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Geodetic observation of contemporary deformation in the northern Walker Lane: 1. Semipermanent GPS strategy

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ABSTRACT

As of October 2005, the semipermanent Global Positioning System (GPS) network called MAGNET (Mobile Array of GPS for Nevada Transtension) included 60 stations and spanned 160 km (N-S) × 260 km (E-W) across the northern Walker Lane and central Nevada seismic belt. MAGNET was designed as a cheaper, higher-density alternative to permanent networks in order to deliver high-accuracy velocities more rapidly than campaigns. The mean nearest-neighbor spacing is 19 km (13–31 km range). At each site, the design facilitates equipment installation and pickup within minutes, with the antenna mounted precisely at the same location to mitigate eccentricity error and intersession multipath variation. Each site has been occupied ~50% of the time to sample seasonal signals. Using a custom regional filtering technique to process 1.5 yr of intermittent time series, the longest-running sites are assessed to have velocity accuracies of ~1 mm/yr. The mean weekly repeatability is 0.5 mm in longitude, 0.6 mm in latitude, and 2.1 mm in height. Within a few years, MAGNET will characterize strain partitioning in the northern Walker Lane to improve models of (1) geothermal activity, which is largely amagmatic in the Great Basin, (2) seismic hazard, (3) the ways in which northern Walker Lane accommodates strain between the Sierra Nevada block and the extending Basin and Range Province, and (4) Neogene development of the northern Walker Lane and its broader role in the ongoing evolution of the Pacific–North America plate-boundary system. MAGNET's design is generally applicable to regions with an abundance of vehicle-accessible rock outcrops and could be replicated elsewhere.

Keywords: GPS, Walker Lane, strain, tectonics.

INTRODUCTION

Scientific Objectives

By October 2005, the semipermanent global positioning system (GPS) network (Fig. 1) known as MAGNET (Mobile Array of GPS for Nevada Transtension) consisted of 60 stations built for the purpose of quantifying and characterizing crustal strain rates in the northern Walker Lane and central Nevada seismic belt. Funded by the Department of Energy, the primary objective of MAGNET is to improve our understanding of geothermal systems in the Great Basin that are known to be largely amagmatic. A working hypothesis is that transtensional tectonics is favorable to geothermal systems through enhanced heat flow (from crustal

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thinning and lower-crustal magmatic intrusion) and permeability (from strike-slip faulting that penetrates the entire crust). Preliminary studies have indicated a correlation between the magnitude and style of crustal strain rates in the Great Basin and the location of economic and subeconomic amagmatic geothermal systems (Blewitt et al., 2003). Since MAGNET will constrain the rate and style of activity on faults in the northern Walker Lane and central Nevada seismic belt, it can also be used to improve seismic hazard assessment in this region.

Both these applications fundamentally depend on the ability of MAGNET to accurately resolve surface strain rates, and on using such kinematic data to improve tectonic models of the region (Kreemer et al., this volume). From this perspective, MAGNET is poised to assess how the northern Walker Lane accommodates strain between the blocklike motion of the Sierra Nevada and the extending Basin and Range Province. From an even broader perspective, MAGNET should provide important data to constrain models of Neogene development of the northern Walker Lane, and the broader role of the Walker Lane in the ongoing evolution of the Pacific–North America plate-boundary system.

Here, we discuss the design and implementation of MAGNET, which is a new type of GPS network that offers advantages in accuracy and resolution time over traditional GPS campaigns, and yet it is far less expensive than permanent GPS networks. Moreover, the semipermanent design of MAGNET allows for a higher density of stations than permanent GPS for a fixed amount of available funding. Thus, MAGNET is primarily designed for the rapid resolution of highly accurate velocities with relatively high spatial sampling density, and thus it can be regarded as near-optimal for purposes of regional mapping of the strain-rate tensor. The emphasis of this paper is on the technological and logistical methodology employed by MAGNET and providing an initial assessment of MAGNET's performance. The goal of this paper is therefore to disseminate information that might be useful to other research groups who could benefit from applying the techniques described here.

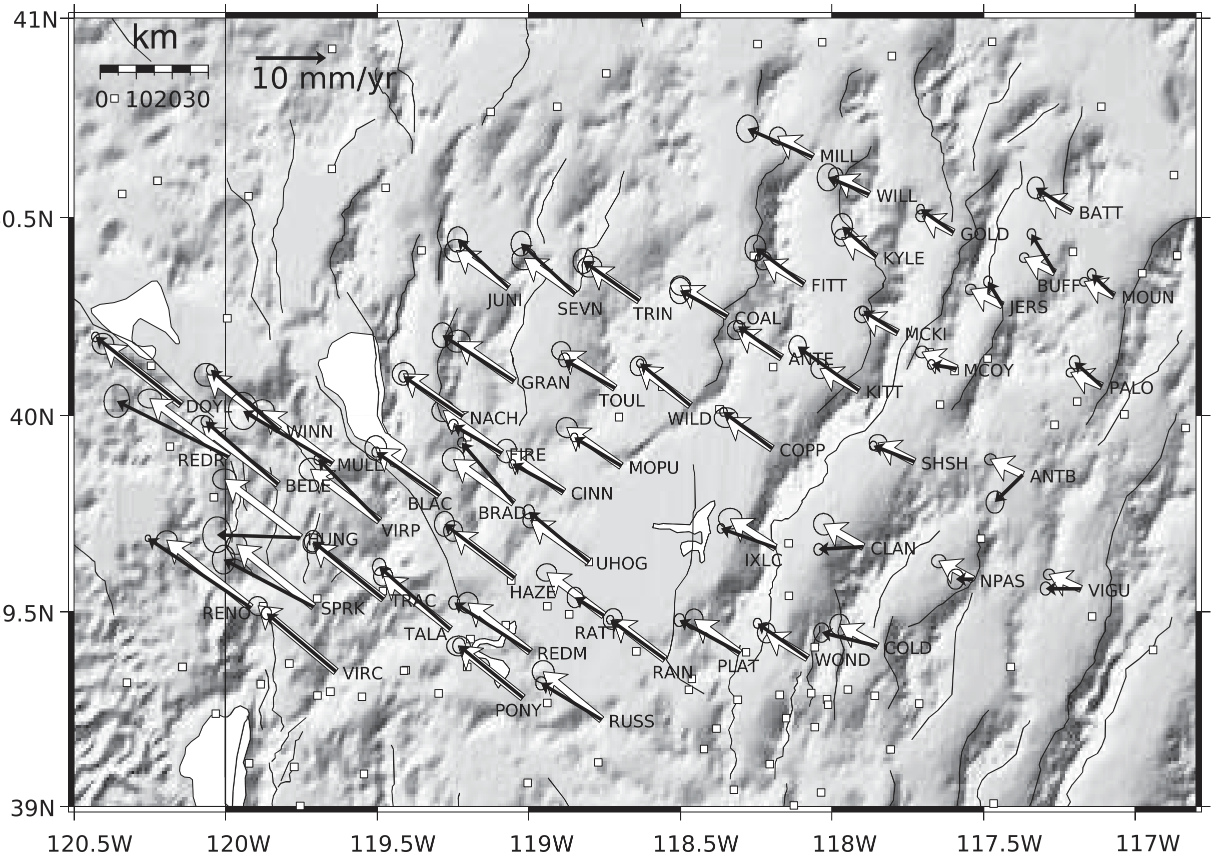

Figure 1. Map of the MAGNET network. Black vectors are velocities from the MAGNET network rotated into the model North America reference frame using only up to 1.5 yr of intermittent data. White vectors are predicted interpolated velocities at the MAGNET sites from the strain rate model of Kreemer et al. (this volume) obtained without the MAGNET results. Error ellipses represent 95% confidence but do not account for known systematic errors that can dominate for newly observed stations. White squares are locations of global positioning system (GPS) sites used in the strain-rate model. The reference frame is attached to stable North America, as defined by the stable North America reference frame (SNARF) Working Group (Blewitt et al., 2005).

Comparison of GPS Geodetic Survey Methods

Geodetic GPS surveys have mainly been conducted in two quite different modes (in the Walker Lane and more generally elsewhere): permanent GPS and campaign GPS. We now briefly describe and compare these methods in terms of advantages and limitations that might relate to specific requirements of a project.

Campaign GPS

Campaign GPS follows the recipe of traditional surveying with certain benefits over previous surveying technology, such as not having any need for line-of-sight between stations, no fundamental limitation on station separation, and all-weather capabilities. Campaigns are typically conducted every year or two over a period of ~10 yr, more or less. GPS antennas are typically mounted on tripods, centered over a permanent monument in the ground using a spirit-leveled optical tribrach. The height of the antenna above the monument thus varies with each setup of the tripod and thus is measured using a steel tape or measuring rod. The ability to center the antenna and measure its height accurately depends on the skill of the surveyor, on the calibration of the tribrach, and on the stability of the tripod, which can be subject to wind disturbance, ground moisture, and settling during the session. The fact that the antenna is physically located at a different point every campaign introduces another type of error. The phenomenon known as “multipath” occurs from the interference of phase arrivals from different paths that the satellite signal can take before reaching the antenna, for example, through ground reflections. This interference pattern can be very sensitive to the height of the antenna above the ground. In general, the outcome of multipath is a systematic bias in the estimated coordinates of the station. Having the antenna set up at different heights thus introduces a different bias each time the tripod is set up. A further possible problem at some GPS campaign sites is monument stability. Campaign GPS ultimately relies on a long time period (~10 yr) to produce accurate station velocities to reduce the effect of setup (or “eccentricity”) error, variable multipath error, and other systematic and random errors in the epoch coordinate estimates. Another aspect of campaigns is budgetary; concern for security often demands that an operator be on site with the equipment during the session, thus adding to the cost of a campaign.

Permanent GPS

Permanent GPS is the ultimate method in terms of accuracy, and it mitigates many of the aforementioned problems with campaign GPS. The key advantages of permanent geodetic GPS are (1) the stability of the antenna, often mounted directly onto a very stable monument that is anchored deeply in bedrock (Langbein et al., 1995), and (2) the product is a continuous time series of station coordinates, which is important to characterize and possibly mitigate transient signals that may or may not be of tectonic origin. For example, seasonal signals can be filtered and removed (Blewitt and Lavallée, 2002), and nonlinear postseismic relaxation signals can be monitored over a broad range of time scales. The two main disadvantages of permanent GPS are (1) for a fixed amount of funding, fewer stations can be installed and have their velocities determined, and (2) siting and installation of a permanent station can be difficult, for example, requiring a permit to develop a permanent structure on the site. Since permanent GPS sites are typically easily accessible by automobiles (as a mobile drill rig is often required to build the monument), security might in some cases be a significant problem. Therefore, the location of a permanent station can in some cases be more of a compromise from a purely scientific point of view. For example, a station on a mountain top may only be permitted to be situated adjacent to other infrastructure, such as microwave towers and chain link fences, which might produce interference or increase the level of multipath. Often such environments (typically in enclosed areas on the tops of hills or mountains) are not static, but undergo sporadic development, further changing the electrical environment. These siting difficulties also add to the total cost, which is now typically in the range of $15,000–30,000 per station. For a relatively small, set amount of funding, permanent GPS may not be an option to meet the goals of a geodetic project, particularly if relatively high spatial sampling is required to map the variations in the strain-rate tensor across a region.

Semipermanent GPS

Semipermanent GPS is a recent concept. As the name suggests, the method involves moving a set of GPS receivers around a permanently installed network of monuments, such that each station is observed some fraction of the time. In practice, a set of GPS receivers can literally remain in the field for their entire life span, thus maximizing their usage. The monuments are designed with special mounts so that the GPS antenna is forced to the same physical location at each site. This has the advantage of mitigating errors (including possible blunders) in measuring the antenna height and in centering the antenna horizontally. This also has the advantage of reducing variation in multipath bias from one occupation session to another. The period of each “session” depends on the design of the operations. At one extreme, some stations might act essentially as permanent stations (though the equipment is still highly mobile), thus providing a level of reference frame stability, and some stations may only be occupied every year or two, in order to extend or increase the density of a network’s spatial coverage.

We suggest that several sessions be planned per year if possible so as to sample potential seasonal signals. For example, if there are twice as many stations as receivers, then each station is occupied on average 50% of the time, and therefore sessions of anywhere in the region of 1–3 mo would suffice to sample the seasonal signal. The advantages of semipermanent GPS include enhanced spatial coverage as compared to permanent GPS, velocity accuracies closer to permanent GPS than campaign GPS, and time to achieve specified velocity accuracy also closer to permanent GPS, as often the seasonal signal is a fundamentally limiting factor (Blewitt and Lavallée, 2002). Another advantage is the lack of complexity in the station structure (only the monument is permanent), and therefore time is saved that would otherwise be needed for permitting (which could translate into more rapid scientific conclusions). A semipermanent station that uses a steel rod epoxied into a drill hole in bedrock can be completely installed and running within 20 min of arrival at the site. This simple setup produces a relatively low-multipath environment as compared to the chain-link enclosures commonly found at permanent sites. Also, the cost savings over permanent stations might be used to purchase more receivers. A disadvantage is that the time series is not continuous, but rather it is intermittent, so a transient geophysical signal might not be resolved very well, or perhaps missed entirely if it occurred between occupations. Another disadvantage over permanent GPS is that the mobile equipment may be more susceptible to damage and power failure due to transportation, wind, or rodents, which translates into a percentage of lost data and the need for higher maintenance costs (especially for solar panels). In contrast, permanent installations can easily be reinforced, as weight is not a design factor. Another advantage of permanent GPS as compared to semipermanent GPS is that a more robust monument can be constructed (Langbein et al., 1995), such as the Wyatt-type braced deep-anchored monuments (at a depth of ~10 m) that are now commonplace in western North America. To do this for semipermanent GPS would defeat the benefits: low cost, rapid installation, and minimal permitting.

Geodetic Requirements

For a general scientific goal that requires the mapping of crustal strain rates, a primary requirement is to sample sufficient stations spanning the region of interest with an appropriate spacing. Furthermore, the station velocities must be determined to within errors that are far smaller than the true (or anticipated) spatial variability in velocity signals of interest. It might also in some cases be important to monitor possible time variation in station velocity that might be geophysical in origin, or possibly due to some systematic error (such as seasonal variation in environmental conditions) that must be monitored and mitigated. There may also be a requirement on how quickly the velocity accuracy can be achieved to meet the goals of a specific project deadline. These considerations summarize the driving factors behind geodetic requirements. In turn, they can lead to very specific requirements for particular projects, which translate into details of experiment design. We shall now consider each of these main general areas that drive the geodetic requirements and relate them to the GPS survey methods discussed previously.

Spatial Resolution

In general, spatial resolution should be compatible with the characteristic distance scale over which geophysical signals vary. For volcano monitoring, this distance scale can be very small. For tectonic strain, the appropriate distance scale is typically much larger. Blewitt (2000) presented a rigorous solution for optimal network design (station placement) and applied it to idealized sample cases. A key feature of crustal strain associated with the earthquake cycle is that, typically, the characteristic distance scale corresponds to the thickness of the seismogenic zone within which faults are typically locked between earthquakes. Therefore, in the interseismic period, the surface strain rate tends to be smoothed and cannot change very much over distances <15 km. Maximum variation in strain rate is typically found adjacent to active faults that have a large slip rate at depth (corresponding to their geological slip rate), with the peak strain occurring in the region above the locked zone. However, there is no way to distinguish from the pattern of surface strain whether the strain field is due to a single very deeply locked fault, or due to a series of subparallel faults that are locked to a shallow depth, such as in a shear zone. An increased density of GPS stations does not help resolve the model in this case. We therefore suggest that there is a point of diminishing scientific return (for a fixed investment in equipment) to measure strain with a spatial resolution smaller than the thickness of the brittle crust. A reasonable nominal spacing for most geodetic networks measuring tectonic strain rates is therefore in the range of ~10–30 km. A spacing smaller than this is unlikely to enhance scientific return, and a spacing larger than this would only serve to constrain the level and style of tectonic activity within a region, but would be less capable of identifying the currently active Quaternary faults. However, it should be noted that a broadly spaced network, such as the BARGEN permanent GPS network with typical spacing ~90 km (Bennett et al., 2003) can serve an important role to provide a regional reference frame and a regional-scale tectonic context to more focused investigations, and it can help to identify regions that deserve more focus.

Velocity Accuracy

A common and simple objective of a GPS geodetic network is to resolve with adequate accuracy the velocities of all stations (within some reference frame). This raises two questions: (1) How long will it take to achieve the required velocity accuracy? (2) How often must the time series of positions be sampled in order to reduce random and systematic errors? This all assumes that the unknown geophysical motion of a site is linear (i.e., a constant velocity), and that any nonlinear motions can be either modeled (such as solid Earth tides) or adequately characterized (such as seasonal coordinate variation). In the case of campaigns where sites are sampled every one or two years, typically ~10 yr are required to achieve an accuracy of <<1 mm/yr in station velocity. However, permanent stations can typically achieve this accuracy within 1.5–2.5 yr, a critical time period when it first becomes possible to characterize and mitigate a seasonal signal (Blewitt and Lavallée, 2002). After 5 yr, permanent station velocity accuracy in a regional reference frame is typically ~0.1 mm (Davis et al., 2003). Stochastic models of permanent GPS time series show that monument stability can be a real issue with regard to how often it makes sense to sample the site position in order to resolve velocity (Langbein and Johnson, 1997; Williams, 2003). In the extreme case that monument instability is dominated by a random walk process it can be shown that, in effect, only the first and last data points provide information on site velocity, and so more frequent sampling does not help. Most GPS time series however, like most natural processes, can be characterized by a power-law noise, implying a finite time correlation (Agnew, 1992). This implies that frequent sampling will improve velocity estimation, but only to a limit, beyond which higher frequency sampling does not help. This suggests that a semipermanent observational strategy might be close to optimal in terms of resolving station velocity, assuming adequate sampling of two key cycles: the seasonal cycle and the diurnal cycle. For this reason, the fundamental epoch estimate ought to be based on a full 24 h session, and the station should be visited several times per year.

Temporal Resolution

The previous discussion addressed how often measurements should be made and for how long in order to resolve station velocities. However, if temporal variation in station velocity is expected, or if transient phenomena are important scientific objectives, then permanent GPS networks may be required. For example, the deep-crustal magma-injection event near Lake Tahoe in 2003 (Smith et al., 2004) produced an ~10 mm transient displacement over a 6 mo period at a permanent GPS station nearby. In principle, GPS campaign data might be used to detect this ~10 mm offset, though a 6 mo transient signal could not have been inferred. It is also possible that the 10 mm offset might be buried in the GPS campaign data noise, or it might have been attributed to a change in equipment or antenna setup error. Semipermanent GPS would not be temporally optimal in this scenario, though the chances of discovery would have actually been enhanced due to the higher spatial density that semipermanent GPS networks can provide. Thus, we can think of semipermanent GPS as trading off temporal resolution for spatial resolution. Indeed, it was fortunate that there was a permanent station that just happened to be within range of a detectable signal, given that the permanent GPS station spacing in this region is ~100 km. Perhaps the most obvious transient phenomenon that might be observed by GPS is a large earthquake. In this respect, permanent GPS is at a disadvantage compared to semipermanent GPS. In the "MAGNET-style" of deployment, all semipermanent GPS instruments are always operating somewhere, so they have no inherent disadvantage and can detect any transient signals as well as permanent stations. Additionally, semipermanent GPS have the advantage that more equipment can be purchased for the same cost, and they can be quickly redeployed to a more optimal configuration to map out the coseismic displacement (because all the monuments would have been presurveyed) and to monitor postseismic deformation. Once an earthquake has occurred, a decision can be made to keep the semipermanent stations in operation continuously (like permanent stations) for as long as the investigation requires. Moreover, instruments that might be borrowed from elsewhere could, in principle, be rapidly deployed to unoccupied monuments in the semipermanent network, or new semipermanent monuments could be quickly installed and integrated seamlessly into the existing network. A disadvantage of semipermanent GPS is the lack of telemetering. The knowledge of a transient is delayed by data acquisition latency, and so the equipment might unfortunately be moved while the transient is in progress (if not associated with an obvious large event). Although this could be rectified with cellular or satellite data transfer, it impacts the cost efficiency (which will be outlined in a later section), and even so, a "silent" transient could still easily go undetected prior to moving the instrument(s).

METHODOLOGY

Semipermanent Network Design

Setting

The MAGNET network is designed to measure tectonic strain rates spanning the region bounded by the Sierra Nevada block to the west and the central Basin and Range to the east at the latitude of the northern Walker Lane and central Nevada seismic belt. This is a region of the Great Basin that has an enhanced number of known amagmatic geothermal systems, and it is a region of relatively high strain, with ~10 mm/yr of relative velocity across the network, mainly focused in the western Great Basin adjacent to the Sierra Nevada block. The central Nevada seismic belt is also expected to be undergoing considerable postseismic deformation as a result of a sequence of great earthquakes during the last century, where the postseismic deformation may exceed the magnitude of interseismic strain accumulation. Scientific goals require a velocity accuracy <1 mm/yr and a spatial resolution of 10–30 km.

Spatial Characteristics

As of October 2005, the MAGNET network consists of 60 stations, for which installation began in January 2004. The network spans 160 km N-S and 260 km E-W (roughly bounded by the quadrilateral defined by Carson City, Susanville, Battle Mountain, and Austin). The network is approximately uniform in distribution. Nearest-neighbor stations spacing ranges from 13.2 to 30.9 km, in accordance with the expected smoothness of the strain field imposed by crustal thickness (as previously noted). The mean nearest-neighbor station distance is 19.2 km. (Note added in proof: As of August 2008 (the time of this proof), the network has grown to 307 stations occupied by 56 receivers, spanning as far north as the Oregon border and as far south as the eastern California shear zone and northwestern Arizona.)

Tectonic Sensitivity

Locating GPS monuments in basins such as the Carson Sink would not be particularly useful, as hydrological effects in unconsolidated sediments can be expected to be significant compared to the underlying tectonic signals (e.g., Bell et al., 2002). Therefore, we have chosen to always site monuments in rock outcrops. Station spacing is in practice limited by availability of suitable and accessible rock outcrops. The largest gaps in the network span the largest basins, such as the Carson Sink. Sites located in bedrock are expected to be relatively immune to hydrological effects, except for possible elastic loading effects, which are computed to be less than one millimeter (relative) in the Great Basin. For example, Elósegui et al. (2003) identified perhaps the largest loading signals in the Great Basin of ~1 mm associated with seasonal loading of the Great Salt Lake. Atmospheric pressure loading and continental-scale hydrological loading may move the Great Basin as much as several millimeters; however, the relative motion within the Great Basin would be an order of magnitude smaller (van Dam et al., 2001). One remaining possible hydrological effect on bedrock sites relates to the sometimes substantial pumping of water from mines in the Great Basin. What is not yet understood is whether the underlying rock behaves purely elastically under such stress (in which case it would not be a significant problem), or whether failure might occur that could produce detectable surface deformation. Such a phenomenon, if it exists, might only be revealed by a sufficiently high-resolution technique such as interferometric synthetic aperture radar (InSAR), which has served as a useful tool to discriminate tectonic from hydrologic signals (Bawden et al., 2001; Bell et al., 2002).

Siting

Other than the criteria discussed previously on general network design to meet scientific goals, there are several practical factors considered in siting stations. The basic principle is to maximize the quantity, quality, and usefulness of the resulting data set, which includes a broad range of considerations, from how fast a site can be visited to securing a site from theft. In general, it is important to note that stringent requirements cannot generally be imposed if adequate spatial resolution (in our case, ~20 km) is to be maintained. This usually requires a site to be selected within a radius of ~5 km of a target candidate site. For comparison, the one standard deviation of our nearest-neighbor separation is 4.1 km. The exception to this rule is where the resulting data from any location in a given area would not be useful, or would divert resources that could be better spent elsewhere. We now consider each important aspect of siting, in a very approximate order of priority.

Accessibility

Of course, if we cannot access a site, it is of no use. Good accessibility means that more sites can be visited, which means more efficient use of funds, and more scientific return. The network has been designed so that operations can be sustained by day trips, where up to ~10 stations can be visited in one day. Typically one or two days of fieldwork per week by a technician is required, driving ~600 km. For this reason, all sites must be reasonably accessible by four-wheel drive all year-round, and the station should be no more than a 10 min hike from the truck. Due to time constraints, a hike should be less than 400 m in distance and less than 50 m in elevation. In most cases, a truck can be driven directly to the site. Whereas most of the time is spent driving on dirt roads, it is crucial to select looped routes that make the most use of the better roads. Seasonal conditions can vary greatly in the Great Basin, and contingency plans must be considered in the event of flash flooding and road washouts. Navigation to the sites (and to new candidate sites) is facilitated by a GPS-enabled field computer with digital maps (U.S. Geological Survey 1:24,000 series), or handheld GPS (which are also used for meter-level recording of the final selected site location).

Security

Nevada is the sixth least densely populated state in the United States, and most of the population lives in a few metropolitan areas. Approximately 83% of the land in Nevada is federally administered (the highest percentage in the United States), with some counties as high as 98%. All of our GPS sites are on open-access land managed by the Department of Interior's Bureau of Land Management. While this is good for access, it can be poor for security. Fences in most areas are rare or nonexistent, and, where they do exist, they are not intended to keep people out (but rather cattle in). Stations are selected so that they cannot be seen from the road, and they are situated away from populated areas and evidence of recent human activity. Needless to say, the impact of a stolen receiver is immense: the loss of data is minor; rather, the loss of the receiver to make future measurements is the main problem, plus the likelihood that the site will have to be abandoned, and so all previous data collected there may be wasted. Nevertheless, security cannot be overly cumbersome, otherwise no data would be collected at all. The issue therefore is risk management. For example, we have assessed that it would be an acceptable risk to lose an instrument once every year or two. A record of zero thefts might be achievable if we only selected areas that were totally unpopulated (and even this is doubtful), but such an approach would be inconsistent with our goals regarding seismic hazard in populated areas. As of 1.5 yr of network operations, we have lost only a $2000 insurance deductible due to the theft of one instrument out of a total of 34, representing ~0.4% loss per year on equipment costs.

Rock Stability

In the case of rock stability, the issue is whether the monument drilled into the rock accurately represents the motion of Earth's crust. If not, then at worst, an anomalous motion will be incorrectly interpreted as tectonic signal; at best, the problem will be detected eventually, but years of fieldwork getting to the site will have been wasted. Rock stability can therefore have the highest priority in cases where "some data" is actually worse than "no data." One exception might be in very sparsely sited regions, where it may be useful in the future to measure near-field coseismic displacement (but not for purposes of measuring interseismic strain). Within the concept of semipermanent networks, monument installation must be inexpensive and quick. Our choice (described in more detail in Station Design/Monumentation) is to epoxy a stainless 7/8-inch-diameter steel pin into ~15-cm-deep hole drilled in a rock outcrop. The selected rock outcrop must not be too weathered or fractured, and it must resound at a high pitch when struck with a sledge hammer. All else being equal, basement rocks such as granite are preferred. Volcanic rocks are sometimes chosen where they have few fractures. For sedimentary rocks, subvertical beds are often avoided because, where the bed planes intersect with the surface, they are susceptible to weathering and fracturing. Detached rocks and boulders are to be avoided, though clearly there are situations where this might be difficult to ascertain even to a trained geologist with only eyes and a hammer. The key therefore is to reject candidate sites that might well be good, but nevertheless are questionable.

Sky Visibility

Sites with the best sky visibility above 15° elevation are preferred. The tops of hills are preferred. Poor sky visibility to the north is acceptable, due to the fact that GPS satellites do not track within an ~35° cone around the north celestial pole. At the latitude of our network, this implies a large blank circle in the sky north of the station. Therefore south-facing slopes are often selected. South-facing slopes are also optimal for powering solar panels set on the ground. Areas with trees or other sky-blocking features, such as power-line towers or buildings, are to be avoided.

Multipath Environment

Good sky visibility also tends to mitigate multipath, because there will generally always be a direct GPS signal that is stronger than any reflected signal. Any significant (large, smooth) reflective surfaces that might create significant multipath should be avoided. Metallic structures such as fences and radio should also be avoided if possible. However, even relatively poor multipath environments can ultimately be acceptable; modern receivers do much to correct the problem through signal-processing techniques (exploiting the fact that reflected signals always arrive late and thus skew the phase-correlation pattern). For example, spatial sampling, accessibility, security, and rock condition took priority in one rare case (Rattlesnake Hill, Fallon).

Station Design

We have developed 12 key principles for the design of a semipermanent station. A station should be:

(1) mobile: to leave as little a permanent footprint as possible to minimize cost and permitting issues, and as a corollary, have as much of the station as possible be mobile;

(2) stable: to attach the monument effectively to the sited rock outcrop to maximize stability, using the same method at each site;

(3) easy: to monument the site as quickly as possible (accounting for the possible need to carry necessary equipment up to 400 m to the site) so that GPS data acquisition can begin immediately, and so that more sites can be installed in one day, and rapidly following a major event such as a large earthquake;

(4) repeatable: to ensure the antenna is force-mounted to precisely the same position at a station every session to minimize eccentricity and multipath error in the determination of velocity;

(5) fast: once monuments have been created, to be able routinely to install and move equipment while on site as quickly as possible, to increase the number of sites that can be visited in one day;

(6) modular: to have interchangeable components to facilitate ease of on-site system testing and repair, and swapping of parts;

(7) convenient: to minimize the time required to download data in the case that the equipment is not being moved (i.e., for stations acting as "permanent" for the time being, such as might be the case following a large earthquake);

(8) uniform: to have functionally identical stations, so that equipment is not specific to certain stations, and thus logistical efficiency is improved (as there are less planning constraints and fewer decisions to be made);

(9) invisible: to be difficult to discover accidentally unless in the immediate proximity to maximize security;

(10) secure: to deter opportunistic theft or vandalism if accidentally discovered;

(11) independent: to have adequate power and reliability while unattended for up to several months to maximize data collection; and

(12) robust: to minimize damage due to rodents, weather, and transportation.

We now describe the currently implemented design that meets these criteria.

Footprint

When the site is not in use, only two items remain on site: (1) the monument described next, and (2) an eye bolt epoxied into the rock as part of the security system. A 1 in. × 6 in. PV pipe with covering cap is placed over the monument for protection. The PV pipe also acts as a warning to avoid possible puncture of a random off-road vehicle (extremely unlikely, though theoretically possible).

Monumentation

The monument (Fig. 2A) is a 7/8-in.-diameter, 10-in.-long stainless steel pin that is epoxied into a hole drilled into a rock outcrop. We use a Hilti rock drill that is AC-powered using a hand-portable Honda generator. The hole is cleaned by blowing using a very light, powerful vacuum cleaner, also AC-powered. The monument design is based on the "Conquest Pin" by UNAVCO Inc. (http://www.unavco.org), with some modifications. Approximately 6 in. of the pin is epoxied below the ground in a hole drilled into the rock. The bottom half of the pin is milled to accommodate epoxy from the hole, and to better anchor the monument in place, withstanding vertical and rotational stresses. The hole itself is essentially friction tight, thus constraining lateral motion. The top of the monument has a 5/8 in. male screw thread for antenna mounting, as described in more detail later. The reference height of the monument is taken to be the collar immediately below the thread. As a backup, a groove is also milled into the side of the monument at a specific distance in case the top part of the monument for some reason gets damaged.

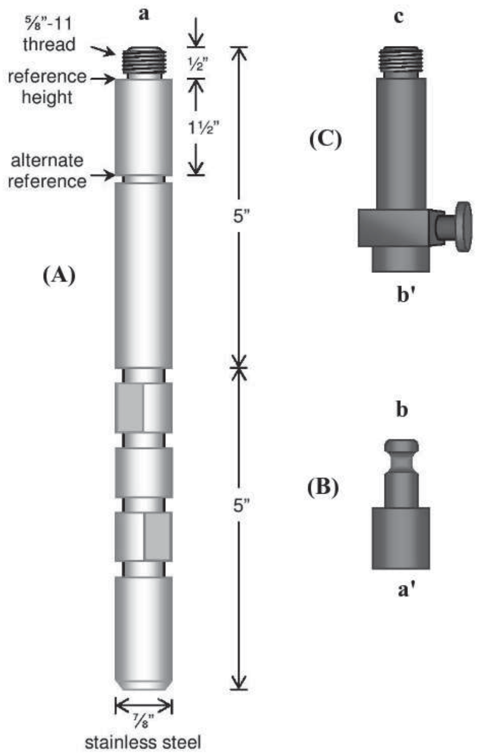

Figure 2. Diagram of monument and antenna mount design: (A) stainless steel monument, (B) monument adapter (Global Positioning System [GPS] quick-release adapter, Seco PN 5187-00), and (C) antenna adapter (GPS quick-disconnect adapter, Seco PN 5111-00). Parts that fit together are a–a′ and b–b′, and c-antenna (not shown).

Care must be taken to install the rod as vertically as possible, for which we use a spirit level several times during the drilling process. A tolerance of <3° is easily achieved, corresponding to <13 mm horizontal displacement between top and bottom of the rod. For example, this will ensure <1 mm horizontal displacement between different antenna types for which there is a 2 cm difference in phase center height. We use the same antenna types everywhere to further mitigate this potential source of error.

Antenna Mount

The international standard geodetic GPS antenna mount is a 5/8 in. male thread that inserts directly into the body of the GPS antenna. We have chosen a mount system that facilitates both rapid and accurate placement of the antenna. The system has two components manufactured by Seco originally intended for survey poles. The first part, the quick-release "monument adapter" (Fig. 2B) directly screws onto the 5/8 in. male thread of the monument down to the shoulder of the monument that defines the reference height. At the top of the monument adapter, there is a concave nipple. The second part, the quick-disconnect "antenna adapter" (Fig. 2C) screws into the 5/8 in. female thread of the antenna, where the bottom is designed to mount on the first part, and it is secured using a quick-release spring-loaded button. This design has important features: (1) it facilitates quick (dis-)connection of the antenna itself, and quick (dis-)connection of the antenna cable; (2) it reduces the wear and tear that would arise from directly screwing the antenna onto the monument; and (3) it allows for arbitrary orientation of the antenna, and specifically, it allows for the antenna to be pointed toward geographic north (manually aided by a compass) so as to minimize the effect of azimuthal variation in antenna phase center**.** Furthermore, to minimize cost, the more-expensive antenna adapter moves with the receiver equipment rather than staying on site. No data logging by the field crew is required regarding the antenna location, because it is force-mounted to the same location every time. The Seco adapters are machined so that their heights are guaranteed to be consistent. The height between the reference mark (the shoulder on the monument at the bottom of the monument's male thread) and the reference point on the antenna (the base of the antenna's female thread) is precisely 100 mm.

Routine Installation

Speed of installation is partly facilitated by the antenna mount. A second important feature to improve the speed of routine installation is the mobile GPS system in a plastic carrying case, which also acts as a field enclosure. Finally, all equipment items, including solar panels, are light and easily portable. For example, the 32 W solar panels are foldable and fit easily into a backpack. The portable GPS equipment case is designed for portability. A 12 V, 80 Ah battery remains at each site in a battery box to facilitate routine fieldwork and can easily be augmented if more power is required (such as during weeks of snow cover), or replaced if depleted after a weeks of poor light conditions. When a receiver is picked up at a site, a compact flash card is swapped in the receiver rather than wasting time in the field downloading data to a computer.

Data Download

Data are recorded onto compact flash cards. The cards we use are manufactured by SanDisk and are of a industrial range, designed to withstand extreme cold and hot temperatures. It so happens that 64 MB cards can hold 3 mo of data. However, at the time of writing, 256 MB cards are the minimum capacity available, and so the card capacity is always going to be overengineered. We have never had a card fail. In the laboratory, data are automatically downloaded using a custom C-shell script running under Linux and converted to RINEX format. Files that are broken due to card swaps are automatically pieced back together using a database. The script connects to a custom database so as to automatically identify the station the card came from, without requiring any data entry from field notes. Data entry is required prior to the next download, so that the database can keep track of which receiver is at which site. The entire system is designed to minimize time in the field and minimize note-taking in the field. The only thing that needs to be recorded is the receiver ID number when it is installed at a site (which is required to identify filenames with sites).

Power and Reliability

We use a 12 V, 80 amp-hour lead-acid battery charged by a 32 W foldable solar panel connected to a 5 A SunWise controller. The battery sits in its own box to prevent possible corrosion of sensitive equipment from acid fumes. The battery also typically remains at the site unless it needs to be swapped out and taken back to the office for desulfation and recharge. We find that in winter months, sometimes the lack of sunlight or snow cover on the solar panels causes the battery to slowly discharge. In some cases, therefore, we double up the batteries in parallel. Another more sustainable option would be to double up the solar panels in winter (or use much more powerful solar panels all the time), though this requires a considerable investment. Even without any solar panels, we find that two 80 A-h batteries in parallel can power a Trimble 5700 receiver for ~3 wk, which is more than sufficient for a good epoch measurement. Given that batteries are subject to deep discharge on occasion, we use marine batteries, which are designed more for deep discharge than car batteries (which are designed rather to provide high current in short bursts). Car batteries would quickly break down if subject to a few deep discharges. By far the most likely cause for losing potential data is failure of the power system. However, by using a large capacity battery at a site, we are almost guaranteed to acquire at least a week of good data.

Station Similarity and Modularity

All stations are designed the same way to facilitate logistics, maintenance, reliability, and GPS accuracy. All systems are modular, which facilitates testing, repair, and swapping out of equipment. The heart of the system is the Trimble 5700 receiver. Three cables feed out from the carrying case: the antenna cable, a power cable to the external battery, and a power cable to connect a solar panel. All power cables are fused, and each segment can easily disconnect and be swapped out. All parts are numbered so that problems can be tracked, which is especially important when swapping out parts. All of the padlocks (240 in total) are keyed exactly the same. Simple repairs are very easy to do by a field technician at a moment's notice. If necessary, the GPS receiver can be reprogrammed or even have its firmware replaced in the field using a laptop computer. On very rare occasions this has been necessary, which we speculate may be associated with electrical storms that are common in the Basin and Range.

Damage Mitigation

We note three causes of damage that have led to failure. The most important is rodent damage, especially in early spring when rodents come out of hibernation. The most expensive loss is the antenna cable, worth approximately $100. Worse than this, by eating through either a battery or antenna cable, data is lost from that time forward. A very simple and inexpensive solution to this problem is to encase all cables in flexible plastic conduit. We use the type commonly used in automobiles that is ribbed, and is split lengthwise to facilitate rapid installation. This actually also makes the cables easier to handle, further improving speed of installation.

The second most damaging factor is the wind. Solar panels are secured using nylon rope attached to available rocks. On rare occasions the rocks might be so sharp that the rope is cut, and the solar panels can then easily get destroyed by flapping in the wind. Detachment of the ropes has also happened if the site is accidentally discovered, then left alone once the warning label has been read (usually concealed by the solar panel which is laid on top of the box). Padlocks are made out of brass and are routinely lubricated. We have not yet suffered any significant damage due to transportation of equipment to the site, from water, extreme temperatures, or ultraviolet (UV) radiation. This is because our equipment is all commercially designed for the rigors of fieldwork. We would not, for example, recommend attempting to use GPS receivers more designed for permanent stations into such a regimen.

Security

Our approach to security is one of deterrence. The most important component to secure is the GPS receiver. This is achieved by binding the receiver inside a very tightly fitting bicycle U-lock (the Mini-Evolution by Kryptonite) that cannot be dislodged once locked. Typically, once locked, the U-lock never needs to be removed. Also, attached to the U-lock, there is a 5/8-in.-diameter, 4-ft-long braided steel cable looped on either end. The free end of the cable is passed through a hole in the carrying case and is then padlocked to an eye bolt epoxied into nearby rock. The cable is also passed through the padlocks holding the case shut, to make it more difficult to use a tool to break open the locks. The solar panel is also padlocked to the eye bolt. Someone sufficiently determined could break the padlocks and walk away with the box. However, removing the bicycle lock from the receiver itself would be extremely difficult without destroying the receiver. Finally, a large orange warning sticker is posted on each box to deliver a message to anyone discovering it, warning that the equipment is under GPS surveillance. While less important, a sticker on the battery box notes that the battery will only work with custom equipment.

Measurement Strategy

Receivers are set to log data every 15 s. Data files start and end on GPS midnight, which in Nevada corresponds to 4 p.m. local time in winter and 5 p.m. local time in summer. Typically, when a GPS receiver is installed at a station during the day, the few hours of data prior to GPS midnight are discarded in the subsequent analysis. In the office, data are subsequently processed in daily epoch batches. As a rule, daily files are only processed if they have at least 18 h of data, to minimize systematic biases associated with quasi-diurnal or semidiurnal signals such as multipath and tidal loading (Sanli and Blewitt, 2001). While in our time zone, the first day of a session never meets this criterion, but often the last day does.

Sites are visited several times per year so as to sample through the seasonal cycle. Typical sessions range from 2 to 12 wk. No attempt has been made to have a regular schedule (spatially or temporally), as we suspected that regularity can more likely lead to systematic artifacts that could be mitigated by a level of randomness in the measurement design. Random sampling leads to many more different ways through which the network becomes interconnected. From a practical point of view, a regular schedule would not be possible to keep anyway, especially due to extreme snow conditions in winter. Moreover, our equipment pool has been ramping up, and the network has been growing.

For velocity accuracy, the most important factor is the span of time since the very first and very last sessions, and, to a lesser extent, the percentage of time occupied. The reason for this is that the error in velocity estimation decreases linearly with the span of time (for a fixed amount of data), but at the most (in the white noise limit), it only decreases with the square root of the number of sessions (for a fixed span of time). Therefore, new station installations take clear priority over repeat occupations of existing sites.

Data Analysis

Data Processing

Starting with daily RINEX files, all data are processed using the GIPSY/OASIS II software from the Jet Propulsion Laboratory (JPL). The strategy used was precise point positioning (Zumberge et al., 1997), using dual-frequency carrier phase and pseudorange data, and precise orbit, clock, and reference frame transformation products publicly available from JPL. After automatic data editing for cycle slips and outliers (Blewitt, 1990), data were decimated to 300 s epochs. Estimated parameters included the three Cartesian coordinates of position as a constant over the day, a receiver clock parameter estimated stochastically as white noise, a zenith tropospheric parameter, and two tropospheric gradient parameters estimated stochastically as a random walk process (Bar Sever et al., 1998), and carrier phase biases to each satellite estimated as a constant. This was then followed by carrier-phase ambiguity resolution (Blewitt, 1989). The output station coordinate time series where then processed using a custom spatial filter, which we will now describe.

Spatial Filtering

Strain is a local quantity, and as such, it is relative station velocity that is important. Geocentric station velocity (referenced to the center of Earth) is not important in this context. However, the GPS data-processing system produces geocentric station coordinate time series. It is possible to filter these time series to optimize the estimation of relative velocities within a region. The key principle is to eliminate a common-mode bias in station coordinates at each epoch, which more reflects a variation in geocentric positioning rather than a variation at any particular station. This common-mode variation may be due to a variety of effects, such as satellite orbit and clock errors, global reference frame realization on that day, and real large-scale geophysical signals such as atmospheric loading. Whether error or real signal, the common-mode variation is not the tectonic signal we seek. Elimination of the common-mode variation in the time series generally improves relative velocity determination, especially if different stations have different spans of data, or are occupied at different times. This is because the stations are sampling the common-mode signal at different times, and any difference caused by such sampling will map into the relative velocity estimates.

Methods to eliminate common-mode variations have been called regional filters or spatial filters, starting with Wdowinski et al. (1997). The basic concept is to estimate the average coordinate deviation over a regional network, and then subtract that deviation from the individual station coordinate time series. This procedure can then be iterated. The original method of Wdowinski et al. (1997) was to compute coordinate deviations with respect to each station's mean estimated position (for the purpose of analyzing data around the time of a large earthquake). For our purposes (to map strain rates), it is more appropriate to compute coordinate deviations with respect to each station's estimated constant velocity model.

A custom regional spatial filter was implemented as a series of C-shell scripts that utilize existing tools to transform data in the GIPSY/OASIS software, and it is available upon request. For this analysis, we implemented a filter that estimates the mean coordinate deviation from an initial model that uses only those sites with the best determined velocities (the longest-running sites). Specifically, stations were selected for which the formal error was <0.4 mm/yr in horizontal velocity components, which selects 34 data sets that span 1.0–1.5 yr. This innovative approach (versus averaging over the entire network) works better in principle because the shorter time series do not have a sufficiently adequate station motion model (epoch coordinate plus velocity) from which to infer the common-mode variation. As a result, the shorter time series tend to underestimate the magnitude of the common-mode variation, and thus bias the estimates.

A series of statistical tests, such as how well daily solutions within one week agree with each other, also serves to eliminate data outliers. The results discussed next demonstrate a factor of five improvement in the statistical quality of the station coordinate time series after performing spatial filtering, and considerable visual improvement in the smoothness of the resulting velocity field, especially for shorter time series, where one would predict the largest improvements to occur.

RESULTS

Network Performance

Table 1 shows a list of all stations, including their names, coordinates, time span of processed data, and "activity" percentage, defined as the fraction of possible weeks that have a valid (quality-assessed) solution (an upper bound on the percentage of weeks a site was occupied). These statistics therefore do not entirely reflect the intended measurement strategy, but

TABLE 1. STATION DATA ACQUISITION AND PERFORMANCE STATISTICS, RANKED BY DATA SPAN

Station	Location			Span	Epochs	Active	Weekly repeatability		
ID	Lat. (°N)	Long. (°W)	Height (m)	(yr)	(wk)	(%)	Lat. (mm)	Long. (mm)	H (mm)
`RENO`	39°31'	119°55'	1490	1.53	63	77	0.62	0.46	1.9
`COPP`	39°55'	118°12'	1280	1.53	35	42	0.42	0.43	1.7
`WILD`	40°01'	118°28'	1230	1.52	40	49	0.74	0.91	2.5
`TOUL`	40°04'	118°43'	1460	1.52	26	32	0.66	0.5	2.4
`FIRE`	39°54'	119°05'	1430	1.52	25	30	0.6	0.55	1.9
`RAIN`	39°23'	118°33'	1210	1.45	48	62	0.66	0.47	1.7
`CINN`	39°48'	118°53'	1290	1.45	41	53	0.69	0.55	2.0
`MOPU`	39°52'	118°42'	1250	1.45	37	47	0.5	0.36	2.5
`ANTE`	40°09'	118°10'	1450	1.42	29	38	0.43	0.55	1.5
`BRAD`	39°47'	119°03'	1330	1.42	37	49	0.43	0.46	1.7
`BLAC`	39°48'	119°18'	1280	1.42	35	46	0.36	0.46	1.8
`NACH`	40°00'	119°13'	1690	1.38	32	43	0.49	0.46	1.9
`IXLC`	39°40'	118°11'	1240	1.36	38	52	0.74	0.59	2.8
`WOND`	39°23'	118°05'	1590	1.36	35	48	0.49	0.45	2.4
`WINN`	39°58'	119°49'	1690	1.32	33	46	0.99	0.87	2.1
`BEDE`	39°49'	119°50'	1570	1.32	30	42	0.65	0.53	2.4
`TALA`	39°27'	119°16'	1640	1.32	16	22	0.39	0.46	1.1
`GOLM`	40°28'	117°36'	1470	1.32	39	55	0.46	0.49	1.8
`MCKI`	40°13'	117°47'	1590	1.32	36	51	0.57	0.3	1.7
`MCOY`	40°07'	117°35'	1180	1.32	34	48	0.39	0.35	2.4
`DOYL`	40°02'	120°09'	1690	1.28	39	57	0.62	0.49	2.2
`VIRP`	39°44'	119°30'	2080	1.27	38	56	0.49	0.44	1.7
`VIRC`	39°21'	119°38'	2010	1.27	29	42	0.59	0.55	3.7
`SHSH`	39°53'	117°44'	1210	1.26	43	64	0.43	0.38	1.7
`JERS`	40°17'	117°26'	1500	1.23	35	53	0.63	0.48	2.9
`MOUN`	40°18'	117°04'	1500	1.23	35	53	0.41	0.44	1.5
`BUFF`	40°22'	117°16'	1480	1.23	34	51	0.45	0.38	2.0
`PLAT`	39°24'	118°18'	1470	1.19	27	42	0.56	0.51	1.7
`PALO`	40°04'	117°07'	1650	1.13	26	42	0.37	0.31	1.4
`VIGU`	39°34'	117°11'	1950	1.13	20	32	0.37	0.28	1.8
`RUSS`	39°13'	118°46'	1380	1.10	27	45	0.62	0.38	1.5
`REDM`	39°24'	119°00'	1460	1.10	21	35	1.54	0.31	2.6
`UHOG`	39°38'	118°48'	1230	1.03	28	50	0.28	0.41	2.8
`TRAC`	39°32'	119°29'	1410	1.03	14	24	0.53	0.82	1.5
`CLAN`	39°40'	117°54'	1440	1.02	46	85	0.44	0.32	1.7
`HAZE`	39°35'	119°03'	1300	1.00	16	29	0.5	0.39	1.5
`PONY`	39°17'	119°01'	1310	0.96	24	46	0.39	0.42	2.6
`COAL`	40°15'	118°21'	1410	0.85	17	36	0.62	0.73	2.4
`FITT`	40°20'	118°06'	1450	0.85	16	34	0.71	0.45	2.8
`KYLE`	40°24'	117°51'	1530	0.85	16	34	1.02	0.36	2.4
`MILL`	40°40'	118°04'	1320	0.85	13	27	0.47	0.73	1.9
`WILC`	40°34'	117°53'	2140	0.85	10	20	0.8	0.53	2.6
`SEVN`	40°18'	118°51'	1220	0.84	18	39	1.13	0.37	2.0
`GRAN`	40°05'	119°03'	1520	0.84	18	39	0.88	0.32	2.1
`JUNI`	40°19'	119°04'	1410	0.84	17	36	0.45	0.73	1.5
`TRIN`	40°17'	118°38'	1660	0.84	9	18	0.72	0.56	1.7
`RATT`	39°29'	118°45'	1250	0.80	20	45	0.95	0.52	2.1
`HUNG`	39°41'	119°45'	1550	0.73	14	34	0.75	0.55	2.0
`MULL`	39°53'	119°39'	1430	0.73	12	29	0.41	0.49	0.9
`SPRK`	39°31'	119°43'	1360	0.71	19	48	0.65	0.53	2.1
`COLD`	39°25'	117°51'	1690	0.71	22	57	0.3	0.37	1.8
`NPAS`	39°35'	117°32'	1720	0.71	19	49	0.43	0.34	1.7
`KITT`	40°04'	117°55'	1660	0.71	17	43	0.43	0.22	2.3
`BATT`	40°31'	117°12'	1510	0.67	26	71	0.36	0.32	1.7
`ANTB`	39°51'	117°22'	1650	0.67	17	46	0.26	0.22	1.1
`REDR`	39°54'	119°59'	1490	0.63	14	39	0.39	0.68	1.6
`MORG`	40°27'	120°04'	1520	0.33	8	41	0.3	0.38	1.0
`FLAN`	40°09'	119°50'	1260	0.17	9	89	0.35	0.19	1.8
`HONY`	40°05'	119°56'	1310	0.17	9	89	0.27	0.32	2.2
`SKED`	40°17'	120°02'	1300	0.17	9	89	0.41	0.31	1.6

they also factor in the real-world problems of equipment failure and detected data problems. The activity of course will always start off high for a new station. For the 35 stations running longer than one year, the average activity was 48%, ranging from 22% to 85%. Therefore, the mean site occupation was around 50%, as planned.

GPS Time Series

Table 2 summarizes the data-quality statistics for the station coordinate time series for the 34 longest-running sites (>1 yr). These statistics are based on coordinate repeatability (defined by Dixon (1991). The table presents mean repeatability (averaged over the 34 stations), the standard deviation in the repeatability distribution, and the range (min–max) of the repeatability values. The statistics are given for each component (longitude, latitude, and height), and they are presented for the daily epoch time series (globally referenced and spatially filtered), and weekly epoch time series (spatially filtered). Table 1 shows weekly repeatability statistics for individual stations.

The longest-running sites were chosen to summarize the statistics because repeatability can be overly optimistic for short time series. The weekly averaged solutions are of interest because in most situations, the day to day variation within a week can be reasonably expected to be entirely due to errors. Slowly varying signals (or errors) are also easier to detect visually in the weekly time series, and therefore weekly solutions give a better visual indication of the quality of the resulting velocity estimates.

Regional spatial filtering on the daily epoch solutions produces about a factor of three improvement in the repeatability of all three coordinate components. Averaging the daily solutions down to weekly epoch solutions further improves the repeatability by about a factor of two in all components, indicating that daily solutions contain random (or high frequency) error that can be averaged down significantly. The resulting weekly repeatability statistics for spatially filtered coordinates are quite typical in magnitude as for the permanent BARGEN network (at 0.4 mm for horizontal components, and 1.7 mm for height). We therefore conclude that GPS time series repeatability is not significantly degraded by the inherent difference in design between semipermanent and permanent networks (for example, that instruments are moved around a semipermanent network). In addition, we note that sampling the time series intermittently through the year produces similar repeatability statistics as sampling the time series continuously throughout the year.

TABLE 2. STATISTICS ON STATION COORDINATE REPEATABILITY

Coordinate component	Mean repeatability (mm)	Standard deviation (mm)	Range min–max (mm)
Daily: globally referenced			
Longitude	2.6	±0.3	2.0–3.2
Latitude	3.2	±0.5	2.3–3.9
Height	7.8	±1.1	5.0–11
Daily: spatially filtered			
Longitude	0.9	±0.2	0.6–1.5
Latitude	1.0	±0.2	0.7–1.6
Height	3.7	±0.7	2.6–5.8
Weekly: spatially filtered			
Longitude	0.47	±0.13	0.28–0.91
Latitude	0.57	±0.22	0.28–1.5
Height	2.1	±0.50	1.1–3.7

Figure 3 presents typical examples of detrended coordinate time series (shown here with no regional spatial filtering) from three stations: CLAN, BLAC, and COPP (for which the height time series is also shown). In the case of CLAN, the station has been operating continuously since installation. CLAN serves as a “best case” scenario, since the antenna and receiver have not changed at all, where as for BLAC and COPP, the antenna and receivers changed randomly and were generally different for each several-week session. There is no obvious qualitative difference in the time series; weekly repeatability (spatially filtered) for all three stations is very similar at 0.4 mm (to within 0.05 mm) in both horizontal components (and 1.8 mm to within 0.2 mm for height).

From this, we conclude that the systematic effect of changing antennas and receivers is not a limiting factor, and it is likely to be ~0.1 mm (order of magnitude) for most, if not all, antennas. It is possible that the summary statistics hide a few antennas that do not meet this specification. If such antennas exist, they may be detected by a systematic deviation (in one direction) from the time series. This type of test would require more data than we have in hand, though it does indicate a possible method of calibration that could be used to fine tune the time series.

The longest-running stations have 1.53 yr of data that have been analyzed here, as of 20 August 2005. It so happens that for close to 1.5 yr of a continuous time series, any annual sinusoidal signal (no matter what the phase) will not significantly bias the velocity estimate (Blewitt and Lavallée, 2002). Figure 1 shows horizontal velocities for sites that have been operating more than 1 yr, with black arrows for >1.3 yr. The black arrows therefore represent velocities relatively less affected by seasonal signals. From now on, the longest-running stations will be contributing velocity solutions that might reasonably be interpreted in terms of their regional spatial pattern (Kreemer et al., this volume; Hammond et al., this volume). Remarkably, following the method of Davis et al. (2003), the smoothness of the velocity field shown by the black arrows in Figure 1 already indicates a degree of accuracy of ~1 mm/yr from only 1.3–1.5 yr of data. Further assessment of this velocity field is given by Kreemer et al. (this volume).

COST-BENEFIT ANALYSIS

Here, we present a first-order cost-benefit analysis to assess whether in fact the semipermanent network we have designed proves more cost-effective than other approaches. Specifically, we compare our semipermanent network with permanent GPS and campaign GPS with regard to their performance in delivering a set of accurate station velocities. The three key cost-driving assumptions that we make are that (1) permanent GPS requires significant site development, (2) campaign GPS requires an average of 3 d on site with an operator present for reasons of security and logistics, and (3) semipermanent GPS requires site visitations ~6 times per year, within day-trip driving distance of a central facility. So the conclusions of our analysis depend critically on the validity of these assumptions. Table 3 provides details on the calculation, which shows that for purposes of mapping strain rates, semipermanent networks outperform permanent networks by a factor of ~3 in spatial resolution, and they also outperform campaigns (with significantly higher accuracy within any specified time frame).

Perhaps surprisingly, annual operational costs for semipermanent GPS networks are less than either permanent or campaign GPS. This is because for semipermanent GPS, fieldwork days are scheduled such that up to nine sites are visited by one technician, thus the incremental cost per station visit is small in terms of transportation and labor. Permanent stations, on the other hand, are visited when there are problems, so no similar efficiency can be made, and therefore visits are relatively costly. Campaign GPS fieldwork is relatively expensive due to security and logistical issues. This extra cost for campaigns is not compensated by the savings that are gained by visiting many sites with one instrument during the year (eight different sites per campaign season are assumed here). Semipermanent GPS requires more up front cost in terms of equipment, but this is more than compensated by efficient (and therefore inexpensive) fieldwork. Adjusting the assumptions in Table 3 will clearly change the numbers, but it is difficult to change the relative ranking of the three techniques.

More competitive performance could in principle be obtained by permanent GPS if site-installation costs (specifically, monument installation) could be reduced. The trade-off would therefore be in terms of fewer more stable sites versus a denser network with potentially more local anomalies. The advantage of expending more on stable monuments is that the permanent network can serve as a stable “backbone” array that provides a good ground truth. Therefore, we view permanent networks as being essential and complementary to other types of networks.

More competitive performance could in principle be obtained by campaign GPS if fewer than 3 d were spent on each site. The best performance is obtained with one day on each site. Of course, the trade-off here is with regard to reliability, and the distinct possibility that a campaign might completely fail for specific sites due to the lack of redundancy. Another problem is the difficulty in the assessment of errors with only one daily epoch per campaign. Nevertheless, the number of extra sites that can be measured for the same cost might be preferable, and so identification of problem sites and the assessment of velocity errors might be done with a more spatial rather than temporal analysis.

Our cost-benefit analysis shows that for commonly assumed situations, semipermanent networks present an effective means

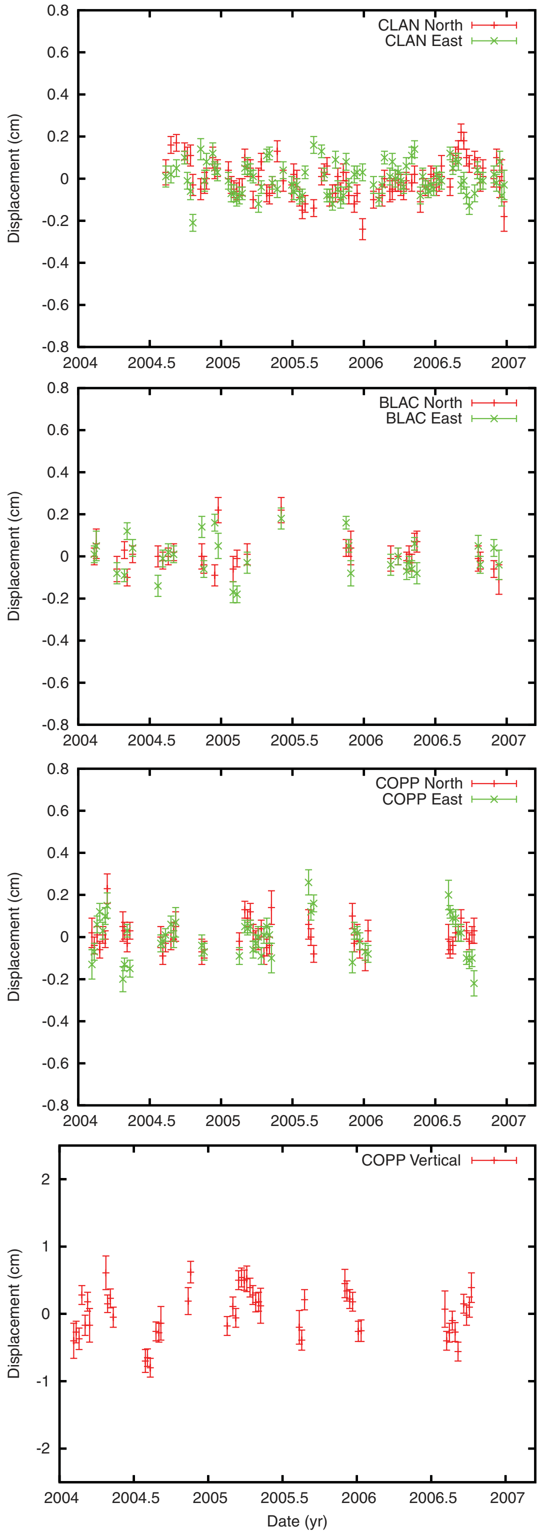

Figure 3. Examples of detrended weekly coordinate time series (unfiltered) from stations CLAN, BLAC, and COPP. Coordinate components are indicated as latitude, longitude, or height. Note that the half-scale is 8 mm for horizontal components and 25 mm for height, reflecting the approximate factor of three in relative scatter for height time series.

TABLE 3. COST-BENEFIT ANALYSIS OF GLOBAL POSITIONING SYSTEM (GPS) SURVEY METHOD

Cost-benefit factors	Permanent	Campaign	Semipermanent
Assumptions			
A. Velocity resolution time (yr)	2.50	10.00	3.50
B. GPS survey equipment set ($K)	8.00	8.00	8.00
C. GPS stations monitored per set	1.00	8.00	2.00
D. One-time installation cost ($K)	10.00	0.00	0.10
E. Site visits per year	1.00	1.00	6.00
F. Days on site per visit	0.50	3.00	0.15
G. Per diem meals and lodging ($K)	0.08	0.08	0.00
H. Transportation per visit ($K)	0.10	0.06	0.03
J. Field technician labor per day ($K)	0.20	0.20	0.20
K. Communications per year ($K)	0.30	0.00	0.00
Subtotals			
L. Capital (D + B/C) ($K)	18.00	1.00	4.10
M. Annual {E[H + F(G + J)] + K} ($K/yr)	0.54	0.90	0.36
Derived costs			
N. Per resolved station velocity	19.35	10.00	5.36
P. Per station over 10 yr	23.4	10.00	7.70
Benefit/cost ratios (relative to permanent)			
Number of resolved station velocities with fixed 10 yr funding (19.35/N)	1.00	1.94	3.61
Number of stations that can be routinely monitored with fixed 10 yr funding (23.4/P)	1.00	2.34	3.04

of mapping variations in crustal strain on the regional scale. Permanent networks retain a complementary utility in providing a backbone reference frame with velocities that can act as a ground truth. Permanent networks might also be essential if the goal is to monitor possible transient behavior. On the other hand, GPS campaigns appear (in comparison to semipermanent GPS) to have little redeeming qualities to justify their use on newly mapped terrain, though their use may be justified in specific cases to add value to existing data from previous campaigns.

CONCLUSIONS

We have embarked on an experiment to characterize strain partitioning in the Northern Walker Lane to improve models of (1) geothermal activity, which is largely amagmatic in the Great Basin, (2) seismic hazard, (3) the ways in which the northern Walker Lane accommodates strain between the Sierra Nevada block and the extending Basin and Range Province, and (4) Neogene development of the northern Walker Lane and its broader role in the ongoing evolution of the Pacific–North America plate-boundary system. To this end, we have designed, constructed, operated, and tested the 60-station semipermanent GPS network "MAGNET" spanning the northern Walker Lane and central Nevada seismic belt, with a mean nearest-neighbor spacing of 19 km (13–31 km range). Now at the watershed period of 1.5 yr (for the longest-running stations), when estimated GPS station velocities begin to converge and make sense (Blewitt and Lavallée, 2002), MAGNET is delivering data products that meet and even exceed the expectation and design specifications for the eventual objective of producing a uniform, high-resolution strain-rate map of the northern Walker Lane.

MAGNET is occupied by a total 34 receivers that are intermittently moved around the network, with a mean station occupancy of ~50% (after accounting for equipment failures). Assessment of the performance of MAGNET has proved that a semipermanent network can provide a cheaper, higher-density alternative to permanent networks, and a more accurate alternative to traditional GPS campaigns. The mean weekly repeatability (spatially filtered) is 0.5 mm in longitude, 0.6 mm in latitude, and 2.1 mm in height; these statistics are very similar to those of permanent GPS networks. This implies that antenna setup error has been mitigated, despite the fact that random antennas (of the same type) are assigned to station sessions (implying that antennas likely fall within the manufacturer's design specifications). MAGNET's design is generally applicable to regions with an abundance of vehicle-accessible rock outcrops, and it could be replicated elsewhere in western North America.

Other investigators may wish to install similar networks in a compatible way, creating a collaborative potential to form a dense (~20 km spacing), uniform, semipermanent GPS network spanning the western States. Such a network would complement permanent GPS networks, such as the Plate Boundary Observatory component of the National Science Foundation's EarthScope Program, with potentially much higher and more uniform resolution. Such a development would represent a major advance in earthquake preparedness, and it would provide a vital, spatially uniform data set to construct strain-rate maps that could be used for a multitude of purposes, including seismic hazard assessment, exploration of geothermal energy, understanding the dynamics of the Pacific–North America plate boundary, and understanding the structure and evolution of the North American continent.

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