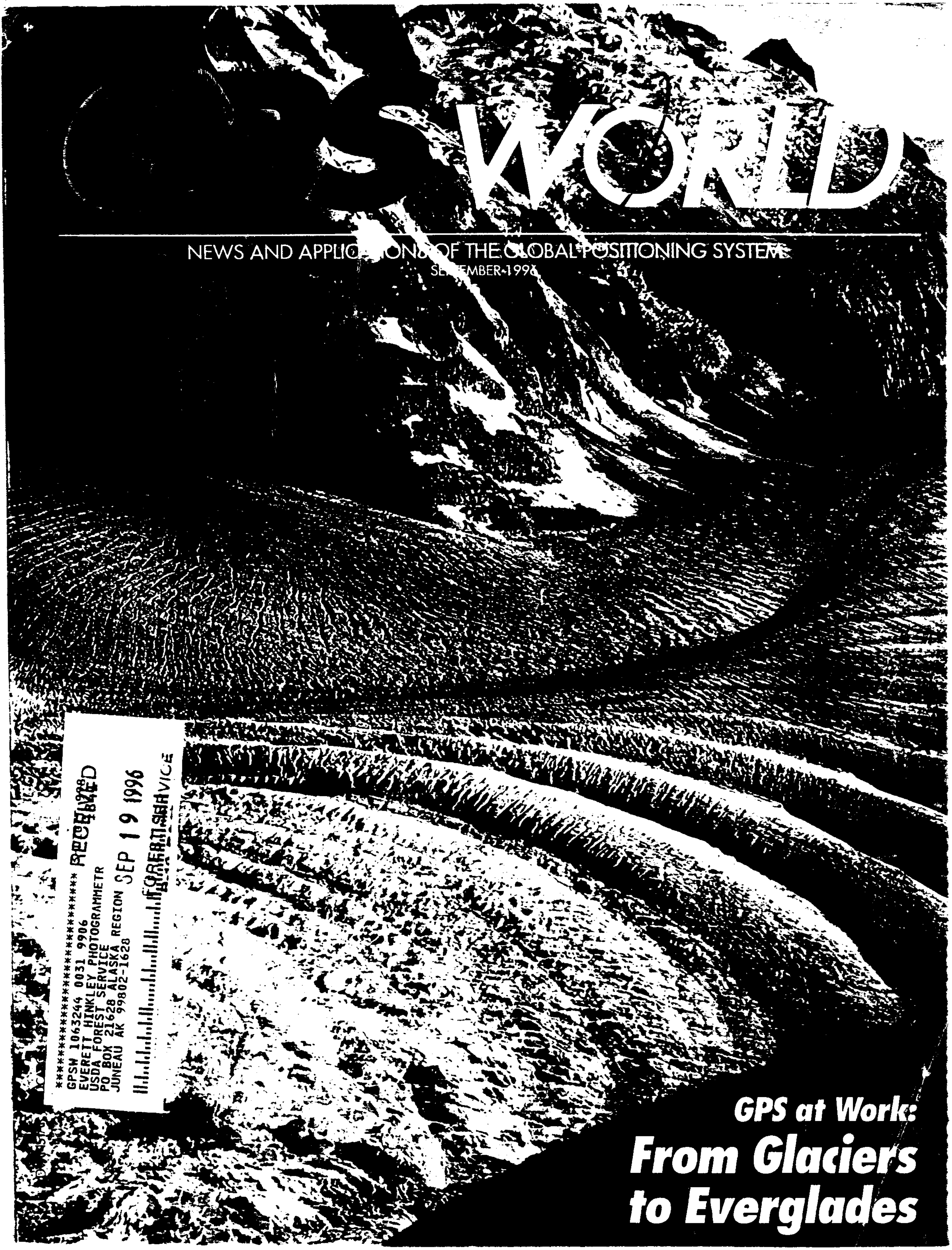
GPS WORLD

NEWS AND APPLICATIONS OF THE GLOBAL POSITIONING SYSTEM

SEPTEMBER 1996

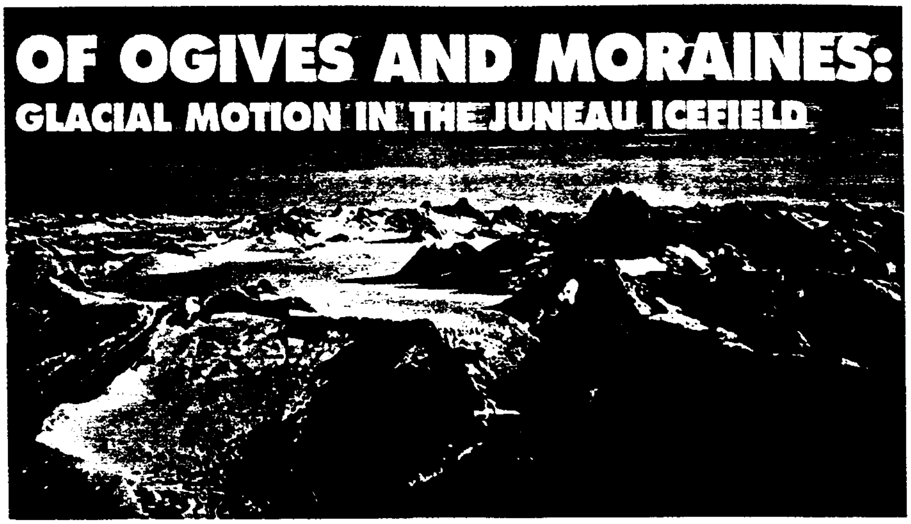


GPS at Work:

From Glaciers to Everglades

OF OGIVES AND MORAINES:

GLACIAL MOTION IN THE JUNEAU ICEFIELD



COURTESY OF AL CLOUGH/JIRP

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When glaciers meet, what happens? How do they move, deform, and ablate? This is what the authors set out to discover last year, as participants in the Juneau Icefield Research Program. With two GPS units and only 10 days, they set up a 36-point monitoring network and performed two surveys. The icy conditions presented a few obstacles, but not enough to prevent the project from being a success.

Excessive rainfall, nighttime temperatures below freezing, the nearest city 35 miles away. These are not the usual attractions of a summer getaway. But each summer for the past 50 years, scientists and students from around the world have been eagerly converging upon just such an environment to participate in the Juneau Icefield Research Program (JIRP). For eight exciting weeks, JIRPers immerse themselves in fieldwork and studies in the glaciology, weather, and geology of the Juneau Icefield in southeast Alaska.

JIRP is run by the Foundation for Glacier and Environmental Research, an organization based in Seattle, Washington, and Juneau, Alaska. The foundation traces its roots back to the early 1940s, when Dr. Maynard M. Miller was surveying numerous glaciers in the Alaskan Panhandle. Miller conceived the idea of establishing a continuing glacier research program on the Juneau Icefield. Shortly thereafter, the program (1946) and the foundation (1955) were born. Since then, with the support of various government and private organizations, JIRP has provided students and researchers with a study area and field laboratory where they can develop a better understanding of glacioclimatic changes.

One of the attractions of the JIRP, the so-called Gilkey trench, is a complex of three glaciers: the Gilkey, the Vaughan Lewis, and the Unnamed. All three merge together and proceed with their majestic flow side-by-side west to the Gilkey river, and finally to Berners Bay and the Lynn Canal. In August 1995, we were fortunate enough to participate in JIRP 95, traveling 6,100 miles from our university — Technion, in Haifa, Israel — to the Juneau Icefield, to join the other program participants already hard at work on their own projects.

The objective of our trip was to study the motions, deformations, and ablation (decrease in volume) of the three glaciers in the area of their merger. Like the other JIRP researchers before us, we were drawn to these fast-moving glaciers (0.3–0.6 meters per day) that could serve as excellent field laboratories for measurement and analysis of earth crustal movement and deformation. We planned to conduct our studies of the glaciers using GPS.

OUR AMBITIOUS PLAN

The area of our study, designated by us as "the intersection," was about 1.5 × 2 kilometers in size, with a drop in elevation of 100 meters. The intersection was marked by a complex pattern of motions and deformations caused by the fairly rapid movement of the glaciers, the sharp turn west of the Gilkey glacier, and the aftereffects of the icefall of the Vaughan Lewis coming from the east. The surface area was heavily crevassed, which could complicate the performance of even routine and simple surveys.

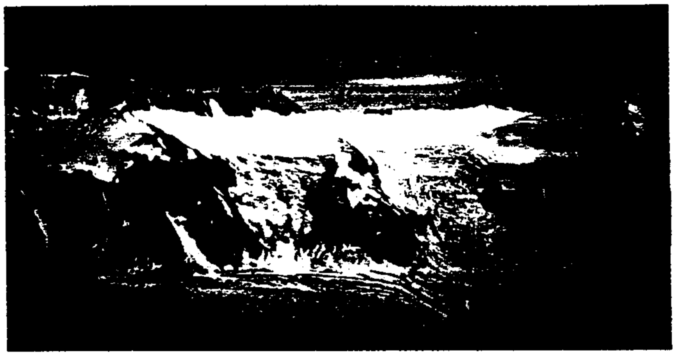
In the past, traditional theodolite and total station surveys had been performed to study surface motion and deformation at the intersection, as well as of other glaciers in the icefield. Martin Lang reported of extensively using GPS on the icefield during the 1993 JIRP season but not in the Gilkey trench.

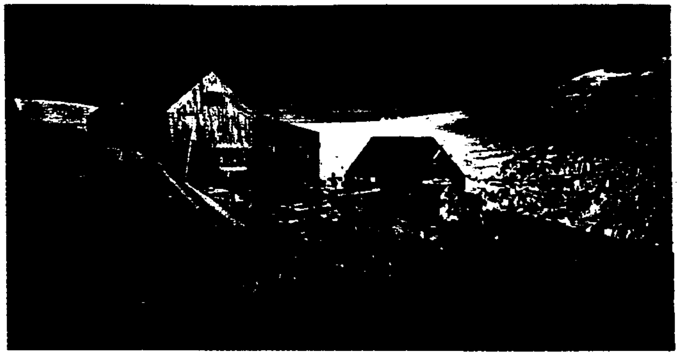
For our 1995 JIRP season's work, we decided on a more challenging approach — a 10-day motion study of the intersection using two 12-channel, L1, C/A- and P-code, L2, P-code geodetic GPS units. At first, monitoring the motion and ablation of glaciers in the Juneau Icefield by GPS measurements may seem like overkill. But we were swayed by the stable and global, in nature, reference coordinate system World Geodetic System of 1984 (WGS84), which is inherent in any GPS measurement. It would be a definite boon for tying future surveys in the icefield.

We started with an ambitious plan — to monitor 50–60 markers using the GPS units in kinematic mode and to repeat the survey at least three times over 10 days. It turned out that we were overly optimistic. Difficult field conditions, described later, forced us to limit our survey to only 36 markers, with only two measurement sessions spaced 4–7 days apart. Still, the work we did was more than satisfactory.

FROM HAIFA TO JUNEAU

Getting to our work site was not easy. The journey from Haifa to Juneau took about 36 hours, with an overnight stop in Seattle. From Juneau, the nearest city to the icefield,





TOP TWO PHOTOS COURTESY OF AL CLOUGH/JIRP

GILAD EVEN-TZUR AND HAIM B. PAPO

The Gilkey and Vaughan Lewis (top left) are part of the Juneau Icefield. The authors stopped at C-18 (top right), their base camp, before heading to the intersection (the Vaughan Lewis icefall is in the middle, the cleaver on the left).

we were flown 25 miles by helicopter to camp C-10, which is the central camp, or headquarters, of JIRP. A day or two later, we were driven 21 miles in a snow vehicle to camp C-18, further in the icefield, which was to serve as the base camp for us and for other researchers. It was exciting to meet other JIRPers at the camp already busy at work on their respective projects. We were joined by three researchers who were assigned to work with us on our project up to its completion. The next day, we loaded our personal gear and surveying instruments into our backpacks and, in snowy and stormy weather, made our descent of a steep rocky mountain (called the "cleaver") overlooking the intersection from the east to the focus of our project — the intersection. Late in the afternoon, we reached the small field camp C-18/B, which consisted of only two small tents set up on the glacier's surface (literally on the ice) between two ogives. (Wave ogives consist of ice and look much like the ripples created when a rock is thrown into water.) This is where we spent our nights for the next week and a half.

THE MONITORING NETWORK

After descending the cleaver (600 meters) to the intersection surface and walking on the surface with its many crevasses and obstacles, it was clear to us that given the amount of time we had, we'd have to change our plans and reduce the scope of our study. In addition, to save even more time, we split our team into two, with one crew setting up the monitoring network, while the other began the GPS measurements for the first survey (described in the next section).

Establishing the network proved difficult for several reasons:

- To meet our position accuracy goal of 1–2 centimeters in three dimensions, we had to create well-defined markers that would keep their positions relative to the surrounding ice mass, thus representing its motion.
- The glacier's surface at the intersection featured high middle moraines (accumula-

tions of earth and rock carried and deposited by glaciers) and 15-meter-high wave ogives, resulting from the Vaughan Lewis icefall. Both the moraines and ogives obstructed the line of sight.

- The extremely wide crevasses that dominated the intersection's surface made it difficult to set the markers in a straight line.

To address the first item, we decided to use thick iron pegs (12 millimeters in diameter and 25 centimeters long) as markers, which our team members hammered into the ice. To enhance our chances of finding the markers for the second survey, they placed nearby the usual bamboo sticks with a colored plastic strip on top.

Experienced JIRPers warned us that ablation greatly intensifies around any object foreign to ice because of its different heat-absorption properties. This meant that there was a real danger that on the second survey, instead of our markers, we would find deep holes in the ice. Against that possibility, we improvised thin (1 millimeter thick) plastic sheets, 20 × 20 centimeters in size, which carried the markers' IDs and most importantly served as "safety belts," holding the markers in place by enabling them to float upon the water's surface.

To address our concerns about the lack of visibility and straight lines, the team set out (in terms of its orientation) the network of markers using a magnetic compass so that, in spite of the occasional offsets, the grid lines would come out roughly parallel. Setting out the markers at equal distances was more difficult, and the team had to resort to crude distance-estimation techniques. The results of this rather primitive setting-out method can be seen in Figure 1 on page 69.

In only three cases did the distances between consecutive markers (mainly in the north–south direction) approach, or even exceed, 400 meters. The general pattern of the monitoring network was a 6 × 6–point rectangular grid set out over the intersection with point distances of 300 meters.

SURVEYING THE NET

Meanwhile, the surveying crew was busy performing the first monitoring session of the points. As with establishing the network, the GPS survey of the Gilkey intersection came with its own share of logistical problems.

The nearest JIRP camp, C-18, where we could recharge our batteries, unfortunately was more than 2,600 meters from the intersection and more than 600 meters above its surface. This meant that recharging our batteries would entail climbing up the cleaver from the intersection to C-18 and coming down to the intersection — a challenging mountaineering exercise that would take several hours of intensive and strenuous climbing using ropes and climbing safety devices. This made conserving our batteries a priority and changed our original plan to use GPS in kinematic mode, which would have required us to keep the unit powered up and operating continuously.

The second problem that changed our planned usage of the GPS units was the challenging terrain and its effect on the stability of the GPS antenna. In order to pass from one marker to the next, we had to leap or jump over many obstacles, such as big rocks and crevasses. These vigorous movements made it difficult to keep the antenna upright while moving from one marker to the next. Sometimes the antenna would tilt and lose lock with the GPS satellites.

These field constraints dictated the only solution that could work, namely:

- We performed the GPS survey in fast-static mode with one receiver set up and working continuously on our fixed reference station at C-18, where a brass marker ("FFGR-43") was set in solid rock. The other receiver, the "rover," moved over the net, collecting measurements at each point. We switched off the rover during the 15–25 minutes needed to move between adjacent markers to save the batteries.
- Counting on the "self-starting" properties of the GPS unit (which needed no known points to initialize the integer ambiguities), we limited the total data collection time at each marker to 10 minutes. Only in two cases did we have to prolong data collection to 25 minutes per point. (Those two exceptions were in the southeast corner of the net and occurred because the steep walls of the trench obstructed part of the sky; see Figure 1, points #53 and #54.) We kept the rover's total working time to less than 10 hours.
- We set the antenna on a tripod that was centered on the marker and measured its height precisely to improve the accuracy of the fast-static positioning and also to address the "floating marker" problem.
- We used a walkie-talkie to communicate to a coworker at C-18 to switch on and off, as needed, the GPS unit that operated at the C-18 reference station in order to cover the working hours of the rover. Rather than sav-

BOTH PHOTOS: GILAD EVEN-TZUR AND HAIM B. PAPO

During the two surveys, the authors located many of the survey points by sighting the bamboo markers (large photo); once there, they used fast-static GPS to position the points. All the point markers consisted of iron pegs equipped with plastic "safety belts" to keep them afloat in what eventually became pools of melted ice.

ing the batteries, the intent here was to conserve space on the GPS unit's solid-state memory. At a recording interval of 10 seconds with seven or eight visible satellites, we were limited to no more than 24 hours of data collection.

Fieldwork. Even given these physical conditions and operational constraints, our two GPS units performed well. As expected, the occasionally icy temperatures decreased the capacity of the batteries by 20–30 percent, but we had brought along two spare batteries, which helped us complete our measurements. Using the rover in fast-static mode, we were able to produce easily two complete sets of measurements. One surveying session of the monitoring network took approximately two days to complete.

Three to four days passed after the first survey before we started the second one. We used the time between the end of the first and the beginning of the second monitoring sessions to climb the cleaver to camp C-18, recharge the batteries, download and check the data (wash and do some laundry too), and then come down to camp C-18/B for the second session.

The Second Session. We conducted the second monitoring session in the same manner as the first. During this survey, we found out that the careful work of our team members done during the establishment of the network grid had paid off.

Between the time of the first and the second surveys, the wind had blown down many of the bamboo sticks that were supposed to indicate the locations of the markers. The magnetic orientation of the grid and a compass helped us spot the markers.

Once we located the markers, we were in for a pleasant surprise. Each and every marker was floating in the center of a small pool of icy water 2–4 centimeters in diameter but kept on the surface by its plastic "safety belt."

PROCESSING THE DATA AT HAIFA

At the end of the second session, we returned to C-18 and used a GPS postprocessing software program to evaluate two sets of vector components for each of the 36 markers in the WGS84 reference system. Our computation was actually a "field check" of the data because the coordinates of FFGR-43 were unreliable due to the possible effects of selective availability.

Four weeks later, back home in Haifa, we repeated the computations and found only small differences in the vector components. At Haifa, based on our many "days" of data, we computed the final WGS84 coordinates of FFGR-43 relative to the three nearest International GPS Geodynamics Service (IGS) stations: YELL (in Yellowknife, 715 miles from the monitoring network), DRAO (in Penticton, 880 miles from the network), and ALBH (in Victoria, 845 miles from the network). The coordinates of the reference station in the WGS84 reference system came out (weighted mean) as follows:

$$\varphi_i = \text{N } 58^\circ\ 50'\ 06.983''$$
$$\lambda_i = \text{W } 134^\circ\ 16'\ 38.031''$$
$$h_i = 1{,}703.78 \text{ meters}$$

We transformed the WGS84 vector components (from FFGR-43 to each marker) into a local geodetic horizon system "e,n,u" defined by the axis of the WGS84 ellipsoid and by the ellipsoidal normal of

the C-18 reference station. We carried out the transformation using the well-known formula:

$$\begin{pmatrix}\Delta e\\ \Delta n\\ \Delta u\end{pmatrix}_{ij} = T\cdot\begin{pmatrix}\Delta X\\ \Delta Y\\ \Delta Z\end{pmatrix}_{ij}$$

where

$$T = \begin{vmatrix} -\sin\lambda_i & \cos\lambda_i & 0\\ -\sin\varphi_i\cos\lambda_i & -\sin\varphi_i\sin\lambda_i & \cos\varphi_i\\ \cos\varphi_i\cos\lambda_i & \cos\varphi_i\sin\lambda_i & \sin\varphi_i \end{vmatrix}$$

φ_i and λ_i are the coordinates of FFGR-43. and j stands for each of the 36 points of the monitoring network.

We converted each Δu_{ij} into ellipsoidal elevation difference Δh_{ij} using the M_i and N_i principal radii of curvature at the reference station and the following well-known formula (spherical approximation), which is appropriate for short vectors:

$$\Delta h_{ij} = \Delta u_{ij} + \frac{(\Delta e_{ij})^2}{2N_i} + \frac{(\Delta n_{ij})^2}{2M_i}\,.$$

"Tabling" the Results. The nine columns in Table 1 summarize the results of our two survey sessions and the subsequent analysis. We gave FFGR-43 arbitrary coordinates ($e_i = n_i$ = 5,000 meters) to render the e_j,n_j coordinates of the network points positive. We set the coordinate u_i at 1,703.78 meters, which is the ellipsoidal height of the reference station.

Columns 2, 3, and 4 (titled "n," "e," and "h") of Table 1 contain the n_j,e_j,u_j coordinates from the first survey session. We used the data in those columns to produce a contour map of the intersection. We computed marker velocities (horizontal $\dot{n}$ and $\dot{e}$ and vertical $\dot{h}$) by dividing the variation in u_j,e_j, and h_j between the first and the second survey by the respective time interval (column 5, or "ΔT," in Table 1).

Columns 6 and 7 (titled "$\dot{n}$" and "$\dot{e}$") show the horizontal components of the velocity vector for each marker. We used those data to draw and superimpose the network's horizontal velocity field on the contour map. The rightmost column (titled "$\dot{abl}$") in Table 1 shows the computed ablation, which we will discuss later.

THEORIES CONFIRMED

We were able to determine the three-dimensional time-variant position of each marker with an accuracy of better than 2 centimeters, relative to FFGR-43, the C-18 reference station. The measurements also confirmed our theories.

As shown in Figure 1, the horizontal velocity field is strongly correlated to the glaciers' topography, with velocities being, in general, normal to the contour lines. The results confirmed our expectations that gravity is the dominant force that moves the glaciers downhill. The two dotted lines represent the middle moraines, which mark the approximate boundaries between the three glaciers as they flow side-by-side downstream.

Similarities in direction and in magnitude of the velocities on both sides of the middle moraines supported our second theory that the moraines are strictly surface features. That would mean that following their merger and the respective compression, the three ice masses continue their motion virtually as a single glacier, with the Gilkey being the dominant glacier in the intersection.

Previous analyses of the surface velocity field in the same area (conducted by the second author in 1990) lead to similar conclusions. There seems to be a strong correlation between the distance downstream between any two adjacent ogives produced by the Vaughan Lewis icefall and the average yearly velocity of that glacier. Additional studies are needed to clarify and quantify this relationship.

RATE OF ABLATION

Although our main objective was to monitor the motion and deformation of the glacier surface using GPS, we found that our two survey sessions provided an excellent opportunity to evaluate directly the rate of ablation at the intersection. The calculated variant three-dimensional relative positions, including precise timing of the measurements, could be used to evaluate the ablation rate.

Column 8 (titled "$\dot{h}$") in Table 1 represents, within the accuracy limits of the two surveys, the average rate of vertical motion of the glacier surface over the respective time

Table 1. Monitoring motion and ablation with GPS at the intersection of three glaciers: the Gilkey, Vaughan Lewis, and Unnamed, August 1995

Point (ID)	n	e (meters)	h	ΔT (hours)	$\dot{n}$	$\dot{e}$ (centimeters per day)	$\dot{h}$	$\dot{abl}$
11	[illegible]	[illegible]	[illegible]	127.4	[illegible]	[illegible]	[illegible]	[illegible]
12	[illegible]	[illegible]	[illegible]	127.7	[illegible]	[illegible]	[illegible]	[illegible]
13	[illegible]	[illegible]	[illegible]	127.5	[illegible]	[illegible]	[illegible]	[illegible]
14	[illegible]	3,406.66	1,084.30	139.9	[illegible]	[illegible]	[illegible]	[illegible]
15	[illegible]	[illegible]	1,090.43	119.8	[illegible]	[illegible]	[illegible]	[illegible]
16	4,907.41	3,087.23	[illegible]	119.8	[illegible]	[illegible]	[illegible]	[illegible]
17	5,208.04	3,073.96	1,118.23	119.8	[illegible]	[illegible]	[illegible]	[illegible]
18	[illegible]	2,832.28	1,109.44	119.7	[illegible]	[illegible]	[illegible]	[illegible]
19	[illegible]	2,801.50	1,132.42	120.0	[illegible]	[illegible]	[illegible]	[illegible]
21	[illegible]	[illegible]	[illegible]	119.8	[illegible]	[illegible]	[illegible]	[illegible]
33	[illegible]	[illegible]	[illegible]	120.7	[illegible]	[illegible]	[illegible]	[illegible]
36	[illegible]	[illegible]	[illegible]	100.7	[illegible]	[illegible]	[illegible]	[illegible]
37	[illegible]	[illegible]	[illegible]	100.0	[illegible]	[illegible]	[illegible]	[illegible]
38	[illegible]	[illegible]	[illegible]	100.4	[illegible]	[illegible]	[illegible]	[illegible]
41	[illegible]	[illegible]	[illegible]	119.8	[illegible]	[illegible]	[illegible]	[illegible]
42	[illegible]	[illegible]	[illegible]	101.4	[illegible]	[illegible]	[illegible]	[illegible]
43	[illegible]	[illegible]	[illegible]	102.1	[illegible]	[illegible]	[illegible]	[illegible]
44	[illegible]	[illegible]	[illegible]	139.9	[illegible]	[illegible]	[illegible]	[illegible]
45	[illegible]	[illegible]	[illegible]	143.8	[illegible]	[illegible]	[illegible]	[illegible]
46	[illegible]	[illegible]	[illegible]	142.7	[illegible]	[illegible]	[illegible]	[illegible]
47	[illegible]	[illegible]	[illegible]	143.1	[illegible]	[illegible]	[illegible]	[illegible]
48	[illegible]	[illegible]	[illegible]	144.3	[illegible]	[illegible]	[illegible]	[illegible]
49	[illegible]	[illegible]	[illegible]	119.8	[illegible]	[illegible]	[illegible]	[illegible]
52	[illegible]	[illegible]	[illegible]	120.1	[illegible]	[illegible]	[illegible]	[illegible]
53	[illegible]	[illegible]	[illegible]	138.3	[illegible]	[illegible]	[illegible]	[illegible]
54	[illegible]	[illegible]	[illegible]	137.9	[illegible]	[illegible]	[illegible]	[illegible]
55	[illegible]	[illegible]	[illegible]	161.3	[illegible]	[illegible]	[illegible]	[illegible]
56	[illegible]	[illegible]	[illegible]	161.0	[illegible]	[illegible]	[illegible]	[illegible]
57	[illegible]	[illegible]	[illegible]	144.9	[illegible]	[illegible]	[illegible]	[illegible]
58	[illegible]	[illegible]	[illegible]	161.4	[illegible]	[illegible]	[illegible]	[illegible]
59	[illegible]	[illegible]	[illegible]	137.9	[illegible]	[illegible]	[illegible]	[illegible]
61	[illegible]	[illegible]	[illegible]	161.5	[illegible]	[illegible]	[illegible]	[illegible]
62	[illegible]	[illegible]	[illegible]	161.7	[illegible]	[illegible]	[illegible]	[illegible]
63	[illegible]	[illegible]	1,100.05	161.7	[illegible]	[illegible]	[illegible]	[illegible]
64	[illegible]	[illegible]	[illegible]	161.5	[illegible]	[illegible]	[illegible]	4.2
65	[illegible]	3,864.49	1,097.96	138.3	[illegible]	[illegible]	[illegible]	5.9

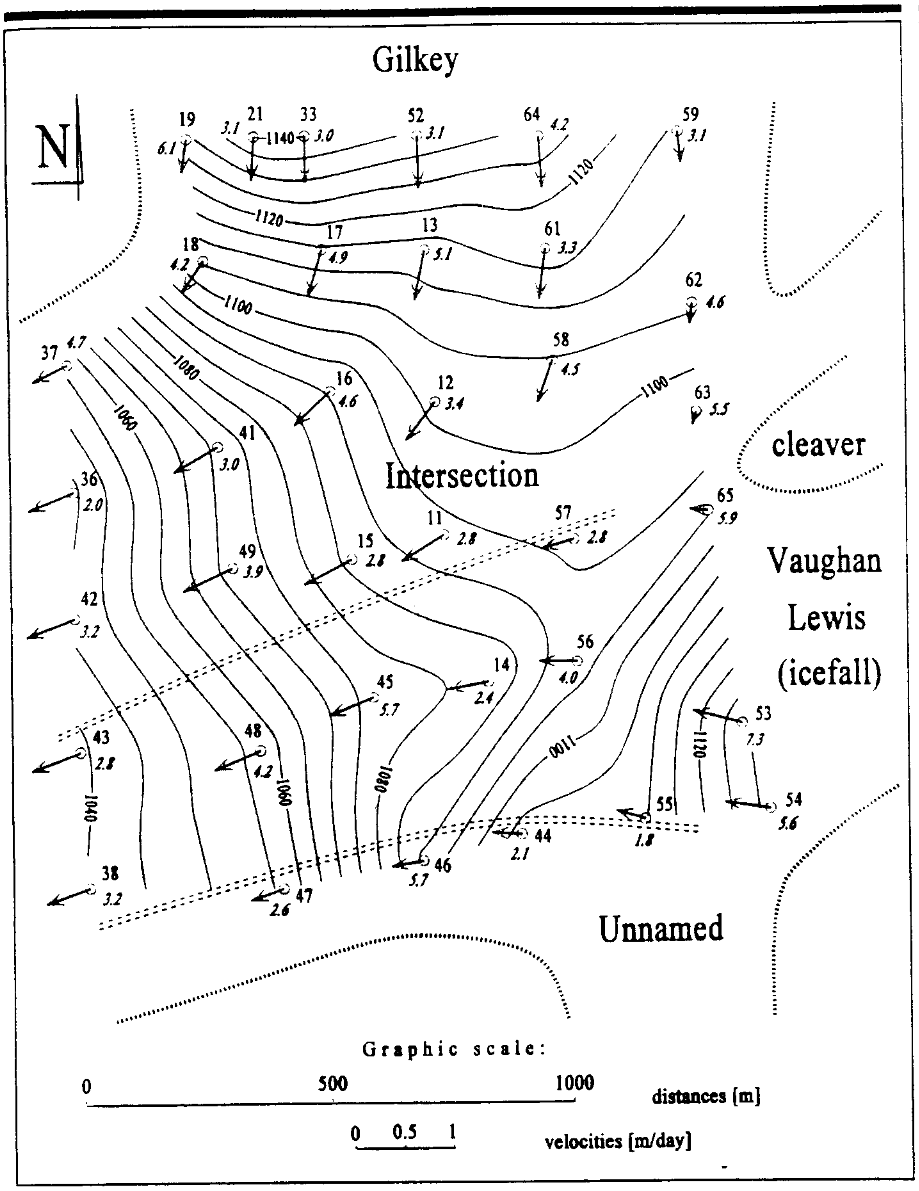


Figure 1. From the two complete sets of GPS measurements of the 36-point monitoring network, the authors were able to create this figure, which shows the velocity field of the glacier intersection superimposed on the topography. The numbers in roman type represent the velocity of the glaciers, and the arrows indicate the direction of movement. The figure also features point values of ablation in italicized type.

interval. The vertical motion of each marker was caused by two entirely different phenomena:

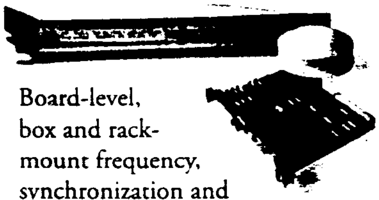
- ablation resulting from the melting, evaporation, and compression of the ice slab; and
- downward movement because of the downhill motion of the glacier.

Not having at our disposal any direct measurement of ice thickness at the intersection, we made the assumption that, on the average, the bottom and the surface of the glacier were parallel. The contour map together with the velocity field of the network served as a database for evaluating the ablation at each marker. We used the following formula:

$$abl = \dot{h} - \sqrt{\dot{e}^2 + \dot{n}^2} \cdot \cos\theta \cdot \frac{1}{m}$$

where abl is the daily rate of ablation, θ is the angle between the horizontal velocity vector and the gradient of the topography, and 1/m is the slope (magnitude of the gradient) at the *j*th marker.

The numbers in italics in Figure 1, next to each marker, represent the ablation rate in centimeters per day. The average rate of abla-



tion over the entire intersection was 3.9 centimeters per day, with a variance of 1.8 centimeters per day squared. We determined the accuracy (standard deviation) of the estimated ablation rates to be about 1.0 centimeter per day.

We must point out that the surface-to-bottom parallelism assumption is most probably wrong in certain parts of the intersection. Factors not considered in our analysis (due to lack of data) were variations in ice color and other relevant properties of the glaciers that could have an effect on heat absorption and ablation.

GPS AND FUTURE SURVEYS

Because of its accuracy, speed, and ease of operation over long distances with no need for intervisibility, it's not surprising that GPS has become the favored tool for monitoring motion and deformation of the earth crust. From our experience, we found it to be ideal for monitoring glaciers, as well. Thanks to GPS, we were able to determine the position of FFGR-43 at camp C-18 relative to a number of IGS stations with a formal accuracy of better than 10 centimeters.

This will be a great help for us and for other researchers. Using the same reference station in future GPS surveys in the area, we will be able to determine long-term yearly motion patterns of the glaciers. Similarly organized GPS surveys of other glaciers in the Juneau Icefield could serve as an excellent basis for obtaining a consistent picture of absolute motions of the ice masses relative to the practically inertial bedrock and the stable worldwide WGS84 reference system. In one of the forthcoming summers, we intend to repeat measurements of the Gilkey intersection by an optimal combination of GPS, total-station, and photogrammetric surveys.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of the Foundation for Glacier and Environmental Research, which made our participation in JIRP 95 possible. In particular, we would like to thank Dr. Maynard M. Miller, the director of the Juneau Icefield Research Program, for his enthusiastic and unconditional support and encouragement. We are indebted to Dipl.-Ing. Martin Lang from the Bundeswehr University Munich, Germany, for providing us with valuable data and suggestions. Last but not least, we would like to thank Mr. Shmuel Grossman from Tel Aviv, Israel, for lending us his precious GPS receivers and for letting us take them on a long and hazardous journey to the Juneau Icefield. ■

MANUFACTURERS

The authors carried out their 10-day motion study of the Gilkey trench using two Z-12 GPS receivers from **Ashtech** (Sunnyvale, California). At the end of the second session, they used Ashtech PNAV software to process the data.