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Summary

The performance of the Parkes 210-ft radio telescope for the reception of data from distant spacecraft has been demonstrated by observations on Mariner IV in the vicinity of Mars. Signal levels and frequencies received from the spacecraft were observed during a two-month period commencing June 21, 1965 and telemetry recordings were made during the picture transmission period following the Mars encounter. An attempt was made to observe the occultation exit which occurred below the normal horizon of the telescope. This report briefly describes the equipment used and the results obtained.

1. INTRODUCTION

Observations of the signals received from deep-space probes have been made with the Parkes 210-ft radio telescope as part of a NASA - supported study of the telescope's performance.

Experience with this type of operation was first obtained in 1962 on Mariner II transmissions from the vicinity of Venus using an L-band, crystal-mixer type, receiving equipment supplied by the Jet Propulsion Laboratory. This system provided signals 3 db above the threshold level and daily observations continued from December 20, 1962 until the spacecraft transmissions ceased on January 3, 1963.

Early in 1965, it was decided to carry out more extensive observations on the Mariner IV spacecraft, which was then on the way to Mars. The objectives of this experiment were to demonstrate the performance of the 210-ft dish for the reception of data from distant spacecraft, to record the picture transmissions during the critical post-encounter period and, if possible, to observe the occultation of the spacecraft by Mars on July 15.

Equipment from J.P.L. for converting the L-band receiver to S-band operation and a Hughes parametric amplifier unit from DS1F42, Canberra were received in Parkes early in June. The first signals from Mariner IV were obtained on June 21 and the experiment concluded at the end of August.

2. EQUIPMENT

2.1 Antenna System The parametric amplifier unit was installed on the focal-plane platform of the 210-ft telescope and connected by a 4-ft length of 7/8 in helix coaxial line to the feed. The latter, designed by D. Yabsley, consisted of a circular conical horn with a one-wavelength aperture operating in the TE_{11} mode and arranged to receive right-handed circular polarization.

With this feed the aperture illumination at the rim was -14 db. From previous performance studies, it was estimated that the antenna would have an isotropic power gain of 60.7 db at the paramp input. (Appendix.) This corresponds to a margin of about 7.7 db over the nominal gain of the standard S-band 85 ft tracking antenna, such as that installed at DS1F42, Canberra.

2.2 Receiving Equipment Before conversion to S-band, the receiver was transferred from the base tower to the turret radio room, which is on the rotating part of the structure. This avoided the problem of taking large-diameter cables through the cable twister and allowed the standard paramp control cables from DS1F42 to be used without modification. Tests of the reassembled receiver showed the performance was similar to that achieved during the 1962 Mariner II observations.

The conversion of the receiver to S-band was made with units supplied by J.P.L. The mixer and R.F. assembly were replaced with new components which were installed in the focus cabin of the telescope. The loop filter and V.C.O. were also replaced and a varactor multiplier added to the local oscillator chain. Special monitoring and test facilities were installed in the turrent room together with telemetry tape-recording equipment. Figure 1 is a block diagram of the final S-band system.

After conversion to S-band, the receiver noise figure was checked using an A.I.L. noise lamp. Initially it was found difficult to obtain a satisfactory noise figure with the new varactor multiplier installed. An improvement was obtained by tuning the remaining varactor multiplier cavity to the difference between the output and input frequencies. This increased the multiplier efficiency more than five times and permitted a mixer crystal current of 1 mA to be obtained.

Having obtained a satisfactory noise figure of approximately 8 db with the noise lamp connected directly to the mixer, the parametric amplifier was included and tuned according to the manufacturer's instructions. While parametric gains of up to 40 db could be obtained under ideal conditions, it was found that the maximum practical gain with the amplifier mounted at the focus was 20 to 25 db varying somewhat with temperature, line voltage etc. from day to day.

The System Noise Temperature Meter was calibrated by substituting a 50 ohm termination for the feed and observing the meter readings at room temperature (reading 500°K) and with the termination in liquid nitrogen (reading 275°K for 23 db parametric gain). This meter was subsequently used as an indication that the receiver was performing satisfactorily when the system noise temperature read between 180° and 230°K with the feed connected. An additional check was made using the radio source 3C 273 the signal from which gives an aerial temperature of slightly less than 30°K.

A system temperature of 200°K corresponds to a threshold level at the paramp input of -164.8 dbm (see Appendix). A typical system temperature for a maser equipped 85 ft tracking antenna is 60°K representing an advantage of 5.2 db. Allowing for the greater gain of the 210-ft antenna, the overall signal-to-threshold advantage of the Parkes facility was therefore about 2.5 db.

To measure the level of the received signals, the test oscillator was calibrated using the HP431B power meter. The oscillator output was fed through the HP394A variable attenuator and cable to the vertex thence through a directional coupler into the input to the parametric amplifier (Fig. 1). The test oscillator was then used to measure signal strength at the input to the parametric amplifier by substitution. Thus, figures for spacecraft signal strength are those measured at the input to the parametric amplifier. The attenuator and power meter calibrations were checked by the CSIRO National Standards Laboratory.

Measurements of the frequency of the received signals were made by measuring the frequencies of the V.C.O. and the reference oscillators (30.455 Mc/s and 455 kc/s) with a digital counter (model HP5245L) which has a frequency stability of about 3 parts in 10^9 per day. The crystal frequency of the counter was continuously standarized against the VLF transmissions from GBR Rugby, England*.

2.3 Telemetry Recording Equipment Tape recordings of the spacecraft telemetry transmissions were made from the phase detectors of both the tracking and telemetry channels of the receiver. (Tracks 2 and 3 of Pemco 4-track recorder, model 101). In all except the first few hundred feet of tape, the DC component of the detector outputs was blocked by 8 microfarad capacitors. Details of each recording were given by voice on the fourth track.

Short recordings of the spacecraft signals converted into binary form were also made. A demodulator was designed by P.R. Crosthwaite to accept the dynamic phase-error output from the 455 kc/s phase detector and to produce an output suitable for driving a Kelvin and Hughes pen recorder running at a paper speed of 1 cm per second.

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*For this purpose, a transistorized receiver giving continuous phase-comparison records was made available by the CSIRO Division of Applied Physics, National Standards Laboratory, Sydney.

The demodulator was designed to process a signal having the following characteristics (observed during setting up of the receiver):-

1. Sub-carrier frequency of 150 c/s produced by phase modulation of the S-band signal, and recovered as the dynamic phase-error output from the 455 kc/s phase detector of the tracking channel.
2. Double-sideband suppressed-carrier amplitude modulation of the 150 c/s subcarrier at a maximum bit rate of $8^{1}/3$ bits per second, the rectangular modulating waveform producing relative 150 c/s subcarrier phases of 0° and 180° at constant amplitude, corresponding to the two binary code states.
3. Required predetection bandwidth in the 150 c/s circuits of the demodulator of the order of 40 c/s to pass frequencies up to the fifth harmonic of the fundamental modulating frequency of $4^{1}/6$ c/s. Post-detection bandwidth of the order of 8 to 16 c/s (both adjusted in operation for best results at a given signal-to-noise ratio).

The block diagram of the demodulator (Fig. 2) shows the mode of operation. The 150 c/s modulated subcarrier, after passing through at 150 c/s bandpass filter, is doubled to provide a 300 c/s constant relative phase reference. This is used to phase lock a voltage controlled 300 c/s multivibrator which synchronizes a second 300 c/s astable multivibrator, followed by a divider to 150 c/s driving a balanced, gated, synchronous detector circuit. The filtered 150 c/s signal after phase shifting and amplification is also applied to the synchronous detector. The output of the detector, after passing through a low pass 8-16 c/s filter and D.C. amplifier/limiter, drives the recorder pen.

The free running stability of the voltage controlled 300 c/s multivibrator was adequate to maintain correct phasing during signal drop outs of several seconds. The polarity of the record obtained must be interpreted in relation to known reference elements, since the demodulation may lock in either the 0° or 180° subcarrier phase.

3. OBSERVATIONS

To fit in with other telescope programmes, Mariner IV observations were scheduled for a two-hour period each afternoon centred approximately on the meridian transit time of the spacecraft. Horizon to horizon observing periods were reserved for July 3, 14, 15 and 16. Arrangements were also made to expand the two-hour viewing period to give full coverage during the post-encounter picture transmissions should the need arise.

3.1 Measured Positions and Signal Levels Employing position data from J.P.L., Mariner IV was first located on June 21, 1965. After a few days of observations, it was possible to predict the spacecraft's position on the sky (right ascension and declination) by linear extrapolation from previously recorded positions. When several days had elapsed since the telescope was last available a second-order correction was made. This method was simple since the day to day changes in right ascension and in declination were small. Position measurements were made by varying right ascension and declination in turn to maximize the received signal.

During the two-month period of the observations the signal level, with the receiver functioning normally was at least 10 db above the level at which lock was lost. It was common to lock the receiver onto one of the two strong sidebands 150 c/s above and below the spacecraft carrier frequency. However, the lower signal level made it easy to distinguish the sidebands from the carrier.

Table I shows the measured position of the spacecraft each day and the strength of the received signal. These signal strengths are plotted in Fig. 3 as a function of distance together with a theoretical curve. For comparison, average measured intensities from DS1F42, Canberra and DS1F41, Woomera are given together with a theoretical curve for an 85-ft antenna. Both theoretical curves and the indicated receiver thresholds are based on the parameters given in the Appendix.

Figure 3 shows that the observed signal levels for both sizes of antenna are in reasonable agreement with theoretical levels and confirms the predicted 7.7 db gain superiority of the 210-ft antenna.

3.2 Telemetry Records Test recordings were made of the telemetry channel output early in July and were processed by J.P.L. Because of the additional signal-to-threshold ratio provided by the 210-ft antenna system, these were found to be of high quality.

Regular telemetry recording continued from July 8 to August 27 during the scheduled daily observing period. Horizon to horizon records were made on the day following Mars encounter when the first picture transmissions were in progress. In all, seven 14 inch drums of tape were recorded at Parkes and transmitted to J.P.L. Insulation leakage in the paramp cable affected the quality of some of the recording taken in August.

During the recording of the picture transmissions on July 27, a record of the signal in binary form was made over a period of several hours. Time did not permit the recording to be made on punched paper tape which would have been suitable for further processing to indicatepicture levels, but direct examination of the binary modulation showed the organization of the signal into the various synchronizing, data, and picture level periods, noted in further detail below.

A short sample section of the recording made is shown in Fig. 4 and the following details are noted, being common to all picture lines examined.

(1) About 174 picture elements or 1044 bits per line convey picture detail.

(2) A variable period of duration in the range 12 to 18 bits, all zero, appears at the end of each line and apparently represents variations in relative line and bit frequencies.

(3) About 90 bits of line and picture data or synchronizing information follow (2) above.

(4) The picture level information is then preceded by 14 repeated 6 bit elements of the form 000001, and 48 bits all zero.

(5) Total period occupied by one picture line plus data, reference and space elements is approxiamtely 154 seconds (recorded at paper speed of 1 cm/second), or 1284 bits with 6 bits per picture element of range 64 levels.

The recording was obtained under the following conditions:

Spacecraft radial distance: approx. 130 x 10^6 miles
Received signal level: -150 dbm
System noise temperature: 210°K
System noise level: -163 dbm (in demodulator post-detection bandwidth of 8 c/s).

Thus the calculated signal/noise power ratio was 13 db. The record shows the system to be operating well above threshold, but no practical assessment of the margin could be made. The measured margin of the tracking channel phase-lock loop above drop out was about 12 db.

3.3 Occultation Experiment The circumstances of the occultation of Mariner IV by Mars were very unfavourable for observations at Parkes with the 210-ft telescope. Predicted occultation entry was one hour (15 degrees) below the telescopes horizon set by the maximum zenith angle of 60°. Resumption of signals at Parkes after occultation was expected to occur 11 minutes (2.8 degrees) below the horizon. The latter corresponds to 18 beamwidths at S-band and coma losses for a normal feed offset to this extent would have been excessive. However, computations by D. Yabsley of the coma phase errors over the dish surface showed that the areas of large error (>90°) were confined to the outer regions. By narrowing the feed response pattern it was possible to practically eliminate the degrading effect of these areas and reduce the coma loss for a given beam deviation. A circularly polarized feed was designed by Yabsley with a response tapering to -13 db at ±30°, corresponding to an effective dish diameter of 93 ft with an f/D ratio of nearly unity. Operated 7.7 ft from the focal point this feed swung the beam 4 degrees below the horizon, (giving a safety margin of about 5 minutes on the predicted reacquisition time). Allowing for the lower system temperature of 175°K due to reduced spillover, the nett loss of signal-to-threshold ratio with the offset feed was 7 db, leaving a 3 db margin for observation of the occultation.

When tracking with an offset feed on an altazimuth-mounted dish, the pointing of the telescope must be continuously corrected to allow for changes of parallactic angle. The magnitude of the beam offset was established approximately from observations on the Moon (using the system temperature monitor) and then more accurately on Mariner IV before setting on July 14. Pointing corrections were computed from this data.

Predicted frequencies for the received signal at occultation exit became unreliable because of last minute changes in the occultation circumstances. A frequency setting for the Parkes V.C.O. was therefore computed from the frequency recorded for the V.C.O. at DSIF42 at occultation entry.

Reacquisition of the signal was achieved first at $03^h26^m20^s$ GMT but lock was lost after 10 seconds. The signal was locked again at $03^h28^m25^s$.

4. CONCLUSION

The experiments on Mariner IV with the Parkes radio telescope have shown that the 210-ft dish equipped with the standard S-band parametric amplifier has a margin of about 2.5 db over a maser-equipped 85-ft dish. The resulting gain in data-transmission performance has been demonstrated. Using identical receivers, the increase in performance with the 210-ft dish should be close to the theoretical figure of 7.7 db.

5. ACKNOWLEDGEMENTS

The observations at Parkes on the Mariner II and Mariner IV spacecraft transmissions have formed part of a performance study of the 210-ft radio telescope carried out under NASA Research Grant NsG-240-62. We wish to acknowledge the cooperation and support of R. Stevens and C. Koscielski of the Jet Propulsion Laboratory, Pasadena.

APPENDIX - THEORETICAL PERFORMANCE

Antenna Gain at 2297 Mc/s

Actual area of 210-ft aperture	:	34600 sq.ft
Efficiency (from radio astronomy measurements)	:	0.50
Power gain	:	60.7 db
Actual area of 85 ft aperture	:	5700 sq.ft
Nominal power gain	:	53.0 db
Deduced efficiency	:	0.53
Gain margin of Parkes antenna	:	+7.7 db

Signal Level

Spacecraft	(transmitter power	:	10 watts
	(antenna gain	:	40

Hence signal levels for spacecraft at 100 x 10^6 miles are found to be

(210-ft antenna	:	-146.9 dbm
(85-ft antenna	:	-154.6 dbm

Receiver Noise Level

Tracking bandwidth	:	12 c/s
Parkes system temperature (with parametric amplifier)	:	200°K
Hence noise power is	:	-164.8 dbm
System temperature for typical maser-equipped 85-ft antenna	:	60°K
Corresponding noise power	:	-170 dbm
Threshold improvement with maser	:	+5.2 db

TABLE I - OBSERVATIONS OF MARINER IV

Date (1965)	Acquisition Time (GMT) h m	Horizon Time (approx) (GMT) h m	Transit Time (GMT) h m	Measured R.A. h m s	Measured Dec. deg min	Measured Signal Level dbm
June 25	06 35	04 15	07 45	11 51 05	+01 03	-150
26	05 30	04 12	07 43	11 53 04	+0 50	-148
27	06 36	04 10	07 41	11 54 59	+0 37	-148
28	06 52	04 06	07 39	11 57 04	+0 24	-148
29	06 06	04 04	07 37	11 59 06	+0 11	-148
30	07 10	04 02	07 36	12 01 04	-0 02	-148.5
July 1	06 56	03 59	07 34	12 03 03	-00 15	-
2	06 09	03 56	07 32	12 05 03	-00 29	-149
3	03 59	03 54	07 30	12 07 06	-00 42	-149
4	06 38	03 51	07 28	12 09 04	-00 54	-148
5	06 10	03 48	07 26	12 11 06	-01 08	-149
6	06 30	03 46	07 24	12 13 09	-01 21	-149
7	06 19	03 43	07 22	12 15 08	-01 34	-148
8	06 14	03 41	07 20	12 17 05	-01 47	-148.5
9	05 58	03 38	07 18	12 19 09	-02 00	-149
10	06 37	03 35	07 16	12 21 14	-02 14	-149
11	06 41	03 33	07 14	12 23 09	-02 28	-149.5
12	05 52	03 30	07 12	12 25 10	-02 40	-
13	06 58	03 27	07 10	12 27 19	-02 54	-
14	04 32	03 24	07 08	12 29 38	-03 08	-
15	07 00	03 22	07 06	12 31 18	-03 20	-149.5
16	03 26	03 20	07 05	12 33 40	-03 34	-149.5
17	06 35	03 17	07 03	12 35 39	-03 45	-151.5
18	09 02	03 15	07 01	12 38 00	-03 59	-149.5
19	06 13	03 13	06 59	12 40 02	-04 09	-149.5
20	07 10	03 10	06 57	12 42 13	-04 22	-149
21	06 43	03 08	06 56	12 44 18	-04 34	-149.5
22	06 26	03 06	06 54	12 46 22	-04 47	-149.5
23	05 54	03 03	06 52	12 48 36	-04 58	-149.5
24	06 30	03 00	06 50	12 50 50	-05 11	-
25	06 20	02 58	06 48	12 52 59	-05 23	-149.5
26	04 43	02 55	06 46	12 55 04	-05 35	-149.5
27	03 25	02 53	06 44	12 57 09	-05 48	-
29	08 55	02 50	06 42	13 01 53	-06 13	-149.5
31	06 38	02 45	06 38	13 06 06	-06 38	-148.5

Date (1965)	Acquisition Time (GMT) h m	Horizon Time (approx) (GMT) h m	Transit Time (GMT) h m	Measured R.A. h m s	Measured Dec. deg min	Measured Signal Level dbm
Aug 1	09 30	02 42	06 36	13 08 30	-06 51	-
2	06 45	02 40	06 35	13 10 33	-07 03	-149.5
3	06 30	02 38	06 33	13 12 45	-07 16	-149db
4	04 00	02 35	06 31	13 14 46	-07 26	-149db
5	04 36	02 34	06 30	13 16 57	-07 39	-149.5
6	05 00	02 31	06 28	13 19 18	-07 52	-
9	04 25	02 24	06 23	13 25 55	-08 27	-150
10	07 10	02 22	06 21	13 28 17	-08 41	-150
11	07 30	02 19	06 19	13 30 37	-08 51	-151
12	08 55	02 17	06 17	13 33 00	-09 06	-150
13	04 39	02 16	06 16	13 34 55	-09 16	-
16	04 13	02 09	06 11	13 41 40	-09 53	-150.5
17	05 18	02 08	06 10	13 43 59	-10 04	-150.5
18	03 25	02 05	06 08	13 46 22	-10 16	-150.5
21	08 00	01 58	06 03	13 53 23	-10 53	-
23	05 56	01 53	05 59	13 57 46	-11 16	-150.5
25	03 45	01 49	05 56	14 02 19	-11 38	-
27	08 46	01 45	05 53	14 07 20	-12 05	-

Notes:

1. Time of acquisition on July 14 applies only for on-axis feed.
2. During August performance was affected by leakage in paramp cable. Breakdown of cable prevented observations after August 27.

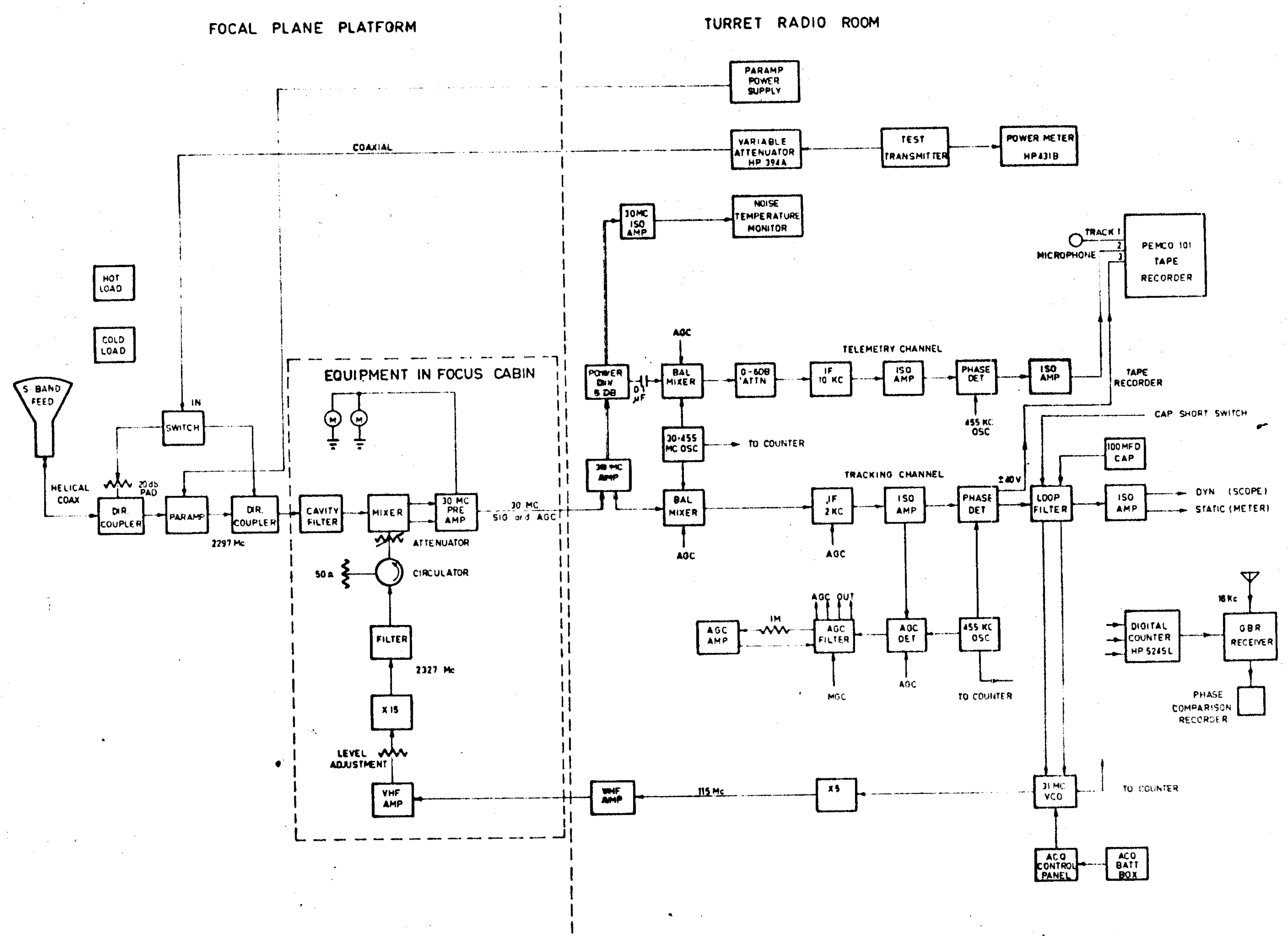

FIG. 1 BLOCK DIAGRAM OF S-BAND RECEIVER, PARKES

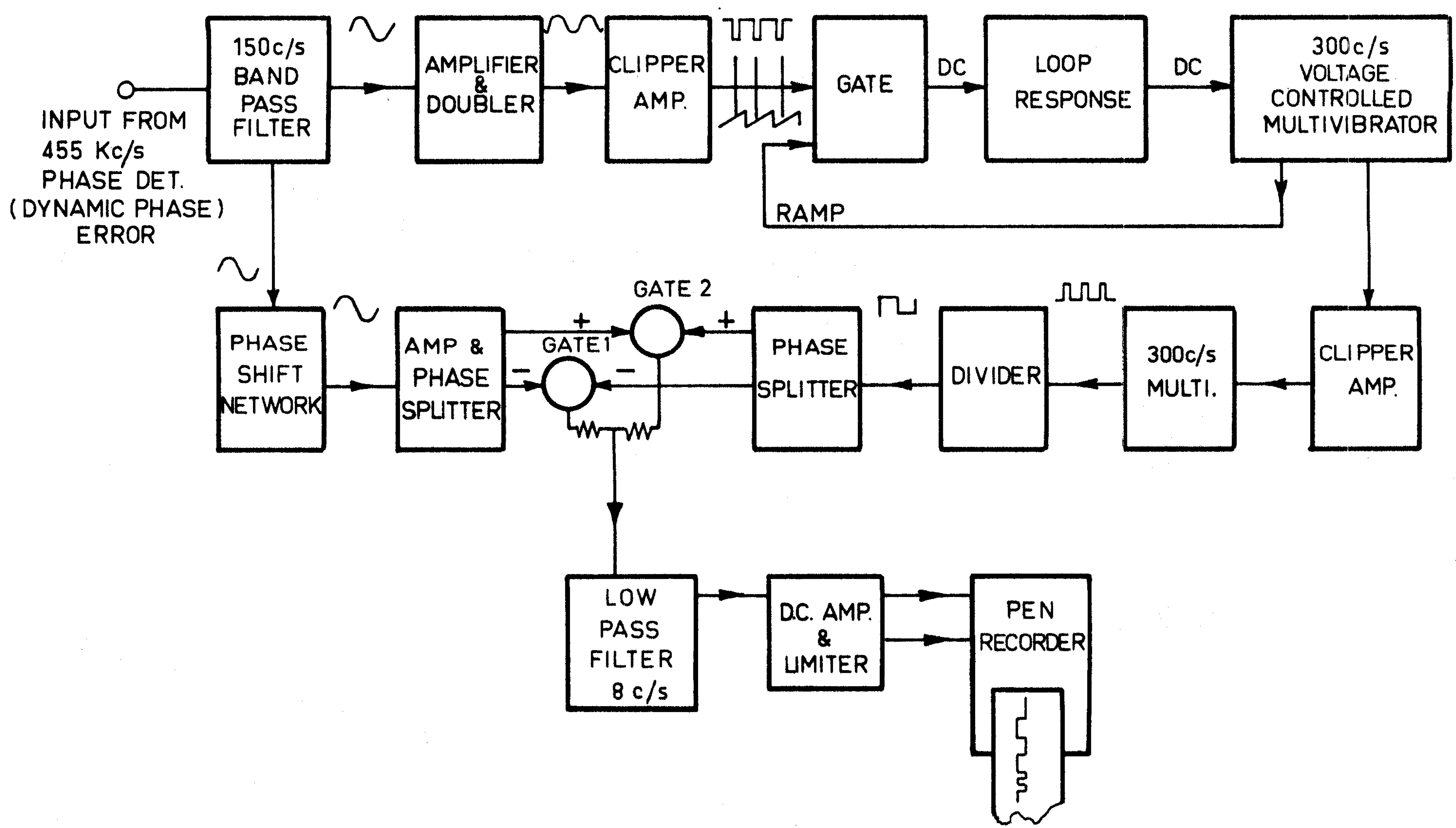

FIG. 2 BLOCK SCHEMATIC of 150 c/s SYNCHRONOUS DEMODULATOR

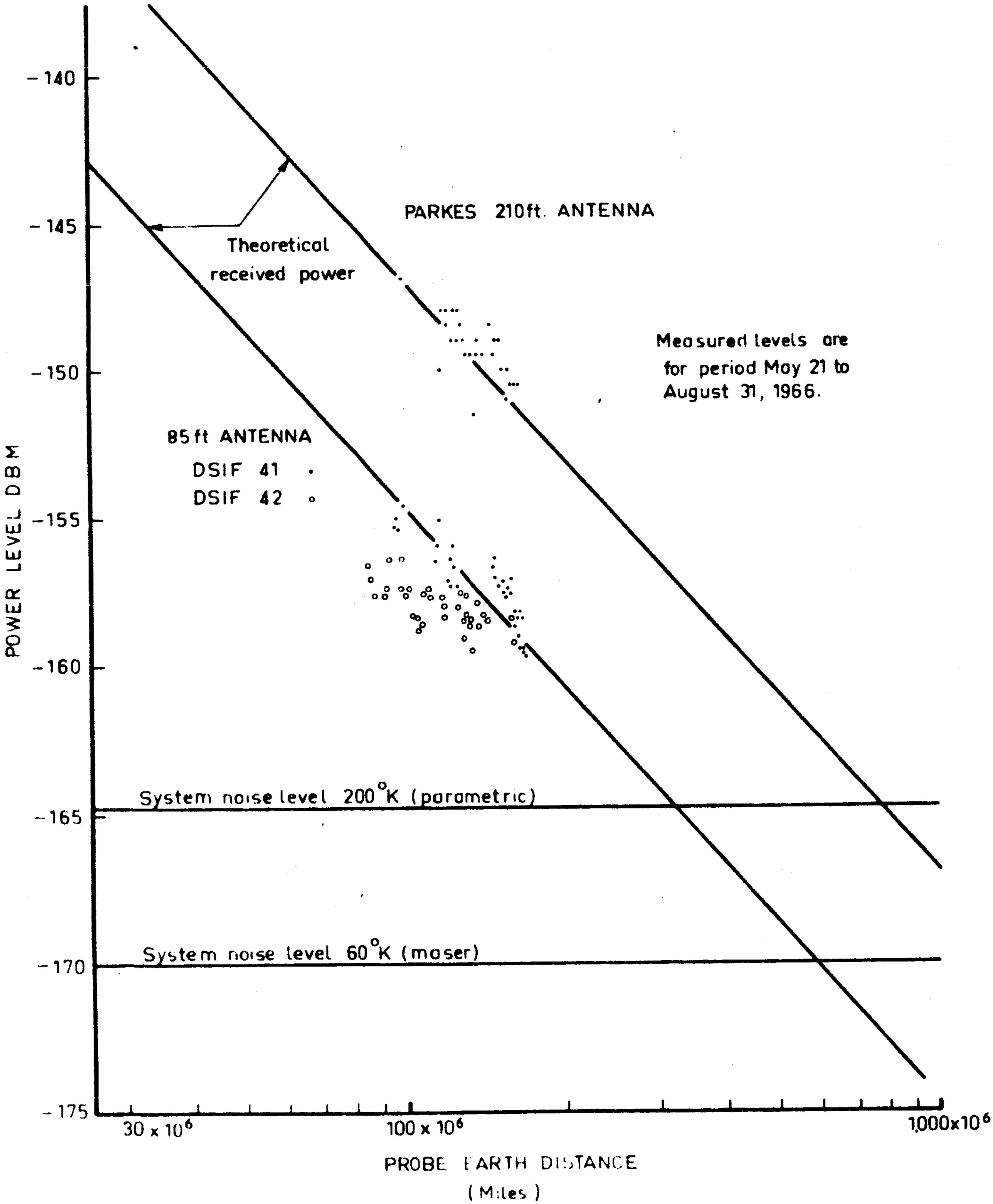

FIG 3 Theoretical and measured powers received from Mariner IV on 210ft and 85ft Antennas

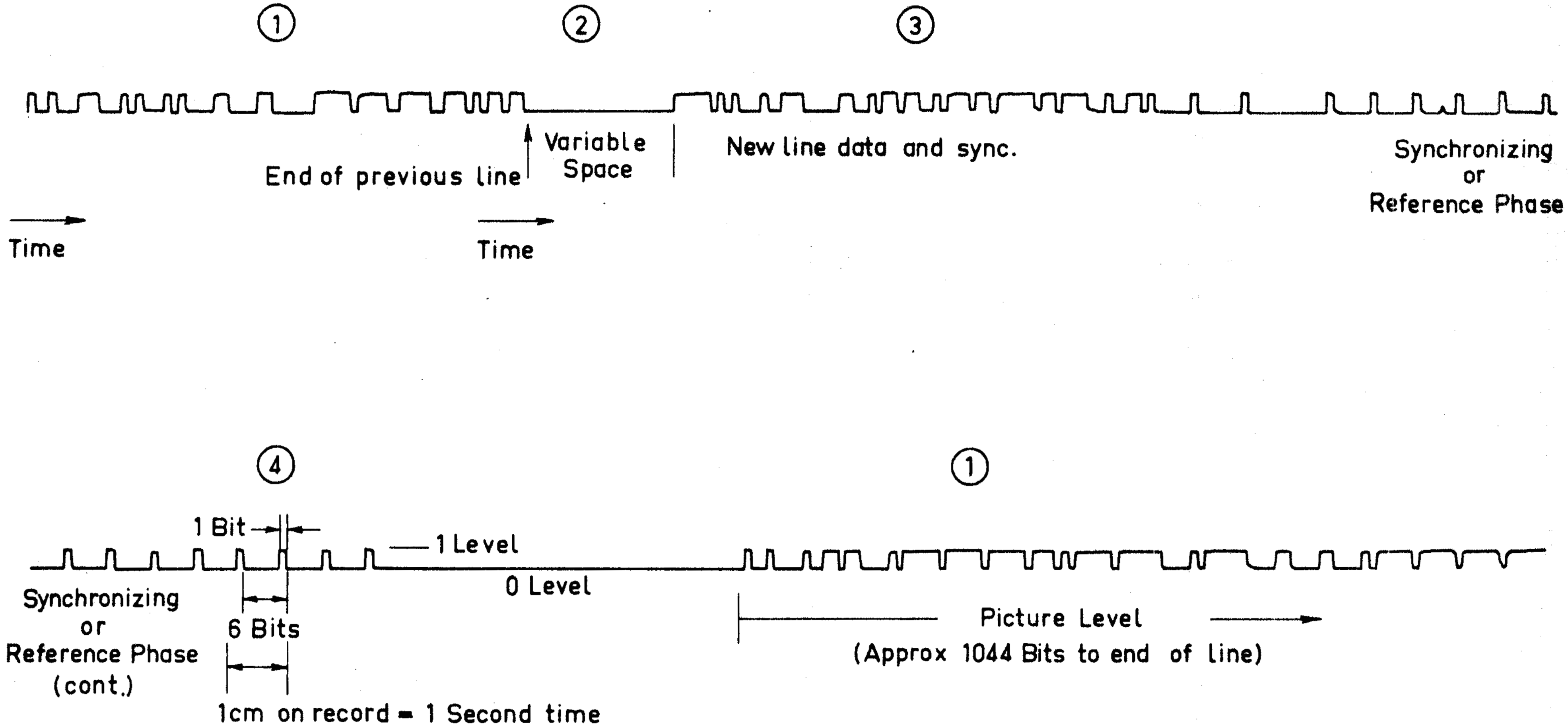

FIG. 4 RECORD OF MARINER IV BINARY MODULATION ON JULY 27, 1965, 0405 G.M.T. (APPROX)