Receiving Oscar-5

by Dr A. Gschwindt, HA8WH*

This is a description of the methods used, and the results obtained by the Budapest Technical University with the Australis-Oscar 5 satellite.

THE INTERNATIONAL AMATEUR RADIO UNION
REGION 1 DIVISION

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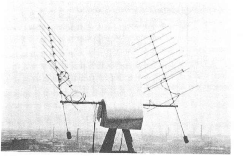

Receiving aerial

THIS article describes the receiving station which was in operation at Budapest Technical University during the lifetime of Oscar-5. The development and construction of the station was carried out by the members of the space research group of the university's microwave chair.

It is hoped that the ideas presented may encourage others to participate in the work connected with future satellites. Unfortunately the high electrical noise level in the heart of Budapest restricted reception to the 144MHz signals.

Basic considerations

Before describing in detail the equipment used, the factors which influenced its design will be considered.

First, consider the signal-to-noise ratio of signals coming from the satellite, assuming the following data:

(a) transmitted carrier power from the satellite $P_t = 50\text{mW}$; or in decibels relative to 1W: $P_t = -13\text{dBW}$.
(b) the distance between the satellite and the receiver aerial, with an assumed orbit height of 1,500km, when the satellite is near the horizon: $D_s = 4{,}500\text{km}$.
(c) the wavelength of reception: $\lambda = 2{\cdot}08\text{m}$.
(d) the gain of the cross-polarized receiver aerial: $G_r = 8\text{dB}$.
(e) free space loss between the satellite and receiver antenna:

$$a_f = \frac{20 \lg 4\pi D_s}{\lambda} = 20 \log \frac{4\pi 4{\cdot}5 \times 10^6}{\lambda} = 148\text{dB}.$$

From previous results the carrier power measured at the receiver aerial terminal can be determined:

$$P_c = P_t + G_r - a_f.$$

To obtain the signal-to-noise ratio of the received signals the noise power at the input of the receiver should be calculated using the following data:

Noise figure of receiver used for reception:

$$F = 4\ k\ T_o.$$

where k = Boltzmann constant

$$T_o = 273°\text{K}.$$

In the 2m band the average sky noise temperature (T_a) approximates to T_o, so the noise power measured in 1Hz bandwidth is:

$$P'_n = [(F - 1)\ T_o + T_a] \simeq F\ k\ T_o \quad \text{WHz}.$$

expressing the power of $k\ T_o$ in decibels relative to 1W:

$$P'_n = F - 204 \quad \text{dBW/Hz}.$$

The i.f. bandwidth in the case of A3 mode transmission must be twice the maximum modulation frequency, which is 1,500Hz. So the minimum receiver i.f. bandwidth is 3,000Hz.

$$B = 3{,}000\text{Hz}.$$

Bandwidth in decibels above 1Hz:

$$10 \log B = 10 \log 3{,}000 = 35\text{dB}.$$

Received noise power in the whole band:

$$P_n = F - 204 + 10 \log B\ \text{dBW}.$$

From previous results the carrier signal-noise ratio is:

$$\frac{P_c}{P_n} = P_t + G_r - a_f - (F - 204 + 10 \log B) = P_t + G_r - a_f - F + 204 - 10 \log B.$$

Substituting in the formula:

$$\frac{P_c}{P_n} = -13 + 8 - 148 - 6 + 204 - 35 = 10\text{dB}.$$

Thus the carrier signal-noise ratio measured before the demodulator will be about 10dB.

After demodulation the sidebands and not the carrier are used, so the result must be modified to obtain the true signal-to-noise ratio for sidebands measured at the af output of the receiver:

$$\frac{P_s}{P_n} = 2 \left(\frac{P_c}{P_n}\right) \left(\frac{m}{2}\right)^2$$

where m = modulation index

P_s = the power of demodulated signal.

Substituting m = 1 in the previous formula:

$$\frac{P_s}{P_n} = \frac{P_c}{P_n}\, 2\, \frac{1}{4} = \frac{1}{2} \frac{P_c}{P_n}.$$

The signal-to-noise ratio for the modulated signal will be half of the carrier signal-to-noise ratio.

The result expressed in decibels is:

$$\frac{P_s}{P_n} = \frac{P_c}{P_n} - 3 = 10 - 3 = 7\text{dB}.$$

These results provide the best possible reception figures and the following considerations have been ignored:

(a) The supply voltage decreases during the lifetime of the

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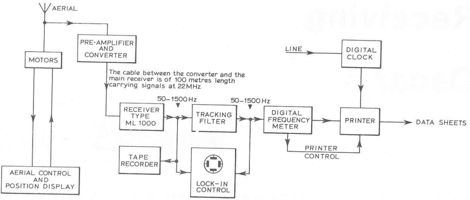


Fig 1. Block diagram of the receiving station

satellite, so the transmitter output power also decreases.

(b) For several days after the launch the satellite was tumbling, and fading was affecting the received signal.

Naturally, reception would be better when the satellite was above the receiving station. In this case the signal-to-noise improvement comes from a decrease in free-space loss. The improvement, which is proportional to the decrease in the satellite-receiver distance, can be calculated easily:

$$\frac{4,500}{1,500} = 3 \text{ times or } 5\text{dB}.$$

A signal-to-noise ratio of about 7dB is not sufficient for high accuracy frequency measuring when the digital frequency meter is connected directly to the output of the receiver. In Budapest Technical University's station the signal-to-noise ratio was improved with a reduction in bandwidth using a tracking filter.

Receiving station operation

The block diagram of the receiving station is shown in Fig. 1.

The signals transmitted from the satellite were received by a cross-polarized aerial system; the pre-amplifier together with the converter, which has an output at 22MHz, were located on the aerial mast.

The 22MHz signal was fed to a commercial hf receiver, at the output of which were the signals of the telemetry channels which lie within the 500–1,500Hz bandwidth. Improvement of the signal-to-noise ratio was carried out by the tracking filter; its correct operation being controlled by an oscilloscope.

During most of the receiving periods the output signal of the receiver was recorded on a commercial tape recorder to retain the telemetry signals in case of a fault in the counter chain.

The frequency of the telemetry signals was measured with a digital frequency meter and was shown on the display of the counter and at the output connection from the counter to the printer. The printer was controlled by the counter to print out the telemetry data every second. The time of the measurements was also printed; the time-signal being generated by a digital clock working with the mains as the time reference.

Aerial rotation was carried out with a hand-operated remote control. For the position display an analogue system was used.

Aerial

The aerial system was located on top of a seven-storey building; this location limiting its size, and because of the nature of the remote control it was decided to choose an aerial of simple mechanical construction.

A nine-element Yagi aerial was chosen, from two of which a cross-polarized aerial system could be produced. The cross-polarization reduced the fading originating from the tumbling of the satellite and the polarization-plane rotation of the ionosphere. The interconnection between the two aerials was designed to produce a 90° phase shift.

In some satellite passes only one half of the aerial was used, in which case the aerial was plane-polarized. This depended on the quality of the received signal which suffered from strong fading and from time to time disappeared in the noise. Although the gain of a single aerial was about 11dB, the two connected in parallel had about 8dB gain over the isotropic radiator. The relatively low gain is associated with a wide beamwidth which is advantageous during the tracking of a satellite.

Because of the simple aerial construction, the two perfectly balanced aerials were located at the ends of a horizontal aerial mast, as shown in the photograph. To reduce the effects of mast disturbances, the aerial plane was rotated relative to the horizon so that the two planes had a 90° angle between them. The rotation of the aerial in horizontal and vertical directions was carried out by two dc motors.

The position display was a simple analogue system. It consisted of two linear potentiometers rotated together with the aerial. The potentiometers, connected as a variable resistor, fed a constant-current dc generator, so the voltage measured on them was proportional to the aerial rotation. The accuracy of the position display was better than ±3 degrees.

Pre-amplifier and converter

The distance between the receiving room and the aerial was about 100m, and to eliminate the effect of large cable-loss a pre-amplifier was placed on the aerial mast, together with a converter and first-stage i.f. amplifier. The gain of the unit was about 40dB and the noise figure was $4kT_0$. All stages consisted of semiconductors; the supply voltage fed the converter via the inner conductor of a coaxial cable.

Receiver

This was a Hungarian hf communication receiver, type ML1000, which had a 3kHz i.f. bandwidth. No circuits for the correction of Doppler shift were incorporated and the tuning correction was performed manually.

During the reception of the satellite's signals, development of a product detector system with automatic Doppler correction was started, but unfortunately it was impossible to prove it during the lifetime of the satellite. This type of detector ensures the elimination of the knee effect in the reception of A3 signals. Where envelope detectors are used with a 3–5dB detector input signal-to-noise ratio, the detector output signal-to-noise ratio decreases very sharply.

Tracking filter

From the estimate of the expected signal-to-noise ratio it was seen that generally the signal-to-noise ratio measured at the output of the receiver would not be sufficient for high accuracy frequency measurement. The process used to improve the output signal-to-noise ratio was based on the following theory:

The frequency of a single signal being received continuously during the 6·5s period had to be measured, and using the receiver output signal a wide noise spectrum was connected to the input of the counter. In the 1,500Hz bandwidth the useful information was a single signal, and the variation of the modulation signal was very low during the 6·5s time interval.

A poor match exists between the receiver output and counter. If we take a bandpass filter and decrease the bandwidth near the desired frequency, for example one-tenth of the original bandwidth, we get a 10dB signal-to-noise improvement at the output of the filter.

However, it is not practical to tune the filter by hand every 6·5s from one frequency to the other; although the tracking filter used in this system operated in this way, the tuning was automatic. The block diagram of the tracking filter is shown in Fig 2; its operation being based on the phase-locked loop.

In the ssb generator the af signal is shifted up into the 450·5–451·5kHz band, a process found in all ssb transmitters. The signal located in the 450kHz band is amplified and then connected to the input of a limiter which removes the amplitude variation of the signal to ensure a constant amplitude signal for the phase detector.

The output of the limiter is filtered with a parallel tuned circuit, and the amplitude and band-limited signal is connected to the input of the phase detector unit through a buffer amplifier.

Phase-locked loops design points

Take one-tenth part of the incoming signal bandwidth, namely 150Hz, as the loop bandwidth. Theoretically it is possible to use a smaller value but this means the decrease of the lock-in band. To make an automatically following loop with, say, an oscillator frequency of 451kHz, the phase-locked oscillator will find the incoming signal in the 451 ±0·5kHz range. Any further decrease in the loop bandwidth will result in the lock-in range being so small that the system will lose the incoming signal when the satellite switches the telemetry channel.

At the output of the phase-locked system the signal frequency is within the range of 451 ± 0·5kHz. This signal is mixed with that originating from the carrier oscillator of the ssb generator, 450kHz, and the difference of the two signals is the channel frequency measured at the output of the receiver.

There is no difference in the frequency of the two signals, but the output of the tracking filter has a 10dB signal-to-noise improvement over the signal at the receiver output.

Tracking filter circuit

The tracking filter consisted of two independent units; an ssb generator and a phase-locked loop.

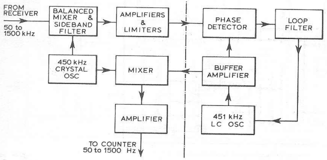


Fig 2. Block diagram of tracking filter

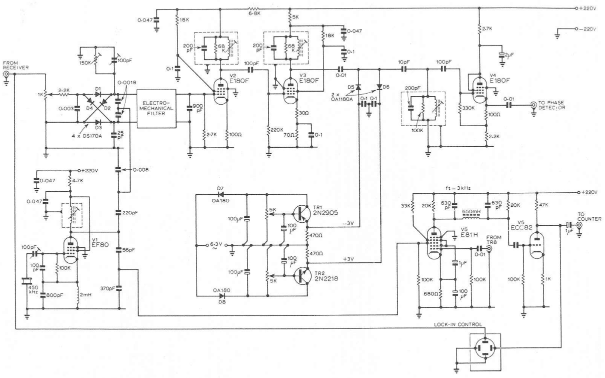


Fig 3. SSB generator and mixer circuit diagram

The circuit diagram of the first unit is shown in Fig 3. The signal from the receiver output is fed to the balanced modulator, the carrier generator having a 450kHz crystal to ensure the stability of the frequency source (V1). From the output of the balanced modulator, where the signal is a two-sided a.m. signal, the upper sideband is filtered out with an electromechanical filter.

The ssb signal, amplified by valves V2 and V3, is limited by a parallel diode limiter; the maximum value of the clipping is about 20dB. The bias voltage for the limiter diodes is produced from the ac heater voltage. TRI and TR2 work in emitter follower configuration to give low internal resistor voltage source for the limiters. From the limiters the signal is fed to the output of the unit through a bandpass filter and a buffer amplifier.

The 450kHz signal produced by V1 is fed into the mixer (third grid of V5), and the first grid of the mixer is fed with the signal of the phase-locked LC oscillator from the second unit. The output of V5 through the low-pass filter is amplified and switched to the counter. The low-pass filter has a cut-off frequency of about 3kHz to remove the 450kHz components.

The circuit diagram of the phase-locked loop unit is shown in Fig 4. The limited signal located in the band 451 ±0·5kHz feeds the input of the phase detector, TR3, TR4, TR5, D3, D4 and D5, which was constructed without a transformer—the asymmetrical inputs giving simple connection possibilities.

The signal at the output of the phase detector, which in the locked-loop condition varies proportionally with the phase and frequency of the incoming signal originating from the satellite, guides the phase and frequency of a Clapp oscillator through the loop filter.

The control devices are two Varicap BA124 diodes connected in parallel. With the help of the potentiometer it is a simple matter to tune the LC oscillator frequency to ensure the lock-in process at the start.

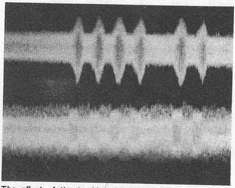
The buffer amplifier, TR7, is an emitter follower after the LC oscillator. The buffer output feeds the phase detector and the output of the unit, while the output signal of this unit feeds the first grid of V5 which is working as a mixer.

Control of the tracking filter

When the tracking filter is working correctly, the frequency is the same at the input as it is at the output of the filter. If the signals at the input and output of the tracking filter are switched into the horizontal and vertical input of an oscilloscope an elliptical (Lissajous) figure is shown when it is in locked condition. If it is a rolling figure, either the loop is not working correctly or the output frequency of the filter is not the same as the frequency transmitted by the satellite. In practice, this mode of loop control was a simple way of watching the tracking filter at work. Except during some extremely bad receiving conditions it was sufficient to control the loop lock-in process at the rising of the satellite, and all went perfectly during the pass.

Frequency measurement

The digital frequency meter used in the experiment was a Hungarian product, type TR5250, which has an upper count frequency of 10MHz. A measurement accuracy of 1Hz was



The effect of the tracking filter on HI signal when the reception was poor

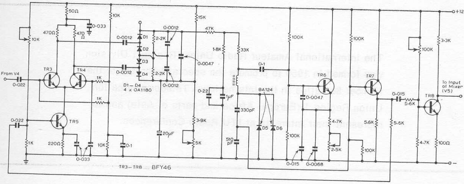


Fig 4. Phase-locked loop circuit diagram

Table 1. Data print-out with time display. Copy of original data sheet during orbit 177

Time (MEZ)	Channel frequency (kHz)	Channel number
15.30.06	1.245	1
15.30.07	1.247	1
15.30.08	1.245	1
15.30.09	1.245	1
15.30.10	1.246	1
15.30.11	1.125	–
15.30.12	0.701	2
15.30.13	0.710	2
15 30.14	0.705	2
15.30.15	0.785	2
15.30.16	1.037	–
15.30.17	0.773	3
15.30.18	0.783	3
15.30.19	0.788	3
15 30.20	0.787	3
15.30.21	0.787	3
15.30.22	0.788	3
15.30.23	0.786	3
15.30.24	0.749	4
15.30.25	0.722	4
15.30.26	0.715	4
15.30.27	0.709	4
15.30.28	0.706	4
15.30.29	0.698	4
15.30.30	0.853	–
15.30.31	1.260	5
15 30.32	1.260	5
15.30.33	1.261	5
15.30.34	1.262	5
15.30.35	1.254	5
15.30.36	1.261	5
15 30.37	1.439	6
15.30.38	1.442	6
15.30.39	1.440	6
15.30.40	1.444	6
15.30.41	1.446	6
15.30.42	1.447	6
15.30.43	1.336	–
15 30.44	1.287	7
15.30.45	1.290	7
15.30.46	1.289	7
15.30.47	1.290	7
15.30.48	1.291	7
15.30.49	1.141	–
15.30.50	0.623	start
15.30.51	1.214	of HIs

Table 2. The effect of the tracking filter on the accuracy of the data

Channel frequency (kHz) Without tracking filter	With tracking filter	Channel number
1.279	1.254	1
1.284	1.256	1
1.269	1.250	1
1.281	1.252	1
1.306	1.236	–
0.960	0.074	–
0.782	0.642	2
0.810	0.642	2
0.838	0.642	2
0.840	0.642	2
0.806	0.641	2
0.860	0.691	3
0.861	0.731	3
0.871	0.729	3
0.875	0.731	3
0.888	0.731	3
0.911	0.729	3
0.869	0.649	4
0.842	0.602	4
0.853	0.605	4
0.822	0.602	4
0.908	0.608	4
0.945	0.600	4
1.295	0.979	–
1.345	1.245	5
1.324	1.234	5
1.336	1.251	5
1.366	1.244	5
1.349	1.210	–
1.122	0.949	–
1.073	0.836	6
1.061	0.812	6
1.061	0.800	6
1.036	0.797	6
1.020	0.777	6
1.378	1.196	–
1.367	1.290	7
1.371	1.273	7
1.354	1.254	7
1.377	1.263	7
1.365	1.250	7
0.980	0.701	–
1.102	0.658	–

sufficient and the 1Hz resolution required 1s of gate time. In the 6·5s channel time four to five useful items of data were obtained because the counter was not synchronized with the channel time.

The measured frequency was readable in the display part of the counter and in parallel code at the output of the counter. The output of the counter fed the printer for automatic measurement and the gate signal controlled the printer start.

Digital clock and printer

In addition to the channel frequency, the time of reception was also printed out. The time signals came from a digital clock made at the university, and as there was no need for high accuracy, the clock was regulated by the mains supply.

A Hungarian fast printer, type PRE-10-P/161, was used. The control signal from the digital frequency meter commanded the printer every second to print the channel frequency and the time of reception on one line.

Results

An example from the output of the printer is shown in Table 1. Between channel numbers 1 and 2 the data is not correct because of the asynchronism between the channel switching and measurement points. The signal-to-noise improvement caused by the tracking filter is shown in two examples, Table 2 and the photograph; in the table the error is greater without the filter, and in the photograph the HI signals are clearer following the introduction of the filter and are lost in the noise without it.

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