A differential electrometer for vector electric field measurements on a balloon platform

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Vector measurements of middle atmospheric electric fields are mostly carried out using a double-Langmuir probe technique on platforms like balloons and rockets. High impedances (up to 10^{13} ohms) and low signal levels (~few millivolts) are the factors that are to be considered in the design of an electrometer for one such experiment. Here, we offer a simple circuit concept that invokes an instrumentation amplifier capable of meeting our several needs, namely generating the guard voltage, ultra-high impedance (10^{15} ohms) input terminals, femtoampere bias current, differencing, gain setting, etc. all in one package. A three-channel differential electrometer was developed based on this concept and flown on a high-altitude balloon platform. Results reveal that the instrument is capable of detecting weak electric field variations at stratospheric altitudes.

The double-Langmuir probe technique is a commonly employed experimental tool to measure electric fields in space plasmas from a variety of balloon, rocket and satellite platforms[1–4]. Close to Earth, the atmospheric impedances could be as large as $\sim 10^{13}$ ohms and the expected electric field signals are in range of a few millivolts per metre (mV/m). With the demand to meet a sensitivity of less than 1 mV/m for such measurements, the challenges are quite real. The current technology allows use of very low leakage current FET-based operational amplifiers as preamplifiers in voltage follower mode along with guard ring layout techniques. Here, we offer a simple circuit concept for electric field measurements that is easy to implement and offers the necessary guarding scheme. This electrometer concept was tested successfully on a high-altitude balloon experiment and meaningful electric field measurements were made.

The electrometer concept

The target for any electric field measurement in atmospheric plasmas is to measure weak electric field signals (few to several tens of millivolts per metre) against an ambient noise background that is created largely by the motion of the measurement platform, any photoelectric effect caused by sunlight impinging on the probes, changing contact potentials of the probes, electrostatic and electromagnetic noise generated by the subsystems, etc. For measurements on a balloon platform that utilize the double-Langmuir probe technique, the electrometer which gets connected to the probe, operates in a voltmeter mode with very high input impedance ($\sim 10^{15}$ ohms). A combination of a pair of voltage follower and difference amplifier would form the essential elements of one such electrometer. Several precautions need to be taken while fabricating an electrometer. It is quite likely that the printed circuit board (PCB) material offers low resistance path to the integrated circuit (IC) inputs in case the ICs are soldered to the PCB. Further, the connectors and cables offer low resistance path to the inputs if they are not shielded with PTFE insulating material.

The usual practice adopted by researchers conducting balloon experiments is to employ a peta (10^{15}) ohm input impedance voltage follower inside the probes, or have it on the central body (not an issue for low frequency measurements). With the impedances brought down to workable levels, the outputs belonging to a pair of probes along a given baseline would be fed to a low-noise instrumentation amplifier that would also serve as a difference amplifier (AD620, for example). In the absence of any noise, the difference output will then be proportional to the component of the electric field along the baseline joining the two probes. As the measured signal is of the order of a few millivolts and the currents, if any, are expected to be less than the bias current (~few hundreds of femtoampere) allowed by the input amplifier for meaningful voltage measurement, it is essential to implement a guarding scheme in order to minimize the leakage current, if any. For this purpose, a voltage equal to that of the probe signal is generated and fed to the shield (outer conductor) of the coaxial cable. This will ensure that the inner conductor and the outer shield of the coaxial cable remain at the same potential implying negligible leakage current between the two conductors. This guarding technique can very well be extended to PCB traces and the BNC connectors so that the set measurement targets could be achieved. Separate voltage follower ICs (AD628, for example) are required to be used in conjunction with the instrumentation amplifiers to generate the desired guard voltage.

In the present scheme, we propose INA116 instrumentation amplifiers that would replace both AD620 instrumentation amplifiers and AD549 preamplifiers. Instead of using four ICs (two numbers of AD549 with AD620 and AD628) with possible circuit complications, INA116 offers the functions of a voltage follower, a difference amplifier and a guard voltage generator, all in one package. This IC has already found applications in pH meters.

Circuit description and implementation on a balloon payload

The concept proposed here was used in a high-altitude balloon experiment conducted from Hyderabad (17.4°N, 78.5°E), India, during the night of 13/14 December 2013. The primary objective of this experiment was to detect weak horizontal electric fields of ionospheric origin at stratospheric altitudes, if any, in the range 25–35 km. Long (~3 m) deployable booms were used to isolate the

electric field probes from the gondola (central body) of dimensions 1 m × 1 m × 1.2 m. Two pairs of probes, denoted as x- and y-pairs, on a rotating gondola contributed to the measurements of horizontal electric fields (E_x and E_y). With ~7 m baseline for the horizontal probes, a 1 mV/m electric field will translate to a ~7 mV potential difference between the probes. The x- and y-directions are referenced with respect to the orientation of the three-axis magnetometer sensors. An inclined boom carried the fifth probe that, when combined with one of the horizontal probes, yielded a measurement of the vertical component of the electric field (E_z). A gyroscope attached to the gondola through a universal joint controlled the rotation of the platform with a telemetry command. The rotating platform enabled easy identification of quasi-DC horizontal electric field signals against large DC offsets. Herein, we will demonstrate the ability of the electrometer to capture the sinusoidal variation of weak horizontal electric fields against a large DC offset by virtue of rotation of the platform.

Figure 1 shows the circuit diagram of a single-channel ultra-high impedance electrometer used in the above experiment. An INA116 instrumentation amplifier forms the heart of the electrometer located in the front. This instrumentation amplifier has special characteristics that maintain very low bias current (~3 fA at 25°C) at the input, 2 mV offset voltage, 84 dB common mode rejection and a sensitivity of 500 nV. By connecting a single external resistor, the amplifier allows a gain to be set. The INA116 amplifier is followed by a 1 kHz second-order Butterworth low-pass filter. The differential configuration of INA116 cancels out the common mode signals (noise signals common to both inputs), and amplifies the difference signal with the chosen gain. The low-pass filter operation is realized with the high-precision quad op-amp LT1014 IC. The high-impedance differential input pins (3 and 6) of INA116 are directly soldered up in the air (to avoid PCB leakage) to the inner conductors of a pair of PTFE-insulated connectors. The guard voltages (pins 2, 4 and 5, 7) are applied to the outer conductors of the respective BNC connectors. The PTFE-insulated coaxial cable (RG188) runs from the BNC connector to the conducting probes via mating BNC connectors. While the central core of the cable is connected to the probe, the outer shield is driven by the guard potential.

For the balloon experiment, three numbers of INA116 amplifiers were used with one LT1014 quad op-amp. The circuit elements comprising the electrometer and the second-order Butterworth filter were soldered on a double-layered glass epoxy PCB. The PCB itself was placed inside a 5 mm thick solid box made of aluminium, which acted as a Faraday cage shielding the electronics from any noise induced by other subsystems inside the gondola. The electrometer gain was selected through a telecommand by activating the respective relay contacts and enabling the gain resistors to provide the gain in steps of 1, 10 and 100.

In the present scheme the analog signals are first converted into digital format by an analog-to-digital converter (ADC) at 12-bit resolution and 100 μs conversion time. The ADC is driven by a ±4.5 V supply voltage. At this resolution of ADC, the probe system will be able to sense a change in the electric field of ~0.3 mV/m. While on the balloon platform, data from the ADC are fed to a pulse code modulator (PCM) which encodes them at rates up to 200 kbps and uses a multiplexer to stream the data in serial format. The serial data are then fed to an S-band transmitter operating at a carrier frequency of 2259 MHz to transmit the encoded signal to the ground station.

Ground verification of probe electronics was carried out prior to the balloon launch. For this, probes were applied with external potentials and telemetry data confirmed the expected performance in terms of sensitivity and linearity. A full characterization in terms of an evaluation of the response of the electrometer to matching ultra-high impedance (~10^{15} ohms or greater) voltage sources is desirable, but the infrastructure available with the experimenters then did not permit such an exercise to be carried out. Rather, they had to rely on the data sheets provided by INA116 instrumentation amplifier and the precautions prescribed therein for the expected performance of the amplifier.

In Figures 2 and 3 we show the telemetry outputs from the two electric field channels in two different time formats: in the top panels the telemetry data for 90 min duration between 04:00 and 05:30 IST are shown, whereas in the next three panels we show datasets of 2-min duration at ~1 h time intervals. The data points were sampled at 72 ms and the amplifier gain was set at 10. The thick curves running through the data for the 2-min segments represent 25-point running averages. In Figures 2 and 3, the DC offsets and gain factor (10) have been removed while plotting the shorter duration samples.

For the present discussion we record here that the balloon reached a float altitude of 35 km at around 03:45 IST. Because of issues with the gyroscope, a stable rotation of the gondola at the float altitude could be achieved only for a little less than 2 h and therefore, the
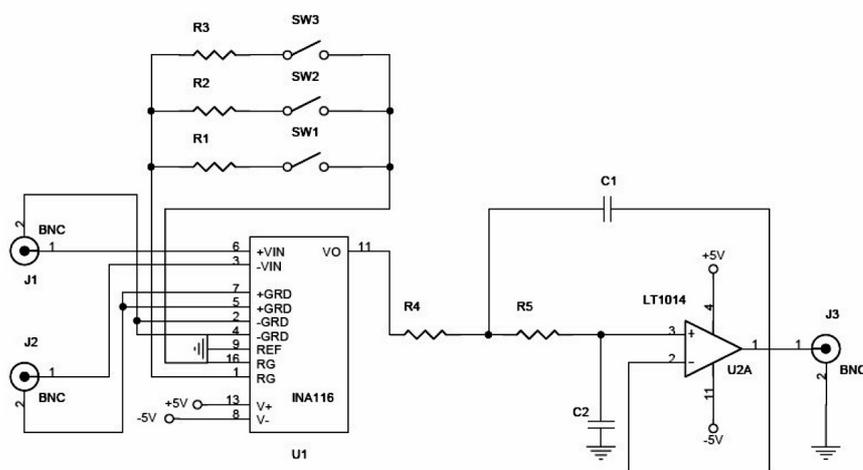

Figure 1. Circuit diagram for a single-channel differential electrometer showing the INA116 instrumentation amplifier whose output is connected to a low-pass second-order Butterworth filter implemented through IC LT1014.
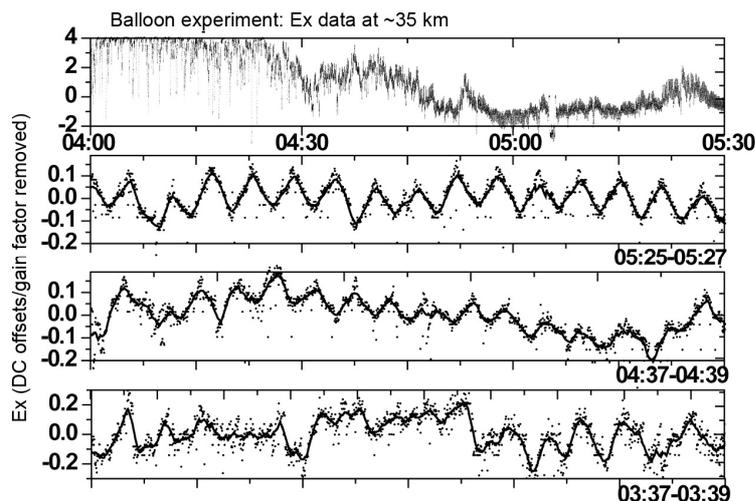
Figure 2. Raw telemetry outputs from the *x*-electric field channel obtained from the high-altitude balloon experiment. The numbers on the ordinate scale are in volts.
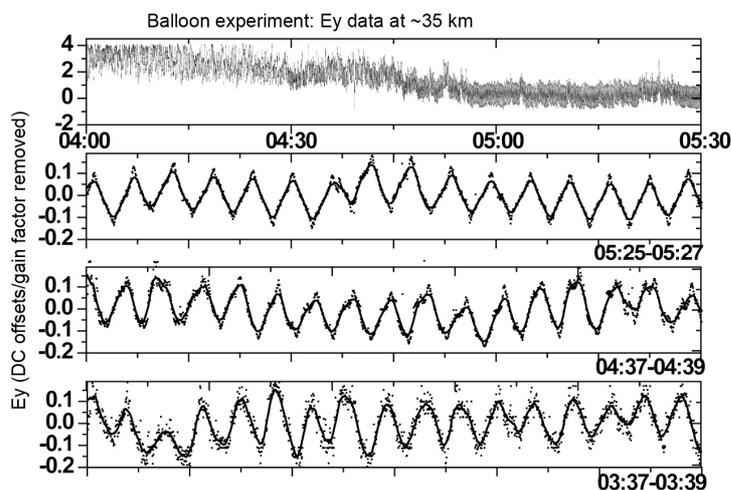

Figure 3. Same as in Figure 2, but for the *y*-electric field channel.

horizontal electric field data for any scientific analysis are considered only for this duration. Out of the two orthogonal pairs of electric field probes arranged in the gondola *x–y* plane, the signals from the *x*-pair were found to be noisy as can be noticed in Figure 2. This noisiness is attributed to the fact that the inclined boom used for the vertical electric field measurements, though was separated from the gondola frame by Teflon spacers, is metallic, and so could have carried the gondola noise to the *z*-probe and that may have possibly influenced the potential around one of the *x*-probes underneath. Further, one of the *x*-channel inputs was coupled to one of the *z*-channel inputs for the chosen five-probe configuration, and the feedback from the *z*-channel then supposedly made the *x*-channel output noisy. The high-frequency noise no-

ticed in the *x*-channel, which was absent in the *y*-channel during these times, is therefore ascribed to the gondola noise. In addition, there was also a suppression of the field output in the *x*-channel when compared to that recorded in the *y*-channel.

In spite of the shortcoming described above, what is strikingly noted in the telemetry data shown in Figures 2 and 3 is their near-sinusoidal variation clearly tracking electric fields of few mV/m. As the payload rotated, the probes sensed an electric field that varied at the rotation rate. A three-axis fluxgate magnetometer served as compass to delineate the magnitude and direction of the ambient electric field. Further improvements in terms of separate probe pairs for measurements of the three components of electric field, deployment of an on-board multi-channel

data acquisition system and a smaller gondola and therefore a smaller payload mass, are being worked out for the next balloon experiment.

Conclusion

We have described a three-channel differential electrometer based on INA116 instrumentation amplifier whose performance was realized in practice on a balloon platform. As shown using the telemetry data, the instrument responded to the atmospheric electric field at stratospheric altitudes. Once certain preconditions like soldering the connectors during flight directly to the concerned pins of the amplifier and implementing a guard scheme, all of which lead to considerable minimization of leakage currents, are addressed, this instrument with simple circuit elements will be a useful tool for future *in situ* probing of atmospheric electric fields on high-altitude balloon platforms as demonstrated herein.

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