Contents

Chapter 14

Telemetry and Navigation

This brand-new chapter in the *ARRL Handbook* was created in support of a relatively new chapter in Amateur Radio — the increasing use of amateur communication as a key element of scientific experimentation. This initial foray into the use of amateur means to collect and track data focuses on high-altitude balloons which are the most popular platform used for this purpose today. Future editions will expand coverage to additional technologies, platforms and applications.

Material in this edition was contributed by Paul Verhage, KD4STH — who contributed material on remote sensing and navigation data — and Bill Brown, WB8ELK, who contributed material on payload design.

Chapter 14 — CD-ROM Content

Supplemental Articles

- "A Simple Sensor Package for High Altitude Ballooning" by John Post, KA5GSQ
- "APRS Unveiled" by Bob Simmons, WB6EYV
- "APRS with a Smartphone" by Pat Cain, KØPC
- "ARRL Education and Technology Program Space/Sea Buoy" by Mark Spencer, WA8SME

Support of scientific experimentation is hardly a new aspect of Amateur Radio — amateurs have supported science almost since the beginning when Tom Mix, 1TS, accompanied the explorer MacMillan to the Arctic aboard the *Bowdoin* in 1923. Even more directly, in 1912 the Radio Act exiled amateurs to the "useless" wavelengths above 200 meters and amateur experimenters rapidly discovered their utility for worldwide communication. The story continued with Grote Reber, W9GFZ, and radio astronomy in the 1930s, broad participation by hams during the International Geophysical Year of 1957-1958, wildlife tracking, propagation reporting, satellite construction, and numerous other instances.

In recent years we have heard more and more frequently of balloons and radio-controlled craft using Amateur Radio for their data links and control signals, even as they cross continents and entire oceans! Other platforms are land-based (such as weather stations or animal tracking) or marine (ocean or river measurement buoys). CubeSats (**www.cubesat.org**) also use Amateur Radio control and data links. Building these platforms combines several technical fields: using sensors and data acquisition systems to measure events and phenomena, mechanical and electrical engineering to construct the platform, 3-dimensional navigation, and the data link and associated radio technologies. These hybrids are attracting the experimentalists and scientists to Amateur Radio, just as they were attracted at the dawn of the wireless age.

This chapter is organized in three parts: sensors, telemetry and navigation, and platform design. In recognition of the rapid innovation in these activities, this chapter will change and expand in the coming editions. Expect to see new digital protocols and miniature telemetry and audio-image transmitters. Improvements will be forthcoming in portable-mobile power sources and antennas. The chapter will report on the engineering necessary to assemble an effective platform. There is no doubt that fulfillment of FCC Part 97.1 is thriving as hams continue to "improve the radio art" by adapting technology to new uses.

14.1 Sensors

The advent of inexpensive microcontrollers combined with Amateur Radio creates opportunities for the amateur to perform experiments in environments that are otherwise inaccessible for one reason or another. Many interesting regions of the Earth, including extremely high altitudes in the atmosphere, fall into this category. Hams can be instrumental in helping amateurs and professionals explore these environments.

The development of GPS receivers and their application in APRS has made it practical to collect data in the near-space environment. Terrestrial and marine data measurement stations and buoys, traditional weather stations, other sensors, and event logging are also being deployed. This section on sensors addresses the "front end" of remote sensing. These sources of data are analogous to the speech and video circuits of traditional amateur transmitters. The same care in their design is required if quality results are to be obtained.

These platforms are enabling *remote sensing* — observing or measuring an object or event without actually being in contact with the condition being measured. Data from the measurement is then stored on the platform for eventual collection after recovery, or transmitted to a ground station for recording and analysis (telemetry). Examples of parameters that are measured by amateur remote sensing platforms include temperature, pressure (air and water/fluid), humidity, ozone and other gasses, acceleration and light.

The first step is to select the appropriate sensor or sensors for the parameter of interest and a means of converting sensor outputs to digital data, usually by connecting the outputs to a microcontroller. A sensor is a device that detects a specific condition of interest, such as temperature or pressure, and produces a predictable output in response. This section divides sensors into the following four types of outputs; *resistance-based, current-based, voltage-based,* and *digital*.

Four common types of outputs produced by sensors are discussed here. Not all of these outputs are directly useful to a microcontroller. However, methods exist to convert the output of these sensors into a form that can be interfaced to a microcontroller. Many microcontrollers have analog-to-digital converters built in that can digitize the data directly. (See the Analog/Digital Conversion section of the **Analog Basics** chapter.)

14.1.1 Resistance-Based Sensors

Resistance-based sensors change an internal resistance in response to the environmental variable they measure. An example includes the photocell, which is constructed of the chemical cadmium sulfide (CdS), a semiconductor that produces electrons and holes when irradiated by light. The production of free electrons and holes reduces the resistance of CdS when it is exposed to light.

In many cases, the change in resistance in response to changes in the measured condition is small. Therefore, sensor manufacturers often incorporate additional circuitry with the sensing element to convert this changing resistance into a more easily measured change in voltage. However, resistive-type sensors are still available and quite useable.

Resistance-based sensors do not create a signal that a microcontroller can measure directly. Instead, the resistance of the sensor is used to vary the voltage from a voltage source. A simple and popular circuit capable of converting a changing resistance into a changing voltage is the voltage divider as described in the **Analog Basics** chapter.

The voltage divider circuit of two resistors as shown in **Fig 14.1**. One resistor is fixed in resistance (R_F) and the other is the sensor and therefore variable in resistance (R_V). The current through the voltage divider circuit is variable. It increases as the resistance of the variable sensing element decreases and vice versa. However, the sum of the two voltage drops is always equal to the supply voltage. The preferred arrangement of the two resistors depends on the response of the sensing resistor to the condition to which it responds — temperature, humidity, illumination, and so on.

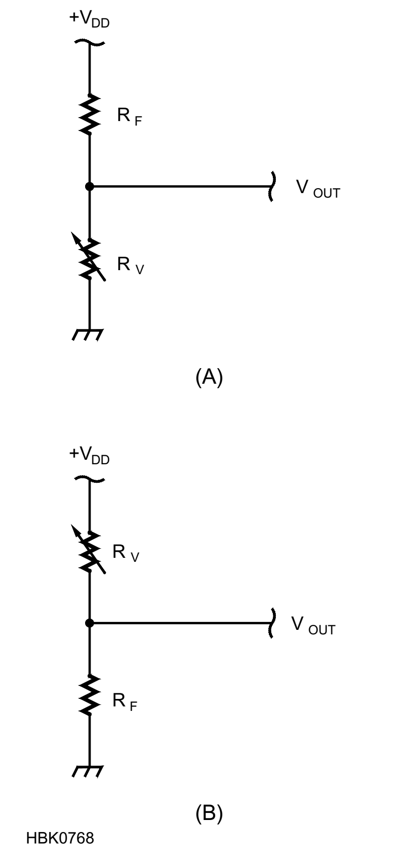

Fig 14.1 — The voltage divider circuit, a series circuit of two resistors. The orientation of resistors in A is preferable when the sensing resistor increases resistance in response to an increasing condition. Use B when the sensing resistor decreases resistance in response to an increasing condition. This results in the output voltage increasing with the increasing condition.

A microcontroller connected to the voltage divider circuit digitizes the voltage across the resistor connected to ground. This permits the design of resistance-based sensors into circuits that produce changing voltages which follow the change in the condition. For example, the resistance of photocells decreases as the light intensity increases. A microcontroller digitizing the voltage across a photocell connected as R_V in Fig 14.1A will observe V_{OUT} *increasing* as light intensity *decreases*. If however, the photocell is connected as R_V in Fig 14.1B, V_{OUT} *increases* as the light intensity *increases*. The latter case is easier to understand and work with than having output voltage and the sensed condition varying in opposite directions.

There are two equations that describe the output of the voltage divider circuit. The first describes the voltage drop across the variable resistor and the second describes the voltage drop across the fixed resistor.

For Fig 14.1A:

$$V_{OUT} = +V\ (R_V/(R_F + R_V))$$

For Fig 14.1B:

$$V_{OUT} = +V\ (R_F/(R_F + R_V))$$

OPTIMIZING R_F

The equations above show that the value selected for R_F has a large impact on the range of output voltages created by the voltage divider circuit. The precision of the sensor output is greatest when the voltage range of V_{OUT} is maximized. The value of R_F that generates the maximum range is the geometric mean of the sensor's highest expected resistance (R_H) and lowest expected resistance (R_L). The equation for calculating the best fixed resistor value (R_F) in a voltage divider circuit is shown below.

$$\text{Optimum } R_F = \sqrt{R_L \times R_H}$$

The maximum range for V_{OUT} of the voltage divider circuit is thus equal to ⅓ of the supply voltage, V_{DD}. Furthermore, the voltage range is centered at the midpoint of the supply voltage. The following three equations calculate the minimum voltage, maximum voltage, and voltage range of an optimized voltage divider.

$$V_{MIN} = V_{DD}/3$$

$$V_{MAX} = 2V_{DD}/3$$

$$\text{Range} = V_{MIN} - V_{MAX} = V_{DD}/3$$

14.1.2 Current-Based Sensors

Some types of sensors generate or change output current in response to the environmental condition they are measuring. Examples include the photodiode, solar cell and light-emitting diode (LED). All three of these devices are similar, although not used in similar ways. When a photon of light is absorbed, its energy gives an electron enough energy to jump across the PN junction inside the device. The electron creates a measurable current from the sensor.

The LED is one of the most surprising current-based sensors. While the photodiode is sensitive to a wide range of frequencies, the LED is most sensitive to light at the wavelength it emits when forward biased. This makes the LED a very inexpensive spectrally sensitive photometer.

A current-based sensor can provide useful data when connected to a digital multimeter (DMM) set to measure milliamps of current. However, this is not a suitable configuration for a microcontroller with the capability to digitize voltage. Therefore, it is necessary to find a way to convert changing current into a changing voltage. Two popular ways to accomplish this are to use a transimpedance amplifier or by measuring the charging time of a capacitor.

THE TRANSIMPEDANCE AMPLIFIER

The transimpedance amplifier in **Fig 14.2** is a popular op amp circuit that converts input current into an output voltage.

The feedback resistor, R, sets the gain of the transimpedance amplifier. The output voltage is given by the following equation:

$$V_{OUT} = I_{IN} \times R$$

The capacitor, C, reduces gain at high frequencies above 1/RC, acting as a low-pass filter to reduce noise. A generally useful value is 220 pF with the usual values of R for LED light-sensing. You will have to take the bandwidth of your measurement into account when choosing the value of C.

It is important that the value selected for the feedback resistor does not attempt to drive the amplifier output greater than the supply voltage. It is critical that the output voltage not exceed the maximum output voltage that the amplifier is capable of producing. In those circumstances, data is lost when the sensor output is too high and the amplifier saturates.

USING CAPACITOR CHARGE TIME

A second method to digitize the current from a sensor is to measure the length of time required for a current to charge or discharge a capacitor to a certain voltage. One example can be found in the book *Earth Measurements* by Parallax (**www.parallax.com**, manufacturer of the BASIC Stamp microcontrollers). Here, the BASIC Stamp is used to charge a capacitor. Then the Stamp measures the length of time required for the capacitor to discharge to ground through a resistor. The capacitor and resistor values are selected according to the expected current output of the sensor. The book uses the circuit in **Fig 14.3** to measure the current output of a photodiode or LED.

The program shown in **Table 14.1** (*Earth Measurements*, Program 4.2) was written to use the schematic in Fig 14.3. It assumes the circuit connects to the BASIC Stamp via I/O pin 6. Change the I/O reference to another pin as needed by your circuit.

The program reports the light intensity once per second. It begins by charging the capacitor to the same potential as the supply voltage through the use of the HIGH 6 command. Afterward, the reverse current emitted by the LED, due to its exposure to light, discharges the capacitor. The changing potential of the capacitor makes the voltage drop across the LED appear to decrease from its start at +5 V. Any voltage above 1.4 V is treated as a logic high by the BASIC Stamp. Therefore, as reverse current from the LED brings the capacitor voltage lower, the voltage across the LED eventually becomes lower than 1.4 V and a logic low.

The RCTime command counts the time (in units of 2 µs) required for I/O pin 6 to change from a logic high (above 1.4 V) to a logic low (below 1.4 V). The result in units of 2 µs is stored in the variable RCT. The greater the intensity of the light shining on the LED, the faster the capacitor discharges and the smaller the value stored in the variable RCT. The value in RCT is then divided into 65535 to invert the relationship and then stored in the variable Light which then contains a value directly proportional to light intensity.

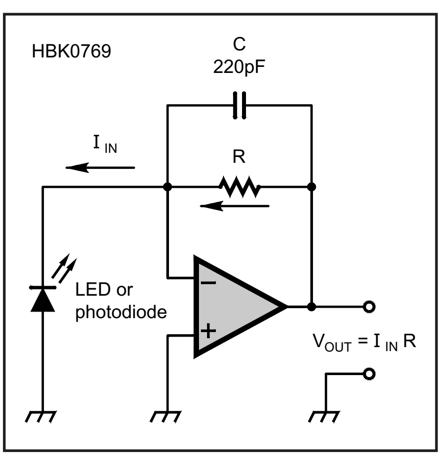

Fig 14.2 — The transimpedance amplifier converts current at its input to voltage at the output by balancing current through R with the input current.

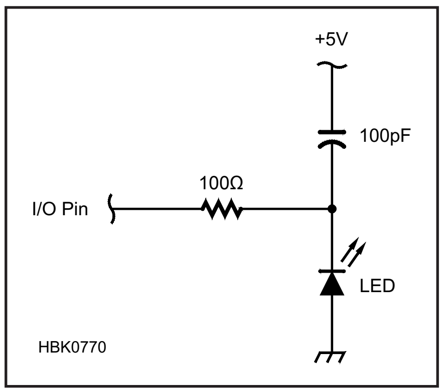

Fig 14.3 — The circuit recommended by Parallax for digitizing the current output of a photodiode or LED. See text for more information about using this circuit for current measurement.

Table 14.1
BASIC Stamp Program

This BASIC Stamp program is used with the circuit of Fig 14.3 for measuring light intensity.

```
RCT VAR Word
Light VAR Word
HIGH 6

Loop:
      RCTIME 6,1,RCT
      HIGH 6
      Light = 65535/RCT
      DEBUG "Light
Intensity: ", DEC Light
      PAUSE 1000
      GOTO Loop
```

14.1.3 Voltage-Based Sensors

Some types of sensors change their voltage output in response to the condition they are measuring. Examples include the LM355 temperature sensor, Honeywell's HIH-4000 relative humidity sensor, and Silicon MicroStructures' line of pressure sensors. These devices are typically current or resistance-based sensors along with circuitry to amplify and condition the output into a useable voltage change.

The voltage-based sensors easiest to interface are those that include signal amplification and correction on the chip. The result can be a ratiometric output that is linear and proportional to the supply voltage. The conversion factor for the sensor needed to convert its voltage into the environmental condition being measured is documented in the device's datasheet.

Pressure sensors can be used as altitude sensors for an airborne platform if a digital solution, such as GPS, is not available. Absolute pressure is preferred although it must be calibrated against ground barometric pressure before launch and, if the flight covers long distance, requires additional corrections based on local pressure data.

14.1.4 Capacitance-Based Sensors

Capacitance-based sensors use changes in capacitance as their primary means of measurement. Capacitance between two electrodes of known area depends on the distance between the electrodes and the dielectric constant of the insulating material separating them. Any process that changes either separation or dielectric constant can be then be sensed as a change in the capacitance. Parameters that are sensed in this manner include motion, moisture, fluid and material level, chemical composition and acceleration.

Sensors based on capacitance are rarely supplied without signal conditioning and linearization. Many have digital outputs that supply the measurement as a digital value. Another option is to have the sensor's capacitance control the frequency of an oscillator which can then be read by a digital circuit. For more information on capacitive sensing, the excellent overview at **www.capsense.com/capsense-wp.pdf** is recommended.

14.1.5 Sensor Calibration

Sensors come in two basic configurations: *sensing elements* and *conditioned sensors*. The voltage divider discussed earlier is an example of a sensing element. There are no electronics associated with the divider — the package contains only the two resistors and the necessary connecting wires or terminals. Conditioned sensors contain electronic circuitry that operates on the signal from the sensing element before it is made available externally. The circuits usually regulate power applied to the sensor and also *linearize* the data so that a linear range of measurements are represented by a linear change in output voltage.

All sensing elements and some conditioned sensors require a calibration equation to convert the output signal into the parameter value the sensor is measuring. In some cases, the equation is simple and linear as in the LM335 temperature sensor. In other cases, the equation may be complicated, such as for the thermistor and photocell when used in a voltage divider circuit.

It is important to understand the range over which a sensor will be measuring a condition before attempting to calibrate it. The calibration equation is usually more accurate when based on the interpolation of measurements than when based on the extrapolation of measurements. There are exceptions to this rule. For example, the calibration equations of linear sensors can be just as accurate when extrapolated, as long as the maximum operating conditions of the sensor are not exceeded. Otherwise, is it best to expose the sensor to the entire range of expected environmental conditions while collecting measurements of its output to create the calibration equation.

The ham can easily create some of these conditions, such as temperature, on the bench top. High temperatures can be created with the use of heat lamps and low temperatures created with the use of dry ice packed in Styrofoam coolers. Other conditions might need to be simulated. For example, light intensity is easily changed by changing the distance between the sensor and a fixed light source. Recall however that light intensity decreases by a factor of $1/r^2$ when using this method to create the calibration curve of a sensor.

The spreadsheet is a powerful tool for creating calibration equations. To create the calibration equation, carefully measure the output of the sensor as the environmental condition is varied. Enter the readings and distance into a spreadsheet. In the next column, calculate the intensity of the source, based solely on its distance from the sensor. Graph the results so that the independent variable (X axis) is the distance and the dependent variable (Y axis) is the intensity. Then select the function to create a regression line from the data in the chart.

14.1.6 Digital Sensors

Some types of sensor outputs are in digital form. These sensors communicate their data as a serial protocol in which data is exchanged as a series of bits over one or more circuits. Data can be transmitted synchronized to an external timing signal (*synchronous protocol*) or synchronized to special signals embedded within the data being transmitted (*asynchronous protocol*).

Examples of synchronous serial data protocols include 1-Wire, Inter-Integrated Circuit (I2C), and Serial Peripheral Interface (SPI). Examples of asynchronous serial data transmission include USB and the RS-232 (COM) ports on PCs. These serial protocols can transfer measured data to a microprocessor without additional conditioning.

Another type of digital sensor is one in which an event's detection is signaled as a voltage pulse or as a switch closure. For example, the detection of ionizing radiation by Geiger counters is signaled by voltage pulses that occur essentially at random. These signals require additional processing, such as by a counter or register circuit that is often implemented by a microprocessor.

SYNCHRONOUS SENSOR DATA PROTOCOLS

The following protocols are by no means the only ones used by sensors, but they are the most common protocols used by sensors on amateur remote sensing platforms. The manufacturer websites mentioned below have numerous resources to support design and development with devices that support these protocols.

1-Wire

1-Wire is a communication system developed by Dallas Semiconductor (now part of Maxim Electronics — **www.maxim integrated.com**) to enable communication between two or more integrated circuits. Devices on a 1-Wire network are daisy-chained together on a single-wire bus, called a *microlan*. (See **Fig 14.4**.) One device acts as the master device, and it controls communication between itself and the slave devices connected to the microlan. Some available 1-Wire devices include:

- Temperature sensor: (MAX51826)
- EEPROM memory (DS24B33)
- Low voltage sensor (DS25LV02)

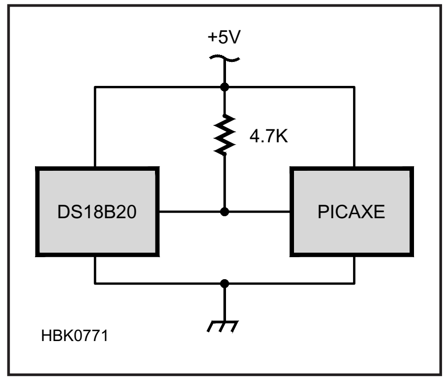

Fig 14.4 — The DS18B20 is a 1-Wire temperature sensor. In this circuit, the device does not use parasitic power and is connected to a 5 V source. A PICAXE microcontroller communicates with this device using the READTEMP or READTEMP12 command.

Since a microlan may not include a separate power wire, many devices attached to the microlan include a small capacitor in their design. The capacitor provides *parasitic power* to the device while communications are taking place. The capacitor is necessary because communication requires the voltage on the single wire to alternate between power and ground. Without some temporary power source, devices would lose power during communications.

The master device communicates with each slave device by transmitting the slave address over the microlan prior to other commands. Because multiple devices can be connected to a microlan, each device must have a unique address to avoid confusion. Slave addresses are laser etched into 1-Wire devices. Alternatively, if a single 1-Wire device is attached to a microlan, communication on the network can ignore addressing altogether.

1-Wire is a two-way communication protocol. The master device begins communication by sending the slave device's address and then commands over the network. Only the device with the address in the message will respond to the commands. With the READTEMP command, communication between the master and slave device requires 0.75 second. The X2 series of PICAXE microcontrollers can communicate over 1-Wire using the OWIN and OWOUT commands

Fig 14.5 — A comparison between an iButton and a nickel.

native to their instruction sets.

iButtons

An iButton is a sealed 1-Wire device resembling a thick watch battery (see **Fig 14.5**). They include memory and a lithium battery. The memory contains the ID of the device and can often be used to store data. The battery permits an iButton to operate independently of a microlan. iButton devices download their stored data when connected to a microlan. The microlan connection is made by pressing the iButton device against a 1-Wire receptor. 1-Wire receptors are available for integration into microcontroller projects. Some available iButton devices include the following:

- Time and temperature loggers (DS1920 Thermochron)
- Time, temperature and humidity data loggers (DS1923 Hygrochron)

The amateur may be interested in the ongoing development of a 1-Wire weather station. Consult Maxim Integrated (**www.maximintegrated.com**) for the latest information concerning 1-Wire devices, including iButtons.

I2C

Inter-Integrated Circuit or I2C is a communication method developed by Phillips to enable communication between two or more ICs. Devices on an I2C network are daisy-chained together on a two-wire bus as in **Fig 14.6**. One device acts as the master device and it controls communications between itself and the slave devices connected to the network. The I2C network is described in detail at **www.i2c-bus.org** and in the application notes supplied by manufacturers of devices that use it.

The first connection in the I2C network is the serial data (SDA) line. This line carries slave device addresses, data, and instructions between devices. The second line is the serial clock (SCL) line. This connection provides timing pulses to synchronize the data sent from the sending IC (master) to the receiving IC (slave). In an I2C network, the SDA and SCL lines are pulled up to +5 V by pull-up resistors. A value of 4.7 kΩ also works well.

The master device communicates with each slave device by transmitting an address over the I2C bus prior to other commands. Because multiple devices can be connected to an I2C network, each device must have a unique address to avoid confusion. Slave addresses may be designed into the IC or may be externally configured for an IC by connecting a combination of address pins to +5 V and ground.

I2C is a two-way communication protocol. The master device begins communication by sending the slave device's address and then commands over the network. Only the device receiving its address in the message will respond to the commands. Serial data can be sent in either in fast (400 kHz) or slow (100 kHz) mode. The master device sends commands and memory addresses in either one byte or one word (two bytes) long commands. Some available I2C devices include the following:

- Memory: the 24LCxxx series of I2C memory.
- Real-time clocks: DS1307
- Analog to digital converters: LTC2903 (12 bit), AD7991 (12 bit), and MCP3421 (18 bit)

SPI and Microwire

Serial Peripheral Interface or SPI is a communication method developed by Motorola (now Freescale) to enable communication between two or more ICs. Devices on a SPI network are daisy-chained together on a two- or three-wire bus. (See **Fig 14.7.**) Like I2C, one device is the master that controls communications between it and the slave devices connected to the network. The Microwire

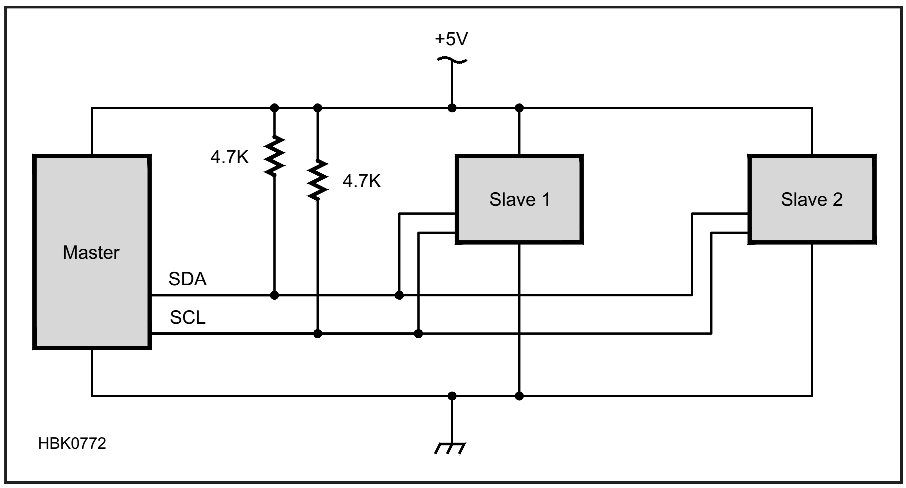

Fig 14.6 — An example of a master and two slave ICs connected via a I2C network.

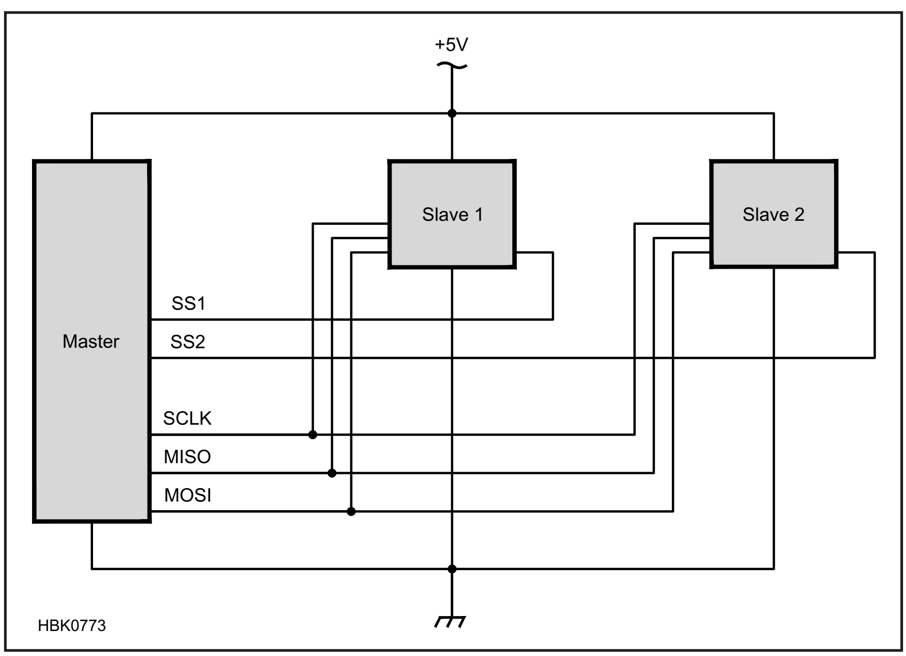

Fig 14.7 — An example of a master and two slave ICs connected via an SPI network.

network originally developed by National Semiconductor (now Texas Instruments) is essentially a subset of SPI. Microchip (manufacturer of the PIC processor family) has published an overview and tutorial about SPI at **ww1.microchip.com/downloads/en/DeviceDoc/spi.pdf**.

Two lines of the SPI bus are used to transmit data and instructions: MOSI (master out/slave in) and MISO (master in/slave out). In some cases, the MISO and MOSI lines can be combined into a single shared line. The third line of the bus is the timing clock line (SCLK) that provides timing pulses to synchronize the data sent between the master device and the slave device. None of these lines requires being pulled high by a resistor.

The master device communicates with the slave devices by activating each slave device's Slave Select (SS) line. To avoid confusion, each slave device must have a unique connection to the master device. This is a major difference between I2C and SPI. An I2C network requires only two communication lines between devices, while an SPI network requires two or three communication lines in addition to an SS line between the master and each slave. A large number of slave devices require a large number of dedicated SS lines between the master and the slave devices.

SPI is also a two-way communication protocol. The master device begins communications by activating the slave device's SS line. Only the device with the activated SS line will respond to the commands. Serial data is sent as fast as the master device pulses the SCLK line. The number of bytes in each transmission between master device and slave device is limited by the design of the slave device rather than to eight or 16 bits. Some available SPI devices include the following:

- Analog to digital converters: MAX186 (12 bit resolution)
- Temperature sensor: LM74
- Hall effect sensor: MLX90363
- Pressure sensor: MPL115A1
- Memory: AT25010B

Note that the popular Dallas Semiconductor DS1620 Temperature Sensor uses a three-wire interface similar to SPI.

ASYNCHRONOUS SENSOR DATA PROTOCOLS

Asynchronous communication is any form of communication that does not use a clock signal to maintain timing between the sender and the receiver. A message begins with a start signal that allows the receiver to synchronize with the transmitter's message. The rest of the communication follows at a predefined rate in bits of data per second or baud. (See the **Digital Modes** chapter for a discussion of data rate.) As long as the sender and receiver use equally accurate clocks, they will transmit and receive the same bits of data.

Some sensors supply their output data using RS-232 and USB ports. The data is transmitted as a stream of characters controlled by a protocol developed by the manufacturer. USB devices often conform to certain classes of data objects so that generic device drivers can be used to acquire data from the sensor. Control and configuration protocols that allow the user to interact with the sensor are usually proprietary.

Time-independent serial devices produce a change in output voltage only at the detection of an event. The primary example is the *event counter*. The simplest event counters detect the closure of a switch, which can be useful for detecting the presence of wildlife. Game cameras use switches in this way to trigger a camera to record an image of wildlife. Thermostats and thermal switches are another example.

Switches can be used to signal a microcontroller by two different methods. In the first, called *active low*, the switch connects a microcontroller I/O pin to ground at the detection of an event. When the event is not present, the I/O pin is connected to positive voltage or pulled up to a positive voltage by a pull-up resistor. In the second method, called *active high*, the switch connects a microcontroller I/O pin to positive voltage at the detection of an event. When the event is not present, the I/O pin is connected to ground. Schematics for both of these switch circuits are shown in **Fig 14.8**.

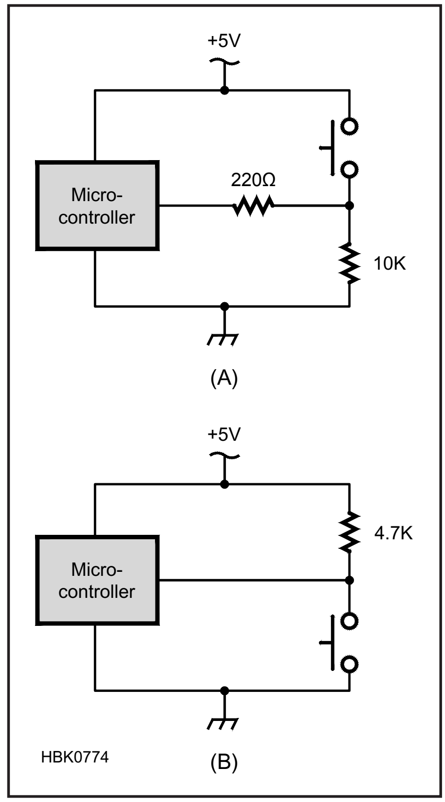

Fig 14.8 — (A) This circuit produces a logic high signal, typically 5 V, when an event is detected. (B) This circuit produces a logic low signal, typically ground or 0 V, when an event is detected.

An example of a sensor that produces asynchronous output is the Geiger counter. The output of the RM-60 Geiger counter from Aware Electronics' RM-60 (**www.aw-el.com**) maintains a 5 V level until ionizing radiation is detected. Then the output voltage drops to 0 V for 20 µs. The amount of radiation detected by a RM-60 Geiger counter is measured by counting the number of pulses emitted by the sensor over a fixed period.

Other event counters can be modified for microcontroller use if they use an LED indicator or piezoelectric annunciator. When an LED is illuminated, greater than 1.4 V appears across its terminals. Wires soldered to the LED can be connected to ground and one of a microcontroller's I/O pins to permit the microcontroller to count the number of LED flashes. Care in counting the number of flashes is necessary since some inexpensive sensors may output several pulses each time the event is detected or in the case of contact bounce for a switch closure.

14.1.7 Powering Sensors

The output of sensing element sensors is typically very sensitive to power supply voltage and noise. Any changes in power supply voltage on the voltage divider also appear, proportionally reduced, at the output of the voltage divider. This includes noise, transients, slowly dropping battery voltage — any change in the sensing element's supply voltage. The sensing element user must provide clean, filtered, regulated power to the sensor to avoid contaminating the sensor output voltage.

Loading of the sensing element is also an issue for the designer to deal with. A high-impedance sensing element will output erroneous voltages if connected to a load impedance that is too low. Be sure you know what the sensing element's ratings are!

Conditioned sensors are far less sensitive to noise and power supply variations. Some kind of voltage regulator circuit is included to make sure the electronics operate with a "clean" supply. The conditioning electronics, which often include laser-trimmed calibration circuitry, assume clean, well-regulated dc voltage from a power supply. They are much less sensitive to the effects of output loading although there are usually limits as to the amount of capacitance they can tolerate at the output, such as from a long run of wire.

In portable or mobile platforms, power is usually supplied by a battery pack. Make sure you have fresh, fully charged batteries before heading out to launch the platform for the experiment. Take into account the gradual reduction in voltage from the battery pack as its charge is consumed — it's awfully hard to swap out batteries with a balloon that is in flight! In the quest to save weight in these platforms, make sure you have enough capacity in the battery pack voltage (see the **Power Sources** chapter) so that the experiment won't run out of power during its mission.

14.2 Navigation Data and Telemetry

Navigation data allows the sensor measurements to be combined with geographical data, which is important for correlating data to location (including altitude). A final step involves using Amateur Radio to either transmit the collected data to a ground station as telemetry or to track and recover a remote sensing payload for later data extraction. Since the most common use of this data is for weather balloons and other near-space missions, that context will be used.

It is important to note that transmitting data as ASCII characters (7- or 8-bit) is preferred to more compact binary formats. ASCII characters have the advantage of being human-readable so that even raw data can be inspected and used. At the low data rates of most amateur remote sensing, little overall throughput is lost by using ASCII characters. The ability to read the raw data stream directly is often invaluable during troubleshooting, as well.

14.2.1 Dead Reckoning

If a digital navigation data source such as GPS is not available, it is also possible to estimate platform position, including altitude by the process of dead reckoning. In dead reckoning, navigation (or tracking) depends on determining a known position — called a *fix* — and then calculating subsequent positions from the platform speed and direction.

Direction data can be obtained from compass sensors that output direction as an analog voltage or digitally encoded signal. Altitude can be calculated based on ground barometric pressure and absolute pressure readings from the platform.

Obtaining accurate ground speed data is difficult for mobile platforms such as balloons or water-borne instruments which move with the wind or current. If some other form of position tracking is available, it is possible to infer ground speed although rarely accurately.

14.2.2 GPS Data

As currently practiced, a GPS (Global Positioning System) module is the usual means of acquiring navigation data which is then transmitted as a telemetry stream using the Automatic Packet Reporting System (APRS). Thus the two are combined in this section.

Depending on the model, GPS receivers produce a number of navigation sentences. Most GPS receivers can form the GPGGA and GPRMC sentences described below. GPS sentences are text-based sentences. They are written in readable text that anyone can understand as long as the format of the sentences is understood. GPS sentences consist of fields separated by commas. Below is a brief description of the two more important GPS sentences (when it comes to high altitude ballooning) and their fields.

THE GPGGA SENTENCE

The GPGGA sentence is the Global Positioning System Fixed Data sentence and a typical GPGGA sentence from a balloon-based GPS looks like this.

```
$GPGGA,153919.00,4332.2076,N,
11608.6666,W,1,08,1.1,13497.
1,M,18.3,M,,*78
```

There are 13 fields in the GPGGA sentence following the sentence identifier, "$GPGGA". The fields from left to right are as follows.

1) Time in UTC (hours, minutes, seconds)
2) Latitude North (degrees and decimal minutes — note that there is no separator between degrees and minutes)
3) N (north)
4) Longitude West (degrees and decimal minutes — note that there is no separator between degrees and minutes)
5) W (west)
6) GPS Quality Indicator (0 = no GPS fix, 1 = GPS fix, and 2 = differential GPS fix)
7) Number of Satellites (number of satellites detected — not all of them may be used in determining the position)
8) Dilution of Horizontal Position (or DOHP, which is an indication of how precise the fix is and the closer to 1.0 the better)
9) Altitude (in meters)
10) M (meters)
11) Geoidal Separation (the difference in the actual height and a mathematic description of the height of an idealized Earth's surface in meters)
12) M (meters)
13) Checksum (result of exclusive ORing the sentence and used to verify that the text is not corrupted)

THE GPRMC SENTENCE

The GPRMC sentence is the Recommended Minimum Specific GPS/Transit Data sentence and a typical GPRMC sentence from a balloon-based GPS looks like this.

```
$GPRMC,153924.00,A,4332.2317,
N,11608.6330,W,24.4,46.3,2310
99,16.1,E*7E
```

There are 12 fields in the GPRMC sentence following the sentence identifier, "$GPRMC". The fields from left to right are as follows:

1) Time in UTC (hours, minutes, seconds)
2) Navigation warning (A = okay and V = warning)
3) Latitude North (degrees and decimal minutes — note that there is no separator between degrees and minutes)
4) N (north)
5) Longitude West (degrees and decimal minutes — note that there is no separator between degrees and minutes)
6) W (west)
7) Speed (in knots)
8) Heading (in degrees true north)
9) Date (day, month, and year — note that there is no separation between them)
10) Magnetic Variation (number of degrees)
11) Direction of magnetic variation (E = east and W = west)
12) Checksum (result of exclusive ORing the sentence and used to verify that the text is not corrupted)

14.2.3 Automatic Packet Reporting System (APRS)

Most balloon flights include an APRS station in order to follow the balloon's position and altitude throughout a mission to the edge of space. The APRS position reports, usually containing GPS data as described above, can be used directly to locate the position of a near-space balloon. (For more details about APRS, see the **Digital Modes** chapter.)

The usual APRS configuration is to transmit a position report once a minute with the recommended path set to WIDE2-1. A power level below 1 W is quite sufficient and many systems work quite well with just 200 mW.

There is a large network of dedicated ground stations, digipeater and Internet gateway stations operating on the US national APRS frequency of 144.390 MHz (144.800 and other frequencies are used elsewhere in the world). Thanks to this network, the balloon's position will be plotted onto a map in near real-time. Two popular websites to view the maps are at **http://aprs.fi** and **http://findu.com**.

Chase crews collect a balloon's APRS data directly over Amateur Radio or over the Internet using a website like **aprs.fi** and **findu.com**. These sites are databases of APRS packets received and routed through APRS Internet gateways. This data is initially used to recover the platform or payload. Later the data is correlated with other sensor data and images that are stored in on-board memory.

There are a number of APRS "trackers" that combine a low-power GPS module with a VHF transmitter and microprocessor that creates the APRS message packets. For example, Byonics (**www.byonics.com**) makes a number of APRS tracking and telemetry products, including the Micro-Trak RTG FA High Altitude Combo that contains an altitude-certified GPS for balloon payloads. The RPC-Electronics (**www.rpc-electronics.com**) RTrak-HAB - High Altitude APRS Tracker Payload is specially made for high-altitude ballooning, as well.

A tracker combination built by the author is shown in **Fig 14.9**. On the right is a GPS module that creates the GPS sentences discussed previously. On the left is the MMT (Multi-Mode Transmitter) that creates and transmits the APRS packets.

APRS POSITION DATA

A simple APRS tracker can generate a stream of useful navigation data for a near-space flight. The data begins at the GPS receiver where two navigation sentences are generated. The sentences are then combined to create a position report in the required APRS format. Like GPS sentences, the raw APRS packets are also readable text that is easily interpreted.

An APRS position report uses a combination of commas and slashes as field delimiters. An example of an APRS report from a near space flight looks like this:

```
13:37:23 UTC: KD4STH-
8>APT311,WIDE1-2,qAS,KC0QBU,
133721h3836.39N/09500.
51W>160/031/A=049114
```

There are 12 fields in the APRS report. The fields from left to right are as follows:

1) Time in UTC (hours, minutes, seconds)
2) Call sign and SSID
3) Routing Information
4) GPS Time (time in UTC — note there is no separator between hours, minutes, and seconds)
5) h (hours)
6) Latitude North (degrees and decimal minutes — note that there is no separator between degrees and minutes)
7) N/ (north)
8) Longitude West (degrees and decimal minutes — note that there is no separator between degrees and minutes)
9) W> (west)
10) Heading (in degrees from true north)
11) Speed (in knots)
12) A= (altitude equals)
13) Altitude (feet)

Note that time and altitude data can be used to calculate the ascent rate of the weather balloon as a function of altitude. In addition, the same information can be used to calculate the descent rate of the parachute. Since a parachute's descent rate is a function of air drag which is controlled by air density, the parachute's descent speed during descent can be used to estimate air density as a function of altitude.

Note also that since a weather balloon is captive to the wind, measurements of altitude, speed, and heading are measurements of wind speed and direction at specific altitudes.

14.2.4 Non-Licensed Telemetry Transmissions

There is a large selection of low-power data links that use the unlicensed 915 and 2.4 GHz bands. Typically, these are intended to be used for short-range applications but with the balloon payload at great altitude, the range of these devices is much longer, particularly if a high-gain Yagi antenna is used to track the payload. (See the **Antennas** chapter for information on VHF and UHF beams.)

Many of the data link modules use a standard two-way protocol such as Zigbee and have direct analog and digital inputs and outputs. Some modules support Ethernet and Bluetooth interfaces, offering even more options for modules that can be assembled into the payload.

It is also important to note that unlicensed transmitters operating under FCC Part 15 rules are also subject to certain restrictions such as field strength. In addition, the type of antenna may be fixed and even required to be attached to the transmitter permanently. These and other restrictions are required in order to limit the range of these devices. Amateurs are used to modifying and adjusting their equipment, and this may not be allowed for some of these devices! Be sure to obtain the full documentation for any unlicensed device you plan on using and be sure you can use it in the way you expect.

14.2.5 Other Digital Modes

The usual method of communication from airborne and other remotely located platforms is via the APRS network. APRS messages are packaged in X.25 packets and usually transmitted as FSK or PSK modulation on FM transmissions. This works well and takes advantage of the extensive ground network of APRS digipeaters and servers.

Nevertheless, APRS might not be the most desirable choice in all circumstances for any number of reasons. In fact, if the payload is within line-of-sight, almost any character-based digital mode will suffice to collect data at the ground station. For example, MFSK modes such as DominoEX work just as well or better on VHF/UHF as they do at HF. Non-character modes such as Hellschreiber may also create very legible data but it will not be in numeric format.

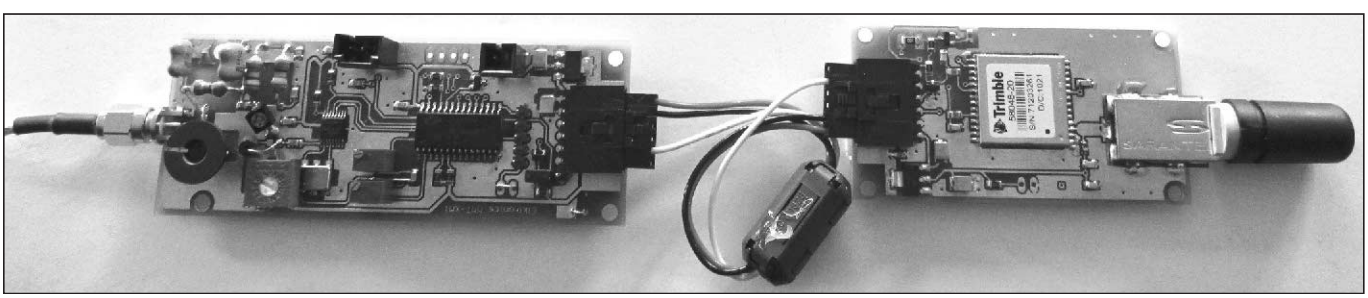

Fig 14.9 — A two-module payload consisting of a GPS receiver module (right) and WB8ELK's MMT (Multi-Mode Transmitter) on the left.

14.3 Platform Design

This section discusses platform design in the context of high-altitude balloon-borne experiments. Similar considerations apply to terrestrial and marine experiment platforms.

14.3.1 Platform Structure

The basic structure of a remote sensing platform is shown in **Fig 14.10**. Along with the power source, there are five separate functions:

1) Sensor data or image acquisition — conversion of analog data into digital format and acquisition of still images or video

2) GPS or navigation data — acquisition of location data in digital form

3) Integration of sensor and location data — collection of all data to be stored and/or transmitted to the ground station

4) Protocol engine — packaging and encoding of data for transmission

5) Amateur transmitter — generates the digitally modulated RF signal

These functions can be implemented by separate modules or everything can be performed by a single microcontroller-based module such as one of the APRS trackers. The choice is completely up to the platform designer and varies with the requirements for the particular mission. For example, Fig 14.9 shows a two-module solution in which everything except GPS location is provided by the single MMT module. The ATV payload described later uses a separate controller to integrate the video and GPS data for transmission as part of the overall audio-video signal. The combinations are endless! The websites listed in the following section on High-Altitude Platforms (balloons) are good places to begin looking for the right subsystems for your mission.

14.3.2 High Altitude Platform Design

It's impractical to track a weather balloon and its payload though optical means. This is why Amateur Radio is such a popular way to monitor the progress of a balloon's flight into the stratosphere. The minimum Amateur Radio system required to track a weather balloon flight consists of a GPS receiver that is certified to operate above 60,000 feet, an APRS TNC (terminal node controller), and a 2 meter FM transmitter.

If other conditions are to be measured or monitored, an additional microprocessor will be required to acquire the data and convert it to digital form. The data can then be stored in onboard memory for recovery. It can also be formatted into a digital data stream and transmitted to ground stations as a telemetry stream. The sensor data can also be integrated with the GPS data for transmission via APRS. Some APRS trackers can acquire analog and digital sensor data and integrate it into the APRS data messages.

Batteries must have sufficient capacity to operate the tracking system for its typical three-hour near-space flight plus additional time spent on the ground prior to launch and awaiting recovery. Those with experience in near-space activity encourage the use of lithium batteries since they handle the cold temperatures experienced during the flight better than alkaline or NiCds.

The maximum weight per payload is six pounds for a total of twelve pounds for the platform. Launching additional weight requires getting special permission from the FAA. This doesn't mean that you can fly 6-pound lead weights. You have to make sure that the density of your payload will not inflict damage to others, and it also needs to protect all those expensive electronics that you have packed inside.

As long as an experiment attached to the balloon can be located and recovered, any data collected by sensors carried by the weather balloon can be analyzed and correlated to the balloon's altitude. Thus, it is extremely important that the payload be able to transmit position data during the flight while collecting data from other sensors.

Here are a few websites with a great deal of information about Amateur Radio high altitude ballooning (ARHAB):

• Amateur Radio High Altitude Ballooning (ARHAB) — **www.arhab.org**

• Edge of Space Sciences — **www.eoss.org**

• WB8ELK Balloons — **www.wb8elk.com**

• UK High Altitude Society — **www.habhub.org**

• Great Plains Super Launch — **www.superlaunch.org**

ENCLOSURE AND INSULATION

A Styrofoam box is one of the most common enclosures. The foam is very light, provides insulation against the extreme temperatures encountered during flight for the payload electronics, and helps with the impact of landing. Even on the hottest summer day on the ground, it can be approximately –60 °C at 30,000 feet above the Earth. Most battery types do not work well at these temperature extremes which are also outside the specification range of most electronic components. Fortunately, a Styrofoam box will help keep the internal temperatures well above those brutal outside conditions.

Another technique is to mount the electronics and batteries on a foam-core board and wrap everything with three layers of small-cell bubble wrap. The insulation and trapped sunlight will keep the electronics warm.

BATTERIES

Lithium batteries are recommended since they can supply power even in sub-zero conditions. Another added benefit is that they have a very high power/weight ratio. The Eveready L91 AA lithium battery is one very popular battery that is used quite often for Amateur Radio high-altitude ballooning.

ALTITUDE RATING

Many GPS receiver modules will not work

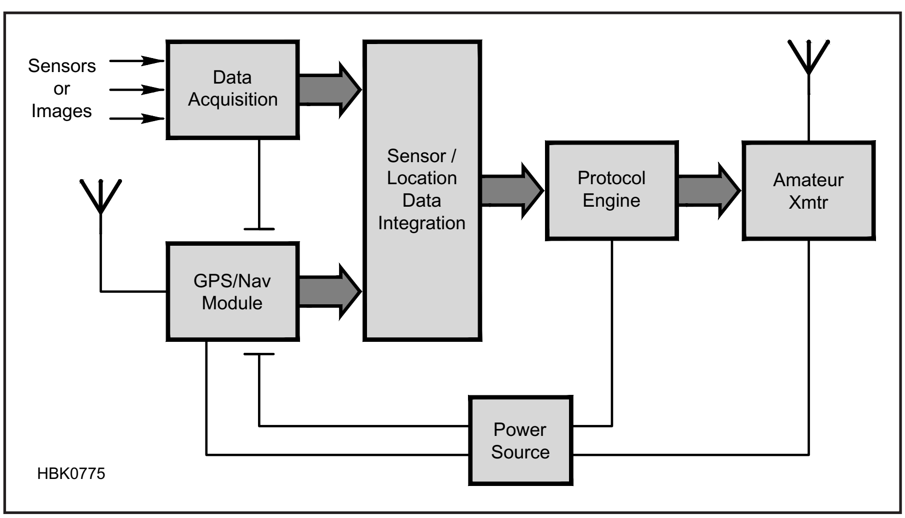

Fig 14.10 — The basic structure of a remote sensing platform using Amateur Radio for the telemetry link.

above 60,000 feet. When choosing a GPS receiver, make sure the datasheet specifies a maximum altitude. Some popular modules known to work at stratospheric altitudes are those made by Trimble, Garmin, u-Blox and Inventek as well as high-altitude modules offered by Byonics and Argent Data.

PREDICTING FLIGHT PATHS

When flying a high altitude balloon, it is a good idea to run a flight prediction a few days in advance as well as the night before a flight to make sure you don't land in a densely populated area or somewhere where you will have great difficulty making a successful recovery. There are two popular online prediction programs that can be accessed at the **www.arhab.org** website.

14.3.3 Types of VHF/UHF Payloads

SIMPLEX REPEATER

A high-altitude balloon at 100,000 feet has a radio line-of-sight of over 400 miles. The formula for radio signal line-of-sight in miles is

$$\text{Distance (mi)} = 1.41\ \sqrt{\text{H}}$$

where H is the height in feet. Since antenna height is so important for operating on VHF and UHF, imagine having an antenna that is 19 miles high.

If you could fly a repeater to that altitude, two ground stations 800 miles apart could communicate with each other through the repeater. One simple way to do this is to fly a single handheld radio operating on 2 meters or the 70 cm band. By connecting a voice recorder and playback device to the handheld radio, you can create what is called a *simplex repeater*. One such device is offered by Argent Data and is their model ADS-SR1. A discontinued Radio Shack simplex repeater module can be sometimes found online.

It takes some practice and patience to get the hang of a simplex repeater conversation, but this provides a very simple way to make some very exciting contacts over a multi-state region using minimal equipment on the ground.

CROSSBAND REPEATER

If you use two handheld radios, one on 2 meters and one on 70 cm, you can build a crossband repeater payload. (Some handheld radios can also operate as crossband repeaters by themselves.) You'll need to build an audio level control to adjust the audio between the two radios and also provide a PTT control.

Although more complicated, heavier and more expensive than the simplex repeater, this does provide a real-time repeater without having to worry about flying large filters to prevent desense. The input is usually on the 2 meter band with the output on the 70 cm band. Although you can set it up the other way around, the 3rd harmonic of the 2 meter transmit can cause desense issues with the 70 cm receiver.

SSTV AND STILL PHOTOGRAPHY

Many balloon enthusiasts fly either a still camera or a video camera payload. From 100,000 feet you can clearly see a spectacular view of the blackness of space and the curve of the Earth since the balloon is above 99 percent of the atmosphere. **Fig 14.11** shows a photo taken from by a balloon-launched camera. Suitable lightweight cameras are available in thumb drive (USB) formats and helmet- or bike-cams designed to be used while being worn.

A great addition to any balloon flight is the ability to actually receive live images during the flight. By using a small handheld radio on 2 meters connected to an SSTV module (for example, the Argent Data SSTVCAM) and a microcontroller, anyone who can hear the VHF signal can also view the live images. There are several programs to decode the SSTV audio signal and display the images on a computer screen. *MMSSTV*, *MixW*, *MultiPSK* and *Ham Radio Deluxe* (DM780) are a few programs that can be used. A good SSTV mode is Scottie 2, which will send down one image in 71 seconds. Although the resolution is not as clear, you can also use Robot 36 mode for quicker transmissions. (See the **Image Communications** chapter on the CD-ROM accompanying this book for more information about SSTV.)

Fig 14.11 — A balloon carrying a camera payload was launched from the Dayton Hamvention in 2010. This picture was obtained a few minutes later from an altitude of about 1000 feet.

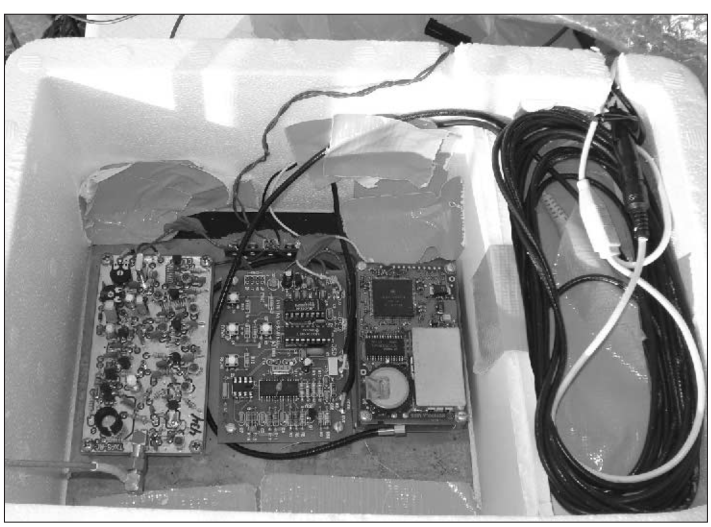

Fig 14.12 — This payload consists of a GPS receiver (right), payload controller (center), and an ATV transmitter (left). Batteries and cables are in the far-right compartment and the entire platform is contained in a Styrofoam enclosure.

ATV

There is nothing like watching a live video camera view from a flight to the edge of space. The very first few amateur high altitude balloon flights in the US carried amateur television (ATV) transmitters on them. Typically a 1 W to 3 W AM-modulated ATV transmitter on either 434 or 439.25 MHz is used for best results. You can also use FM ATV transmitters on higher frequencies, such as the 23 cm and 13 cm bands, but the path loss will be much higher on those frequencies and that will limit your maximum downrange reception distance. There are many lightweight video cameras that can be used as long as they can provide an analog video output. (See the **Image Communications** chapter on the CD-ROM accompanying this book for more information about ATV.)

Remember that the power requirements for a continually operating 1 W TV transmitter will be much higher than an APRS or audio repeater payload. You'll typically need at least 12 V with an Ah rating sufficient to allow for at least three hours of operating time. A surplus military lithium pack is a good option or you can use enough AA lithium batteries to meet the requirement.

Fig 14.12 shows a typical ATV payload in the insulating Styrofoam box enclosure. On the left is the low-power 70 cm transmitter. In the middle is the microprocessor-based controller. The GPS receiver module is on the right. The batteries and cables are placed in the separate compartment at the far right. Note that the three electronics boards are mounted over a common PCB ground-plane to provide mechanical stability and to minimize RFI from the transmitter. The antenna for the ATV link hangs below the package.

You will need a good antenna on the ground, an ATV downconverter, and an analog TV receiver. If you are flying in an area where horizontal polarization is used for local ATV activity, the "Big Wheel" antenna is a good option for the payload's ATV antenna. It provides good coverage at the horizon as well as underneath the payload. You can also use a vertical antenna, but there will be a null directly underneath a vertical radiator. PC Electronics (**www.hamtv.com/wheel.html**) carries the Olde Antenna Labs line of "wheel" antennas for various bands as well as video camera modules, ATV transmitters and receivers.

14.3.4 HF Payloads

The RF range of a high altitude balloon at peak altitude is limited to about 450 miles when using VHF and UHF. Some balloon groups have flown transmitters on the HF bands with reception reports many thousands of miles away. It's a great way to include Amateur Radio operators far outside your local region.

There are several digital modes that can be programmed into a small microcontroller without having to invoke floating point math (see **www.elktronics.com** for an example of a multi-mode HF balloon transmitter). Morse Code, RTTY, PSK31, DominoEX and Hellschreiber have all been successfully flown, as well.

Transmit power levels under 1 W will work well due to the weak signal advantage of some of these digital modes. DominoEX, Hellschreiber and PSK31 are particularly good for very weak signal reception.

It is recommended to have a way to turn the HF transmitter on or off under remote control. There are a number of inexpensive and lightweight UHF handheld radios that can be used as a control receiver along with a DTMF decoder board.

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