ADVANTAGES OF GPS OVER RADAR IN WIND WEIGHTING OF UNGUIDED SOUNDING ROCKETS

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ABSTRACT

"Wind Weighting" is the process of assessing the effect of wind on a launch vehicle and determining launcher settings which would counteract that effect. This paper discusses the advantages of using GPS radiosondes to determine wind profiles over the historical method of tracking balloon positions with radar for the purposes of Wind Weighting. The primary advantages are lower costs and greater portability. Also presented is evidence of improved accuracy and reliability. Engineering testing is described and test results are reported.

KEY WORDS

WIND WEIGHTING
GPS RADIOSONDE
UNGUIDED

INTRODUCTION

Wallops Flight Facility (WFF, or Wallops), located at Wallops Island, Virginia, is part of NASA's Goddard Space Flight Center, and is the home of the NASA Sounding Rockets Program Office. Sounding rockets carry scientific payloads several hundred miles in altitude. These missions return a variety of scientific data about such things as "the chemical makeup of the atmosphere, physical processes, natural radiation surrounding the Earth, information on the Sun and stars, and many other phenomena"[1,2]. In addition, sounding rockets provide a low-cost test-bed for new scientific techniques, instrumentation, and technology, eventually flown on satellite missions[3].The mobile launch facilities of WFF enable scientists and engineers to launch rockets around the world … to conduct their science "where it occurs"[4].

Most of the sounding rockets launched by WFF are unguided, which saves the cost of a guidance system and makes them an even more inexpensive way to launch experiments into space. However, unguided rockets are greatly affected by winds -- especially near the surface, where the vehicle is still traveling slowly. Under ideal conditions (no wind), it is possible to calculate the launcher azimuth and elevation so that an unguided rocket will fly to a desired impact point. During the Wind Weighting process, the actual winds are assessed, and the launcher settings are adjusted to correct for wind effects on the trajectory of the launch vehicle. This process "is the primary means of vehicle containment for a rocket without a Flight Termination System"[5]. Thus, the Wind Weighting system is a safety-critical component of a launch range.

Traditionally, wind profiles have been determined for the purposes of Wind Weighting at WFF and elsewhere by the radar tracking of a series of meteorological balloons carrying radar reflectors. At Wallops, the radar data is transmitted to the Wind Weighting system (PC) in the Range Control Center via ethernet. The Wind Weighting software (a system with source files written in C, C++, and Java, and presently running on Windows 2000) computes the wind speeds and directions from the reported positions of the balloon.

A typical wind profile is, of course, not uniform from the ground to the top of the atmosphere. However, it can be approximated by a finite number of discrete layers within which the wind is considered to be constant in magnitude and direction[5]. The Wind Weighting software is set up with these (previously determined) layers, and, as soon as a balloon rises above each layer, the vector-averaged wind speed and direction are computed for that layer and displayed in what is called the wind table. Meanwhile, the 300-foot Wallops wind tower is constantly updating the wind table every second with the wind speeds and directions reported by anemometers at the 50-, 100-, 150-, 200-, 250-, and 300-foot levels.

The Wind Weighting software, using the current wind table winds, together with the previously-determined relative contributions of each wind layer to the overall wind displacement for the vehicle being launched, computes the effect of the wind profile on the rocket, and then calculates the adjusted launcher settings that would cause the rocket to fly to the desired impact point, given the winds through which it would fly.

Measuring winds by releasing and tracking balloons has obvious limitations. Most glaring is the fact that the balloon does not go where the rocket will go. Equally troubling is the fact that the winds are seldom constant. Also, some of the data for higher altitudes may be several hours old by the time of the launch. Despite these limitations, the balloon-tracking method of measuring winds has achieved an impressive safety record over the history of the Sounding Rockets Program at Wallops Flight Facility and elsewhere. Many other methods of measuring winds have been investigated, but they have all been found to have one or more of the following problems: (1) they are prohibitively expensive; (2) they were not designed to measure near-surface winds (say, below 1000 feet); (3) they are not appropriate for our range; (4) they are not portable.

My task was to integrate into the Wallops Wind Weighting system the capability of measuring winds by tracking balloons carrying GPS radiosondes (as opposed to radar reflectors).

THE CASE FOR GPS WIND WEIGHTING

When I began my task, Wallops was already using the Lockheed Martin Sippican GPS W-9000 Meteorological Processing System with LM Sippican Mark II Microsondes (radiosondes carried into the atmosphere by the same type of weather balloons as we were using for radar Wind

Weighting) to obtain meteorological data, including wind speeds and directions, for weather prediction. These GPS radiosondes and ground stations use the GPS L1 frequency band and the C/A code. In such a system, position information is generated from GPS radiosonde data derived from the GPS satellite network. While ascending, the Microsonde transmits data on a 403 MHz carrier to the ground station receiver. The main processor of the GPS W-9000 System is a PC, which processes, displays, and stores the data[6]. It was a conceptually simple idea to use that same wind data for Wind Weighting.

There are many advantages of GPS Wind Weighting. One is that it uses a network of satellites already in place at no cost to a project. Another appealing aspect involves shipping costs; GPS Wind Weighting is highly portable, requiring only liter-sized radiosondes and PC-sized ground stations. By contrast, it cost $45,900 to ship a radar van to Kwajelein Atoll for the Wallops EQUIS II Campaign in the summer of 2004.

Still another advantage of the GPS approach has to do with improving the chances of launching (fulfilling the mission objectives). If radar is used for tracking, the three operators must report an hour before Wind Weighting begins, a process which itself usually takes at least four and one-half hours. Then the launch windows can be many hours long, and if conditions are not right for the launch, the whole process is repeated the next day. This can go on day after day, night after night. More serious than the labor cost is the fact that the radar personnel can soon be in danger of exceeding the maximum number of hours that safety rules permit them to work in a week. If this happens, the whole mission must be put on hold until the radar operators can work again. The GPS ground station, on the other hand, can be run by one person. It is also easier to learn how to use the GPS system than it is to become a radar operator. If we could use GPS radiosondes (at a cost of about $150 each) for at least several of the Wind Weighting hours, it would free enough radar hours that we would not be in danger of losing the support of the radar personnel for the remaining tracking tasks of the mission.

Another consideration is that radars cannot track directly overhead; if the Wind Weighting balloon happens to drift over the radar, data will be lost. There is no analogous limitation of the GPS system. Also, radar acquisition is often aided by optical tracking at balloon release. There must be at least some degree of visibility, so radar Wind Weighting cannot even begin in, say, fog or heavy snow. These conditions do not limit the use of GPS radiosondes. GPS Wind Weighting would enable us to proceed even under conditions of no visibility, in hopes that conditions would improve as the beginning of the launch window approached.

In addition, in our testing, GPS radiosondes have started reporting wind data closer to the surface than have the radars. It is important that the tracking device (radar or GPS) be able to start reporting wind velocities before the balloon rises past the top of the wind tower; otherwise, there would be a critical, near-surface layer above the wind tower about which we know nothing. When radar is used to track a balloon, obtaining "lock" is often difficult,[7] and so far, the shortest wind tower we have been able to use at remote sites is 150 feet tall. The erection of such a tower costs over $50,000. The GPS system might allow the use of a shorter, portable tower, which could be completely prepared at Wallops, shipped ready for service, and reused at other sites. Still another important feature of the GPS system is that multiple radiosondes can be tracked simultaneously. This means that we would not have to wait for one balloon to finish its ascent before releasing another. For example, a mid-altitude balloon could be released while a high-altitude balloon was still rising. This would decrease the necessary tracking time and increase the freshness of the data. Multiple radars can duplicate this but would not be cost-effective.

Finally, our research and testing indicate that GPS radisondes provide wind profiles of accuracy at least comparable to those obtained from radar-tracked reflectors.[7,8] In fact, the consensus among our engineers is that that the GPS approach provides greater accuracy than does the use of radar. This is due in part to a signal processing strategy that uses a measured Doppler shift (the frequency shift caused by the rate of change in range to a moving satellite) to help the receiver smoothly track the GPS signal, allowing more precise velocity and position measurement. By contrast, radar data tends to be noisy.[1] In addition, we carefully survey the position of a DGPS antenna near the ground station antenna system; this allows the W-9000 to use differential techniques to determine more accurate winds and height data. In fact, research at Wallops on the relative trajectories of four GPS receivers attached to four separate sections of a payload (at fixed and known distances from one another) from liftoff to payload separation showed relative payload-to-payload coordinate accuracies within four centimeters, even at rocket speeds.[2]

COMPARING GPS WIND DATA TO RADAR WIND DATA

However, for the purposes of this paper, we are limited by the fact that we cannot show that one wind profile is better than another when we do not know what the actual (real) winds are. We must leave that discussion to meteorologists and other experts who have access to high-quality wind profilers. Meanwhile, because of the long-established safety record of radar-based Wind Weighting, my task was to demonstrate that a GPS profile would provide Wind Weighting information equivalent to that provided by the corresponding radar profile.

Although I will discuss in detail only the most recent GPS-radar Wind Weighting comparison tests, such testing started at Wallops in 2000. In October and November of last year (2005), final engineering tests were performed for the new version of the Wind Weighting software that incorporates use of GPS. Test days were selected based on Wallops range schedules and not on meteorological conditions. On each day, a balloon was released carrying both a radar reflector and a GPS radiosonde. The balloons were inflated so that the rise rate would be 900 to 1000 feet per minute. On each day, the balloon was tracked by two radars (“R2” and “R3”) and by the GPS ground station. This paper will present data and results from three of those days of testing.

One way of comparing the wind measurements reported by each wind data source is to examine the speeds and directions in the wind tables produced by each. Therefore, on test days, wind tower data was *not* acquired lest it overwrite data obtained by R2, R3, and GPS for those lowest levels. Because the Wallops Flight Safety personnel are accustomed to viewing wind velocity data as wind table speeds and directions, with the directions plotted in Cartesian coordinates (as opposed to polar coordinates), that is how the data will be presented, despite the fact that Cartesian plots of directions present us with the problem of “zero crossover” (from 360 to 0).
It is important to note that, by the time a level’s wind speed and direction appear in the wind table, much processing of the raw data has gone on behind the scenes. For the ten points-per-second radar data, the Wind Weighting software uses a second-degree alpha-beta-gamma filter, a

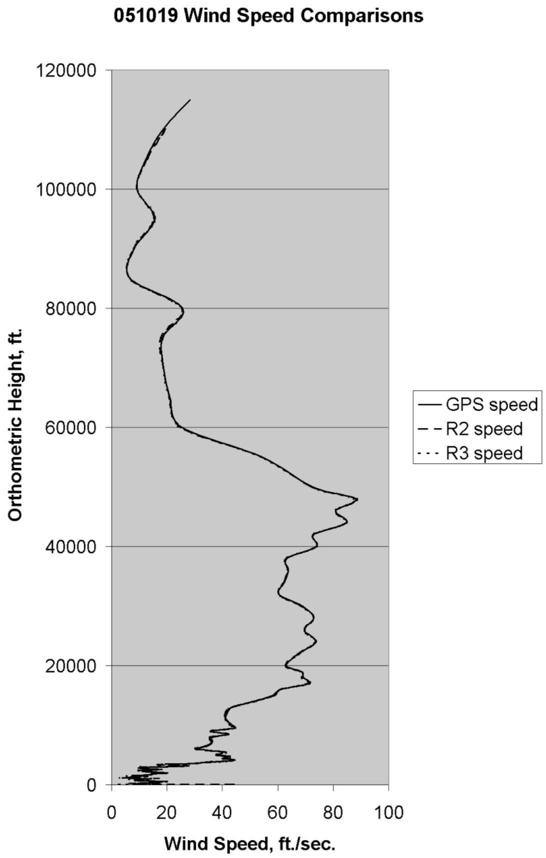
software filter class developed by Wallops engineers to include a combination of an expanding memory filter and a steady-state critically-damped filter, assuming acceleration to be relatively constant. The theta value (a measure of the trade-off between responsiveness and smoothness) can be assigned in the Wind Weighting software set-up files; its default value is 0.5.[9]

For the GPS data, we have deferred to the expertise of the engineers at LM Sippican, who have shared with us a complete description of their proprietary filter[10]. The parameters for this GPS W-9000 System software filter have been established by the manufacturer based on a large number of actual flight data sets, and are optimized for use with a 21-meter tether, the length of train supplied with each Microsonde. (The World Meteorological Organization recommends a tether length between 20 and 30 meters to insure the integrity of the radiosonde temperature and humidity sensor data[10].) Therefore, in all of our tests, the radar reflector was attached immediately under the balloon, and the radiosonde was suspended 21 meters below.

It turned out that the 21-meter tether length presented us with a dilemma. The radiosonde reports wind speeds and directions together with *its own* altitude, but it appeared that the reported wind speeds and directions actually belonged to the (much larger) *balloon*, which was 21 meters higher. From talking to the manufacturer and doing a literature search, it appears that the difference between heights of the radiosonde and balloon is typically ignored. But the GPS data corresponded more closely to the radar data when I added 21 meters (68.9 feet) to the altitude in each GPS one-second data triple (altitude, wind speed, wind direction). Note that this dilemma might negate a hoped-for advantage of GPS tracking over radar; if we have to add 68.9 feet to the heights reported by the radiosonde, then GPS might *not* report accurate wind velocities closer to the surface than can radar.

Meanwhile, in all data presented below, 68.9 feet (21 meters) was added to all heights reported by the radiosondes before the Wind Weighting software built the wind tables. Space limitations necessitate the presentation of just one set of wind-table speed and direction plots; the plots from October 19, 2005, are selected as representative examples (Figures 1 and 2). As can be seen from the plots, the Radar 2, Radar 3, and GPS tracks are almost indistinguishable from one another at this scale. If the data for only 0 to, say, 5000 feet were shown, it could be seen that the radar data appears to oscillate about the smoother GPS curve.

For a second way of comparing GPS and radar wind data, we shall think about the wind velocities (vectors) as ordered pairs of numbers (speed, direction) and use one-way analysis of variance, or ANOVA, to compare our three samples of first elements of the ordered pairs (speeds) and our three samples of second elements (directions) for each test day. Preliminary analysis using the statistical software Minitab 14[11] showed that the wind table speeds and directions were not normally distributed, but because we have sufficiently large samples, we are justified in using this technique by the Central Limit Theorem. (We must keep in mind the limitation that, when using ANOVA, we are considering that all the layers are equally important, whereas this is not actually the case for this application.)



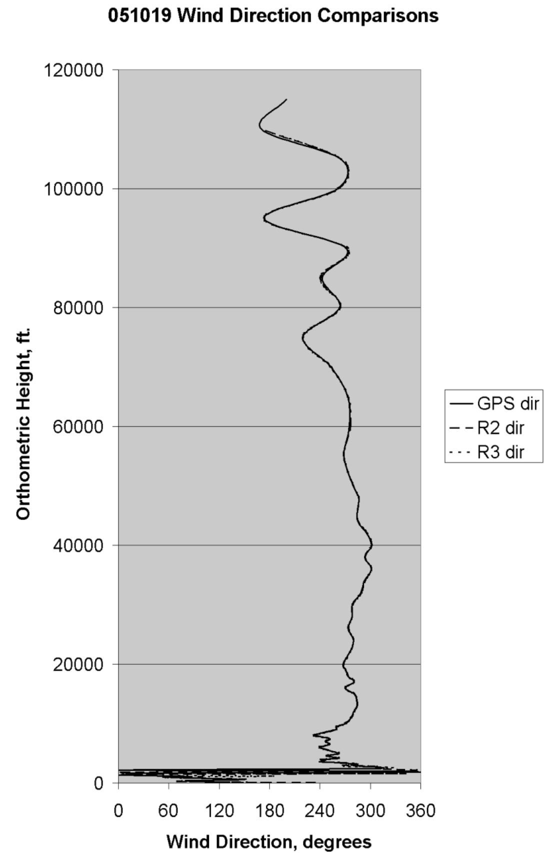


Figure 1. Wind Table Speed Comparisons

Figure 2. Wind Table Direction Comparisons

We wish to show that the data does not provide evidence sufficient to conclude that there exists a difference between any two of the three population means. (For example, the three populations we will start with will be, for October 19, 2005, R2 wind-table speeds, R3 speeds, and GPS speeds.) The null hypothesis is that the means are the same. The alternate hypothesis is that at least two of the means are different from each other. The P value we will get is the observed level of significance; if the P value is high (close to 1.000), we cannot reject the null hypothesis.

Before doing these analyses, the data was edited in two ways. (1) A level was removed unless at least two wind data sources had reported values for that level. If two but not all three wind-data sources reported values for a particular level, that level was retained as one with a "missing value". (2) With regard to wind directions, if one wind-data source reported a value of, say, 358 degrees, whereas another source reported, say, 2 degrees, those two directions are actually only 4 degrees apart, but an ANOVA would judge them very different. To correct for this, some of the directions were changed to an equivalent direction modulo 360.

The results for October 19, 2005 were:

P = 0.970 for speed (one-way ANOVA: GPS speed, R2 speed, R3 speed) up to 110,000 feet,
P = 0.923 for direction (one-way ANOVA: GPS dir, R2 dir, R3 dir) up to 110,000 feet,
P = 0.909 for speed just up to 5,000 feet, and
P = 0.934 for direction up to 5,000 feet.

On October 20, 2005, Radar 2 had trouble obtaining lock, and did not start continuous tracking until the 1300-foot level. So the results for this day were:

P = 1.000 for speed 1,300 feet and above, and
P = 0.978 for direction 1,300 feet and above.

On November 17, 2005, Radar 3 had trouble obtaining lock, and also lost track again after achieving it; Radar 3 did not start continuous tracking until the 1800-foot level. So the results for this day were:

P = 1.000 for speed 1,800 feet and above, and
P = 1.000 for direction 1,800 feet and above.

On all days, when all three of Radar 2, Radar 3, and GPS were tracking, the P values of the ANOVAs were exceptionally high; thus, we do not reject the null hypothesis. That is, we can not conclude that there is any significant difference among the means of the readings from the three wind-data sources.

Since wind tables with missing data are not typical of those used during actual Wind Weighting, the test data was further modified as follows. The wind tables produced from Radar 2 data and from Radar 3 data for each of the test days were augmented by filling in levels missed by one radar with data from the other. Also, for each of the three days, the 50-foot levels of all three wind tables were filled in with the same values, as if those values had come from the tower. These "complete" wind tables made possible additional GPS-radar comparisons.

Four vehicles were selected: "TESTRK", a small test rocket; "21125", a Black Brant VC 21.125GE (a one-stage rocket), "29035", a Terrier Malemute 29.035UP (a two-stage rocket), and "39006", a Black Brant XI (TALOS-TAURUS-BBVC – a three-stage rocket). Then the "Lewis" method (part of the Wind Weighting software) was used, for each day, for each vehicle, for each wind table (R2, R3, and GPS), to compute the "ballistic wind" and estimate launcher corrections. (A ballistic wind is that [fictional] constant wind, uniform from the ground to the top of the atmosphere, which would have the same ultimate effect on the rocket's trajectory as the actual, varying winds encountered during its flight.)

To interpret the results, we will use the following criterion: "… two wind profile generation techniques are to be considered functionally identical if they consistently produce ballistic wind solutions with vector differences of less than 1.0-ft/sec when measuring the same wind. Two wind profile generation techniques must be considered materially different if they consistently produce ballistic wind solutions with vector differences greater than 2.5-ft/sec when measuring the same wind. … If the new technique produces results that are in the gray area between identical and materially different, further investigation … is warranted, and a satisfactory explanation must be produced before the new technique can pass muster."[12]

To use this third way of comparing GPS and the two radar wind profiles, we must compute the vector difference between the ballistic winds (computed from the wind tables) produced by each pair of wind-data sources, for each vehicle, for each day. The magnitudes of these vector differences for October 19, 2005 are presented below (Figure 3).

Vehicle	Magnitude of vector difference between ballistic winds produced by:		
	R2 and R3	R2 and GPS	R3 and GPS
TESTRK	2.45		
TESTRK		1.69	
TESTRK			1.49
21125	1.76		
21125		1.26	
21125			0.87
29035	1.29		
29035		0.92	
29035			0.55
39006	1.11		
39006		0.77	
39006			0.41

Figure 3. Ballistic Wind Vector Difference Magnitudes for October 19, 2005

This table, and the ones for October 20 and November 17, showed, as did the complete ANOVA analyses, that "the radars do not agree with each other better than they do with the GPS."[1] Also, ironically, by remaining as close as possible to our original test data, we have produced substandard wind tables; before an actual launch, an entire series of balloons would be tracked, and the wind tower would be on. For these reasons, I was not discouraged by GPS/radar results outside the "functionally identical" range. Instead, let us go on to compare the radar and GPS data in a fourth way: by using the Wind Weighting software's trajectory-simulation capability.

The Wallops Wind Weighting software uses the procedure described in a report entitled "SENS-5D Trajectory and Wind-Sensitivity Calculations for Unguided Rockets"[13]. SENS-5D uses a fourth-order, modified Adams-Bashforth predictor-corrector method to integrate the equations of motion, supplemented by a fourth-order, modified Runge-Kutta method to change the step size. The "5D" refers to the use of a 5-degrees-of-freedom rigid-body dynamics model.

In Figure 4 below, (and in similar tables for the other test days), I ran the SENS-5D trajectory-simulation part of the Wind Weighting software for each vehicle under four conditions. I "flew" each rocket through the model with no winds, with Radar 2 winds, with Radar 3 winds, and with GPS winds, to see where it would land. When I was using Radar 2 winds, I entered the adjusted launcher settings estimated by the Lewis method for that day for that vehicle when we used Radar 2 winds. An analogous procedure was used when the model was run using Radar 3 winds and when using GPS winds. Our hope is that the rocket will land, despite the winds through which it flies, where it would have landed if there were no wind and the original, no-wind launcher settings were used. For the sake of brevity, I include results only for October 19, 2005, and for multi-stage vehicles I include the impact range and azimuth for only the last stage.

Over the long history of the Sounding Rocket Program at Wallops Flight Facility, the Flight Safety Group has established pre-launch condition restrictions and controls[14]. These limits, combined with the dispersion characteristics of a launch vehicle, "result in an envelope of

	Vehicle	Wind data source	No-wind azimuth (Degrees)	No-wind elevation (Degrees)	Adjusted azimuth (Degrees)	Adjusted elevation (Degrees)	Impact Range (NM)	Impact Azimuth (Degrees)
051019	TESTRK	NONE	130	75			2.4	130.15
051019	TESTRK	R2	130	75	134.80	76.49	2.6	130.46
051019	TESTRK	R3	130	75	134.93	76.28	2.6	130.40
051029	TESTRK	GPS	130	75	135.37	76.38	2.6	130.44
051019	21125	NONE	130	84			189.6	134.95
051019	21125	R2	130	84	125.97	84.80	175.9	137.20
051019	21125	R3	130	84	126.98	84.34	181.8	137.32
051019	21125	GPS	130	84	128.25	84.53	179.5	138.03
051019	29035	NONE	90	73			800.2	92.84
051019	29035	R2	90	73	89.93	72.52	807.0	93.14
051019	29035	R3	90	73	90.27	72.41	807.9	93.17
051019	29035	GPS	90	73	90.25	72.48	807.1	93.18
051019	39006	NONE	90	83.5			405.8	92.85
051019	39006	R2	90	83.5	90.76	82.68	403.1	94.53
051019	39006	R3	90	83.5	91.39	82.57	404.4	94.62
051019	39006	GPS	90	83.5	91.32	82.62	402.8	94.56

Figure 4. Trajectory Simulations for October 19, 2005

permissible aimpoints for the spent stages and other impacting vehicle hardware"[15]. We would need such envelopes to determine whether the impact points in the tables above are "close enough" to the target impact points. We shall not go through that analysis for these engineering tests; such analysis is included in the certification testing currently being done by the Flight Safety Group, which involves tests done under much more realistic, launch-like conditions.

CONCLUSION

Software engineering tests indicate that GPS radiosondes provide a highly reliable, portable, and cost-effective method of obtaining wind profiles for the purposes of Wind Weighting unguided sounding rockets. The precision of tracking balloons by GPS is at least as good as that of the better tracking radars[16]. Including GPS among our wind-data sources for Wind Weighting "can reduce the burden on range radar operations"[7], and improve the chances of launching.

Because of the importance of near-surface winds in the Wind Weighting of unguided sounding rockets, a subject for further investigation is a more extensive comparison of radar- and GPS-derived wind data in the first few thousand feet above the surface. Related to this is the question concerning the tether length; if it is kept at 21 meters, should that length be added to all orthometric heights reported by the radiosonde, as has been done in this paper? Or would it be better to attach the radiosonde right under the balloon, allowing acquisition of data closer to the surface, but causing other problems? A third area for further investigation concerns accuracy lost due to the self-induced and possibly erratic motions of the balloon itself.[8,16]

The work done in this paper has possible application to other range activities in addition to the Wind Weighting of unguided sounding rockets; for example, "low-altitude wind conditions that impact the final approach and landing" of UAVs "are particularly critical to safety and postflight engineering analyses."[7]

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REFERENCES

[1]Bull, Barton, "A Real Time Differential GPS Tracking System for NASA Sounding Rockets," ION GPS 2000, Salt Lake City, UT, Sept. 19-22, 2000.

[2]Martell, Hugh, and Bull, Barton, "Tracking the Relative Motion of Four Space Payloads Launched from a Sub-Orbital NASA Rocket," ION GPS 1999, Nashville, TN, Sept. 14-17, 1999.

[3]http://rscience.gsfc.nasa.gov/srrov.html

[4]http://www.wff.nasa.gov/code810/

[5]Lanzi, R. James, "Wind Weighting Tutorial", NASA Wallops Flight Safety Group Internal Memo.

[6]Lockheed Martin Sippican, Inc., "W-9000 Meteorological Processing System: Operation and Maintenance Manual, GPS Supplement, Version 1.2, 9010-812, Jan. 7, 2000.

[7]Teets, Jr., Edward H., and Harvey, Philip O., "Comparison of Three Wind Measuring Systems for Flight Test," American Meteorological Society's Ninth Conference on Aviation, Range, and Aerospace Meteorology, H-2415,Orlando, Florida, Sept. 11-15, 2000.

[8]Wilfong, T. L., Barat, J., and Crosiar, C. L., "Characteristics of Wind Profiles Derived from a Stabilized Balloon and Differential GPS Technology," Amer. Meteor. Soc. Ninth Conference on Aviation, Range, and Aerospace Meteorology, Orlando, FL, Sept. 11-15. 2000.

[9]Smith, Donna C., and May, Linda R., "Wind Weighting Software Balloon Track Test Results," NASA Wallops Systems Software Engineering Branch Internal Memo, Feb. 26, 2004.

[10]Lockheed Martin Sippican, Inc., "Radiosonde Balloon Motion Filter Used in the GPS W9000 System", Lockheed Martin Sippican Proprietary Information.

[11]Minitab 14, Software Package, Student Release 14 for Windows, Minitab, Inc., State College, PA, 2005.

[12]Lanzi, R. James, "Safety Analysis Report: Methodology for Developing Launcher Correction Limits for Sounding Rocket Vehicles with Applications to 21.125/Pfaff", NASA Wallops Flight Safety Group Internal Memo, Aug. 26, 1999, and subsequent discussion at a Dec., 2003 meeting.

[13]Singh, Raghubansh P., Huang, Louis C. P., and Cook, Ronald A., "SENS-5D Trajectory and Wind-Sensitivity Calculations for Unguided Rockets," NASA CR-141402, Dec., 1975.

[14]WFF Safety Office, Suborbital and Special Orbital Projects Directorate, "Range Safety Manual For Goddard Space Flight Center (GSFC)/Wallops Flight Facility (WFF)," RSM-2002, June 28, 2002.

[15]Lanzi, R. James, "Surface Wind Variability Limits: A Proposed Approach", NASA Wallops Flight Safety Group Internal Memo.

[16]Barat, Jean, "Stabilized Balloons for GPS Radiosondes", Flow-Tronic S.A., Welkenraedt, Belgium.