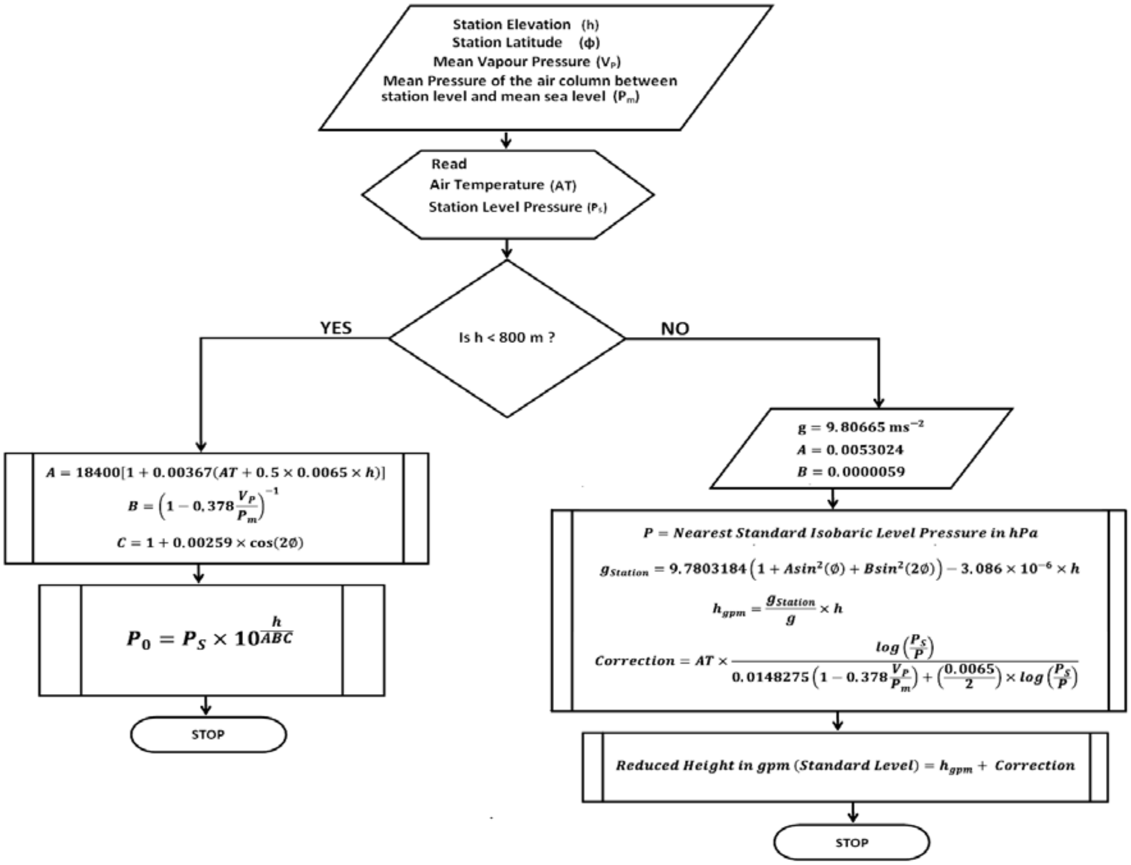


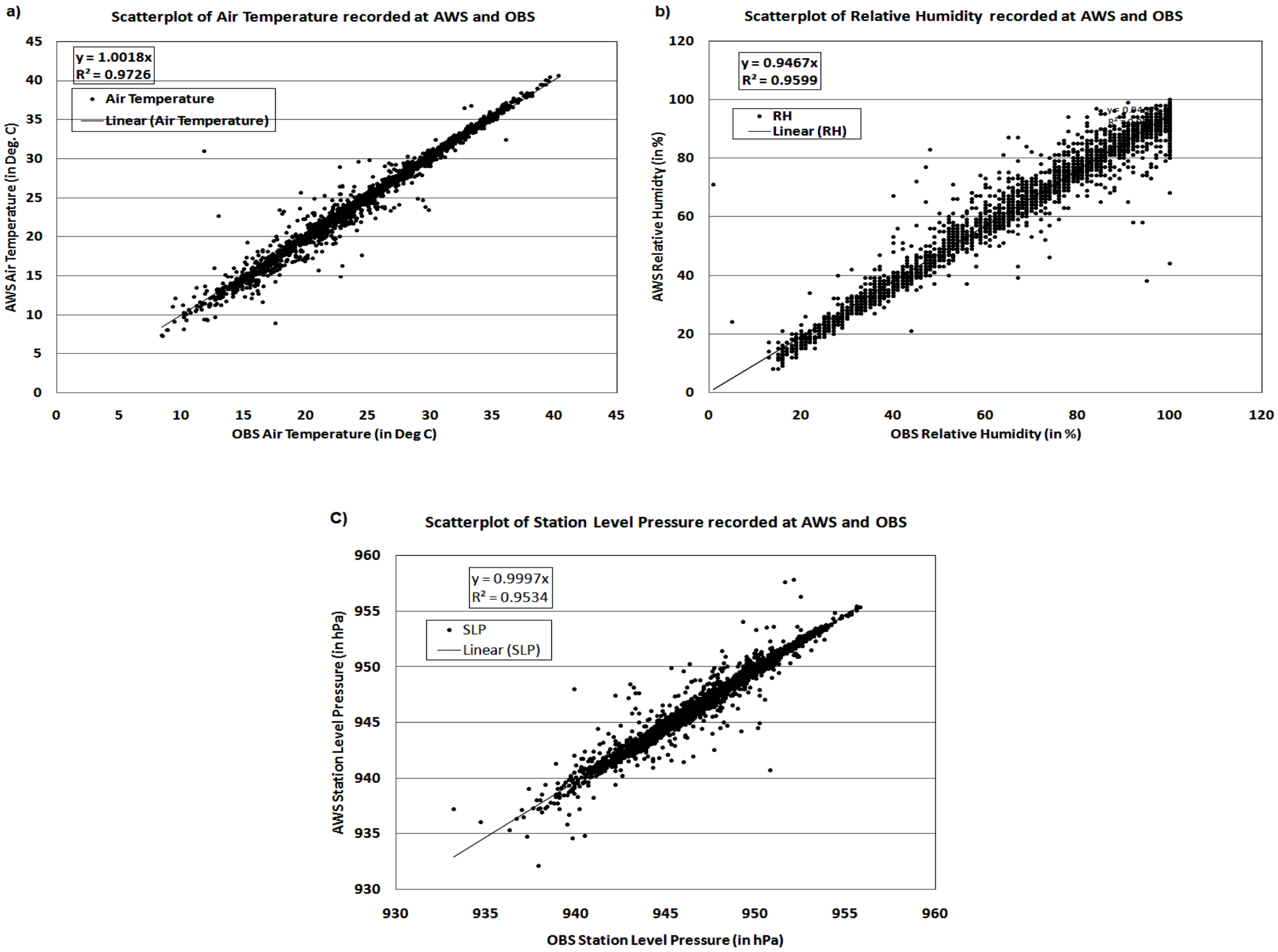
Fig. 9. Flowchart of algorithm to derive Mean Sea Level Pressure or gpm height of the nearest isobaric level at the receiving Earth Station

performance of the AWS is comparable to that of surface observatory with a bias of 0.31 hPa for SLP, -0.002 °C for Air Temperature and 3.6% for RH and RMSE of 0.8 hPa for SLP, 0.9 °C for Air Temperature and 6.3% for RH. The scatter plot of Rainfall recorded at Pune AWS and observatory is shown in Fig. 11. It has a bias of -1.0 mm and RMSE of 1.9 mm. This implies that rainfall recorded at AWS is less than that recorded at surface observatory. This may be attributed to loss of pulses by TBRG during high rain rate and evaporation loss of rain water due to heated metallic collector of TBRG. The Annual variation of global solar radiation recorded at Pune AWS during the year 2007 is shown in Fig. 12. The comparison of daily maximum temperature recorded at AWS with that observed at conventional manned observatory during the year 2008 is shown in Fig. 13(a) and that for daily minimum temperature is shown in Fig. 13(b). The bias for daily maximum temperature is -0.5 °C and that for daily minimum temperature is 0.4 °C. Similarly RMSE for daily maximum and daily minimum temperature is 1.4 °C and 0.6 °C respectively. Thus daily minimum temperature measured by AWS is in general higher than that measured at observatory and reverse is the case for daily maximum temperature.

10. Discussion

The network of 125 AWS provides an opportunity to collect data of basic meteorological parameters at a desired temporal resolution for operational utilization. The conventional observatories would still have an important role to play as visual observations can be reliably estimated by human than instruments. However, with the pace of technological advancement a full featured AWS is not far from reach.

The preliminary analysis shows that AWS data are in general in good agreement with co-located surface observatory data. However, there have been sporadic



Figs. 10(a-c). Scatterplot of (a) Air Temperature, (b) Relative umidity and (c) Station Level Pressure recorded at Pune AWS and Observatory during 2008

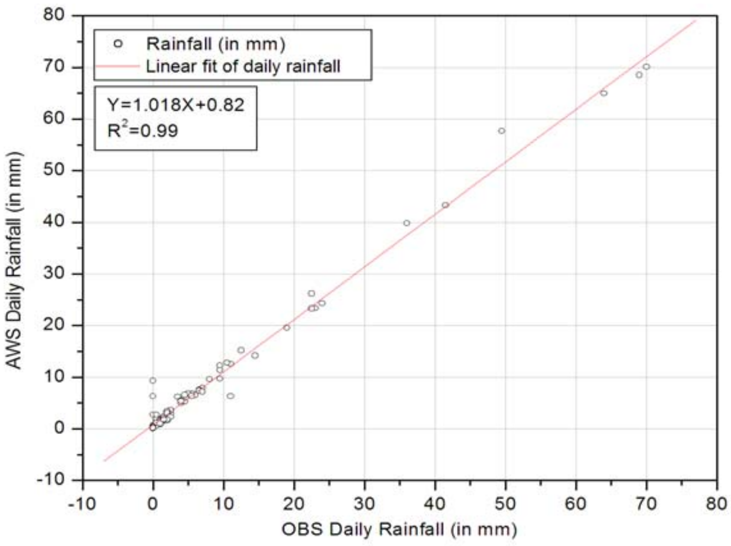


Fig. 11. Scatter plot of rainfall recorded at Pune AWS and Observatory during 2008

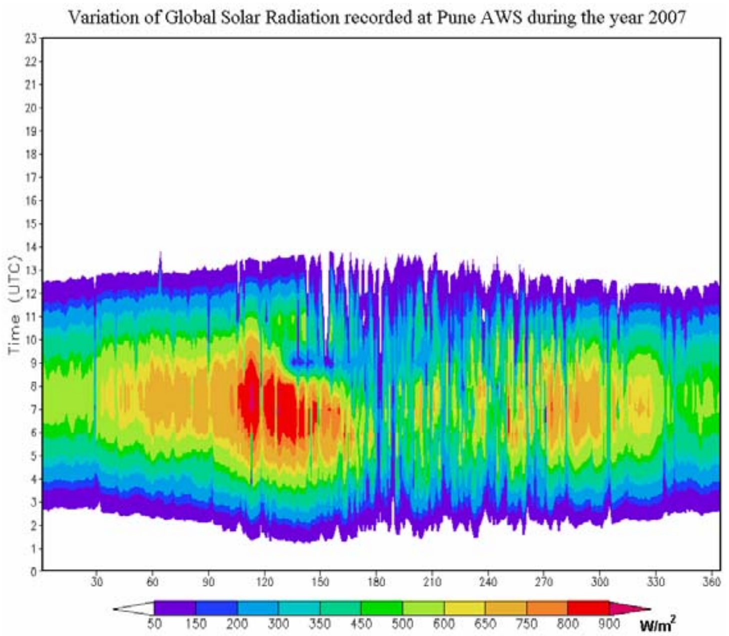
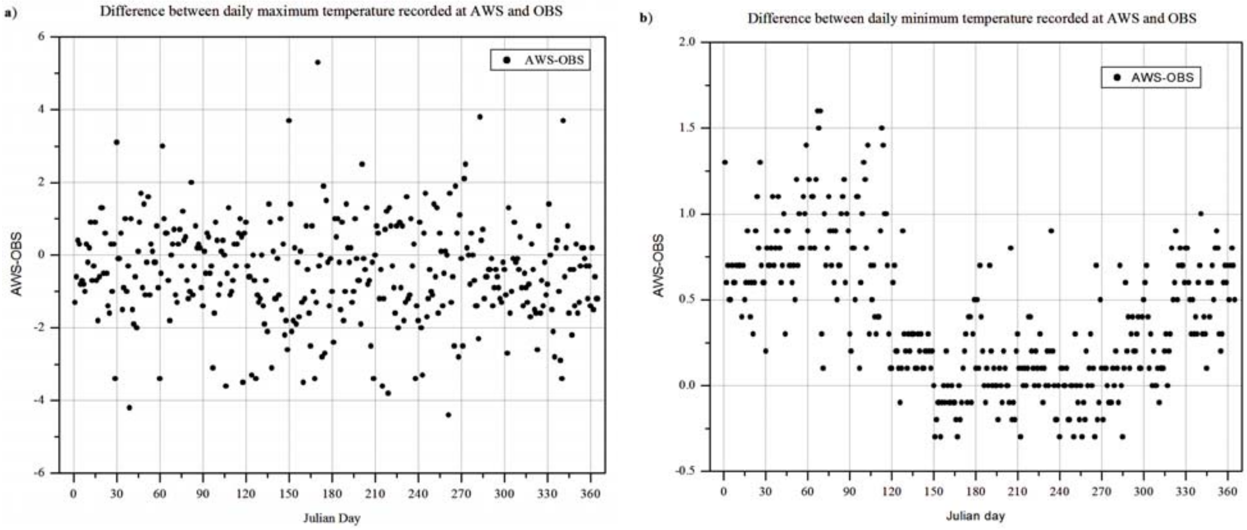


Fig. 12. Variation of Global Solar Radiation (in Wm^{-2}) recorded at Pune AWS during the year 2007



Figs. 13(a&b). Deviation of (a) daily maximum temperature and (b) daily minimum temperature as recorded at AWS and Observatory during 2007

instances of receipt of erroneous data from AWS. Few stations do show low correlation and large biases and RMSE for various parameters. There could be varied reasons for differences in two datasets. One significant outlier in the data can contaminate the final result even if rests of the data points are strongly correlated. The distance between co-located AWS and surface observatories may range from about 20 m to 200 m and the height at which sensors are installed in the stations may differ significantly. These may also be reasons for observed deviations between AWS and observatory data.

The loss of AWS data due non-functionality of station often results in broken time series. Timely preventive and corrective maintenance is a key to obtain uninterrupted AWS data. Efforts are in progress to ensure routine maintenance of stations through a three tier maintenance system *viz*., Regional Instruments Maintenance Centre, State Instruments Maintenance Centre and Field Maintenance Unit with technical support from Surface Instruments Division of IMD. This set up will help improve network availability and quality of data.

11. Scientific utilization of the system

The AWS network is extremely efficient in monitoring weather at user defined temporal and spatial resolution. Near real time availability of AWS data makes it a valuable input for numerical weather prediction models especially short and medium range forecasting models. The hourly AWS data finds application in conventional synoptic forecasting and also in cyclone warning to precisely estimate landfall point. The meso-network of these systems could be very useful in monitoring development, growth, dissipation and movement of thunderstorm cells. The agro-meteorological data being recorded at AWS could be valuable input for crop yield forecast models and agro-meteorological advisories etc. The data also has potential application in validation of radar and satellite derived estimates of rainfall.

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Note : Mention of specific make and model of proprietary items and results presented in this paper shall not be construed as an endorsement of the product by India Meteorological Department.

Appendix 1

BCH check bits matrix and procedure to use it

Check bits Matrix (BCH Code)

22	=	1	4	6	9	12	13	14	15	17	19	21				
23	=	1	2	4	5	6	7	9	10	12	16	17	18	19	20	21
24	=	1	2	3	4	5	7	8	9	10	11	12	14	15	18	20
25	=	2	3	4	5	6	8	9	10	11	12	13	15	16	19	21
26	=	1	3	5	7	10	11	15	16	19	20	21				
27	=	1	2	8	9	11	13	14	15	16	19	20				
28	=	2	3	9	10	12	14	15	16	17	20	21				
29	=	1	3	6	9	10	11	12	14	16	18	19				
30	=	2	4	7	10	11	12	13	15	17	19	20				
31	=	3	5	8	11	12	13	14	16	18	20	21				

Procedure to use the BCH Matrix:

As an example, take the basic left adjusted 21 bit hexadecimal address 1E806 which in binary mode is

b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	b_{11}	b_{12}	b_{13}	b_{14}	b_{15}	b_{16}	b_{17}	b_{18}	b_{19}	b_{20}	b_{21}
0	0	0	1	1	1	1	0	1	0	0	0	0	0	0	0	0	1	1	0	0

Thus b_{21} is 0. To calculate b_{22} examine the binary values of (0 or 1) of b_1, b_4, b_6, b_{12}, b_{13}, b_{14}, b_{15}, b_{17}, b_{19}, b_{21} (see the first row of Table above). If the number of "ones" are even in number then $b_{22} = 0$. Conversely, if the number of "ones" is odd in number then $b_{22} = 1$. In above mentioned example, four bits, *viz*., b_4, b_6, b_9 and b_{19} are "ones", so $b_{22} = 0$. Proceed in the same manner to compute b_{23} through b_{31}.

Appendix 2

Features of Pseudo Random Burst Sequence (PRBS) technique

We assume that all AWS bursts are transmitted independently of each other. Therefore, the knowledge of burst transmission from j^{th} AWS will give no information about when next data burst transmission will occur. That is data bursts are transmitted randomly. In other words, each AWS data burst is statistically independent of any other data burst.

Let probability that k data bursts arrive in time τ at DRT be $P(k,\ \tau)$. Therefore, probability of no data burst arriving in time interval τ_1 is $P(0,\ \tau_1)$ and the probability of no data burst occurring in time τ_2 is $P(0,\ \tau_2)$. Since the burst transmission is statistically independent the probability that no burst transmission will occur in time interval $\tau_1 + \tau_2$ is

$$P\ (0,\ \tau_1 + \tau_2) = P(0,\ \tau_1)\ .\ P(0,\ \tau_2) \tag{1}$$

$P(0,\ \tau)$ is a function of τ alone so it can be represented as $f\,(\tau)$. Thus, Eqn. (1) is of the form $f\,(\tau_1 + \tau_2) = f\,(\tau_1)\ .\ f\,(\tau_2)$. This suggests that $f\,(\tau)$ is of the form J^{τ} where J is some fixed base. Since, $J^{\tau_1+\tau_2} = J^{\tau_1}.J^{\tau_2}$. We may therefore write

$$P(0,\ \tau) = e^{-\lambda\tau} \tag{2}$$

Where, λ is yet to be determined.

If we let τ decrease to a differentially small value $\Delta\tau$, then Eqn. (2) reduces to

$$P(0,\ \tau) \cong 1 - \lambda\ \Delta\tau. \tag{3}$$

Thus, $P(0, \tau) \to 1$ as $\Delta\tau \to 0$. It is therefore reasonable to assume that in the interval $\Delta\tau$ at the most one data burst can be received. The probability that k data bursts are received in time interval $\tau + \Delta\tau$ can be written as

$$P(k, \tau + \Delta\tau) = P(k, \tau) \,.\, P(0, \Delta\tau) + P(k-1, \tau) \,.\, P(1, \Delta\tau) \tag{4}$$

The first product term is the probability that all k data bursts are received in time interval τ and none in the interval $\Delta\tau$ and the second product term is the probability that k - 1 data bursts are received in time interval τ and one is received in $\Delta\tau$. (The possibility of receiving two or more data bursts in the interval $\Delta\tau$ is neglected).

From Eqn. (3) it follows that

$$P(1, \Delta\tau) = 1 - P(0, \Delta\tau) = \lambda\Delta\tau$$

and hence Eqn. (4) becomes

$$P(k, \tau + \Delta\tau) = P(k, \tau)\,(1 - \lambda\Delta\tau) + P(k - 1, \tau)\,(\lambda\Delta\tau)$$

$$\frac{P(k, \tau + \Delta\tau) - P(k, \tau)}{\Delta\tau} = \lambda[P(k-1, \tau) - P(k, \tau)] \tag{5}$$

in the limit as $\Delta\tau \to d\tau$ Eqn. (5) becomes

$$\frac{\mathrm{d}P(k, \tau)}{d\tau} = \lambda[P(k-1, \tau) - P(k, \tau)] \tag{6}$$

The solution of the differential Eqn. (6) is $P(k,\tau) = \dfrac{(\lambda\tau)^k e^{-\lambda\tau}}{k!}$ which is a Poisson distribution.

Thus, AWS data burst arrival at the satellite Data Relay Transponder (DRT) follows a Poisson distribution. The mean value of k is given by

$$\sum_{k=0}^{\infty} k.P(k, \tau) = \sum_{k=1}^{\infty} k.\frac{(\lambda\tau)^k e^{-\lambda\tau}}{k!}$$

$$= e^{-\lambda\tau} \sum_{k=1}^{\infty} \frac{(\lambda\tau)^k}{(k-1)!}$$

$$= e^{-\lambda\tau}\left[\lambda\tau + \frac{(\lambda\tau)^2}{1!} + \frac{(\lambda\tau)^3}{2!} + \ldots\ldots\right]$$

$$= e^{-\lambda\tau}.\lambda\tau.\left[1 + \lambda\tau + \frac{(\lambda\tau)^2}{2!} + \frac{(\lambda\tau)^3}{3!} + \ldots\ldots\right]$$

$$= e^{-\lambda\tau}.\lambda\tau.e^{\lambda\tau}$$

$$= \lambda\,\tau \tag{7}$$

Thus, λ is the mean number of data bursts per unit time.

Let each AWS transmit a data burst of duration t_b. Consider that AWS1 transmit a data burst at some time t_i, then if any other AWS transmit data in the time interval $t_i - t_b < t < t_i + t_b$ (*i.e.*, over an interval $2t_b$) there will be collision and none of the data burst will be received correctly. The interval $2t_b$ is thus a vulnerable period.

Prob [No other data burst is received within the vulnerable period $2t_b$]

$$= \mathrm{P}\left(k = 0,\ \tau = 2t_b\right) = e^{-2\lambda t_b} = e^{-2G}$$

Mean number of data burst arrival in time t_b is $\lambda t_b = \mathrm{G}$. Mean number of data bursts that are successfully received per unit time which is also known as throughput (S) of the ALOHA technique is given by

$$\mathrm{S} = \lambda t_b . e^{-2\lambda t_b} = G.e^{-2G}$$

The maximum throughput is achieved when

$$\frac{\mathrm{dS}}{\mathrm{d}G} = 0$$

$i.e., -2G\, e^{-2G} + e^{-2G} = 0$

Hence,

$$G = \frac{1}{2} \text{ and } \mathrm{S}_{\max} = \frac{1}{2e} \cong 0.182 \tag{8}$$

Now, Prob {data burst is transmitted successfully after exactly i attempts}
= Prob {first $(i - 1)$ times failure and i^{th} time success}

$$= (1 - e^{-2G})^{i-1} .\ e^{-2G}$$

Average number of attempts each AWS has to make for successful data transmission is

$$= \sum_{i=1}^{\infty} \text{Prob}\,\{\text{data burst being successfully transmitted after } i \text{ attempts}\}.i$$

$$= \sum_{i=1}^{\infty} (1 - e^{-2G})^{i-1} . e^{-2G} .i$$

$$= e^{2G} \tag{9}$$

For optimal configuration with $G = 1/2$ the average number of attempts needed for successful transmission is $e \cong 3$. Each AWS is therefore programmed to transmit a data burst thrice to overcome collision with bursts being simultaneously transmitted by two or more AWS.
