Practical Guidelines for building a Magnetometer by Hobbyists

Part 3 : Gradiometer Project

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Version 3.1

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1. Overview

1.1. Versions 1 and 2

This is the Block Diagram of the Gradiometer system version 1 and 2. It will be built with 4 distinct boards:

- Two identical channels of Polarization Control/Signal Amplification/Filtering/Analysis with an I2C Bus connection
- One main Control Board
- A small PCB with a 5-button keyboard.

The result of the frequency calculation from each channel is written to a small central RAM. They are picked-up one at a time from this RAM by the central control program and subtracted to get the **field gradient**. This value is then stored into the large (32Kbytes) EEPROM as a table with their associated 2D coordinates of the survey map. The gradient will also be displayed in real-time on the LCD with an evaluated quality factor based on a number of observations. If the quality of the result is not satisfactory to the operator, he could attempt to redo the same measurement immediately.
At the end of the survey or of the day of work, A PC is connected to the system through the RS232 link and all the survey values uploaded to be permanently stored and studied later on a 3D graphical map.

1.2. Versions 3

This is the overview of the version 3 (Overview Version 3)

2. Polarization Circuit

2.1. Versions 1 and 2

This is the first version of the Polarization Circuit of the Gradiometer system. Both channels are simultaneously controlled by four digital lines (POL_CTL, SQUELCH, SERIES, QUENCH) coming from the Main Control Board.

2.2. Version 3

The third version of the Polarization Circuit of the Gradiometer system is controlled by three digital lines only(POL_CTL, SQUELCH, SERIES) and they are under control of the local 16F628 CPU of the channel board. (see complete Circuit of the Version 3)

3. Amplifier/Signal Analyser Channel

3.1. Version 1

These are the Signal Amplifier/Filter Circuit and the Signal Analyzer Circuit (combined on the same slave board together with the Polarization circuit) of the version 1 of the Gradiometer system. Both channels are controlled by a distinct digital line (PICK1 and PICK2) coming from the Main Control Board. The PICKx line ON conditions the beginning of the signal frequency analysis coming from the TTL_OUT line and the PICKx line OFF conditions the storage of the frequency result on the main board through the I2C Bus (SCL, SDA lines).

3.2. Version 2

These are the circuits of the three channel sub-modules of the version 2 of the Gradiometer system. This is based on the latest revision (revision 7) of the proven PPM design from Jim Koehler.

3.3. Version 3

This version of the amplification chain has been defined from almost the same design as version 1.

Both channels are controlled by a distinct digital line (PICK1 and PICK2) coming from the local 16F628 CPU of the channel board. (see complete Circuit of the Version 3).
The circuit of the analog output from the last amplifier stage has been directed both to an external comparator stage and to the internal comparator of the 16F628 to be able to evaluate this last option and thus, simplify the circuit in the future.

4. Main Control Module

4.1. Versions 1 and 2

This is the Main Control Circuit of the Gradiometer system. It simultaneously controls the polarization and signal pick-up cycles through four digital lines (POL_CTL, SQUELCH, SERIES, QUENCH) and controls the capture of the frequency calculation from the two channels by setting OFF their PICKx line in sequence.
It is based on the traditional **PIC16F876** from Microchip with 8Kwords flash program.
The **I2C EEPROM** of 32Kbytes temporarily (but safely) stores the field gradients and their associated XY survey coordinates.
The **LCD** is used to display the current field gradient and XY coordinate as well as menu display for parameter settings.
The **four-arrow keys + OK** is the keyboard of the system.
An **RS-232 interface** to connect a PC for survey results up-loading and system parameter set-up.
A **Buzzer** is used for aural feed-back (key press, alarm…)
A special **trigger push-button** (connected in parallel with the **OK** button) is depressed by the operator to start each measurement cycle in manual mode.

4.2. Version 3

The board of the main control module of the version 3 has been re-packaged to have the same dimensions and connectors as the channel board. (see complete Circuit of the Version 3).

5. PCB layout

5.1. Version 1

This the first version of the placement of Components for the three boards in a colored 2/1 scale (with the indications of the vias and straps) and the corresponding Component Side and Copper Side in black 1/1 scale ready to be printed on a good laser printer.
These boards have been designed for double layer PCB (with a number of vias) and two ground planes covering almost all their surface.
This is a compiled Part List.

5.2. Version 2 Revision 1

This the second version of the placement of Components for the three boards in a colored 2/1 scale (with the indications of the vias and straps) and the corresponding Component Side and Copper Side in black 1/1 scale ready to be printed on a good laser printer.
These boards have been designed for double layer PCB (with a number of vias) and two ground planes covering almost all their surface.

5.3. Version 2 Revision 2

This the revision 2 of the second version of the placement of Components for the three boards and the corresponding Component Side, Copper Side and PCB see-thru. This revision mainly changed the PCB layout to improve the layout of the GROUND planes in a low noise environment.
This is the partlist as generated by Eagle program.

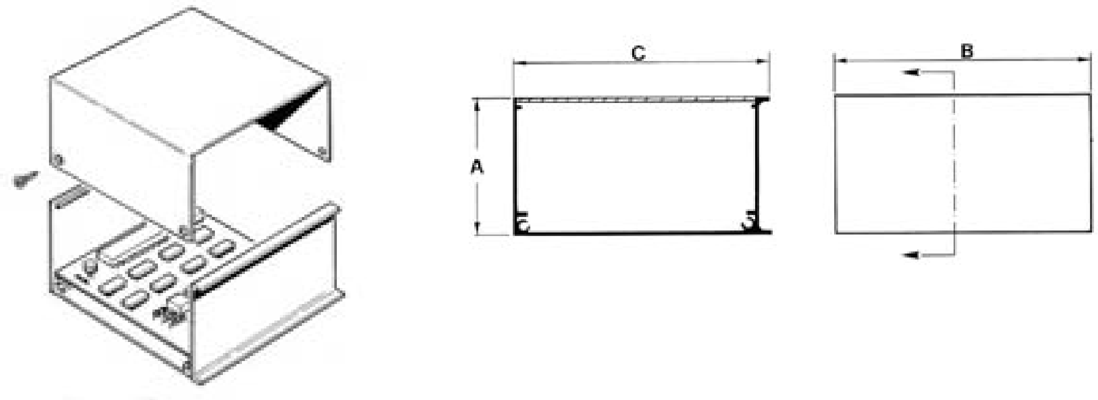
5.4. Version 3

This the third version of the placement of Components for the three boards and the corresponding Component Side, Copper Side and PCB see-thru (PCB layout).
This is the channel part list and the Main control part list as generated by Eagle program.

6. *Packaging*

6.1. Version 1 and 2

The main board holds all the Voltage Regulators and the main control module. This PCB is also the backpanel onto which the two slave boards vertically plugs in through their male header connectors. The main board has been dimensioned to be exactly inserted into the PCB slides of an electronic box made of aluminum extrusion with a size of 155x105x80mm.



The top of the box cover will hold the LCD, the Buzzer and the keyboard.
The first side of the cover will hold the two BNC connectors to the sensors.
The second side of the cover will hold the RS-232 connector and the 12V power supply connector to an external gel cell battery.

6.2. Version 3

The layout of the version 3 of all the boards has been designed to plug into a common Back panel providing the raw battery power to the local voltage regulators and the interconnection of the I2C bus.

7. *Program Descriptions*

7.1. Signal Analyzer (Basic Version)

This is the pseudo-code of this simple program which could easily be written in Assembler:

- Main code:
    - Init all
    - Set Interrupt OFF
    - Do forever
        - Wait for PICKx = ON
        - Clear 16-bit **period_counter** and 24-bit **long_timer**
        - Wait for TTL_OUT = OFF
        - Wait for TTL_OUT = ON
        - Clear 16-bit Timer1
        - Set Interrupt ON
        - Wait for **period_counter** = 512
        - **Long_timer** = **long_timer** + Timer1
        - Set Interrupt OFF
        - Wait for PICKx = OFF
        - **nT =** 5 * 1,000,000 * 512* 23.49624 * 10 / **long_timer** (long_timer is the number of 0.2 µsec periods of 512 consecutive signal periods)

- Send **nT** to I2C RAM at address 0 on 4 bytes as units of 0.1nT.

- Interrupt code:
  - If TTL_OUT going ON
    - **period_counter**++
  - If TIMER1 Overflow
    - **long_timer** = **long_timer** + 65536

7.2. Signal Analyzer (Noise-reducing Version)

- Main code:
  - Init all
  - Set Interrupt OFF
  - Do forever
    - Wait for PICKx = ON
    - Clear 16-bit **period_counter**, 24-bit **long_timer,** 32-bit **accu**
    - Wait for TTL_OUT = OFF
    - Wait for TTL_OUT = ON
    - Clear 16-bit Timer1
    - Set Interrupt ON
    - Wait for **period_counter** = 256
    - **accu1 = accu**
    - **accu** = 0
    - Wait for **period_counter** = 512
    - Set Interrupt OFF
    - **accu** = **accu** – **accu1**
    - Wait for PICKx = OFF
    - **nT =** 5 * 1,000,000 * 65536 * 23.49624 * 10 / **accu** (accu is the number of 0.2 µsec periods of 256*256 consecutive signal periods)
    - Send **nT** to I2C RAM at address 0 on 4 bytes as units of 0.1nT.
- Interrupt code:
  - If TTL_OUT going ON
    - **period_counter**++
    - **accu = accu + long_timer** + Timer1
  - If TIMER1 Overflow
    - **long_timer** = **long_timer** + 65536

7.3. Main Control Program

The main control program is rather large, although not so complex, it will be written in C.
It has two distinct operation modes:

1. **Survey Mode** (Default on power on)
An area to be surveyed is delimited as a rectangular surface preferably oriented in the North/South direction.
It is sub-divided into squares whose side length depend on the required survey resolution and on the surface to be covered. When making the first phase survey on a large area or when searching for large field disturbances, one uses squares of 10x10m or even 100x100m. For locating small field disturbances, the squares are more like 1x1m.
The square corners are given 2D coordinates X and Y with the 0,0 base located anywhere on the surface but usually, at the lower left corner of the rectangle.
During the survey operations, the LCD displays the X,Y coordinates of the next field measurement cycle.
Initially, the XY values are 0,0 but the operator can start his survey campaign anywhere on the surface area by pressing the four arrow keys to set the current XY where he wants. Going there and pressing the VALID key will start a polarization/signal pickup cycle.

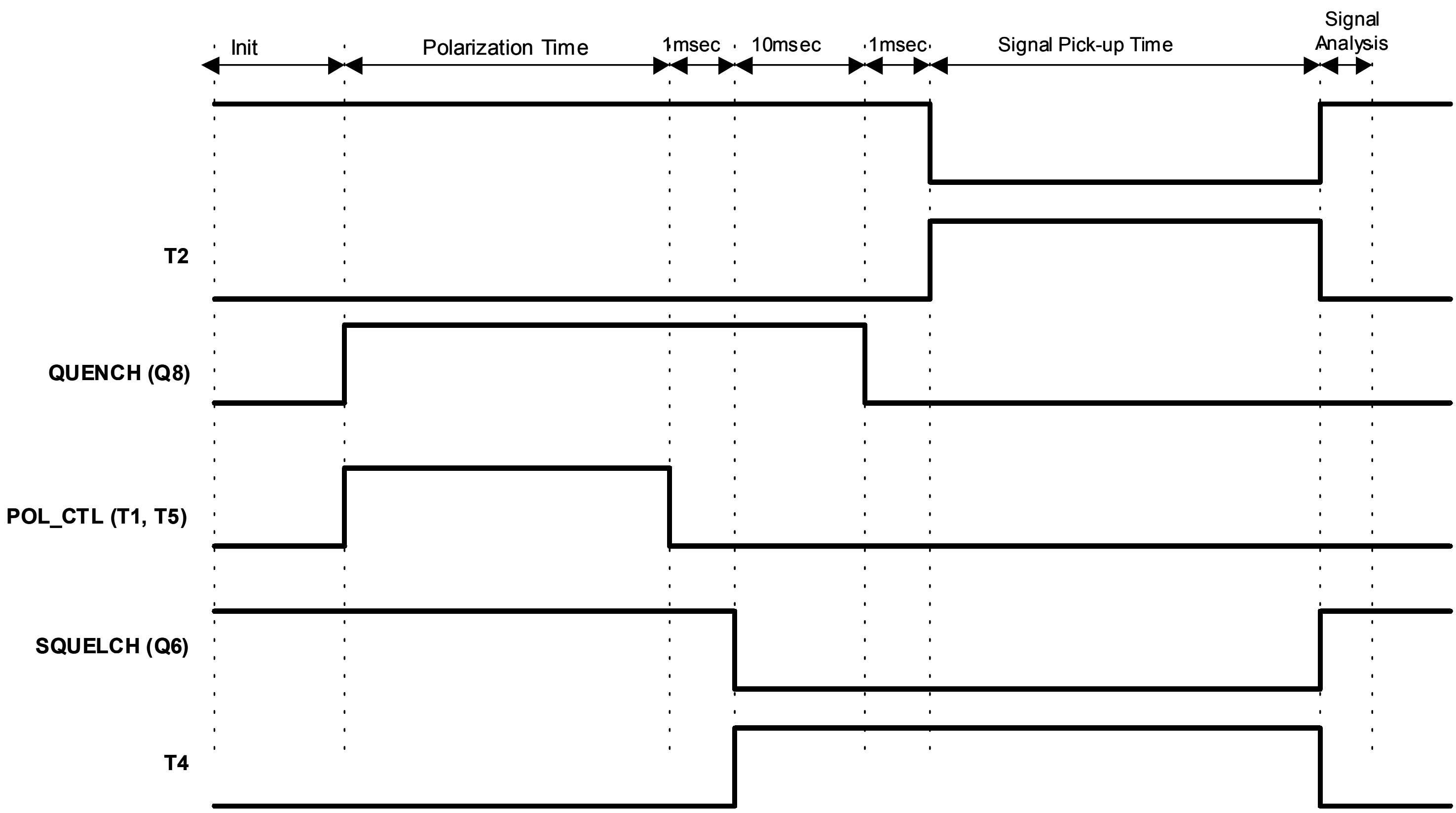
2. **Menu-driven Parameter Setup Mode** (Power on with VALID key pressed**)**
This mode of operation allows to clear the EEPROM log list and to receive commands from a PC program to upload the EEPROM log and to setup system parameters.

7.3.1. Survey Mode pseudo-code

- Do forever
  - Set SQUELCH = ON and SERIES = ON
  - Wait for VALID = OFF
  - Wait for any keyboard key pressed
  - If ARROW key pressed then
    - Increment or decrement **current_X** or **current_Y**
  - Else If VALID key then
    - Make a single Measurement giving **Field_Gradient** in units of 0.1nT
    - Display **Field_Gradient** on LCD
    - Append **current_X**, **current_Y**, **Field_Gradient** at end of EEPROM log list.
    - Validate **Field_Gradient** against **maximum and minimum thresholds** (system parameter)
    - If valid then
      - Make a Positive Aural feed-back on the Buzzer
    - Else
      - Make a Negative Aural feed-back on the Buzzer

7.3.2. Make a single measurement

- Set POL_CTL = ON and QUENCH = ON
- Wait for **polarization_time** (system parameter)
- Set POL_CTL = OFF
- Wait a msec
- Set SQUELCH = OFF
- Wait for 10 msec (to skip switch off spikes)
- Set QUENCH = OFF
- Wait a msec
- Set SERIES = OFF (connect the two pre-amp input channels to sensors)
- Wait 10msec for amplifier transients to die away
- PICK1 = ON, PICK2 = ON (start the two slave signal analyzers)
- Wait for **signal_pickup_time** (system parameter)
- Wait 1 msec (give some lag time)
- Set SQUELCH = ON and SERIES = ON (short-circuit the two pre-amp channels)
- Set PICK1 = OFF (trigger signal analyzer of channel1 to send its absolute magnetic field value to the I2C RAM)
- Read nT value from the I2C RAM and save it into **nT1**
- Set PICK2 = OFF (trigger signal analyzer of channel2 to send its absolute magnetic field value to the I2C RAM)
- Read nT value from the I2C RAM and save it into **nT2**
- **Field_Gradient** = **nT1** – **nTt2** → **Field_Gradient** is expressed in 0.1nT



Polarization Cycle Version 2

7.3.3. Parameter Setup Mode pseudo-code

- Do forever
  - Display Main Menu and wait for entry selection
  - If **Clear_EEPROM** is selected then
    - Clear all EEPROM log list entries
    - Set **current_X** and **current_Y** = 0
  - Else
    - Wait for RS-232 Command from PC
    - If Command = EEPROM Upload then
      Send EEPROM Log list to RS232 line
    - Else if Command = Download System Parameters then
      Read System Parameters from RS232 Line and save them in EEPROM.

8. *Test Procedures*

8.1. Power Supply tests

- With a continuity tester, check that all the components of the boards with a GND connection are indeed connected to the ground plane. It could be that some small copper-side ground plane area are left isolated from the general ground plane. It is necessary to connect them to the component-side ground plane through vias. The vias are clearly visible on the component view of the PCB as SQUARE pads.
- Do not insert ANY chip in the DIL sockets. Do not connect the amplifier channel board. Feed the system with a 12V gel-cel battery or a lab power supply through a 100 ohms resistance and measure the current. It should be around 15mA at that point. If you see a much higher value, stop immediately the power and re-check your circuits.
- Measure the +5V on all the main control circuits, more specially at the DIL level of the active chips.
- Measure the +10V and +12V voltage at the level of the amplifier channel board connectors.
- Insert an amplifier channel and measure the current. It must now be around 20mA.
- Perform all the necessary positive voltage tests (+12V, +10V, +5V).
- Re-do the same with the second amplifier channel (if you have already built it).

8.2. Amplifier Channel tests

- Insert the chips IC1 and IC2.
- Power the system and check the current which should be slightly higher than before.
- Make a 100000/1 voltage attenuator (resistance bridge e.g. 1 Mohm/10 ohm)
- Connect the pre-amp to the low side of the bridge.
- Connect a **Spectrum Analyzer** adjusted to the audio band to the output of the pre-amp.
- Check level of noise with nominal input impedance only, it should be very low : **-90 dB**.
- Connect an **AF/FUNCTION Generator** to the high side of the bridge.
- Adjust the generator to a sine wave signal of around 100 mV RMS @ 2 kHz
- The output signal magnitude will give you the gain of the pre-amp. You should observe a **single, clean, narrow FFT peak @ 2 kHz with an height of x mV on the vertical scale**. The total gain would then be 1000 * x.
- The noise level should still be very low: max. **-80 dB**.
- You should now build at least one sensor to continue the tests.
- Remove the attenuator.
- Connect the sensor (**W/O any resonant circuit**).
- Wind a small auxiliary coil made of a few hundreds of turns of thin wire.
- Connect it to the AF/FUNCTION generator adjusted as a sine wave of 2 KHz
- Set the vertical scale of the spectrum analyzer to mV instead of dB
- Observe the amplitude of the FFT peak at the pre-amp output, adjust the amplitude of the generator and/or modify the position of the auxiliary coil to get a peak of 1 to 2 mV.
- The signal-to-noise ratio (SNR) should probably now be higher because the coil is now picking up external electromagnetic disturbances and low frequency radio electric waves. (At this stage, it could even be possible to hear some music). The noise level could now be around **-40 dB.**

8.3. Polarization tests

- Without connected sensor, feed each digital control line at U3 level (POL_CTL, SERIES, SQUELCH, QUENCH) with 5V and 0V and measure its consequences on the polarization circuit with a DMM.
- Do the same with a sensor and measure the polarization current when POL_CTL is ON.
- Due to the complexity of the polarization sequence, the following tests can only be performed with the help of a specific micro-controller-based test program.
- Connect a small manual switch from GND to pin 25 (RB4, TRIGGER) of U3. This will only be used for testing, it will be disconnected during the normal operations of the system.
- Load U3 with this polarization test program1. For each depression of the manual switch, this program executes a polarization cycle of 3 seconds (long enough for fluid = water) followed by a signal pick-up duration of 300 msec. Note that this test program does not calculate the frequency of the signal and does not display anything, actually the LCD and the KBD do not

need to be connected at this point. The signal should be picked-up at the level of test point TP1 and connected to the audio card of a PC loaded with the SpectrumLab program.

- Insert a single amplifier channel board.
- Test first the switching cycles of your circuit **without coil connected** by pressing once the manual switch for each polarization cycle you want to execute and check the voltage changes with a DMM.
- Then, put the coil in circuit and redo the test with measuring the DC current going through. It should normally be at least 1 Amp. If you have a digital scope, it's now the right time to check the quality of the switch ON and switch OFF voltage and current transitions. They should be as clean as possible to get the best results on the quality of the signal.
- You could now perform the most critical test procedures after making sure that you apply ALL the imperious test conditions described at chapter 5 of Practical Building Guidelines. For these tests, a 12V Gel-Cell battery is required to feed the system (no lab power supply, please)
- You should now **start a real polarization cycle** by pressing once the manual switch. At the end of this cycle, you should observe a **growing and quickly decreasing FFT peak at around your nominal precession frequency**. The water fall display option of the spectrum analyzer will show this very clearly.
- If you see it now, you have successfully executed most of the critical steps of the project. Use the spectrum Analyzer to record the signal into a WAV file and analyze it in more details using a WAV file editor.
- Now, if you do not see anything but noise on all frequency bands, you should first carefully double-check all the connecting circuits (and possibly redo the previous modular test steps) and verify that you have met ALL the imperious conditions.
- If you still do not see anything, there can be several possible reasons:
  - Check your battery, it could be that you do not get enough current out of it.
  - If you did not make a resonant coil, it could be that your total amplification gain is not enough. You could try to increase the gain or to make your coil resonant.
  - It could be that the location of your sensor happens to be disturbed by an hidden strong source of magnetic or electromagnetic noise. Move your sensor away to an other place which you feel safe and retry.
- Do the same with the second amplifier channel board.
- If you were successful up to here, I think you are in a very good shape in your project.

8.4. Main Control Board tests

- These tests will also be performed with the help of a specific micro-controller-based test program. The amplifier channel boards need not be inserted in their connectors at this time.
- Connect the Buzzer, the LCD and the KBD circuits to the main board.
- Insert IC3, U3, U4 and U8. (Note that U6 is not necessary)
- Make a preliminary power on cycle and check the current at the 12V level. Switch off the power.
- Connect a PC to the RS232 line and load any terminal emulator program (like Hyper-Terminal) set to 9600 bauds, 8 bit, W/O parity.
- Load U3 with this Main Board test program. It will execute the following test list.

1. You should already see the title of the test displayed on the LCD on all its 16 characters.
2. Testing the KBD→Each depression on one of its keys will display its symbol on the LCD and will make a short beep on the buzzer (U=Up, L=Left, D=Down, R=Right). Pressing the OK (Validation) key will end this test step and will generate a longer beep on the buzzer.
3. External EEPROM tests→
   a. Reads initial value of a few EEPROM addresses and display their values in Hexadecimal on the LCD.
   b. Writes values 0x55AA on a few EEPROM addresses, reads them back and display them on the LCD
4. RS232 tests→
   a. Sends a small text to the PC to be displayed on the terminal emulator screen.
   b. Wait for character input, Display input on LCD and will make a short beep on the buzzer.
   c. Terminates this test step when receiving Carriage Return character (0x0D). Makes a long beep on the buzzer.
5. The test procedure loops back at 1.

8.5. I2C Simulation tests

This procedure tests the communication link between each channel and the main control system. Initially, this link was designed as a common I2C RAM (PCF9570) located on the main control board but this design has been simplified by making a software-only communication procedure on the main control CPU (16F876).

- Load the signal analyzer U1 (12F675) on one channel with this I2C Master test program. (this test should be performed with a single channel at a time)
- Load the main control U3 (16F876) with this I2C Slave test program.
- Power ON the system
- The title of the test will first be displayed, then, a few seconds later, a full displayed line with the values: 3132333435363738 corresponding to the HEX values of the message transmitted from the channel CPU to the main CPU.
- Re-do the same procedure with the second channel.

8.6. Integration tests

8.6.1. Single Sensor Test

As soon as the previous tests have been successfully executed, it is now time to attempt a complete system test cycle. This test is still executed with a single channel and a single sensor with a permanent connection to a PC loaded with a terminal emulator program. The test program loaded on the main control system will trigger a polarization cycle every 2 seconds, trigger the measurement of the absolute magnetic field value in nT by the channel CPU, get the result and send it to the RS232 line in ASCII to be displayed by the terminal emulator on the PC. With a sensor positioned at a fixed location, the absolute field values will slowly change according to the diurnal variations.

- Load the signal analyzer U1 (12F675) on one channel with the Signal Analyzer program. (this test should be performed with a single channel at a time)
- Load the main control U3 (16F876) with this Integration test program.
- Connect a PC loaded with a terminal emulator program (9600 Bauds) to the RS232 line.
- Power ON the system
- The title of the test will first be displayed, then, a few seconds later, the magnetic field value will be displayed in nT every 2 seconds on the LCD and simultaneously sent and displayed on the PC.
- Re-do the same procedure with the second channel.

8.6.2. Double Sensor Test

Now, if you have built a second sensor, you could try the gradiometer configuration test. With the sensors separated by one or two meters and positioned at a fixed location, the field gradients will be displayed. Whatever their value, if there is no moving ferro-magnetic object around, it must be pretty much constant within the limits of the resolution of the instrument.

- Load the signal analyzer U1 (12F675) on the two channels with the Signal Analyzer program.
- Load the main control U3 (16F876) with this Gradiometer test program.
- Connect a PC loaded with a terminal emulator program (9600 Bauds) to the RS232 line.
- Power ON the system
- The title of the test will first be displayed, then, a few seconds later, gradient values will be displayed in nT every 2 seconds on the LCD and simultaneously sent and displayed on the PC.

9. Alternate System Configuration

The above description corresponds to a lightweight **stand-alone system configuration** designed to survey ground area with back-packing.
The surveying of water area on a boat gives the opportunity to use a different system configuration, a **PC-based remote-controlled system**.
In such a configuration, the **Main Control Module** does not need any external EEPROM, LCD, buzzer nor keyboard. The PC can remotely control all these tasks through the RS232 link and can optionally associate each gradient value with GPS coordinates captured from a GPS Device. The PC can then permanently store the survey results on disk and display the 3D graphical map in real time.

In this configuration, it is also possible to precisely evaluate the quality of the received signal in terms of S/N ratio by analyzing the amplified analogue output of each channel using Fast Fourier techniques. In case the signal is too weak or the noise is too high, the operator can be alarmed and the measurement can be attempted again.

The **Main Control Program** would have the following, simpler, pseudo-code:

- Set PICK_CTL = ON
- Do forever
  - Wait for PC_Command from the RS232 link
  - If Command is “Parameter_Setup” then
    - Get and store system parameters into the internal EEPROM
  - Else If Command is “Measure” then
    - Make a single measurement giving **Field_Gradient**
    - Send **Field_Gradient** to the RS232 link

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