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an amplifier and filter system for telluric signals

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Contents

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Abstract. A high-performance amplifier and filter system is described which is very suitable for amplifying the variations of potential difference which occur between a pair of electrodes in the ground. Salient characteristics include a high impedance differential input, a band-pass characteristic with -3 dB roll-off points at 10^{-4} Hz and 10^{-1} Hz and low output drift.

Résumé. L'auteur décrit un amplificateur à haute performance et un circuit de filtrage qui est bien adapté à l'amplification des variations de difference de potentiel qui ont lieu entre deux électrodes placées dans la terre Les traites saillants comprennent une entrée différentielle à haute impédance, un filtre passe-bande qui a comme caractéristique des points d'échappement de -3 dB à 10^{-4} Hz et 10^{-1} Hz et une dérive de sortie peu élevé.

Introduction

Electric fields induced in the earth by natural geomagnetic variations have been recorded for over a century, with a great variety of equipment. In recent years, research into the electrical conductivity of the crust and upper mantle has created a demand for portable apparatus which will amplify the telluric signals appearing between a pair of electrodes in the ground, filter the signals, and provide an output suitable for various types of recording meters or magnetic tape recorders. The apparatus currently available suffers from one or more of the following limitations – large size, high power consumption, high cost, inadequate band-pass characteristic, insufficient input isolation to permit operation from a common power supply or susceptibility to damage caused by input transients. This paper describes a new design, shown in block diagram form in Figure 1, which is intended to overcome the limitations mentioned.

Input stage

The primary requirements for the input stage are that it have a differential configuration and that the impedance looking into each input terminal be high. Both these requirements are met by the circuit depicted in Figure 2, the operation of which is described by the expression:

$$E_3 = [R_1 (R_3 + R_4) E_2 - R_4 (R_1 + R_2) E_1]/R_1 R_3.$$

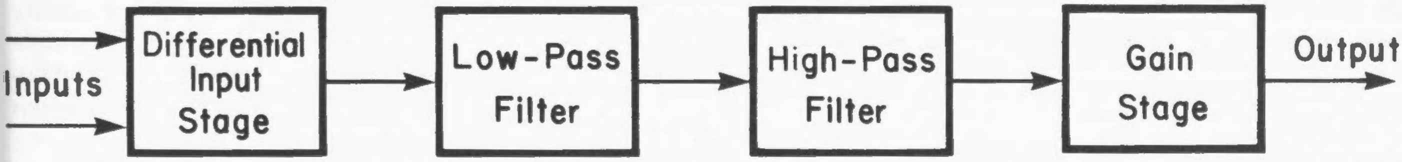

Figure 1. Block diagram of the telluric amplifier.

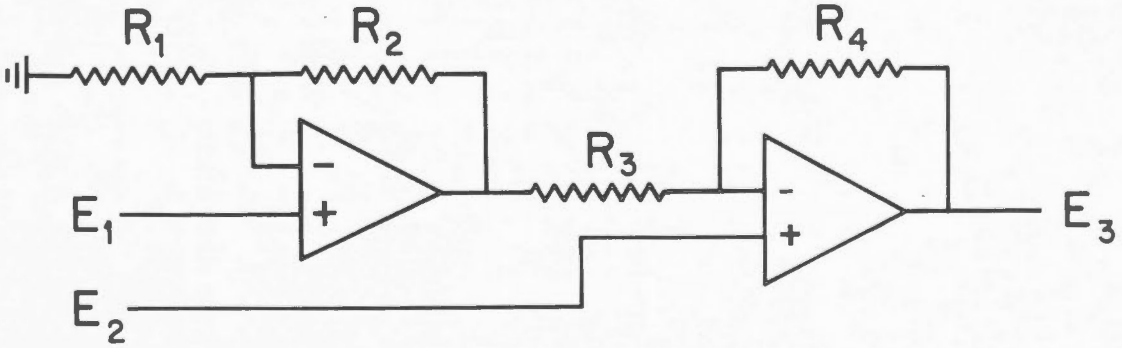

Figure 2. The basic differential input stage.

In the special case used in the telluric amplifier, all resistors have the same value, resulting in:

$$E_3 = 2(E_2 - E_1)$$

If a common-mode voltage is applied to the inputs ($E_2 = E_1$) the output should be zero. A common-mode rejection ratio CMRR defined by:

$$\text{CMRR} = 20 \log_{10}\left\{\frac{\text{common mode input voltage}}{\text{output voltage error}}\right\}$$

and expressed in dB units is often used to characterize the ability of amplifiers to reject common-mode signals. In the case just mentioned (all resistors the same) the upper limit of CMRR is determined by the specification for the operational amplifier, typically 100 dB. A mismatch of 1 per cent in tolerance on any one of the resistors will reduce the circuit CMRR to 40 dB. For this reason, and also to provide an accurate gain for the input stage, the four resistors in Figure 2 should be specified to a tolerance better than 1 per cent. An important advantage of this circuit compared with the conventional differential input configuration is that the source resistances do not form a part of the resistances which determine gain and common-mode rejection.

Both operational amplifiers in Figure 2 are connected in a non-inverting configuration. The input impedance at each terminal is then the input resistance of the operational amplifier multiplied by the loop gain. In the present case this amounts to more than 10^9 ohms. A finite source impedance must be present between each input and the circuit ground point to ensure correct operation. This implies a three-terminal arrangement to measure one telluric component with, for example, north and south electrodes connected to their respective input terminals and an arbitrarily located ground rod connected to circuit ground.

Low-pass filter

A low-pass filter has been incorporated into the telluric amplifier to reject signals with periods shorter than 10 seconds. This circuit, shown in Figure 3, is a special case of the Controlled Source type of active filter[1] where the source is a voltage follower. Such circuits have several advantages over other types of active filter circuits. In particular, the cutoff frequency may be changed to suit the application simply by changing the values of the resistors or the capacitors, without affecting the gain in the pass-band. Use is made of this fact in the design of the high-pass filter stage, described later, which is also a Controlled Source circuit. Other advantages of this design include zero output impedance, a minimum number of frequency-determining components and a small spread of component values. Inspection of Figure 3 reveals that as input frequency tends toward zero (d.c.) the capacitor impedances tend to infinity or open circuit, and the filter is just a unity gain voltage follower and is non-inverting. At the high frequency extreme the capacitors become short circuits and the filter appears as an inverting amplifier with zero gain.

The gain G of the low-pass filter as a function of frequency f is given by the expression:

$$G = [(\pi\sqrt{2}\ RCf)^4 + 1]^{-1/2}$$

This is a Butterworth second-order low-pass filter response with −3 dB roll-off occurring at a frequency $f_0 = 1/\pi\sqrt{2}RC$. The output voltage lags the input by an angle ϕ given by:

$$\text{Tan}\ \phi = 2\pi RCf\,[(\pi\sqrt{2}\ RCf)^2 - 1]^{-1}$$

High-pass filter

The role of the high-pass filter in this circuit is to attenuate signals having a period longer than 10^4 seconds (about 2 3/4 hours). This eliminates the need for a bias scheme for offsetting the effect of a d.c. potential between electrodes. A high-pass filter with such a long period for the −3 dB roll-off point has only recently become a practical reality because of advances in operational amplifier technology and component fabrication techniques. Practical problems

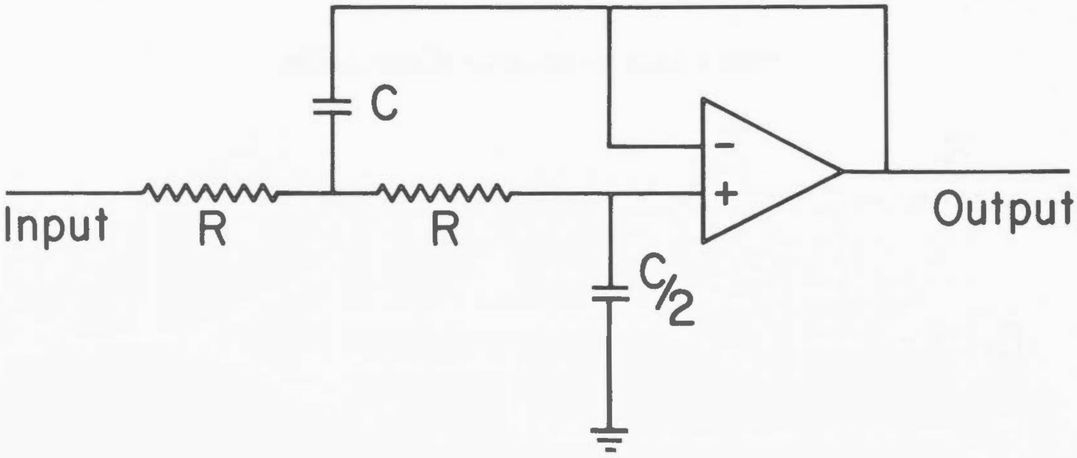

Figure 3. A Controlled Source low-pass filter.

with the high-pass filter are discussed in later sections and need not be of concern at this point.

A schematic for the high-pass stage is presented in Figure 4. It is a second-order Controlled Source circuit very similar to the low-pass stage of Figure 3. Gain G and phase response ϕ for the high-pass filter as a function of frequency f are as follows:

$$G = (\pi\sqrt{2}\,RCf)^2\,[(\pi\sqrt{2}\,RCf)^4 + 1]^{-1/2}$$

$$\mathrm{Tan}\ \phi = 2\pi\,RCf\,[(\pi\sqrt{2}\,RCf)^2 - 1]^{-1}$$

Figure 5 is a plot of the composite gain and phase response for the low-pass and high-pass stages.

A point of particular interest in the gain versus frequency characteristic is the frequency f_1 at which the gain G has rolled off to 99 per cent of the pass-band value. Squaring the expression for gain versus frequency and solving for f_1 when $G^2 = 0.98$ results in $f_1 = \sqrt{7}\,f_0$, where $f_0 = 1/\pi\sqrt{2}\,RC$ is the frequency at which roll-off is - 3 dB.

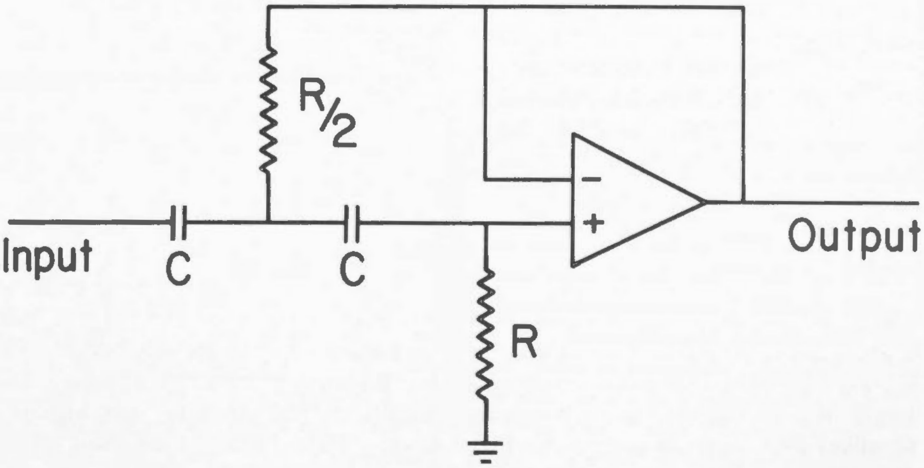

Figure 4. Circuit schematic of the high-pass stage.

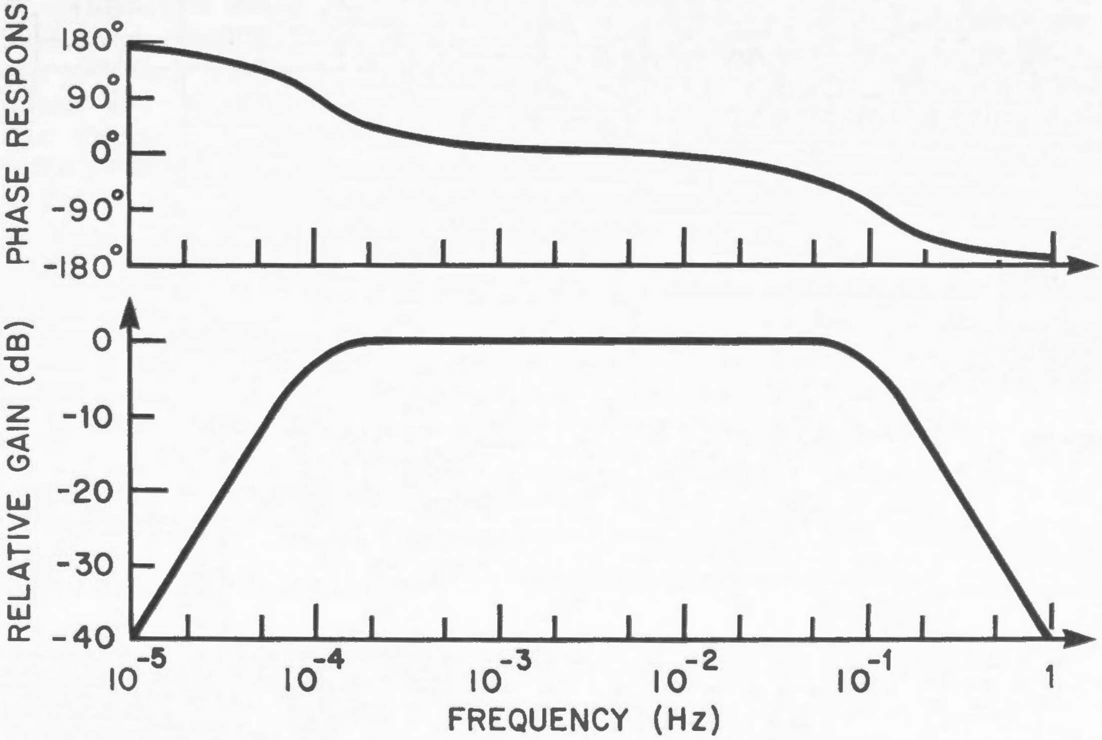

Figure 5. Relative gain and phase response of the telluric amplifier.

Circuit details

Figure 6 is a schematic of the complete circuit, and it includes several important details not mentioned in the earlier discussion. The first of these is the two resistors on the input lines. These serve, in conjunction with input protective diodes built into the operational amplifiers, to protect the input stages from damage arising from transients induced on the telluric lines. Experience has shown that lightning strikes some distance from the lines can induce voltage spikes on the order of tens of kilovolts on the lines (enough to spark across a 1/2 inch air gap), with disastrous effects on the amplifier. The 1 megohm input resistors limit input currents during transients to values that can be accommodated by the protective diodes. The inclusion of these resistors is only possible because of the extremely high input impedance of the input stage, which must be at least two orders of magnitude greater than the effective source resistance.

Another protective feature is the 12-kilohm resistors inserted in series with the amplifier inputs of the low-pass and high-pass stages. Here the problem is one of safely dissipating charges accumulated on the large capacitors in these stages in the event of a sudden shutdown of power. These resistors limit the current discharged into the amplifier input terminals in such an event. Again they are negligible in value when compared with the amplifier's inherent input impedance.

Provision has been made for switching the characteristic of the high-pass filter. This is accomplished with the 2-pole switch depicted in Figure 6. In actual use this is almost an essential capability. The -3 dB roll-off point for the high-pass filter is 10,000 seconds, or about 2 3/4 hours. In a typical field setup there is some d.c. potential between electrodes. When these are connected to the telluric amplifier and power is applied, a period several times longer than the -3 dB period is required before all capacitors can charge to their normal working potential and the high-pass output settle down to zero. This means a wait of perhaps eight hours if no roll-off switch is available. The roll-off switch cuts the -3 dB period to 100 seconds, the circuit can then settle down in about five minutes and be switched back to 10,000 second roll-off with all capacitors fully charged.

Finally, a variable gain stage has been provided as part of the telluric circuit. This is just a simple inverting amplifier of standard design giving a stage gain variable from 1/2 to 50. It must be kept in mind that the input stage of the telluric amplifier has a gain of 2 so that the overall circuit gains are 1, 2, 5, 10, 20, 50, 100.

Drift

Output drift occurs as a result of inherent offset voltage drifts $\dot{V}_{os}$ (derivatives with respect to temperature), offset current drifts $\dot{I}_{os}$ and bias current drifts $\dot{I}_b$ at the operational amplifier inputs[2].

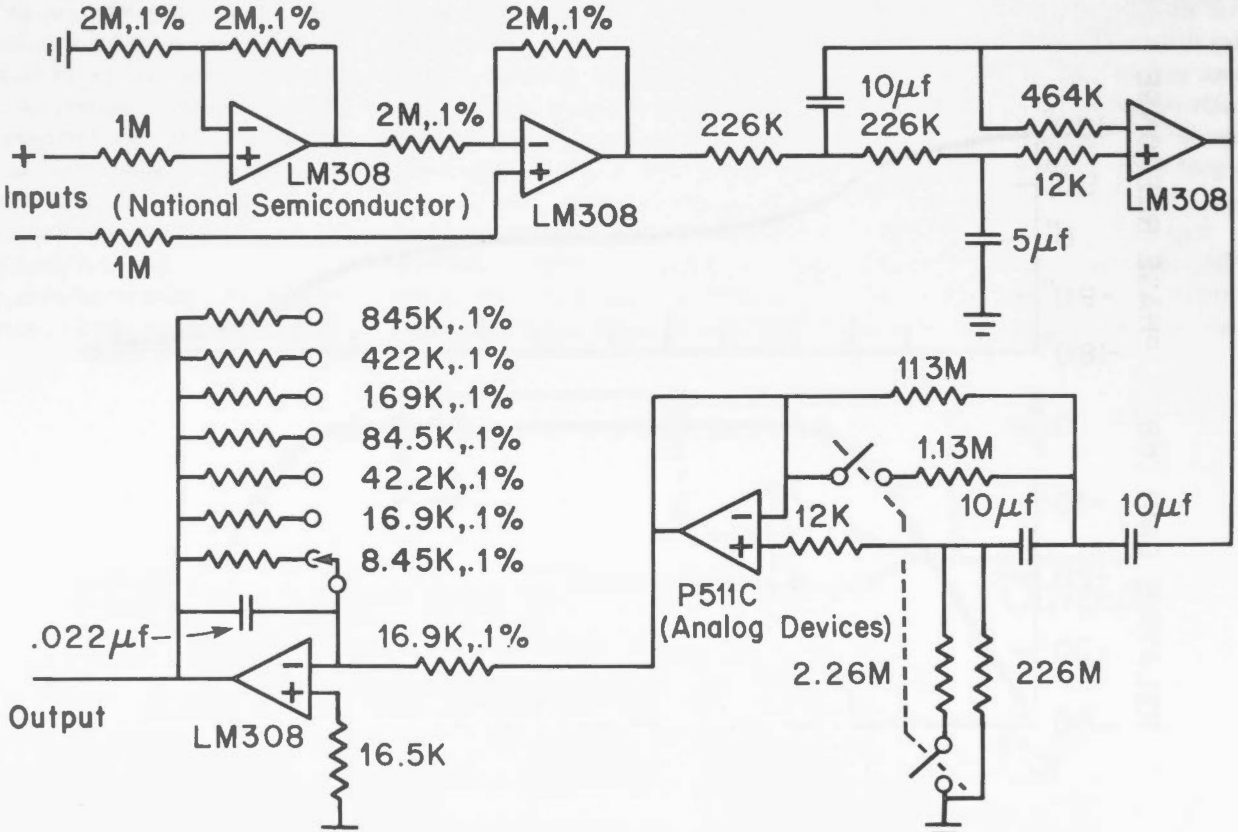

Figure 6. Detailed schematic of the telluric amplifier

The output drift component caused by $\dot{V}_{os}$ for a stage with gain A is equal to $A\dot{V}_{os}$ for a non-inverting stage and $(A+1)\dot{V}_{os}$ for an inverting stage. In the case where both input terminals of an operational amplifier see the same equivalent resistance R_e to ground, the output will experience a drift component of $\dot{I}_{os}R_e$. When one input terminal sees zero resistance to ground (as in the high-pass stage) the bias current drift in the other input will generate an output drift component equal to $\dot{I}_bR_e$.

Worst-case drift specifications for the LM308 are $\dot{I}_{os}$ = 10pA/°C, $\dot{V}_{os}$ = 15uV/°C and for the P511C are $\dot{I}_b$ = 0.5pA/°C, $\dot{V}_{os}$ = 25uV/°C. The following table shows the output drift components (uV/°C) generated within each of the first three stages.

	$\dot{V}_{os}$	$\dot{I}_{os}$	$\dot{I}_b$
Differential input	60	20	–
Low pass	15	5	–
High pass	25	–	113

Since the filters are unity gain these figures may be added to give a total worst-case drift of 238 uV/°C at the high-pass output. Drifts generated within the variable gain stage range from 23 uV/°C at minimum gain up to 765 uV/°C, but are always insignificant compared with that produced by amplification of the 238 uV/°C figure previously obtained. At the minimum gain of 1/2, corresponding to an overall telluric amplifier gain of 1, the worst-case total output drift would be 142 uV/°C.

One can reasonably expect the actual circuit drift to be smaller than 142 uV/°C by a factor of 5 or more. The specifications for typical drifts of the operational amplifiers are one fifth of the worst-case values. It is very unlikely that all drifts would be of such a polarity as to add at the telluric amplifier output. Furthermore the drift contributions from the input stage and low-pass filter, being long-term effects, would be attenuated to some extent by the high-pass filter.

Physical details

Care must be exercised in the selection and handling of components and in the choice of physical layout for the circuit. Resistance values as high as those used in the high-pass filter are readily available. As a rule such resistors come individually packaged and should remain that way until used. Metallized polycarbonate capacitors should be used throughout the circuit. These combine a very high insulation resistance of 100,000 megohms x microfarads minimum with very small physical size (0.66 in. dia. x 0.75 in. length for 10 microfarads, 50V). A 10-microfarad capacitor can be expected to have a resistance of 10,000 megohms, roughly 50 times the largest resistance used in the high-pass filter.

A printed circuit board for this circuit requires careful layout. First, the electrode side of the 1-megohm input resistors should not run close together or close to other circuitry as arcing may occur on the board during an electrical disturbance, with very predictable results for the telluric amplifier. It is also desirable to design so that the high impedance points of the circuit are as far removed from adjacent circuitry as is possible. This applies to anything connected to the non-inverting pin of the P511C amplifier and to the junction of the 10-microfarad capacitors in the high-pass filter. In spite of these restrictions the circuit can be produced on a board 11.5 cm by 14.5 cm. The board should be thoroughly cleaned to remove all traces of solder flux. Trichloroethylene works well for this job. After the circuit has been tested to verify its performance, the board should be given a protective coating to prevent any contamination.

Testing

Use of a sinusoidal oscillator for the purpose of checking the band-pass characteristic and phase response of this circuit is just not practical. Oscillators capable of generating something more than a 10,000-second period are decidedly scarce and in any case the process would be very time-consuming. Fortunately the high-pass filter behaves as an underdamped second order system when provided with a step input (damping ratio, = $1/\sqrt{2}$). This fact, along with the provision for switching in a 100-second roll-off point can be used to create a very convenient test procedure. The circuit is tested in conventional fashion with the −3 dB roll-off set at 100 seconds, to confirm that operation is as predicted. Then a step input is provided and a typical underdamped response characteristic will occur. Next the filter is switched to the 10,000-second −3 dB roll-off and another step input is provided. The performance can then be assessed by comparing the resulting underdamped characteristic with that generated previously in the 100-second mode. In particular, the ratio of the interval between the first two crossings of zero output in the two cases may be used to determine the actual time constant in the latter case.

References

1. "Handbook of Operational Amplifier Active RC Networks," Burr-Brown Research Corp., Tucson, Ariz., 1966.
2. "A Selection Handbook and Catalog Guide to Operational Amplifiers," Analog Devices Inc., Cambridge, Mass., January 1969, p. 4.