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Handheld Theodolite Concept

by Alan E. Wetmore

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Alan E. Wetmore
Computational and Information Sciences Directorate, ARL

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14. ABSTRACT

Currently, artillery meteorology uses observations of a pilot balloon taken using a theodolite as a backup to a full rawindonde system. The theodolite is an expensive and cumbersome single-use system that is a candidate for replacement. This technical note examines the feasibility of using a “smartphone” as a replacement for a traditional theodolite. The smartphone can serve as both the observation/recording system and the system for deriving a sounding from the observations.

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1. Problem Statement

Currently, there are some portable solutions for measuring upper air winds using pilot balloons. These solutions require a 20-lb theodolite, a heavy tripod, batteries, and a computer to process the data, all in addition to the pilot balloon itself. The U.S. Army Research Laboratory (ARL) has developed a version of the software for reducing the observations that runs on a handheld computer (*1*). This report discusses the development of a system concept and basic requirements for replacing the $20,000 theodolite with a $300 iPhone-type device.

Current handheld devices are becoming ever more powerful, compact, and versatile. One example is portable cellular telephones such as the Apple iPhone. This device contains a graphical display, computer, a camera, three-dimensional (3-D) accelerometers, a global positioning system (GPS) receiver, and timers; as well as a multiband global system for mobile communications (GSM) telephone. The latest iPhone model 3GS also includes a magnetic compass. Conceptually, this is enough equipment to operate a handheld pibal tracker and compute the wind profile.

This report describes how a handheld tracking and computation system could be designed and built. The basic concept from measuring technology to message delivery includes the following:

1. Three-axis accelerometers that can respond to tilt and orientation then translate these into azimuth (Az) and elevation (Elev) readings
2. A live-view camera to track the balloon, add crosshairs, offer digital zoom, or provide external telephoto adapter
3. Built-in GPS for setting latitude, longitude, and surface elevation readings
4. A magnetic compass
5. A timer for measuring ascent times
6. Image processing for finding the balloon relative to crosshairs
7. After recording time, Az, and Elev data, the ability to process that data in order to generate wind profile/meteorological (Met) messages
8. A network enabled for relaying the computed Met message to the fire direction center

Some proposed advantages of the handheld solution are reducing the weight of the theodolite and tripod; providing automated calculations without transcribing data; and using built-in radio links to transmit wind profiles to the fire control system.

2. Literature Consulted

The following manuals and guides were consulted to assist in understanding the current and historical perspective of pilot balloon operations and requirements:

- Pilot balloon Web pages by Martin Brenner (*2*)
- Theodolite information from the Warren-Knight Instrument Company (*3*)
- *Federal Meteorological Handbook No. 3: Rawinsonde and Pibal Observations* (*4*)
- *A PDA-based Backup System for Generating Marine Corps Artillery Meteorological Messages*, ARL-TN-244, by Terry Jameson and David Sauter (*1*)
- *A Refined System for Pibal Theodolite Observations* by Dunckel, Hasse, and Schriever (*5*)
- *Field computation of winds-aloft velocities from single theodolite pilot balloon observations* by Bill Ryan, U.S. Forest Service (*6*).

3. Basic Theory

Basic pibal theory makes some assumptions. The balloon is filled to a certain size creating a known lift. The size of the balloon creates drag as the balloon ascends. The lift and drag sum to create a known ascent rate, typically 300 m per minute. Observing the balloon at specific times is equivalent to observing the balloon at specific altitudes. The vector from the observer to the balloon (specified by an elevation and azimuth angle measured by the theodolite) intersects the plane at an altitude (above ground level [AGL]) in a single point. The horizontal difference in the intersection of the pibal trajectory and the two reference planes is an integrated effect of the wind in the layer the balloon is passing through. Using geometry, we can extract the net horizontal motion, as distance and direction, of the balloon as it moves through the layer. Dividing the distance traveled by the time to travel gives the speed; the direction has already been determined.

The proposed concept of handheld balloon tracking makes several assumptions:

1. The handheld knows its location latitude, longitude, and altitude via GPS.
2. The handheld knows its orientation with regard to north (true or magnetic).
3. The handheld knows its orientation (*x*-, *y*-, and *z*-axes) and three angles via accelerometers; these can be converted to an Az and Elev angle.

4. The operator can view the pilot balloon via the camera and display. Since the camera resolution exceeds the display resolution, we can use the "digital zoom," i.e., cropping, to focus on the region of the image containing the balloon.
5. A set of crosshairs can be drawn on the display to aid the operator in tracking the balloon.
6. The motion of the device can be filtered/averaged to obtain a set of "good" orientation angles.
7. The rate of balloon ascent is the same as used by traditional theodolite tracking.
8. Empirical equations are available to link the rate of rise with the altitude, as in traditional pilot balloon tracking.
9. The series of time, Az, and Elev angle measurements can be processed on the handheld.
10. The image of the balloon can be processed to obtain a location within the field of view and is combined with the device orientation to derive a complete altitude and Az reading.
11. The image the camera sees at the scheduled observation time can be saved.
12. The handheld can warn the operator of impending reading times to aid in centering the balloon in the display.

4. Concept of Operations

This is an overview of the proposed concept of operations for using the proposed handheld theodolite.

The operator prepares a pilot balloon for release. This procedure is the same as what is currently done using a conventional theodolite system. There is no savings in time or logistics for these actions.

The operator prepares the handheld, first by verifying that GPS location and compass information is available, then by starting the theodolite application, and finally by orienting and sighting on the balloon. This provides a significant cost and logistics savings. We are replacing a heavy, expensive, single-purpose instrument (the theodolite) used for backup purposes with a much cheaper multipurpose handheld device. In addition, the time required to unpack, set up, and repack the theodolite is much longer than to prepare the handheld.

The operator releases the balloon and tracks it with the handheld. This activity is approximately equivalent for both methods. It may be slightly less trouble to track the balloon using the handheld. If the balloon drifts out of the field of view, it may be easier to reacquire it with the handheld than by tracking it with the theodolite. Since the camera is a traditional red, green, blue

(RGB) sensor, there is the capability to do some "enhancement" of the images to assist in observing the balloon. If the tracking operator is interrupted during the flight, the operator may be able to successfully reacquire the balloon and complete the flight. This suggests that the operator may be capable of some multitasking during the mission.

The handheld counts down to each recording time to aid the operator in centering the balloon on the display. During that time, the operator attempts to center the balloon in the display. The operator should probably acknowledge the data acquisition event and perhaps verify if the balloon was in the field of view of the camera. If the system records a series of orientation readings, a smoothed fit of the instantaneous pointing direction can be made.

At each recording time, the handheld processes the image to "find" the balloon and refine the Az and Elev calculations. If possible, the onboard computer should be able to identify the pixels making up the balloon and automatically compute the location of the balloon's center in the image to complete the calculation of Az and Elev angles. If a series of images are recorded, we could compute a sequence of "locations" and choose a maximum likelihood for the balloon's location at the desired measurement time. Since the data are available internal to the iPhone, the operator is not required to record or transcribe the readings. This both eliminates a potential source of error and reduces operator workload.

As time is available, the handheld processes the time, Az, and Elev data and produces a wind speed and direction profile. The computational capabilities should make this reasonably simple: the geometry is trivial; smoothing is slightly more complex. One unknown is the difficulty of image processing to assist in identifying the location (center) of the balloon during flight. In principle, we could transmit incomplete Met message as each level is reached. This would allow a firing solution to be calculated before the balloon has completed its flight. However, it has yet to be determined if this offers a significant advantage.

When the flight is complete, the handheld displays and transmits the profile to the fire control center and other consumers of the Met messages. This step presumes that the iPhone can be accredited for operation on the tactical network. This is an open question at present.

5. Notes on Accuracy Requirements

Theodolite requirements are assumed based on the procedures documented in *Federal Meteorological Handbook No. 3: Rawinsonde and Pibal Observations* (*4*), i.e., the measurement errors are ±0.05° and the scale reading errors are ±0.1°. These can be converted to radians, π = 180°, as follows:

$$0.05^\circ\ \pi/180^\circ = 873\ \mu\text{radians.} \tag{1}$$

The iPhone 3GS is reported to have a 3-megapixel sensor. If this translates into a 2000×1500 pixel image with a 50° horizontal field of view, a single pixel corresponds to

$$50° \div 2000 \text{ pixels} = 0.25° \text{ per pixel.} \quad (2)$$

This is five times less resolution than needed if we are limited to resolving at the resolution of a single pixel. We could perhaps double or triple this resolution by frame averaging. The other alternative is using a telescopic auxiliary lens.

The question is, what field of view does a pibal fill at a range of 10 km? If we use the small angle approximation that $\sin\theta = \theta$ (radians), then 1 m at 10,000 m is θ=100 μradian (0.0057°) per meter of balloon diameter. This suggests that a 50× telescope is needed to resolve to a single pixel a 1-m pibal at 10-km range. Thus, what remains to be answered is, how much diameter do we gain as the balloon expands during ascent?

Considering the telescope attachment alternative presents several issues: Can we use a telescope for the entire flight or do we need to add it during the flight? If we need to add it during the flight, how critical are alignment issues? If attaching the telescope changes the center of the field of view, it would introduce an error as a discontinuity in the tracking of the Az and Elev coordinates. Knowing that the coordinates are a continuously varying series of readings, we could use continuity before and after the addition of the telescope to correct for any alignment uncertainty associated with adding the telescope.

The Warren-Knight Web page (*3*) lists the specifications of their theodolites as having 21× power telescope with a 2° field of view and 0.1° reading for the Az and Elev scales. These values are in rough agreement with the design criteria developed here. Other technology is reported by Custom Craft (*7*) using a similar concept of magnetometers and inclinometers linked to a handheld computer. That system uses an existing telescope to track the pibal. These solutions suggest that we need to be tracking near the individual pixel accuracy with the iPhone sensor and optics.

We will need to have some good stabilization techniques and balloon tracking options. For stabilization, we can perform a running smoothing of the orientation to both smooth out operator bounce and average reading uncertainty. This is a critical experiment to perform. We need to see how stable the readings from a motionless device really are.

We can also try to use more than one set of crosshairs to locate the balloon. Furthermore, we can snap a photo of the balloon with a timestamp to record the instantaneous orientation and run an object detection algorithm to determine the geometric center of the balloon in the image. This offset from the center would correct the raw pointing data from the orientation sensors.

The current pibal data reduction technique is predicated on knowing "exactly" what the Az and Elev values are at the start of each minute during the ascent. These values are recorded from an instantaneous reading of the vernier scales, which is one source used to meet the requirement for verifying a very stable instrument. Knowing these values also results in an integrated wind effect for the layer. It does not exploit the fact that the pibal is ascending smoothly through the atmosphere.

Based on using a handheld rather than tripod-mounted system and lower magnification optics, we can expect our data stream to have significant noise or jitter superimposed on the tracking data we measure and record even when tracking a smoothly moving object. An alternate strategy for processing the data would be to continuously record the noisy data and extract the time averaged trends. We know that it is physically unlikely for the pibal to be bouncing either up and down or right and left as it ascends. Thus, the part of our signal that claims it is bouncing must be “noise.” We can use several averaging and filtering techniques as part of the development effort to better understand the nature of the noise to select an appropriate technique.

6. Conclusion

This technical note has examined the feasibility of replacing the theodolite used for tracking pilot balloons with a smartphone and specialized software. In the system envisioned, the smartphone serves as both the observation and recording system as well as the data processing system to derive the desired sounding from the observations. Further, the communications capabilities of the smartphone might be exploited to transmit the sounding file to users who require it. Based on capabilities such as field of view, number of pixels, resolution of orientation sensors, availability of GPS, current smartphones appear capable of allowing development of a handheld theodolite system as an add-on application.

7. Future Experiments and Tests

The following are suggestions for experiments and tests that should be conducted to continue work on this effort:

1. How stable are the sensors while at rest?
2. What is the resolution of readings returned by the sensors? Is it an integer, fixed point, or floating point format?
3. What is the repeatability of readings when pointing at both a stationary target and a moving target?
4. With regard to the contrast and blur of the camera images, can we detect the edges of the balloon using software on the phone?

5. How rapidly can we take a series of frames to track the balloon and/or average its movement, and how quickly can we obtain readings to determine the Az, Elev, and magnetic bearing? How does this compare with the standard assumption that we took the Az and Elev readings at the correct moments? We expect that we could take the readings more accurately with regard to time if the computer is doing the data acquisition.
6. What is the actual initial radius and at altitude radius of a nominal pilot balloon?
7. How well does the proposed smoothing of a series of readings actually work to meet the level of accuracy we require?

8. References

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