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# Use of global positioning system technology to track subject's location during environmental exposure sampling

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Global positioning system (GPS) data recorders were worn by subjects in the Oklahoma Urban Air Toxics Study (OUATS) for automatic logging of their location as they went about their normal daily activities. The location information obtained by the GPS units had an uncertainty of about 10–20 m, which was sufficiently precise to track subjects' movements on trips outside the immediate vicinity of their homes. Due to instrument problems, primarily related to reduced battery life, the units operated for only about 30% of the total monitoring time attempted in 25 trials. The GPS data were compared to time–activity diaries kept by the subjects. In almost all cases, the GPS data confirmed all travel events reported in the subjects' diaries. Additionally, in five out of five trials in which the logging period covered most or all of the subjects' daytime activities, at least one travel event that was not recorded in the diary was detected by GPS. Notwithstanding the limitations of present technology, GPS was found to be a promising means for tracking of research subjects in community-based exposure assessment studies. *Journal of Exposure Analysis and Environmental Epidemiology* (2001) **11,** 207–215.

**Keywords:** *environmental exposure, global positioning system, time diary.*

## Introduction

Environmental exposure sampling studies, such as the Total Exposure Assessment Methodology (TEAM) Study (Wallace et al., 1987, 1991) and the National Human Exposure Assessment Survey (NHEXAS) (Freeman et al., 1999), have traditionally relied on time–activity diaries and surveys to provide information about study subjects' activities and locations during the exposure monitoring period. Variations of the diary method include the "yesterday" diary, in which the research subject is interviewed in-depth about the duration and location of his or her activities during the previous calendar day (Robinson and Silvers, 2000), and the "tomorrow" diary, in which the research subject is given instructions to complete a diary of activities the next day (Robinson and Godbey, 1997). NHEXAS piloted the use of an 8-day diary consisting of two parts: a timeline, which tracked the subject's location at every hour of the day, and an activity diary, which elicited yes/no and duration information on 29 activities or exposures (Freeman et al., 1999).

A number of strategies have been employed to assess and improve the accuracy of diary data (Robinson and Godbey, 1997). The overall reliability of time diaries — that is, their ability to yield reproducible results — has been demonstrated by the similarity of aggregate time use patterns obtained using different diary methodologies (Robinson and Godbey, 1997). In the NHEXAS time diary, internal consistency was determined by comparing responses to different questions that covered the same information (Freeman et al., 1999). The validity of time diaries has also been studied by comparing data recorded by the research subject in their diaries to data obtained in a manner that is to some extent independent of the diary. A variety of methods have been used in diary validation studies, including (Robinson and Godbey, 1997): (1) use of a beeper at random times to prompt the subject to record the activity in progress when the beeper was activated; (2) follow-up interviews to elicit recall of the subject's activity during a randomly selected hour of the period covered by the diary; (3) corroboration of the subject's activity by another person who was reported by the subject to have been present; (4) "shadowing" of the subject by an observer; (5) head counts of church attendance, relative to aggregated diary reports of attendance; (6) video or audio monitoring of television viewing. In these validation studies, agreement between the diary and the independent method typically measured about 80–90%, except in the case of church attendance, which tended to be overreported by 50–100%, and television viewing, which was underreported by 20–50%. A "zero sum" approach to time diaries, requiring an accounting for all 1440 min in a day, is recommended to reduce problems with

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inaccurate reporting of time spent in socially approved or disapproved activities (Robinson and Godbey, 1997; Robinson and Silvers, 2000).

Global positioning system (GPS) technology may present an additional method for continuous, contemporaneous validation of time–activities diaries. The United States government manages the GPS as a free public asset. The system consists of 24 active satellites, plus additional back-up satellites, which travel in well-defined orbits around the earth and transmit precisely synchronized radio signals. A GPS receiver on earth that detects the signals can calculate its distance from each satellite based on the travel times of pulse sequences encoded in the radio signal. The position of the receiver is then estimated by triangulation (U.S. EPA, 1992). Originally, the U.S. Department of Defense employed a technique called "selective availability" to degrade the real-time precision of GPS for nondefense users. The effect of selective availability was to superimpose a time-dependent dithering pattern with a radius of about 100 m on the apparent location of the GPS receiver. To calculate the location of a mobile GPS receiver more precisely, albeit with some delay, the user could mathematically remove this dithering by applying differential corrections that were determined from the measured dithering in the location of a GPS base station of known coordinates. Selective availability was turned off by presidential order on May 1, 2000, after the U.S. government decided that more localized methods could be used to protect the United States and its allies against potential hostile uses of GPS. The end of selective availability resulted in an estimated 10-fold improvement in the real-time precision of GPS for civilian users.

Although GPS has been widely used in applications such as land surveying, mapping, and navigation, it has limitations that potentially reduce its usefulness in some spheres of human activity. To calculate coordinates (i.e., longitude, latitude, and altitude), the GPS receiver must have line-of-sight reception of at least four satellites. The radio waves transmitted by the satellites can pass through clouds and vegetation without significant attenuation, but they are blocked by conductive materials such as earth and metal. Due to the Faraday cage effect, the signals typically cannot penetrate through steel-reinforced structures. Partial blocking of the sky by embankments or tall buildings may result in reduced precision of location measurements. Precision of GPS location estimates is highest when signals are received from satellites that are widely separated in azimuth and elevation. The reduction in precision due to poor relative geometry of satellites is termed positional dilution of precision (PDOP) (U.S. EPA, 1992).

GPS technology has been used for wildlife tracking and for tracking of fleet vehicles, such as taxicabs and emergency vehicles, but use of GPS for tracking individual humans during their daily activities appears to be quite limited to date. The U.S. Forest Service has reported on the research use of backpack-mounted GPS recorders to track elk hunters over 6-h periods in Montana (Lyon and Burcham, 1998). A lightweight GPS receiver was also used to measure the velocity of a human volunteer engaged in short-term outdoor athletic activity (Schutz and Chambaz, 1997).

The present study of the use of GPS location tracking to validate 24-h time–activity diaries was undertaken within the context of the Oklahoma Urban Air Toxics Study (OUATS). The primary objective of OUATS is to develop generalized models for estimating personal exposure in broad populations, based on an investigation of how temporal, personal, and urban factors influence the relationship between personal and area exposure measurements. Exposure is estimated from two sequential 12-h (nighttime and daytime) integrated air samples for volatile organic compounds collected simultaneously in the personal breathing zone of the research subject, in the main living area of the subject's home, and in the subject's backyard. Activity patterns of the research subject will serve in the data analysis both as potential determinants of exposure and as potential outcome variables determined by independent factors such as weather conditions, size of urban area, occupation of the research subject, and the presence of young children in the household. The specific purpose of the GPS study was to test the application of currently available GPS data recorders as a means of validating time–location data recorded in participants' time–activities diaries in community-based exposure assessment studies.

## Materials and methods

The use of human subjects in this study was approved by the Institutional Review Board of the University of Oklahoma Health Sciences Center.

### *Study Population*

Research subjects for the OUATS were recruited from the populations of four cities in Oklahoma: Oklahoma City, Ponca City, Stillwater, and Tulsa. The primary means of recruitment were flyers posted in public areas, news media reports, and personal contacts in workplaces and public gathering places. Participation in the study was limited to adults between 21 and 55 years of age who lived in nonsmoking households in detached single-family dwellings.

### *Selection Criteria for the GPS Data Recorder*

The GPS data recorders used in this study had to be capable of performing their data-logging function with a minimum of inconvenience and effort on the part of the research subject. In brief, the device had to be capable of logging positions automatically every 5 to 15 min (or more frequently, if possible) and storing 16 to 24 h of data. The battery life had to be sufficient to allow continuous logging with no more than one or two battery changes in a 24-h period. The unit had to be small enough to be worn comfortably around the waist, without impeding normal activities. The antenna had to be configured so that it would not be damaged during use and its appearance would not be unacceptable to the research subject. Finally, because selective availability was in effect at the beginning of this project, the GPS unit had to be capable of storing data in a form that could be postprocessed with differential corrections.

Product information was solicited from a number of GPS manufacturers. In accordance with institutional requirements, the purchase of GPS data recorders followed a competitive bidding process, subject to the performance specifications described above and the constraints of the project budget. The unit purchased was the March II-E GPS data recorder (Corvallis Microtechnology, Corvallis, OR), an eight-channel receiver with a reported 95% confidence radius of 5 m for positions determined from differentially corrected code phase measurements. The unit was powered by an internal rechargeable lithium metal hydride battery, which was designed to provide 4 to 5 h of charge. Operating time was extended by the use of an external rechargeable lead–acid battery, designed to provide an additional 12 h of charge. The unit included a built-in antenna, but for improved reception, an external patch antenna was used. The external antenna was a flat oblong disk measuring 8 cm by 6.5 cm by 1 cm thick, with a magnetic back designed for mounting on a vehicle. The total weight of the unit with battery was about 2 kg. The data storage capacity was 2 MB, which was claimed to be sufficient to hold 14,400 data points.

*Monitoring Procedure*

The 24-h monitoring period generally began and ended in the early evening. The GPS data recorder was set to log every 4 to 8 s. After it was verified that the unit was receiving satellites and starting to log data, the unit was secured inside a nylon hip pack, the external battery was plugged into a nine-pin com port on the unit, and the hip pack was fastened around the subject's waist. The external antenna was magnetically mounted on a large steel button that was pinned to the shoulder of the subject's clothing. The subject was instructed to wear the GPS unit at all times except when bathing or sleeping and to replace the external battery in the morning, after 12 h. A photograph of the monitoring equipment as worn by the subject is presented in Figure 1.

After monitoring was completed, the GPS data files were downloaded to a computer using the PC-GPS version 3.6b or version 3.6d2 software purchased from the manufacturer. Differential corrections were computed within the PC-GPS software using continuously operating reference station (CORS) data provided online by the National Geodetic Survey. The GPS data points could be imported into MapInfo and superimposed on a street map, but generally the locations of the logged points were determined by visually comparing the plotted points to a separate printed street map. It should be noted that location data had to be secured as confidential information because it could be used to identify the residence of the study participant.

*Activities Diary*

The time–activity diary used in this study was based on the Multinational Time Budget Research Project method (Harvey et al., 1984), which served as the pattern for the diaries used in the TEAM studies (Ott, 1985). The standard diary form employed in time budget research was modified to elicit information on exposure to environmental tobacco smoke and use of consumer products, chemicals, equipment, etc. A sample page of the diary is provided in Figure 2. Subjects were given oral and written instruction on how to complete the diaries. The subjects were instructed to:

- make entries in the diary as soon after each activity as possible;
- identify his or her main activity during each time interval;
- specify indoor locations where the time was spent, e.g., room in home (kitchen, living room, bath, garage, etc.) or other indoor location by type (workshop, restaurant, office, supermarket, dry cleaners, etc.);
- specify outdoor locations where time was spent, e.g., car, bus, yard, street, gas station, construction site, etc.;
- record exposures to environmental tobacco smoke; and
- record the use of consumer products, chemicals, tools, etc. by self or others in the same location.

After the diary and the GPS data were reviewed by an investigator, the subject was called by telephone to clarify diary entries, fill information gaps, and resolve any apparent discrepancies between the diary and the GPS tracking data.

## Results

*Assessment of GPS Data Recorder Performance*

*Acceptability to Study Subjects* No study participants objected to wearing the GPS monitors. Several participants of wide girth found it more comfortable to wear their GPS unit in a minibackpack than in a hip pack.


**Figure 1.** Personal monitoring equipment worn in the study. The GPS data recorder is carried inside a dark-colored nylon "fanny pack" worn at the subject's waist (shown here on viewer's right). The external battery is contained in a separate pouch worn on the belt of the fanny pack. The external patch antenna, attached to the data recorder by a thin cable, is positioned at the subject's shoulder. The air-sampling pump is also typically worn at the waist, attached by flexible tubing to a sorbent tube in the subject's breathing zone, as shown.

*Satellite Reception* In preliminary trials, it was found that some individuals had poor reception of satellites when the built-in antenna was used with the GPS unit worn at the waist. Use of the shoulder-mounted external antenna dramatically improved reception for these individuals and was therefore made part of the standard procedure.

In the best case, satellite reception was sufficient to allow the GPS unit to log position data nearly continuously every 4 to 8 s throughout all outdoor activities. In addition, reception was typically good enough to allow logging inside dwellings. As expected, however, partial blocking of the sky by the metal body panels of some vehicles and by urban

**Figure 2.** Sample page from the time-activity diary used in this study.

| Time | What did you do? | Time began | Time ended | Where? | Did anyone smoke? | Chemicals, products, equipment & tools used |
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**Table 1.** Results of first 25 trials of GPS tracking of community volunteers.

| Trial no. | GPS logging duration, inclusive (hour:minutes) | Performance of GPS unit | Correspondence between GPS and diary[a] |
|---|---|---|---|
| 1 | 10:26 | Apparent battery failure | No trips during logging period |
| 2 | 23:19 | Logging terminated due to memory limit | Diary omitted two of five trips shown by GPS; terminated when disk full |
| 3 | 22:04 | | Diary omitted four of nine trips shown by GPS |
| 4 | 0:00 | No logging because unit was on default settings | |
| 5 | 9:56 | Apparent battery failure | No trips during logging period |
| 6 | 13:06 | Truncated data file; spurious coordinates; apparent battery failure | GPS showed two of four trips reported in diary (sparse logging during travel by car). |
| 7 | 21:40 | Logging terminated due to memory limit | GPS showed six of eight trips reported in diary; diary omitted one drive around block shown by GPS |
| 8 | 9:18 | Apparent battery failure | GPS showed one of two trips reported in diary (sparse logging during travel by car) |
| 9 | 0:00 | Failure cause unknown | |
| 10 | 16:02 | Logging terminated due to memory limit | Diary omitted one of six trips shown by GPS |
| 11 | 0:31 | Failure cause unknown | |
| 12 | 0:01 | Failure cause unknown | |
| 13 | 3:06 | Apparent battery failure | GPS did not log walk to neighbor's house and back. |
| 14 | 2:59 | Apparent battery failure | No trips during logging period |
| 15 | 0:03 | "New work week" fault | |
| 16 | 0:08 | Failure cause unknown | |
| 17 | 0:08 | "New work week" fault | |
| 18 | 10:55 | Apparent battery failure | No trips during logging period |
| 19 | 6:50 | Apparent battery failure | No trips during logging period |
| 20 | 4:07 | Apparent battery failure | GPS showed two of two trips reported in diary |
| 21 | 7:51 | Apparent battery failure | GPS showed one bicycle ride reported in diary |
| 22 | 0:02 | Failure cause unknown | |
| 23 | 8:22 | Apparent battery failure | GPS showed three of three trips (sparse logging during travel by car) |
| 24 | 12:24 | Apparent battery failure | Diary omitted one of four trips shown by GPS |
| 25 | 0:00 | Failure cause unknown | |

[a]A trip is defined as a travel segment from one location to the next destination. Only trips reported during the logging period were counted.

canyons often reduced the fraction of outdoor time for which position data was successfully logged. Logging usually stopped inside commercial buildings due to the shielding effect of metal-reinforced construction. After exiting a shielded location, the unit often took 5 to 10 min to start logging again.

*Data System Performance* Although the 2-MB data storage capacity of the GPS unit was theoretically sufficient to hold 14,400 locations, it was found in the course of this study that the size of the raw data file was proportional, not to the number of points logged, but rather to the total time satellite signals were received. Each hour of satellite reception required about 100 KB and each point logged required about 50 bytes of disk space in a second "feature" file. These constraints effectively limited logging time to about 17 h when positions were logged every 8 s. To conserve data-storage capacity, an additional instruction was given to the subject to shield the antenna with aluminum foil during the subject's sleep period; however, it was evident from the logged data that many subjects did not comply with this instruction.

The software package purchased from the manufacturer of the GPS unit had limited capabilities for data export. Longitude and latitude for each logged point could be exported as an ASCII file. Time, longitude, latitude, and other data could also be printed out in hard copy. However, the Open DataBase Connectivity (ODBC) interface provided with the software did not appear to function properly, and it was therefore not possible to export complete information, such as the time at which each point was logged, to other databases. Within the PC-GPS mapping software, time labels were not readily available for plotted data points; time could only be read on a point-by-point basis outside the map window, a very laborious process.

*Precision* Under selective availability, position readings had a radius of uncertainty of about 60 m. Differential correction of position readings, using base station data downloaded from the National Geodetic Survey CORS website, improved precision to about a 10–20 m radius. After the end of selective availability, precision without differential correction improved to about a 10 m radius. However, artifactual 30–60 m long jumps in position still occurred, associated with high PDOP that probably resulted from temporary loss of reception of one or more satellites.

*Battery Performance* The GPS units required battery power throughout the entire period when the receiver was on, even under shielded conditions when data were not being logged. The charge status of the internal battery could be monitored through the unit's installed software, but neither the external batteries nor their chargers were equipped with a charge status indicator.

Reliability of the external batteries was found to decline rapidly with repeated use; after as few as three or four cycles of charging and use, the combined operating life of the internal and external batteries typically decreased from 16 to 17 h to less than 9 to 10 h. Battery failure was observed in bench tests as well as in field trials.

*Overall Reliability Experience* In aggregate, in the first 25 GPS trials on subjects recruited from the community, the units operated for only about 30% of the total monitoring time attempted. The duration and results of these trials are summarized in Table 1. In 12 trials, the GPS unit terminated logging after 3 to 13 h of monitoring; in the absence of other likely causes, these failures were ascribed to short battery life. In one of these 12 trials, the unit stored a highly truncated raw data file and many of the calculated coordinates were spurious; the reason for this malfunction was unknown. In two trials that began on a Saturday evening, the unit suspended operation at midnight Greenwich Mean Time, apparently due to a software limitation. In one trial, the unit was apparently unable to find the appropriate satellites because its most recently stored position coordinates and internal clock time had reverted to their default settings. Finally, in six trials the unit either failed to record any logging data or stopped logging within 30 min. The reasons for these failures were unknown.

*Validation of Diary Data*

This section summarizes the results of the first 16 trials in which significant amounts of GPS data were logged, for periods ranging from 3 to 23 h.

In five trials, the subject reported staying at home throughout the period logged (3 to 11 h), and the GPS data appeared to confirm this report. In five other trials, the subject's diary reported leaving the home on one or more occasions during the period logged (8 to 13 h) and the GPS data confirmed each item of point-to-point travel reported. However, in several of these five trials with confirmed trips, there was a discrepancy between the duration of the activities as reported in the diary and the duration indicated by GPS tracking. For example, in one trial a subject reported taking a 30-min bicycle ride, but the GPS data showed the ride lasted only 10 min. Also, in three of these same five trials, GPS tracking during vehicular travel was rather sparse, probably due to shielding by the vehicle body panels. In one trial, the GPS failed to log a reported trip to a neighboring house. In another trial, in which monitoring lasted for nearly 22 h, the GPS failed to log two reported trips, apparently due to lack of satellite reception, but on another trip the GPS data indicated an additional leg that

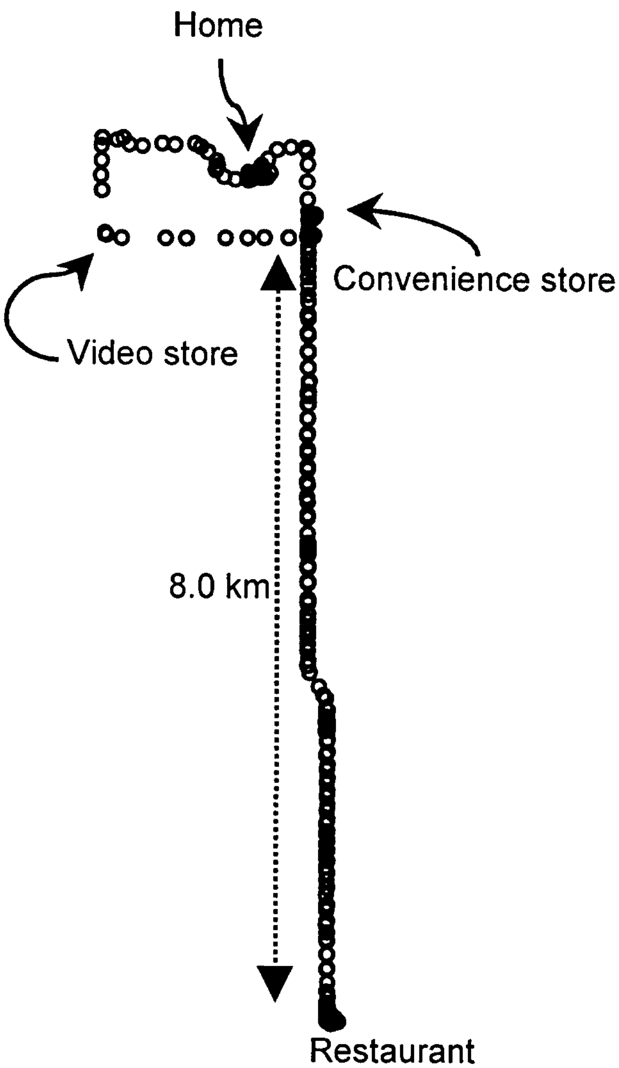


**Figure 3.** Plot of more than 3000 locations (open circles) logged by GPS on a community volunteer in the course of 1 day. Coordinates and street overlay have been omitted to protect the volunteer's privacy. Distance scale and destination labels have been added.

was not recorded in the diary. When questioned, the subject did not recall this additional leg.

In four trials, ranging from 12 to 23 h monitored, the GPS confirmed all reported trips and also indicated additional stops that were not recorded in the diary. In all cases, these unreported stops were of short duration and were only one in a series of errands. For example, one subject recorded in her diary that she drove from her home to a restaurant for lunch, then drove on to a video store, and then returned home. The GPS location plot for this trial is presented in Figure 3. The GPS data indicated that an additional stop, lasting about 3 min, also occurred on this trip. When the subject was prompted, she recalled that she had stopped at a convenience store on the way to the restaurant.

## Discussion

GPS was found to be a promising technology for tracking of research subjects in an environmental exposure study. However, some limitations of the technology must be noted that preclude its use as the sole or primary source of location tracking data. For individuals in urban settings, the most serious limitation is the blocking of GPS satellite transmissions by steel-reinforced structures, vehicle body panels, and other electrically conductive media. Shielding within vehicles can be reduced by placing the GPS antenna on the dashboard of the vehicle or mounting it on the vehicle exterior.

The 10-m resolution obtained using a code phase GPS data recorder after the cessation of selective availability was not sufficient to track movement between rooms inside the subject's home, or between the house, the yard, and neighboring dwellings. Code phase GPS is therefore best suited to validating and supplementing diary data relating to travel outside the immediate vicinity of the residence. If necessary, however, more expensive carrier phase instruments, which offer precision on the order of 10s of centimeters or less, could potentially be used to track subjects' movements inside the home and other unshielded structures. Carrier phase GPS achieves this higher precision by measuring the phase not only of the pulse code sequences, but also of the much higher frequency carrier waves transmitted by the satellites.

The GPS model utilized in this study was designed for mapping applications in which the logging of data takes place under the active control of a trained technician. The adoption of this instrument for continuous 24-h logging with a minimum of attention by the volunteer thus represented a major departure from its primary design purpose. For this reason, several manufacturers of GPS data recorders who were contacted by the investigators declined to submit bids to supply devices for this study. The types of problems encountered during this study with short battery life, poor reception, and software glitches would be mitigated in situations where the GPS instrument could be more closely monitored. Unfortunately, this may not be a realistic option in community-based studies. An alternative approach, which was considered, would have been to modify GPS units designed for animal tracking. However, the manufacturers who were contacted about this idea were not sanguine about the feasibility and affordability of converting the standard collar-mounted unit, with a built-in dipole antenna oriented vertically between the animal's shoulders, to fit human anatomy and posture, i.e., waist-mounted with a relatively small antenna on the shoulder.

The weight and bulk of the GPS units did not appear to present a problem for the subjects in this study, who were all healthy adults. However, the 2-kg weight could be excessive for young children or frail adults.

Currently, we are in the process of making limited modifications including the selection of new batteries. These changes are expected improve the GPS performance considerably. Based on preliminary work, checking and reinitialization of the GPS unit after 12 h, coupled with improved battery life, ought to reduce the operational error rate by about two-thirds.

Notwithstanding the inherent limitations of GPS technology and the disappointing reliability of the batteries provided with the specific model used in this study, some interesting results were obtained. In each of the five trials (numbers 2, 3, 7, 10, and 24) in which the logging period covered most or all of the subject's daytime activities, at least one travel event that was not recorded in the diary was detected by GPS. A common characteristic of all these events was that they consisted of one or more incidental trips of short duration that occurred as part of a series of errands. (This same pattern was recognized earlier during pilot runs in which the investigators wore the GPS units and kept diaries during their normal, rather hectic daily activities.) None of the errands that the subjects omitted from their diaries involved the subject directly handling potential sources of air contaminants, e.g., pumping fuel. However, in several cases the subject briefly visited a shop where volatile materials such as painting supplies were sold.

With the exception of the line-of-sight limitation on GPS reception, the difficulties noted in this study are tractable. GPS tracking of subjects' daily trips is feasible, and it appears that GPS tracking is useful in supplementing and correcting diary entries in a way that is not solely reliant on subjects' guided or unguided recollection of their day's activities.

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## References

Freeman N.C.G., Lioy P.J., Pellizzari E., Zelon H., Thomas K., Clayton A., and Quackenboss J. Responses to the Region 5 NHEXAS time/activity diary. *J Exposure Anal Environ Epidemiol* 1999: 9: 414–426.

Harvey A.S., Szalai A., Elliott D.H., Stone P.J., and Clark S.M. Time Budget Research: An ISSC Workbook in Comparative Analysis. Campus Verlag, Frankfurt, Germany, 1984.

Lyon L.J., and Burcham M.G. Tracking Elk Hunters with the Global Positioning System. U.S. Departmental of Agriculture, Forest Service, RMRS-RP-3, Ogden, UT, 1998.

Ott W.R. Total human exposure. *Environ Sci Technol* 1985: 19: 880–886.

Robinson J.P., and Godbey G. Time for Life. Penn State Press, State College, PA, 1997, pp. 57–67.

Robinson J.P., and Silvers A. Measuring potential exposure to environmental pollutants: time spent with soil and time spent indoors. *J Exposure Anal Environ Epidemiol* 2000: 10: 341–354.

Schutz Y., and Chambaz A. Could a satellite-based navigation system (GPS) be used to assess the physical activity of individuals on earth? *Eur J Clin Nutr* 1997: 51 (5): 338–339.

U.S. EPA. GIS Technical Memorandum 3: Global positioning systems technology and its application in environmental programs. U.S. EPA/600/R-92/036, Washington, DC, 1992.

Wallace L.A., Pellizzari E.D., Hartwell T.D., Sparacino C., Whitmore R., Sheldon L., Zelon H., and Perritt R. The TEAM Study: personal exposures to toxic substances in air, drinking water, and breath of 400 residents of New Jersey, North Carolina, and North Dakota. *Environ Res* 1987: 43: 290–307.

Wallace L., Nelson W., Ziegenfus R., Pellizzari E., Michael L., Whitmore R., Zelon H., Hartwell T., Perritt R., and Westerdahl D. The Los Angeles TEAM Study: personal exposures, indoor–outdoor air concentrations, and breath concentrations of 25 volatile organic compounds. *J Exposure Anal Environ Epidemiol* 1991: 1: 157–192.