1

OUTER PLANETS GRAND TOURS

PLANETARY RADIO ASTRONOMY

TEAM REPORT

1 February 1972

Prepared By: James W. Warwick

Date of Preparation: 6 March 1972

NGR-06-003-185

U. Colorado

(NASA-CR-133500) OUTER PLANETS GRAND TOURS: PLANETARY RADIO ASTRONOMY TEAM REPORT (Colorado Univ.) 101 p HC $7.25 CSCL 22A N73-28844

Unclas

G3/30 10325

# OUTER PLANETS GRAND TOURS

# PLANETARY RADIO ASTRONOMY EXPERIMENT

Report Prepared by

James W. Warwick

Leader, PRA Team

Department of Astro-Geophysics

University of Colorado

Boulder, Colorado 80302

The objective of this experiment is to observe short-wave radio emissions from the giant planets. Only one is known at present to produce these emissions, although that single case is extraordinary. Jupiter was predicted to be a radio source by Velikovsky (Worlds in Collision, Doubleday, New York) in 1950. He could not have guessed how unusual the wildly-fluctuating, highly intense signals Jupiter actually produces would be even in today's radio astronomical world full of quasars, masers, and neutron-star supernova fragments. A receiver flown into the vicinity of these planetary "transmitters", not only at Jupiter but also, by extension, at the other giant planets promises to determine the geometrical source of the emissions, and as well their physical source in intense plasma-wave phenomena in the planetary ionospheres and magnetospheres.

The experiment consists of a swept-frequency reciever covering the frequency range from about 10 kHz to about 30 MHz. Useful data should appear in the range 100 kHz to about 1 MHz covered in frequency steps of about 10 kHz (90 steps), and in the range 1 MHZ to 30 MHz, covered in frequency steps of about 300 kHz (90 steps). There are two receivers, one each for RH and LH polarized signals. A scan in frequency alternates between these two states at alternate frequency points. The strongly-polarized planetary emissions therefore tend to alternate with the galactic flux from channel to channel. The sensors for the receiver are crossed electric dipoles; they may consist in a pair of orthogonal monopoles, loaded against the spacecraft frame, and 10 meters long from base to tip.

The experiment operates in several different modes, depending on cruise or encounter phases of the overall mission. In cruise, emphasis lies on construction of full diagrams representing planetary emission as functions of both the aspect of the target planet, and the aspect of its satellites. In encounter, emphasis lies on high-time resolution series of data at a limited set of frequencies. In addition the receiver carries a calibrate mode for noise (broadband) standard recording, and a harmonic radiation mode, to study the high-level interference spectrum generated by the spacecraft.

The total weight of the experiment, including two 10-meter monopoles that weigh 3/4 pounds each, is less than five pounds, and its power consumption is less than three watts. The bit rate for continuous operation is 2 kilo bps, but even at 10 bps the experiment attains its objectives in the cruise mode. The design goal is 140 bps at Jupiter. The receiver uses a 6 - bit word format; there are switched attenuators in the front-end, to introduce the total of 100 db reduction in signal necessary in the encounter phases of these missions.

010101

20 January 1972

I. Introductory

The Planetary Radio Astronomy Team has met five times beginning in April, 1971, through January 1972. At its initial meeting, the Team defined generalized experimental objectives. In priority order these are:

(1) To measure the spectrum of planetary radio emissions;

(2) To measure the polarization of planetary radio emissions:

(3) To measure the direction of arrival of planetary radio emissions.

Through the course of the past year, the Team has defined scientific and experimental goals with greater precision. Today, goals (1) and (2) appear to be essentially related inasmuch as detection of even nominally strong planetary emissions will be impossible for most of the time on these missions, without our using their polarization properties as identification. Goal (3) appears to add complexity beyond cost and weight boundaries that have gradually become more stringent on our experiment (as well as other OPGT experiments) throughout the past year.

This report summarizes the status of Team efforts, reported in the actual documents -- e.g. Team minutes and individual studies, -- generated over recent months. It is in no sense complete. Early reports and minutes are for the most part omitted since the present experiment design has evolved quite rapidly in the recent two months.

The "Investigation Summary" (pp 6 - 24) was prepared by Warwick for SSG and NASA Hq uses; its main emphasis is on scientific rationale underlying the PRA efforts.

The "PRA Instrument Capabilities - Frequency Scan Sequences" (pp 25 - 34) was prepared by F. T. Haddock and R. G. Peltzer, and describes techniques for spectrum analysis. It includes outline of our proposed frequency synthesizer.

Team minutes for the meeting of 13, 14 October 1971 (pp 35 - 40) describe in some detail model programming of our receiver; the programming developed rapidly from that time through January 1972. Other matters discussed then were antenna pattern and impedance measures and power system interference.

A JPL - generated power system radiation level - versus - frequency study appears (pp 42 - 69). It is generally as we had expected, save for the low-level spikes lying at half-integral harmonics of the PS fundamental.

Glen Lockwood provided ISIS - II diagrams of receiver frequency scans above a fixed-frequency transmitter signal, rich in harmonics. This record dramatically emphasizes the potential value in these observations aboard OPGT spacecraft (page 70).

C. C. Harvey (Paris Observatory; pp 71 - 77) provides a rationale on which to base measurements of antenna reactance in the PRA experiment.

Team minutes for the meeting of 10, 11 January 1972 (pp 78 - 88) describe in considerable detail the range of problems under active study by the Team at that time.

A memo by Warwick, on 26 January 1972, describes a still later version of our basic design, in which the immediately concluded Team discussions are made a part (pp 89 - 92).

Finally, at the request of the SSG, Warwick created a "Budget Estimate for PRA Team - OPGT - Fiscal Years 1973 - 1992" (pp 93 - 100). This document is included both because it indicates the long term magnitude of the PRA task, but also because it developes in some detail the rationale for making estimates of how much the cost of scientific data studies of PRA results will be.

II. Vocabulary

The documents that comprise the bulk of this report are for the most part self-explanatory. Some terms need perhaps explicit descriptions, however.

Throughout, we have used "nominal intense event" to describe a planetary radio emission occurence where the planetary received power is about one-seventh the galactic noise background received power. The equivalent flux level is assumed to be such that -- as galactic noise varies with frequency -- the ratio one-seventh is independent of frequency. It happens to be a "baseline" design number appropriate to actual observations of Jupiter emissions at those frequencies (less than about 40 MHz) where Jupiter is a known source. The antenna system is assumed to be a simple dipole, essentially isotropic in its reception pattern.

The PRA experiment will operate in different modes appropriate to cruise or encounter phase of the mission, and also to a certain extent subject to ground command. These modes are:

| | |
|---|---|
| POLLO: | meaning low data rate measurements of spectrum and polarization |
| POLHI: | high data rate |
| VLOBR: | very low bit rate measurements of spectrum and polarization |
| LEVEL: | calibration on standard noise source |
| HARRAD: | harmonic radiation monitoring |
| TEMP: | thermal emission from planets |

Other modes are mentioned from time to time, but are defined then.

# PLANETARY RADIO ASTRONOMY ON THE OUTER PLANETS GRAND TOURS

Investigation Summary

Prepared by

James W. Warwick
Department of Astro-Geophysics
University of Colorado, Boulder, Colorado 80302

## A. Scientific Objectives

1. The purpose of the investigation is to observe planetary radio emission especially at low frequencies where non-thermal, cooperative plasma phenomena play a major role. These phenomena are of fundamental importance in astrophysics today, especially in the understanding of quasars, pulsars, and solar radio emissions. The model for these phenomena is provided by the nearest giant planet, Jupiter, which is an intense source of radiation at decametric wavelengths observed from the ground.

Non-thermal planetary radio emission also is generated by incoherent synchrotron emission. This important emission will be much better understood through data from the particles and fields experiments aboard the Grand Tours spacecraft. Planetary radio emissions occur also through normal black body processes in the planetary atmospheres, and if it is possible without compromise to our major objective we will attempt to observe this emission as a secondary scientific goal.

We hope to measure the spectrum, polarization, and position of the low-frequency radio waves, as well as their detailed time variations. For the outer planets, except for Jupiter, these measurements will if successful constitute the discovery of each planet's non-thermal emission. For many reasons, connected with the remoteness of the outer planets, the relative weakness of their expected magnetic fields, and perhaps the nature of the solar wind in this region of interplanetary space, observations of non-thermal emission from Saturn and beyond have not been successful from the earth. Nevertheless we consider it highly probable that each of the giant planets has both a magnetic field and non-thermal radio phenomena at low frequencies.

One measure of these phenomena is the strength of the planetary magnetic field. Despite many decades of careful researches, there is today no deductive theory of planetary magnetism. For this reason, we turn to a purely empirical basis for estimating the magnetic fields of the outer planets. The assumption is that the ratio of angular momentum to dipole moment is constant throughout the solar system, at the value $1 \times 10^{15}$ cgs. This value is correct for the earth and probably correct for Jupiter. The following table results.

| PLANET | JUPITER | SATURN | URANUS | NEPTUNE | |
|---|---|---|---|---|---|
| M | $4\times10^{30}$ | $8\times10^{29}$ | $1.9\times10^{28}$ | $1.4\times10^{28}$ | cgs |
| $B^*$ | 5.5 | 1.8 | 0.7 | 0.6 | gauss |
| $f_{el.\ gyro}$ | 15.4 | 5.0 | 2.0 | 1.7 | MHz |
| $N_{sol\ wind}$ | 37 | 12 | 2.7 | 1.1 | $\times10^{-3}$ $cm^{-3} \cdot AU^{-2}$ |

* Equatorial surface field strength for a centered dipole

The Jupiter surface electron gyro frequency is close to the typical frequency of decametric emissions from the planet. Very sketchy evidence for Saturn's radio emission exists at or near 18 to 22MHz; it has probably not been positively identified as a source. Jupiter has been observed from the ground at 5MHz and 2.5 MHz spottily, on infrequent occasions; however these data are probably valid. No evidence for low-frequency emissions from Uranus or Neptune exists in the literature.

For the planet Jupiter alone, whose non-thermal radio emission has been observed for more than twenty years, we can give detailed information on the kinds of results we expect. Near the planet measurements of the radio source position will be quite feasible with even crude antenna systems. Furthermore, the spacecraft commonly crosses a significant range of latitudes in the planetocentric coordinate system and gives us a radically different perspective on these highly directive sources. Also, the nearness of the planet as the spacecraft flies by increases the signal-to-noise ratio enormously and permits the detection of much weaker sources than is possible from, or near, the earth. Note in this connection that non-thermal radio emission from the planet Jupiter has not been observed yet from spacecraft, despite the ease of its detection on the ground.*

There are a number of "secondary" scientific objectives of our experiment, anyone of which can lead to major results.

Our equipment is essentially a set of passive radio receivers that measure spectrum, polarization, and position of radio emission. We are therefore capable of measuring the same three sources of radio waves previously studied from spacecraft. However, Milky Way radio waves should be observable to the new lower limit of frequency (10 kHz) set by the plasma density of interstellar space, as the spacecraft proceeds to the outer reaches of the planetary system.

We have also under active consideration the possibility of using the electromagnetic radiation from the spacecraft for scientific purposes.** The radiation can provide an in situ plasma probe. The harmonics of the spacecraft power system are signals lying at a countable infinity of fixed frequencies which cover the frequency domain densely. Ambient plasma resonances can be observed and measured, through their effects on the amplitude of spacecraft harmonics as a function of frequency.

We may be able to measure atmospheric thermal emission at low frequencies and correspondingly high pressure levels deep within the atmosphere. This black body emission has its spectral peak at much shorter wave lengths than the metric and decametric frequencies we will observe. The emission we expect at metric wave lengths originates at pressure levels of typically 10 or 100 atmospheres. The loss of radio energy plays no role in the thermodynamics of these pressure levels. On the other hand, it provides us with a tracer indicative of temperature conditions deep within the atmosphere. Nothing short of deep atmospheric probe vehicles can

---

* In fact radio from space has detected only three sources: the sun, the earth, and the Milky Way.

** This radiation should also be understood from a spacecraft engineering point of view.

provide equivalent information.

It may also be possible to measure the direct high-frequency component of lightning strokes produced by the atmospheric electricity of the giant planets. It has been suggested that this emission could be detected via its generation of guided magnetospheric whistlers at VLF; our experiment in a complementary way observes instead the freely-propagating HF radiation from the stroke. Of course, the lightning which occurs in the giant-planet atmospheres is at present totally unobserved. The case might be argued that its detection is a purely speculatively possibility. On the other hand, the giant planets certainly contain clouds consisting of both dielectric solid and liquid particles in violent hydrodynamic motion. Precisely these circumstances are involved in terrestrial thunderstorm activity. Interestingly enough, the initial physical interpretation of the low-frequency non-thermal radio waves from Jupiter was in fact that they resulted from Jupiter's atmospheric electricity. But, it was quickly realized that thunderstorms on Jupiter must have been many more orders of magnitude violent than those of the earth. This interpretation seems no longer to be valid.

2. The most significant scientific implications of radio astronomy observations of the giant planets lie in the area of the interpretation of cooperative plasma phenomena in magnetospheres and ionospheres (from the point of view of either plasma physics or the astrophysics of energetic processes), and in the area of the phenomenology of planetary magnetic fields (from an astronomical or planetological point of view).

Jupiter's radio waves stand out among the most intense radio sources in the cosmos. On occasion their flux is as strong as moderately large solar radio bursts at 20 MHz, a wave length of 15 meters. Their flux density is then of the order of magnitude of $10^{-19} W \cdot m^{-2} \cdot Hz^{-1}$.

The radio astronomical parameter commonly used to describe sources is brightness temperature. The brightness temperature depends on the solid angle subtended by the source as it is seen on the earth. Several investigators have measured Jupiter's sources interferometrically, and none has yet succeeded in resolving them... this, despite the use of interferometer baselines many thousands of kilometers long! The resulting upper limit to source angular dimension is 0.1 arc seconds. These data are representative of both angular coordinates, i.e., the necessary two-dimensional interferometery has been carried out on several occasions. The corresponding solid angle is less than $3 \times 10^{-13}$ sr. The flux density, S, relates to the brightness temperature T, the solid angle $\Delta\Omega$, and the wave length, $\lambda$, as follows:

$$S = \frac{2kT_B}{\lambda^2} \Delta \Omega$$

Boltzmann's constant k equals $1.4 \times 10^{-23}$ joules $\cdot$ $deg^{-1}$. Putting in the other observed parameters leads to a brightness temperature of $2 \times 10^{18}$ °K! This equivalent brightness temperature should not be assumed to indicate the presence of electrons at energies $E = k T_B \approx 10^{14}$ electron-volts. Particles with this energy greatly exceed the normal energy even of cosmic ray electrons and protons, and are more energetic than the electrons present in great numbers in the Crab Nebula. On the other hand the standard of comparison provided by the black-body theory is a very strong one; if the particles did not have a purely thermal distribution in energy, their presence would be nonetheless required to produce Jupiter's decametric emission <u>if no cooperative processes were involved.</u> The argument should, in fact, be turned around: the requisite energies are so large for particles acting incoherently that we must conclude that cooperative phenomena are surely present in Jupiter's decametric sources.

The same computation of brightness temperature for solar radio emissions yields values of the order of $10^{10}$ or $10^{11}$ °K. The main difference between the sun and Jupiter, whose observed flux densities compare to those of the sun, is that the solar bursts extend over many orders of magnitude larger ranges in solid angle. Nevertheless, for the sun the conclusion has historically been drawn that plasma wave mechanisms create the bursts. For other radio sources in the cosmos, such as the compact extra galactic sources called "quasars", the upper limit to source size is gained rather indirectly from observations of the time variations of the sources. In this way some of the most compact sources are known to be as small as $1 \times 10^{-11}$ radians, which for example, for the source CTA 102 leads to a brightness temperature of $10^{17}$ °K. The unusual molecular emissions from the Milky Way are very intense and occur in extremely narrow-band spectral regions. Correspondingly their brightness temperatures, of the order of $10^{12}$ or $10^{13}$ °K, are very great, more intense than solar radio waves. The only radio sources we are aware of in an astrophysical context whose intensities are greater than Jupiter's decametric emission are pulsars. Here, again, the source size follows from the time variations, which typically are on a scale of a few milliseconds. These are galactic objects, at distances, for example, of $10^{20}$ centimeters. Since their dimensions are only, say, $3 \times 10^7$ centimeters, and since the observed flux densities are of the order of $10^{-24}$ $W \cdot m^{-2} \cdot Hz^{-1}$ at 5 meters wave length, the equivalent brightness temperatures are as great as $10^{25}$ °K.

Ginzburg and Syrovatskii (Ann. Rev. of Astronomy and Astrophysics, 7, 375-419 (1969)) discuss the classical theory of synchrotron radiation as it applies to galactic and extragalactic sources. The main thrust of their development is towards the "nonuniversality" of the synchrotron mechanism for radio emission. They point out that the early successes of the synchrotron theory have lead to its wide and often nonjustifiable application. They note cases such as these compact radio sources like CTA 102, where the theory simply does not apply. Curiously they emphasize that the nonsynchrotron mechanisms for the sun have been well known for a long time, and they further note that pulsar radiation also must involve a plasma mechanism. But they fail to comment on the much more dramatic sources epitomized by the planet Jupiter. We can only speculate on why. Certainly these authors are aware of Jupiter and its importance as a radio source. Ginzburg's student and colleague Zhelezniakov has written several important papers, and a major monograph, on the subject of planetary radio emission.

But, from the point of view of the Grand Tour Missions, and astrophysics in general, we need to consider very seriously the conclusion that Ginzburg and Syrovatskii draw: "one of the most urgent problems needing further investigation is a more detailed and comprehensive analysis of coherent processes and effects in dense cosmic radiation sources."

It is outstandingly apparent that the planet Jupiter is, after pulsars, the most intense cosmic radio source known. But it is more important to the space program because of the fact that Jupiter alone of all cosmic non-thermal radio sources is accessible to direct *in situ* investigations of the plasma physical mechanisms involved in the production of radio emission. Nevertheless, despite its importance to astrophysical science, the physical interpretation of Jupiter's radio emission is in a very primitive state. (The same conclusion may be drawn for the other non-thermal radio sources as well, particularly pulsars and solar radio emission.)

The present knowledge of Jupiter's magnetic field depends solely on the characteristic radio emissions and their interpretation in terms of a planetary magnetic field. Recent observations by Kemp, *et al.*, of continuum circular polarization in Jupiter's visual wavelength reflected sunlight are, to put it mildly, inconsistent with the radio wave interpretations. The derived field strength from the visual observations is $10^3$ to $10^4$ gauss. The basis for this value is the splitting of the continous opacity coefficient in the presence of a strong magnetic field. Kemp, *et al.* offer an alternative explanation of the circular polarization, in terms of the oblique scattering of sunlight off of Jupiter's atmosphere (a non-magnetic effect). It appears that this alternative explanation may be a better one in view of the radio observations.

A third way of explaining these data might be in terms of the normal, or we should say ordinary, Zeeman affect. What is required is Zeeman pattern shifts with respect to non-Zeeman-sensitive lines in the same spectral region. The observed visual polarization levels are extremely low, of the order of 1 part in $10^5$. Only a small differential absorption between left and right circular polarization states could thus account for the data. We emphasize that this explanation is at present hypothetical, and that no presently observed molecular or atomic line in Jupiter's atmosphere shows such a phenomenon.

Despite the many successes of the space program in clarifying important astrophysical phenomena, such as cosmic rays and the solar wind, it is correct to say that planetary magnetism remains an enigma. Smoluchowski's recent discussion of the magnetic fields of Jupiter and Saturn provides a stimulating argument for the potential richness of magnetic field data, insofar as planetary interior structure is concerned. It also indicates the fundamental difficulties of a deductive theory of planetary magnetism.

In 1940 Chapman and Bartels wrote:

"Unfortunately we are as yet unable to judge whether any other celestial body has a magnetic field or not, with the one exception of the sun. If more examples were available, and particularly if we could investigate any magnetic fields that may exist on other planets, like Mars or the Moon, in physical conditions partly like and partly unlike those of the earth, our opportunities of testing theories of the origin of such fields would be much more favorable than they now are.

Some authors, assuming that the earth's magnetism is a fundamental physical phenomenon, have endeavored to find an explanation of it that would, at the same time, explain the sun's magnetism. Some theories of the geomagnetic field have attempted to account also for maintenance of the earth's negative electric charge, and even for gravitation. A review will be given of these various theories, although it cannot be said that at present any satisfactory explanation of the earth's main field is available."

It appears that this comment, with a few qualifiers supplied by the space program for Mars and the Moon, is still essentially valid thirty years later.

Parker (Ann. Rev. of Astronomy and Astrophysics 8, 1-30, (1970)) discusses in detail the origin of planetary and solar magnetic fields. The basis which has permited any quantitative calculations of planetary magnetic fields at all is the formulation of the fundamental hydromagnetic equation. He points out that there is an important body of expert opinion on these matters which holds that physical arguments do not suffice to explain the details of magnetic fields in turbulent flow; formal calculation is necessary. From our own perspective on the periphery of this extraordinarily difficult field, we strongly agree with this conclusion. Despite this opinion, Parker does in fact attempt precisely this feat: to give a qualitative physical and

B

topological description of a self-excited dynamo.

Whether this (at best) semi-quantitative picture is correct or not, we would find it comforting if the theory were able to predict what, e.g. Jupiter's magnetic dipole moment is. As Parker notes, the question is the fundamental origin of the magnetic flux which makes up the field. For the sun, and even more for the planets, the original field that may have been trapped at the time of condensation of these objects should have long since disappeared. Parker emphasizes the fact that electrical charges neutralize electric fields, but that there are no free magnetic charges to neutralize magnetic fields. This asymmetry ultimately creates dynamo action in rotating conducting cosmical bodies, in which the fluid motions in detail are consistent with electrical currents and magnetic field within the body.

We wish strongly to emphasize that at present this theory has no predictive value. It is a fact of the planetary system, and possibly of the galaxy, that there is a relation between angular momentum and magnetic fields. We suggest that it be regarded as analogous to Bode's law for planetary orbits. And, it is not obvious where this fact fits into the theory of cosmical magnetism.

## B. Measured Parameters

1. We will detect and measure the electric field component of radio noise, consisting of the continous power spectrum within a narrow pass band, of the order of 10 kilohertz in width. Our receiver will be capable of shifting its central response frequency from about 10 kHz to about 100 MHz. In this frequency range, Jupiter is the only known non-thermal radio source in the solar system other than the earth and the sun, and therefore we use its signals to set the sensitivity levels required for the entire mission.

Almost independent of frequency, the limiting sensitivity for studies of Jupiter as seen from the earth is set by the cosmic radio noise generated within our own Milky Way. This background noise is so high in level that it exceeds receiver noise for any reasonably well-designed electronics. As the spacecraft approaches a given planet the emisssions from the planet increase as the inverse square of the distance to the planet, up to the point where the spacecraft is as close to the source as a typical dimension of the emission. The dynamic range required for missions to Jupiter is greater than 100 db. Therefore, near Jupiter, the planetary signals will override the cosmic noise background by about 100 db.

The dynamic range of the receiver must exceed 100 db for two reasons: first, the emission (as seen from the earth) on occasion greatly exceeds the cosmic noise level, by about 20 db; second, to compute the 100 db factor, we assume that the spacecraft comes no closer than about 10, 000 kilometers from the source of the emission. However, on several occasions the diameters of the radio sources have been shown to be at least one order of magnitude smaller than 10, 000 kilometers. If our receiver is not to saturate when, perchance, it comes within 1, 000 kilometers of the source of radiation, requires a further 20 db. This supposes that the spacecraft is no closer than $10^3$ kilometers from the source, or alternatively, that the source is not much smaller than $10^3$ km. The total dynamic range implied is a factor of 140 db.

We shall estimate the absolute upper limit for the data rate our experiment requires in its most verbose mode. A given instantaneous measurement of electric field, i. e., equivalent to radio frequency power across a bandwidth, need not require more than seven or eight bit words for its description. With this accuracy, we can hope to define the shape of bursts fluctuating in power within our frequency passband, 10 kHz. The absolute maximum data rate required to define the noise can be described as a new eight-bit word for each independent time sample of data, every 0.1 milliseconds. This totals to about $8 \times 10^4$ bits per second.

We have used the conditions at Jupiter to establish receiver parameters. This seems reasonable even for the detection of those planets that as yet have not been observed from space or from earth in this non-thermal emission mode. We know that Jupiter's non-thermal emission has an exceedingly sharp high frequency cutoff in the neighborhood of 40 MHz as observed from the earth (e. g., in the ecliptic plane.) These cutoffs for

Saturn, Uranus, and Neptune almost certainly lie below the frequency range from which earth-based planetary observations have been successful, say, about 5 MHz, and could not and have not been detected from the radio astronomy experiments so far flown in space. The point is that radio astronomy techniques in space have not yet been capable of observing even Jupiter at 9 and 10 MHz where it is known to be a strong and virtually continuous source. This is no more than a description of the limited capabilities of previous radio astronomy experiments for source identification. However, it suggests the strong desirability of upgrading our own capabilities along this line. Two techniques are under consideration. The first is that we should use crossed dipole antennas to generate electrically the equivalent of a single rotating dipole. The directional response of the hertzian dipole is very broad, but contains rather well-defined nulls. By phase-detecting our output power synchronously at the rotation period of the dipole, we can eliminate the sky background noise, and identify planetary emissions sensitively. This technique also permits direction of arrival information to be obtained for sufficiently strong sources. The second technique under consideration is to phase-detect signals between the two circularly-polarized propagation modes. The sky background is essentially unpolarized, but the non-thermal emissions, at least from Jupiter, are known to be strongly polarized, usually right-hand elliptical or circular. Detecting the receiver output synchronously with polarization switching of the receiving antennas therefore should substantially eliminate the sky background. This technique can, of course, be combined with direction-finding, inasmuch as both involve rapid mode-switching of the input stages of the receiver and synchronous detection at the output stages.

2. All of these requirements relate directly to the scientific objective of observing and measuring radio emission from the planets. We have assumed that the giant planets other than Jupiter are emitters like Jupiter but in a lower frequency range. The limiting sensitivity is clearly not a strong condition on our experiment and does not pose unusual instrumental requirements. Without any difficulties whatsoever we expect to observe

the Milky Way-galactic noise background easily.

### C. Derived Parameters

1. The gross presence of dynamical processes and magnetic fields near the planet can be directly inferred from the existence of measurable non-thermal planetary radio emissions in this low frequency range. At some upper limit of distance from any planet which has this characteristic emission (and in the case of Jupiter this upper limit is no closer than the distance from the earth to Jupiter!) we will be able to make strong predictions of the future plasma environment to be experienced by the spacecraft as it flies through the planetary encounter that lies months or years ahead along the spacecraft trajectory. This should make the experiment valuable from an engineering point of view.

The plasma environment to be encountered not only involves the number-density and energy of ionized constituents, but also the electric and magnetic fields in the gas. At least for Jupiter the observed HF wavefield is very large. We anticipate levels as high as $10^2$ RMS volts across different parts of the spacecraft at 20 MHz, within 1000 kilometers of the radiation source. This interference level may be highly deleterious to the spacecraft and its equipment. Our experiment has as its objective not only to measure these planetary emissions remotely, before encounter, but in situ as well. For this reason, we may be able to provide other experiments aboard the spacecraft information as to just how serious the electromagnetic environment of the spacecraft has been so far as the other equipments are concerned.

On the basis of the Jupiter low-frequency emission seen from the earth, quite accurate "measurements" of Jupiter's magnetic field have been presented in the literature; very high-accuracy determinations, for example, of the rotation of Jupiter's interior are now available. The same measurement is obviously feasible for any planet that exhibits non-thermal, low-frequency radio emission. Cruise mode observations will build up a corpus of planetary information.

The observations of Jupiter's magnetic field made from its characteristic radio emission permit gross conclusions on the structure of the field. In a sense, of course, these interpretations are now derivitive; but, they will, after the Grand Tour spacecraft flies past Jupiter, be up-graded, that is, either confirmed, or modified. The emission characteristics are so striking in terms of frequency and directional stability that there is no possibility that they will be shown to have been worthless insofar as interpretation of planetary fields is concerned.

Looking down the line still further, we can assume that structural features of the magnetic field of the other planets such as, for example, Saturn, can be estimated even though the spacecraft may not go sufficiently close to the planet to establish from in situ measurements sensitively what the higher magnetic field moments may be. The prior interpretations of Jupiter emission, now strengthened through independent in situ field measurements at that planet, will permit the validization of purely passive radio emission measurements of the other planets.

Measurement of the magnetic fields at the spacecraft by magnetometers, and by the radio receiver itself in its harmonic mode, are therefore important experiments for the full interpretation of radio emission.

We expect to be able to determine from measurements of the various spacecraft harmonic radiations a completely independent set of plasma parameters characterizing the spacecraft ambience. These include the electron gyro-frequency, the plasma frequency, and possibly also plasma parameters such as ion and electron temperatures. In planetary radiation belts, plasma probes designed for the low-energy interplanetary space environment may saturate. Our experiment will be too coarse-grained in frequency resolution to measure accurately plasma parameters in the cruise mode. On the other hand, near the planets, where plasma density and magnetic field should be much larger, our experiment should be effective, and thus complementary to the plasma experiments. Magnetometry aboard the spacecraft as done by classical techniques, will depend on two basic techniques, atomic resonance and search coils. On the other hand, magnetic fields determined by the harmonic technique will refer to the total plasma response within, say, 1 or 2 kilometers of the spacecraft.

The passive radio receivers should thus provide field measurements experimentally independent of the spacecraft magnetometers.

In this respect our experiment has had to assume that the spacecraft power system generates considerable harmonic radiation. There appears to be no way that that circumstance can be avoided by deliberate and purposeful design. If, however, as a result of good fortune the spacecraft is harmonically clean, we may end up by applying spacecraft power to our antenna system. This high impedance load constitutes no drain on the system but provides controlled harmonic radiation.

2. We can determine the rotation rate of Jupiter's magnetic field with a precision that depends on the data rate and the time interval over which measurements are made. The rotation should be established to within one second of time in a typical $4 \times 10^4$ second rotation period with only one or two years of cruise-mode data, taken at a nominal one kilobit per second. Io's strong influence on decametric emission appears as a close correlation of the low-frequency emission with the 42-hour satellite revolution. Periodogram searches of our data for the various Keplerian satellite orbits around each of the major planets should define the presence of satellites to approximately the same level of precision. No influence of Jupiter's outer Galilean satellites has yet been detected although the expected effects may lie at still lower frequencies, or in other angular relations to the planet than have yet been observed from the earth. There is no difficulty to derive these periodicities in the statistics of low-frequency planetary radio emission. The methods are classic and have demonstrated unequivocally on the one hand the fundamental differences between the rotation of Jupiter's atmosphere and its interior, and on the other hand the presence of electromagnetic coupling between Io and Jupiter's surface. The study both of the interiors of the giant planets and the electromagnetic properties of their satellites should be feasible on the basis of their low-frequency emissions.

The detection of low-frequency coherent radio emission in itself demonstrates the existence of cooperative plasma phenomena in the giant planets. Theoretical understanding of these phenomena is still too primitive for us to predict confidently what the experiment will discover. We do not have the advantage of previous space experiments to guide us to what the conditions at the giant planets are. For example, the earth's magnetosphere does not create freely propagating emission at wave frequencies near the gyro-frequency, far above the electron plasma frequency. The present state of the theory suggests we may deal with streaming instabilities involving either MHD waves or electron beams propagating through the magnetosphere toward the planetary ionosphere.

For Saturn these phenomena must depend to a significant extent on the huge planetary ring system. If satellite influences on non-thermal emission depend on the propagation of electron beams along the magnetic field from the satellite to the planet's ionosphere, then Saturn's rings might be irrelevant to the low-frequency non-thermal emission. If, on the other hand, the satellite influences depend on Alfvén waves propagating in the equatorial plane of the planet, the waves may be colored by the particulate matter that they must cross enroute to the ionosphere. The mere existence of recordable low-frequency non-thermal emission from Saturn should identify with great precision whether or not a satellite correlation exists for that planet, and which of one or several satellites, for example, the large satellite Titan, or the smaller Rhea, is involved.

The improvements in the interpretation we expect to be able to give to Jupiter's low-frequency emission as a result of these fly-bys should make it possible to confirm the various detailed magnetic-field models that have been proposed for Jupiter's surface field. With this improved interpretation in hand, we expect to be able to use the low-frequency emission from the other giants to determine their magnetic geometry. The many present ambiguities of interpretation should be resolved by the time that the Outer Planets Grand Tour arrives at the planets beyond Jupiter. Under these circumstances it seems quite plausible to expect to be able to determine magnetic dipole orientation, location, and moment.

### D. Major Obstacles

We foresee two potential difficulties for our experiment. The greatest obstacle would be a very high level of spacecraft-generated radio frequency interference. This difficulty would take the form of limiting our ultimate sensitivity to values much greater than the cosmic noise background. The design of our receiver is based on principles which minimize the effects that this interference has. We plan to operate our local oscillator phase-locked with the spacecraft power system switch cycle. This technique has been used successfully on the Imp I Radio Astronomy experiment. We see no reason why it should fail in the OPGT spacecraft, but wish to make it clear that reasonable measures need to be taken to prevent RFI. The second obstacle to the success of our experiment would be a strongly variable spacecraft power system radiation at switch harmonics. We believe that if this were the case the spacecraft would be in serious difficulties in other respects. On the other hand, we must depend on, essentially, the calibration reliability of this spectrum.

### E. Likelihood of Success

We will certainly observe Jupiter's low-frequency emissions. Observing the emission from other planets, of course, cannot be guaranteed. We feel, however, that to assume these planets have no significant particles and fields properties would be foolish... and these seem to be both necessary and sufficient for emission.

We feel quite certain that the plasma studies we propose as a by-product of our investigation can be achieved if, again, there is a nominal magnetic field and plasma environment around the planets.

### F. Major Requirements

1. Our estimated weight will be at least 5 pounds and no greater than 15 pounds including antennas. The estimated power lies between 5 watts and 15 watts. A proper antenna system can be located at a variety of spacecraft positions: attached to or an integral part of the large telemetry dish, part

of the plasma or magnetometer booms, or separately mounted on the body of the spacecraft itself. We require four monopoles, arranged in two orthogonal dipole pairs. Each monopole is about 10 meters in length, and weighs one-half a pound. These antennas must be electrically effective, and therefore impose on us the need to make spacecraft impedance and pattern measurements. The two dipoles, 20 meters tip to tip, define a plane; the orientation of this plane may be perpendicular to the roll axis of the spacecraft or may lie in another direction, still to be chosen. Viewing directions are implied by the positioning of our antenna system; no special arrangements need to be made. In the cruise mode our data rate lies in the range from $10^2$ to $10^4$ bits per second. The average bit rate will not exceed 2 kilobits, and probably will be 1 kilobit per second or less. Data rate in the encounter mode will not exceed the average cruise mode rate; we expect that the upper limit of storage required then is significantly less than $1 \times 10^9$ bits, and is probably closer to $1 \times 10^8$ bits. No sensitive requirements on the operating range in temperature seem necessary; wide extremes need to be avoided but we expect this will be easily possible within the experimental sections of the spacecraft. The experiment will contain a number of different modes subdividing the cruise mode and encounter mode. The experiment will contain a significant part of the software and hardware required to program these modes. On the other hand, we also must rely on the spacecraft to supply some of them. Throughout the mission we expect receiver gain to be adjusted on command from the ground, at intervals of several months or perhaps longer. Cruise mode data will be taken in several different configurations, automatically and without special commands from the earth. The program sequence of these different modes will, we hope, be controlled from the spacecraft data system. The encounter mode will require a much more limited sequence of controls from the spacecraft, but probably will require a somewhat higher data rate at least at a few limited times. Potential sources of interference appear to us primarily to result from the spacecraft power system and its distribution to the various experiments. We are also concerned about the RF excitation fields used for the sensitive magnetometers. Each of these potential interference sources will be much less difficult to cope with if we know when it is present and what is its level. If this can be determined from spacecraft housekeeping records it is quite possible that the interference can be allowed for without major interference to our experimental results. As mentioned above, we hope to time our experiment from the spacecraft; this timing includes phase-locking of the LO to the spacecraft power system. We expect to control the sequence of cruise and encounter mode configuration of our experiment from the spacecraft data system. The detailed sequence of these has not as yet been defined. On the other hand, we expect operation in a given mode for several minutes at a time, followed by a sequence of 5 or 6 modes occurring at roughly equal intervals.

2. Our experiment ideally will come as close as possible to the surface of each planet. In addition we hope in the course of the Grand Tours to approach closely to Jupiter's Galilean satellite Io, either just above or below the satellite at a distance comparable to the satellite diameter. Furthermore at least one of the approaches to Jupiter should preferably occur when Jupiter's magnetic dipole axis has a specified orientation, generally so that the northern tip points towards the spacecraft. There are no conditions on our experiment for solar or earth occultation. Planet-centered latitude should reach as far from the equator as possible. Time of arrival at the planet is conditioned primarily by our desire to view the northern tip of Jupiter's magnetic dipole on the one hand, and to fly close to Io on the other. The trajectory requirements in interplanetary space are completely open to choice except that it is desirable for the spacecraft to cross the earth-Jupiter line enroute to the Grand Tour.

3. The spacecraft, since it is not a spinner, requires that we design our experiment so that it can electrically swing the antenna pattern in space. This may not be a major limitation, but does need to be taken into account in our design. The spacecraft also has large electrically-conducting structures, such as the magnetometer and plasma-probe booms. These also may not be a limitation on our experiment, but need to be carefully taken into account so that we can establish how they influence the electro-

magnetic properties of our receiving antennas. We do not see other limitations on our experiment from either the spacecraft or the mission.

## G. State of Development of the Experiment

1. Similar experiments have been performed most recently on the Imp I spacecraft, so far as phase-locked local oscillators and radio astronomy receivers are concerned. The use of spacecraft harmonics to detect plasma resonances has been demonstrated successfully aboard the Isis I and Isis II spacecraft. The oldest spacecraft carrying experiments like this are Alouette I and II; these were designed as ionosondes, but successfully detected Milky Way radio waves and solar radio bursts. Their lifetime as successful space experiments is now approaching one decade.

2. The major design difference between the OPGT investigation and earlier radio astronomy experiments in space lies in the greater flexibility, in the form of different modes of operation, required for the Grand Tour experiment. This includes the need for polarization switching and antenna beam-swinging requirements. We anticipate covering a wider frequency range than have earlier experiments in radio astronomy aboard spacecraft. No difficulty can be traced to this requirement.

3. The changes represent a moderate fraction of the previous design efforts, measured in terms of the numbers of separate projects which have in different institutions created the present state of the art in radio astronomy from space.

# PRA INSTRUMENT CAPABILITIES
## FREQUENCY SCAN SEQUENCES

The PRA frequency synthesizer is capable of performing many more scan sequences than presently required to implement the LEVEL, HARRAD, POLLO and POLHI modes. Each added scan sequence will require additional logic in the form of gates and command decoding circuitry. In some cases the additional circuitry consists of one gate and one ground loaded command (GLC) bit, while in other cases the additional circuitry is extensive. The major emphasis here will be on the easily achieved (least amount of circuitry added) scan sequences which have not been previously discussed in detail. This discussion is aimed at increasing the scientists understanding of the proposed PRA instrument so that he may more intelligently optimize the scientific return per bit of telemetry data.

### SLOW SCAN

The present PRA instrument design calls for a scan rate of one frequency step every 4.61 msec. Some investigators feel that the instrument sensitivity is severely compromised by the very low post integration time constant ($\tau$) required for this scan rate. It is therefore proposed that the present scan rate be decreased by a factor of 32 (4.61 msec dwell $\rightarrow$ 73.7 msec and $\simeq$ 3.5 msec $\tau \rightarrow$ 72.5 msec) by the addition of a 1-bit GLC. The additional hardware would consist of four gates, several timing pulse (TP) wires, switching circuits to change $\tau$ and integrator gain, and three or four resistors.

### POINT SCAN

The addition of one gate, one wire and one GLC will change the POLLO scan to a point scan. The point scan would be a scan of the 15 frequencies below the frequency set by the GLC. This scan of the 15 frequencies would be repeated and no other frequencies would be monitored for this type of operation. The point scan is implemented by inhibiting the program counter change-frequency command pulses.

COARSE SCAN

The addition of two gates, one wire and one GLC bit will allow the instrument to scan the spectrum from high to low in steps of 417 KHz instead of the present POLLO frequency step of 27.8 KHz. The coarse scan is implemented by inhibiting the variable-modulo prescaler control change-frequency pulses and routing them to the program counter (the normal change-frequency pulses into the program counter are inhibited). Attention must be paid to the synthesizer settling time for this type of operation.

COARSE-FINE SCAN

It is interesting to see what would happen if we interchange the program counter change-frequency pulses and the variable-modulo control change-frequency pulses. Each of the set of 16 frequencies scanned would be spaced 417 KHz apart; however; each set would be displaced from the previous set by 27.8 KHz. Eventually all (or all but 128) of the frequency channels would be monitored.

HARMONIC SCAN

The f/4 jump frequency operation is required for the POLHI mode. The addition of several gates, wires and one GLC bit would allow a harmonic scan or f/2 jump frequency operation. This scan is not exactly harmonic with the present synthesizer design. We have just started to look at another synthesizer design which could give true harmonics down to f/16 regardless of the GLC start frequency and to lower frequencies depending on the GLC start frequency.

SKIP-ONE SCAN

We can modify a POLLO mode scan so that every other channel is monitored (skip one channel for every channel monitored) by injecting the frequency-change pulse into the 2nd lowest order binary of the variable-modulo prescaler control counter instead of injecting it into the lowest order binary. This operation is implemented by adding two gates, one wire and one GLC bit.

SKIP-THREE SCAN

This is a variation of the skip-one scan and is implemented in much the same way. We monitor one channel, skip the next three channels, monitor the fourth channel, etc.

SKIP-SEVEN SCAN

This is another variation of the skip-one scan and is also implemented in a similar way. There are problems with this operation on the present synthesizer design which would be alleviated by the 16 step increment design.

SCRAMBLED SCAN

This type of scan is quite sophisticated compared to the previous types. It is an attempt to maximize the number of options available for data processing. The present synthesizer design uses a parallel transfer of the frequency determining bit configuration from the control counters to the dividers. The scambled scan uses a nonparallel transfer where several bit positions are interchanged. The above scans are not achievable when the scambled scan is in use. Quite a few gates would have to be added to switch between scrambled scan and the POLLO mode scan.

C

The basic scans described above are the ones that immediately come to mind. There may be others which could be achievable with a further increase in hardware complexity. The basic scans described above could be combined. e.g., Harmonic scan plus point scan. The increase in hardware would be less than the sum of the individual increases.

# PRA INSTRUMENT
## MODE SEQUENCE AND TIMING DESCRIPTION

Enclosed are the "1st Cut of CCL for PRA" by R. Easton (JPL), the "2nd Cut of CCL Design for PRA", by F. T. Haddock (U of M) and a Mode Sequence Diagram. The "2nd Cut of CCL Design" has not been submitted to R. Easton as yet, pending decisions to be made at the next PRA meeting on January 10, 1972.

A complete sequence of the modes takes 161 min. and consists of 8 equal time increments of 20 min. each which we will call sub-sequences. The subsequence is further divided into 8 equal time increments of 151 seconds each. During seven of the eight sub-sequences, the sequence of instrument is as follows: HARRAD mode operation for the first 151 seconds, POLLO mode operation for the next 453 sec., POLHI mode operation for the next 151 sec, POLLO mode operation for the remaining 453 sec. During the eighth sub-sequence, the LEVEL mode operation is substituted for the HARRAD mode operation.

The sequence within the various modes are as follows:

POLLO: Change frequency every 4.61 msec for the first 36.9 msec. Wait 36.9 msec (50% duty cycle). Repeat the above operation 127 more times for a total data gathering time of 9.44 sec. Wait the remaining 143 sec of the 151 sec period. Repeat the 151 sec period operation two more times for a total of 453 seconds in the POLLO mode.

HARRAD: Same as the 151 sec period operation during POLLO mode except change IF filters for required frequency shift.

LEVEL: Same as the 151 sec period operation during POLLO mode. The operation of the Calibrator is as shown in Figure 2 (Figure 2 has not been modified to reflect the 50% duty cycle data gathering change).

POLHI: Select the GLC frequency f and sample it 128 times at a 288 μsec sample rate for a total of 36.9 msec. Wait 36.9 msec (50% duty cycle). Repeat the above operation once more for a total time at f of 147.4 msec. Shift to the f/4 frequency and repeat as in f. Shift to the f/16 frequency and repeat as in f. Shift to the f/64 frequency and repeat as in f. The total time consumed for the above is 590 msec. Wait for the remaining 150.4 sec of the time in this mode. For the POLHI mode where you choose to say at f, the sequence is the same but the frequency is not changed.

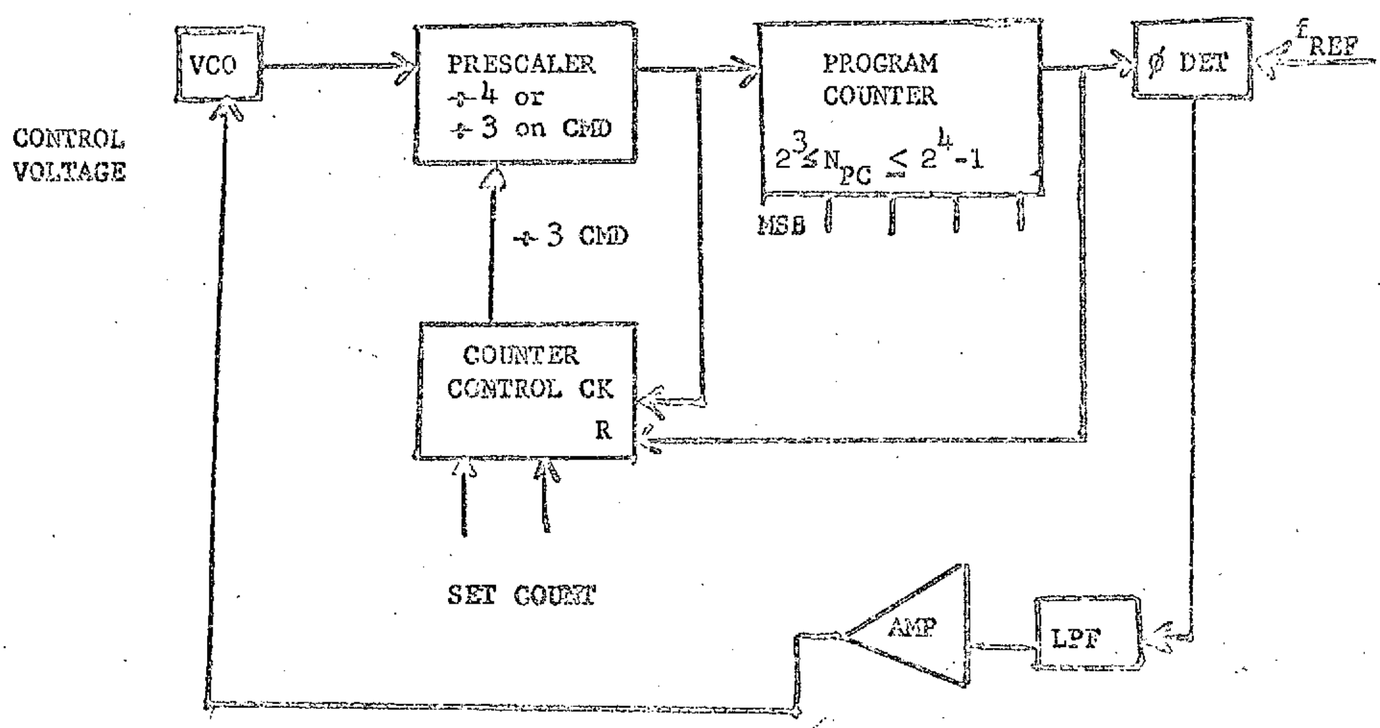
PRELIMINARY

APPENDIX 1

# VARIABLE MODULO PRESCALER TYPE FREQUENCY SYNTHESIZER DESCRIPTION

This frequency synthesizer is based on the variable modulo counter technique. This technique (or variations of it) have been presented in references 1, 2, 3, 4, & 5.

A block diagram of a simple variable modulo prescaler type of frequency synthesizer is shown below. It operates as follows:



The voltage controlled osc. freq. $f_{LO}$ is an integral multiple of the reference frequency ($f_{REF}$). This integral multiple is determined by the combination of the program counter and the ÷3 or ÷4 prescaler (variable modulo counter). The equation is

$$f_{REF} = \frac{f_{LO}}{N_{TOT}}$$

where $N_{TOT}$ is an integer

the difference between a straight forward frequency synthesizer and a variable modulo counter type is the variable modulo divider and its associated control circuitry. The program counter is a straight forward programable counter which simply divides the incoming pulses by the programable divide ratio ($N_{PC}$). For every $N_{PC}$ incoming pulses, the program counter puts out one pulse. In other words, when the system is in lock, the frequency going into the program counter is $N_{PC} \times f_{REF}$ and the frequency out of the program counter is $f_{REF}$.

The variable modulo prescaler will divide the incoming frequency by 4 until it is commanded to divide by 3. The counter control block is a programable counter that puts out a pulse (or changes level) when the number of incoming pulses are equal to the programmed input and it will maintain that state until reset by the output of the program counter. Let us assume that the "set count" on the counter control block is set to 2 (the 2nd input pulse will initiate the ÷3 command) and $N_{PC} = 11$. The progression of events for each $1/f_{REF}$ period will be as follows:

the first 4 pulses into the prescaler will yield 1 output pulse which will go to the program counter and to the counter control. The 5th through 8th pulses into the prescaler will yield the 2nd pulse into the program counter and into the counter control. On receipt of the 2nd pulse, the counter control block initiates a command to the prescaler to ÷3 and ignores all future incoming pulses until reset by the program counter output pulse. The 9th through 11th pulses generate the 3rd pulse into the program counter. The next 21 pulses (pulses 12 through 32) into the prescaler produce 7 pulses into the program counter. The 35th pulse into the prescaler produces the 11th pulse into the program counter. This 11th pulse initiates a pulse output which goes to the phase detector (ϕ DET.), resets the counter control block, and reloads the program counter. The progression of events for the next $1/f_{REF}$ period will be identical to the last if the set inputs to the counters remain the same.

The equations for the variable modulo prescaler type of frequency synthesizer are as follows:

$$f_{LO} = N_{TOT} \times f_{REF}$$

$$N_{TOT} = N_S \times UM + N_{LM} \times LM$$

where $N_S$ = the set count of the counter control block ($N_S = 2$ for above illusration)

UM = the upper modulo of the prescaler (UM = 4 for above illustration)

LM = the lower modulo of the prescaler (LM = 3 for the above illustration)

$N_{LM}$ = the number of pulses out of the prescaler when it was operating at LM,

$$N_{LM} = N_{PC} - N_S.$$

The above equations yield the fact that the variable modulo prescaler type of frequency synthesizer is not as efficient as the straightforward type in that the number of steps possible with an n binary divider is not $2^n - 1$ but $(2^n-1)\frac{LM}{UM} - K$. K steps are lost when $N_{PC} < UM$ (very low divide ratios).

The main reason fur using the variable modulo prescaler type of frequency synthesizer is that the logic speed requirement for the majority of the synthesizer logic is reduced considerably.

REFERENCES:


Middleton, Joan H.: "A Digitally Controlled Very High Frequency Synthesizer", NASA TN D-6389, September 1971.

Stinehelfer, J., and Nichols, J.: "A Ditigal Frequency Synthesizer for an AM and FM Receiver", Fairchild-Semiconductor Application Note 201, June 1971.

Burhans, Ralph W., and Blake, Richard K.: "Divide Frequencies by An Integer - Use a common-gate TTL or RTL ripple counter and save on components while preserving flexibility", Electronic Design 3, p. 42, February 4, 1971.

Nichols, John, and Shinn, Charles: "Pulse Swallowing", EDN, p. 39, October 1, 1970.

Blachowicz, Leon F.: "Dial any Channel to 500 MHz", Electronics, p. 60, May 2, 1966.

Minutes of the Planetary Radio Astronomy Team

JPL 13, 14 October 1971

I. Minutes of the 15, 16 June 1971 meeting were approved as circulated.

II. Walt Brown will attend SSG No. 8 at Goddard on 2, 3 December 1971 in place of J. W. W.

III. Warwick discussed OPGT since meeting of 15, 16 June.

IV. Team Functions:

A. The power system interference is still unknown. Dave Martin will write memo to Ray Heacock to request both data processing and power supply noise levels. Roll-off of power pulses may render P/S impotent above a few MHz, but data systems may create serious interferences even at 100's of MHz.

Gulkis contributed a memo on the computor interface to experiments, including buffer storage levels of $1 \times 10^5$ bits.

Peltzer will visit the project in the near future to start EMC work.

B. Alexander reports AVCO is at work on theoretical antenna patterns predictions (computer outputs) and antenna dynamics. Warwick should get drawings of Cottony's S/C antenna models to Alexander. Question of Vee beams from existing S/C monopoles was raised by Warwick. Brown will supply Vee beam patterns. Tom Clark will send J. W. W. details of terminating resistors for Vee's. Haddock is said to doubt usefulness of Vee beams, and will be in touch with J. W. W. after he comes to a conclusion. Brown notes that the original PRA Team proposed to use S/C medium gain antenna for decimetric studies, as is now also proposed by the Radio Science Team of the OPGT.

C. Dave Martin reports new parts list in preparation, and it will be sent to Peltzer when it is available. Peltzer points out filter qualification is difficult until design is complete. Clark suggest delay lines and quadrature hybrid at IF (not at RF as implied by our design so far); hybrids that cover 5 Hz to 2 MHz are available. Phase shifters and hybrids should be separate.

D. 1. Reactions to the experiment proposed in J. W. W.'s memo of 17 August 1971 were sought in view of some criticism that it seems too complicated. Peltzer proposes to create a block diagram such that the costs of added science can be figured. The general team reaction was that the experiment was technically simple, but its capabilities were manifold. The memo of 17 August 1971 by J. W. W. did not present the experiment in a way in which it was easy to identify the technical simplicity of the approach.

2. Tom Carr emphasized the need for high data rate, even at the cost of frequency resolution.

3. Bob Peltzer believes that switching times in the proposed experiment, 4.5 msec per frequency step, are short, that is, will almost work but are on the ragged side.

4. Joe Alexander believes that impedance measures are useless, and Peltzer agrees. Tom Clark points out that reactance is known accurately, but resistance is tough to measure although R/Z is what is needed (where Z is dominated by reactance). Possibly measure Z on the ground, and don't try to get R at all? The team concluded that we will for the time being include reactance measures on the full-blown and minimum experiment (the latter at 8 lbs. and 4 W). J.-L. Steinberg will send a description of reactance measurement devices. The minimum - minimum experiment (see Section E. below) will not include impedance measures.

5. The team agreed that noise calibration devices stay, with three modes: a load resistor measurement, and two solid-state noise generators, one shielded, and one not, in order to evaluate radiation degradation.

6. Temperature stability appears assured at the proposed levels for TOPS. The equipment must operate $\pm$ 60°C, and in the electronics compartment 5°C to 20°C.

7. Warwick gave his rationalization of the impact of a 140 bps average rate on the PRA experiment (140 bps is assigned to the experiment by the project in its guidelines for the minimum experiment): A 5° x 5° grid on planet-satellite longitude coordinates implies 72 x 72 elements. If at each we make 10, 8-bit observations, and each observation is repeated at

$10^4$ points across the radio spectrum, there are $\sim 4 \times 10^9$ bits required to define this basic relation. If one year is available to make the measurement per planet, the average data rate is $4 \times 10^9 / 3 \times 10^7$ secs = 133 bps. Since our minimum experiment time-shares POL, TEMP, HARRAD, LEVEL, and HI modes, 140 bps is probably minimal for one planet.

8. Tom Carr proposes that the programming of our receiver include a full frequency scan, a 16-step scan, and a two step (RH and LH) scan, at 4 controllable frequencies.

E. 1. Fred Scarf, Team Leader, and Al Frandsen, ER, of the Plasma Wave Team were present 13 October 1971, early PM, to discuss a combined PW and PRA Team experiment; this is called "minimum-minimum" experiment. The guidelines for this combined experiment are: weight, 10 lbs; power, 6W. We have assumed a total bit rate for the two experiments of 400 bps.

2. Scarf questions PRA antenna length, ~ 20 meters tip-to-tip -- since this is close to the Debye length under circumstances to be encountered.

PW team would like an air coil loop on the magnetometer boom.

3. Scarf believes that PW can usefully occupy as little as 2 1/2 to 3 lbs of the 10 lb. total, leaving 7 1/2 to 7 lbs. in PRA. Bit rate might be divided evenly 200/200 bps. Fred Scarf, Dave Martin, and Al Frandsen will generate a MED (Minimum Experiment Description) for a combined experiment, with two sets of science objectives, and one black box.

V. A. Beginning on 14 October 1971, 8:00 AM, PRA team discussed a minimum experiment, with a detailed presentation by Warwick based on a limited frequency range, $2^{11}$ steps of 14.4 kHz each, no DF modes at all and a modified HI data rate mode which (in response to Tom Carr's suggestion of 13 October 1971) consists of 4 sets of two fixed frequencies, at adjacent channels in RH and LH, spaced 14.4 kHz, rather than the 16-step frequency-scan mode of the 17 August 1971 description

Reducing scan range from $2^{13}$ to $2^{11}$ reduces scan time in POLLO modes by 4 x, to 8.50 seconds (instead of $34\overset{s}{.}1$).

B. The data rate in POLHI is set by the output time constant, 0.195 msec and the bit accuracy of the reading. The time constant ratio is 4.17/0.195, ~21.4 times faster than POLLO. J. W. W. (as of writing these minutes) proposes a 3-bit read out in POLHI (3/8 of POLLO). POLHI now consists of a set of simultaneous RH and LH measurements on adjacent frequency channels at frequency $f_1$ (to be controlled by ground command), $f_2 = f_1/4$, $f_3 = f_1/16$, and $f_4 = f_1/64$. If $f_1$ is set so low that $f_1/64$, $f_1/16$, or $f_1/4$ fall below 21.6 kHz, that frequency will be simply not be observed and the receiver will return immediately to $f_1$ and continue its cycle with one (two, or three) less fixed frequency points. POLLO is also proposed to operate only to some upper frequency limit $f_o$, also to be controlled by ground command.

C. The following scheme for cruise mode programming was presented (numbers may differ in detail from the actual presentation):

1. 70% POLLO - consisting of 7 scans 21.6 kHz to 29.484 MHz each occupying 8.50 sec = 59.5 seconds.

2. 10% POLHI - consisting of RH and LH for 0.46 seconds simultaneously at $f = f_1$ and $f_1$ + 14.4 kHz, this observation to be repeated at $f_2$ and $f_2$ + 14.4 kHz, $f_3$ and $f_3$ + 14.4 kHz, and finally $f_4$ and $f_4$ + 14.4 kHz. The total POLHI time is 1.86 (x2) seconds ( = 59.5 sec ÷ (2 x 21.4 x 3/8)). POLHI produces 10% / 70% = 1/7 the data that POLLO does, if it is switched on after 416.5 seconds ( = 7) POLLO runs for 1.86 (not x2 because RH and LH are simultaneous) seconds, followed by 57.6 dead seconds.

3. 10% LEVEL - consisting of a POLLO frequency scan, on a calibration source, after 476.0 seconds for a total of 59.5 seconds.

4. 10% HARRAD - consisting of a POLLO frequency scan at the frequencies 14.4, 28.8 ... kHz, after 535.5 seconds and occupying 59.5 seconds.

D. 1. Buffering requirements are set in the extreme case by POLHI which produces 32 Kbps for 1.86 seconds followed by 57.6 dead seconds. At 140 bps, the S/C telemetry system can transmit only 8330 bits in this 59.5 second window. The POLHI mode therefore is strongly output limited by the S/C; whatever buffering system we wish to employ need be no larger than required to accommodate the minimum unit of time in our system.

2. We probably will have $1 \times 10^5$ bits of buffer storage (in the form of a CCL black box book-kept as part of the S/C). Therefore Warwick proposes

a system in which the receiver cycle is interupted by the buffer condition until the receiver's output can be accommodated. This output should be in steps no smaller than the data corresponding to one 8.5 second POLLO scan, a little less than 20 kilobits. This is also about the same total data obtained in POLHI at $f_1$ and $f_1$ + 14.4 kHz, or the other $f_i$'s by themselves. Then our experiment can function with one buffer storage unit of the order of 20 K-bits, if the unit can be used simultaneously for read and write.

3. The function of buffering is to limit our experiment's average data rate to whatever the S/C can accommodate. As the OPGT S/C moves farther and farther beyond Jupiter, the telemetry data rate decreases, and our experiment perforce outputs at a slower and slower average rate. No external controls need be provided to fit the experiment into the overall S/C performance.

4. The effect on the Cruise Mode programming of the telemetry rate at Jupiter is to reduce the single-scan repetition in POLLO to once every two minutes, approximately. The POLHI mode appears about once every 1.4 hours, and lasts for about 10 minutes. In the Encounter Mode, there will be 70 minutes in POLHI, for 14 minutes in POLLO. These rates decrease at the outer limits of the mission, where the S/C data rate is two orders of magnitude lower; POLLO then occurs about once a day, and POLHI, once a week.

5. The encounter mode programming is the reverse of the cruise mode, with 10% POLLO and 70% POLHI.

6. Mode programming was discussed broadly, with considerable sentiment for less frequent LEVEL (and <u>no</u> IMPED or TEMP), say only 1% of the time instead of the 10% previously specified.

To accomplish this with the same 70% - 10% split described before, I propose changing LEVEL to a single 8.50 second POLLO frequency scan on a calibration source. The change is that before, POLLO would make 7 frequency scans in the LEVEL mode. The mode distribution therefore changes to about

| | | |
|---|---|---|
| | 70% - POLLO | ~77 % |
| CRUISE | 10% - POLHI | ~11 % |
| | $\frac{10}{7}$% - LEVEL | 1.4% |
| | 10% - HARRAD | 10.6% |
| Normalization factor = | 91.43% | 100 % |

| ENCOUNTER | POLLO | 11 % |
|---|---|---|
| | POLHI | 77 % |
| | LEVEL | 1.4% |
| | HARRAD | 10.6% |

At the outer limits of the OPGT, LEVEL would turn on once every seven weeks or so, if it is set at this 1.4% distribution figure.

VI. Warwick described A. Farmer/Vogt Prioritization document.
B. OPGT Long Term Science Schedule
C. OPGT Experiment Selection and Review
D. OPGT Data Handling and Release

VII. Joe Alexander inquired as to value of the world-wide Jupiter Monitoring Network to OPGT. The Team's reaction was unanimously in support of the basic importance of the Network to space radio observations of the giant planets.

VII. Sam Gulkis reported that Paul Penzo's program outputting magnetic geometry for Jupiter flybys is now operational, with inputs given as the dipole location (three coordinates) and orientation (two direction cosines) and rotation rate (System III (1967.0)), and outputs as magnetic colatitude and L shell of S/C.

IX. Tom Clark reported 330 kHz/26.3 MHz autocorrelation studies of Jupiter emissions by the VLB technique (e.g. autocorrelation and cross-correlation).

X. The next PRA Team meeting is scheduled at JPL on Friday, 7 January 1972, from 8 AM on, all day. Saturday, 8 January, is held provisionally for extension of the meeting if necessary. N.B. This meeting place, time, and date. A similar action item in Team Minutes for 15/16 June 1971 was overlooked by most Team members.

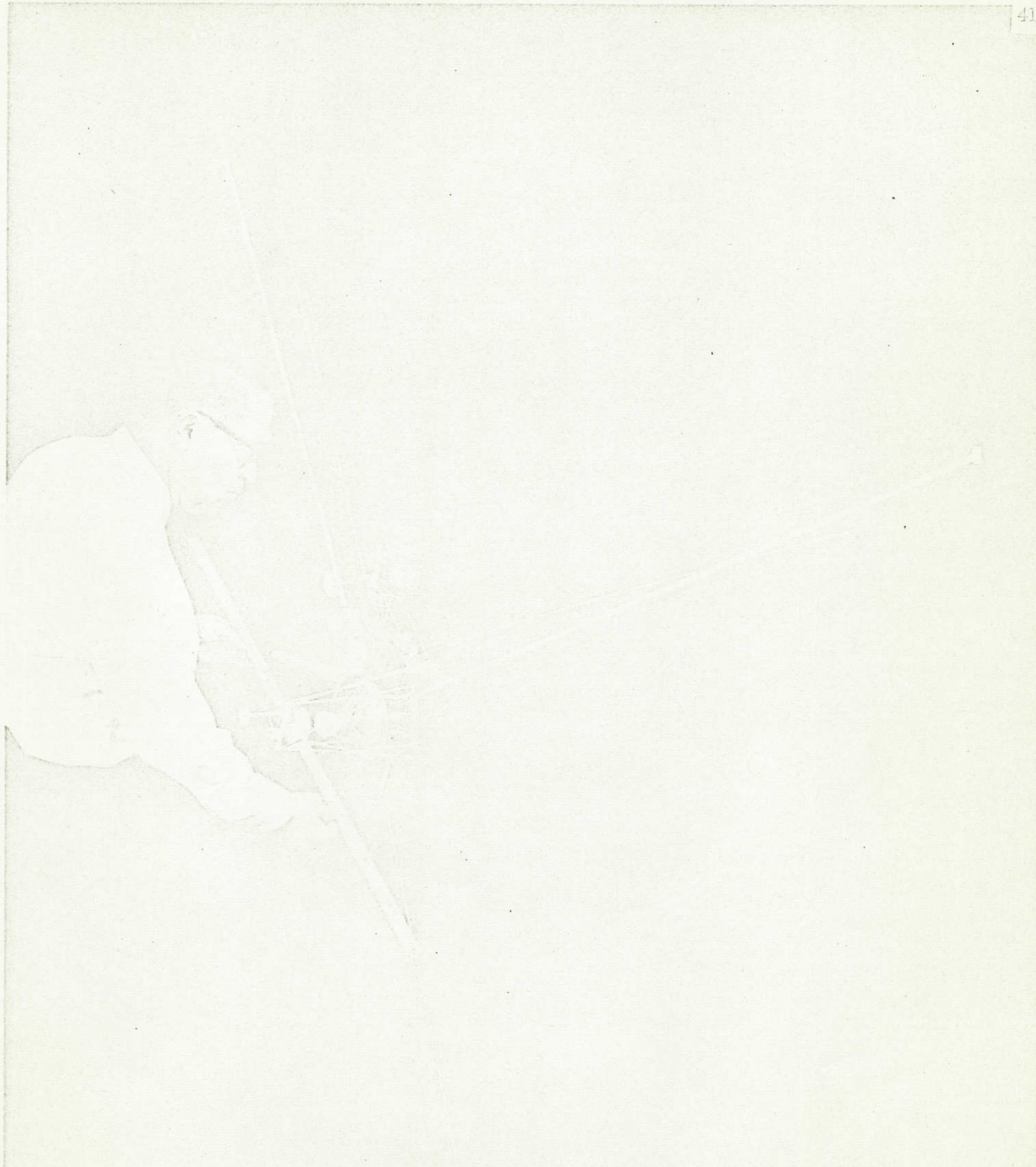
XI. The meeting was adjourned.

Attendance: Bob Peltzer, Walt Brown, Dave Martin, Sam Gulkis, Tom Clark, Joe Alexander, Rog Phillips, Andre Boischot, Dave Staelin, Tom Carr, Tom Bird (momentarily on 13 Oct. 71), Fred Scarf and Al Frandsen (on 13 October as P.W. Team Representatives), and Warwick.

James W. Warwick

J. W. Warwick

1 November 1971





D

TEST REPORT

EMI Test of OPGT 4.8 kHz
Main Inverter
(Breadboard Model)

19 November 1971

J. G. Bastow

## INTRODUCTION:

At the request of Dave Martin, cognizant engineer for the OPGT Radio Astronomy experiment, a test was performed on a breadboard model of the OPGT 4.8 kHz main power inverter to determine the nature of any inverter generated extraneous signals between the discrete odd harmonic frequencies of the 4.8 kHz square wave voltage under various load conditions. These tests were performed on 8 November 1971 in the EMI group screen room, Building 229. Although it had been desired to obtain information on the power supply frequency stability, this was not performed because of a lack of equipment with sufficient precision for this type measurement.

## TEST DESCRIPTION:

The tests performed were a measurement of the conducted interference output on the 4.8 kHz lines from the breadboard power inverter while operating into a resistive load of 100, 200, and 300 watts. TOPS-4-2004 rates the main inverter as having a maximum and minimum load of 315 and 60 watts, respectively. Measurements were made by recording on an X-Y recorder the frequency spectrum observed on a spectrum analyzer. Measurements were made over the frequency range from 0 to 300 kHz, and spot checked over the bands 1.475 to 1.525 MHz and 5.95 to 6.05 MHz.

A differential voltage probe was attached to terminal jacks on the power supply chassis which were connected in parallel with the power supply output to load resistors. Three non-inductive load resistors, each providing a 100 watt load to the power supply, were available on the load board.

One load resistor was permanently connected across the output and additional resistors were connected, as required, with parallel jumper wires. The differential probe with a 10X attenuator fed a probe amplifier with an additional 20X attenuation to provide a 46 dB attenuation and approximately 0.5 volts input to the spectrum analyzer. To prevent mixer distortion and spurious responses in the spectrum analyzer, an additional 50 dB of attenuation was required at the input to the spectrum analyzer mixer. Output to an X-Y recorder was taken from the spectrum analyzer vertical output and scan output connections. All recordings were made with the slowest available scan time of 10 seconds per inch on the X-Y chart. The X-Y recorder X input was set at 1 volt/inch (calibrated) and with zero input at the center vertical line (5 inches from left border). The Y input was set at 0.1 volt/inch (calibrated) and with zero on the horizontal line one inch from the top of the grid. Calibration of the grid was made by recording the -30 dBm, 30 MHz calibration signal from the spectrum analyzer.

For obtaining power supply measurements, a signal generator was adjusted for proper center frequency using a frequency counter and then fed to the input of the spectrum analyzer for adjustment of the spectrum analyzer to place the signal at the center of the spectrum analyzer grid. The power supply output was then connected to the spectrum analyzer through the differential probe and amplifier and a recording made on the X-Y recorder. Bandwidth and Video Filter on the spectrum analyzer were adjusted as narrow as possible, consistent with a calibrated output and the selected scan width. Each of these settings are recorded on the X-Y plot.

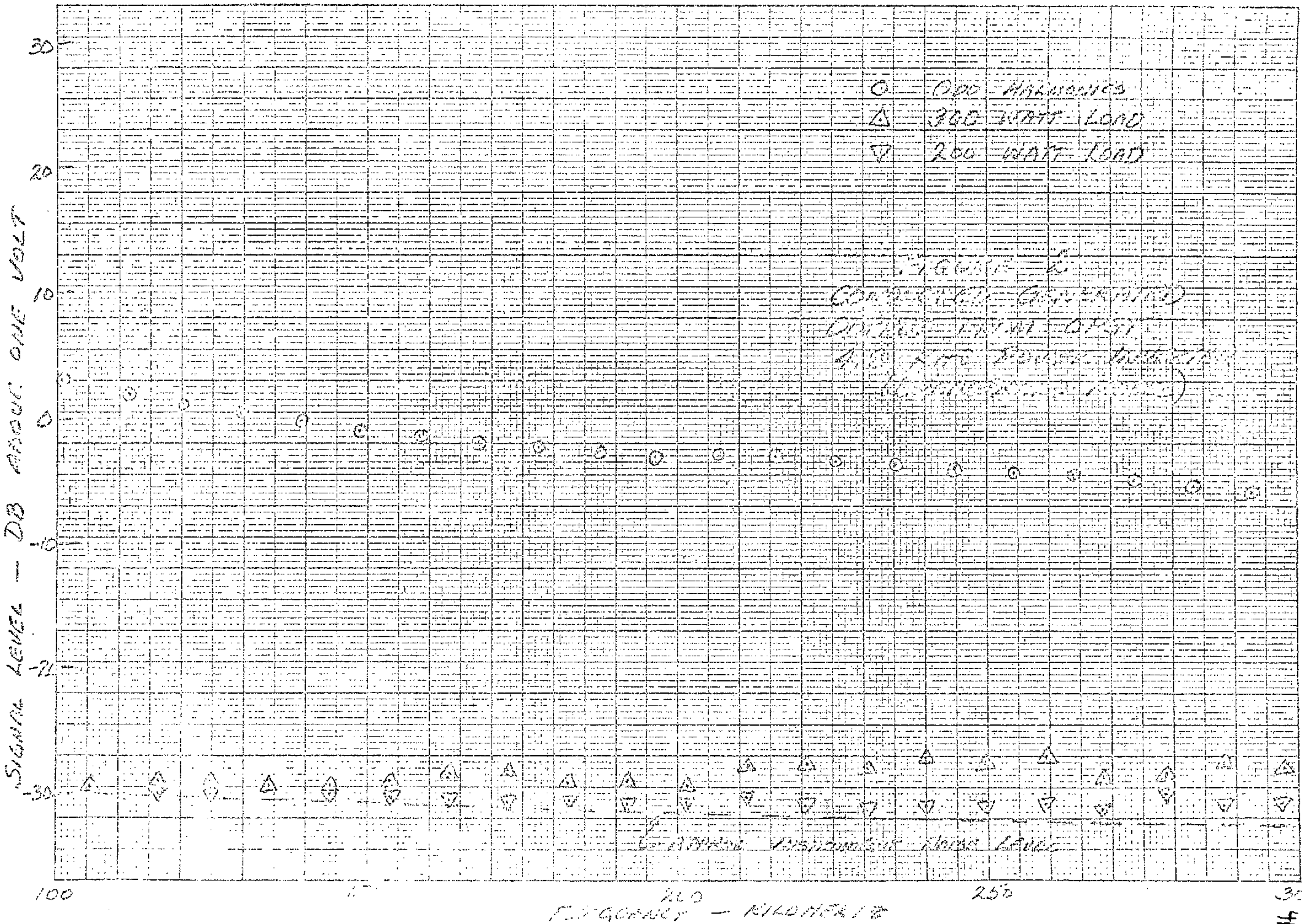
A listing of the test equipment employed is given in Appendix A. The recorded X-Y charts are contained in Appendix B.

TESTS RESULTS:

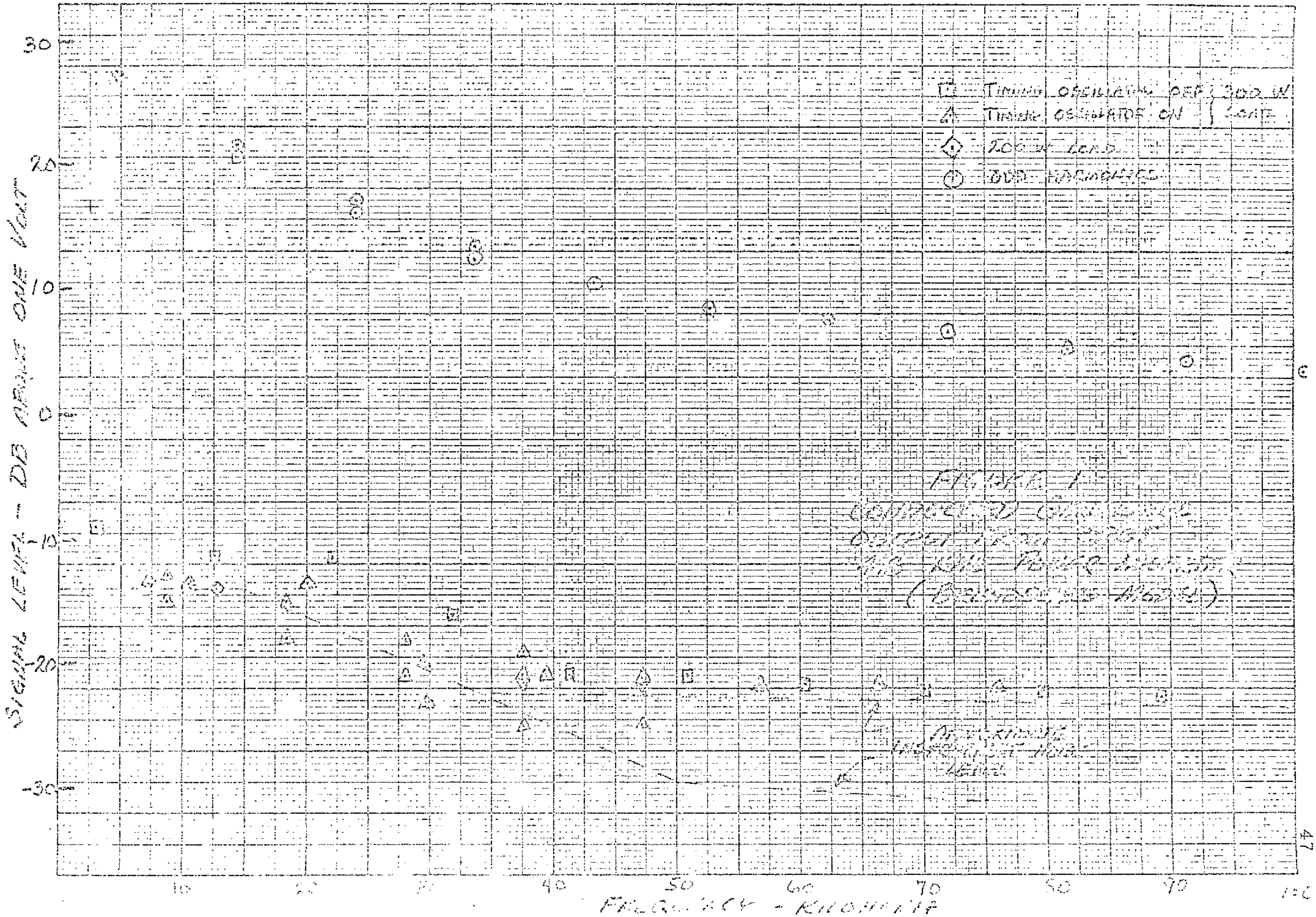
The test data contained in Appendix B has been consolidated and summarized for the frequency range 0 to 100 kHz on figure 1 and from 100 to 300 kHz on figure 2. Extraneous signals are most evident at 300 watt load with virtually no interference at the 100 watt load. The vertical scale in figures 1 and 2 has been corrected to provide signal levels in dB above 1 volt at the power supply output by converting the spectrum analyzer and X-Y recorder value in dBm by adding 33 dB (46-13). Most of the extraneous signals in figure 1 are apparently related to the power supply synchronization. With the timing oscillator turned on, these signals appear approximately 4.0 kHz above each odd harmonic of the power supply frequency and 7.7 kHz above when the oscillator is off. These signals are evident up to about 90 kHz.

In the 100 to 300 kHz range, even harmonic signals are evident under 200 and 300 watt loading. These harmonics appear strongest at about 250 kHz and do not appear at frequencies below 100 kHz. Even harmonic signals are still evident at 1.5 MHz at 300 watts load, but not at 100 watts load. At 6 MHz no extraneous signals are observed; although, the random noise appears slightly larger under the 300 watt load than with the 100 watt load.

It is pointed out that these results can only be considered as possibly typical for a spacecraft flight inverter and not necessarily representative of the interference that may actually be generated on the spacecraft. It is apparent, however, that special care in the inverter design will be required to insure that extraneous signals between the power supply odd harmonics are at a sufficiently low level to minimize interference to low frequency science experiments.



○ ODD HARMONICS
△ 300 WATT LOAD
▽ 200 WATT LOAD
SIGNAL LEVEL - DB ABOVE ONE VOLT
30
20
10
0
-10
-30
100
200
250
FREQUENCY - KILOHERTZ



TIMING OSCILLATOR OFF
TIMING OSCILLATOR ON
ODD HARMONICS
SIGNAL LEVEL - DB ABOVE ONE VOLT
30
20
10
0
-10
-20
-30
10
20
30
40
50
60
70
80
90
100
FREQUENCY -


FIGURE 1

# APPENDIX A

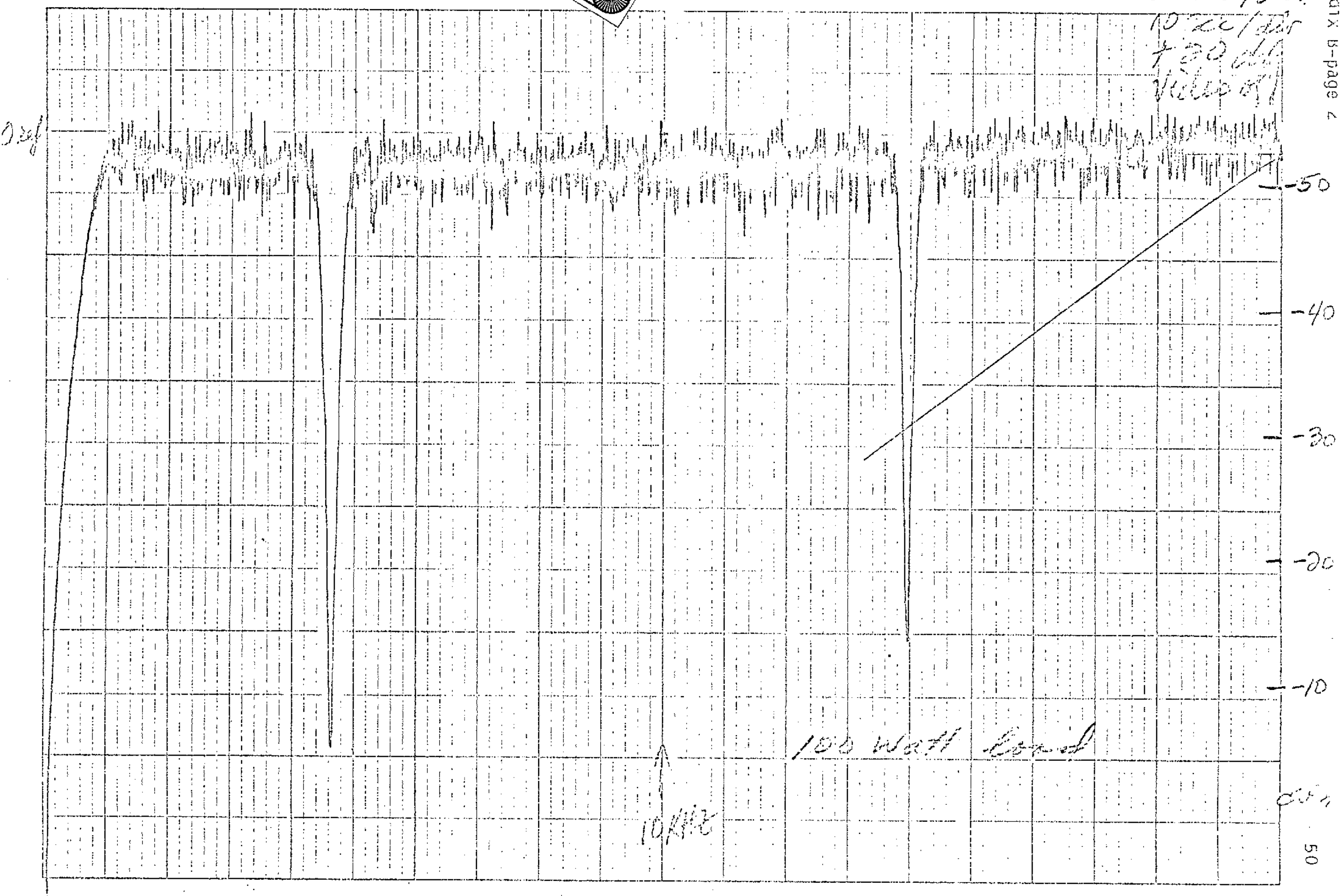
## TEST EQUIPMENT LIST

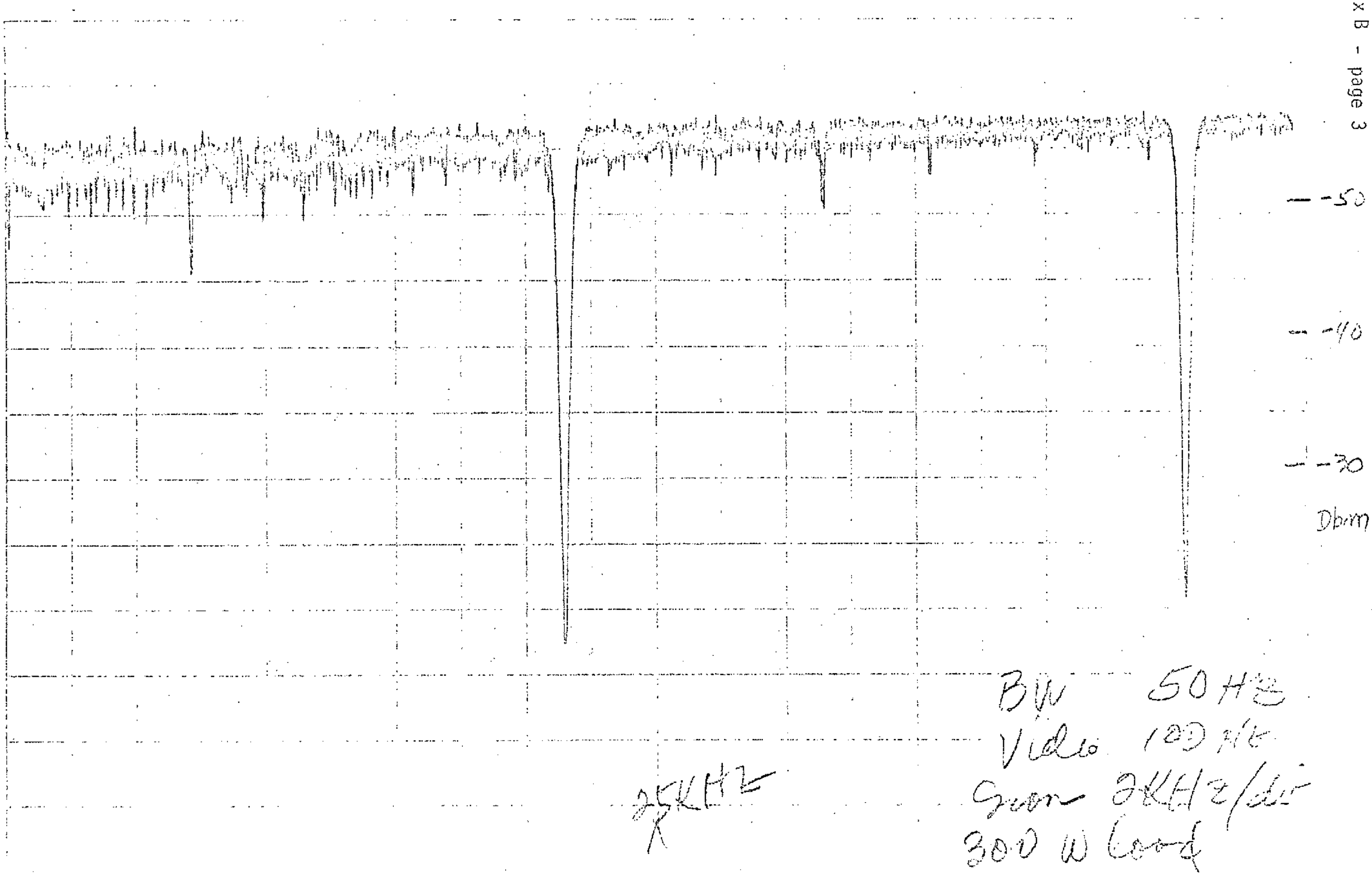
| | | |
|---|---|---|
| Differential Probe and Amplifier | Tektronix P6046 | |
| Spectrum Analyzer | Hewlett-Packard 8552A/8553L | S/N 849-00481 |
| Frequency Counter | Hewlett-Packard 5245L | S/N 307-00346 |
| Audio Oscillator | Hewlett-Packard 200 CD | S/N 9471 |
| Signal Generator | Hewlett-Packard 606 A | S/N 008-01972 |
| X-Y Recorder | Moseley 135A | S/N 616-00641 |

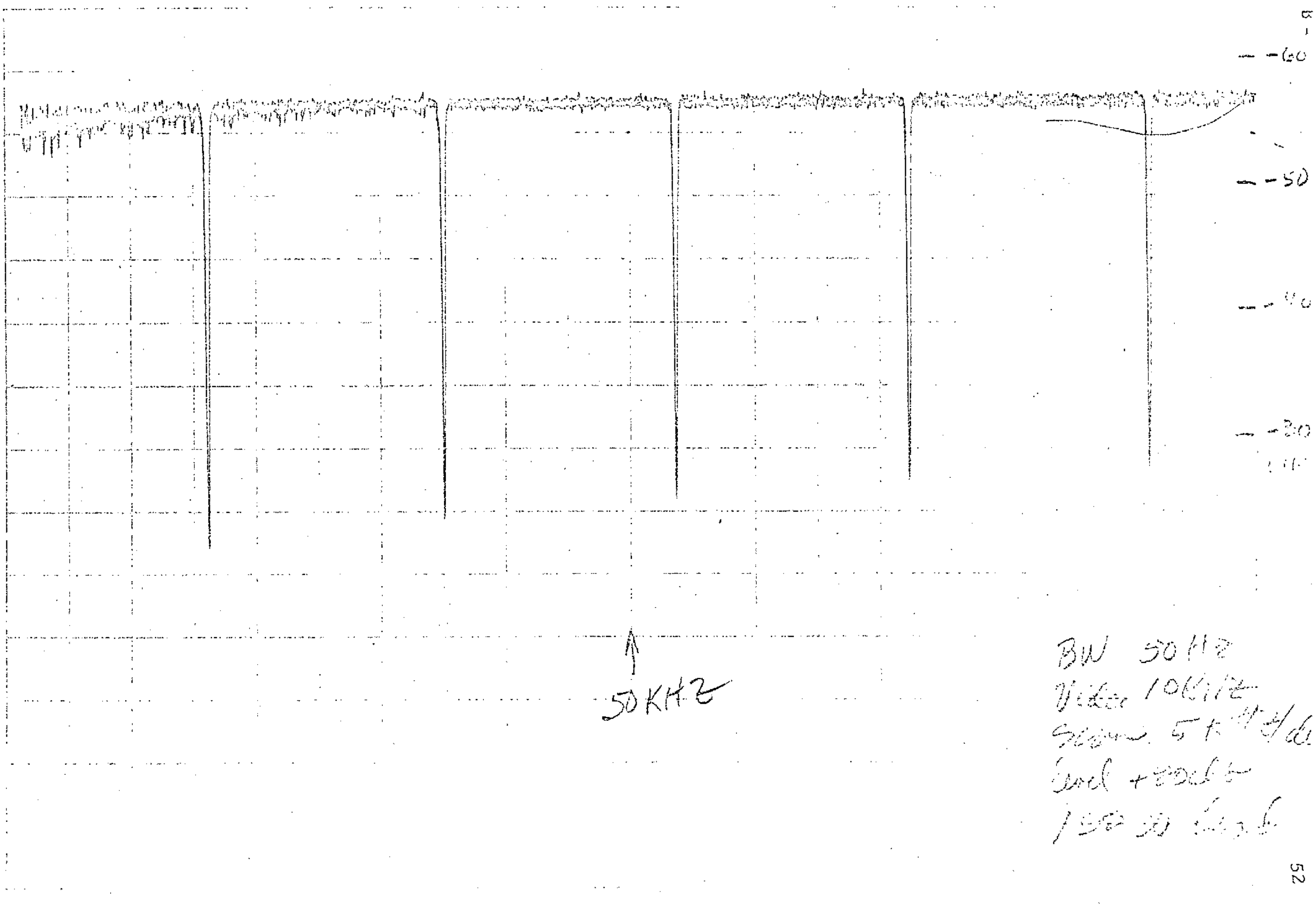
# APPENDIX B

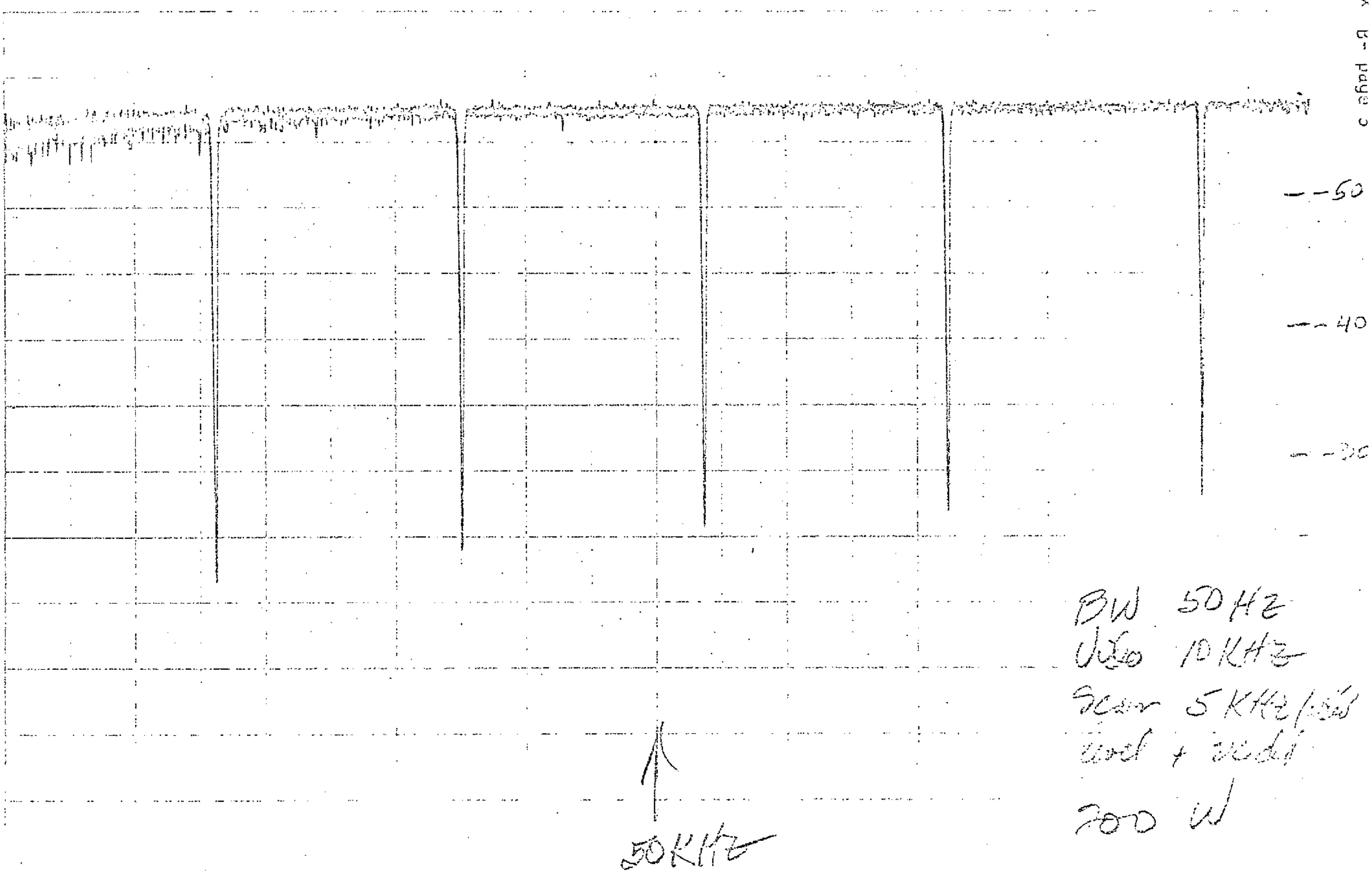
## Recorded X-Y Charts

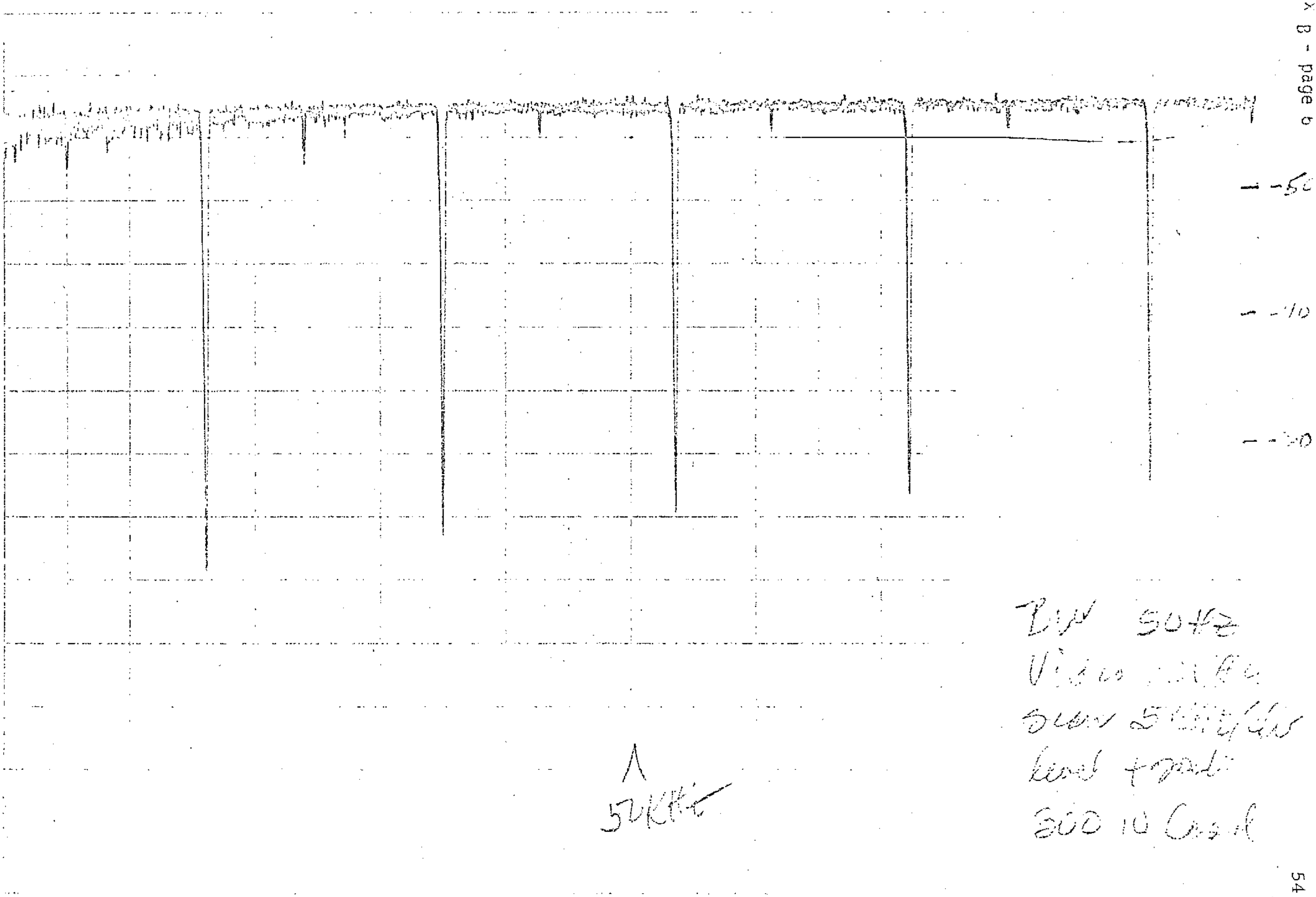
BW .05
2KHz/div
10 dB/div

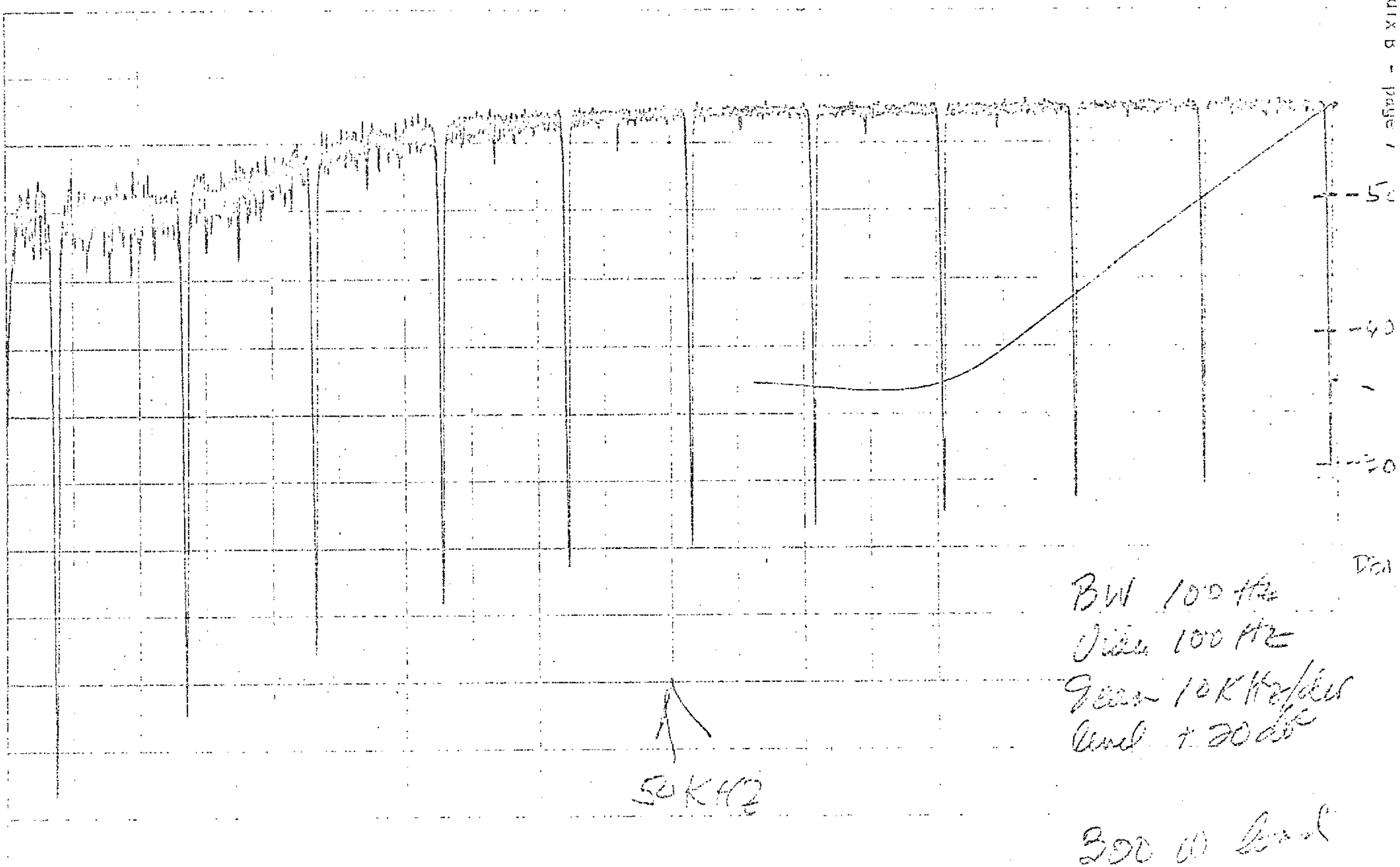



-50
-40
-30
Dbm
25KHz
BW 50 Hz
Video 100 Hz
Span 2KHz/div
300 W Load

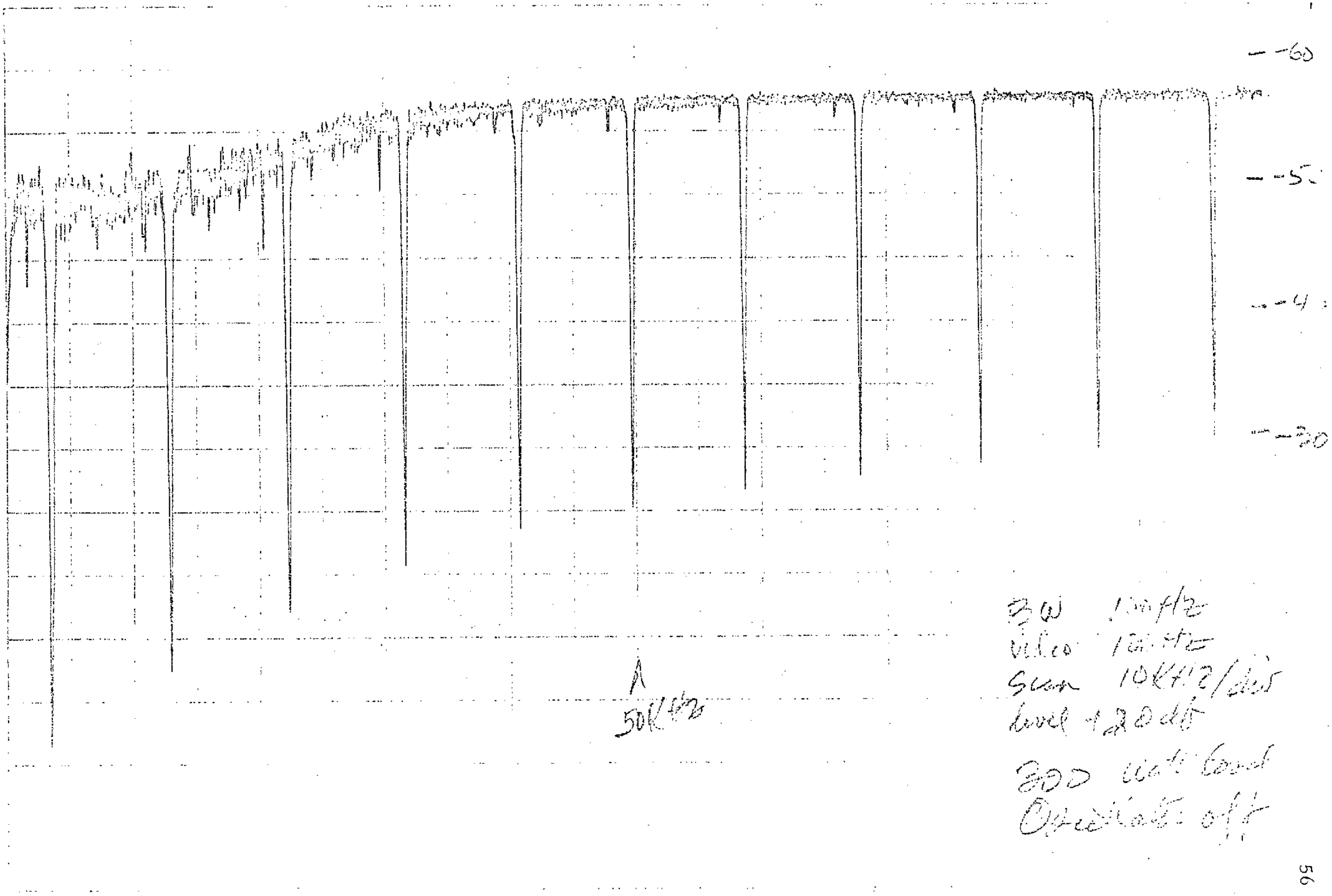

-60
-50
-30
50KHz
BW 50 Hz

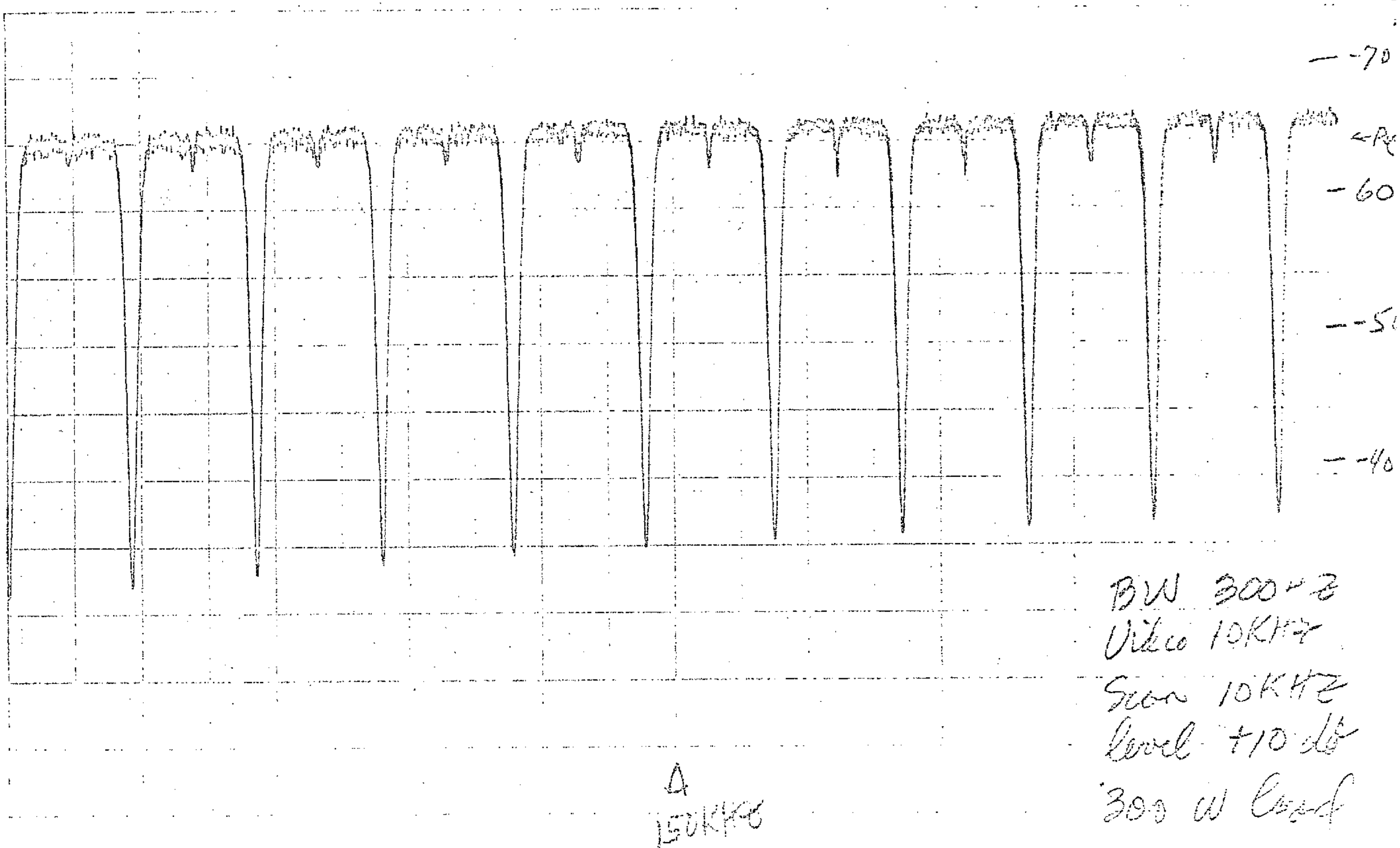

-50
-40
BW 50 HZ
10 KHZ
200 W
50 KHZ

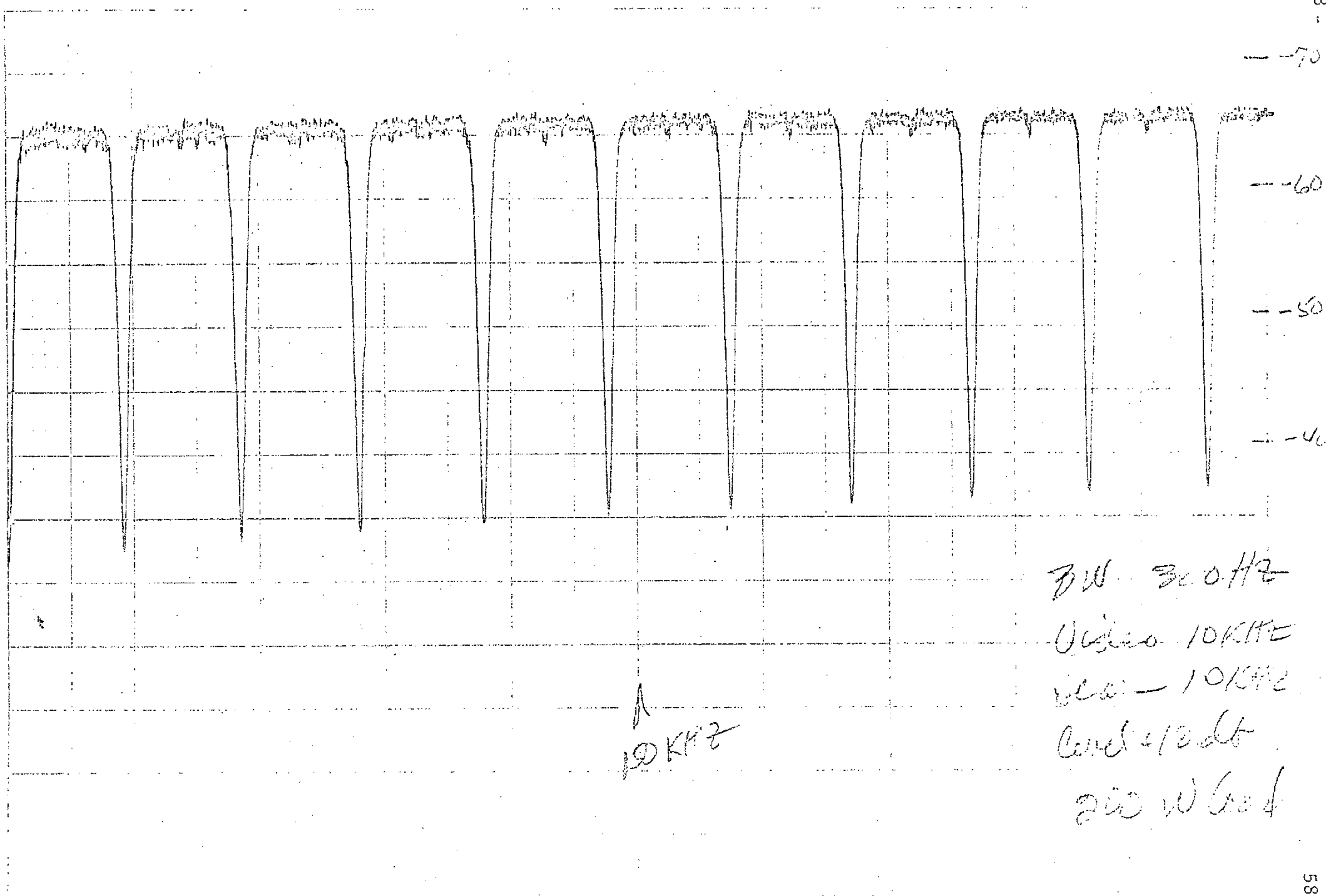

-50
52KHz
BW 50Hz

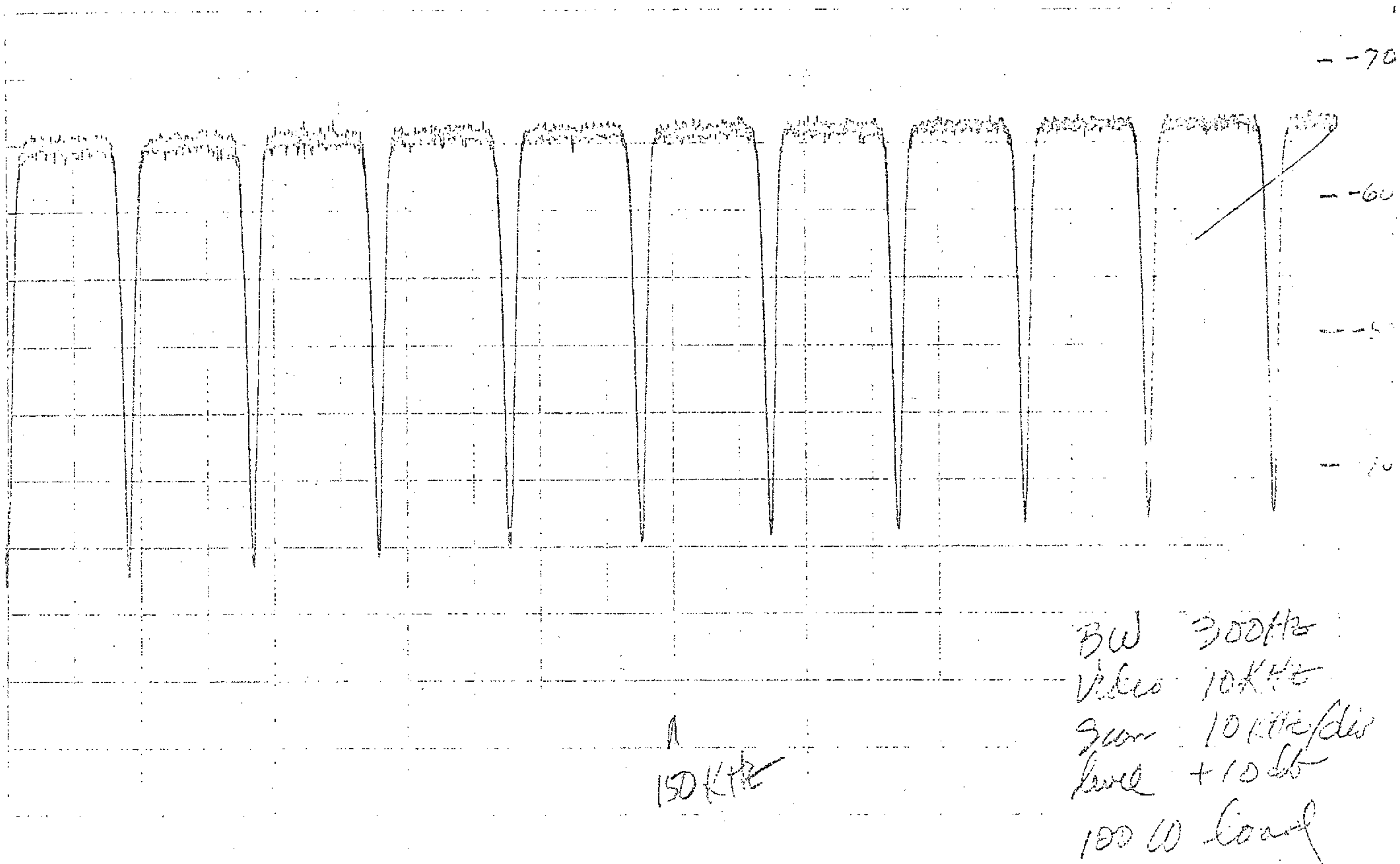


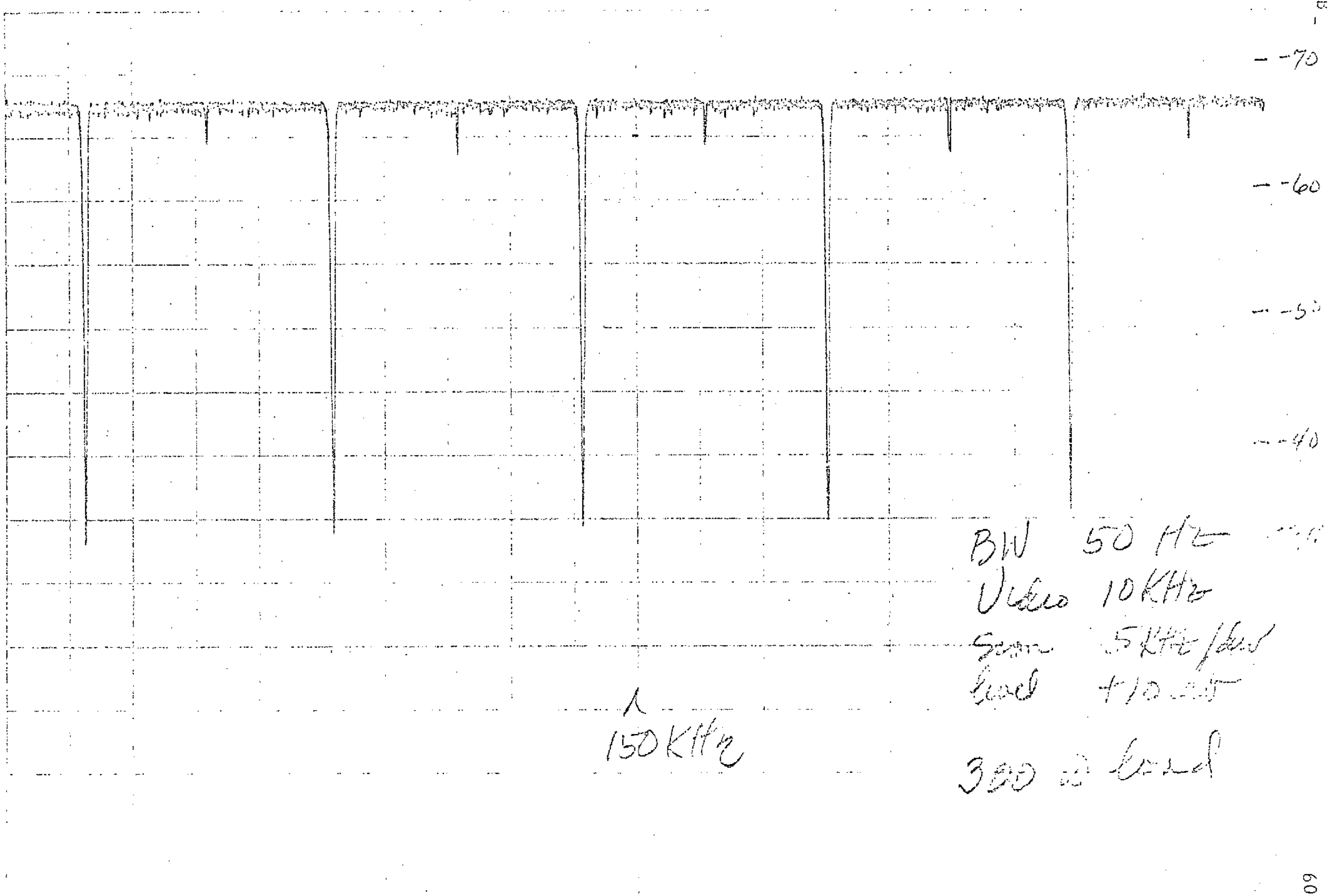

E

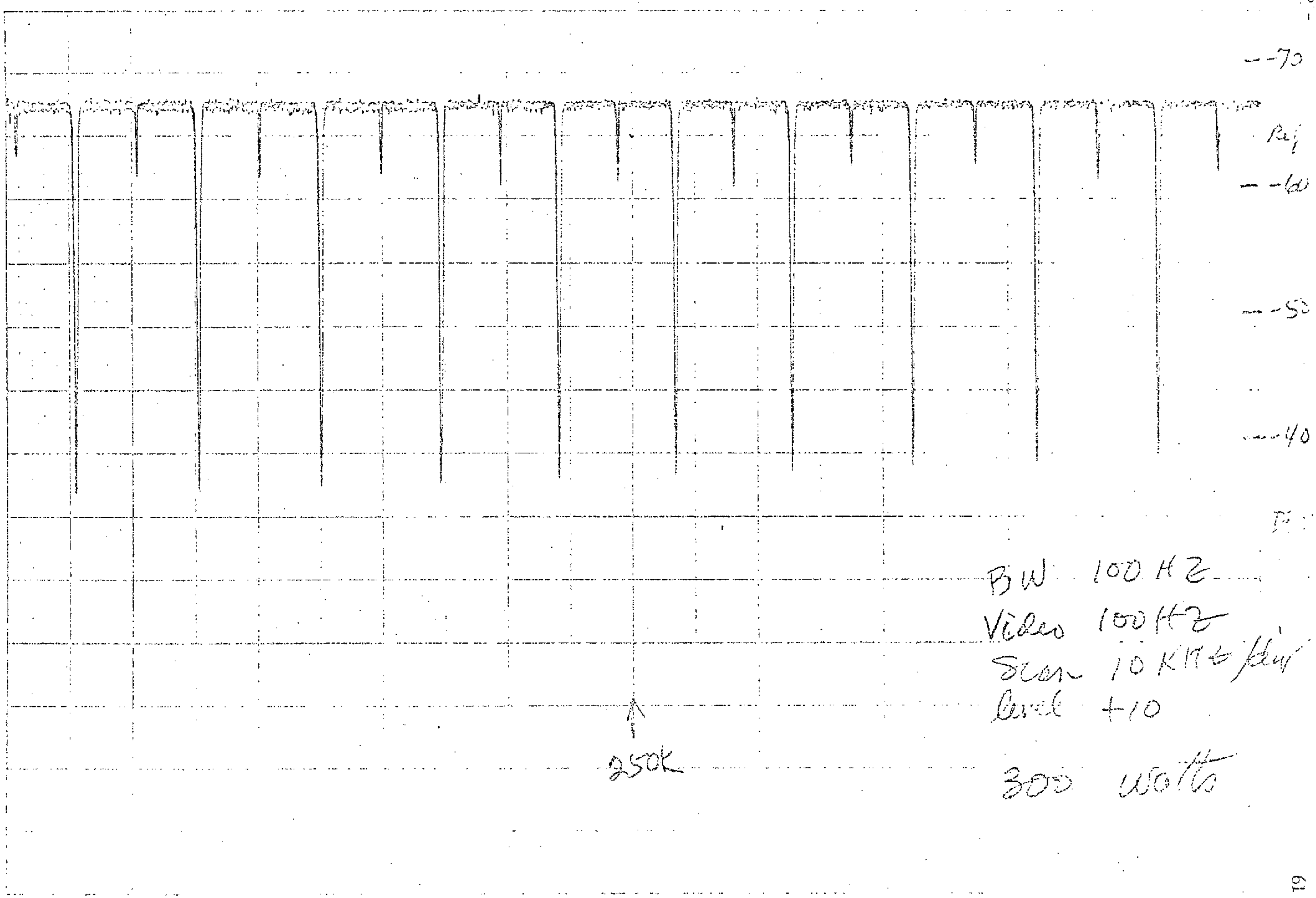

-60
50KHz
BW 100Hz
Video 100Hz
Scan 10KHz/div
level +20dB
300 watt load
Oscillator off

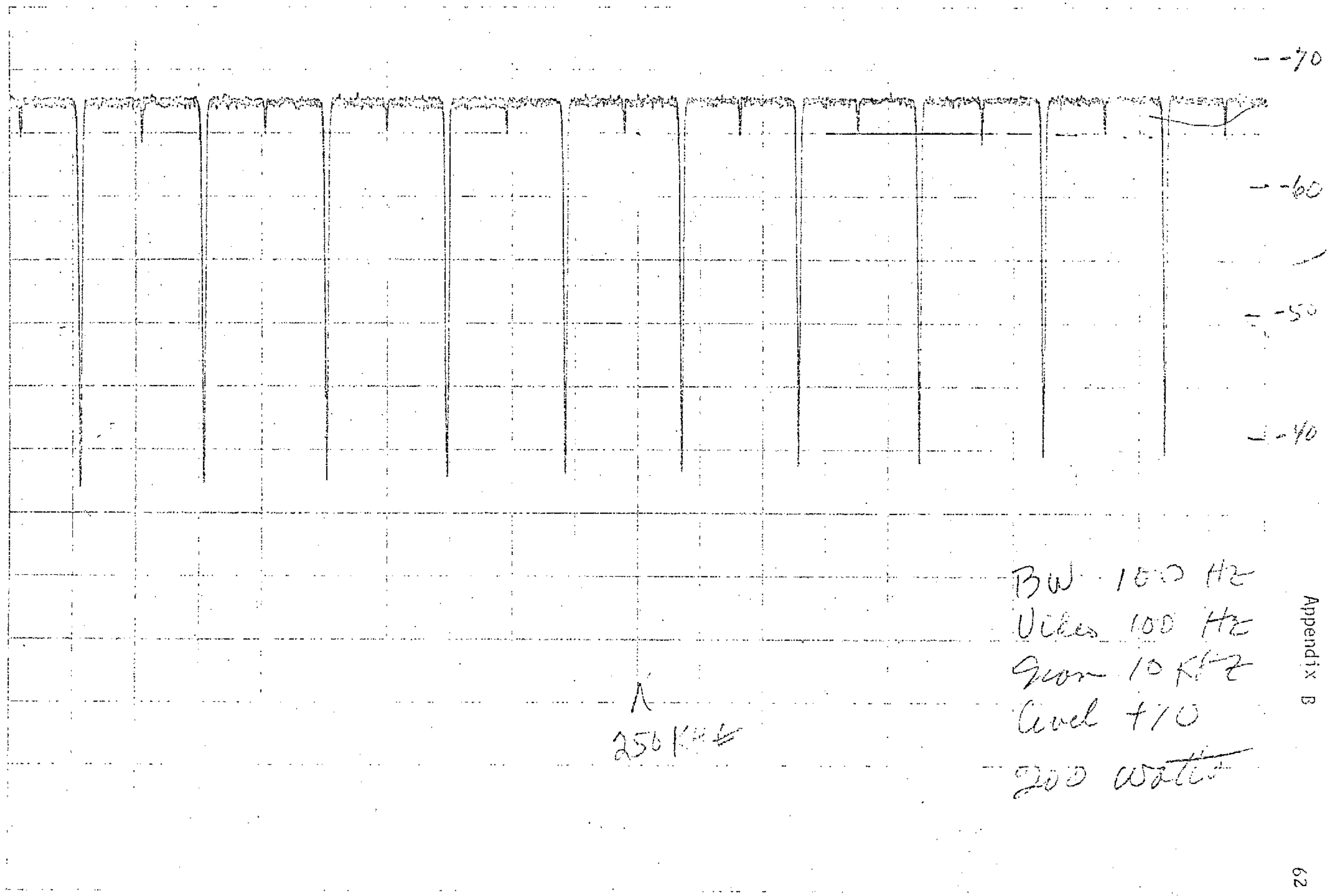

-70
←Ref
-60
-50
-40
Δ
150KHz
BW 300 Hz
Video 10KHz
Scan 10KHZ
level +10 db
300 W load

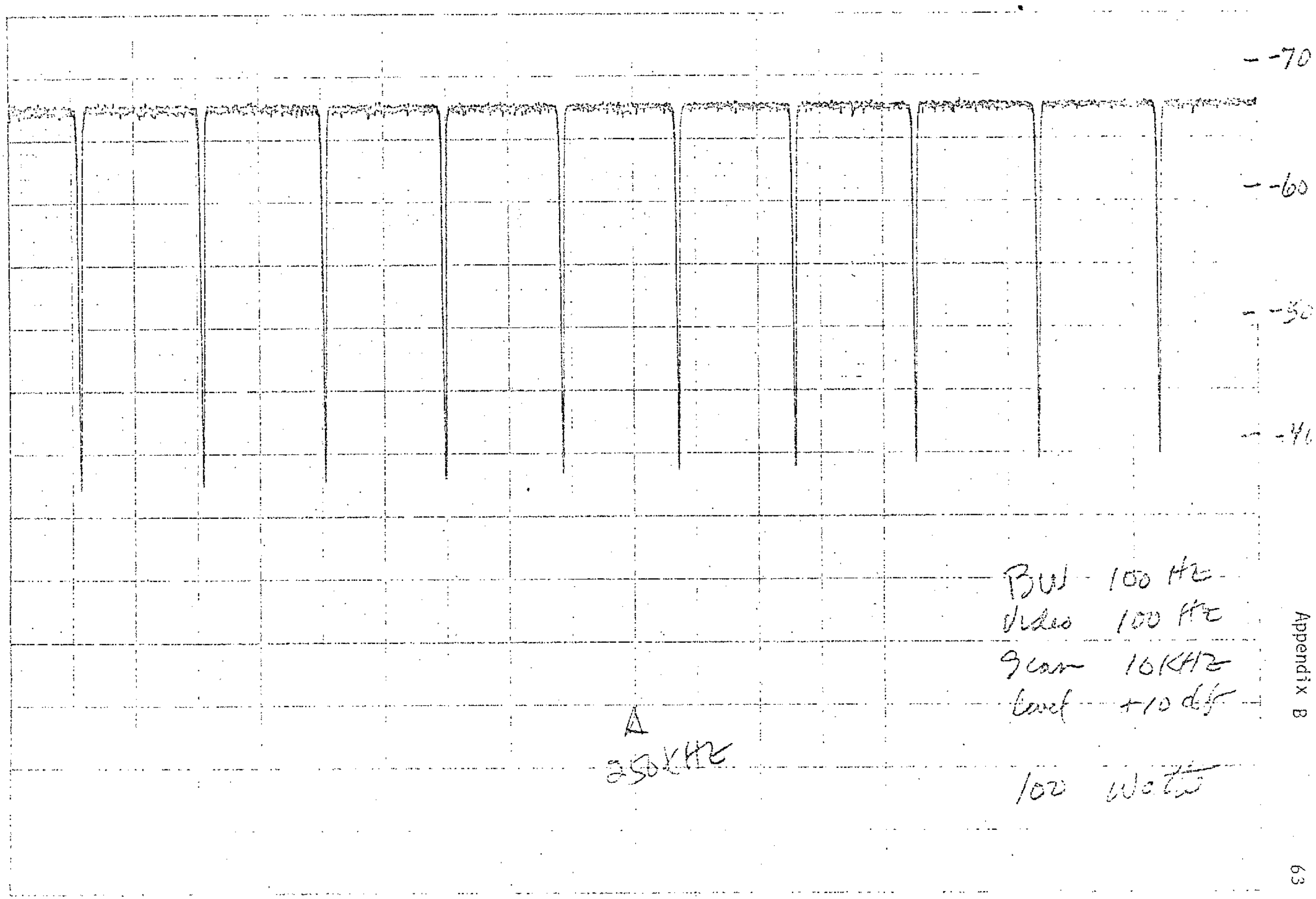

-70
-60
-50
-40
10 KHZ
BW 300 HZ
Video 10KHZ

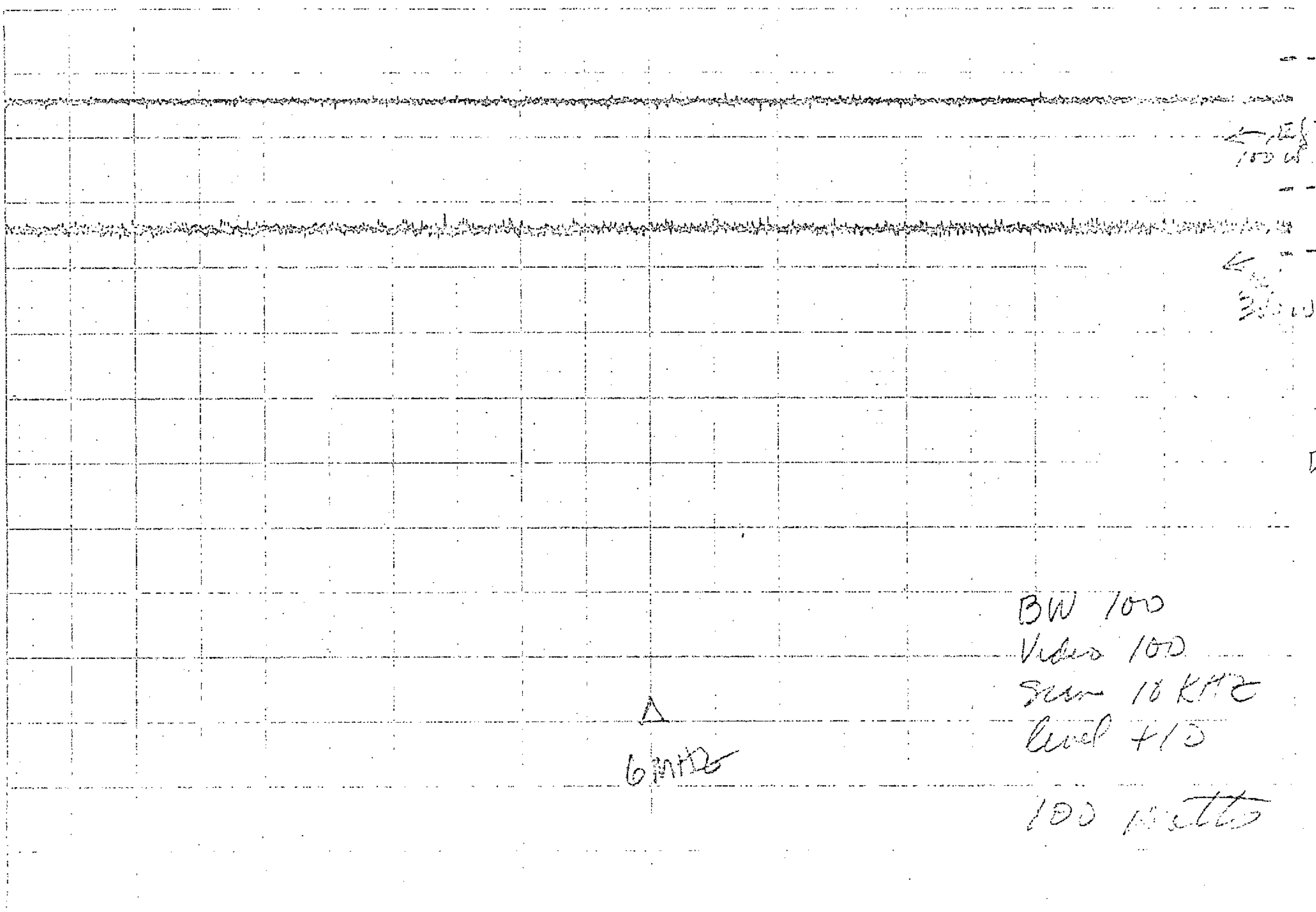

-70
-60
150KHz
BW 300Hz
Video 10KHz
Span 10KHz/div
Level +10db
100 Ω load

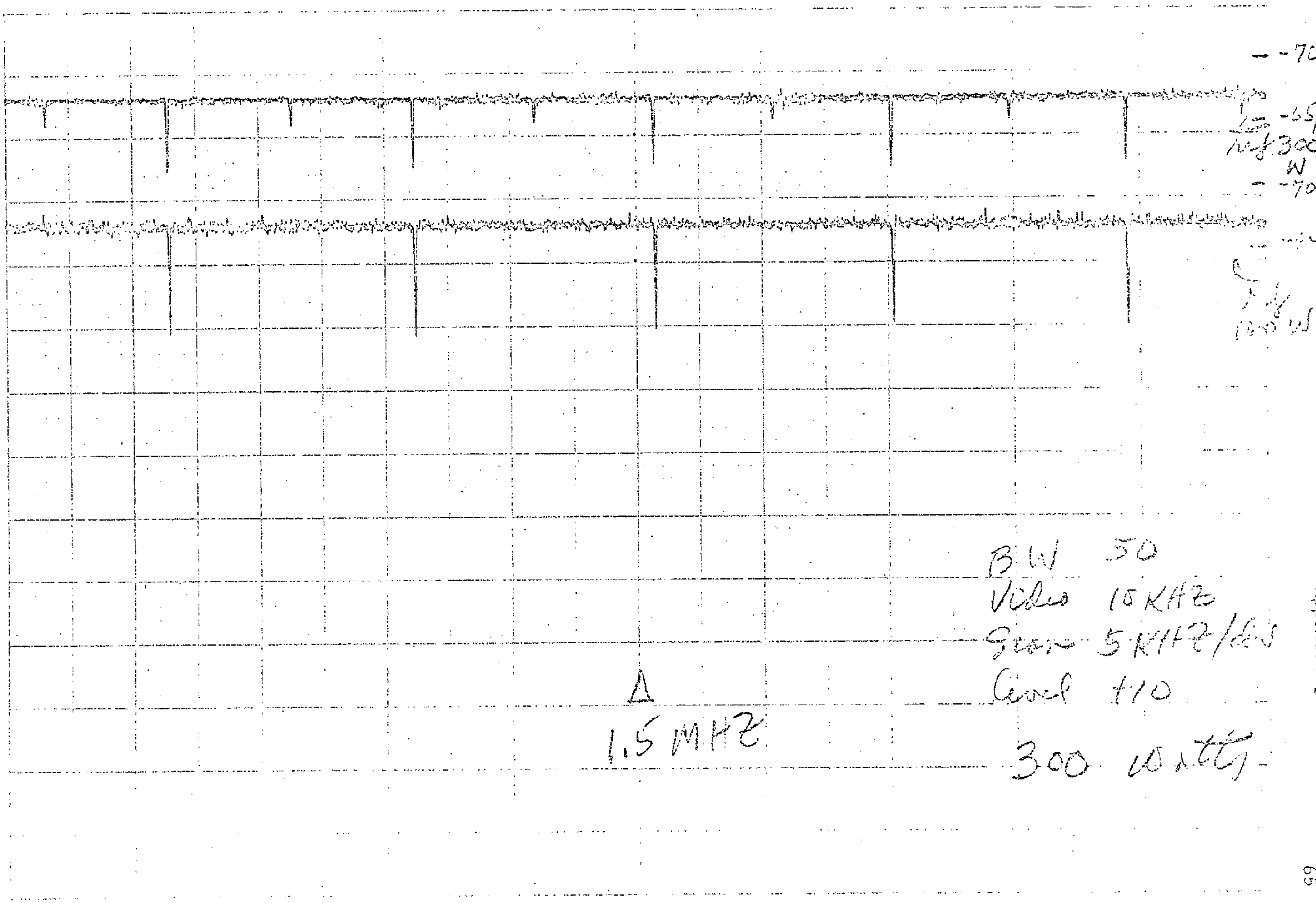

-70
-60
-40
150 KHz
BW 50 Hz
Video 10 KHz
300 Ω load


-70
Ref
-60
-50
-40
BW 100 HZ
Video 100 HZ
Scan 10 KHz/div
Level +10
300 Watts
250K

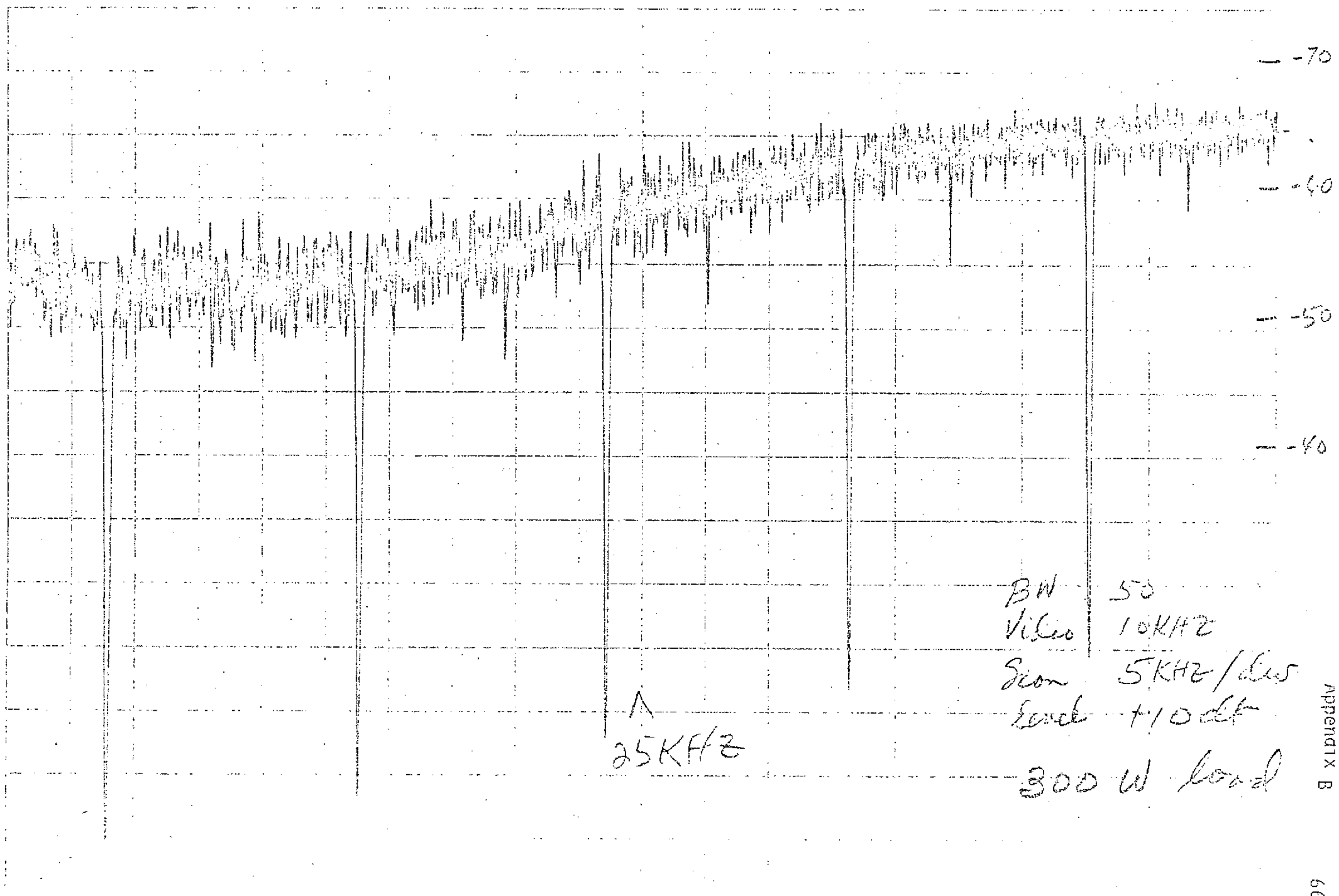

-70
-60
-50
-40
250 KHz
200 Watts

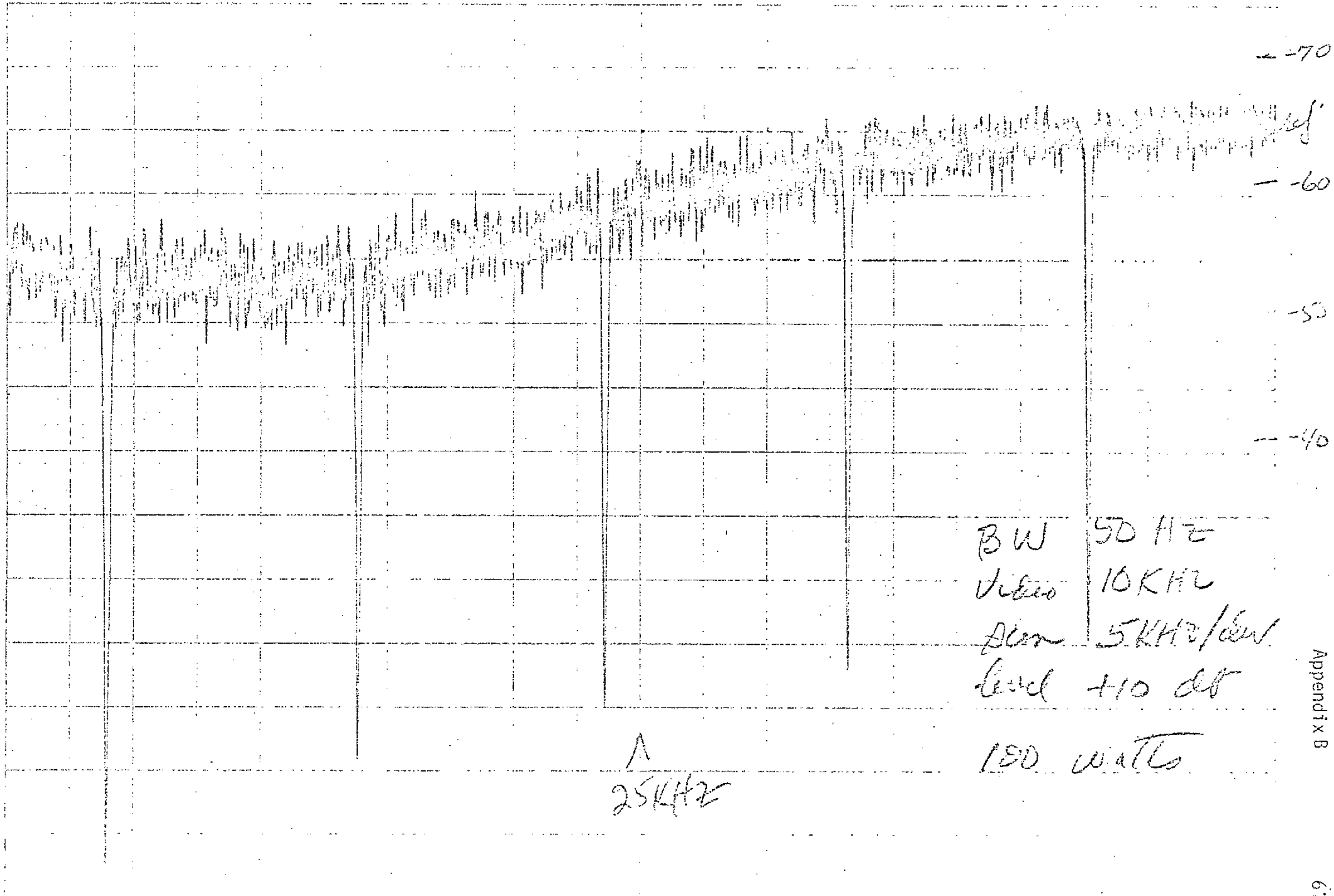

-70
-60
BW 100 Hz
Video 100 Hz
Scan 10KHz
Level +10 dB
250KHz
100 Watts

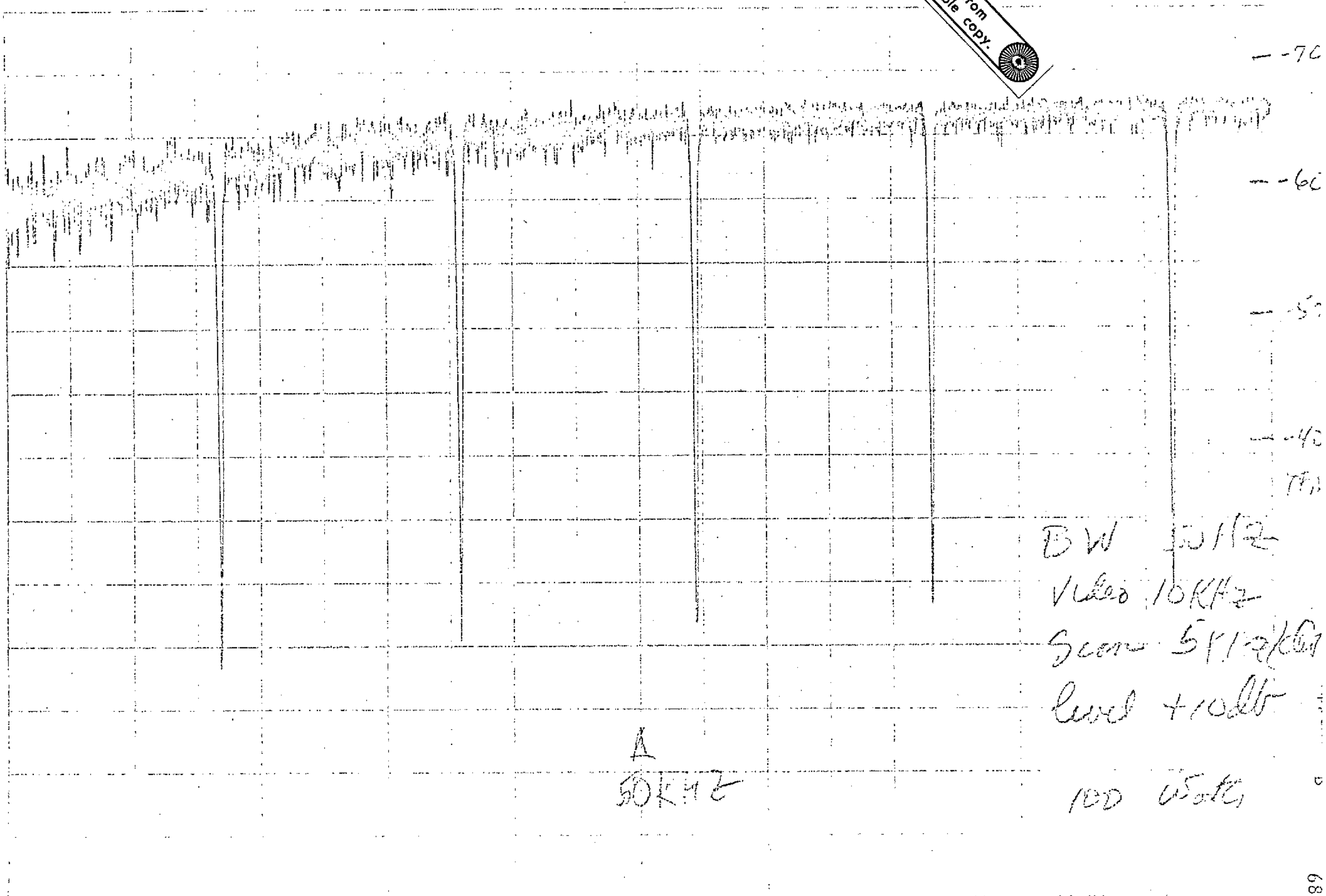

-70
-65
100 W
-70
-65
BW 100
Video 100
Scan 10 KHZ
Level +10
100
6 MHz

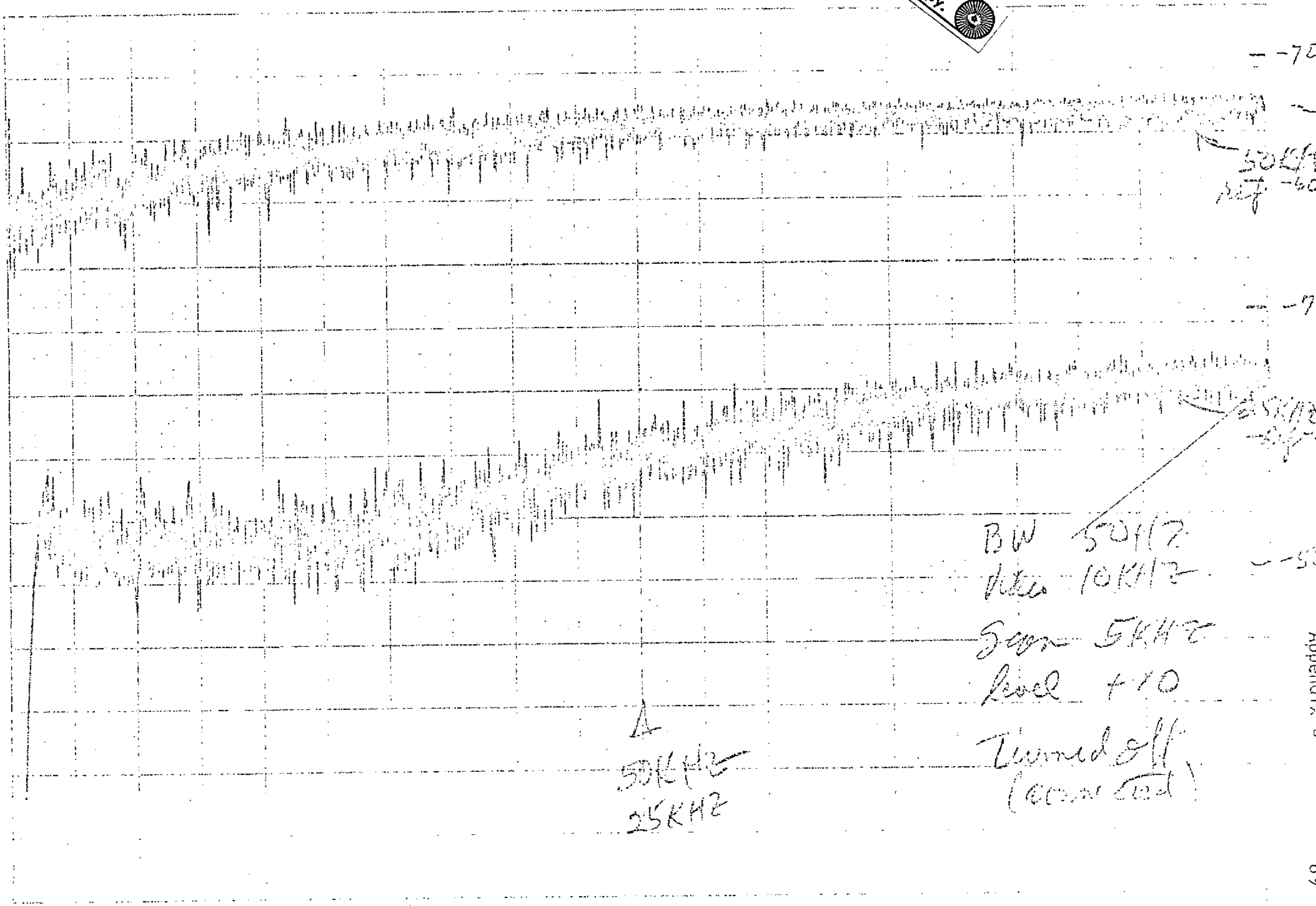


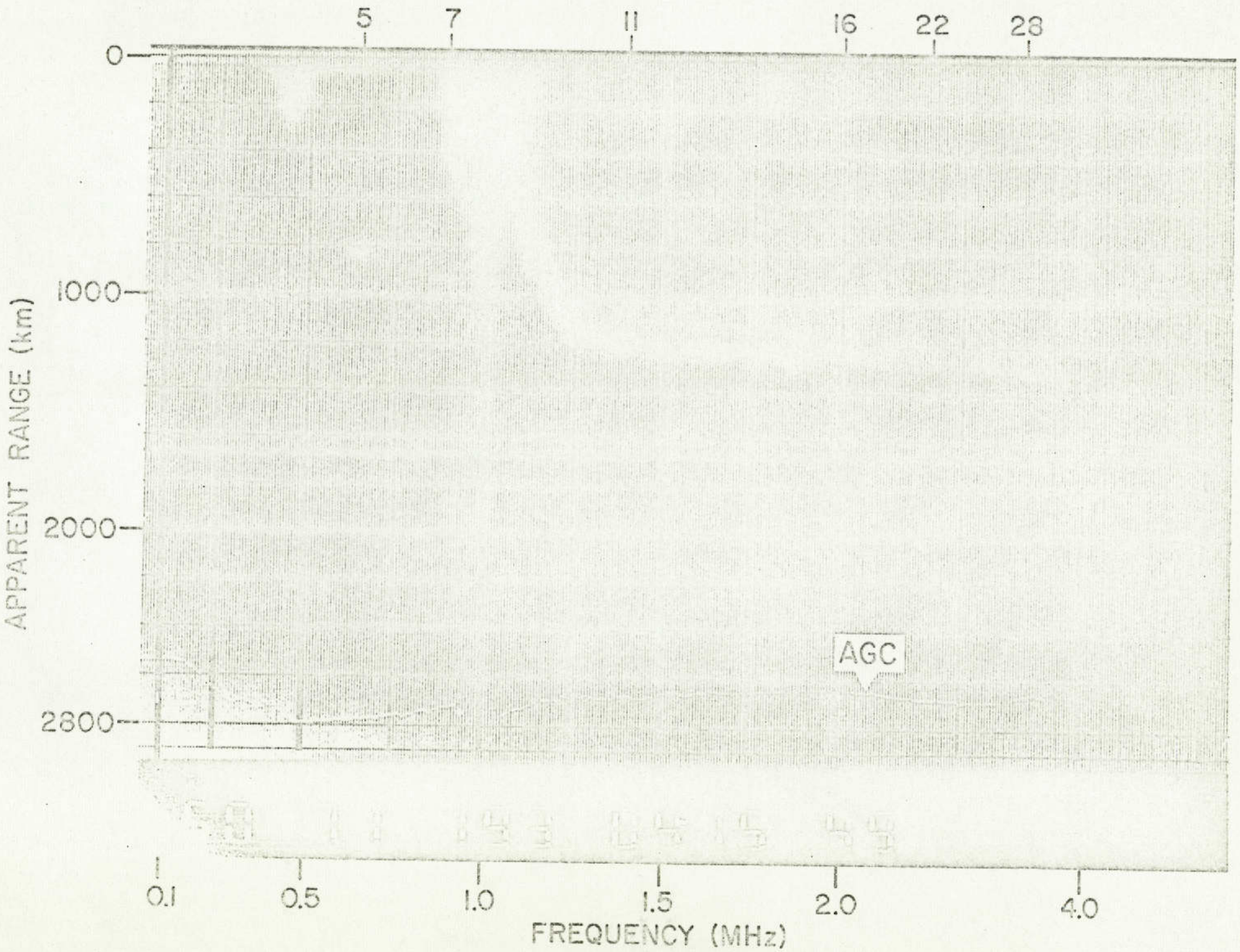
-70
-70
BW 50
Video 10 KHz
Span 5 KHz/div
Level +10
1.5 MHZ
300 watts


-70
-60
-50
-40
25KHZ
BW 50
Video 10KHZ
Scan 5KHZ/div
Level +10 dB
300 W load


-70
-60
-50
-40
BW 50 Hz
Video 10KHz
Span 5KHz/div
level +10 dB
180 watts
25KHz


-70
-60
-40
BW 50 HZ
Video 10KHz
level +10db
50KHZ
100 watts


-70
50KHz
ref -60
-90
-50
BW 50HZ
Scan 5KHZ
level +10
Tuned off
50KHZ
25KHZ



12 JULY 1971 (57° N, 74° W)
SATELLITE HEIGHT 1430 km

OBSERVATOIRE DE PARIS
SECTION D'ASTROPHYSIQUE
92-MEUDON (HAUTS DE SEINE)
TÉL. 626.16-30 ET 26-20

MEUDON, LE 6 January 1972

TO : PRA Team

FROM : C.C. Harvey

SUBJECT : PRA Antenna Impedance Measurements

Antenna impedance measurements were discussed at the last PRA team meeting (minutes, §D4), and it was concluded that for the time being reactance, but not resistance, measurements will be included on both the full - blown and minimum experiment.

The attached memo defends this decision, and points out the assumptions which must be made in deducing absolute noise intensities when only the antenna reactance is known.

To : P R A team

From : C.C. HARVEY

Subject : THE UTILITY OF ANTENNA IMPEDANCE MEASUREMENTS for the P R A Experiment

For the P R A experiment the sole interest in the measurement of the antenna impedance is its application to the determination of the absolute noise intensity. But the measurement and use of the resistive part of the impedance for this purpose presents two serious difficulties ; one is experimental, in that the antenna resistance will be almost impossible to measure at most frequencies of the P R A experiment : and the second theoretical, in that it is not clear how to determine the cosmic noise intensity from the measured resistance if the latter should differ from the theoretical value. Nevertheless, a case can be made for measuring the antenna reactance.

## Experimental Difficulties

Consider an antenna of length 2 l and diameter 2 a. For frequencies less than the half-wave resonance frequency, the expressions for for the antenna radiation resistance R and susceptance B are approximately

$$R = \frac{2}{3\pi} \zeta_0 \tan^2\left(\frac{\pi \nu l}{c}\right) , \qquad B = \frac{2\pi}{\zeta_0} \left\{2 \ln(l/a) - 2\right\}^{-1} \tan\left(\frac{2\pi \nu l}{c}\right) \qquad (1)$$

where $\zeta_0$ is the impedance of empty space (see, for example, Harvey, Proc. Camb. Phil. Soc. 70, 351, 1971, equations 11, 2). The antenna admittance may be expressed in terms of its amplitude $|Y|$ and phase $\phi$ by

$$G + i B = Y = |Y| e^{i\phi} = \frac{1}{Z} = \frac{1}{R + i X} , \qquad (2)$$

and this equation may be solved to give

$$|Y| = B / \sin\phi , \qquad \phi = \frac{1}{2} \sin^{-1}(2 R B) \qquad (3)$$

Equations 1 and 3 have been used to construct the following table for an antenna of overall length 2 l = 20 m and diameter 2 a = 2 cms ; the free-space half-wave resonance frequency of such an antenna is approximately 6.9 MHz. Also shown in the table are the antenna effective length h and capacitance C, defined respectively by

$$h = \frac{c}{\nu}\left(\frac{3}{2\pi}\frac{R}{\zeta_0}\right)^{1/2}, \qquad C = B/2\pi\nu . \tag{4}$$

| $\nu$ (kHz) | R (m$\Omega$) | $B = \|Y\|$ ($\mu$℧) | $\frac{\pi}{2} - \phi$ | h (m) | C (pF) |
|---|---|---|---|---|---|
| 30 | 0.79 | 8.85 | $7.0 \times 10^{-9}$ | 10 | 47.1 |
| 100 | 8.72 | 29.5 | $2.6 - 10^{-7}$ | 10 | 47.1 |
| 300 | 78.9 | 88.7 | $7.0 \times 10^{-6}$ | 10 | 47.1 |
| 1000 | 884 | 300 | $2.7 \times 10^{-4}$ | 10.04 | 47.7 |
| 3000 | 8450 | 1024 | $8.7 \times 10^{-3}$ | 10.34 | 54.3 |

In practice it is very difficult to measure the real part of the antenna impedance when the phase $\phi$ is very close to $\frac{\pi}{2}$, and only at frequencies above about 3 MHz would it be possible to measure the resistance with reasonable accuracy (e.g., ± 5 % at 3 MHz). But it is questionable what use such measurements would be for planetary observations at frequencies above the full-wave resonance at about 14 MHz where the antenna gain pattern becomes relatively complicated.

A cold homogeneous (no plasma sheath) isotropic plasma would not appreciably alter the above conclusion. It may readily be shown from 1 that in such a medium of e.m. wave refractive index n, when the condition $\left(\frac{\pi\nu l}{c}\right) \simeq \frac{\pi\nu l}{c}$ (which is equivalent to $h \simeq 1$) is satisfied,

$$R = n R_o , \qquad C = n^2 C_o , \qquad \frac{\pi}{2} - \phi = n^3\left(\frac{\pi}{2} - \phi_o\right) , \tag{5}$$

where $R_o$ $C_o$ and $\phi_o$ are the values of R, C and $\phi$ in vacuo. The resistance becomes even more difficult to measure, unless there are other plasma effects which increase the antenna resistance ; but in this case the interpretation of the measurements runs into theoretical difficulties.

## Theoretical Difficulties

The plasma surrounding the P R A antenna is neither cold nor homogeneous in the neighbourhood of the antenna (nor isotropic in the vicinity of Jupiter). The finite temperature introduces the possibility of plasma waves propagating and coupling with the antenna. For the determination of the absolute e.m. noise intensity it is necessary to know both the antenna impedance and the e.m. reception efficiency, defined (in an isotropic plasma) by

$$\eta_r = \left(\frac{n}{\lambda_0}\right)^2 \iint_{4\pi ster} A(\theta, \phi)\, d\Omega \qquad (6)$$

where A (θ, ∅) is the effective receiving area for e.m. waves ; the directivity is also required to interprete observations of sources of limited angular size. Strictly speaking, the plasma wave reception efficiency is also required in order to estimate the noise received from the plasma waves. The effect of the plasma waves is to change the antenna impedance and reduce the e.m. reception efficiency. The two effects are undoubtedly related, but the nature of the relationship is not clear ; but it certainly depends upon the geometry of the plasma sheath which forms around the antenna. The sheath thickness depends upon the Debye length of the plasma and also the potential of the antenna, and the latter in turn depends upon the photoelectric properties of the surface of the spacecraft. In other words, it may be said that the reduction of the antenna e.m. wave reception efficiency due to plasma waves is not known. Therefore there would appear to be little point in measuring the antenna impedance ; for if the measured impedances differs from the calculated cold plasma impedance, this merely indicates that plasma wave (and/or sheath) effects are important, and that the reception efficiency has been reduced by an unknown factor.

## The Antenna Reactance

Faced with the above experimental and theoretical difficulties, it is nevertheless possible to progress by making an assumption which is quite plausible under certain conditions. Subject to its validity, it is possible to measure the e.m. noise intensity by means of a receiver with a high input resistance provided that the antenna reactance is also measured.

The method was first used successfully by Walsh, Haddock and Schulte (Space Research IV, 935, 1964) to measure the e.m. noise intensity at 1.225 and 2.0 MHz in the topside ionosphere.

The assumption is that each mode of propagation which couples with the antenna gives rise to an associated partial antenna impedance which depends (for a given antenna) upon the propagation characteristics of only the mode concerned, and that the total impedance of the antenna is the sum of the partial impedances of all the modes propagating ; that is, the partial impedances due to the different modes are all connected in series. Thus in a warm isotropic plasma, for example, the apparent antenna impedance $Z_a$ may be expressed

$$Z_a = Z_{em} + Z_p \tag{7}$$

where $Z_p$ is the impedance due to plasma waves and $Z_{em}$ is the impedance due to the e.m. waves, and which is (neglecting sheath effects) the same as for a cold plasma (the propagation characteristics of e.m. waves being almost independent of the plasma temperature). This assumption enables the e.m. wave reception efficiency to be expressed in terms of the change $R_p$ in antenna resistance :

$$\eta_r = R_{em} / (R_{em} + R_p) \; .$$

The above assumption can be justified in special cases using the expression

$$Z_a = -\frac{1}{I^2} \iiint \underline{E} \cdot \underline{J} \, d\tau \; ,$$

where $\underline{J}$ is the current density distribution on the antenna when driven by a current I at the feedpoint, and $\underline{E}$ is the electric field which would be produced by the same current density distribution flowing in the medium in the absence of the antenna material (see, for example, Balmain, K.G., Electronics Letters 4, 301, 1968). $\underline{E}$ is linearly related to $\underline{J}$ via the tensor Green's function. Evidently sufficient conditions for the validity of this assumption are that the relative current distribution $\underline{J}/I$ is independent of which modes are propagating, and that the tensor Green's function may be written as the sum of independent terms, each of which arises from a separate mode of propagation. The first condition is certainly true for a short thin (compared with the plasma wavelength) antenna, for which the current distribution is linear ; and on a longer antenna the current distribution is not appreciably changed by the presence of warm plasma if the latter is sufficiently tenuous. The second condition, upon the Green's function has been proved using a kinetic treatment (Kuehl, H. H., Radio Science 1, 971, 1966) and an m. h. d. treatment (Kuehl, H.H., Phys.Fluids 6, 1465, 1963) for a homogeneous isotropic warm plasma in which there are two modes of propagation (e.m. and plasma), and also for a homogeneous anisotropic cold plasma (Kogelnik H., Jour. Res. N.B.S. 64 D, 515, 1960) in which there are also two distinct modes (ordinary and extraordinary).

It will now be shown how, having made this assumption, it is in principle possible to determine the e.m. radiation temperature. Let each mode i of propagation have a temperature $T_i = \frac{1}{4\pi} \iint D_i(\theta,\phi)\, T_i(\theta,\phi)\, d\Omega$. ($D_i$ = antenna directivity for mode i) associated with it ; then, because the associated partial impedances $R_i$ are effectively all in series, the total open circuit mean square noise potential appearing across the antenna terminals is, from Nyquist's theorem,

$$\bar{V}^2 = 4k \sum_{\substack{\text{all}\\ \text{modes}}} T_i R_i \quad \text{per unit frequency.} \tag{8}$$

Let $\bar{v}^2$ be the mean square voltage which is measured across the antenna by a receiver of input impedance $Z_1 = R_1 + i X_1$. Evidently

$$\bar{v}^2 = \left| \frac{Z_1}{Z_1 + Z_a} \right|^2 \bar{V}^2 = \frac{R_1^2 + X_1^2}{(R_1 + R_a)^2 + (X_1 + X_a)^2} \times 4k \sum T_i R_i \tag{9}$$

Hence, by measuring $\bar{v}^2$ and also measuring $Z_a = R_a + i X_a$, it is possible, in principle, to determine $\sum T_i R_i = T_{em} R_{em} + T_p R_p$ ; $R_{em}$ may be calculated, and this also gives $R_p = R_a - R_{em}$ ; so that if $T_p$ is known, it is possible to determine the e.m. radiation temperature $T_{em}$.

There remains, however, the practical difficulty that $R_a$ may be too small to measure accurately (and $T_p$ may not be known). To overcome this it is necessary to use of receiver for which $R_1 \gg R_a$ (which is not a difficult condition to satisfy), so that $\sum T_i R_i$ may be determined via (9) from measurements of $\bar{v}^2$ and $X_a$ alone. To determine $T_{em}$ it is necessary to assume that $T_p$ is sufficiently small for the following inequality to hold,

$$T_p R_p \ll T_{em} R_{em} , \tag{10}$$

so that

$$\sum_{\substack{\text{all}\\\text{modes}}} T_i R_i = T_{em} R_{em} . \tag{11}$$

Then, from the computed value of $R_{em}$, $T_{em}$ may be found.

Thus, provided that the approximations 7 and 10 are valid, it is possible to determine the e.m. radiation temperature using a receiver with a high ($R_1 \gg R_a$) input resistance, provided that the antenna reactance is also measured. It is clearly impractical to measure the reactance at a large number of frequencies ; therefore two or three frequencies must be chosen, and other values interpolated using a suitable theoretical model. The optimum choice of these frequencies depends upon the P R A receiver characteristics. Owing to the variation of the antenna reactance with frequency and ambient plasma density, it is not a practical proposition to try to match the receiver reactance to the antenna reactance.

## The Spacecraft Antenna

The above discussion has been based upon an ideal cylindrical dipole antenna ; in fact, the P R A antenna consists of four coplanar monopoles of length 10 m, protruding from the spacecraft body, each one with its own separate preamplifier. Each monopole forms, together with the spacecraft, a dipole antenna, and the gross behaviour of each of these four dipole antennas will resemble that of the ideal cylindrical dipole.

******

Minutes of the Planetary Radio Astronomy Team

JPL - 10, 11 January 1972

I. Minutes of the 13, 14 October 1972 meeting were approved as circulated.

II. Warwick discussed OPGT since 13, 14 October 1972 meeting.

A. JWW will prepare and submit "Science Support and Data Analysis Budget Estimate for Minimum Experiments", due 14 January 1972, without further feedback from PRA Team members.

B. Field of view (FOV) problem with optical sensors in the face of PRA monopoles. The Team agreed that many possible fixes of this problem were feasible, including symmetrical sweep-back of each of the four monopoles, tilting the plane of the original crossed dipoles, mounting one of the monopoles on the scan platform itself and paralled to a scan axis, or in the worst case (for PW and PRA experiments) falling back to sensors consisting just of two orthogonal monopoles, loaded against the S/C. Their location clearly can completely avoid FOV problems. Don Gurnett's (PW Team) objection to this arrangement was discussed and believed to be less of a difficulty than possible elimination of the experiment(s) due to the FOV problem!

C. OPGT politics and gyrations; NAS 1971 Woods Hole report.

III. A. Electromagnetic compatibility: Bob Peltzer

(1) S/C Power Supply Spectrum now has been measured. It seems to be as we had expected except for unidentified "spurs" or spikes at intervals of 1/2 the PS base frequency (e.g. in between the single PS harmonics).

(2) Doesn't think there will be "a real quiet Spacecraft out of JPL".

(3) To control RFI substantially, we need a cannister type of S/C, rather than the TOPSY type that has been typical of JPL.

(4) Warwick described the memo from Wick to Draper RE locating PS frequency at 9.6 kHz instead of 4.8 kHz; the power system would weigh 4.5 lbs. more as a result. Peltzer notes that experiments individually would then be much more efficient, since transformer weights are drastically reduced, and since at the low-power, individual experiment level transistor switching efficiency is no longer a serious consideration. This may implie an overall S/C weight and power saving which, however, has not been factored into the power system frequency decision at present. The project is still working with 4.8 kHz PS; when a new iteration comes through, the frequency may go higher, but they are not now discussing it.

The Plasma Wave Team endorsed our proposal for a shift to higher frequency.

B. Antenna Designs: Joe Alexander

(1) Theoretical Studies of mechanical and electromagnetic properties of 10-meter monopole/dipole antennas are under way at AVCO, but no detailed results will be available before 1 February 1972. In a preliminary fashion, they have run a principal-plane pattern on a swept-back dipole, in which the angle between one monopole and the other is 102° (instead of 180° as in an ordinary, linear dipole). In the principal plan: the pattern strongly resembles a conventional dipole, but with a end-On cusp much less sharply defined (~10 db). The Vee formed by adjacent monopoles in a swept-back turnstile configuration of these dipoles is 70° opening angle.

(2) Peltzer suggests control of antenna IR thermal emission through proper coating (painting).

(3) Warwick described Cottony's preliminary results of scale model tests of TOPS configuration 12L, and of another model with the 14 foot telemetry dish electrically split into quadrants. With 10 meter monopoles, the radiation patterns are nearly pure dipolar at frequencies less than 7 MHz (the first resonance is at 7.5 MHz); the same holds for patterns in the split-dish configuration. Impedances are considerably more favorable for the monopole/dipole configuration than for the split dish however. Obviously, capacitative coupling of the different portions of the dish/antenna heavily load these measurements. Finally, for either configuration, polarization measures as a function of frequency are likely to be difficult; each monopole, for example, is in a unique, unsymmetric position relative to other S/C structures. As a result strong impedance changes result on the individual monopoles that would result in unjustified inferences on polarization changes. From this point of view a system of just two orthogonal monopoles might be easier to locate so as to preserve polarization isolation between RH and LH states as a function of frequency than four monopoles that are pair wise quasilinear.

C. Receiver Design: Peltzer

(1) Weight, power, and size of equipment designed to carryout the experiment, essentially as described in Team minutes of 13, 14 October 1971.

The most costly and weighty component is the frequency synthesizer. The preliminary logic design uses TTL low-power technology, with one or two high speed TTL's. Estimates of package counts and current consumption are now in hand, and it is time to begin breadboarding with standard (not low power) TTL. The design uses discrete flat packs, and no hybrid design; it is thus utilizing 10 to 15 year old devices. For the entire receiver, there are 75 packages, except for D/A converters and a long divide chain from the S/C clock down to a few hours; the latter will come from either CCL or computer. A/D are included in this estimate, and also a byte multiplexer for frequency identification. The design includes CCL as part of the PRA weight. 75 modules take 1.4 watts at 5 volts (a worst case estimate in which all gates are on all the time), and 0.94 watts with 2/3 of the gates on. Voltage controlled oscillator (VCO), amplifiers, and buffer altogether require one watt, and imply a total wattage of 2 watts. Use high density packaging 0".26 x 0".26 per each, with 21 square inches of board for 75 packages. 1/4 square inch per pack implies 4 packs/1 square inch. Each package equals 0.6 gram, including wiring (pack alone equals 0.2 grams). For 75 packages, we have 58 grams, or 2 ounces. The synthesizer in total weighs 1/4 lb., and one receiver is 1/2 lb., or two, 1 pound. 1/2 lb. for power supply, and 1/4 lb. for calibrator; 1 lb. for skin and connectors lead to a total package weight = 3 pounds. With 4 monopole antennas weighing 3/4 lb. apiece, we have a total PRA experiment weight of 6 pounds.

Can we save weight? One receiver weighs 1/2 lb., which is obviously a fruitless direction to proceed. The antennas ought to be a more useful area; two monopoles only would save 1 1/2 lbs. of this original 6 pound estimate, leaving 4 1/2 pounds total. This weight does not include cabling to the antennas. MSI or LSI could yield interconnection reliability, RFI reduction through superior shielding through smaller packaging, and higher weight savings in an alogue circuits.

Other space radio astronomy experiments have been comparable in weight, although much less ambitious in terms of their function: OGO-5 weighs 5.2 lbs. (with discrete logic; 5 boards on OGO-5 are replaced by 1 board on OPGT-PRA). With crystal oscillators (!) RAE-B weighs 3 lbs.

(2) The radiation hazard at Jupiter is estimated to be a proton fluence of $5 \times 10^{10}$ at a minimum approach of 5 $R_J$. The present experiment can survive a fluence of $5 \times 10^{11}$ $cm^{-2}$.

(3) The proposed variable modulo frequency synthesizer was discussed in detail. In this device, a coarse D/A converter is used to set the LO approximately; LO output is down converted digitally in a series of pre-set counters whose final output is compared with the S/C timing pulses in a phase detector. The output is used to vary the control voltage on the VCO until lock is achieved. Basic to the entire receiving system is the servo loop settling time in this synthesizer, which needs to be short so that our observing time at a newly-set observing frequency can be long. Since this settling time can at best only be estimated, we feel that breadboarding of the synthesizer has the highest priority for realization of our receiver. Dave Staelin strongly proposes a redundant synthesizer (a penalty of less than 1/4 lb.)

be used; the RX is then completely redundant.

(4) The earth-to-Jupiter increase of planetary emission signal strength, as a result of the inverse square law, is always less than 140 db.

[N. B. This is JWW's estimate as of writing these minutes: at 4 A. U. I assume a maximum Jupiter signal equal to the cosmic noise background (not a nominal maximum or nominal intense event; an absolute maximum). I assume that the source at Jupiter is 100 kms in dimension and that the S/C comes within that distance of the source. Then $\left(\frac{6 \times 10^8 \text{ km}}{10^2 \text{ km}}\right)^2 = 36 \times 10^{12} \simeq 16$ db + 120 db, which I round to 140 db.]

Switchable attenuators in the front end are required to accommodate this range, since receiver dynamic range is unlikely to exceed 60 db between the toe and shoulder of its linear operating range. These attenuators insert 30 to 40 db over the entire frequency range; with large attenuation values the feasible attenuation tends to be non-uniform. The S/C will "probably" not fly within 100 km of the source on Jupiter. Therefore, a larger attenuation than a total of 80 db is surely not necessary, and a much smaller value may be sufficient. If we require simply that at earth the most intense event lie at the toe of the response and at Jupiter, in the source, it lie at the peak (60 db higher), then 80 db of attenuation is required. If we are only at the closest about 1000 km from the source, the 80 db value can be reduced to 60 db, and at 10, 000 km, further reduced to a total value of only 40 db. [N. B. JWW's evaluation as of writing: it seems possible, if unlikely, that we approach within $10^4$ km of a radiation source; it seems conceivable, but highly unlikely, that we come within $10^3$ km; it seems to me inconceivable that we come within $10^2$ km of a source; even if we did, we would stay there only for a few seconds.] 60 db attenuation appears therefore to be generously adequate to provide measures of any radiation levels we might encounter.

This attenuation should be inserted by ground command separate from the loaded program.

(5) The team agreed that a true integrator was desirable, instead of an RC-filter.

(6) A discussion of the 8-bit word length focussed on the possibility that a shorter word might be sufficient. The 8-bit word is necessary to discriminate Jupiter from the cosmic noise background at the distance of 4 A. U. in a nominally intense Jupiter event ($10^{-20}$ watts $m^{-2}$ $Hz^{-1}$); the discrimination involves comparison of the total power received in adjacent frequency channels of RH and LH polarized radio noise. On the other hand, if we form the difference of RH and LH channel readouts (presumably in successive frequency channels), the cosmic noise will cancel in the difference. An appropriate word length for the total flux

would be, say, 5 bits; this same word would be useful for the difference flux as well.

The differential measurement implies a storage of successive channels (RH and LH, at adjacent frequencies) and the forming of the output voltage difference. This coarsens frequency and time resolution on the difference channel. Within 1 AU of a planet (say, Jupiter) the planetary signals are intense enough to overcome the cosmic noise background (in nominally intense events) and suggest 5 bit words for both RH and LH channels instead of 8 bit words in any case. For POLHI measures, especially near the planets, a still smaller word, 3 bits, seems necessary (see minutes of 13, 14 October 71) from an information-theoretic point of view. [ As of writing, Warwick suggests that we might consider a ground-controllable word length (tied to the attenuator control? ) variable from 3 to 5 to 8 bits.] This question of data format, especially word length, vitally needs further team discussion. Let me observe, for example, that 8 bit words (even) divide 60 db into 60/256 $\simeq$1/4 db steps, only! Our logarithmic receiver therfore displays the cosmic noise as a given signal, but a nominal intense Jupiter signal will appear as an enhancement (in one channel only) of ~14% 3/5 db, somewhat better than one in the next to last bit of the 8 bit word. Since $\sqrt{Bt}$ considerations barely identify this Jupiter event in one sample anyway, from this point of view the 8 bit word is appropriate.

On the other hand (vide infra) our system has low sensitivity for planetary emissions seen in the cruise mode, although the long light time in that mode demands that we make some of our basic observations then (i. e. remote detection of planetary non-thermal phenomena, radiation belts, etc. ). If we broaden the bandwidth or increase integration time to enhance signal smoothing, we require a longer word to pick out the planetary emissions.

The differencing scheme provides a way to make use of this increased sensitivity with a decrease in word length in one channel. It appears (to JWW) that the sumchannel in any event still requires 10%. Accuracy in the measurement of its contents, and this, in turn, implies an 8 bit word over 60 db of dynamic range.

Another alternative seems (to JWW) to be to reduce the dynamic range below 60 db and increase the number of attenuation steps (a trend towards a switched gain receiver). For example, with 20 db dynamic range, and 100 db of attenuators, under ground control, we get a system reading $\frac{20\text{db}}{256}$ = 0. 08 db with 8 bit words. This scheme detects 2% enhancements, in the 8th bit, which makes use of the additional sensitivity of a bandwidth $10\text{ kHz} \times \left(\frac{60\text{db}}{20\text{ db}}\right)^2 = 90\text{ kHz}$.

Alternately, it describes the cosmic flux to a precision of 2%, greater than we need. Therefore, the 20 db range system permits us to back the word length down to, say, a 6-bit word. At that word level, if we are to make use of the increased precision of the wider passband to detect planetary emissions as sensitively as we are able, we must use the differencing scheme.

The scheme I propose then consists of 20 db of dynamic range, plus 5-20 db increments of attenuation controlled from the ground. The word length is 6 bits, the channels are RH + LH and RH - LH, and the bandwidth is $\simeq$100 kHz.

(7) The master clock on the S/C as proposed by the project requires a stability of $10^{-5}$ per year. Our experiment heterodynes the low frequencies (say below 1 MHz) up to a IF of 20 MHz. There are about $2^{11} = 2048$ PS harmonics between 20 kHz - the nominal center of our lowest response passband - and the IF. A change in PS frequency of $\Delta f$ therefore becomes a change in the IF of $2 \times 10^3 x \Delta f$ at the lowest (least affected) frequency. If $\frac{\Delta f}{f} = 10^{-5}$ where f =14 kHz (perhaps a little too high), $\Delta f = 1.4 x 10^{-4}$ kHz and results in a shift of the least heterodyned frequency by more than $2.8 x 10^{-4}$ MHz, or 0.28 kHz. This shift may cause our receivers' crystal filter response to perhaps intersect a power system harmonic. It would be a much more comfortable situation if the stability of the PS could be assured to one decimal order of magnitude higher precision, say $10^{-6}$ per year. This seems to the PRA Team to be a quite normal and easily attained objective. For example the several crystals flown to provide redundant control or majority-vote control of the PS could be selected on the basis of matched aging curves.

(8) Parts qualification at present seem to be shaping up reasonably well, with the newest list containing most of our components. It doesn't contain voltage tuned diodes or Schottky diodes (Staelin has some of the latter already in earth - orbiting satellites). Dave Martin and Bob Peltzer will confer on qualifying those of our components that need to be.

(9) Radiation Workshop, JPL in early December 1971 -- The story on radiation hardening of an experiment appears to be to run emitter currents in the 100 ma - density region. Apparently we have no problems here.

IV. Reactions of the Team to the 13, 14 October 1971 Design

A. In general people feel that design places too much emphasis on detailed frequency coverage on a 14.4 kHz (10 kHz passband) point-by-point basis. Several proposals for reducing the number of spectral points were submitted to Warwick since then, in particular from the French members of our team. They involve restricting the number of spectral points by at least one order of magnitude, and dwelling on each point by a time increased by one order of magnitude, with respect to the 13, 14 October 71 design.

Warwick pointed out that that design was primarily based on the need to

G

avoid S/C harmonic radiation. Without that requirement, a bandwidth (and step size) of several hundred kHz is very useful. Although the one example, Jupiter, of planetary emissions has very narrow band structure on occasion, it also more often, say 90% of the time, generates bandwidths of at least several hundred kHz or more. But, Warwick emphasizes, the need is to have continuous coverage in frequency, since planetary spectral character is known to change dramatically on scales of one MHz or so. He therefore suggests a receiver which switches passband, nominally at 1 MHz, from the largest passband that can fit between successive harmonics, to the passband required to gain adequate sensitivity, contiguous spectral coverage, and appropriate dwell time on each spectral point. By going from 10 kHz to 100 kHz, integration times can be increased the fold (for the same overall sweep time in POLLO); as well the overall system sensitivity increased by 10-fold. Alternatively, the increase in sensitivity could partly be used to decrease scan time 3 fold. In this case, sensitivity would be increased by just 3 fold.

The justification for this modification of our spectral scan lies in the fact that at some frequency, near or somewhat above 1 MHz, the S/C PS frequency will generate relatively less harmonic energy as a result of the $\mu$-second switch times characteristic of PS transistors. The "keying" of the PS is soft, or, in other words still, its spectrum will show a "roll-off" somewhere above 1 MHz.

Peltzer suggests using the LC IF filters alone, that is, by-passing the sharp crystal filters necessary to fit our passband in between S/C harmonics. This switch could be hard wired into the system in the synthesizer network; the switch would be keyed at the appropriate significant bit of the counter control. Our passband would then permanently broaden by about the appropriate amount at the appropriate roll-off frequency.

Warwick will generate and circulate a new systemic description, hopefully to contain responses to the developments of the present team meeting and still remain within the outlines of the current hardware design.

B. Final disposition of the Thermal Mode

From the point of view of outer planets atmospheric science, planetary thermal emission at low frequencies (say 10 to 100 MHz) represents information on deep atmospheric levels (1000 atmospheres) otherwise completely inaccesible. Our Team efforts a year ago were aware of this circumstance and attempted to include blackbody emission as an experimental objective to be "pasted on" our non-thermal emission experiment, if necessary with separate ad hoc antenna and receiver. It became clear in the last summer that this style of thermal experiment was out of the question owing to general cutback in the size and scope of the Grand Tour concept. Warwick raised the possibility of such an experiment once more in order to demonstrate our recognition of overall OPGT science objectives to all space scientists on the one hand, and, on the other, to do all the homework required to demonstrate that our experiment could not include an effective thermal mode because of its technical limitations.

This point of view met with vigorous, and largely negative, response at the meeting. The group felt that the thermal emission objective had been adequately discussed and discussed at earlier meetings. Warwick asked, nevertheless, for information from Sam Gulkis (via Mike Klein who represented Sam at this meeting) on theoretically predicted giant planet emission at decametric wavelengths, and for the antenna patterns formed by 10-meter monopoles in $90^{\circ}$ - Vee beams from Joe Alexander. Joe was going to provide plots of antenna patterns with 1 and 2 wavelength Vee's (30 and 60 MHz observing frequencies); Mike determined from Sam that $T_B \gtrsim 10^3$ °K below 100 MHz for giant planets, and that observations at several frequencies and within 1' radius of the target planet would probably be necessary for an experiment of this sort to be worthwhile.

With these inputs (Alexander's remains to be in his hands) Warwick will once and for all put the matter (predictably) to rest.

V. Plasma Wave -- PRA subgroup meeting on 4 January 1972 at University of Colorado, Boulder (attendees were Fred Scarf, Paul Kellogg, Don Gurnett, and Dave Cartwright of PW; Fred Haddock, Bob Stone and Warwick of PRA).

The Team discussed this subgroup meeting, especially the felt need of the PW Team for electric field sensors that are dipoles (rather than monopoles loaded against the S/C). It concluded that we also would prefer balanced sensors, but that if the S/C mechanical design requires unbalanced sensors we can live with that configuration. In the course of the subgroup meeting there emerged the clear possibility of much wider passbands for PRA above the S/C PS roll-off frequency; this input appears factored into these minutes in earlier sections. Warwick emphasized that a minimal experiment in PRA could be justified at frequencies restricted to below 10 MHz. Peltzer notes that the impact of this decision on receiver design is virtually nil (no weight or power saving of any significance). Furthermore (as noted above), the wider passbands (100 to 500 kHz) above 1 MHz actually improve the PRA experiment substantially so far as 90% of (at least) Jupiter's emissions are concerned.

In the discussion it was brought out by Alexander that RAE - B contains preamps to cut down shunt capacitance losses from 50 picofarads to 5 pfd at the antenna bases. At VLF, the radio astronomy experiment gives way, in experiment priority, to the plasma wave experiment. The subgroup viewed the appropriate cross-over frequency as near 100 kHz. In any case, the PRA antennas are so short that at 100 kHz the receiver should act essentially as a high impedance voltmeter. This point of view should make the common usage of the electric field sensors (e. g. the 10 meter monopoles) much simpler to accomplish, since the radio astronomers are in no sense expecting to deal with matched antennas at VLF.

VI. Low Bit Rate Experiments

Warwick feels that the funding "crunch" insofar as telemetry is concerned (i. e. the Deep Space Net), may limit OPGT to one or two 8-hour shifts per week during which there are, say, $3 \times 10^4$ seconds. At 20 kbps, $6 \times 10^8$ bits can then be transmitted. This bit stream was initially projected for the full-blown TOPS Grand Tour Missions. Per week, this averages out to $1 \times 10^3$ bps, but to make that figure realizable requires on-board storage (Tape recorders, probably) holding $1 \times 10^9$ bits. But the crunch may also apply to these sophisticated recorders, in which case the weekly-averaged bit rate may be essentially only what can be transmitted in real time once a week.

Our experiment, operating steadily at 2000 bps, could in a $3 \times 10^4$ second-shift transmit $6 \times 10^7$ bits, or the equivalent of 100 bps average over a week. This would be a superior experiment since we could then observe a complete planetary rotation, continuously, once each week, and in the course of one year would thus build up a library of 52 complete rotations. I therefore stated to the SSG that this was a good solution to the DSN funding problem as far as PRA is concerned.

On the other hand, there is ample reason to doubt that this position will be feasible on OPGT. 20 kbps at Jupiter may be one or two orders of magnitude larger than the bit stream designed into vehicle actually flown on the OPGT. Therefore Warwick asked Tom Carr to present his views on an experiment generating a much smaller bit stream, say 1-10 bps.

Carr proposes a scheme with the objectives:

(i) To measure power in RH and LH components;

(ii) To study time structure;

(iii) To measure average power spectrum;

all of these as functions of planetary and satellite aspects. The measures are made each 10 minutes (about $6^\circ$ of a giant planet's rotation). Measures are made at two frequencies simultaneously of:

(i) 10-minute average of RH component;

(ii) 10-minute average of LH component;

(iii) Peak of RH component in this 10-minute interval;

(iv) Peak of LH component in this 10-minute interval;

continuously for one month. 200 kHz bandwidth is suggested, otherwise, if necessary, 5 kHz. The switching to a different pair of frequencies would be by ground command. The bit rate is: 8 bits/word x 1 word/10 $^{\text{min}}$ x 4 channels x 2 frequencies = 0.1 bps average. In six months, 12 frequencies would be covered; for example of the range, 30, 20, 10, 5, 2, 1, and 0.5 MHz, perhaps in harmonic pairs.

The critical feature of this scheme is that it requires a different receiver backend than we have previously discussed, though probably quite insignificantly different in power, weight, or size. The receiver, for example, of the RH component requires now a pair of signal processors operating in parallel at its output. One processor is a signal integrator accumulating the receiver's output for 10 minutes, the other is a peak detector, a "peak holder".

The Team agreed that a signal processors of this sort should be incorporated in the design of our experiment. Even with a (possible) high bit rate allowed to us during, say, telemetry periods, we can operate this low bit rate experiment continuously, otherwise, without strain on S/C resources.

Warwick pointed out that the data received at two frequencies in one month would provide one (two frequency) point per element of the 72 x 72 element grid of satellite-planet aspect. The contours of such a diagram require at least ten times that many independent data points. Even so, the bit rate increases only to 1 bps.

Haddock asked why our previous discussions required as much as 100 bps; why the gross discrepancey in bit rates? Warwick answered that, roughly, Carr's experiment is observing only at about 10 discrete frequencies, while our previous experiment is observing at about 1000 discrete frequencies. This is a factor of 100: 1; Carr's proposed bit rate, for one point per grid element, is 0.1 bps; the earlier experiment assumes that ten points per element are essential. The latter requirement increases the ratio of data rates from 100:1 to 1000:1; this ratio is in fact about the ratio of the data rates between Carr's proposed experiment, and the one that the Team has been previously discussing in detail.

The Team next discussed how many frequencies are required to define the emission contours on a planet-satellite aspect plot. The one known example is the Jupiter-Io diagram. Several Team members, especially Carr and Haddock, felt that one or two MHz make little difference in the appearance of the diagram. Warwick, on the other hand, argued that just one MHz makes the difference between seeing the emission and not seeing it (at, e.g., 39.5 MHz in the early source, or at 36 MHz in the main source).

The previous-to-Carr experiment has evolved, in any case, into a set of about ten-times fewer discrete frequency points, as a result of the wider bandwidths assumed above 1 MHz. The advantage needs to be computed in detail, But for the same frequency range as before, but covered in fewer jumps, and with a somewhat smaller word length, it is probably correct to assume that the previous experiment will now come in at 10 bps or perhaps slightly less, for the same number of frequency scans and integration times at each frequency point.

Carr's idea suggests a useful technique to substitute for spectral scans when the data rate is pushed to radically smaller values even than 10 bps. Our experiment will be much more valuable at 100 bps than we had originally expected it to be; it will be just as valuable at 10 bps as we had originally hoped it would be at 100 bps; and it changes character, although it is still useful, at 1 bps and below.

VII. The meeting adjourned upon the departure of the Leader at 12 noon, 11 January 1972.

Attendance: Bob Peltzer, Tom Carr, Joe Alexander, Fred Haddock, Walt Brown, Dave Staelin, Chris Harvey, Glen Lockwood, Mike Klein, Rog Phillips, Dave Martin, occasionally Tom Bird.

James W. Warwick

James W. Warwick

17 January 1972

26 January 1972

Dear Team Members:

The occasion of writing up the minutes of our last meeting led me to consider a different set of receiver parameters. I hope they are thoroughly consistent with our recent discussion. Furthermore, I hope they are fully consistent with the receiver and mode designs we have already accomplished; changes should not impact on package counts, weights, and power in any very significant way.

I. Antennas: two ten-meter (base-to-tip) monopoles, orthogonally mounted on the S/C so as to balance the impedance function of frequency, and avoid field-of-view problems with imaging and other optical experiments. Probably mounted in the roll-plane, opposite the scan platform. (Rabbit-ears proposal)

II. Pre-amps at antenna bases: to minimize capacitative losses into our receivers, and to isolate the plasma-wave and PRA experiments. Essentially converts our experiment from a power metering device to a high impedance voltmeter.

III. Attenuators: This is the most radical new suggestion I have to make (see minutes of 10, 11 January 1972 meeting). I propose a basic six-bit word to divide the 20 - db logarithmic response dynamic range in our receiver. This is $\frac{20 \text{ db}}{64} \cong 0.3$ db per one bit in the least significant place. The intensity range we design for is 120 db : 0-20 db (no attenuator), 20-40 db (1 attenuator), ------, 100-120 db (5 attenuators). [I discuss this point in more detail under "LH and RH IF strips" section V, below and "system sensitivity" section VII].

IV. Local Oscillator: Up-converting signals from 7.2 kHz (center of passband) to 1.2192 MHz (center of passband), which is 256 frequency settings every 4.8 kHz.

The LO also converts signals centered on 1.324 MHz + 0.182 MHz x an integer, through to 39.336 MHz. This is a total of 8192 = $2^{13}$ frequency steps of 4.8 kHz (above the base frequency of 7.2 kHz). There are 216 frequency steps of 0.182 MHz required for the range 1.32 to 39.34 MHz. (Our previous design required 2048 steps overall. This one requires 216 + 256 = 472 steps, less by 4x. The ultimate frequency we would reach with $2^{11}$ frequency steps is only 10 MHz, instead of 29 MHz as with the 14.4 kHz PS frequency.) I assume that the ability to go higher than 20 MHz is worth the price of a synthesizer with $2^{13}$ steps over one with only $2^{11}$ steps. The fine-grid stepping below 1.2192 MHz should contain $2^8$ steps exactly, in order that control of the passage to wide bandwidth should lie in precisely one bit change in the 8th significant bit of the synthesizer "dial". $2^9$ steps might be more appropriate, from the point of view of PS roll off; on the other hand that would imply 209 + 512 = 721 frequency steps instead of 2048. The advantage in less steps is reduced by about one-third.

V. LH and RH IF strips: each strip has a crystal lattice filter to define the receiver pass band between successive PS harmonics spaced at intervals of

4.8 kHz. The narrowness of the Xtal should be sufficient to drop adjacent harmonics by 90 db only 1.0 kHz from the central peak of the filter response. The equivalent ideal rectangular filter is probably going to be no wider than 2 kHz. I shall assume this figure in what follows (see especially section VII, below, concerning system sensitivity).

VI. Backends: after square-law detection, and true integration of the signals in each channel, with a time constant of 20 milliseconds (in POLLO), the signals in each channel are differenced (every 40 milliseconds) and this difference A/D converted into a 6-bit word; the signals in the LH channel are also A/D converted (every 40 milliseconds) into a 6-bit word. The LH channel is read in a period alternating with the period in which RH-LH is read; that is 20 milliseconds after RH-LH is read. (I suggest the total power read out normally be in the RH channel since Jupiter signals are usually strongly RH.)

We also require peak detection and, separately, integration over a very long time (measured in basic 20 millisecond time constants). This is roughly an interval of 20,000 time constants (10 minutes). The mode defined by these time constants is new to our experiment; I propose calling it the Very Low Bit Rate Mode - acronym VLOBR - pronounced "Vlobber" (!) The difference, RH-LH, and the RH output are separately formed in basic 20 millisecond time constants as in POLLO. The two channels are then each separately split into two further channels one for identification of the peak, and the other for formation of the average. The Team didn't decide whether it wanted VLOBR to detect RH-LH and LH at precisely the same frequency, or whether it would be content to form these channels from consecutive frequencies (spaced 4.8 kHz below 1.2 MHz, and 0.18 MHz, above 1.2 MHz). I propose that consecutive frequencies be accepted. They are a simplification of the receiver control system.

VII. System sensitivity: I propose the same scan time as in the previous POLLO mode (roughly 9 seconds to cover 0 to 40 MHz), and therefore the present experiment dwells $\frac{2096}{472}$ x 4.5 milliseconds = 20 milliseconds on each frequency point.

[The fewer points in frequency could have been used to reduce the scan time to, say $9/4 \approx 2$ seconds. The dwell time at each frequency is then 4.5 milliseconds. For a given overall bit rate our experiment would have had increased sensitivity (above 1.2 MHz) of about $182/10 \sim 4$ x. We would have had 6 times as many spectra (as compared with our original experiment) in a given cycle of POLLO as well as this much higher sensitivity.]

With the same scan time (9 seconds), the fewer points in frequency, and the implied longer dwell time on each, we will operate with a sensitivity $\left[\frac{182 \text{ kHz}}{10.0 \text{ kHz}} \times 4\right]^{1/2} = [73]^{1/2} \simeq 9$ x higher than previously. Since there are 4 x fewer points in frequency, and their word length is now 6 instead of 8 bits, the number of spectra observed in a given POLLO mode will be 6 x what we originally defined (as in the immediately preceding paragraph) as well as

9. x higher sensitivity, all within the same 140 bps overall average for PRA.

The implication is that for the same total range in frequency as before, and the same total number of spectra we can operate with $\frac{140}{6} \approx 23$ bps.

I emphasize strongly that the price we pay for this undoubtedly superior experiment is greater vulnerability to interference above 1.2 MHz, especially from PS radiation.

Incidentally, I propose that HARRAD, in this revision, operate only below 1.2 MHz; the rationale is that minimum distance to Jupiter (with its strong field) is no less than 5 $R_J$ where $|\underset{\sim}{B}| \sim \frac{1}{20}$ gauss, f (cyclotron, electron) = 140 kHz, and f (plasma, electron) 50 to 100 kHz. Therefore HARRAD should easily observe all plasma resonances near the giant planets.

The question of word length, dynamic range, and attenuators is raised above (section III, "attenuators"). The relative power in planetary emissions is assumed to be 1/7 the galactic flux at all frequencies we study. (The assumption is valid only during a nominal strong Jupiter event in the range near 20 MHz, where the flux density is $1 \times 10^{-20}$ $W \cdot m^{-2} \cdot (Hz)^{-1}$.)

The "new" bandwidth, 182 kHz, and the "new" time constant, 20 milliseconds, imply $\sqrt{B\tau} = \sqrt{3640} \simeq 60$. The fluctuations in galactic power from one sample integrated over 20 msecs to the next will therefore typically be 1/60 of the power. Suppose now that a planet's emissions are perfectly circularly polarized. They will lie entirely in the difference channel, RH-LH power. The natural fluctuations in that channel will be about 1/60 of the galactic flux, and will cause the channel to wander above and below zero by that amount; from one 40 msec period to the next. The planetary signal, if it persists for, say, 40 msec, will cause two successive RH-LH measures to deviate from zero in the same sense, if it is just one galactic fluctuation in level. That implies a planetary flux density of $1 \times 10^{-21}$ $w \cdot m^{-2} (Hz)^{-1}$, which is a moderate event, one-tenth the intensity of a "nominally intense" event. This constitutes a definition of what I will call the sensitivity of the system - e. g. the least flux density detectable in two consecutive difference channel measures.

Now the total power, which lies essentially only in the RH channel when the S/C is remote from a planet, is measured to 1:64 by six-bit words. Suppose the range of the receiver is such that the galactic flux lies near the toe of its response, and it is linear (in the logarithmic of the received power) for 20 db above the galactic flux. $2^6 = 64$ steps correspond to 0.3 db each, or 7% in power; the fluctuations are much smaller than this by 4 x. As a matter of operational check on the receiver we ought to set the gain of the receiver so that galactic flux lies at value above the zero of our range, say on the 10th step. Then we can detect directly in the galactic flux a planetary LH burst which amounts to 1/14 the total power, i. e. has 1/2 the flux density of a nominal strong event. We can measure the power in nominal strong planetary events (or in moderate solar bursts) with this amount of digitization of the 20 db range.

The RH-LH channel contains essentially only planetary emission power. We should set the gain of this channel so that 1/20 of the galactic flux lies, say, on the 3rd step out of 32. One bit of the 6-bit word here needs to correspond to the sign of RH-LH. A moderate planetary event with a flux density of $1 \times 10^{-21}$ units, that is RH polarized, will produce an increase in this level by six scale units, of 14% each. Since the galactic level fluctuates as often three units negative as it does positive, the output during the event will fluctuate between three units and nine units positive. The planetary event can rise to as much as $2 \times 10^{-20}$ flux units before the RH-LH channel fails to measure it (i.e. goes off scale). At that point, the event will appear on the RH record above, and will not be off-scale there, for another 20 db. We should therefore be capable of recording the most intense planet events, in the cruise mode.

If we use a larger range than 20 db, our problem will be to use a longer word to scale it. 40 db requires a seven-bit word for the same precision on planetary emissions or galactic flux that we had above with six bits. This seven-bit word requires 1/6 more data on the RH record alone, even though it will never be required except during planetary events even stronger than 20 db above the galactic fluctuations. This statement holds only if the S/C is farther than 1 AU from the planet. Closer in, the 40 db-wide scale of the RH record permits us to record all of the events, from very weak ($10^{-23}$ units) to very strong ($10^{-19}$ units) as seen from the earth.

To put it another way, the experiment at points remote from the planet makes use of the weakness of the planetary signals combined with two output channels of different sensitivities to cover the entire flux density range anticipated with only 20 db. Within 1AU of a planet, the signals are stronger by 10-fold; there we expect that the important signal range can be covered by 20 db on either the RH channel or on the RH-LH channel. That hope may not pan out.

I have proposed this compromise in order to make it possible to use 6-bit words. Going to 7-bit, or 8-bit, words does not increase our information during most of the cruise mode observation. But, it may increase our knowledge of the minimum signals observable near the planets. Note, however, that our 20 db pads can be switched around by ground command, if we wish to probe deeper into the low signal level region when we are near a planet, and that 5 such pads cover the entire dynamic range of all bursts we can expect to see. What we give up by going to a 20 db range is the possibility of automatically recording over a larger range, not the possibility of discovering that emission is present over a larger range. This seems to me a worthwhile compromise in order to achieve 6-bit words which are in fact as useful as any for 90% of the mission anyway.

Sincerely yours,

James W. Warwick

cc: Fred Scarf

# Budget Estimate for Planetary Radio Astronomy Team

## Outer Planets Grand Tours

## Fiscal Years 1973 - 1992

I. Science Support - See Table I for costs year-by year

A. Principal Investigator's Support

| | | | |
|---|---|---|---|
| 1. | Annual Salary (1972, including 41% overhead | | $42, 000 |
| 2. | Annual travel - two trips per month to JPL @ $275 | | 6, 600 |
| 3. | 1/2 - Time secretarial support (1972 FTE $6, 600) | | 4, 650 |
| 4. | Phones $10/week | 520 | |
| | Supplies | 1,000 | |
| | | | 1, 520 |
| | Total (A) | | 54, 770 |

B. Team Members' Support

| | | |
|---|---|---|
| 1. | Annual average salary including overhead ($40, 000); 10 Team members working 1/2 FTE | 200, 000 |
| 2. | Annual travel - 4 trips to JPL x 10 @ $250/trip | 10, 000 |
| 3. | No administrative support assumed | |
| 4. | Miscellaneous - $250 supplies x 10 | 2, 500 |

C. Programmer and Computer Costs

1. Team-directed studies. PRA antenna dynamics and EM properties should be computed early in the program on the basis of realistic configurations. These programs will be made a part of our Team's competence in hand, and require an on-going programmer specifically dedicated to this task (and two others, see (2) and (3) below)

| | |
|---|---|
| Programmer one-third FTE | 13, 000 |
| Computation time at $350/hour | 3, 500 per year |

2. Mission and/or S/C trade-off studies. Various trajectory possibilities impact our experiment directly in many ways. We will need computation time to carry out analyses of these possibilities, in which orbits and experiment operations are combined to generate various mission profiles.

| | |
|---|---|
| Programmer one-third FTE | 13,000 |
| Computation Time at $350/hour | 3,500 per year |

3. Theoretical modeling. We need to model the operation of our receivers so that various modes can be studied under failure conditions and so that the logic can be diagnosed under all operational conditions. This will require both programmer and computer time.

| | |
|---|---|
| Programmer one-third FTE | 14,000 |
| Computer time at $350/hour | 3,500 per year |

D. Miscellaneous

1. The Team will carry out antenna model pattern and impedance measurements in detail. They will be concentrated in the earliest years of the project, FY 73 ($100K) and 74 ($150K), and taper off to zero in FY 76.

2. The Team will construct bread-board models of the receiver, and S/C power system, or alternatively, carry out these studies in connection with the JPL PS engineering groups who will have created our PS, to test as realistically as possible the overall operation of the PRA receiver concept aboard OPGT missions. This study will also be carried out as early in the program as possible. Breadboarding is estimated at $200K for the first year, and engineering time at $100 K in the second year. This task will taper off strongly as the design hardens in the year immediately preceding the first launch (FY 76, 77)

II. Data analysis cost estimates - see Tables II and III for costs year-by-year.

A. Encounter data analysis estimate - Table II

1. Preparation to be ready to reduce and analyze the data once they are received in final form.

   We assume that one encounter = $1 \times 10^6$ seconds at $1 \times 10^2$ bps = $1 \times 10^8$ bits. [N.B. we assume that these $1 \times 10^6$ seconds may not be contiguous during encounter; $1 \times 10^8$ bits is not therefore necessarily storable aboard the S/C for just our experiment.] This implies a data editing job on approximately 5 - 2400 foot-tape reels of one-inch magnetic tape. The $10^8$ bits are organized in words of 6 bits; therefore about $10^7$ words are in total involved. Each word requires $10^3$ steps of 1 $\mu$ second computer processing, or 1 m seconds per word or $10^4$ seconds = 3 hours of computer time. Subsequent encounters to the first may not entail savings here.

| | |
|---|---|
| Computation 3 hours at $350 | 1, 050 |

   These data need to be studied by a data-analyst-programmer to ensure that their format and editing are correct.

| | |
|---|---|
| Analyst 1/40 FTE at $40, 000 | 1, 000 |

2. Data reduction.

   This process requires S/C attitude and S/C status tapes to be processed in conjunction with the tapes of data described in (1) above. In addition the calibration and different modes of operation of our experiment then will be factored into a master program that decodes the bit stream into the various experiment modes, calibrates these modes, and tags the different data points with overall S/C status and orientation. An encounter will probably involve about as much S/C data taken independent of PRA, but relevant to PRA, as the PRA data themselves. Processing therefore will involve an additional 5 reels, beyond the PRA data reels themselves. These combined data will require approximately 10 x as many steps of processing as the data in (1) above. For the first encounter of a series:

| | |
|---|---|
| Computation 30 hours at $350 | 10, 500 |
| Scientist 1/12 FTE | 3, 300 |
| For subsequent encounters, we estimate 1/24 FTE and 10 hours | 3, 500 |
| | 1, 650 |

3. Data analysis

Encounter data will consist of primarily high time resolution, low frequency resolution records of planetary radio emissions. We expect to see strong inverse square effects in the emission power as a function of distance near to the planets. Data supplied to NSSDC will be deconvolved in this respect. The high resolution data will also be collated so that the changing source aspect with respect to a S/C reference direction will be discernible. Tapes of the various other experiment outputs will be prepared as functions of encounter time; this implies a tape of the S/C radiated harmonic level, another of the broad range, slow time constant dynamic spectrum in the two circular polarization states; and of the receiver calibration output. Approximately 5 reels of reduced data will be required for a given encounter. Costs of preparing these tapes are minimal after (2) is completed, and will in some cases be included in (2) already.

| | |
|---|---|
| | 1, 000 |
| A written report of these data is also required. | |
| Scientist 1/24 FTE | 1, 700 |

B. Cruise data analysis estimates

Our estimate depends on a baseline of $4 \times 10^9$ bits of data for each cruise data period, five in all being required. With four missions, there are in total only 12 cruise data periods to be budgeted, since none of the S/C performs a cruise between all of the five outer planets. We assume the same preparation costs for each period, and that each stands in relation to encounter costs precisely as the ratio of bits per cruise period to bits per encounter, viz. $4 \times 10^9 / 1 \times 10^8 = 40:1$. Data reduction should be much less expensive, since rapid changes in environment are unexpected. Finally, analysis will be comparable in cost.

1. Preparation of the data:

| | |
|---|---|
| Computation, per cruise period (200 tapes) | 40, 000 |
| Analyst 1 FTE | 40, 000 |

(works on all cruise periods simultaneously)

2. Data reduction

| | |
|---|---|
| Computation, per cruise period (400 tapes) | 40,000 |
| Scientist 1 FTE | 40,000 |
| (works on all cruise periods simultaneously) | |

3. Data analysis

| | |
|---|---|
| Computation (200 tapes) | 40,000 |
| Scientist 1 FTE | 40,000 |
| (works on all cruise periods simultaneously) | |

19 January 1972

C2

TABLE I

SCIENCE SUPPORT ESTIMATE

| | FY 73 | FY 74 | FY 75 | FY 76 | FY 77 | FY 78 | FY 79 | FY 80 | FY 81-92 | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| P. I. | 54, 770<br>(PI 1 FTE) | 54, 770 | 54, 770 | 54, 770 | 54, 770 | 33, 770<br>(PI 1/2 FTE) | 33, 770 | 33, 770 | 279, 000 | 654, 160 |
| Team | 212, 500<br>(Team 1/2 FTE) | 212, 500 | 212, 500 | 212, 500 | 212, 500 | 112, 500<br>(Team 1/4 FTE) | 112, 500 | 112, 500 | 750, 000 | 2, 150, 000 |
| Programmer & Computer | 50, 500 | 50, 500 | 50, 500 | 25, 000 | 25, 000 | 25, 000 | 12, 500 | 12, 500 | 150, 000 | 401, 500 |
| Miscellaneous | 300, 000 | 250, 000 | 100, 000 | 50, 000 | 50, 000 | 25, 000 | -0- | -0- | -0- | 775, 000 |
| Total | 617, 770 | 567, 770 | 417, 770 | 342, 270 | 342, 270 | 196, 270 | 158, 770 | 158, 770 | 1, 179, 000 | 4, 030, 660 |

FOLDOUT FRAME 1

FOLDOUT FRAME 2

TABLE II

Encounter Data Analysis Estimate

| Planet | | Initial Encounter: R/A Prep | Initial Encounter: Data Reduct | Initial Encounter: Data Analysis | Subsequent Encounter: R/A Prep | Subsequent Encounter: Data Reduct | Subsequent Encounter: Data Analysis |
|---|---|---|---|---|---|---|---|
| Jupiter | Scientist | -0- | 3, 300 | 1, 700 | -0- | 1, 650 | 1, 700 |
| | Other | 1, 000 | -0- | -0- | 1, 000 | -0- | -0- |
| | Computer | 1, 050 | 10, 500 | 1, 000 | 1, 050 | 3, 500 | 1, 000 |
| | Misc. | -0- | -0- | -0- | -0- | -0- | -0- |
| Saturn | | Same | | | Same | | |
| Uranus | | Same | | | Same | | |
| Neptune | | Same | | | Same | | |
| Pluto | | Same | | | Same | | |

Table III

Cruise Data Analysis Estimate

| | | | Reduction and Analysis Prep. | Data Reduction | Data Analysis |
|---|---|---|---|---|---|
| E-J | (a) | Scientist | -0- | 50, 000 (x4) | 50, 000 (x4) |
| 4 S/C | (b) | Other support | 50, 000 (x4) | -0- | -0- |
| | (c) | Computer Time | 40, 000 (x4) | 40, 000 (x4) | 40, 000 (x4) |
| | (d) | Other | -0- | -0- | -0- |
| J-S | (a) | | | | |
| 2 S/C | (b) | | | Same (x2) | |
| | (c) | | | | |
| | (d) | | | | |
| S-P | (a) | | | Same (x2) | |
| 2 S/C | (b) | | | | |
| | (c) | | | | |
| | (d) | | | | |
| J-U | (a) | | | Same (x2) | |
| 2 S/C | (b) | | | | |
| | (c) | | | | |
| | (d) | | | | |
| U-N | (a) | | | Same (x2) | |
| 2 S/C | (b) | | | | |
| | (c) | | | | |
| | (d) | | | | |
| Totals | | | 1, 080, 000 | 1, 080, 000 | 1, 080, 000 |

We assume a single programmer - analyst, and two scientists working full-time from FY 1977 - 1992 (15 years total elapsed). This is a budget of 120, 000 per year; averaged over 12 "missions", the budget is 15/12 x 120, 000 = 150, 000 per cruise period; between three persons, this works to 50, 000 per person, per cruise period as above.