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Subject: International Assignment; Executive Summary

Date: 2 June 2000

To: Jerry Hammond
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A. **Background**: I attended the Eighth International Conference on Ground Penetrating Radar. The conference was held at the Gold Coast, Queensland, Australia, on 23 to 26 May 2000. The University of Queensland and the Cooperative Research Centre for Sensor Signal and Information Processing (CSSIP) hosted the conference. I authored and presented a paper entitled "Improved radar interpretations of water table depths and groundwater flow patterns with predictive equations" (see Enclosure 1). I was also selected to chair a session on "Geological Applications."

B. **Participants:** Enclosure 2 is a listing of the conference participants. Participants were from twenty-seven countries and represented universities, government agencies, consultants, and manufacturers involved with ground-penetrating radar.

C. **Benefits:** This is the only conference in the world devoted solely to ground-penetrating radar (GPR) and is my principle interaction with this geophysical community. The conference is held every two years and offers presentations and exchanges of ideas, applications and design innovations for GPR. It allows me to renew and form contacts within an international community. The conference helps to insure NRCS's leadership, technical knowledge, and expertise with GPR. At a conference session, I was introduced as one of the "Godfathers of GPR." This introduction before this community provided a most special and personal boost to our work and me.

D. **Follow-up Plans:** I convened an informal discussion on the use of GPR to investigate tree roots and its potential role in monitoring carbon sequestration. Since January 2000, I have been involved with the USDA-Forest Service in this endeavor. The informal group consisted of Dr Tony Farmer of CISRO-TIP, Dr Kelvin Montagu of the Forestry Department of New South Wales, and Dr Lucian Wielopolski of the Brookhaven National Laboratory, USDOE. We arranged a field demonstration of GPR to detect tree roots by Mala Geoscience. The group plans to correspond, share results, and work with John Butnor (Biologist, USDA-FS, Research Triangle, NC) in preparing research papers.

   Discussed equipment needs with Peter Haeni and John Lane of the US Geological Survey. The graphic recorder of the radar unit that was given to the NRCS Soil Staff in New York by the National Soil Survey Center (NSSC) is malfunctioning and is in need of repair. Pete Haeni (Chief, Geophysical Applications) offered to transfer two SIR-3 radar units with a supply of paper to the NSSC. If this proposal is acceptable to my supervisors (Drs Robert Ahrens and Carolyn Olson), transfer will take place in early July 2000. These units can be transferred to New York.

   Significant advancements have been made in image processing and the use of two- and three-dimensional models. The NSSC has appropriate software, but I am in need of training on its use. Geophysical Survey Systems, Inc., of North Salem, New Hampshire, has offered to provide training to me at no charge. I will request the opportunity to attend training next fiscal year.

   The participation of soil scientists and the agricultural community grew at this conference. Three papers were presented dealing with soils by Dr Ronald Yoder (University of Tennessee), Gary Paterson (ISCW, South Africa) and myself. I was approached to organize special sessions on soil and agricultural applications of GPR for the Ninth International Conference on GPR (2002) and the Annual Meeting of the Environmental and Engineering Geophysical Society (Denver, March 2001). The geophysical community is largely uninformed of the uses of GPR and electromagnetic induction within the agricultural sectors.

   I was greatly gratified to have the opportunity to attend this conference and confer with other knowledgeable users on various topics relating to GPR. My confidence in my work and interpretations has been immeasurably bolstered. I was humbled and appreciative of the views within the international GPR community of the role that our agency has played in the use and development of this technology.

With kind regards,

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Enclosure 1.

Doolittle, J. A., B. J. Jenkinson, D. P. Franzmeier, and W. Lynn. 2000. Improved radar interpretation of water table depths and ground-water flow patterns from predictive equations. 488-493 pp. IN: Proceeding of the Eighth International Conference on Ground-Penetrating Radar. David A. Noon, Glen F. Sticky, and Dennis Longstaff (editors). May 23 to 26, 2000, Gold Coast, Queenland, Australia. SPIE Vol. 4084. 908 p.

IMPROVED RADAR INTERPRETATIONS OF WATER TABLE DEPTHS AND GROUND-WATER FLOW PATTERNS WITH PREDICTIVE EQUATIONS

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ABSTRACT

Recent interest in soils and hydrologic modeling has increased the need for information concerning the depth and movement of ground water. Ground-penetrating radar (GPR) was used eight times over a two-year period to chart water table depths and ground-water flow patterns within a 32-ha forested site in northwestern Indiana, USA. Radar imagery was correlated with depths to the water table in 16 observation wells. The velocity of propagation ranged from 0.0508 m/ns to 0.1606 m/ns at these wells. Propagation velocities were generally slower during the spring and early summer months when depths to the water table were relatively shallow. Propagation velocities were faster through dunes than through the more poorly drained interdunes. Because of the spatiotemporal variability in propagation velocities and the known complexity of soil and landform patterns, a predictive equation based on water table depths and two-way travel times was developed for each GPR survey. In this setting, the use of a predictive equation based on multiple GPR measurements over a known reflector substantially improved the accuracy of radar depth interpretations over single or averaged measurements.

Key words: ground-water flow patterns, velocity of propagation, water table.

INTRODUCTION

The depth and movement of ground water through landscapes affect the physical and chemical properties and the morphology of soils (Richardson et al., 1992). Redoximorphic features, distribution of secondary carbonates and bases, and the development of morphological features in soils have been related to the depth, fluctuation, and movement of water tables and to recharge and discharge processes (Simonson and Boersma, 1972; Franzmeier et al., 1983; Knuteson et al., 1989; Richardson and Daniels, 1993; and James and Fenton, 1993).

Traditionally, information on the depth and movement of ground water has been obtained by in-situ measurements at monitoring or observation wells. By recording water levels in these wells, depths to the water table are determined and potentiometric maps can be prepared. Typically, potentiometric maps are prepared from data collected from a few, widely spaced wells. These wells provide detailed information about soil and hydrologic conditions at specific points. However, hydrologic conditions for the areas among and beyond the wells must be inferred. In relatively level landscapes containing homogeneous soil and geologic strata, hydrologic conditions are often relatively uniform and predictable. In areas of intricate and contrasting soil patterns, undulating topography, and non-homogeneous or anisotropic materials, depths to the water table and flow patterns are difficult to assess. Often in such areas, because of limited data, hydrologic models and maps are simplistic and susceptible to errors (Violette, 1987). Improved methods are needed to better understand the depth, flow, and seasonal variations of the ground water through complex landscapes.

New tools are available to chart water table depths and ground-water flow patterns. In areas of coarse-textured sediments, GPR can provide a continuous record of the water table, more comprehensive coverage of sites, and significantly reduce the number of wells. Ground-penetrating radar has been used to chart water table depths among observation wells and into nearby areas (Johnson, 1987; Bohling et al., 1989; Iivari and Doolittle, 1994). In addition, GPR has been used to provide data for hydrologic models (Violette, 1987; Taylor and Baker, 1988), define recharge and discharge areas (Johnson, 1987; Bohling et al., 1989), predict ground-water flow patterns (Steenhuis et al., 1990; Iivari and Doolittle, 1994), and delineate near-surface hydrologic conditions (Beres and Haeni, 1991).

Proper radar interpretations of water table depths and ground-water flow patterns require accurate depth scales. These scales are based on the average velocity of pulse propagation through the vadose zone. The velocity of propagation is principally affected by changes in soil moisture contents and is therefore spatiotemporally variable. The objectives of this study were to (1) measure the spatiotemporal variations in the average velocity of pulse propagation and (2) assess statistical methods for determining the depth scale across a topographically diverse landscape.

STUDY SITE

A 32-hectare site was selected in northeastern Jasper County, Indiana (see Figure 1). The study site is within a broad, poorly drained physiographic region known as the Kankakee outwash and lacustrine plain (Mallot, 1922). During Wisconsinan glaciation, sandy outwash was deposited across portions of this region. Thickness of these deposits ranges from about 15 to more than 60 m (Fenelon, 1994). Some of these deposits were later reworked by wind into low (1 to 10 m) transverse sand dunes.

Figure 1 contains a three-dimensional contour plot of the study site. The site consists of two major dunes separated by lower-lying, nearly level interdunes. Within the study site, relief is about 10 meters. Soils consist of about 50 to 90 percent fine sands, 0 to 25 percent very fine sands, and less than 10 percent silts and clays. Soil patterns within the site are intricate. On dunes, soils are well drained. Soils on lower-lying interdune areas are more poorly drained and have higher clay, organic matter, and/or water contents than soils on dunes. Soils on interdune areas are frequently ponded for brief periods by runoff from surrounding areas and have water tables that are often near or above the surface during the winter and spring (Smallwood and Osterholz, 1990).

The vegetation is an oak-hickory forest (Petty and Jackson, 1966). During the late spring and summer, as leaves emerge, plant roots absorb large quantities of soil water and the water table is rapidly lowered. With the cessation of the growing season in early fall, the water table begins to rise.

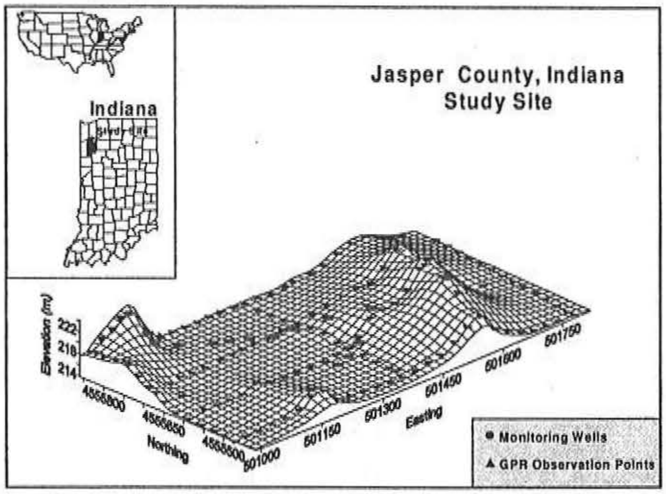

Figure 1. Three-dimensional surface net diagram of the study site showing the locations of the monitoring wells, GPR observation points, and transect lines. Coordinates are in Universal Transverse Mercator (UTM) and expressed in m.

FIELD PROCEDURES

A Subsurface Interface Radar (SIR) System-2, manufactured by Geophysical Survey Systems, Inc.[1] was used in this study. This unit is backpack portable and, with an antenna, requires two people to operate. Investigations were completed with 120, 200, and 300 mHz antennas. However, only the data obtained with the 200 mHz antenna are discussed in this paper.

Two radar traverse lines were laid out connecting the sixteen wells (16 reference points). These observation wells had been previously installed to measure depths to the water table and estimate the directions of ground-water flow. Wells were installed on both dune and interdune areas, in different soil types, and to an average elevation of 213 m. At the time of each radar survey, the depth to the water table was measured in each well and correlated with the radar imagery.

To estimate water table depths and ground-water flow patterns across the site, radar traverse lines were established on three, north-south and two, east-west access trails. The

[1] Manufacturer's names are provided for specific information; use does not constitute endorsement.

length of each north-south trail is about 400 m. The length of each of the east-west trails is about 800 m. Two additional interior lines were established through the woods. The lengths of these lines are about 640 and 700 m. Along each of these seven lines, reference flags were inserted in the ground at 30-m intervals. This procedure provided 147 observation points. The coordinates and elevation of each reference and observation point were obtained using standard surveying methods. The locations of these points are shown in Figure 1.

Radar surveys were conducted at intervals of three to four months. Pulling the 200 mHz antenna along each of the nine lines completed the radar surveys. As the antenna passed each observation or reference point, a vertical mark was impressed on the radar profile. At each marked point on the radar profile, the water table reflection was identified and the two-way travel time to this reflector was measured.

DATA ANALYSIS

Ground-penetrating radar measures the time it takes electromagnetic energy to travel from an antenna to an interface (i.e., soil horizon, water table, stratigraphic layer) and back. To convert travel time to depth requires knowledge of the velocity of pulse propagation. Several methods are available to determine the velocity of propagation. These methods include use of table values, common midpoint calibration, and calibration over a target of known depth. The last method is considered the most direct and accurate method to estimate propagation velocity (Conyers and Goodman, 1997). The procedure involves measuring the two-way travel time to a known reflector on the radar profile and calculating the propagation velocity by following equation (after Morey, 1974):

$$V = 2D/T \qquad [1]$$

Equation [1] describes the relationship of the average propagation velocity (V) to the depth (D) and two-way pulse travel time (T) to a reflector. At each of the sixteen wells, the two-way radar pulse travel time was compared to the water level and used to estimate the velocity of propagation. During the course of this study, the measured depth to the water table ranged from 0.0 to 10.14 meters. The estimated velocity of propagation determined at each well and for each sampling period is shown in Table 1.

The velocity of propagation is both temporally and spatially variable. Temporal variations are attributed to snowmelt, rainfall, and throughflow events that influence soil moisture contents. In general, higher propagation velocities were recorded during the months of August through February compared to the months of March through July. During the latter months, soil moisture contents are higher and the depth to the water table is shallower (higher elevation).

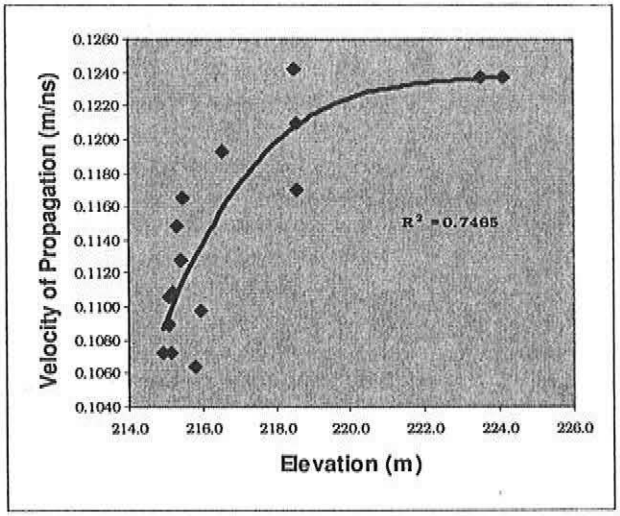

Figure 2. Relationship between the averaged propagation velocity and elevation at each well site.

Lateral variations in propagation velocity occur as a result of changes in soil properties (i.e., amount of organic matter, clay, and moisture contents). Figure 2 shows the relationship between the averaged propagation velocity and the elevation of each well. Soils on dunes (elevations >217 m) are better drained, above from the influence of the water table, and have faster propagation velocities. On dunes, the mean propagation velocity was 0.1214 m/ns for the well drained Oakville soils and 0.1156 m/ns for the somewhat poorly drained Morocco soils. Propagation velocities are slower on the lower-lying interdune areas (< 217 m). On the lower-lying interdune, the mean propagation velocity was 0.1095 m/ns and 0.1098 m/ns for the very poorly drained, Newton and Zadog soils, respectively. For each soil type, a range of propagation velocities was observed.

The velocity of propagation and the dielectric permittivity were spatiotemporally variable among the wells. The calculated velocity of propagation ranged from 0.0508 m/ns to 0.1606 m/ns at the sixteen wells. The estimated dielectric permittivity ranged from 3.5 to 35. Because of this variability it would be difficult to accurately predict water table depths across the expanded site using a single or mean velocity of propagation.

If a mean propagation velocity was used for each of the eight radar surveys, the average difference between measured and predicted depths to the water table at the sixteen wells would be about 0.46 m with a maximum difference of 3.62 m. If a mean propagation velocity was used for each landscape component (dune or interdune area), the average difference between the measured and the predicted depth to the water table at the wells would improve slightly to 0.34 m, but with a maximum difference of 3.98 m. To measure the depth to the water table and assess ground-water flow patterns, these differences between the measured and the predicted depths are considered unacceptable.

Because of the spatiotemporal variability in propagation velocities and the known complexity of soil and landform patterns, a predictive equation based on water table depths and two-way travel times was developed for each GPR survey. The measured depth and the two-way travel time to the water table at the sixteen wells were compared. For each GPR survey, a strong relationship (r^2 ranged from 0.9926 to 0.9994) was found to exist between the two-way travel time of the radar pulse and the measured depth to the water table (see Table 2).

A least square line was fitted to the data for each survey and used to predict the depth to water table at all observation and reference points. The relationship is expressed as:

$$D = b + aT \qquad [2]$$

Where D is the depth to the water table, T is the two-way travel time to the water table reflection, b is the intercept term, and a is the slope of the line. Bohling and others (1989) found that three wells were sufficient to correlate radar-interpreted and observed water table depths. In this study, all sixteen wells were used to correlate the two data sets.

For the eight radar surveys, using predictive equations, the average difference between the measured and the predicted depth to the water table at the sixteen wells was 0.16 m with a maximum difference of 0.69 m. Half of the predicted water table depths were within -0.14 to 0.13 m of the measured values. The use of a predictive equation substantially improved the precision of radar depth interpretations over single or landform averaged measurements.

GROUND-WATER FLOW PATTERNS

For each radar survey, a predictive equation was developed to estimate the depth to the water table. At each observation point, the elevation of the water table was determined by subtracting the interpreted depth to the water table from the ground surface elevation. Figure 3 contains two-dimensional plots simulating the elevation of the water table surface at different times of the year (1998-1999) within the survey site. In each plot, a two-dimensional simulation of water table elevations has been overlaid upon a three-dimensional surface net of the study site. In each of the overlaid two-dimensional plots of water table elevations, the isoline interval is 0.5 m. These lines are equipotential lines as they connect points of equal pressure head. The arrows indicate the conceptual flow paths of water. Flow lines cross equipotential lines at right angles. Water flows from areas of higher to areas of lower equipotential values.

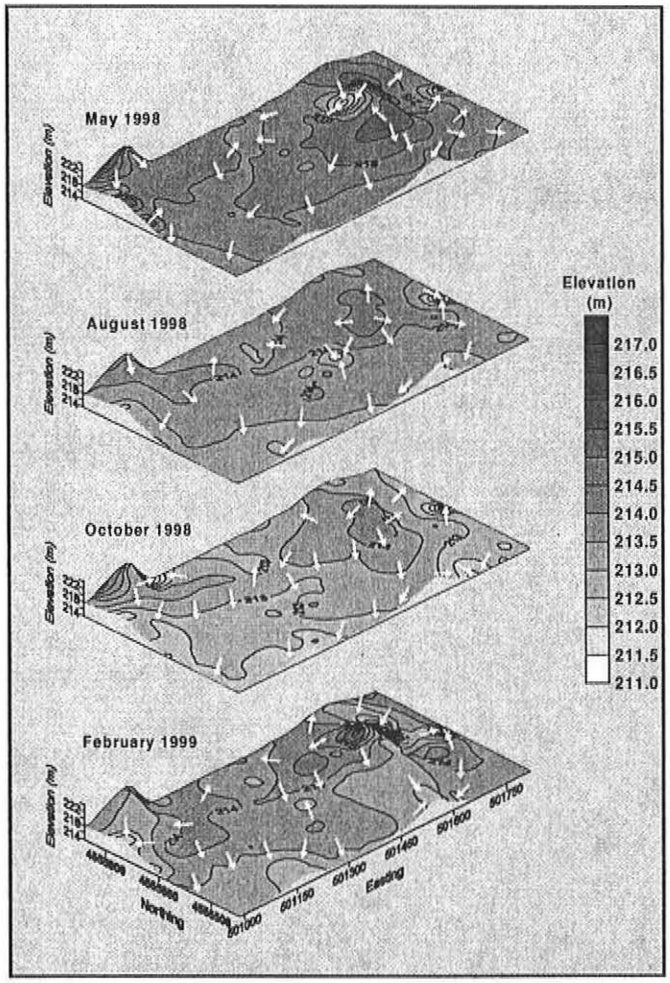

Figure 3. Plots of water table elevations superimposed on three-dimensional surface net diagrams of the study site. Based on GPR surveys conducted in 1998 - 1999. Directions of ground-water flow have been indicated with arrows.

The plots in Figure 3 show the spatial and temporal variations in water table depths. The water table mounds under dunes and is at a lower elevation beneath the adjoining interdunes. The dunes are recharge areas; the interdunes are discharge or flow-through areas. However, GPR data indicates that the water table does not always follow this pattern. In late winter and early spring, the water table rises faster in the interdune area. As the water table rises, water flow reverses in some portions of the interdune area, discharging into portions of the dunes.

CONCLUSIONS

In areas of coarse-textured sediments, GPR can provide comprehensive coverage of sites and reduces the number of monitoring or observation wells needed for water table and ground-water flow studies. The velocity of propagation was found to be spatiotemporally variable across a 32-hectare, topographically diverse study site having intricate soil patterns. Propagation velocities were faster on well drain soils on dunes than on more poorly drained and somewhat poorly drained soils on lower-lying interdunes. Propagation velocities were slower during the months of March through July. During these months, soil moisture contents are higher and the water table is closer to the surface. In this setting, the use of a predicted equation based on multiple GPR measurements over a known reflector substantially improved the accuracy of radar depth interpretations over single or averaged measurements. The use of predictive equations increased confidence in radar-interpreted depth measurements of the water table and ground-water flow patterns.

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Table 1 – Estimated Velocities of Propagation. Estimates were determined using the two-way travel time to the water table reflection that appeared on radar profiles, the measured depth to the water table at each monitoring well, and equation [1]. Velocity is expressed in m/ns. Elevations are expressed in meters.

Soil	Well #	Elevation	Jul-97	Jan-98	May-98	Aug-98	Oct-98	Feb-99	Apr-99	Jul-99	Mean Velocity
Oakville	1	223.49	0.1129	0.1369	0.1082	0.1321	0.1409	0.1426	0.0824	0.1338	0.1237
Oakville	12	224.11	0.1068	0.1382	0.0956	0.1320	0.1412	0.1441	0.0928	0.1389	0.1237
Oakville	11	218.55	0.1074	0.1289	0.1239	0.1363	0.1292	0.1328	0.0820	0.1262	0.1209
Oakville	14	218.55	0.0813	0.1289	0.1191	0.1363	0.1292	0.1328	0.0820	0.1262	0.1170
Oakville	2	218.52	0.1033	0.1283	0.1175	0.1291	0.1283	0.1580	0.0856	0.1433	0.1242
Oakville wet	10	216.55	0.0967	0.1127	0.1153	0.1223	0.1310	0.1257	0.0898	0.1606	0.1193
Oakville wet	9	215.96	0.0803	0.1169	0.1158	0.1214	0.1125	0.1110	0.0770	0.1438	0.1098
Brem	15	215.79	0.0813	0.1092	0.0820	0.1214	0.1233	0.1159	0.0817	0.1364	0.1064
Morocco	16	215.45	0.0781	0.1301	0.0603	0.1336	0.1494	0.1450	0.0980	0.1373	0.1165
Newton	8	215.42	0.0637	0.1164	0.1133	0.1249	0.1392	0.1126	0.0758	0.1569	0.1128
Morocco	17	215.33	----	0.1206	0.0508	0.1312	0.1441	0.1294	0.0891	0.1383	0.1148
Newton	7	215.22	0.0639	0.1206	0.0826	0.1161	0.1411	0.1056	0.1071	0.1505	0.1109
Newton	6	215.14	0.0599	0.1251	0.0590	0.1121	0.1394	0.1079	0.1037	0.1501	0.1072
Zadog	4	215.11	0.0587	0.1175	-----	0.1271	0.1296	0.1146	0.0965	0.1307	0.1106
Zadog	3	215.07	0.0587	0.1149	0.1439	0.1102	0.1281	0.0952	0.0989	0.1213	0.1089
Newton	5	214.91	0.0547	0.1006	----	0.1305	0.1282	0.1063	0.0882	0.1419	0.1072
Mean velocity		----	0.0805	0.1216	0.0991	0.1260	0.1334	0.1237	0.0894	0.1398	0.1146
Mean Water Table Elevation			214.84	214.10	214.98	214.16	213.63	213.94	214.30	214.13	----

Table 2 - Summary of Basic Statistics. Prediction of water table depths based on regression of measured water table depths with two-way travel times to the water table. Comparison is based on observations obtained at sixteen observation wells. The range in water table and residuals are in m.

Date of Observation	Water Table Minimum Depth	Water Table Maximum Depth	r^2	Maximum Residual	Standard Error	Student T
July 1997	0.75	9.22	0.9977	0.22	0.001	53.41
Jan. 1998	0.63	9.86	0.9989	0.28	0.001	77.01
May 1998	0.00	8.71	0.9926	0.66	0.002	32.45
Aug. 1998	0.78	9.28	0.9994	0.18	0.001	107.66
Oct. 1998	1.37	10.14	0.9972	0.41	0.001	48.78
Feb. 1999	0.82	10.13	0.9970	0.68	0.002	46.96
Apr. 1999	0.68	9.85	0.9964	0.69	0.001	42.05
July 1999	0.91	9.96	0.9979	0.44	0.001	36.94

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