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Satellite-Receiver Ground Stations: Low Cost Options

By

R E Aitchison
Summary: This paper discusses alternatives to the purchase of commercial turn-key ground stations for the reception of satellite transmissions. The emphasis is on the design and assembly-construction of such ground stations by operators using the basic design principles involved and commercially available components and user-built interfaces. Specific examples apply mainly to 2GHz weather satellite ground stations, but are applicable for other satellite transmission.
SATELLITE GROUND STATION RECEIVER SYSTEMS - LOW COST OPTIONS

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1. Introduction
2. Overall Design Philosophy
3. Site Location and Services
4. Antenna and Antenna Feed System; Design Construction and Testing
5. R.F. Amplifier, Local Oscillator and First Mixer

Note: This printed paper is a summary of some of the material presented as a lecture. The overhead projector material has not been included, but is given in reference format. Some non-technical material has been included for participants interested in the social, national, and political aspects of the use of satellite technology. It is not a report on the state of satellite communications technology in Australia, but it is a report on the successful use of satellite technology by a non-paying user using do-it-yourself receive-only ground station construction to access satellite transmission of infra-red and visible images of earth.
1. A. INTRODUCTION

While satellite ground station receiver systems have in the past been mainly of interest to very large government, semi-government, or commercial organisations in developed countries, new applications of satellites open up exciting possibilities to many other classes of potential users if the major barrier of high ground station cost can be overcome.

The extreme case is represented by Direct Broadcast Satellite (DBS) systems, where television (colour picture and sound) is broadcast directly from a geostationary satellite to the final users. Although the potential exists for lowering cost in such systems because of the economies introduced by large scale production, cost is still a major factor simply because it has to be so low, and comparable to the cost of a colour television receiver (i.e. doubling the basic price).

However there are many other uses of satellite transmission, both from existing satellites and future systems, where the high cost of a ground station receiver system severely limits the uses to which satellite transmissions can be applied and the number of potential users. This particularly applies in developing countries.

Examples include transmission for remote sensing, the most common being the weather data transmitted as visible and infra-red images of earth; navigational data such as the Global Positioning Satellite (GPS) transmissions; and marine communications, safety and distress transmissions such as the Marots system. [2-6]
This article summarises some alternatives to the purchase of turn-key complete systems from suppliers. While the direct experience reported relates mainly to the 2 GHz geostationary weather satellite transmissions and their reception and processing, many of the approaches outlined can be applied with appropriate modification to the 4-6 GHz and 12 GHz bands. As a major part of the cost of satellite ground station receivers is in the design of the system, emphasis is given to design principles.

Apart from the reduced cost, participation in the design and construction of such system is essential if the user country is to receive the full benefits from the wide range of services available from satellite systems.

While few countries can at present develop facilities for the manufacture and launch of satellites, ground based facilities, receiving systems and even up-link transmission systems are a straightforward extension of existing communication services.

However, it is necessary for national governments and politicians to take the step forward of making local involvement a pre-requisite to the introduction of these new and expensive technologies.

Participation can occur in a number of ways, i.e.:

(i) By "offset" programmes. Overseas purchase is conditional on a portion of the contract cost being offset in manufacture in the user-country.

(ii) By the requirement of full technical information as a condition of full purchases, this to include documentation or all hardware and software and preferably training programmes.

(iii) Supplementation of such systems by increased training of engineers, scientists and technicians as a national priority. Training either locally, overseas, or both.

(iv) By manufacture by the user of system components and systems, with the aim of high user-country content in the system.
B. HISTORICAL NOTES

When the first orbitary satellites, of the USSR and the USA, were launched, many of the transmissions, either by accident or design, were passive and required no interrogation from ground. In the cause of the weather satellites transmitting VHF (around 137 MHz) reception of the signals and processing to produce image was an interesting challenge, with lots of experimental projects for students — in addition there was no charge for access to the transmissions, which gave valuable data to every country under their orbital path.

The techniques involved are a trivial extension of those used in radio astronomy, so that even with scant details of the modulation systems, it was possible to produce daily or hourly images of earth in the visible and infra-red, which were of great value and interest in weather recording and forecasting. These systems in the 1970-1975 period gave way to higher resolution systems, both orbiting as far the NOAH and TIROS series of the USA, and geostationary (GMS 1, 2, 3 of Japan). The transmission were at L-band, around 1.7 GHz, at the systems more complex. But again these systems were passive and accessible at no charge to any user.

The cost of ground stations for these high resolution systems deterred many from using the transmissions. Even government for example in Australia, took many years to take the plunge and buy a ground station at great expense from overseas sources.

But we simply set about building a station which has operated successfully for some time and even pays its own way by the sale of images to TV and radio networks (in competition with a government weather bureau which now has a station).

This paper is a record of designing and building a receiver only ground station at 2 GHz for satellite images.
However, it is a minor detail to extend the system to receive only orbiting satellite stations and details are given of such a system which is operational.

It is also a relatively minor problem to extend the design and construction to 4-6GHz receiving stations, and up-link transmitters are also feasible, but involve high-level negotiations with organisations and owners of the satellites. The limit on UP-LINK antenna size is approximately 7 meters using simple construction techniques.

The first hurdle is having personal able to and interest in the design and construction of a satellite receiving station. With a suitable approach to the design costs are low and the necessary facilities available in any small mechanical and electronic workshop.

The design philosophy is vital and is given in some detail. The bibliography and references cited give further details for those interested in construction and design of receiver systems for satellite transmissions.
OVERALL DESIGN PHILOSOPHY

The single most important factor in the overall design of the ground station is the signal to noise ratio of the final signal. This in turn depends on the carrier to noise ratio of the signal at the ground station receiver system input, and the particular method of modulation used in the satellite transmission. As the amount of power available in the satellite transmitter is limited, particularly during earth-eclipse periods, while a relatively large bandwidth is available, some form of wide band modulation such as frequency modulation of the satellite transmitter is commonly used. As more satellites, particularly geostationary satellites, come into service this trading of power for bandwidth of satellite transmissions may not be as readily available, and high carrier to noise values referred to the receiver system input may have to rely more on higher antenna gain and higher output from the transmitter in the satellite, and rely less on wide bandwidth to achieve satisfactory carrier to noise ratios.

The relationship between the variables concerned is given in equation (1).

\[ T_s = T_a + (F-1)T_o + (1-L)T_o \]  

where \( T_s \) is the system noise temperature  
\( T_a \) is the antenna noise temperature when pointing to the sky, due to sky and background noise and feed losses.  
\( F \) is the noise factor of the receiver system (noise figure = 10 \log_{10} F \text{ (dB)}); \( F \) is mainly determined by the input stage, but may include contributions due to later stages.  
\( T_o \) reference temperature, 290°K  
\( L \) rain loss (rain attenuation = 10 \log_{10} L \text{ (dB)}) .  
Mainly refers to higher frequencies i.e. 12 GHz.

Given the system temperature we can then determine the carrier to noise ratio referred to the input of the system. A figure of merit which is
used for satellite receiver systems is $G/T$ (in effect $G/T_s$ in equation 1 above), where $G$ is the antenna gain. It is usually expressed in $\text{dB/K}$.

The carrier to noise ratio at the system input is given in equation (2)

$$C/N = \left( P_s \right) \left\{ \frac{G}{L_s} \right\} \left\{ \frac{1}{k T_s} \right\}$$  \hspace{1cm} (2)

The first bracketed term is the equivalent power transmitted by the satellite (the equivalent isotropic radiated power), the second gives the reduction in power due to path loss ($L_s$) and rain loss ($L_r$), and the increase due to antenna gain ($G$), while the third term in brackets is the system noise power, where $k$ is Boltzmanns constant, $T_s$ the system equivalent noise temperature, and $B$ the system bandwidth in Hertz.

If all quantities are expressed in decibels equation (2) becomes

$$C/N = P_s + G/T - L_s - L_r - k - B$$  \hspace{1cm} (3)

(Note that $k$ is -228.6 in equation (3).)

For simple modulation systems such as amplitude modulation $C/N$ must be large for good reception (40 to 50 dB). For FM systems with a high modulation index ($m > 1$) $C/N$ may be much lower (10 to 20 dB) with the final signal to noise ratio improved by the demodulation process and the characteristics of FM.

For more complex coding schemes using pseudo-random codes and spread spectrum techniques $C/N$ may be much lower (less than 1 or negative when expressed in decibels).

In the overall system design it is necessary to set values for the various quantities in equations (1) and (3) on the basis of the required final
performance of the system, expressed mainly in terms of signal to noise ratio. However margins are necessary to account for degradation in performance due for example to rain input losses and noise through corrosion of antenna feeds, changes in input amplifier characteristics, interference etc. Even more important is the balancing of system component cost against performance. For example the same system performance can be achieved with a small antenna with a very low noise input system, or by using a much larger antenna with a higher noise input stage. It is only by a careful analysis of the cost and benefits that an optimum final design can be produced.

In the following sections the principles governing the choice of the variables in equations (1) and (3) are considered as a guide to balancing system and component performance against costs. It is important to reorganise that the satellite-ground station link (and vice-versa) introduces problems different to those found in terrestrial communication system. Once a signal of adequate signal to noise ratio is available, the existing signal processing and communication system technologies used on land (and in undersea cable systems) can be applied, with perhaps some problems due to the long transit time of signals to satellites and from satellites to earth.
3. SITE LOCATION AND SERVICES

Ideal sites in remote locations shielded by the surrounding terrain from sources on man-made interference, with stable mains supply, offer no problems.

Practical sites, often in the middle of large cities, with fluctuating electricity mains and mains-propagated and radiated interference may produce problems in any complex electronic installation, including a satellite receiving station.

Most of the problems can be avoided by appropriate design of:

(i) Mains Supply, i.e. mains filtering, isolating transformers, protection from lightning transients etc.

(ii) Radiated interference suppression, i.e. reduction of antenna side-lobes (see below), avoiding aircraft flight paths etc.

(iii) Rain alternation margins; i.e. for 10-12 GHz systems (and alone) some margins maybe needed for potential rain alternation (see below).
4. **ANTENNA AND ANTENNA FEED SYSTEM**

### 4.1 Antenna Size and Gain.

The antenna is normally a paraboloidal reflector with an appropriate feed system. The antenna gain $G$ in dB at the operating wavelength $\lambda$ is given by

$$G = 10 \log_{10} \left( \frac{4 \pi A_r}{\lambda^2} \right)$$

where $A_r$ is the effective area of the paraboloid. This is less than the geometric aperture of the paraboloid, the quantity $\eta$ denoting the aperture efficiency i.e.

$$A_r = A_0 \eta$$

Hence where $G$ is expressed in dB we have

$$G = 10 \log_\eta \left( \frac{\pi D^2}{\lambda^2} \right)$$

Values of $\eta$ are typically in the range 0.5 to 0.6 (refer later sections). Hence using $\eta = 0.55$ we obtain the results shown in Figure 1 where the gain $G$ in dB is given in terms of the parameter $D/\lambda$. The appropriate physical diameter of the antenna aperture is obtained by multiplying the values of $D/\lambda$ by 15cm, 5cm, and 2.5cm for the frequency bands 2GHz, 6GHz, and 12GHz respectively.

The beam width is also determined by $D/\lambda$ and the way in which the aperture is illuminated by the feed. For the type of tapered illumination giving a value of $\eta \approx 55\%$ the value of the 3dB beamwidth is approximately $\left( \frac{\pi}{D/\lambda} \right)$ degrees. This is also plotted in Figure 1. Again the appropriate physical diameter for a given beamwidth for a particular frequency band can be derived. For the illumination of the aperture used for Figure 1 the first null in the antenna pattern is at $\approx \frac{118}{D/\lambda}$ degrees, the level of this side-lobe being approximately -25.5 dB down on the main lobe.

The surface accuracy of the antenna will affect both the gain and the beam angle. The usual criterion is for the peak-to-peak
deviations not to exceed $\lambda/16$ from the desired surface to keep errors to acceptable levels. The surface may be either solid metal (usually aluminium sheet) or perforated mesh. With mesh of $\approx 50\%$ open area (holes 4.75 mm diameter at 6.35 mm centre) the reflectivity is $\approx 98\%$ at $\lambda = 15$ mm, so even with this type of mesh the performance is adequate up to the 12 GHz band. Large dishes (up to 5 m diameter) can be fabricated using simple workshop equipment and jigs and can give good performance certainly up to and including the 12 GHz band.

4.2 Antenna Temperature.

Ideally a directive antenna pointing to the clear sky should have an antenna temperature approaching that of the background $4^0K$ radiation. However practical antennas are not ideal, and there are contributions to the antenna temperature from both non-ideal components and due to emissions received from galactic sources and from earth through the antenna side-lobes.

The galactic contributions decrease rapidly at frequencies over 1GHz. Practical antennas of simple construction at 12GHz have typical antenna temperatures of $\approx 40^0K$, with values around $60^0K$ at 2GHz. Lower values are achieved for special applications (such as deep space communications and radio astronomy research). The antenna feed system (refer below) also contributes significantly to the antenna temperature.

4.3 Antenna Feed.

The type of antenna feed is determined by the $f/D$ (focal length over diameter) value of the paraboloid. Shallow dishes ($f/D > 0.4$) are simpler to construct, and the small illumination angle for the antenna feed permits the use of simple feed systems. For deep dishes with $f/D = 0.4$ or lower the illumination angle exceeds $139^0$ and adequate illumination of the antenna surface is more difficult, the difficulty increasing rapidly as the $f/D$ ratio falls below 0.4.
For narrow angle feeds (<130°) a tapered cylindrical waveguide can be used to illuminate the paraboloid, with the illumination adjusted to give reduced illumination at the edges of the dish [25,26]. A satisfactory performance in both E and H planes can be obtained by varying the parameters of the design. For wide angle feeds (≥130°) it is necessary to spread the illumination of the cylindrical waveguide by placing corrugated choke flangs on the outer walls of the cylindrical guide [27,28,29]. Although the design is not as straightforward and may involve modelling of the antenna feed it can be designed to give the required illumination taper and equal or near-equal E and H plane responses.

For linearly polarised antenna feeds the dipole or other system which excites the circular guide uses standard coaxial to waveguide transitions or in-guide amplifier systems. However as circular polarisation is often used [24] to separate transmissions some form of circularly polarised feed is often needed. Feeds based on the turnstile junction are capable of supplying output for both RH and LH circularly polarised transmissions [30,31].

### 4.4 Antenna Testing

Testing of antennas must be carried out with far-field illumination. Basically this involves a point source at a distance

\[ R > \frac{2D^2}{\lambda} \]

where \( D \) is the antenna diameter. For \( D = 5 \text{ m}, \lambda = 17 \text{ cm}, \quad R_f > 280 \text{ m} \). Carrying out such tests is difficult without a suitable source. A simple procedure is to use radiation from the sun as a means of calibration. An advantage is that movement of the sun across the sky can be used for determining the beam width, allowing appropriate corrections for the finite size of the source [32] which is about
32 minutes of arc at microwave frequencies. The actual flux density varies widely on both a short-time and long-time-scale basis, but is measured daily and this data is available for absolute calibrations [33,34]. Alternatively geostationary satellite transmissions can be used, but with some problems due to the complex modulation systems used in the transmissions.

With adequate information on the flux density and angular width of the source the antenna efficiency and beam width can be determined.

4.5 Antenna Mounting.

For geostationary satellites the antenna mounting is straightforward, and the altitude and azimuth of the fixed antenna mount can be calculated from the orbital data, the final trimming of the mount being effected with small adjustments to the fixed mounting. As the inclination of the orbit introduces a North-South apparent motion of the satellite over its sub-point, it may be necessary for the antenna to have some motion in the mounting to give maximum signal. This particularly applies if the antenna beam width is narrower than the N-S variation in satellite position, as may be the case for large dishes. A simple adjustment can be carried out by a hydraulic cylinder and appropriate hinges in the mounting.

For orbiting satellites the mounting and drive system are a significant part of the overall cost of the installation. An X-Y mount is particularly suitable for satellite tracking, and manually controlled steering or pre-programmed steering is normally adequate for antennae with beam widths of a few degrees. For narrower beam-widths much more complex system are necessary.
5. R.F. RECEIVER

5.1 Low Noise Stage.

While the design and construction of low noise radio frequency amplifiers for microwave signals is not straightforward, recent advances in low noise gallium arsenide field effect transistors have simplified the problem, provided adequate testing and measurement equipment is available. In addition it is possible to purchase suitable off-the-shelf amplifiers. Usually these are wide-band (i.e. octave band) amplifiers, so that there is a problem with image frequency noise. Ref. 35 gives some details of commercially available GaAs transistors, and Ref. 36-37 of some low noise amplifiers. The noise and gain of GaAs amplifiers are also improved dramatically by cooling the transistor to low temperatures, as shown in Ref. 38. Peltier cooling is inexpensive and practical.

While some selectivity in the input stage is desirable it involves a custom design. Some image rejection occurs in the antenna feed system if the first IF frequency is high enough (see below). However it is quite practical to introduce some selectivity in the output of the first RF amplifier stage. Image reject mixers (see below) are an alternative.

5.2 1st Mixer, Local Oscillator and IF Amplifier

A stable local oscillator for the first mixer normally would be an expensive special design. However harmonically locked oscillators with voltage controlled oscillators and phase locked loops are becoming available. Some examples of commercial units are given in Ref. 39. The locking signal at relatively low frequencies can be produced by straightforward techniques using 5th overtone crystal oscillators and bipolar frequency multipliers. The first IF frequency is normally
a relatively high frequency (70 MHz or higher), and suitable mixer IF amplifiers are available for this application (Reference 40). Image-reject mixers which give 15 to 20 dB rejection of the image frequency can eliminate the need for selectivity in the radio frequency stage.

5.3. Power Supplies, Interconnections, Monitoring

Most interconnectors of microwave components involve coaxial connectors and cable. The best systems use one connector type (i.e. SMA 4 mm) and the best coax i.e. semi-rigid copper-jacketed-PTFE insulated coaxial cable with soldered connectors. Power supplies and power supply monitoring are routine items, but vital in system maintenance.
6. SECOND IF SYSTEM AND SIGNAL PROCESSING

The main part of the systems ability to reject unwanted signals and noise is obtained in the second IF amplifier. The improvement in signal to noise ratio given by demodulation of FM signals or PCM signals is also produced in the high signal level portions of the system. Also the final information (in our case images of earth) must be decoded, produced in useful form, and often stored where systems operate unattended.

However, all of these electronic techniques are common in consumer appliances such as TV receivers and AM-FM radio receivers so that both components, systems and circuits are familiar to designers and technicians. The large cable TV, HBO (Home Box Office) TV, TVRO (Television Receive Only) and DBS-TV (Direct Broadcasting Service Television) markets have produced a wide range of components - systems at low cost. In addition the standard telephone communication system of any country introduces a high level of technical, design, and component knowledge which can also be applied to processing of the signals.

The details vary with the application, but by making use of the existing situation, particularly as regards consumer radio-TV appliances, systems can be designed and produced at low cost.

LASER PRINTER

In our case a major hurdle was a high resolution laser printer. Cost at the time (1979) approximately US $24,000. This barrier was crossed by building one using dry silver paper (3 m), thermally developed, and standard laser and optical components as used in basic research.
7. FUTURE TRENDS

As geostationary and orbiting satellites come into use more widely the components involved in a ground station are most likely to be readily available on an off-the-shelf basis at low prices. Additionally components intended for other applications on the consumer market (laser printers, synthesiser receivers etc.) make available high performance components at low prices which can be used as sections of a complete system given some ingenuity on the part of the designer and construction personnel.
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