Grounding

"Grounded" is an archaic electrical circuit term with a literal meaning; the circuit is connected to a metallic rod driven into the earth. The British expression "earthed" has the same meaning. The term became commonplace in the electrical power distribution and the radio/electronic fields at about the same time in history. I haven't researched the word Ben Franklin used to describe the connection of his lightning rods to the earth; perhaps the term is older than I think!

In the early days of radio, receiving and transmitting antenna systems required a good earth ground for best performance. A pipe driven into the ground was always connected to the chassis of the radio receiver or transmitter. At the same time, the people who designed receivers and transmitters used the chassis for a common connection of all the power supplies and signals within the radio set. The meaning was diluted when the electronics people began to use an earth ground symbol to denote connection to the chassis of an electronic assembly.

I have a couple of books on electronics published in the late 30's and early 40's, given to me by an uncle when I was about 10 years old. These books mark my introduction to electronics. I noted that radio antenna installations in automobiles referred to the automobile chassis as "ground" and schematics for some radio receivers used the earth ground symbol to refer to a common or chassis connection whether or not a true earth ground was needed for best performance.

Over the years the term "grounded" has acquired a variety of meanings in as many technologies. In some cases, it can have different meanings in the same technology. Some ambiguities were resolved with additional terms for ground such as "common, counterpoise, ground-plane, return and neutral." All have been used to impart a more precise meaning in specific instances. I will try to be both concise and properly descriptive when using the word "grounded." Figure 5-1 illustrates a variety of symbols used to indicate electrical connections to ground. I know of no other electrical entity which shares so many different symbols.

Grounds fall into three broad categories in aircraft. The first and most familiar is a carry-over from other vehicle systems and it refers to the metallic portion of the chassis and skin of the vehicle. The term is common to both the power distribution (first category) and antenna (second category) systems when working with a metal vehicle. The third category is a special type of ground which is unique to the internal workings of a particular black box or piece of equipment.

The need for an independent section in this publication on "grounds" is brought about largely by the evolution of composite aircraft but we'll see that grounding in a metal airplane isn't necessarily "a piece of cake" either. If the frame and skin of the vehicle are not conductors, then special requirements need to be placed on the various categories of grounds. Furthermore, they may or may not be related to each other. For example, in order to provide for a power distribution ground system, a combination of conductors must be installed to provide common connection for all of the equipment which normally works with an airframe ground in a metal airplane. Antenna grounds may (and in most cases should) be separate from a power distribution ground system. Wiring diagrams which appear in later chapters will make clear distinctions as to the nature and fabrication of any required ground.

In Figure 5-1, one of the ground symbols depicted is an open triangle with the conductor to be grounded attached in the center of one side. There are characters inside the triangle that I will use to identify exactly which ground is to be used

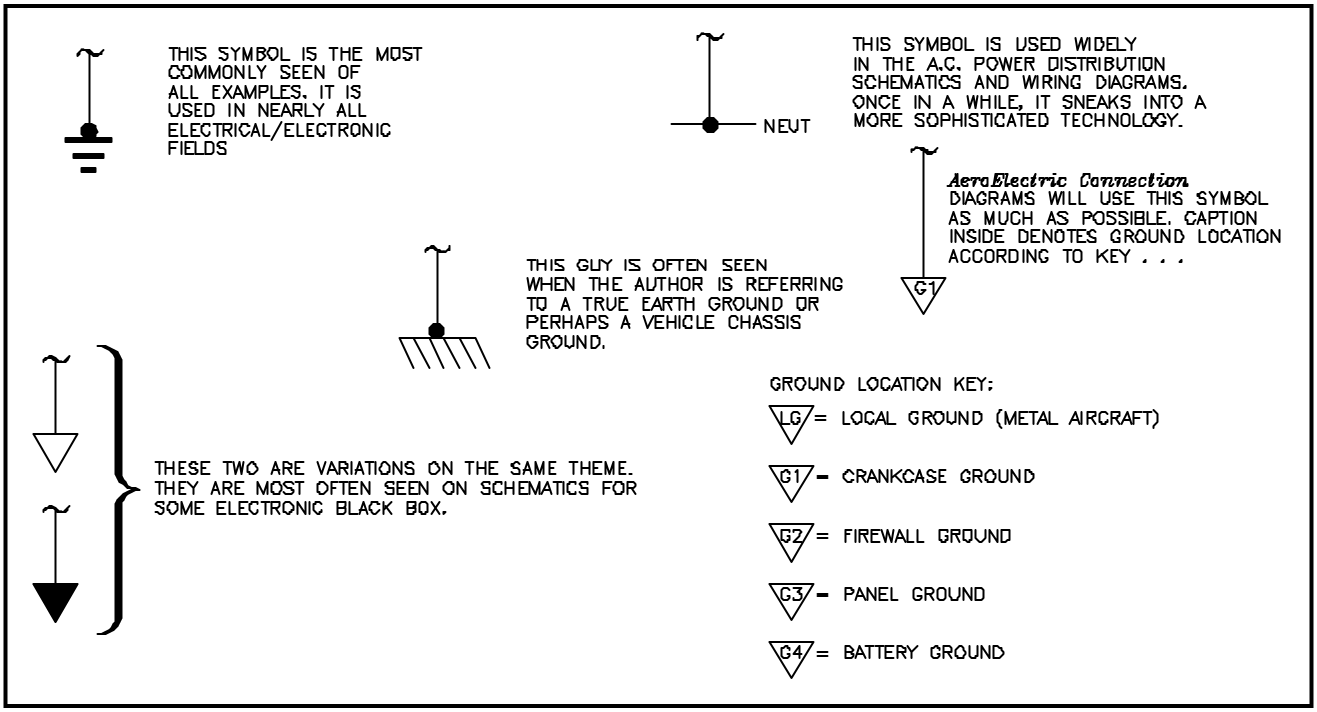

Figure 5-1. The Many Faces of a GroundSystem

for a particular conductor.

When it's important to make the distinction, labels within the ground symbol triangle will be tied to specific grounding locations within the airplane. For example, an engine crankcase is one specific location, a ground bus behind the instrument panel will certainly be another, and the battery may have a ground bus located adjacent to it. Every power distribution diagram, set of wiring diagrams or large illustration will have a list of symbols key and describe where they are located. In our drawings used throughout the book, we're trying to standardize on ground symbols by location as follows: G1 is crankcase, G2 is firewall, G3 is instrument panel, and LG is used to denote local ground to the airframe in metal airplane. If the triangle is empty, it means (1) the diagram is a simplified discussion of wiring where a ground is needed but not defined until a specific installation is determined or (2) a ground is needed for operation but its location in the system is non-critical. In writing, the term "ground" will usually refer to a power distribution ground except when we are discussing an antenna or installation of a particular piece of equipment with special grounding requirements.

Power distribution always requires a path out and back for electrical energy but in some diagrams it is not always clear as to the need for the ground. For example, a schematic or wiring diagram may show a single wire from switch to lamp fixture. If the diagram describes a metal airplane, the "ground" path is implied: power return is made by physically mounting the fixture to surrounding metal structure. If the draftsman takes the trouble to really finish the diagram, a ground symbol will be included right on the edge of the appliance's symbol to confirm suspicions as to how ground is to be supplied. In the case of special accessories, all of the connections required for the device to function may be carried on individual wires and the ground symbol may only connect to the enclosure of the device for radio noise shielding. Further, the amount of current which flows in the "ground" connection may not be known to you, which might further complicate the choice of how to treat the connection in a composite airplane. We cannot anticipate all of the cases here in this section and provide detailed coverage. You need to be aware of the possibilities.

WHEN IS A GOOD GROUND *NOT*?

Problems with poor conduction in high current paths (especially grounds) are most difficult to diagnose. Investigations into poor voltage regulation or starter performance always begin with conductors other than grounds. However, it's important to remember that for every electron that leaves the battery another electron has to return via the other terminal; the same currents that flow in the power distribution wiring also flow in ground return wiring or conductors.

Let's do an analysis on a hypothetical composite airplane where the battery is mounted about 6 feet from the engine. Let's assume the battery is a pretty good flooded (wet), lead-acid battery with an internal resistance of about 10 milliohms. Without welding it's difficult to make a joint between any two conductors that's better than 1.0 milliohms per joint. Consider 2AWG wire with a resistance of 0.156 milliohms per foot. Total length of "fat" wires in the cranking path will be about 15 feet. Therefore 15 x 0.156 = 2.34 milliohms resistance in the wire alone. How about the battery and starter contactors? Hmmmmm . . . two contacts each in series held closed by an energized electromagnet. Can't be better than 1 milliohm per contact so there's another 4 milliohms total. Add 'em up . . .

Cranking Path Resistance - how BAD is it?

Battery resistance	10.0 milliohms
2 Contactors	4.0 milliohms
15' of 2AWG wire	2.3 milliohms
Bolted Joints (4 wire segments with 2 joints at 0.5 milliohms each)	8.0 milliohms
Total resistance	24.3 milliohms

24 thousandths of an ohm? ? ? ? It is difficult to imagine how so tiny a resistance can make a difference but consider that for all but the smallest engines, a starter may easily draw over 200 amps! Ohm's Law says that for every ampere of current pushed through 1 ohm of resistance, there will be 1 volt of drop across the resistor or volts = amps x ohms. 24.3 milliohms times 200 amps equal 4860 millivolts or 4.86 volts of drop. If we started with a 12.5 volt battery, we'll now see about 12.5 minus 4.86 or 7.5 volts at the starter terminals. We've lost about 1/3 of our cranking energy in the trip from battery to motor! On a cold morning, the engine is stiffer and battery resistance goes up. Just when the engine would like to have more cranking energy, the battery's ability to deliver it goes down.

Purists among you may take issue with some of the numbers I've used. To be sure, a little care in selection and assembly of parts can reduce the resistance numbers somewhat. The point is that resistance of wire, contactors and battery are built in: we have no control over them and they are never zero. Also note that bolted joints make up a significant percentage of total drop. Even minimizing wire length has a rather small effect compared to reduction in number of bolted joints. Some of the worst performing cranking circuits are found on metal airplanes where the battery is bonded locally to airframe. Engine is bonded to mount by jumpers around the vibration isolators and the mount is "grounded" to airframe through its mounting bolts.

If I had my fondest wish for ultimate performance in an aircraft electrical system, the battery, starter and alternator would all be within 1 foot of each other! Interestingly enough, Van's RV series airplanes come closer to that goal than most kitplanes. RV batteries are on firewall centerline with starter and alternator just an engine length away. Further, many single-engine Cessnas have the battery on the firewall just inches from starter and alternator on the rear of the engine.

In a grounding figure back in Appendix Z I've illustrated the most important wires in the airplane. The first wire I install is from battery minus to firewall ground stud. A braided bonding jumper goes from this bolt to the crankcase. For canard-pushers with forward batteries, an instrument panel ground bus is wired to battery minus in the nose. Ground points for stuff in the rear are provided with a second ground bus mounted on the firewall and wired to the crankcase just like a tractor airplane. This grounding architecture optimizes engine cranking performance and minimizes ground loop problems which may degrade voltage regulation, cause noises in an audio system or radio and affect the accuracy or stability of engine instruments. This mechanically simple system is the antithesis of a system installed in a Long-Eze by one of my readers: because his airplane was plastic and glass, he wanted, "plenty of places to attach wires to a good ground." A wire came forward from his crankcase and bolted to one end of a brass strip over the spar. The strip was drilled and tapped for 8-32 screws which he thought handy for making local grounds. Each end of the strip was drilled for a 5/16" bolt to which a ground wire was attached. This ground strip was repeated at the panel and AGAIN near the battery. From battery post to engine crankcase he had fabricated a bus conductor with 8 soldered and 8 bolted joints! To top it off, he used 4AWG wire as the ground conductor and steel hardware for bolting it all together. The cranking performance was abysmal!

While we're discussing ground system fabrication . . . if the battery and engine are on opposite ends of a composite airplane it's important to run battery (+) and (-) cables right next to each other as they traverse the cockpit and instrument panel areas. Tie-wrap them together every 6 inches or so. I've seen several kit manuals suggest that a couple of studs on a firewall are sufficient for termination of all system grounds. The problem with this is that all ground wires behind the panel have to come through the firewall to be stacked on the few ground studs. This is poor practice. A single stud is responsible for many grounds . . . a broken bolt or loose nut causes problems in multiple systems. The ground bus I've illustrated is a special product I designed and asked B&C Specialty Products [1] to manufacture. Forty eight, .25" wide, Fast-On-on tabs are sweat soldered to a piece of sheet brass about 1.5" wide and 6" long. A 5/16" stud is soldered to one end. There are enough ground points to give each system all the structurally independent grounds it needs without having to share. I highly recommend its use.

There's an interesting fallout of this architecture. A few years ago we ran an airport for a short time. One of our mechanics was reinstalling an engine that had been removed for overhaul. After hooking up everything he could find that was loose, he crawled into the left seat, primed the engine and hit the starter. The propeller didn't move and a cloud of smoke poured out from behind the panel! Seems that everything got replaced EXCEPT a ground strap from crankcase to firewall. The starter tried to find a ground through shields on the p-leads along with throttle and mixture controls jackets which caused them to get very hot, very quickly! Grounding the battery directly to crankcase eliminates this possibility.

Minimizing high-current path resistances has another benefit: many airplane designs don't need a lot of battery capacity but some builders find that a larger battery (lower internal resistance) improves cranking performance. A number of single-engine Pipers have 35 ampere-hour batteries in the tail: they didn't need the extra capacity, but the lower internal resistance improved cold weather cranking operations. One of my consulting clients holds STCs for replacing the 35 ampere-hour batteries with a 25 ampere-hour, recombinant gas battery. The new battery has a 5 milliohm internal resistance and weighs 22.5 pounds. Cranking performance is greatly improved in spite of the new battery's smaller and lighter package.

METAL AIRFRAME GROUNDING

Ground connections on a metal airplane are relatively simple but some cautions should be observed. First, clean all of the paint, primer and corrosion from around the hole which is used to ground a connection. A round wire brush with a pilot in the center is called a "bonding brush." It is designed to be used in a drill motor for this type of cleaning. Grounds for heavy current flows such as for the negative lead of the battery or the grounding strap between an engine and airframe should connect to the heaviest structure available; avoid making these connections to thin sheet metal even if "heavier structure" is several feet away and you would rather not have the extra weight of the wire! Antennas may require grounding not just around mounting screws but to the total area of metal under the antenna base. Read installation instructions carefully and if you are still not sure, then check with the manufacturer directly.

COMPOSITE AIRFRAME POWER GROUND SYSTEM

In the composite airplane a builder must provide for a "common" conductor or power distribution ground which is missing because the airframe structure and skin are made of epoxy and non-conducting fibers. In a conventional tractor design the task is somewhat simpler than with the canard pusher; the major power sources, controls and loads are more concentrated in the front of the airframe. Many canard pusher designs mount the major source (alternator) along with the major power load (starter) at one end of the airframe with the battery as far away as possible on the other end with the controls and loads being scattered along in between!

FIREWALL / INSTRUMENT PANEL GROUND

Earlier I wrote about the 24 and 48-point, Fast-On tab ground bus offered by B&C and from our website catalog. These products offer a means for creation of a low noise, single point ground for all the equipment located on an instrument panel. For tractor airplanes, two such ground busses may be used back to back on the firewall to provide high quality grounding for equipment on both sides of the cowl. The technique simply calls for bolting two ground busses back to back using a single brass bolt to provide solid electrical connection between the ground busses AND a sturdy attach point for the crankcase to firewall bond strap or wire on the engine side. Battery minus lead needs to go to the same bolt on either side of the firewall depending on where the battery is located.

A word of caution when bolting the two busses back to back through a composite firewall. Don't depend on any intermediate composite material to maintain ground stud tension. In Figure 5-2 I've shown a brass bushing or stack

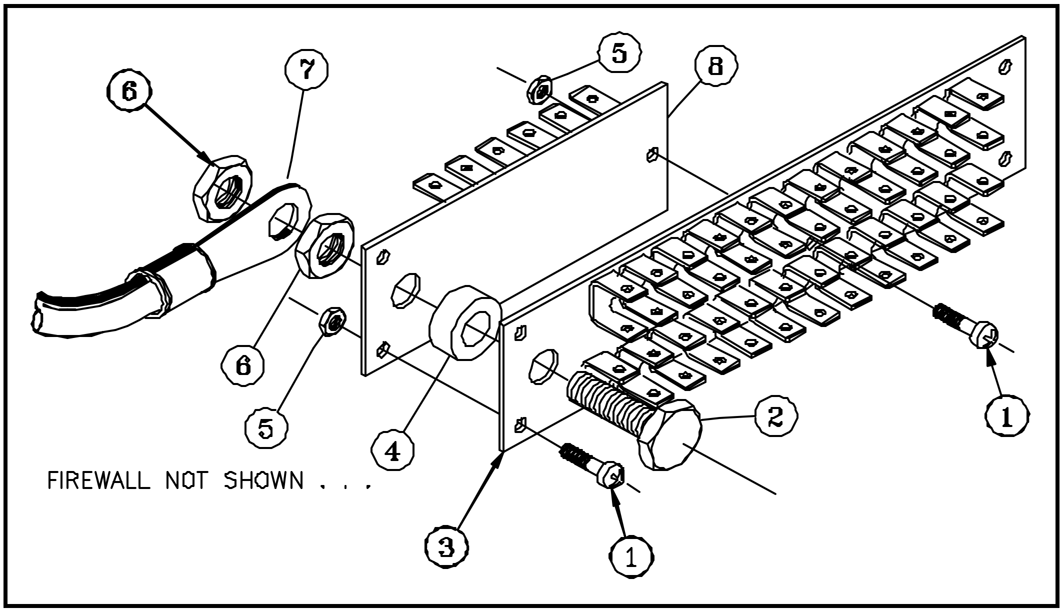

Figure 5-2. Forest of Fast-On Tabs Firewall Groundblock.

of brass washers (Item 4) with a 5/16" i.d., a 3/4" o.d. and a length equal to the nominal thickness of the firewall. First, a 5/16" hole is drilled all the way through the firewall. Next, from the cockpit side, a 3/4" hole is spotfaced down to the surface of the firewall sheetmetal. Make temporary installation of the small ground bus (8) on the firewall using bolt (2), bushing or spacing washers (4) and one nut (6). Use ground bus (8) as a drill guide to make three #18 holes all the way through. Remove ground bus and reinstall all hardware with large ground bus (3) inside, bushing (4) in firewall, small ground bus (8) under cowl. Hold all this stuff in place with three screws (1) and nuts (5). Small hardware is for anti-rotation only; don't put a lot of torque on these fasteners-- just snug 'em up.

Install bolt (2) with first nut (6). Torque this feller down good. The remaining nut (6) is used to install a firewall to crankcase bond strap or wire (7).

Except for rare special grounding cases, everything in the airplane will ground to one side or the other of this system. This single-point system of grounding will provide the most trouble free, electrically quiet installation possible.

HOW GOOD IS IT?

Measuring the quality of any low resistance conductor paths would appear to be difficult. After all, not even Radio Shack sells ohmmeters that read out in fractions of milliohms . . . at least not that they would know about! A few years ago I was investigating an accident where electrical conductivity was in question: measurements in the milliohm range were called for. I visited a local Radio Shack and bought two digital multimeters. One needed to be capable of reading current on the order of 5 to 10 amperes. The other was for reading millivolts; hopefully to the nearest 0.1 millivolt. I also purchased a D-size alkaline cell, some 18 gauge lamp cord, test probes and banana plugs. The man behind the counter loaned me a soldering iron and I built the rig shown in Figure 5-3, Poor-Man's 4-Wire Milliohmmeter.

Touching the two probes together places a dead short in the D-cell . . . well, almost a dead short. Obviously, the cell has an internal impedance which limits the current that a shorted cell will deliver. The wire between cell and probes has some resistance too. As it turns out, when the two probes are touched together, multimeter M1 indicates about 6 amps. Now, observe that the other multimeter is set up to measure the voltage between the two probes through a path that is independent of the D-cell current path. The operative feature here is that no voltage drop will occur along the voltage sense leads and multimeter M2 will read the voltage between the two probes irrespective of the voltage dropped along the D-cell current path.

> Note:
> You might be tempted to build this tool using a spring clip type battery holder for the D-cell . . . because of the large current that flows while taking a measurement, spring loaded holders are inadequate to the task. Solder wires right to the cell.

The leadwires in this case had to be long enough to reach from battery in tailcone to crankcase. Obviously, the measurement requires two people as well. When I pushed one probe down very firmly on the battery minus terminal bolt while probing the crankcase with the other, a current on the order of 6 amps flowed in the ground path between battery minus and crankcase. Let's assume the M1 reads 5.8 amps voltmeter reads 30.6 millivolts. Ohms law sez ohms = volts/amps so .0306/6 = .0051 or 5.1 milliohms. Hmmmmm . . . 200 amps through this path will drop 1.2 volts . . . . not great but probably typical.

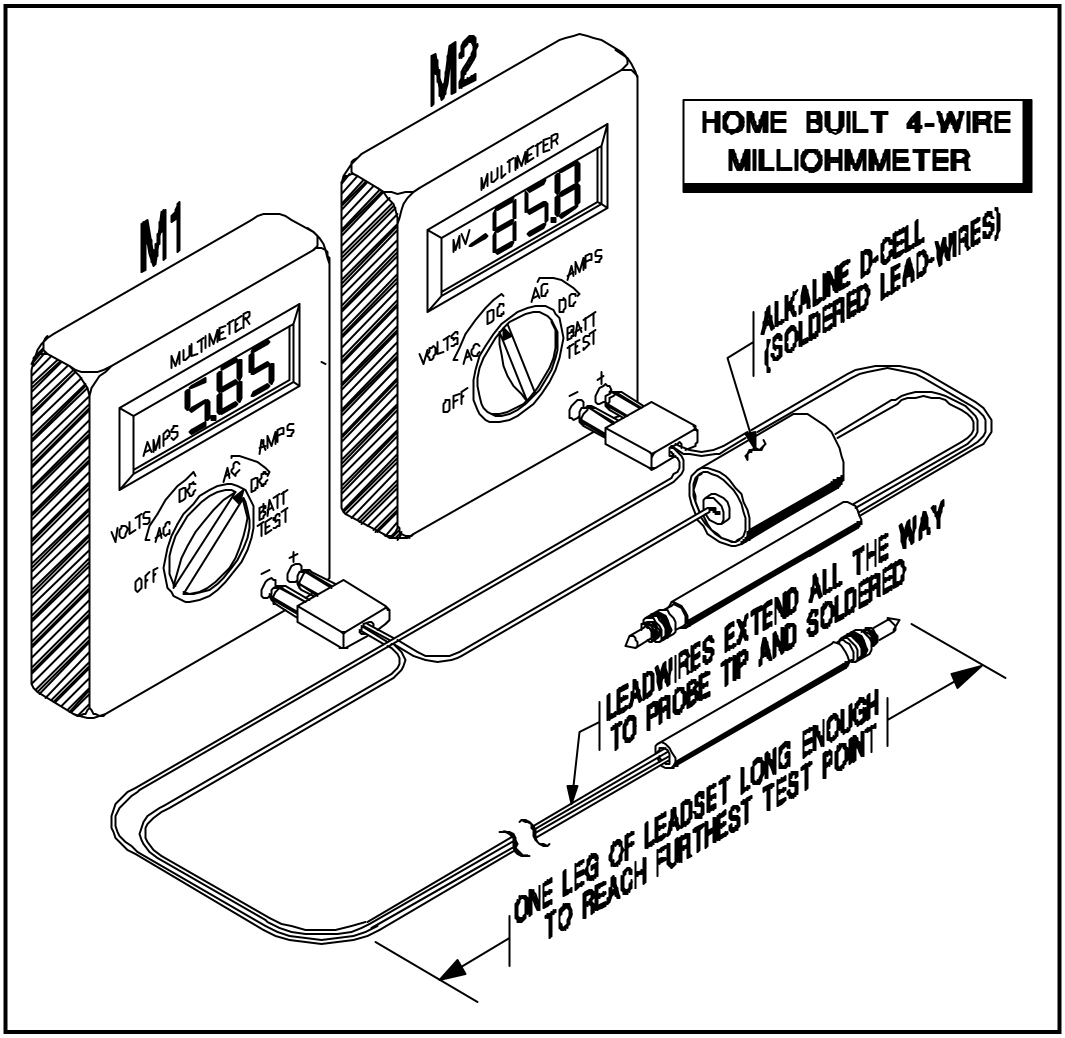

Figure 5-3. Poor Man's 4-Wire Milliohmeter.

Yeah . . . I know. There are some pretty nifty clamp-on type ammeters for DC current. Why not just measure starter current and the voltage drop while cranking? Several reasons. First, starter current is anything but steady. Compression strokes cause it to oscillate in a manner that prevent good readings from a digital instrument. For the same reason, voltage-drop readings jump around in sympathy with current fluctuations. Second, and most importantly, I don't like working around swinging propellers even if the plugs ARE disconnected. I was there to investigate an accident, not participate in one! A third reason was that this airplane was all wrapped up in a wad of aluminum, the prop was bent and the battery was dead. An independently excited measurement system was indicated.

The same measurement can be applied to components of the positive power path as well. Remember, we're measuring the resistance of wire plus bolted and crimped joints. When measuring the resistance of the lead between battery contactor and the starter contactor, probe the bolt ends on each contactor. Obviously, this same test fixture can be used to check path resistance on any other circuit on the airplane and produce results with great integrity. FBOs will often have the instruments necessary to set up this fixture but not one in a hundred knows how to do it, how it is used or what the readings mean. The 4-wire ohmmeter is a standard inspection and diagnostic aid in my toolbox. Elsewhere in this work, I'll discuss techniques for using the 4-wire ohmmeter tool to track down the elusive, "jittery ammeter" syndrome.

GROUND LOOPS

A recurring problem experienced by our readers is the complaint that engine gages on a composite, canard pusher shift reading in response to changing electrical loads or when turning the alternator on and off. Another common "noise" complaint is strong alternator whine in the headsets . . . sometimes when radios and intercom are OFF! Both of

these phenomenon are commonly driven by what are called ground loops.
Ground loops are pretty simple and occur only when two components of the same system (victim) are grounded in different places in the airplane. In Chapter 8, I discussed the fact that wire--no matter how big it is--can never have zero resistance. In preceding paragraphs of this chapter, I discussed the 4-wire ohmmeter as a practical means for quantifying very low resistance values and their effects on starter system performance. Starters are not the only potential victims of voltage drops around what one usually considers to be a very low resistance, ground conductor path.

Consider that engine instrumentation measures small changes in voltage on a variety of sensors exposed to phenomenon of interest such as temperature, pressure, etc. Let us suppose that an engine-mounted, oil pressure transducer has a resistance variation of 100 to 500 ohms over the range of 0 to 100 psi on the panel-mounted indicator. Let us further suppose that the indicator system biases the sensor with 10 milliamperes of current. The voltage change across the sensor will be (500-100) x (0.01) = 4 volts for 0 to 100 psi or 25 pounds per square inch per volt. Consider a Vari-Ez with alternator but no starter, an oil pressure sensor grounded to crankcase and an indicator grounded to nose mounted battery, and 15 feet of 10AWG used to connect the crankcase to battery minus. Yes, 10AWG is too small for engine cranking but not too small for a 30 amp alternator. 10AWG wire has a resistance of 1.0 milliohm per foot.

If the alternator is putting out 20 amps of current to power systems and recharge the battery, the voltage drop in a #10 ground wire between crankcase and battery will be on the order of 0.2 volts. This voltage appears to the oil pressure indicator as an ADDITIONAL oil pressure of 5 psi. Turning the alternator on and off will produce a 5 psiwiggle in the oil pressure gage when in fact, oil pressure is stable.

In the case of headset grounds consider this: alternators are three-phase ac devices with full-wave, bridge-rectifiers having an unfiltered ripple equal to 5% of system voltage. On a 14 volt system, ripple voltage will be on the order of (14 x 0.05) equals 0.7 volts peak-to-peak. This same ripple applies to output current so if the alternator were loaded to 20 amps, (20 x 0.05) equals 1.0 amps, peak-to-peak. Let's assume an RV4 as the hypothetical airplane with front and rear-seat headset and microphone jacks in both seat locations. The audio signal voltages associated with both microphone and headphones are on the order of tens of millivolts. If the 1 amp of ripple we just described is flowing through airframe resistances of as little as 5 milliohms, an alternator ripple noise of up to 5 millivolts can appear between two separate places on the airframe. Depending on where the headset brackets are riveted to structure, the 5 millivolts of ground loop noise may appear in series with a headset or microphone audio and produce audible interference in the headsets or your transmitted signal.

In metal airplanes, headset and microphone jacks should be mounted on insulating panels or insulated from metal panels by the use of fiber shoulder washers. We supply extruded fiber washers from our website catalog for the specific purpose of insulating headset and microphone jacks from local airframe ground. Microphones and headsets should take their low-side audio connections on shields or separate wires all the way back to where the interphone, audio distribution amplifier and/or radios are grounded . . . usually right behind the panel. This is one reason why I recommend the B&C forest-of-Fast-On-tabs for grounding all instrument panel mounted equipment. Single point grounds are, by definition, loop-free.

ANTENNA GROUNDING

This topic is covered in detail in Chapter 13. Suffice it to say for now that antenna grounds have nothing to do with grounds for any other systems. The manner in which an antenna seeks a "ground reference" is dependent on the antenna design, frequency of operation and whether or not the airplane is metal skin or Fiberglass.