The Iceland GPS Geodetic Field Campaign 1986

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Introduction

For a number of years, geophysicists have followed the development of the Navigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System (GPS) in anticipation of conducting geodetic surveys of such a size and accuracy [*Bossler*, 1984] that the detailed monitoring of neotectonic movements on a regional scale will be permitted. During 1986 the technology had considerable application in this field, including studies conducted in California, Mexico, the Caribbean, and New England. The largest of the 1986 projects was a survey of Iceland that involved ultimately the use of 26 TI4100 receivers by over 30 scientists from nine nations. Twenty different universities, institutions, and companies were involved in the effort. This article briefly describes the field campaign and the concurrent data processing.

Surveying With GPS

GPS surveys use special receivers to record coded signals broadcast by the NAVSTAR GPS satellites. Signals recorded simultaneously from the same constellation of satellites are processed subsequently to provide three-dimensional vector lengths between the ground control points. High accuracies are achieved by observing four or more satellites from horizon to horizon [*Wells et al.*, 1986].

GPS surveying offers a number of fundamental advantages over traditional terrestrial methods:

- Accuracies of around 1 cm in the horizontal direction and 2 cm in the vertical (height) are achievable for baselines of up to 100 km. This is an order of magnitude more accurate than is feasible by using terrestrial geodesy [*King et al.*, 1985; *Strange*, 1985].
- Line of sight between ground control points is not necessary, so measurements can be accomplished in areas of rugged terrain. Also, points can be sited in accordance with scientific priorities and logistic convenience (e.g., beside roads). This factor can greatly accelerate surveys in rugged terrain, which typifies areas of active tectonics. It can also significantly lessen the cost of such surveys.
- Hundreds of baselines can be measured in a few days by the use of several receivers simultaneously; that is, if n receivers are used, $n(n-1)/2$ baselines are measured [*Bock et al.*, 1985].
- There is no instrumental limit to the length of baseline that can be measured, although in practice, baselines more than a few thousand kilometers are limited in accuracy by the accuracy to which satellite orbits are known.

The accuracy attainable at present is limited by orbital uncertainties, uncertainties in receiver clock offsets and rate changes, the problem of identifying cycle and half-cycle slips in the phase observational data, and signal delays caused by uncertainties in the propagation velocities in the ionosphere and troposphere. Accuracy is limited to a few parts per million (ppm) if orbital parameters broadcast by the satellites are used. Accuracies approaching 0.1 ppm may be obtained by using precisely calculated satellite orbits and by correcting the data for atmospheric conditions during observations [e.g., *Beutler et al.*, 1985*b*].

Tectonic Setting of Iceland

Iceland is a 100,000 km^2 volcanic island that straddles the mid-Atlantic Ridge at approximately 65°N. It exists because of excessive volcanism related to the large ridge-centered Iceland hotspot [*Vogt*, 1983] that has built up a pile of basaltic volcanics that rises to 2 km above sea level. Studies of magnetic anomalies and fracture zones in the north Atlantic indicate a full spreading rate of 2.2 cm yr^{-1} in a direction of N100°E [*Bjornsson*, 1983]. Because the plate boundary is subaerial, Iceland offers a rare opportunity to study the mechanisms of accretionary tectonics in greater detail than is possible on the seafloor.

The Mid-Atlantic Ridge comes onshore and traverses the country as the continuous Neovolcanic Zone (Figure 1), where postglacial (less than 10,000 yrs) volcanic activity is concentrated. This zone consists of about 25 volcanic systems, most containing a central volcano and fissure swarm. The fissure swarms have the structure of shallow grabens and are arranged en echelon within the Neovolcanic Zone. The mechanics and kinematics of crustal accretion were elucidated during 1975–1985 by the reactivation of the Krafla volcanic system, where up to 8 m of crustal widening and 2 m of relative vertical crustal movements were observed [*Bjornsson*, 1985]. This activity clearly demonstrated the interplay between horizontal and vertical tectonic movements and also the highly episodic nature of crustal extension at the plate boundary, as compared with the continuous, slow motion usually envisioned for the interior of the plates.

The plate boundary in Iceland also contain two complex zones of transform faulting that exhibit large-magnitude ($M > 7$) seismicity. In the north the Tjornes Fracture Zone contains at least three parallel faults that lie mainly offshore but extend onto land in

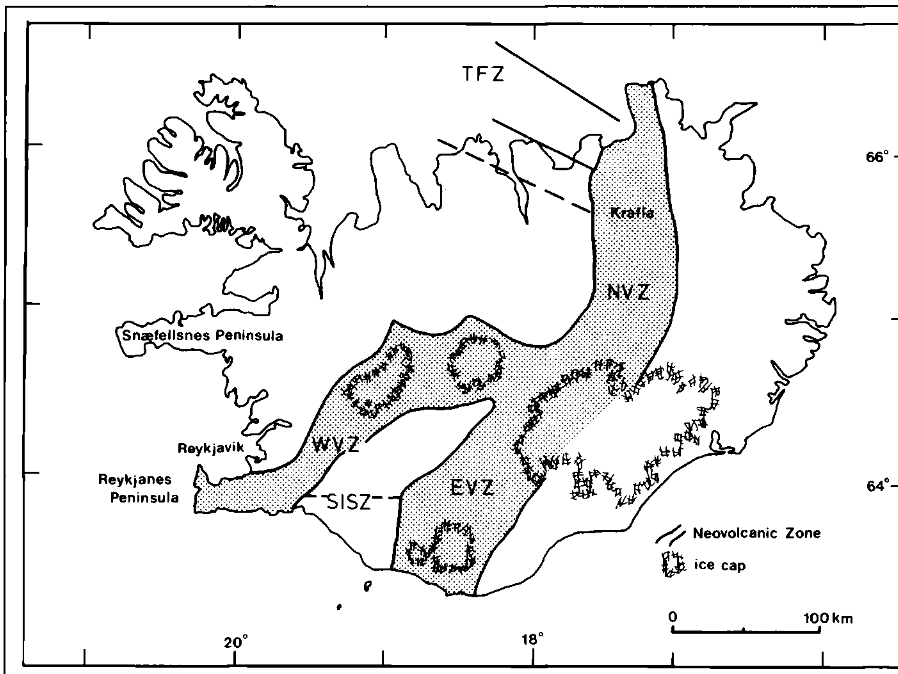

Fig. 1. Simplified tectonic map of Iceland. TFZ indicates the Tjornes Fracture Zone; NVZ, the Northern Volcanic Zone; WVZ, Western Volcanic Zone; EVZ, Eastern Volcanic Zone; SISZ, South Iceland Seismic Zone. The shaded area indicates the neovolcanic zones.

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north Iceland [*Einarsson,* 1976]. In the south, an 80-km-long fracture zone connects the twin parallel branches of the Neovolcanic Zone. Destructive shocks or series of shocks occur there at 50–100-yr intervals [*Einarsson et al.,* 1981]. The last major sequence occurred in 1896, and renewed activity, with events possibly exceeding magnitude 7, is anticipated within 1–2 decades.

Goals of the Survey

This project laid the foundations for addressing several different neotectonic issues, in addition to supplementing existing geodetic networks within Iceland.

- The primary objective of the project was to establish a broad survey network in the South Iceland Seismic Zone. Repeated surveys will constrain coseismic crustal movements that accompany the anticipated destructive earthquake sequence there. Preseismic deformation may also be detected.
- Repeated surveying of the complex rift zones will eventually uncover the pattern of spreading over the island, which is poorly understood as yet, and kinematic relationships between the discrete en echelon fissure swarms,
- The dissipation of strain into intraplate regions in the wake of the Krafla spreading episode could be monitored by a network in north Iceland. This will provide information about the rheology of the upper mantle and insight into the transference of stress between discrete tectonic units, e.g., the rift and transform zones.
- Models of the local Icelandic geoid could be tested by relating GPS measurements to mean sea level.
- Accurate measurements of the position of Iceland relative to Europe and North America would be made, allowing intraplate deformation close to an accretionary plate boundary to be studied.
- Repeated measurements will permit study of the transfer of spreading from the Western Volcanic Zone to the Eastern Volcanic Zone.

The Fieldwork

Initial plans for a survey of Iceland were discussed in December 1985. During spring 1986, a large number of individual researchers and institutions became involved. As a result, a significantly larger project became possible.

The final plan was tc observe 51 sites in Iceland (Figure 2). The observing program was constrained by satellite observation windows, site accessibility, and the desirability of occupying control points in existing geodetic networks. The far north position of Iceland permitted two 4-satellite observation windows per day: a 1-h 10-min window in the morning and a 1-h 50-min window in the evening (Figure 3). The network is densest in the South Iceland Seismic Zone, where it encompasses most of the area that is in imminent danger of slipping and incorporates a number of ground control points that were surveyed by conventional methods in 1984.

A network of lower density covers central, western, and northern Iceland, providing a broad framework for future detailed surveys. Supplementary ground control points were occupied on either side of the rift zone in the Krafla area, the site of the recent spreading episode.

Fieldwork began in late June, when accessibility to the Icelandic interior improves. A team of seven Icelandic geophysicists and geodesists visited all 51 planned sites, prepared detailed site descriptions, and installed new ground control points where necessary. This was an indispensible part of the fieldwork, since the observation and drive schedule left no time for site searches. The rest of the field personnel arrived in Iceland early in July, and 5 days were spent in practice sessions and readying the equipment.

The network was occupied by two fixed receivers and five mobile ones. One receiver was maintained as a spare unit. The two fixed receivers were operated with GESAR (Geodetic Satellite Receiver) software to permit long observation windows that included different constellations of satellites, while the five mobile receivers were operated with TI4100 software for shorter four-satellite windows. The two fixed receivers were stationed at points S13 and N17, which are strategically located in the southern and northern parts of the network, where shelter and ac power were readily available. The five mobile receivers were powered by pairs of car batteries supplemented by generators. The network shown in Figure 2 was mostly occupied by four of the mobile receivers as a chain of quadrilaterals. Two of the receivers were moved after each observation window, which meant that the majority of the sites were occupied for a morning and an evening window.

Each mobile crew consisted of two to four people and included an Icelandic geodesist who was familiar with the ground control points to be visited, along with an experienced TI4100 operator. Accommodation was available at some sites, but crews had to camp in the more remote areas. All crews were equipped with radio telephones that permitted contact with headquarters at Reykjavik.

Surveying commenced July 13 with the observation of a small calibration quadrilateral close to Reykjavik. This quadrilateral will be used for comparison with conventional methods and future GPS surveys. The Reykjanes Peninsula was then occupied, and the South Iceland Seismic Zone was surveyed from west to east. The survey then proceeded north through central Iceland, west onto the Snaefellsnes Peninsula, and across north Iceland from west to east. In central and northern Iceland, the times needed to drive between sites were sometimes as long as 8 hours. The last date of observation was July 24, making 12 observation days in all. Of the 143 observing sessions scheduled, only one was missed.

In Reykjavik a communications and processing base operated 24 hours a day to handle logistic and instrumentation problems arising during the fieldwork. All field tapes from the mobile receivers were delivered to Reykjavik soon after being recorded and were processed with GEOMARK™ software in three microcomputers. Receiver functioning was thereby continuously monitored, and initial estimates of all the vector lengths were usually available within a day of the measurement.

While the Iceland campaign was being conducted, researchers in other countries were operating a large number of TI4100 receivers, using GESAR software. Fixed VLBI sites were occupied at Onsala (Sweden), Haystack (Massachusetts), and Fairbanks (Alaska), and also at four additional Alaskan sites (which were part of the National Aeronautics and Space Administration's Crustal Dynamics Project), five Canadian VLBI sites, six additional Canadian sites, a four-station network in New Brunswick (Canada), and at three locations in Greenland (Figure 3). These represent some of the longest baselines measured so far with GPS receivers (over 5000 km). Of the 76 sites

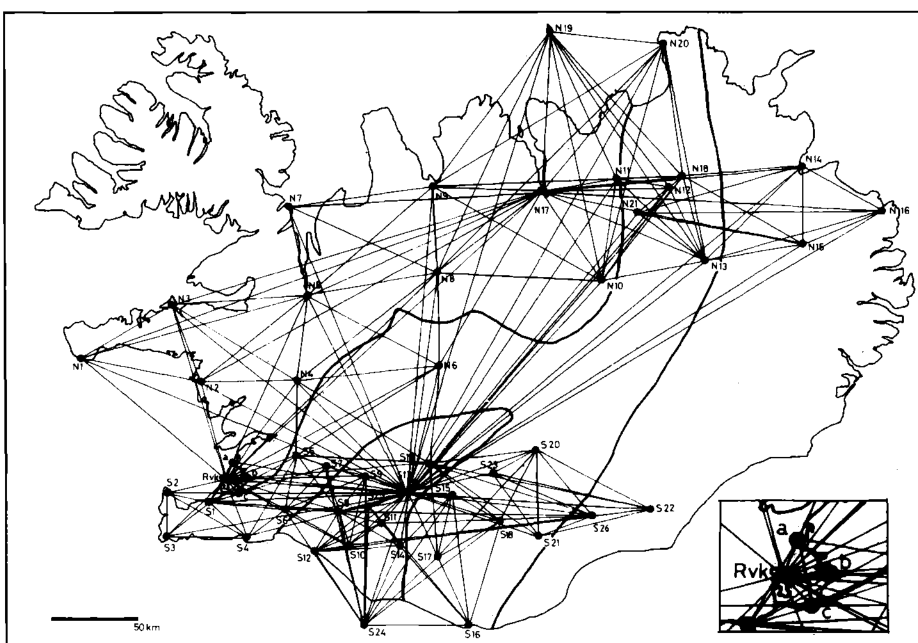

Fig. 2. Network of sites occupied in July 1986. Lines indicate all direct measurements. Sites S13 and N17 were occupied permanently by receivers using GESAR software, and the other sites were occupied by mobile receivers using TI4100 software. The outline of the neovolcanic zones is indicated by the bold line.

occupied, 15 were occupied only once, 27 were occupied twice, and the remainder were occupied three or more times. Three sites were occupied for 24 observing sessions.

Processing

Concurrent with the fieldwork, all lines measured directly with TI4100 software were transferred from tape to disc and processed using the program Geomark™. This was to provide a continuous monitor of receiver performance and to produce immediate results for the Icelandic Geodetic Survey. Geomark™ uses broadcast orbits and permits very little operator interaction during processing. The internal consistency of the data was assessed by examining three-dimensional vector closures for each observing session and by comparing results for the same baseline measured on different days. Loop closures and repeatability varied from 0.3 to 10 ppm. Subsequent examination of the data showed that most of the larger misclosures were caused by blunders in entering weather data or by weak solutions due to fluctuations in signal strength associated with multiple reflections. There are, however, additional reasons for the variability in repeatability and loop closures yielded by Geomark™ processing (for example, extreme ionospheric and tropospheric variability), and these factors are now under investigation.

Although several of the GPS points were already control points of Icelandic geodetic networks, few comparisons with directly measured geodimeter lines were possible because the GPS baselines were typically much longer than existing baselines. A quadrilateral with sides 11, 12, 13, and 16 km in length was occupied close to Reykjavik (RVK-a-b-c, Figure 2) to provide data for such a comparison, and there are plans to measure these lines with a geodimeter in the near future. A 1.4-km baseline near Reykjavik agreed to within 3 mm (2 ppm) of the geodimeter length. Three 15–33-km-long GPS baselines in south Iceland were a part of a geodimeter network surveyed in 1984. The GPS and geodimeter results differed by more than the formal geodimeter uncertainties. The source of these discrepancies is presently under investigation.

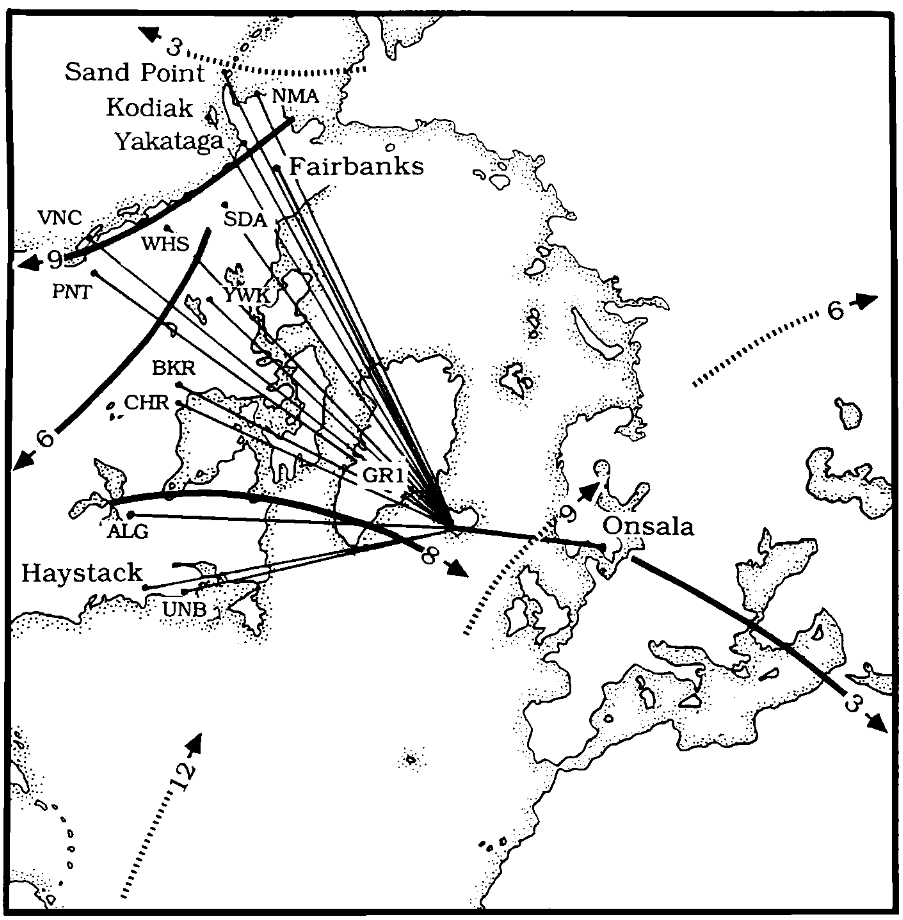

Fig. 3 GPS observations during July 1986. Multiple sites were occupied at UNB (four), GR1 (three), BKR (two), and in Iceland (51). Water vapor radiometers were operating at the named locations. The four dashed arcs correspond to the projected ground paths of NAVSTAR (Navigation Satellite Timing and Ranging) satellites (space vehicle (S.V.) numbers indicated) during the 69 minute-long Icelandic morning observation windows. The longer (solid) arcs are those used during the 109-minute evening observation window. The wide simultaneous coverage of the northern hemisphere was possible because of close collaboration between the U.S. National Geodetic Survey, Canadian Geodetic Survey, Danish Geodetic Survey, Defense Mapping Agency, the University of New Brunswick, and scientists in radio observatories at Haystack (Mass.) and Onsala (Sweden). The observations resulted in 2629 baselines.

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During September 8–20, a small working group began postprocessing the data at Bern, Switzerland, under the direction of G. Beutler. Beutler's group used the Bernese Second Generation Software [*Beutler et al.*, 1985*a*], which uses orbit refinement techniques and is capable of simultaneously inverting multistation data sets for station coordinates and calculating vector lengths. In 2 weeks the group derived a solution for all the Icelandic data (1275 baselines) and approximately half the intercontinental data (the rest were not available at that time). No problems were encountered in combining the GESAR and TI4100 data. The strength of the network solution was assessed by adjusting selected parameters (for example, minimum satellite elevation and weather criteria). Preliminary indications are that most of the baselines are associated with a 0.2-ppm (1-σ) uncertainty.

Summary

The large data set offers many challenges for processing refinement, a number of which are already being pursued. A great number of lessons were learned, and subsequent surveys will doubtlessly incorporate many improvements in design, resulting in improved accuracy in the final results. The Icelandic GPS network will be supplemented in local areas of particular interest, and the first of these was an Iceland/Federal Republic of Germany/United Kingdom project in the Northern Volcanic Zone that measured an additional 63 points in August 1987 [*Foulger*, 1987]. These networks will include nearby points from the 1986 survey, thereby tying them to the broad framework and providing repeat measurements of selected lines. Remeasurement of the entire 1986 network is not planned for the immediate future because of the low average spreading rate (2 cm yr^{-1}).

The enormous data set collected (a total of 2629 baselines in only 12 days) was only possible through the cooperation and generosity of numerous individuals and institutions from several nations, many of whom contributed their work and resources with little expectation of personal professional gain. Clearly, such a spirit will be indispensible if future surveys are to be made on a similarly large scale. If more of this spirit is forthcoming, GPS geodesy may prove to be a powerful tool in breaking down international distance as well as measuring it.

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